NATIONAL
FIRE PROTECTION
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Halon 1301 Discharge Testing:

A Technical Analysis

by Philip J. DiNenno, P.E.
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Prepared by:
National Fire Protection Research Foundation
Quincy, MA 02269 USA

Authors:
Philip J. DiNenno, P.E., and
Edward K. Budnick, Jr., P.E.
Hughes Associates, Inc.
Wheaton, MD 20902 USA

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This report fulfills the commitment to assemble a bibliography and analysis of the related technical issues, comprehensive through the summer of 1988.

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ABSTRACT

This report summarizes the results of a literature review and analysis on the technical issues and alternatives to Halon 1301 total flooding system discharge tests. The need for alternatives is driven by the environmental risk of ozone depletion due to Halon 1301 emissions. Seven objectives of discharge testing are identified. From these seven objectives, three predominant areas of technical uncertainty emerged: (1) methods of flow calculation, (2) mixing of nozzle flows and initial distribution of agent, and (3) post discharge leakage from enclosures. The review focuses on these three areas.

The technical literature is analyzed relative to the ability of current technology to eliminate or reduce the need for discharge testing with Halon 1301. Several strategies are proposed for the resolution of the problem. Near and moderate term research, development, testing, and evaluation objectives are developed relative to these strategies.

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EXECUTIVE SUMMARY

Background

Recent concerns regarding the potential impact of Halon 1301 fire suppression system discharge testing on the depletion of stratospheric ozone has led to re-evaluation of the need for such testing. As part of this re-evaluation a technical literature review and analysis were performed to (1) identify the relationships between discharge testing and system performance, (2) examine potential alternatives, and (3) identify any technical gaps requiring further study.

While not expressly required in NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems* (1987 ed.), a recommended procedure for such testing is provided as an appendix to the standard. Discharge tests, frequently conforming to the procedures outlined in NFPA 12A, are conducted to evaluate installed systems. The primary design and installation parameters to be evaluated in discharge tests include:

(1) Mechanical integrity of piping, connections, etc.;
(2) Detector/control device and interface functions;
(3) Flow characteristics through piping;
(4) Nozzle discharge and mixing; and
(5) Compartment integrity (e.g., leakage)

These parameters are examined through attainment of several critical objectives implicit in the discharge testing procedures. These objectives are:

(1) Verification of hardware integrity and absence of foreign material or obstructions in the piping and hardware system;
(2) Verification of the operation of detection/actuation/alarm system components;
(3) Verification of adequate initial agent distribution;
(4) Verification of design concentrations;
(5) Verification that discharge time is within required limits;
(6) Verification of enclosure boundary integrity; and
(7) Verification that agent discharge does not present a hazard to the enclosure or its contents, and to personnel.

Beyond compliance with NFPA 12A, hardware components and proprietary flow calculation programs are listed by Underwriter's Laboratories, Inc. (UL) under UL Standard 1058, *Halogenated Agent Extinguishing Systems Units.* The impetus for these listing procedures is a concern for the uncertainties associated with flow hydraulics and nozzle performance, two critical factors in actual system performance.

The available data on acceptance test failure rates and *in situ* reliability and performance does not permit a rigorous, quantitative assessment of the adequacy of total flooding Halon 1301 fire suppression systems. However, a qualitative review of the data provides a non-statistical but reasonable assessment of performance and failure expectations. For example, the dominant cause of acceptance test failure appears to be enclosure leakage. Even though the designer of a total flooding Halon 1301 fire suppression system cannot be expected to directly control leakage sources in construction and ventilation systems, some means of assessing leakage magnitudes is necessary to assure successful in situ performance. Another significant cause of acceptance test failures included difficulties with attainment of initial agent concentrations. This is potentially the result of incorrect flow calculations and pipe sizing, and/or problems with nozzle performance. These problems are within the purview of the design engineer, as well as the standard's organizations and listing laboratories.

It would appear from the available experience that the objectives implicit in acceptance test procedures are valid and must be maintained. Therefore, any attempt to substitute for full discharge testing should preserve and incorporate the objectives of discharge testing.

Of the seven objectives implicit in discharge testing, several can be accomplished by direct substitution of alternative procedures. These include: (1) piping and mechanical component integrity, (2) detection/alarm/actuation component performance, and (3) limited evaluation of unwanted discharge effects. However, limitations in our technical understanding of several aspects of Halon 1301 discharge in enclosures limits our ability to directly substitute for other discharge test objectives. These objectives include determination of:

(1) initial agent concentration;
(2) spatial distribution of the agent;
(3) discharge time; and
(4) enclosure integrity.

These objectives can be directly related to three technical aspects of Halon 1301 design: the accuracy of agent flow calculation procedures, nozzle discharge and mixing characteristics, and the effects of enclosure leakage.

Flow Calculations

A source of uncertainty in the design of Halon 1301 systems lies in the agent flow calculation procedures. Halon 1301 discharge is characterized by two phase flow. Essentially, the fluid goes through a partial phase change from liquid to gas as it flows through the piping. This complicates estimation of pressure drop and agent distribution along separate branches of piping. The effects of these complications are greater in systems designed with unbalanced pipe networks, e.g., systems which supply large or multiple enclosures.

The NFPA 12A Standard provides design procedures for both balanced and unbalanced flow. The procedures associated with balanced flow problems are relatively straightforward. However, the complexities inherent in unbalanced flow potentially exaggerate the uncertainties embodied in the procedures. A qualitative sense of several sources of potential errors is provided in Section 2 in a detailed discussion of two phase flow phenomena and the NFPA 12A flow calculation procedures. A discussion of the "critical" assumptions associated with the flow calculation procedures offers a sense of the uncertainty and potential inaccuracies. Examples of critical assumptions include:

(1) the procedure assumes a homogeneous flow regime;

(2) all calculations are based on "average" homogeneous fluid conditions;
(3) the expressions for pressure and density dependent variables (e.g., Y,Z factors) as well as tabulated values for these variables are not documented, and cannot be replicated from general expressions for two phase flow; and
(4) equivalent lengths are treated similarly to those for water flow for hydraulic calculation purposes.

In addition, there are several other sources of potential error in the calculation procedures (detailed further in Section 2). While the magnitude of the effect of these sources of error on actual flow conditions cannot be determined without detailed study and empirical work, one would expect such errors to manifest themselves in several ways. For instance, the system may not provide adequate initial agent concentrations, spatial distribution may be poor, and discharge times may be excessive. The limited discharge test failure rate data available for Halon 1301 systems indicate the existence of such problems, in some cases requiring modifications to the flow characteristics of the system to correct for these deficiencies.

A further complication regarding the accuracy of flow calculation procedures involves the development and use of proprietary computer programs. Manufacturers have developed such programs which incorporate several "correction" factors to compensate for inaccuracies implicit in the flow calculation procedures. To assure a reasonable level of consistency UL lists these computer programs in accordance with UL 1058. Briefly, UL compares the results from the computer program for several design cases against actual discharge test results. The cases are designed to examine "worst case" conditions relative to a wide range of performance parameters.

While every effort is made to test the limits of the flow calculation procedures, a true parametric evaluation cannot reasonably be performed. The large number of tests required to evaluate program validity across the range of likely flow conditions to be encountered is prohibitive.

These limitations, along with (1) important assumptions regarding the completeness and interrelationships of the performance parameters considered in UL 1058, and (2) the absence of rigorous evaluation of the computer programs' limits (e.g., functional limits of the algorithms) directly impacts any estimates of the confidence limits, presumed or otherwise. The current practice of discharge testing obviates most of the uncertainty associated with these limitations. However, if one considers elimination of such testing, the need to accurately assess flow calculations and minimize the relative uncertainties becomes necessary. This would require a far more rigorous treatment of the flow processes prevalent in Halon 1301 system discharge.

An approach to this problem would be to develop an agreed upon benchmark calculation procedure as a standard, similar to the hydraulic calculation procedure in NFPA 13, *Standard for the Installation of Sprinkler Systems*. This standard could be used in a comparative manner for extensive evaluation of proprietary programs. Such a calculation procedure is within the state of the art. Benchmark two phase flow calculation procedures developed for application in other industries are described in Section 2.

Nozzle Mixing and Agent Distribution

Adequate mixing and distribution of agent in the protected enclosure are critical factors with regards to performance. Discharge tests provide some measure of effectiveness in terms of the adequacy of nozzle design and placement, and the effects of flow obstructions in the enclosure. In order to provide some measure of these factors in the absence of discharge testing, methods to characterize nozzles and account for flow and mixing in an enclosure are needed.

Considerable work has been done in other areas (e.g., fuel spray combustion, spray drying) directed at characterization and optimization of spray nozzles for specific applications. Some of this work is reviewed in Section 3. In addition, studies directed at mixing and distribution of Halon 1301 in enclosures indicate that satisfactory performance is usually achieved in simple enclosure geometries with maximum ceiling heights on the order of ten to twelve feet. Problems appear most prevalent in large, complex enclosures with high ceilings.

Since precise limits cannot be readily determined, elimination of discharge testing based on enclosure geometry criteria introduces some uncertainty. An alternative would be to develop an analytical procedure for predicting the nozzle mixing and agent distribution in an enclosure. A framework for such an approach is presented in Section 3, based essentially on forced jet entrainment theory. While not explicitly addressing all of the necessary nozzle characteristics the methodology provides a means of analysis which goes beyond the single parameter approach currently used in UL 1058 (e.g., nozzle spacing).

Additional work is needed to: (1) verify the approach experimentally, and (2) develop means/procedures for empirically measuring specific nozzle characteristics. However, it is not beyond the technical state of the art, and could be accomplished in a reasonable time period. This would eliminate the dependence on discharge testing to evaluate nozzle mixing and agent distribution.

Enclosure Leakage

A substantial fraction of the discharge test failures has been attributed to enclosure leakage. Such leakage can be caused by mechanical and weather induced pressure differentials and hydrostatic pressure differentials resulting from Halon 1301/air mixtures.

The technical feasibility of replacing total discharge testing of leakage affects with an alternative procedure appears attainable. Such a procedure must:

(1) determine leakage rates and locations;
(2) account for appropriate ranges of pressure differentials and flow directions; and

(3) provide accurate prediction of Halon 1301/air mixture concentrations relative to required design concentrations.

The most viable approach involves some combined use of simulant test gases and fan pressurization. Such an approach should account for the primary physical processes influencing enclosure leakage and agent concentrations.

Further development and testing of these techniques is encouraged. The key to successful use of door fan pressurization techniques in the prediction of halon leakage (other technical issues notwithstanding) is the ability to correlate leakage area with halon concentration decay. Various methods for scaling total leakage area have been proposed, including dividing total leakage area by the total floor area.

Ongoing work on development of simulant test gases is promising, demonstrating reasonable agreement with discharge concentrations and leakage for Halon 1301. This work should be continued in order to arrive at adequate correlations for agent mixing and leakage for Halon 1301 and substitute gases.

Strategy Development and Evaluation

Several strategies are developed in Section 5, based on consideration of the objectives implicit in discharge testing, and the technical state of the art of alternative methods. Proposed strategies include:

(1) Permit the use of Halon 1301 for full scale discharge tests.
(2) Selectively permit the use of Halon 1301 as a discharge test agent for specific conditions.
(3) Eliminate discharge testing, strengthen other test methods, and accept the associated risk of system failures.
(4) Use an environmentally acceptable, physically realistic test gas substitute.
(5) Limit the design flexibility of total flooding Halon 1301 systems.
(6) Develop improved, public domain design and evaluation procedures for flow calculation, mixing, distribution, and leakage assessment.

Conclusions/Research Agenda

The results of the literature review indicate that total discharge testing is an important element in Halon 1301 system performance verification. There are seven objectives embodied in discharge testing which should be preserved in the selection and development of alternative strategies. Elimination of discharge testing without consideration for meeting these objectives would introduce additional risk in terms of system performance.

The state of the art in technologies other than that for Halon 1301 flow analysis could be directly applied to the Halon 1301 problem. Several technical uncertainties associated with Halon 1301 performance could be resolved in the near term. Particular areas of interest include two phase flow, combustion fuel spray technology and chemical spray drying technology.

Three distinct areas of technical uncertainty have been identified. Gaps in our understanding of Halon 1301 flow characteristics, nozzle mixing, and enclosure leakage complicate efforts to replace full discharge testing. However, these uncertainties can be overcome through carefully focused research. A fundamental basis for two phase flow characteristics is well established in the general literature for similar problems outside the area of Halon 1301. Computer based generic two phase flow models are available which could be modified to address Halon 1301 flow characteristics. A theoretical basis and related experimental correlations exist for flow nozzle characterization for other fluids such as combustion fuels and paint sprays. A framework for providing an analytical approach to nozzle mixing and agent distribution is provided. Significant advancements have been made in enclosure leakage testing involving pressurization techniques and development of test gas simulants.

Relatively modest research efforts would be necessary to assess the applicability of available generic computer models to the problem of Halon 1301 flow characterization. A favorable assessment would most likely lead to necessary modifications to one or more available codes in order to address halon flow problems. Experimental work is required to establish correlations for nozzle discharge mixing. This effort requires relatively sophisticated measurement technology, but similar efforts have been successfully conducted in other industries. Ongoing work in development of pressurization techniques and test gas simulants should provide valuable insights in the short term.

To summarize, while elimination of discharge testing appears inappropriate, alternative strategies which address the performance objectives implicit in discharge testing are well within reach. Technical uncertainties require research in specific areas, but all of the areas are technically well supported in more advanced technologies reported in the open literature.

Several explicit conclusions as well as a proposed near term research agenda are included in Section 6.

1. INTRODUCTION

1.1 Background

Halon 1301 (Bromotrifluoromethane, CF_3Br) fire suppression systems are used extensively for special hazards protection. The successful performance of these systems depends on several factors, including: (1) the characteristics of the fire, (2) the reliability and response characteristics of the detection and actuation systems, (3) the Halon 1301 agent delivery time and concentration, and (4) the geometry and perimeter integrity of the protected enclosure. Confidence that these systems will perform as intended depends on design, installation, and maintenance as they relate to system reliability and effectiveness. While not expressly required in NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems*, full discharge acceptance tests are often conducted to assure the adequacy of design and installation.

A recent report by the U.S. Environmental Protection Agency indicates that Halon 1301 emissions may contribute significantly to the depletion of stratospheric ozone [Anderson, 1987].[1] Approximately 30 percent of all Halon 1301 emissions in 1986 (752,000 lbs) were attributed to Halon 1301 discharge testing [ICF 1987], presenting itself as the largest single source of Halon 1301 emissions. In addition, of the two dominant halon suppressants (i.e., Halon 1301 and Halon 1211), Halon 1301 has a considerably greater impact on ozone depletion, having a weighted ozone depletion factor of 3.3 to 1 relative to Halon 1211. As a result, it appears that full discharge testing of Halon 1301 systems may in effect be responsible for approximately 30 percent of all ozone depletion attributed to halons used in fire protection.

1.2 Scope and Objectives

This report summarizes a technical literature review and analysis directed at examination of alternatives to Halon 1301 discharge testing. Technical gaps associated with various alternatives are identified, and necessary areas of research to improve the viability of these alternatives are discussed.

1.3 The Basis for Discharge Testing

Discharge tests are performed to assist in the verification of adequate design and operation of Halon 1301 fire suppression systems. Typically, discharge tests form part of the acceptance procedure for a new installation, as required by the building/system owner, insurance carriers, or public authorities having jurisdiction.

The primary design and installation parameters to be evaluated in discharge testing include:

(1) Mechanical integrity of piping, connections, etc.
(2) Detector/control/electromechanical device and interface functions
(3) Flow characteristics through piping

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[1] References in brackets are listed in the Reference section.

(4) Nozzle discharge and mixing
(5) Compartment integrity (e.g., leakage)

These parameters are examined through several implicit objectives in discharge testing procedures. These objectives include:

(1) *Verification of hardware integrity and absence of foreign material or obstructions in the piping and hardware system.* Discharge testing provides information on the mechanical integrity of the piping, nozzles, manifolds, hangers and other hardware under dynamic structural loading (response) associated with system actuation. Data is also provided on agent flow characteristics and quantities and potential problems resulting from obstructions or foreign materials in the piping or hardware.

(2) *Verification of the operation of detection/actuation/alarm system components.* A precursor to actual discharge testing involves checking the location and response of each detector. The discharge test provides information on the continuity and performance of system actuation hardware, local and remote alarm sequences, and the performance of manual pull station devices. This objective is indirectly tied to discharge testing.

(3) *Verification of adequate initial agent distribution.* Discharge tests include measurement of agent concentrations at specified heights in the enclosure to assure that the Halon 1301 is distributed throughout the compartment. This also provides verification of system mechanical integrity, the adequacy of pipe sizes, agent quantity and flow characteristics, and nozzle discharge and mixing.

(4) *Verification of design concentrations.* Agent concentration measurements are taken throughout the duration of discharge tests to verify that required concentrations are maintained for a specified time period for the type of hazard to be protected, in accordance with the authority having jurisdiction.

(5) *Verification that discharge time is within required limits.* The rate of discharge significantly influences mixing and resulting agent concentrations in the enclosure. Therefore, it is critical that discharge rates result in acceptable agent discharge times. Discharge testing provides a means of measuring the discharge time, and therefore determining the acceptability of pipe and hardware flow characteristics and nozzle discharge characteristics.

(6) *Verification of enclosure boundary integrity.* Given that the required initial agent concentration is achieved, the ability of the system to maintain the associated design concentration for a specified time period is a function of leakage from the enclosure. One of the most important advantages of discharge tests is the ability to identify unacceptable leakage rates and subsequently verify that adequate adjustments have been made. Major sources of leakage include construction openings and ventilation systems.

(7) *Verification that agent discharge does not present a hazard to the enclosure or its contents, and to personnel.* Nozzle selection and location are important considerations. In addition to the effectiveness in attaining required agent concentrations, the issuing turbulent spray may splash flammable liquids, or damage objects and materials, or cause injury to personnel in the enclosure. Discharge testing confirms that nozzles are positioned to minimize such incidents. In addition, once the required hold time has been exceeded, ventilation systems used to exhaust the Halon 1301 can be assessed relative to personnel reentry.

The discharge test objectives impact design and installation parameters to varying degrees. For example, in cases where several spaces are simultaneously protected, the ability to attain the design concentration in each space may be a function of both flow characteristics (a result of design calculations) and any partial blockages of a branch pipe due to obstructions (a result of installation procedures). Similarly, adequate initial mixing will be influenced by flow characteristics, nozzle discharge, and mixing within the space(s) protected.

1.4 A Review of Failure Rate Experience

1.4.1 General

There are several sources of field data on acceptance testing, system reliability, and system performance for installed total flooding Halon 1301 fire suppression systems. Due to variations in study procedures, criteria, and reporting methods, it is difficult to correlate the results from these various studies in any quantitative fashion.

1.4.2 Acceptance Testing

The Fire Suppression Systems Association (FSSA) began collecting and evaluating acceptance test data from its membership in 1984. Based on an evaluation of the data accumulated from July 1, 1984 to March 24, 1987, the FSSA reported an acceptance test failure rate of just under 7 percent [Fire Suppression Systems Association, 1987]. The FSSA data also provides a detailed breakdown of causes of acceptance test failure, presented below in Table 1.4-1.

Table 1.4-1 Causes of Acceptance Test Failures [FSSA, 1987]

Cause Categories	Number	% of Total	% of Failures
Concentration did not hold	30	4.5	65
Failure to trip completely	3	.45	6.6
Ventilation fan problem	4	.60	8.6
Other system dependent failures	3	.45	6.6
Ventilation damper problem	3	.45	6.6
Design conc. not initially reached	3	.45	6.6
Totals	46	6.9%	100%

* Based on 667 cases

Additional information on acceptance testing has been compiled by the U.S. Department of Energy (DOE) and the U.S. Navy.

Ford [1975] reports on 307 halon concentration tests performed by DuPont in support of system designers and installers over the 2 year period from 1973 to 1975. A total of 57 (18.6 percent) failures were reported. The primary reason given for these failures was faulty installation, some involving mechanical installation deficiencies such as faulty pipe threads (pipes separated upon discharge of the agent), and pipes obstructed with construction debris.

A general breakdown of the causes as provided in Table 1.4-1 appears consistent with these studies. As the data indicates, the primary cause of failures (approximately 65 percent of all failures) during acceptance testing is the inability to maintain the design concentration of Halon 1301 in the enclosure for the required "hold" time (i.e., 5 percent for 10 minutes).

The major source of leakage from enclosures is through openings in the perimeter construction. In reality, the failure rate associated with inadequate hold time of agent concentrations may actually be higher than 65 percent since other causes such as ventilation fan and damper failures can further contribute to leakage of the agent from the enclosure.

While enclosure leakage appears to represent a major source of acceptance test failure, the other causes listed in Table 1.4-1 should not be neglected. There are important implications relative to the accuracy of flow calculations and nozzle mixing characteristics. An analysis of acceptance discharge test results sponsored by the U.S. Navy [Lee, 1987] indicates high system failure rates and a wider variation in causes. Actual total flooding Halon 1301 system acceptance tests in complicated geometries such as high ceiling compartments (e.g., shipboard machinery spaces) indicate both enclosure leakage and initial agent mixing as significant problems. This latter problem suggests that either the flow rate calculations and subsequent pipe sizing are incorrect, or the nozzle design, direction, orientation and/or spacing guidelines are inadequate.

Discharge test failure rate data provide no real information on the reliability of installed halon systems. A discharge test failure does not necessarily indicate that the system would not have controlled or extinguished a fire. This is especially true where the failure was due to the inability to maintain design concentration for a specified hold time. This type of failure is tied to the issue of "safety factors" in conservative design and will be discussed later.

In principle, a discharge test failure will result in alterations or modifications such that the system will function properly. In this sense discharge test failures are independent of system failures under fire conditions.

1.4.3 Performance Data

There is a dearth of published data on the failure rates of halon systems under fire conditions.

A review of the National Fire Protection Association's (NFPA) Fire Incident Data Organization (FIDO) data files between 1971 and 1983 by the NFPA Fire Analysis Division identified 29 halon related incidents [NFPA, 1985].

Six of the 29 fires reported were successfully extinguished. However, four fires occurred outside the area protected causing extensive losses to the spaces protected by halon systems. Six system failures were reported, two were due to initial explosions and hence outside the performance expectations of the systems. The other four failures were due to operational and maintenance problems. The relevance of these four failures to discharge testing is unknown.

1.4.4 Anecdotal Data

In addition to the studies on acceptance test failure rates and system in situ reliability and performance reviewed above, there are several anecdotal sources of information which are relevant to the evaluation of acceptance testing of Halon 1301 total flooding systems. For example, Brenneman reported the importance of full scale acceptance tests in identifying major sources of enclosure leakage [Brenneman, 1975]. Significant sources of leakage were corrected in a large computer facility, and acceptance tests were conducted to verify that system performance met minimum requirements. Presumably, in the absence of some form of acceptance test, the leakage problem could have gone uncorrected.

In terms of system performance, a report by DuPont [1976] demonstrated acceptable performance of Halon 1301 total flooding systems for a wide range of applications under actual fire conditions. A list of 17 fire incidents was compiled, where Halon 1301 systems successfully extinguished fires in chemical process facilities, computer rooms, telephone switching stations, shipboard machinery spaces, and onboard aircraft.

Two isolated incidents described in the DuPont report illustrate concerns over performance limits/expectations and adverse impact on personnel. One was a shipyard fire, where manual actuation of the 1301 system resulted in the fire fighting team backing out of the enclosure area, interfering with manual fire fighting efforts. The exact nature of the interference is not clear. A second unusual incident was a short circuit induced fire at an electronics equipment facility. The fire was reported to be too small to actuate a detector, hence the installed Halon 1301 system was not discharged. Nevertheless, this small fire resulted in the loss of a particularly valuable memory board ($100,000).

1.4.5 Discussion

The available data on acceptance test failure rates and in situ reliability and performance does not permit a rigorous, quantitative assessment of the adequacy of total flooding Halon 1301 fire suppression systems. However, a qualitative review of the data provides a non-statistical but reasonable assessment of performance and failure expectations. For example, the dominant cause of acceptance test failure appears to be enclosure leakage. Even though the designer of a total flooding Halon 1301 fire suppression system cannot be expected to directly control leakage sources in construction and ventilation systems, some means of assessing leakage magnitudes is necessary to assure successful in situ performance. Another significant cause of acceptance test failures included difficulties with attainment of initial agent concentrations. This is the potential result of incorrect flow calculations and pipe sizing, and/or problems with nozzle performance. These problems are within the purview of the design engineer, as well as the standard's organizations and listing laboratories.

It would appear from the available experience that the objectives implicit in acceptance test procedures are valid and must be maintained. Therefore, any attempt to substitute for full discharge testing should preserve and incorporate the objectives of discharge testing.

1.5 Acceptance Criteria

The requirements against which discharge test results are compared are derived from specified design requirements. These acceptance criteria are generally in excess of conditions required for fire suppression. The discrepancies, if any, form the basis of factors of safety in the design and installation. This section examines the design criteria and particularly the factors of safety. Generally, these requirements are embodied in NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems.* The principle design parameters evaluated during a discharge test include:

1. discharge time;
2. agent concentration; and
3. agent hold time.

In addition, the proper functioning of required actuators, predischarge alarms, and discharge alarms is evaluated.

1.5.1 Discharge Time

Agent discharge time is a critical parameter in total flooding Halon 1301 system performance and rapid extinguishment. NFPA 12A requires substantial completion of agent discharge in 10 seconds. This 10 second discharge time refers to the period of liquid agent flow from the nozzle(s).

Such rapid agent discharge is intended to create a heterogeneous flow regime in the pipe network (i.e., a well mixed liquid and vapor phase) and high mass flow rates and turbulent discharge from the nozzles. These conditions in turn promote rapid extinguishment. The assumption that a heterogeneous flow regime exists in the pipe network is critical relative to the accuracy of the pressure drop and flow rate computations. Relatively high discharge pressure (100 psig minimum) is necessary for initial agent mixture with the enclosure air. The resulting rapid extinguishment is necessary since delays in extinguishment can result in decomposition of the halon gas and the subsequent formation of halogen acids (HCl, HF, HBr), free halogens (Br_2), and small quantities of carbonyl halides (COF_2, $COBr_2$) [Ford (1972, 1975), Shineson et al (1972, 1981, 1982)].

1.5.2 Agent Concentration

The required agent concentration is a function of the expected fuel, fuel geometry, and type of fire. There are two levels of required concentration. The system can be designed for either inerting or flame extinguishment. A comparison of NFPA 12A requirements for inerting and flame extinguishment for a range of flammable liquids and gases is given below in Table 1.5-1. Most systems are designed for flame extinguishment.

Guidelines for design concentrations for solid materials are less well defined. For solid fuel surface fires the NFPA 12A standard recommends a Halon 1301 design concentration of 5 percent by volume for a duration (referred to as hold or soak time) of 10 minutes.

Table 1.5-1 Required Halon 1301 Concentrations [from NFPA 12A, 1987]

Fuel	Inerting Concentration (% by volume)	Flame Extinguishing Concentration (% by volume)
Acetone	7.6	5.0
Benzene	5.0	5.0
Ethanol	11.1	5.0
Hydrogen	31.4	–
Methane	7.7	5.0
N-Heptane	6.9	5.0
Propane	6.7	5.2

For gaseous and liquid fuels the required design concentrations incorporate a safety factor of 10 percent for inerting and 20 percent for flame extinguishment applications. However, any safety factor incorporated in the 5 percent concentration for solid fuels is implicit and not well defined. The primary difficulty arises when faced with deep-seated solid fuel fires rather than surface fires. While such fires are typically a problem associated with cellulosic fuels, they have occurred in non-cellulosic solid fuels such as wire and cable insulation under extended preburn periods and atypical fuel geometries. The effect of any safety factor (implicit or otherwise) on deep-seated solid fuel fires has a critical bearing on acceptance testing.

1.5.3 Agent Hold Time

Halon 1301, used in the correct concentration, is an extremely fast suppressant of gas phase combustion reactions. Suppression of liquid and gaseous fuel diffusion flames occurs within seconds of an adequate concentration of 1301 being introduced into the atmosphere. The required duration of agent hold time—typically referred to as "soak" time—will vary with the type of fuel, geometry, preheating, etc. or any variable that affects deep-seated combustion.

The NFPA 12A standard uses a soak time requirement of 10 minutes where deep-seated fires *are not* expected to occur. This time frame is to permit suppression of embers, or solid phase reactions, primarily in cellulosic fuels. The 10 minute soak time is not designed to suppress fires in depth in large fuel packages (e.g., cable arrays). Such fires may occur as a result of long preburn times or from large exposure fires. The actual required soak time for a given fuel array cannot be determined without extensive testing [Williamson (1972), DiNenno and Starchville (1987), Ford (1972, 1975)].

The problem of deep-seated fires should be put in context. The impact of not extinguishing all of the locations in a fuel array which are undergoing condensed phase reaction is the possibility of a reflash or transition to flaming combustion when the halon concentration is reduced below approximately 4 percent. These reflash conditions are expected to be slowly developing (in typical solid fuels) and are part of the reason for the fire service practice of overhaul. Typically they will not be immediately threatening.

A less obvious consequence of deep-seated fires is the increased production of halogen acids and other decomposition products of Halon 1301. This occurs at temperatures above the Halon 1301 decomposition temperature of 482°C (900°F) [NFPA 12A, 1987]. A worst case reflash problem which is not related to the problem of deep-seated fires involves flammable and combustible liquids where hot reignition points such as machinery, piping, etc. exist after the prescribed soak time. In these instances the expected reflash can be quite rapid and hazardous. Such concerns should be addressed in the design of protection systems for these hazards.

1.6 Relationship Between Design Requirements and Fire Suppression

A basic assumption implicit in this survey and analysis is that the current design requirements are adequate, not overly conservative, and form a reasonable basis for discharge test requirements. Typically, system failures have not resulted from inadequate design requirements; e.g. minimum required agent concentrations, maximum discharge times, and minimum hold times. Rather, failures appear to also violate the design requirements.

Actually, one could make the case that current design requirements are conservative. As previously discussed, the design concentration requirements in NFPA 12A have a 10-20 percent factor of safety incorporated. While other design requirements such as discharge time and hold time are generally based on limited experimental data, the requirements appear reasonable and lie well within performance limits.

The implications of test and approval requirements on the ability of the system to extinguish a fire are uncertain. For example, suppose the leakage in an enclosure is such that after 5 minutes the concentration in the uppermost 3 feet of the enclosure is below 3 percent Halon 1301 (by volume). This condition would be unacceptable in terms of system design, but acceptable by some discharge testing protocols. Would the system extinguish a fire located at the ceiling? The answer is uncertain. This is due primarily to (1) the instantaneous suppression of the gas phase reactions immediately following discharge, and (2) the convective mixing which occurs in the enclosure due to energy from the fire or heated surfaces, resulting in a higher upper elevation Halon 1301 concentration. In addition, any entrainment occurring as a result of hot buoyancy sources will further enhance agent mixing with the compartment gases.

This problem is currently under evaluation by the Naval Research Laboratory.

In summary, the acceptability of a system has three components: (1) the design requirements, (2) the testing criteria, and (3) expected results under fire conditions. Each of these three areas involves some degree of uncertainty and conservatism. The magnitude of either is not quantifiable at this time. While current design requirements appear adequate, significant limits in our ability to quantify the problem discourages any notion of relaxing testing requirements or the associated test criteria.

1.7 NFPA 12A Testing Requirements

The current edition of NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems*, contains a general requirement that for approval of installation the system be tested to (1) "meet approval of the authority having jurisdiction," and (2) successfully pass a hydrostatic pressure test of the piping system. The hydrostatic pressure test requires a test pressure of 150 psig for 10 minutes with a maximum drop of 15 psig over the 10 minute period. This hydrostatic test need not be performed where the piping contains not more than one change in direction.

In addition to the hydrostatic test requirement a physical inspection of the piping, nozzle, and supports is required to ensure piping system movement is within acceptable limits during discharge. This presumes that the pipe support system has been adequately designed with respect to dynamic loading.

Additional inspection and maintenance requirements include annual inspections to ensure that the system is in "full operating condition," including a warning that "suitable discharge tests shall be made when inspection indicates their advisability." Semiannual agent quantity and storage pressure checks are required. System hoses require hydrostatic testing every 5 years.

Note that there is no requirement for discharge tests, hardware cycling, puff tests, etc., in the body of the standard. However, the Appendix to Section

1-7.4, "Approval of Installations," gives very detailed guidance on what items should be checked relative to approval of installations. (In the 1988 12A Technical Committee Report it has been proposed that this material be incorporated in the body of the standard, as a requirement.) This guidance is in two parts. Part I includes all items *except* discharge tests;

a. verification of piping network relative to design including size, location, etc., of nozzles, fitting, and piping;
b. check of piping joints and supports;
c. orientation of discharge nozzles;
d. detector location and installation, manual pull stations, reserve/main switches, abort switches;
e. check of agent storage, containers, quantity, etc.;
f. electrical checkout including wiring, circuits, power supply, alarm display/sounding devices, air handling shutdowns, power cut-offs, etc.; and
g. predischarge or functional test; includes verification of operation of all detectors, alarm devices, system initiator circuits, manual release, etc.

Part II of Appendix 1-7.4 includes detailed guidance "when a full discharge test is conducted." Specifically the section discusses recommended procedures for predischarge checklists, functional tests, placement of gas sampling probes, securing the system, post-test restoration procedures, etc.

This section of the Standard states further that "Halon 1301 should be used as the testing agent unless specifically waived by the Authority Having Jurisdiction (AHJ)." A common alternate test agent, Halon 122, can be used if permitted by the AHJ. The standard lists some of the known differences between Halon 1301 and Halon 122.

The appendix provides acceptance test guidance on the placement of Halon 1301 concentration meters. For example, it is recommended that concentration data are taken at the point of the highest combustible or at a point of 75 percent of the height of the enclosure, whichever is greater, but not less than 12 inches from the ceiling unless there are combustibles at the ceiling level.

Only one sampling point is required in each protected space. The design concentration must be attained at this sampling point in no more than 60 seconds, and 80 percent of the minimum design concentration must be held at the sampling point for the required hold time. Surface fires (other than flammable liquids or gases) typically require a hold time of 10 minutes. The discharge time should not exceed 10 seconds.

System failures are categorized in NFPA 12A as follows:

(1) *primary failures*: the failure of equipment necessary to complete system discharge and achieve initial design concentration (includes hydraulic calculation errors, control panel failures, etc.).

(2) *secondary failures*: ancillary equipment failures which do not prevent the system discharge or attaining initial design concentrations (dampers, door closers, bells, etc.).

(3) *Room Integrity Failure*: failure of the enclosure to hold the specified concentration for the specified holding period.

In summary, NFPA 12A leaves most decisions regarding the testing of Halon 1301 installations to the discretion of the Authority Having Jurisdiction. The AHJ may include the insurer or its representative, the facility owner, building official or local fire authority. The current NFPA 12A standard does not provide mandatory requirements for the conduct of system checkout procedures, and/or system discharge tests. No guidance or information is presented on whether or not a discharge test may be appropriate.

1.8 UL 1058 Standard

In addition to compliance with NFPA 12A, components of Halon 1301 Systems and the pipe flow calculation programs used in system design are listed by Underwriters Laboratories under UL Standard 1058, *Halogenated Agent Extinguishing Systems Units.*

The UL standard provides for a wide range of hardware tests. The most important requirements from the standpoint of discharge testing are:

(1) Nozzle area coverage tests

(2) Verification of flow calculation methods.

These areas are of particular concern because they are among the most uncertain in terms of design versus expected performance. The technical issues associated with initial mixing and the flow of Halon 1301 through piping networks are very complex and difficult to predict and verify.

1.8.1 Nozzle Coverage Tests

UL 1058 requires that nozzles used in Halon 1301 systems be tested to verify the mixing and distribution of the agent when discharged through the nozzle. The test procedure involves discharging the nozzle into a test enclosure with the maximum area and height limitations of the nozzle. (Maximum enclosure heights are not required if the height limitation is between 2 and 30 feet). The test enclosure simulates vertical floor to ceiling obstructions which occupy 20 percent of the length or width of the enclosure.

1.8.2 Verification of Flow Calculations

The standard also provides a means for partially verifying the flow calculation programs used in the design of Halon 1301 systems. These flow calculation procedures are proprietary computer programs written and submitted for approval by each halon system equipment manufacturer. The standard requires that the manufacturer submit calculations for five different piping arrangements and three enclosures of different volumes. The performance of the flow calculation program is then compared with measured performance.

The manufacturer is required to submit limitations (if any) on the calculation procedure. Any verification tests are due within those limitations. Typical limitations of flow calculation programs include:

(1) Minimum/maximum percent agent in piping
(2) Minimum/maximum discharge time
(3) Minimum/maximum container fill density
(4) Minimum pipeline flow rates
(5) Variance of piping volume to each nozzle
(6) Maximum variance of nozzle pressures within a piping arrangement
(7) Maximum orifice area to inlet piping diameter ratio
(8) Piping arrangement most likely to cause a "vapor time imbalance condition at the nozzle"
(9) All types of tee splits, including bull head tees, side tees, etc.
(10) Minimum/maximum flow split at each type of tee split

The flow calculation program is tested relative to limits placed on the above parameters. For example, a particular manufacturer may have confidence in a program at 40-60 percent agent in piping, but not at 70 percent agent in piping. The program would be tested against a piping arrangement giving a percent agent in piping between 40 and 60 percent.

Likewise a manufacturer may choose to limit the program to flow networks with no side split tees, etc.

It should be recognized that the UL 1058 procedure for verifying flow calculation methods is in essence a "spot check" of the program's accuracy. As opposed to full program verification, the program is checked against approximately five piping conditions The performance of the calculation program is compared to the following performance measures:

(1) discharge time ± 1.0 sec
(2) nozzle pressure ± 10 percent
(3) weight of Halon 1301 discharged −5, +10 percent.

The discharge time and nozzle pressure are measured directly. The weight of Halon 1301 discharged is inferred from the concentration in each test enclosure.

The value of UL 1058 as a quality assurance tool for Halon 1301 system hardware and design methods is unquestionable. However, it is not clear that UL 1058 approval is a necessary and sufficient condition for successful system performance. This is discussed further in Section 2.

1.9 Technical Problems Associated with Discharge Testing

There were seven objectives of discharge testing discussed in section 1.3. These objectives are summarized below:

(1) Piping and mechanical component integrity
(2) Detection/alarm/actuation components and interfaces
(3) Spatial distribution of agent
(4) Initial agent concentration

(5) Discharge time
(6) Enclosure integrity (hold time)
(7) Unwanted discharge effects.

In order to eliminate the need for Halon 1301 discharge tests, these seven objectives must be met by other means. Based on the technical literature review and analysis, it appears that several of these objectives cannot be met without further development and improvement of design and test and evaluation procedures. Table 1.7-1 summarizes the relationship between current testing procedures and the objectives of discharge tests.

In lieu of discharge testing, piping integrity can be checked by hydrostatic pressure testing. Pipe obstructions, construction debris, etc. may be located by ultrasonic testing, x-ray imaging and, if performed properly, by discharging a gas (e.g., nitrogen) at high velocities. Piping structural integrity under dynamic loads can be evaluated by assuring proper design of hanger systems (e.g., physical testing), careful inspection of piping supports, and by discharge of a gas such as nitrogen.

It is worth noting that the present piping design criteria in NFPA 12A follows the ANSI Power Piping Code. This code requires dynamic loads to be evaluated but does not specify how the loads are to be calculated. The only example of dynamic loads contained in the Power Piping Code is for pressure relief valves, and is located in the Appendix.

The proper operation of detection, actuation, alarm and signalling devices and their interfaces through control panels can be ascertained without discharge tests by proper "dry run" testing procedures. In fact, it is impossible to check all of these devices and subsystems in a single discharge test.

Unwanted discharge effects such as overpressurization damage to compartments or missile danger resulting from the halon discharge dislodging loose objects can be treated by a combination of careful installation, consideration of potential gas discharge effects, and partially through the discharge of gases such as nitrogen.

The remaining four objectives are tied to three technical engineering and design problems. These three problem areas are:

(1) flow of Halon 1301 through piping systems,
(2) discharge and mixing of Halon 1301 in compartments,
(3) enclosure leakage.

The state of the art in design testing procedures embodied in NFPA 12A and in UL 1058 is sufficiently uncertain to warrant close consideration of these three technical problem areas. The primary issue is to what extent these design problems can be treated such that Halon 1301 discharge tests could be discontinued with no loss of confidence in the design and installation of the system. This report addresses these three difficult problem areas from the viewpoint of eliminating the need for full Halon 1301 discharge tests. The issues of the adequacy of hydraulic calculations and enclosure leakage have been previously identified as problem areas [Grant, 1985, 1987, 1988].

Test Procedures	DISCHARGE TEST OBJECTIVES						
	1. Mech. integrity	2. Functional test	3. Mixing	4. Concentration	5. Discharge Time	6. Hold time	7. Discharge effects
1. Hydrostatic tests	P	O	O	O	O	O	O
2. Puff tests	P	P	O	O	O	O	P
3. Functional tests	O	F	O	O	O	O	O
4. Discharge tests, H-122	P	P	P	P	P	P	P
5. Discharge tests, H-1301	P	P	F	F	F	F	F
6. UL 1058	O	O	P	O	P	O	O

P = partially meets objective
F = fully/substantially meets objective
O = little or no relationship

Table 1.7-1 Discharge Test Objectives vs. Current Test Procedure

1.10 Summary

There are several important objectives associated with total flooding Halon 1301 discharge testing, and these objectives can be related directly to elements of design and installation of such systems. Experience suggests that some of the most important design and installation parameters include pipe flow, mechanical integrity, electrical reliability, ventilation control, and enclosure leakage.

In order to reduce the impact of Halon 1301 emissions on ozone depletion, alternatives to full discharge testing must be developed. Such alternatives must provide similar confidence in system reliability and capability to that currently provided by full discharge testing. In theory, some combination of at least four alternative approaches could be considered. They include:

(1) a large incident data base,
(2) an improved design and hardware evaluation package,
(3) a simulated test agent, and/or
(4) a replacement suppressant.

Analogous to the first two alternatives is the acceptance of a particular automatic fire sprinkler system. The hydraulics of automatic sprinkler system design are well understood, and are generically embedded in engineering design procedures. In addition, the confidence that the existing design procedures are acceptable is supported by extensive incident data which clearly demonstrate long term system reliability and performance capability. A similar data base does not exist for Halon 1301 suppression systems, and a well-recognized generic design procedure based on technical fundamentals is not currently available.

Another alternative would be to substitute a compound for test purposes which simulates the appropriate properties and performance characteristics of Halon 1301. And, of course, a remaining alternative would be to replace Halon 1301 with an alternative suppression agent which is not as detrimental to stratospheric ozone.

While these potential alternatives to full discharge testing exist, it is unlikely that any single alternative will adequately address all of the objectives of discharge testing. For example, mechanical integrity and pipe system dynamics could potentially be evaluated through: (1) the use of hydrostatic pressure testing, (2) expanded pipe design requirements, and (3) visual inspections. The specific problem area of pipe obstructions requires improved quality control measures and/or non-destructive test procedures such as ultrasonic or x-ray techniques. All of these capabilities are within the state of the art.

Functional tests of detectors, audible and visual alarms, manual pull stations, abort switches, actuating devices, and door closers are adequately treated in the Appendix of NFPA 12A. These functional tests can be performed and the operator verified without resort to discharge testing.

However, while selected discharge test objectives can be met by alternative means, there are several important objectives which pose technical problems in direct substitution of alternative strategies. Based on the information reviewed in this section, at least three aspects of discharge test objectives require a more rigorous examination if one is to propose alternative procedures. These include:

(1) verification and accuracy of agent flow calculation procedures,
(2) nozzle discharge and mixing characteristics, and
(3) the effects of enclosure leakage.

The remainder of this study focuses on the technical state of the art relative to these factors, identification of weaknesses or gaps in their technical basis, and proposed directions to develop a sufficient understanding of these factors to support substitution of viable alternatives for current discharge testing.

2. HALON 1301 FLOW CALCULATIONS

Accurate flow calculations of Halon 1301 in total flooding piping systems is a prerequisite for an acceptable system design. The importance of accurate flow calculations on system performance involves:

(1) Assurance that the design quantity is discharged into each enclosure or hazard area.

(2) Assurance that the 10 second discharge time limitation is met. (This discharge time limit impacts the effectiveness of the system, the decomposition of Halon 1301, and the mixing of the discharged agent.)

(3) Assurance that adequate flow (and hence mixing) occurs at each nozzle in enclosures with multiple nozzles. This is also dependent on the characteristics and placement of the nozzles.

The accuracy of flow calculations is less demanding in uncomplicated modular systems consisting of a storage tank, short runs of pipe and one or two nozzles on a short balanced network. However, this is not true for systems using central banked storage of Halon 1301 with long, unbalanced pipe networks. Calculations are especially critical in applications where several enclosures are protected simultaneously or where the protected enclosure is large, with high ceilings and nozzles placed to avoid discharge problems due to vertical and horizontal obstructions. The latter dependence reflects the situation where the relationship between nozzle pressure and flow rate to mixing and distribution is most important.

The problem is exacerbated somewhat by the use of proprietary calculation procedures, rather than the use of an "open", fully documented design procedure with well defined assumptions and limitations.

Halon 1301 discharge is characterized by two phase flow. The essential problem is that the fluid changes from predominantly liquid to an increasing percentage of gas as the fluid flows through a pipeline. The resulting density change causes complications relative to the estimation of pressure drop due to friction loss or elevation difference. But perhaps more critical, the prediction of the distribution of agent through various legs of a pipe junction, i.e. tees, becomes considerably more complex. This complexity, along with the empirical basis embodied in conventional two phase flow methods, results in considerable difficulty in determining the adequacy of calculated accuracy for Halon 1301 flow.

The 1987 edition of NFPA 12A contains a design procedure for balanced flow networks. They are characterized by:

(1) actual pipe length from container to nozzle for each leg is within 10 percent of the longest pipe length;

(2) equivalent pipe length from the container to each nozzle is within ± 10 percent; and,

(3) the nozzle flow rates are equal.

Under these conditions simplified design procedures specified in the Appendix may be used.

For unbalanced pipe networks the standard also provides a design procedure in the Appendix. The validity of the flow calculation procedures embodied in NFPA 12A are sufficiently uncertain to warrant independent third party listing of flow calculation programs by Underwriters Laboratories, Inc. (UL). However, some concern exists that due to the complexity of two phase flow phenomena and the simplifications inherent in NFPA 12A, the design procedures for unbalanced piping systems may yield erroneous results [Williamson (1976), Weisma (1978, Grant (1987)].

2.1 Description of the Discharge Process

The discharge of a Halon 1301 system is a complex physical process. When the storage cylinder valve is opened the pressure initially drops as a supersaturated solution of Halon 1301 and nitrogen flows into the piping network. As the liquid and gas expand in the storage cylinder the temperature of the agent drops. At a pressure of approximately 3.8 MPa, the nitrogen superpressurant begins to be released from solution, causing a slight increase in the cylinder pressure. Following this pressure increase the cylinder pressure drops, as does the temperature as the fluid expands in the cylinder and flows into the piping network. Simultaneously, the cylinder walls are being heated by the atmosphere.

Once in the piping, the fluid, which is initially primarily liquid, heats up as energy is absorbed from the pipe walls. The proportion of vapor to liquid increases as the temperature rises, and the pressure drops as the fluid flows down the pipe toward the nozzle. This initial mixture of bubbles in a primarily liquid medium may change to a number of other flow patterns. For example, if most of the liquid is evaporated, a mist of liquid droplets in a primarily vapor medium may result. If they occur these flow pattern or flow regime changes will substantially change the pressure drop and flow characteristics. In an attempt to ensure "bubbly" flow, the NFPA 12A standard requires fairly high mass flow rates.

During the flow process, the fluid is changing density, pressure, and temperature with respect to time and position in the piping network. This may cause changes in flow regime and pressure drop characteristics. If a change in direction occurs in the pipe network, accompanied by a flow split, the vapor and liquid may preferentially separate. This is especially true at side tees, and is complicated further if the fluid is stratified or annular, i.e. the phases are separated as opposed to well mixed. Apparent equivalent lengths of fittings, such as elbows and bell reducers will also vary with the density of the flow.

Once the fluid reaches the nozzle, the mass flow rate from the nozzle will be determined by the fluid density, nozzle pressure, and discharge coefficient of the nozzle. After the fluid exits the piping network any remaining liquid rapidly evaporates or flashes, cooling the room and entraining air in the jet issued from the nozzle. The decay of velocity of the jet, the jet geometry, and quantity of air entrained help to determine how well the 1301 flow mixes with the enclosure air to form a stable mixture.

2.2 NFPA 12A Flow Calculation Procedures

The development of the flow calculation methods in NFPA 12A followed pioneering work in the two phase flow characteristics of carbon dioxide by Hesson [1953] and Williamson [1958].

The central feature of the procedure involves calculating the pressure drop between two points along an equivalent length of pipe. In NFPA 12A, the pressure drop due to friction loss is given by the expression:

$$Q^2 = \frac{1.013D^{5.25}Y}{L + 8.08D^{1.25}Z} \qquad (2\text{-}1)$$

where: Q = flow rate, lbs/second
D = inside pipe diameter, in.
L = equivalent length of pipe, ft
Y,Z = factors depending on density and pressure

The Y and Z factors and the assumptions implicit in their development are the heart of this calculation scheme. Values for Y and Z are functions of the initial storage pressure, filling density and pressure. These values are tabulated in the Appendix of NFPA 12A for typical conditions; based on the equations:

$$Y = -\int_{P_1}^{P} \rho \, dP \qquad (2\text{-}2)$$

$$Z = \ln \frac{\rho_1}{\rho} \qquad (2\text{-}3)$$

where: P_1 = storage pressure, psia
P = pipeline pressure, psia
ρ_1 = density at pressure P_1, lb/cu. ft
ρ = density at pressure P, lb/cu. ft

The initial pipeline pressure is the average container pressure during discharge. This average container pressure is a function of initial storage pressure, filling density, and percent of agent in the pipeline. The percent of agent in the pipeline is estimated by:

$$\%\text{ in piping} = \frac{k_1}{(W/V_p) + k_2} \qquad (2\text{-}4)$$

where: W = initial charge weight of Halon 1301, lb
V_p = internal piping volume
k_1, k_2 = constants, functions of filling density and storage pressure

Alternatively, the percent in piping is given by:

$$\% \text{in piping} = 100 \frac{V_p(\bar{\rho})}{W} \quad (2\text{-}5)$$

where $\bar{\rho}$ is the average pipeline density.

At this point the Y,Z factors at the beginning of the pipeline section are obtained from the tabulated values. It should be noted that both Y and Z can easily be calculated numerically if an appropriate equation of state for the Halon 1301 is known. However, the presence of the nitrogen superpressurant complicates this process, and in fact the Y and Z factors are obtained by the best fit of empirical data on superpressurized Halon 1301.

The Y and Z factors at the end of the pipeline section are then computed by rearranging equation 2-1. In the first iteration, the Z factor is neglected, and the Y factor is obtained from the equation and the pressure corresponding to that Y factor is the estimate for the terminal pressure of that pipeline section. The Z factor is then determined using that terminal pressure, and the Y factor is corrected. A corrected terminal pressure is then determined.

The subsequent sections of piping are done in an analogous manner until the nozzle is reached. The flow characteristics of the nozzle are functions of the nozzle pressure, nozzle design, and most importantly, the state of the fluid at the base of the nozzle. No universally applicable procedure exists for calculating the discharge of Halon 1301 from a nozzle. (Nozzle discharge is discussed in detail in Section 3.)

The procedure given above is modified in the case of an unbalanced system. The same overall procedure is applied but initial estimates of flow rates in each branch of the system and percent of agent in piping must be iterated.

The reason for reviewing this procedure is to draw attention to the assumptions implicit in the procedure and more importantly to give the reader a feel for sources of uncertainty and potential inaccuracy. Several critical assumptions can be identified.

(1) The entire calculation scheme is based on the use of average conditions; that is, average flow conditions as a function of time and along a length of piping. This was initially done for ease of calculation prior to the widespread availability of computers.

(2) The procedure implicitly assumes some homogeneous flow regime. It presumes therefore that no separated flow conditions develop or that no flow regime changes occur which substantially alter the

pressure drop characteristics. The fluid is assumed to be characterized by a fluid of some average density.

(3) The derivation of the Y and Z factors is unpublished. While these values can be replicated for a pure gas, such as CO_2, the values in NFPA 12A are difficult to replicate using standard thermodynamic property data.
(4) Equivalent lengths of pipes and fittings are assumed to be hydraulically similar to equivalent lengths determined by water flow tests.
(5) Flow splits are expected to occur as functions of computed pressure drop. This is a natural consequence of a homogeneous flow approach but has been shown to be inadequate, at least in unbalanced systems.
(6) Heating of the fluid and the subsequent temperature, and hence density and pressure changes are approximated by using average pipeline conditions as a function of both average container pressure during discharge and percent of agent in piping.

These assumptions and their unknown effect on the efficacy of the calculation procedures gives rise to a multitude of correction factors in the proprietary flow calculation programs of the manufacturers. This uncertainty contributed to the need for some verification of these programs as embodied in UL 1058, and is a major area of concern relative to the need for discharge tests.

2.2.1 Third Party Listing and Validation

One of the unique features of halon system design is that the pipe flow calculation schemes which are embodied in computer programs are subject to third party evaluation. UL 1058, *Halogenated Agent Extinguishing Systems Units*, provides a listing procedure for calculation programs developed by halon equipment manufacturers and used by distributors and installers. Recent proposals to NFPA 12A mandate that calculations be performed only by tested programs. As discussed in Section 1, the UL approval requires calculations to be compared against actual discharge tests. Each program is checked against its range of applicability relative to flow conditions. At least five tests are conducted in different piping geometries. Ten parameters describing the range of applicability of the program relative to possible flow conditions are evaluated. These include:

(1) percent of agent in piping (maximum);
(2) minimum and maximum discharge times;
(3) minimum pipeline flow rates;
(4) variance of piping volume to each nozzle;
(5) maximum variance of nozzle pressures within a piping arrangement;
(6) maximum ratio of nozzle diameter to inlet pipe diameter;
(7) arrangement most likely to exhibit vapor time-imbalance condition at nozzle;
(8) all types of tee splits, including through tees, bullhead tees, etc.;

(9) minimum and maximum container fill density; and
(10) minimum and maximum flow split for each type of tee.

Combinations of these worst case parameters are tested in each of the five tests. There is no systematic variation of parameters (e.g., holding all except one parameter constant) since this would require a prohibitively large number of tests.

Limitations associated with this standard relative to using it as necessary and sufficient evidence of satisfactory accuracy and correctness in design flow calculations can be characterized as follows:

(1) The range of applicability of testing is determined by the scaling of the ten parameters discussed. For example, the percentage of agent in piping is used as a scaling parameter for average container pressure during discharge, as well as a bulk flow heat gain scaling factor. It is of course directly related to other parameters such as container fill density, etc. A program successfully tested against a piping system utilizing 50 lbs. of Halon and two-inch diameter pipe which results in a percentage of agent in piping of 60 percent, is assumed to work for any piping geometry resulting in an identical or less percentage agent in piping, e.g., 100 lbs of agent in a certain length of six-inch diameter pipe (all other parameters constant). It is not clear that these scaling parameters are a correct and complete set. They cannot be derived from the fundamental governing equations [Cheremisinoff (1983), Hetsroni (1982)].

(2) The large number of tests required to evaluate the validity of the program across the range of possible flow conditions, assuming the parameters are correct, cannot reasonably be performed. As a practical matter this makes sense; it does not however contribute to the validation of the design program.

(3) Validation of computer programs, especially programs used for design, requires evaluations beyond verifying the physical calculation method. As a minimum, the proper operation of the programs across all possible input and internal calculation procedures is required. Having programmed a reasonably adequate calculation scheme and tested it against five cases does not ensure that the algorithm was successfully translated to a correctly operating program. These problems can be as simple as errors in the program "looking up" the correct thermodynamic properties or internal pipe diameter for a specified nominal pipe size and schedule. The inability of the user or approving authority to independently check the results of these programs exaggerates this problem.

It is practically impossible to verify the proper operation of computer programs under conditions where the calculations are not in issue. In the case of Halon 1301 piping system design the calculation procedures are largely empirical and hence subject to restrictions in their range of utility. With the efficacy of the physical bases for the calculations in doubt, it seems at the very least imprudent to rely on the current third party approval standards as necessary and sufficient condition for the velocity of the flow calculation and pipeline designs.

2.3 Review of the Two Phase Flow Literature

The technical literature on two phase flow is extensive and for purposes of this study, precludes a complete review. Cheremisinoff [1983] cites an estimate of 12,000 papers available on the subject. Reference to the Bibliography section gives the reader an idea of the range of information available.

The purpose of this section is to describe qualitatively the important processes in Halon 1301 flow as they relate to typical calculation methods for general two phase flow problems. This helps to illustrate the complexity of the flow problem while at the same time providing background on how these problems are treated in other, often more demanding, applications.

Wiersma [1977] evaluated the behavior of Halon 1301 flow in pipelines. Of particular interest was the dependence of the Halon 1301 discharge and flow characteristics on temperature. Piping was small diameter (.19 to .440 in ID). Both Halon 1301 and Halon 122 were evaluated. Pressure drop and flow rate were measured over the range of pipe diameters for both copper and steel tubing, under heated and unheated conditions. Flow rate changes over a temperature increase of 10 to 40°F (5 to 22°C) were evaluated.

The problem of nitrogen pressurization and the release of dissolved nitrogen was noted. Wiersma reported that a 30 percent increase in flow rate could be obtained if the nitrogen were separated (e.g., stored in a membrane) from the halon. Several suggestions are provided for improving design practice. These include more careful consideration of agent storage temperature (storage at 100°F will result in a 17 percent decrease in flow rate for a 600 psig storage cylinder), and caution in using Halon 122 as a substitute test agent, because of marked differences in flow behavior.

This brief discussion focuses on two key issues relative to Halon 1301 flow calculations:

(1) What are the major areas of uncertainty in two phase flow computation? and,

(2) Can existing work on two phase flow be readily adopted to Halon 1301 system design?

Most of the work centers on defining the flow regimes, pressure drop, void fraction (or hold up), and flow at junctions in a gas liquid flow. Much of the literature centers on steady-state or quasi-steady-state problems. Limited information is available on transient flows and even less on Halon 1301 flows.

2.3.1 Flow Regimes

The starting point for any discussion of two phase flow is the definition of various flow regimes and transitions between flow regimes. Barnea and Taitel [1986] define the following flow regimes:

a. For horizontal pipe flow (see Fig. 2.3-1)

(1) *Stratified.* Liquid flows along the bottom of the pipe, gas along the top. The regime is further subdivided as stratified smooth or stratified wavy.

(2) *Intermittent.* This flow regime is characterized by a non-uniform distribution of liquid and vapor along the length of the pipe. Intermittent flow may be slug flow, where the liquid moves down the pipe in a series of plugs of liquid interspersed with a stratified flow. Elongated bubble flow is a special case of slug flow, where the liquid has not entrained any gas bubbles.

(3) *Annular.* In the annular flow regime, the liquid forms a film around the inside circumference of the pipe. Vapor flows in the center of the pipe. Annular flow usually occurs at low flow rates. Annular flow can consist of waves of liquid in the vapor space or as dispersed liquid droplets in the vapor space.

(4) *Dispersed bubble.* This flow regime is characterized by vapor bubbles dispersed in a predominantly liquid flow. The bubble concentration will be greater at the top of the pipe. Williamson [1976] reported this type of flow regime for Halon 1301 flow.

b. For vertical pipe flow (see Fig. 2.3-2).

(1) *Bubbleflow.* An approximately uniform distribution of vapor bubbles in liquid.

(2) *Slug flow.* Vapor transported in large bullet shaped bubbles, interspersed with plugs of predominantly liquid flow.

(3) *Churn flow.* Similar to slug flow, except more chaotic, or disordered. At high flow rates may be referred to as froth flow.

(4) *Annular flow.* Liquid flows along a wetted inside perimeter of the pipe. Vapor transporting dispersed liquid droplets flow along the center of the pipe.

While this terminology is not universal it is similar to and includes categorization done by Choe and Weisman [1976].

The process of defining flow regimes and transition between flow regimes is very important in the context of Halon 1301 flow computation. A primary reason is that pressure drop characteristics vary dramatically with the flow regime at a constant mass flow rate. Fig. 2.3-3 [from Hsu and Graham, 1976] illustrates this behavior. The x-axis is the volume ratio or ratio of gas to air by volume, the y-axis is the pressure drop per unit length and hold up ratio. The data is for a constant water flow velocity of .135 ft/s. This particular flow case is air in water. Fig. 2.3-4 from the ASHRAE Handbook of Fundamentals states this behavior as more general trends. The plot is of friction factor versus liquid fraction in the flow across a wide range of flow regimes.

A second major aspect of defining flow regimes is that the distribution of flow at a junction may be strongly dependent on the flow regime at that particular point in the pipe. A side split tee will have drastically different flow splits under conditions of stratified flow versus conditions of dispersed or bubbly flow. That the issue of flow regimes is so critical to defining the pressure drop and/or flow rate splits is evidence of the empirical nature of two phase flow computation and design.

The regime or state of a particular flow and possible transitions from one regime to another is determined with the aid of flow regime maps. There are many presentations of flow regime diagrams and they are typically done for horizontal and vertical flow. They may or may not be specific to a particular two phase system (e.g. air-water, steam-water, etc.). A well known example is the Baker flow pattern map. This is shown in Fig. 2.3-5. The coordinates are given as follows:

G_l: liquid mass velocity
G_g: gas mass velocity

$$\lambda = \left[\left(\frac{\rho_g}{.075}\right)\left(\frac{\rho_l}{62.3}\right)\right]^{1/2}$$

$$\psi = \left[\frac{73.0}{\alpha}\left(\frac{u_l}{1.0}\right)\left(\frac{62.3}{\rho_l}\right)^{2}\right]^{1/3} \qquad (2\text{-}6)$$

where: u_l = liquid viscosity (centipoise)
ρ_g, ρ_l = gas and liquid densities (lb/cu. ft)
α = surface tension (dyne/cm)

There are numerous flow regime prediction methods with a wide range of correlating variables. Of particular interest to Halon 1301 flow are studies on refrigerants [Weisman et al, 1981; Hashizume and Ogiwara, 1985, 1986; Hashizume, 1982, 1983].

The sample Baker chart shown as Fig. 2.3-5 illustrates the philosophy behind the high mass flow rates typical in Halon 1301 system design. By maintaining high velocities, the flow regime will be either bubbles or dispersed phase, both more amenable to homogeneous flow model assumptions. The precise boundaries of these flow regime maps are not important here. The reader is referred to reviews by Barnea and Taitel (1986), and Choe and Weisman (1974, 1976), Crawford et al (1985, 1986), Hashizume and Ogawa (1987), Hashizume (1983), Hashizume et al (1985), Dukler and Taitel (1977), Soliman (1986), and Weisman (1979, 1981, 1983) for additional detail.

2.3.2 Hold Up in Two Phase Flow

Hold up refers to the relative volume of a particular phase in the pipe. Hold up is closely related to pressure drop within a specific flow regime. The well known Lockart and Martinelli relation (on which the work of Hession was based) gives pressure drop as a function of void fraction. Typical correlations are for hold up versus quality (or dryness fraction) [Spedding and Chen, 1986]. Hold up ratios are also plotted against volumetric flow rate ratios (liquid to gas) and may be specific to a particular flow regime, although most are attempted for all regimes of a given two phase system. Typical hold up fraction correlations are given in Figs. 2.3-6 and 2.3-8.

2.3.3 Pressure Drop

All generalized pressure drop correlations account for the following properties, or their analogs:

(1) vapor and liquid densities
(2) vapor and liquid viscosity
(3) void fraction
(4) ratio of gas to liquid flow rates.

Hence, if the state and velocities of both phases of a fluid are known at some position, the pressure drop can be predicted with good accuracy. This is in essence the procedure in NFPA 12A with the special condition that the flow regime is bubbly or dispersed (e.g., associated with high mass flow rate) and that flow can be represented as a flow of liquid with effective properties approximating the two phases.

Husain et al [1974] evaluated the application of a homogeneous flow model to predict pressure drops. The advantage of a homogeneous flow model approach is its relative analytical simplicity. Homogeneous flow models have been found to successfully correlate high pressure high velocity flow pressure drop data. Typical pressure drop correlations are given in Figs. 2.3-7 and 2.3-9. Pressure drop data and calculation procedures for pipeline flow are given in: Chisolm (1983, 1986) Hashizume and Ogawa (1985, 1987), Husain et al (1974) Hwang and Lakey (1987), Kadambi (1983), Laurinat et al (1984), Mandhane et al (1977), Mukherjee and Brill (1983, 1985), Norstebo (1986), Norster (1983), Olujic (1985), and Pal et al (1980).

2.3.4 Flow at Junctions

The preferential partition of either of the two phases at a junction has been briefly discussed. Williamson [1975] provides data on the uneven split of Halon 1301 at bullhead tees due to separation of liquid and vapor phases. Balanced flow in each direction at a tee (i.e., flow equal in both legs of tee) indicated that the flow split occurred as expected. As more extreme flow splits occur, the predicted flow is less accurate. Flow through side tee configurations is more complex, with preferential flow of liquid in the straight or through direction.

In addition to cautions on flow splits the data obtained from a FEMA test program indicated the importance of accurate pressure drop calculations for unbalanced flow conditions. Azzopardi [1986] reviewed data from approximately twenty sources on the split of flows at junctions in piping systems. Variables identified by Azzopardi as effecting the ratio of gas to liquid split at side tees included:

(1) inlet quality
(2) diameter ratio

(3) angle of junction
(4) side arm inclination

This assumes that the pressure drop across each flow split direction can be accurately determined. The literature concentrates on side tees because in principle the case of bullhead tees is straightforward if the flow calculations upstream and downstream of each leg have been accurately determined, and the flow is not separated (i.e., stratified or annular).

At a flow dividing junction (e.g., side tee), data from Azzopardi [1987] indicate that for high quality flows the liquid phase emerges preferentially from a side tee, at low quality flows the gas exits the side tee first. Other data indicate that the degree of phase distribution is strongly dependent on the flow quality.

At low qualities for bubbly flow, the phase distribution is not stratified and the phase velocities are similar. In this case the gas flow will exit the side tee due to its lower momentum. The dependence of the flow split on flow regime at the dividing junction is further discussed by Azzopardi [1987].

The orientation of the side tee also has substantial effect on the distribution of phases and flow at a dividing junction. Entrainment and pull-through, particularly for stratified or annular flows, is typically observed. Azzopardi summarizes the available analytical procedures for estimating flow splits. He summarizes five approaches to the problem, none of which are universally applicable across all flow conditions.

In addition to the problem of defining flow distribution at a junction, there is sparse data on the pressure drop across a junction. This problem is exacerbated by the wide range of correlations used to describe flow at junctions. Some generic correlations for pressure drop at a junction are available. They typically require a two phase flow parameter such as that developed by Lockart-Martinelli [1949], the mass flow rate of liquid or gas, liquid and gas densities, the relative flow rates and flow qualities, and the cross-sectional areas of the legs of the junction being evaluated.

Specific recent work has been performed on annular flow at a vertical tee using water/air flows [Azzopardi, 1987], and steam/water flows addressing entrainment and pull-through at side tees [Anderson, 1987]. Saba and Lakey [1984] present a complete set of air/water flow data for horizontal tees demonstrating the flow split and pressure drop dependence on entrance quality, and liquid mass flow rate. The empirical model developed appears to work well for well mixed flow regimes, indicating the dependence of any flow split calculations on flow regime.

Hwang and Lahey [1987] present pressure drop data for flow dividing horizontal tees, and wyes. They conclude that existing correlations can be used to successfully predict pressure drop in tees, at least for air/water flows. Rieman and Domanski [1987] performed flow distribution data for tees over a wide range of inlet flow conditions and a diameter ratio between .08 and .52. They conclude that no existing model adequately describes the flow redistribution over the range of flow regimes studied. More success was attained with pressure drop measurement correlation using homogeneous flow model approaches [see Azzopardi, 1986].

Carver and Salcudean [1987] studied the problem of phase redistribution which occurs around bends and obstructions, not involving flow splits. A two dimensional finite differencing method was used to simulate the flow. Good agreement was attained for bubbly flow. Scaludean [1986] summarizes the literature on flow around obstructions, sudden enlargements and contractions and through orifices.

Especially difficult cases are stratified flows where the liquid phase is below or partially submerges a side outlet of a side tee. Smoglie and Reiman [1986] show cases where a side tee on the bottom of a horizontal pipe completely submerged by liquid entrains gas through the liquid through vortices. Liquid entrainment due to a high pressure drop (similar to a venturi eductor) across the side leg occurs in stratified flow where the liquid level is below the elevation of the side leg of the tee [Smoglie et al, 1987]. Annular flow regimes cause special problems at bulkhead or impacting T junctions. Azzopardi et al [1987] successfully predicted the flow distribution of vertical annular air-water flows across the entire range of liquid-gas flow splits. Fig. 2.3-10 illustrates these phenomena. The orientation of the dividing junction is quite important in this case.

Essentially the problem of defining flow splits at tees requires prediction of the relative proportion of liquid and gas which flows in each direction. This is a complicated problem, and none of the approaches taken to date are universally applicable [Azzopardi, 1986]. There is a problem in defining the pressure drop across tees, for all flow regimes.

In summary, there has been success in predicting flow characteristics and splits for both impacting and side tees for specific liquid-vapor systems, and these approaches point the way for progress relative to Halon 1301 flows. However, no generic prediction scheme currently exists which addresses flow splits at junctions for two phase flow.

2.4 Toward a General Halon 1301 Two Phase Flow Calculation Method

The relationship between this relatively complex flow behavior and the need for "open," verifiable, calculation schemes is subtle but very important. For simple flow cases (e.g., water flow through piping systems), the equations to be solved are well known: essentially those of continuity and energy.

Although the source codes of typical commercial sprinkler hydraulics programs are proprientary, the details of how the equations are solved in a particular hydraulics program are not really important. This is true for several reasons. First and primarily, the equations to be solved are well understood and not subject to much controversy. Secondly, there are only a few empirical correction factors (equivalent lengths, friction factors, discharge coefficients, etc.), input requirements are well described, and data is widely available in the open literature. Finally, the results can be readily checked with simple hand calculations, e.g. the pressure drop across a pipe length can be easily verified.

Halon flow programs used by equipment manufacturers in the design of halon systems and approved by UL 1058 share none of these features with the well known sprinkler analog. The equations which are solved for pressure drop, heat transfer, vapor/liquid ratios, nozzle flow, splits at tees, etc. vary widely. In principle, full continuity, energy, momentum, and species equations could be solved by appropriate numerical schemes, but this is impractical and not done for piping schemes. Hence the calculation procedure is simplified and this simplification can take many forms. The current NFPA 12A design method is one possible simplification. In addition each simplification brings with it certain assumptions, empirical correction factors, etc. which can only be evaluated if these factors are well described and supporting data is provided. More importantly there is no way to check the results of a particular two phase calculation scheme unless pipe flow data for fluid under consideration in a similar pipe network is available for comparison. No such data or calculation schemes exist for Halon 1301 flow.

Some of these concerns can be mitigated through third party approval or testing of Halon 1301 piping design programs. This was discussed in Section 2.1.1 and several problems and uncertainties were identified. Sufficient validation cannot be accomplished through third party approvals for a wide range of empirically based proprietary design programs, where results cannot be verified to a generally agreed upon standard by the approving authority or responsible engineer.

It is not necessary for current proprietary programs to be made public. The requirement is for an agreed upon calculation procedure, with all assumptions and empirical simplifications and input supported by test data, and agreed upon as a standard against which the results of proprietary programs can be checked for a particular installation geometry. This is largely independent of the third party approval of proprietary software issue. The following discussion addresses the feasibility of the development of such a calculation procedure.

Design procedures are available for a wide range of two phase flow problems involving air-water, steam-water and refrigerant flows using computer based calculation procedures. These procedures time step the discharge process over a discretized piping network. The time stepping and geometrical discretization permit more detailed treatment (and less overall averaging) of the flow in a short section of piping.

The need for accurate two phase flow calculations in the power and chemical process industries has given rise to many two phase flow computation programs, most of which are public domain. A brief list is given below:

Title	Author	Date
K-TIF	Amsden and Harlow	1977
FLOW3	Beus and Anderson	1984
SOLA-NET	Campbell et al.	1982
FLOW22	Dalen	1975
SOLA-LOOP	Hirt et al.	1979
RAPVOID	Porter	1971
SOLA-DF	Hirt et al.	1984
RETRAN	Hughes and Fujita	1978
VORT	Cook and Harlow	1984
	Blis et al.	1982
	Boure	1972
COBRA-TRAC	Thurgood et al.	1983
–	Rohatgi et al.	
FLOW-NET	Rivard and Sicilian	1987
COMMIX-1B	ANL (Argonne National Lab)	1985
COMMIX-2	ANL	1985
PHOENICS	Spaulding	
KFIX	Rivard and Torrey	1977
GEVATRAN	Boure, J.A.	1972

Most of these programs have been used in nuclear power plant applications, although at least one has been successfully applied to a Halon 1301 pipe network. The remainder have not been compared to transient Halon 1301 flows.

The degree of sophistication and detail varies widely among these models. Clearly, a program which predicts the three dimensional behavior of two phase flow in power reactors is more sophisticated than is needed for a pipe network which is essentially a one dimensional flow problem. The point is that despite the complexity of the 1301 pipe flow process, the problem has been essentially solved for much more physically complex flow conditions. Furthermore the "open" nature of these programs facilitates their acceptance as design and analysis tools.

Programs which are well developed and appear to contain an adequate level of detail for Halon 1301 pipe flow calculations include: SOLA-NET, SOLA-LOOP, and FLOW-NET; others are certainly acceptable but appear to have much higher levels of technical detail then is necessary for a pipe flow problem.

Previous discussions on hold up, pressure drop, flow splits etc., indicate the need for some empirical inputs or sub-models to generalized mathematical models of two phase flow. The acceptability of these empirical submodels is driven by the applicability and validity of the data on which they are based. This requirement increases the need for "open" flow calculation schemes.

Elliot et al [1984] successfully adapted computer based calculation procedures written for water-steam-air systems to the problem of Halon 1301 flow from a cylinder through a pipe network [Hirt et al, 1979]. The agreement between calculated and measured results was excellent in terms of the time history of the discharge, and successful prediction of the dynamic effects such as pressure oscillations in the piping. The only modification made to the program was to substitute nitrogen pressurized Halon 1301 properties for the water-steam-air properties.

Figs. 2.3-11 and 2.3-12 illustrate the agreement between measurements and the SOLA-LOOP computer program results [from Elliot et al, 1984] for a single nozzle system. Unbalanced two and three nozzle flows were also successfully predicted.

The authors also developed a more simplified Halon 1301 flow calculation program, HFLOW. The model derived in Elliot et al [1984] consists of two sections: one calculates the conditions in the storage cylinder as the halon is discharged; the second section calculates flow rate through the piping as a function of storage cylinder outlet conditions. The model assumes quasi-steady flow through the piping.

Multiple nozzle systems are simplified to an equivalent single branch line. The mass discharged from each nozzle in the multiple nozzle system is obtained by multiplying the total mass discharged by the ratio of nozzle area for each nozzle to total nozzle area. This apparent gross simplification results in good agreement between experimental and theoretical data. The piping system tested, the bottle discharge pressure, and pressure at the tee and at each nozzle is shown in Figs. 2.3-13 through 2.3-16.

While the agreement is very good, the piping system used involved short lengths of small diameter pipe. These flow conditions do not represent the most challenging relative to typical Halon 1301 piping system calculations.

The program HFLOW was compared to a sample calculation performed under NFPA 12A-1973. The authors applied the HFLOW program to a sample design in a Walter Kidde design manual, using an equivalent single pipe for an unbalanced three nozzle system. Although no direct comparison was provided, the HFLOW predicted discharge time was 7.2 s, which is within the 10 second discharge time limit imposed in NFPA 12A.

This evaluation of both the SOLA-LOOP and more simplified HFLOW program indicate that the use of a modified public domain two phase flow software and design procedure as a basis for evaluating proprietary Halon 1301 flow calculation programs may be readily available.

2.5 Summary

Several simplifying assumptions are incorporated in the calculation procedure outlined in NFPA 12A. While these assumptions are deemed necessary due to the complexities associated with a more detailed approach, they may introduce significant errors in flow calculations. This is of particular concern for the more complicated "unbalanced" systems.

The magnitude of the performance problem associated with inadequate Halon 1301 flow calculation schemes cannot be quantified at this time. In addition to cases of incorrect distribution of agent in simultaneously protected individual enclosures (a clear indicator of poor calculation scheme performance) cases of excessive discharge time (greater than 10 seconds) and inadequate initial mixing of the agent have been identified. It is unknown whether the poor mixing is caused by incorrect nozzle placement or due to unexpected flow distribution through piping networks. Concerns for the potential impact on system performance resulting from such variations lends support for the need for discharge testing.

In addition, there is concern, primarily among specifying engineers and authorities having jurisdiction, with accepting the design calculations performed with UL 1058 approved flow calculation programs. The procedure in UL 1058 essentially provides for spot checks of the programs against selected worst case program limitations. This concern is also mitigated by discharge testing.

The accuracy of flow calculations has a direct effect on the performance limits of an installed total flooding Halon 1301 system. The lack of confidence which exists in two phase flow calculation procedures for Halon 1301 has led to dependence on discharge testing to assure the accuracy of the calculations and the ability of the system to meet key design criteria. There are several alternatives to discharge testing which may be considered. An obvious short term alternative would involve mandating the use of simple, modular systems with (1) short pipe distances to individual nozzles, or (2) balanced flow through short pipe distances to multiple nozzles. This would not result in a better understanding of the flow phenomena associated with Halon 1301 systems. However, it would alleviate demands on discharge testing due to the higher confidence in the application of current flow calculation methods to these uncomplicated systems.

A second alternative would be to consider the use of alternate test gases in discharge testing which simulate the flow and dispersion characteristics of Halon 1301. Substitute agents have been used in acceptance testing with promising results, and such a strategy could be more completely developed within a year. A more detailed discussion of this concept is provided in Section 5.

The most attractive alternative in terms of long term confidence and performance dependability would be to develop a benchmark or generic flow calculation method. Such a method appears quite feasible, and would most likely involve modification of available computer based two phase flow programs.

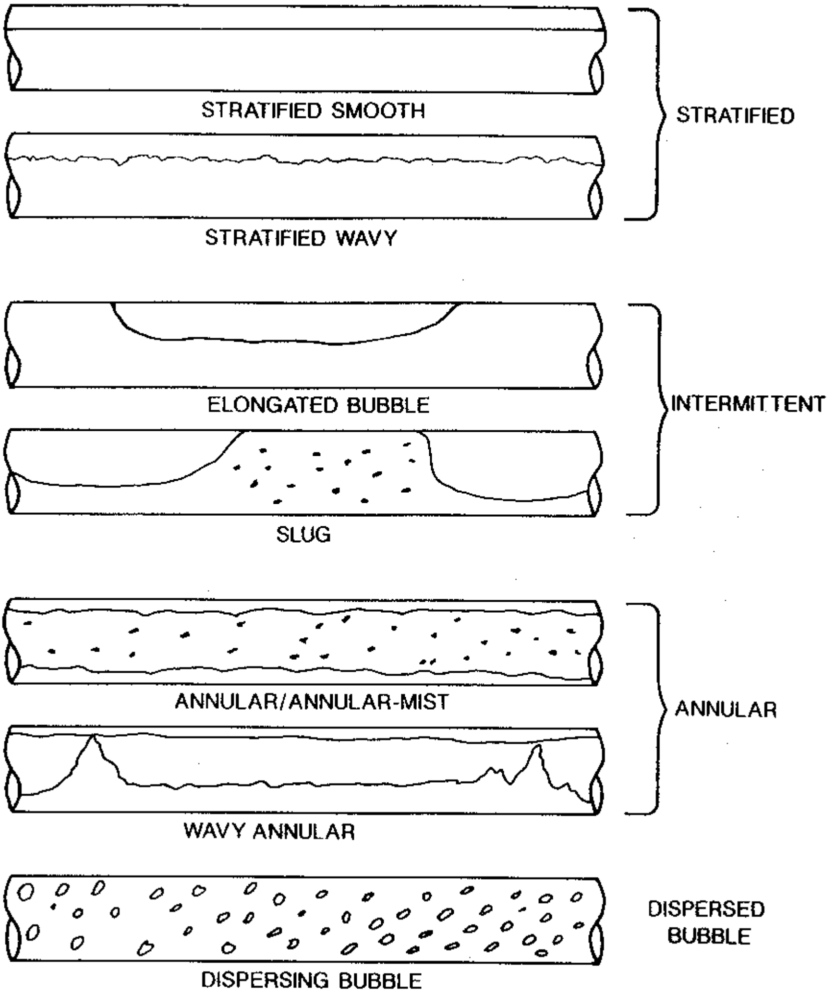


Fig. 2.3-1 — Horizontal pipe flow regimes [Barnea and Taitel, 1986]

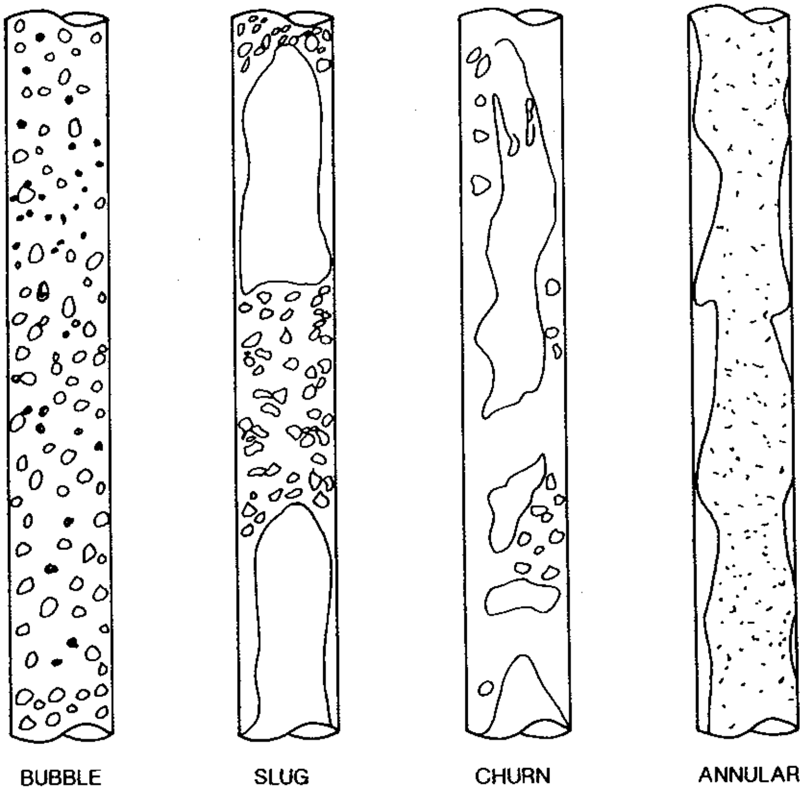


Fig. 2.3-2 – Vertical pipe flow regimes [Barnea and Taitel, 1986]

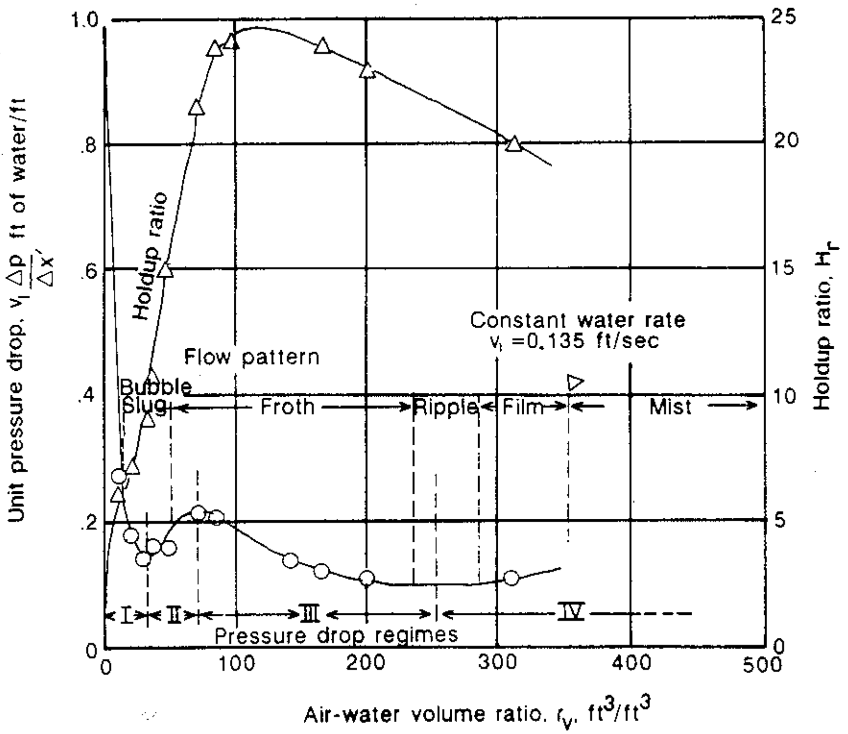


Fig. 2.3-3 – Flow regime vs. pressure drop [Hsu and Graham, 1976]

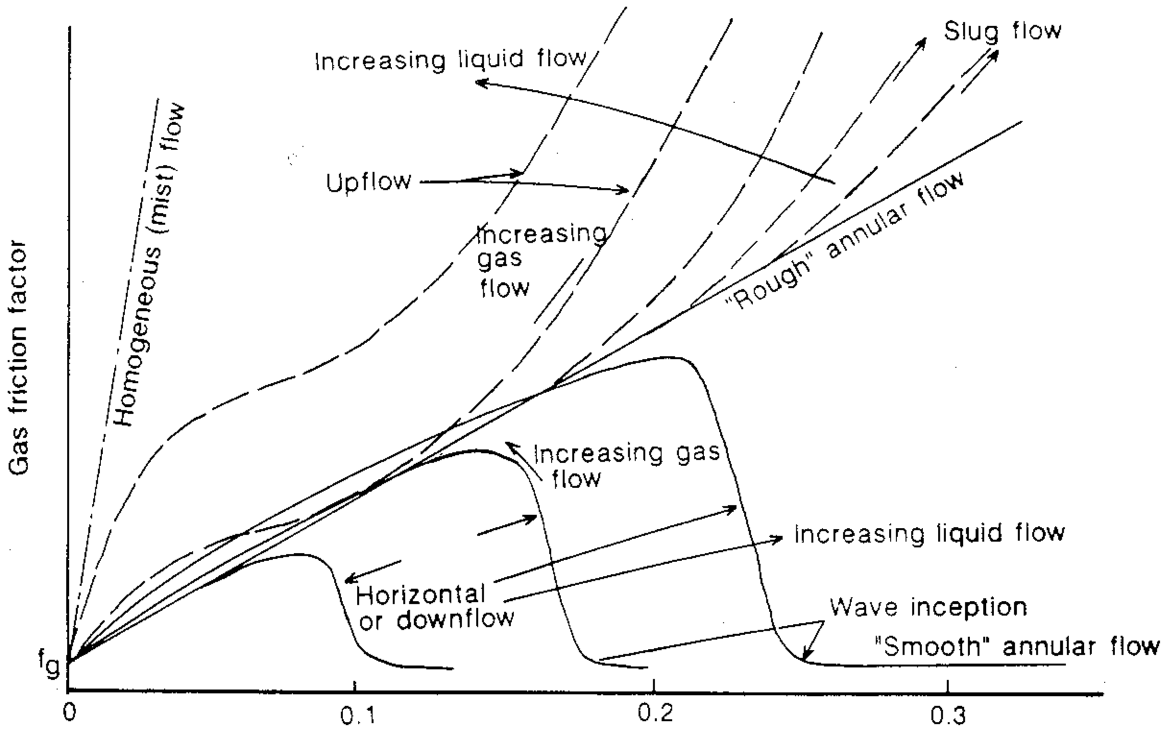


Fig. 2.3-4 — Friction factor vs. liquid fraction in various flow regimes [ASHRAE, 1986]

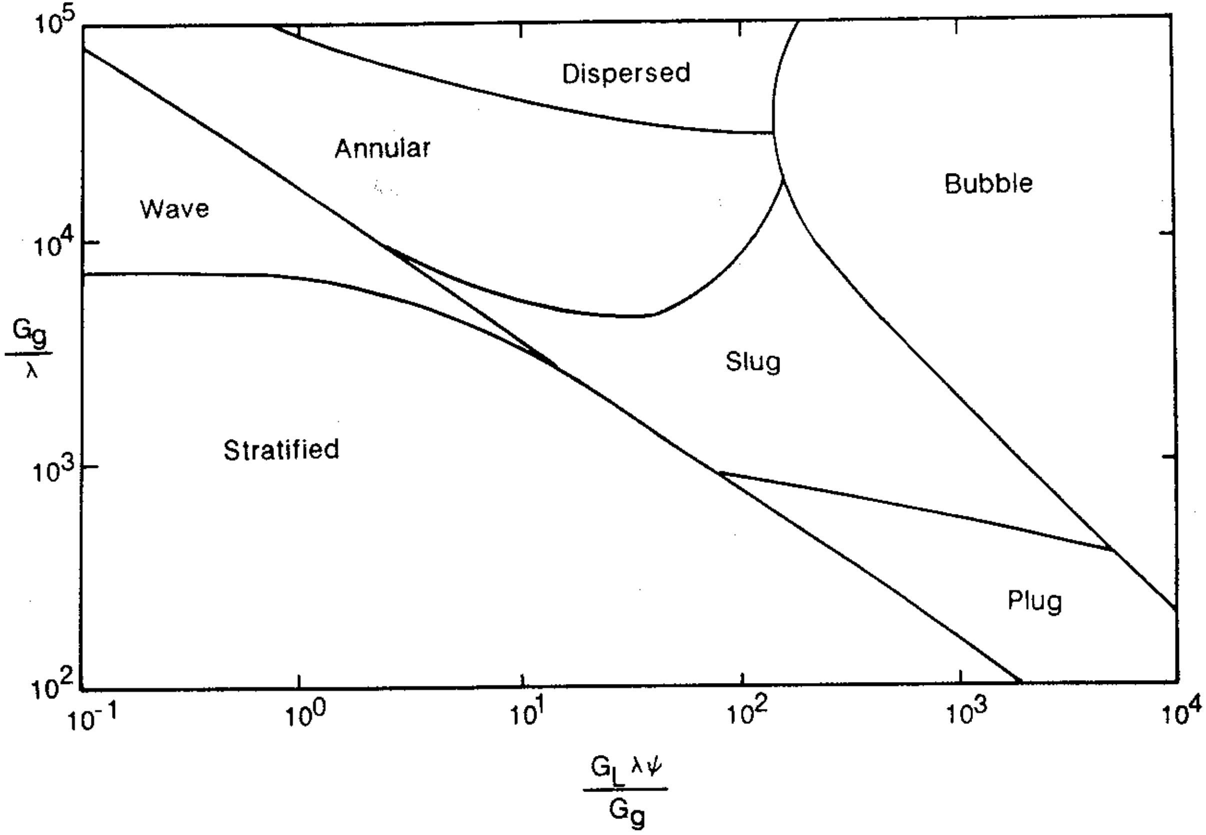


Fig. 2.3-5 – Typical flow regime map, Baker chart [Hsu and Graham, 1976]

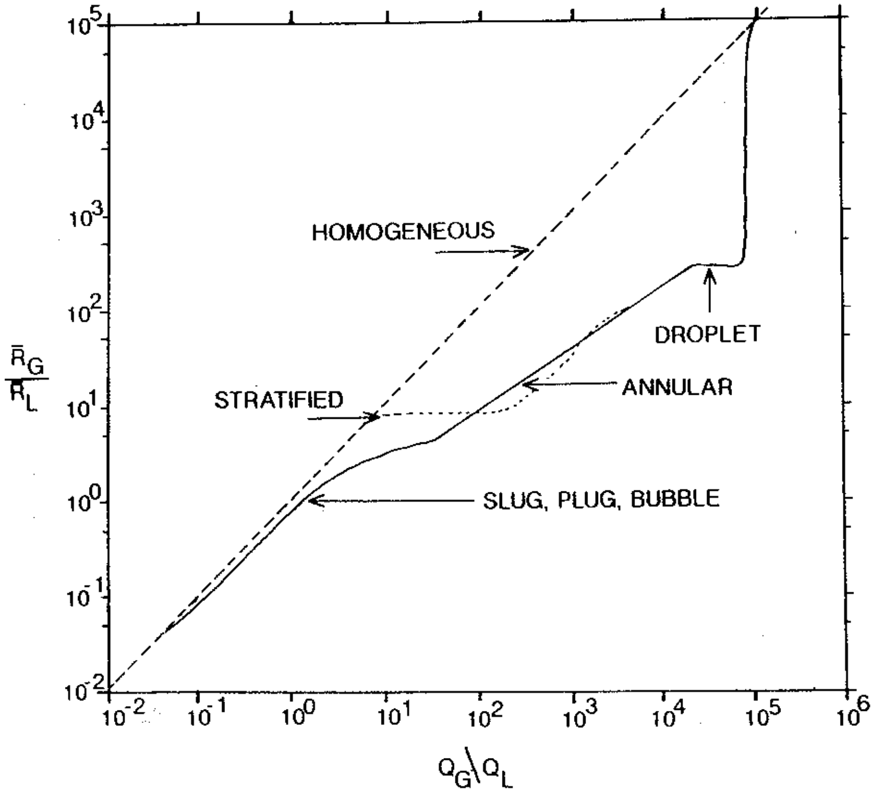


Fig. 2.3-6 – Hold up regimes vs. gas/liquid flow ratio [Spedding and Chen, 1986]

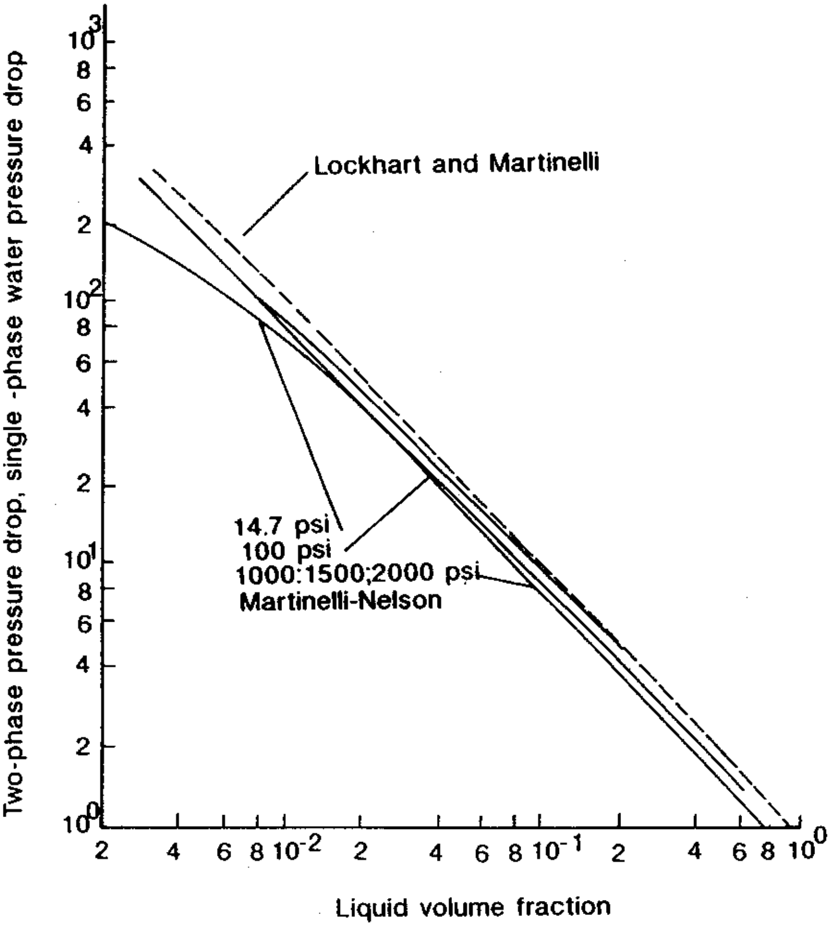


Fig. 2.3-7 – Pressure drop vs. liquid volume fraction [Hsu and Graham, 1976]

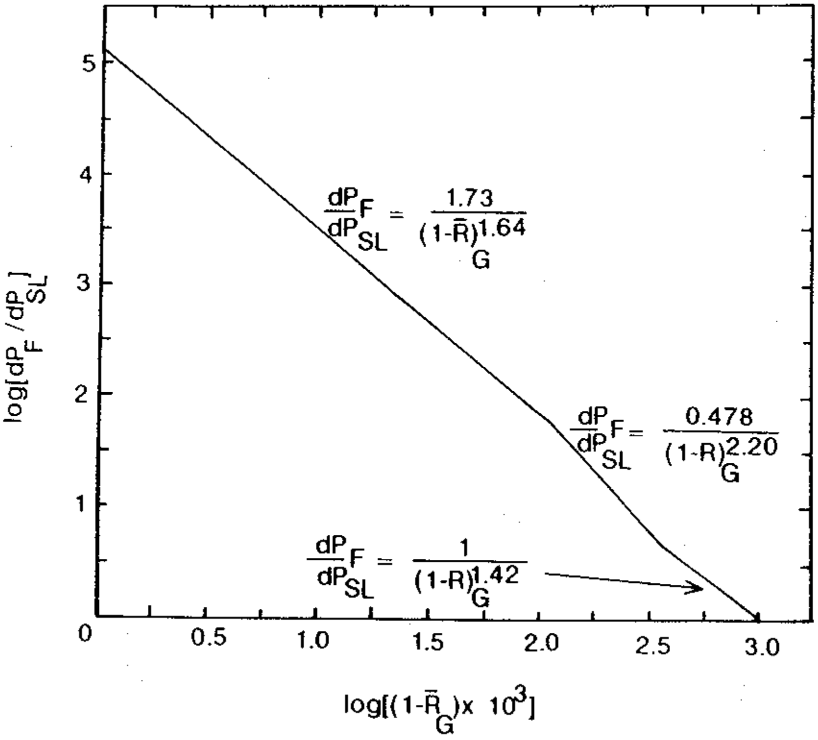


Fig. 2.3-8 – Pressure vs. hold up [Spedding and Chen, 1986]

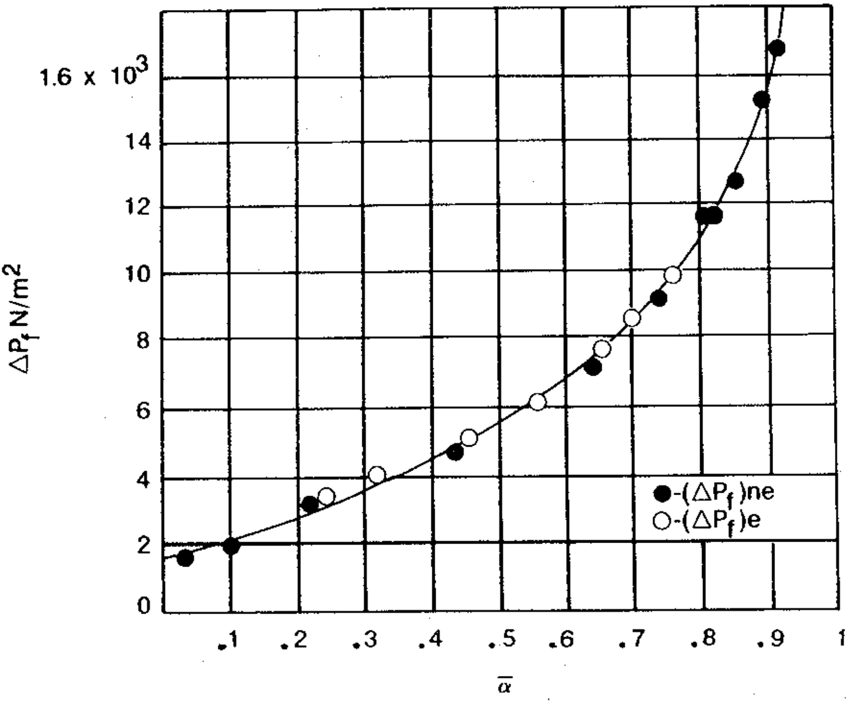
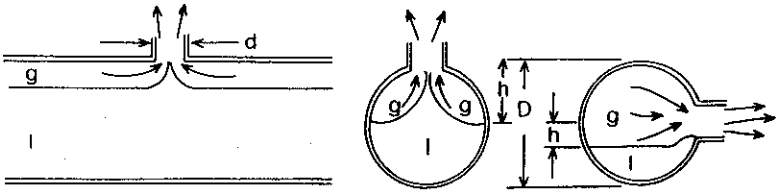
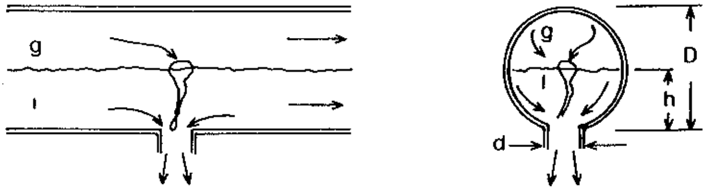


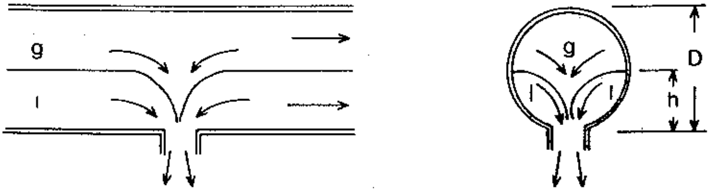
Fig. 2.3-9 – Plot of pressure drop vs. void fraction [Hsu and Graham, 1976]



Liquid entrainment due to Bernoulli effect



Gas entrainment due to vortex formation



Gas entrainment in vortex free flow

Fig. 2.3-10a – Mechanisms of liquid/gas separation at junctions [Smoglie et al, 1987]

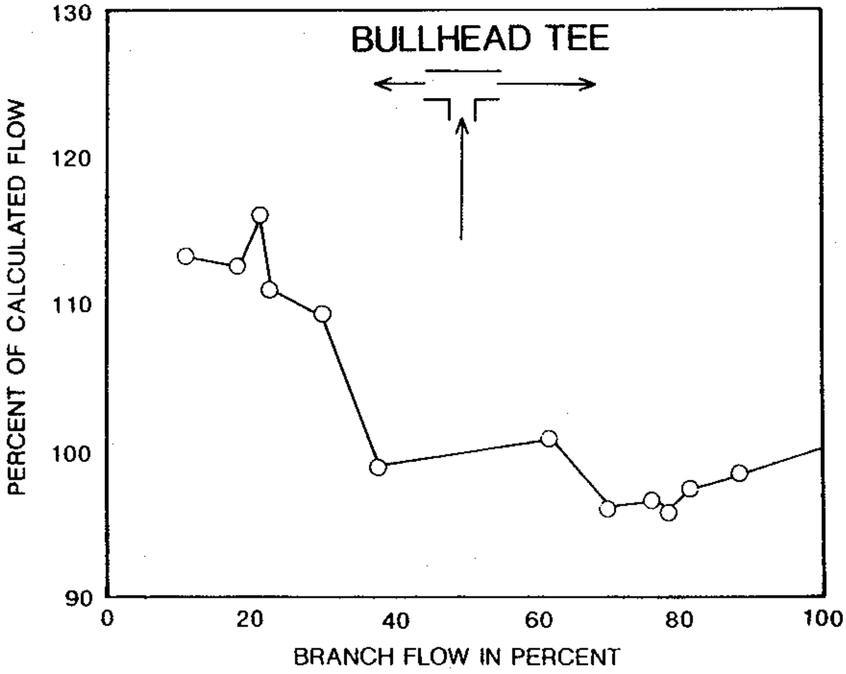


Fig. 2.3-10b — Bullhead tee flow splits [Williamson, 1976]

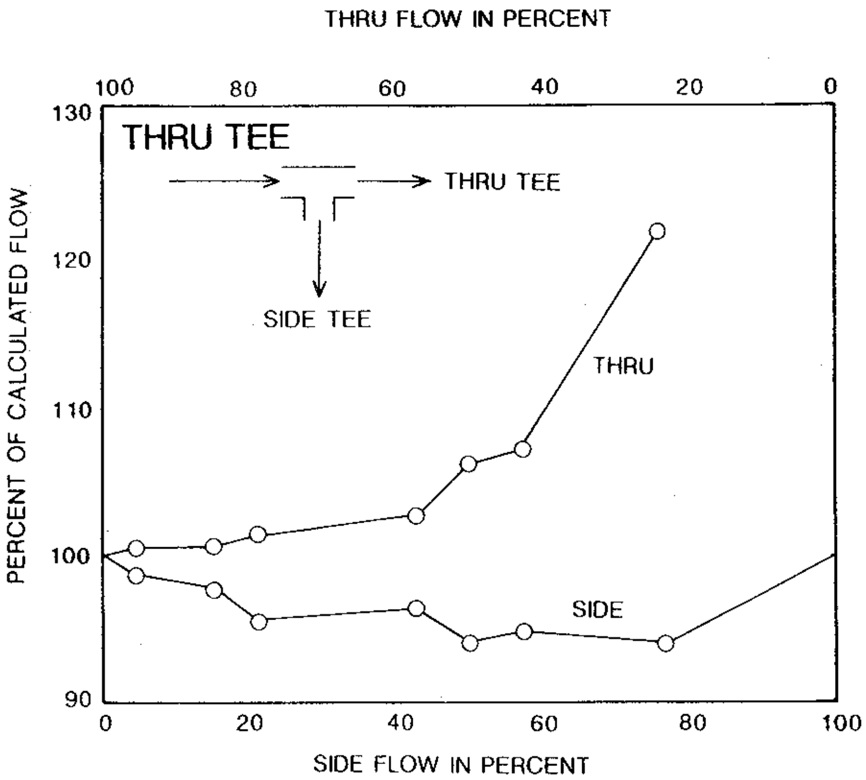


Fig. 2.3-10c — Side and through tee flow splits [Williamson, 1976]

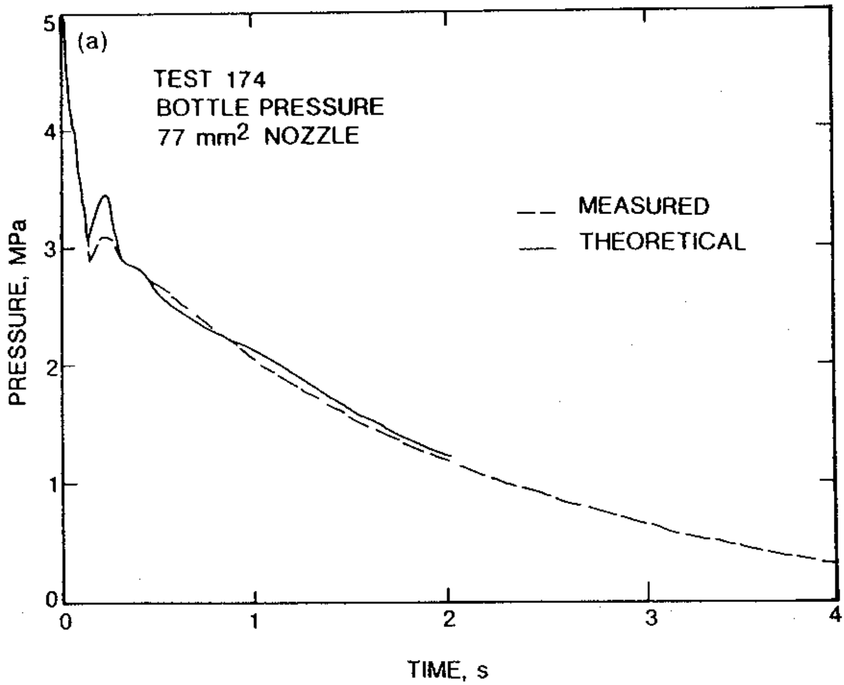


Fig. 2.3-11 – Experimental vs. predicted cylinder pressure data [Elliot et al, 1984]

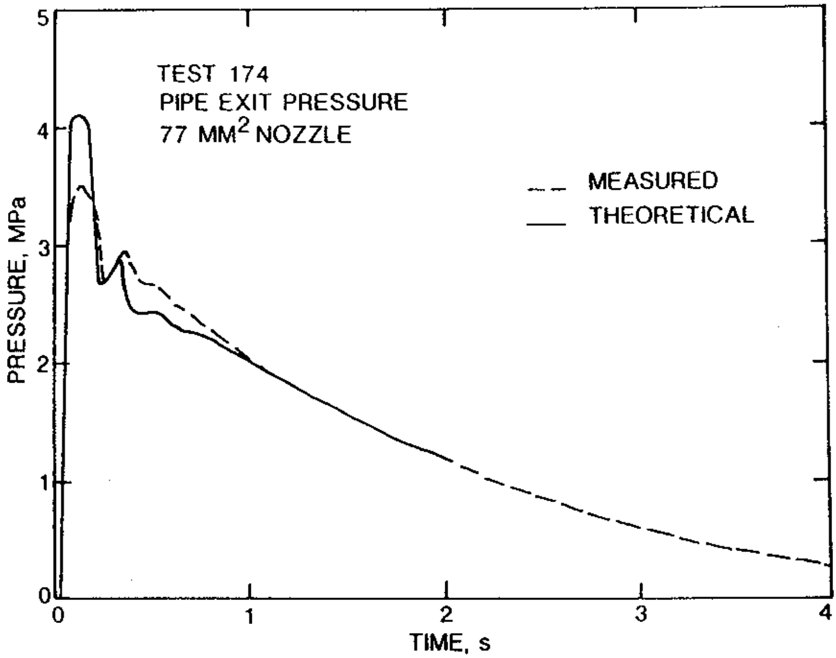


Fig. 2.3-12 — Experimental vs. predicted nozzle pressure data [Elliot et al, 1984]

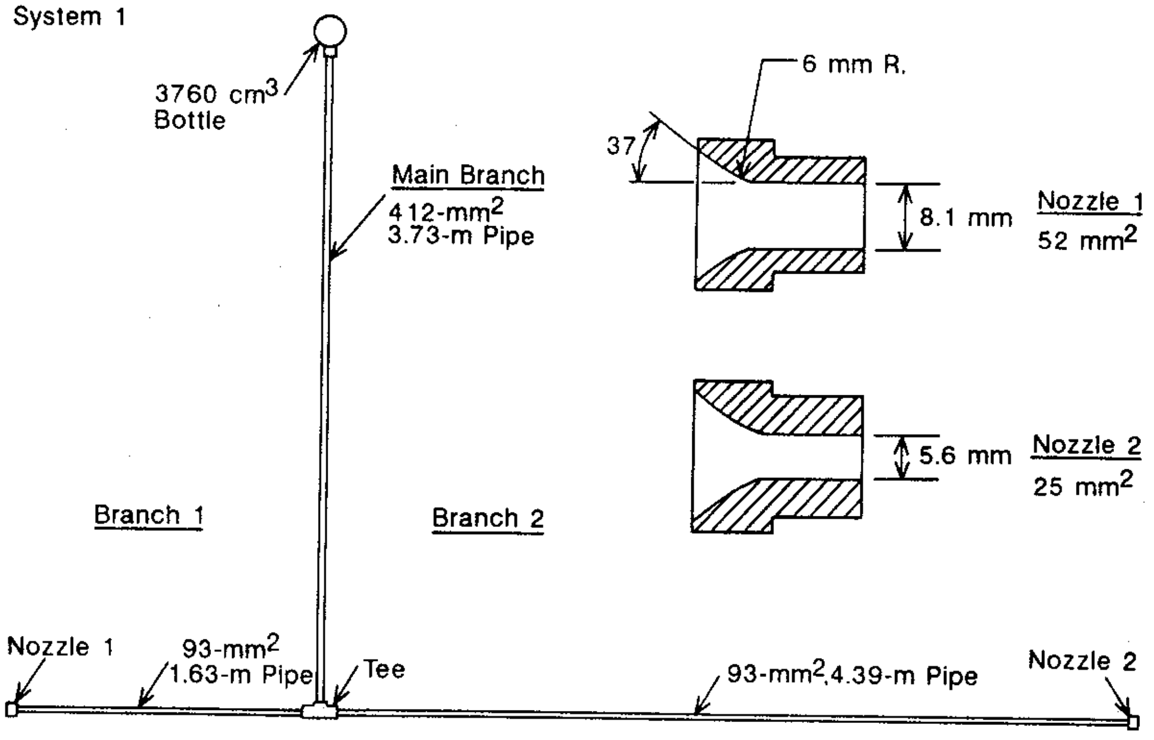


Fig. 2.3-13 – Piping schematic for calculation procedure evaluation [Elliot et al, 1984]

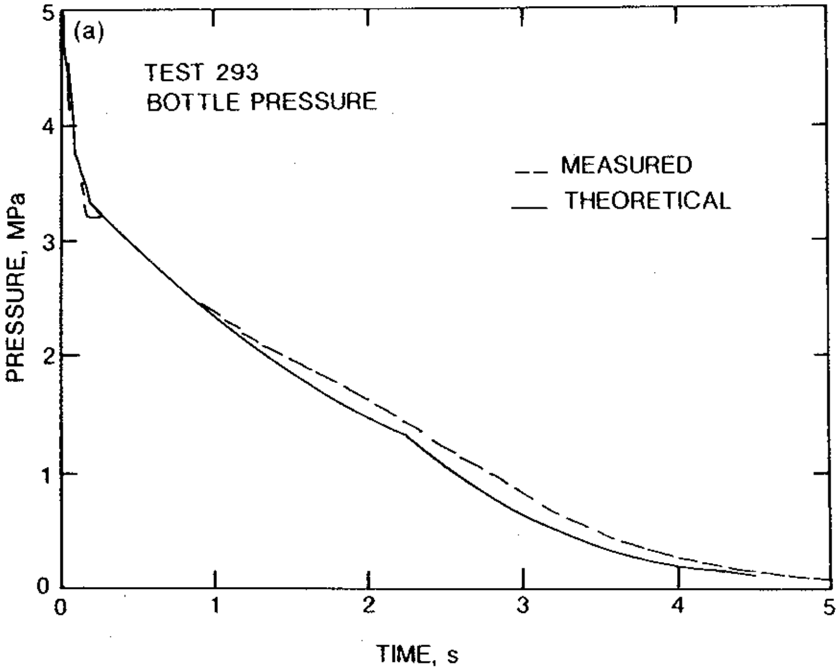


Fig. 2.3-14 — Experimental vs. predicted cylinder pressure [Elliot et al, 1984]

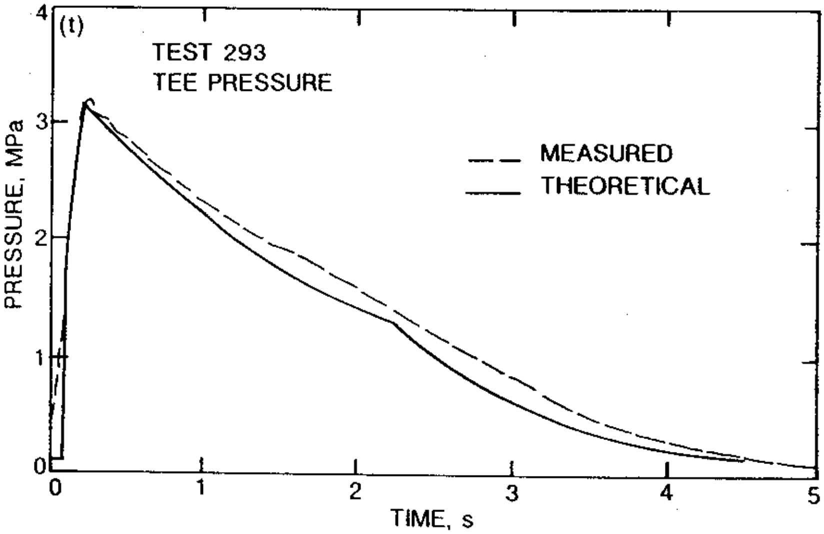
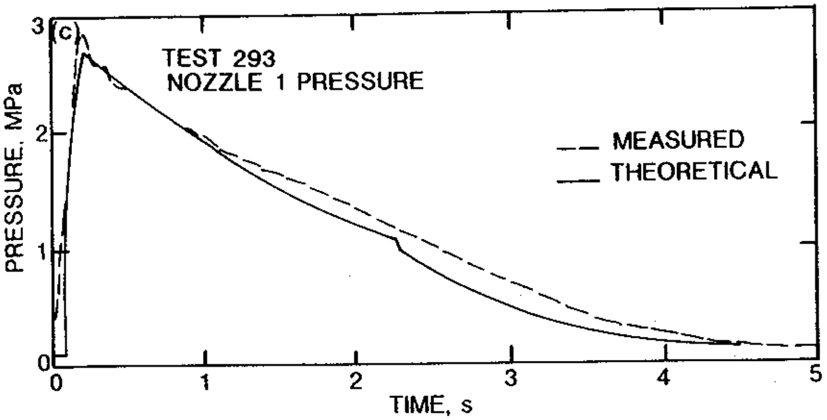


Fig. 2.3-15 – Experimental vs. theoretical agreement, pressure at tee [Elliot et al, 1984]



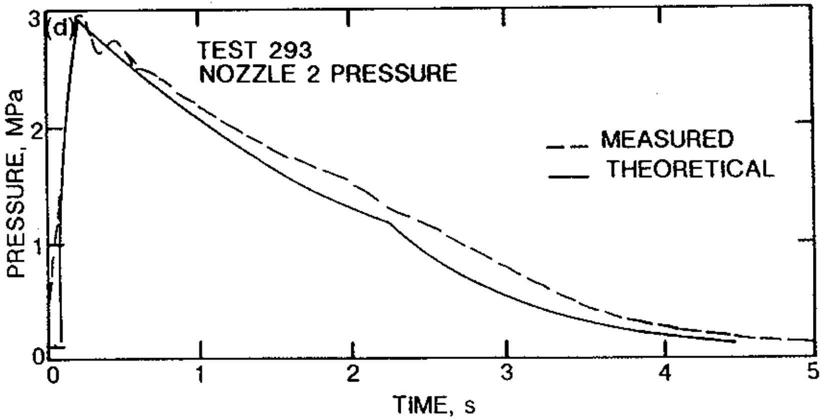


Fig. 2.3-16 – Experimental vs. theoretical agreement of nozzle pressures [Elliot et al, 1984]

3. AGENT MIXING AND DISTRIBUTION

3.1 Background

Another important reason for performing discharge tests on Halon 1301 total flooding systems is to ensure that the Halon 1301 discharged from the nozzle is adequately mixed and distributed throughout the compartment.

Upon discharge, any remaining liquid is mechanically atomized at the discharge exit of the nozzle. Once exiting the nozzle, liquid droplets evaporate rapidly (flash) in the room. This process cools the room, causing an initial negative pressure across the enclosure boundary. As mass is added due to continued flow of Halon 1301, the pressure in the room increases, expelling a halon/air mixture through enclosure boundary leakage paths.

The flow out of the nozzle mixes with air by entraining the surrounding air into the nozzle discharge stream. The entrainment is a function of the flow velocity of the stream. As air is entrained the velocity of the stream decreases. The key to good mixing is to entrain enough of the surrounding air into the nozzle discharge and to ensure that the stream has adequate reach and volume. This requires relatively high agent flow rates, well designed discharge pattern (geometry), and the absence of substantial obstructions to the flow.

The jet of agent and entrained air may encounter obstructions in the centerline direction of the jet. In some cases these obstructions may actually contribute to the mixing process. For example, when a jet strikes the floor and is redirected vertically upward along a wall, it results in increased circulation in the room. Following this example, the presence of equipment on the floor will block this floor/wall jet. If the equipment is sufficiently tall to block substantial redistribution of the agent, pockets of air or reduced halon concentrations may develop. A similar situation may result from deep beam pockets located along the ceiling that can block the recirculated jet.

Another type of obstruction which is more difficult to treat is the obstruction oriented perpendicular to the jet flow. Typical examples include intermediate floor grates, large piping runs, cable trays, etc. The location, spacing and type of nozzles used are largely based on an empirical art. Discharge tests have been used to verify this judgement and to identify problem areas of reduced agent concentration. If discharge tests are to be eliminated, increased confidence in the design relative to nozzle type and spacing is required.

This implies that either improved design methods and/or improved empirical nozzle test and evaluation is required. The ultimate goal should be a procedure which ensures mixing in any specific enclosure/obstruction situation. This review examined quantitative procedures to evaluate spray characteristics and mixing toward the goal of verified generalizable design of nozzle types and location.

The conceptually simple yet very powerful way of evaluating a gas jet is through a boundary layer approximation of a free jet [Schlichting, 1979]. The theory applies to a gas jet flowing into a gas of equal density. A "spray" of Halon 1301 is not a simple gas jet, in that the discharge is often liquid and undergoes rapid vaporization. Turbulent jet theory is, however, widely used in applications involving the mixing of gas jets in process industry applications [Ajinkya, 1983].

The simplest approximation of nozzle flow of Halon 1301 is a turbulent circular gas jet. Decay of jet velocity and gas concentration along the trajectory of the jet is caused by entrainment of air. The radial variations of velocity and concentration are similar and follow a Gaussian distribution.

If it were possible to characterize the mixing performance of Halon 1301 nozzles in a simple way (e.g., jet radius and velocity as a function of distance from the nozzle), and this performance could be related to compartment volume and height, then uncertainties relative to nozzle mixing could be partially alleviated. The remaining problem is primarily related to flow obstructions. It is possible to predict the flow field around, past, or through an obstruction although such procedures are not very practical design tools.

The problem of rapidly evaporating turbulent sprays of two phase mixtures occurs in a variety of applications including combusting fuel sprays [Soloman et al, 1982, 1983, 1984], spray drying in chemical engineering [Marshall, 1954], and automatic sprinkler discharge modeling [Alpert, 1982]. Recent reviews of spray structures and characteristics include those by Faeth [1983], Yeung [1986], and Cheremisinoff [1986]. The problem involves a breakup of the liquid stream at the nozzle, subsequent breakup after discharge, evaporation of the spray (often dense), the dynamics of the spray, and entrainment. While a wide range of experimental and theoretical studies exist, often using refrigerants such as R-12, the practical design problem remains a largely empirical task. This is due primarily to the following:

(1) Theoretical analysis is well developed for "sparse" sprays of evaporating sprays but not for dense sprays. Halon 1301 sprays within 2-3 ft of the nozzle would be considered dense sprays.

(2) The need to characterize the nozzle discharge in terms of droplet size and velocity and spray density as a function of time and position is a time-consuming experimental task.

(3) The impact of complex obstructions in the enclosure is not calculable in a practical manner.

This implies that near term utilization of numerical prediction schemes for spray mixing is not practical. Some mix of empirical nozzle characterization and computation is required.

3.2 Halon 1301 Nozzle Flow Studies

Limited published studies on the dispersion and mixing of Halon 1301 streams are available. Eklund [1983] treated the discharge of Halons 1211 and 1301 and CO_2 portable extinguishers as well mixed and perfectly stirred for purposes of evaluating the concentrations of those gases in an aircraft cabin.

Burgess et al [1971] evaluated the jet velocity and concentration at a distance of 38 in. from the nozzle and at varying radial portions of time for a modular Halon 1301 system. The nozzle was a hemispherical head with holes dulled to yield a fairly wide pattern. Six tests were performed at fill weights of 40, 25, and 15 lbs in a .65 ft^3 cylinder at a storage pressure of 280 psi. The nozzle pattern was such that in some cases higher Halon 1301 concentrations were measured at increased radial distances from the nozzle axis.

The initial discharge velocity of the Halon 1301 was measured at 600-700 ft/sec, slowing quickly to 200-300 ft/sec. There was no effect of the compartment filling on the discharge pattern. Circulation within the 6-ft high, 18 ft × 24 ft compartment continued for approximately 2-3 seconds after the discharge. The discharge time was approximately 8 seconds for the 40 lb fill weight. Since the system and subsequent tests were designed to evaluate a local application explosion suppression system, the "steady state" intermixture of the compartment was not evaluated.

Elliott et al [1984] evaluated a variety of nozzle geometries relative to discharge pattern, atomization, and mixing. Four nozzle designs were evaluated using visual, photographic, and high-speed motion pictures of nozzle discharge of water and nitrogen mixtures. Based on these visual observations of jet breakup and degree of atomization, a nozzle was developed consisting of a series of multiple cones, discharging in a hemispherical nozzle. The commercially available nozzles did not provide the same degree of atomization and entrainment.

Sarkos [1975] extended previous work by conducting 17 discharge tests in the passenger compartment of a DC-7 aircraft. Modular and perforated tube discharge systems were evaluated. Several interesting features of the discharge tests in a test of a modular system consisting of four storage containers resulted in a very uneven distribution of Halon 1301 concentration (between 3 and 21 percent by volume Halon 1301) for the first three seconds. Following that, the mixture was stable between 4 and 6 percent by volume, until approximately 5 minutes had elapsed, when decay of the concentration became applicable (less than 3 percent). It was not known whether this resulted from poor mixing or leakage. The test was repeated and concentration meters were located vertically as opposed to a single elevation. This test confirmed that leakage, not mixing, was the problem.

The tests also evaluated the impact of leaks (in the form of vents) at different elevations on the initial mixing and leakage. A perforated pipe discharge system was tested during these tests. The perforated pipe system resulted in a poor but not unacceptable degree initial distribution of agent.

The interesting feature of these perforations was that good mixing occurred between the Halon 1301 "waterfall" from the tube without highly turbulent jet discharge and associated entrainment.

Tests were also conducted with exit doors open. These tests indicated than "a reasonably good degree of inerting protection" would be attained for a time period similar to that required for evacuation.

There is a wealth of leakage, temperature, and pressure rise data contained in this report. It is particularly valuable with respect to mixing and leakage studies.

3.3 Design Problems

3.3.1 Background

The essential design and analysis problem involves describing the number and location of nozzles in a compartment. Presumably, the nozzle flow rate is known from hydraulic calculations. The only other information available is the UL 1058 listing information. Typical nozzle spacings are 30 ft. The question is therefore, under what conditions, if any, is more information required such that mixing is ensured without resort to discharge tests.

Obviously, obstructions located in the path of the discharge have some impact on the resultant mixing. All compartments, even typical computer rooms, have obstructions. Most of the time the resulting mixing is not a problem. What are the "limiting conditions" of ceiling height, nozzle spacing, and compartment volume? Which will result in mixing problems?

From a design standpoint a relatively simple set of parameters is desirable. Currently, of course, there is one parameter—nozzle spacing (and elevation) per UL 1058. The applicability of the UL 1058 nozzle spacing with respect to other obstructed flow pattern conditions is unknown.

The design of nozzles considers the breakup (of any liquid Halon 1301), pattern, and reach of the resultant spray or gas jet. Some nozzles offer 180 ft spray jet coverage. Presumably, this occurs at some penalty in terms of nozzle reach or momentum as one moves away from the nozzles. Other nozzle designs have more gradual radial dispersion. Clearly the nozzle design impacts mixing and one design should be superior to others in terms of mixing for certain conditions, assuming equivalent UL 1058 spacings and approval.

3.3.2 Nozzle Listing and Approval

Currently the only testing procedure invoked relative to nozzle spacing and location is the listing standard for halon system hardware. The UL 1058 standard provides for mixing and distribution tests of nozzles in open and partially obstructed flows. It is clearly not practical to list a given nozzle against all possible obstruction conditions. UL 1058 provides one data point for an obstruction oriented parallel to the nozzle flow.

A more generally applicable procedure for characterizing halon spray nozzles is required, at least under certain use conditons. The obstruction in UL 1058 is a vertical panel oriented parallel to the nozzle flow. Mixing problems typically occur in large complex spaces usually with high ceiling elevations and complex flow obstructions. It is not clear whether this is due to errors in the mass flow rate calculated for each nozzle or due to the mixing characteristics of the nozzle. The problem does not seem a widespread concern for low ceiling heights (8-10 ft) with reasonable length to width ratios. The frequency at which these mixing problems occur during actual discharge tests is not known, although several have been reported [Lee (1987), Lepple et al (1983)]. It is not known to what extent inadequate nozzle pressure or flow rate contributed to these problems.

3.3.3 Directions for Further Work[1]

There are several possible ways of simply characterizing nozzle discharge such that the nozzle spacing and resultant mixing can be evaluated for a particular set of compartment and obstruction conditions. Several are listed below:

The dispersion of halon in a space needs to be accomplished using the momentum of the halon discharge. This dispersion process needs to overcome the negative buoyancy of halon as it is discharged. The simplest method of discharging halon into a space is by way of a simple downward facing jet. As the halon moves toward the floor, air is entrained into the jet and the concentration of halon on the center line as the jet reaches the floor may be used as an indirect measure of the amount of air entrained. As the jet hits the floor the gases turn, forming a floor jet. Because the floor jet is heavier than air due to the halon, entrainment of air from above may be reduced. As the floor jet strikes a wall or other object, the flow turns upward. Depending on the ratio of the jet momentum to the jet buoyancy, the flow may climb the wall or simply layer out. If the jet climbs the wall, the gases will ultimately turn downward due to the negative buoyancy of the flow, but will entrain additional air before again layering out.

Because some form of layering will generally occur, it is useful to consider the situation in which entrainment by the floor jet and wall jets are negligible. From a design point of view, it is reasonable to ignore these effects since the presence and location of walls in any reasonable proximity cannot be guaranteed in general. In the most general case the entrainment by the downward jet must be relied upon to provide the required mixing.

3.3.3.a Modeling the Filling Process

As a first approximation, consider a jet of halon discharging as a gas in the downward direction. Initially the jet will entrain ambient air the full distance to the floor (H). Ignoring entrainment by the floor or wall jets, the gases entrained will layer at the floor. In order to assure that halon is well distributed in the compartment, the entrainment of air at the outset must be more than sufficient to reduce the concentration of halon in the jet as it reaches the floor to amounts well below the design concentration.

As the process continues, a layer of halon/air mixture forms at the floor and the height over which pure air is entrained is reduced (see Figure 3.3-1). The questions to be addressed are 1) how deep will the halon/air layer be at

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[1] This section prepared by: Dr. Craig L. Beyler, Fire Science Technologies, Cincinnati, OH.

the end of the discharge and 2) what will the concentration of halon be in the layer. Clearly, a good design will nearly completely fill the compartment to the design concentration. In order to address these questions, the problem can be formulated as a "smoke filling" problem. The situation is analogous to the filling of the upper portion of a room with buoyant smoke at the beginning of a fire in a substantially closed compartment. The smoke filling problem has been addressed by Baines and Turner [1969], Zukoski [1978], and Cooper [1983]. The principle difference between the problems investigated by the above authors and the current problem is the nature of the injected flow. These authors considered a buoyant plume, whereas the halon discharge more closely approximates a forced jet.

The analysis proceeds, as in the smoke filling problem, to consider the rate of contraction of the pure air layer initially filling the whole space. Conservation of mass applied to this control volume yields:

$$\frac{d}{dt}(\rho_a Y A_f) + \rho_a \dot{Q} = 0 \qquad (3\text{-}1)$$

where A_f is the floor area in the compartment, Y is the height of the pure air layer, ρ_a is the density of air, t is time, and $\dot{Q}$ is the volumetric entrainment rate from the pure air layer by one or more halon jets. In order to solve this equation a jet model must first be introduced.

Following Schlichting [1979], the entrainment rate from a momentum jet is given by

$$\dot{Q} = 0.4n \ \sqrt{K_n Y} \qquad (3\text{-}2)$$

where n is the number of jets and K_n is the kinematic momentum of each jet. The kinematic momentum is given by

$$K_n = \frac{\dot{m}_n 2}{A_n \rho H} \qquad (3\text{-}3)$$

where $\dot{m}_n$ is the mass flow rate of halon from each nozzle, A_n is the nozzle area, and ρH is the gas density of halon.

Using this jet model, Equation 1 can be solved using the initial condition that at t = O, Y = H

$$y = Y/H = \exp\left(\frac{-0.4n\sqrt{K_n}}{A_f}\right) \qquad (3\text{-}4)$$

The concentration, C, of halon in the halon/air layer is simply given by the number of moles (or volume) of halon discharged up to the time, t, divided by the number of moles (or volume) of gas within the layer

$$C = \frac{\dot{m}_H t/\rho H}{(H-Y)A_f} \qquad (3\text{-}5)$$

where $\dot{m}_H$ is the total discharge rate of halon, ρH is the density of gaseous halon, and H-Y is the height of the halon/air layer. The design concentration, C_d, is simply related to the discharge of halon by Equation 5 with $Y=0$ and $t=t_d$, the design discharge time.

$$C_d = \frac{\dot{m}_H t_d/\rho H}{HA_f} \tag{3-6}$$

Using Equations 5 and 6 the time dependent layer concentration can be related to the design concentration:

$$\frac{C}{C_d} = \frac{t/td}{1-Y/H} \tag{3-7}$$

so that at $t-t_d$, $C/C_d = (1-Y/H)^{-1}$. If room filling is perfect, the concentration equals the design concentration. Otherwise, the layer concentration will be higher than required, though it does not fill the room.

Equation 4 is the solution to the problem and Equations 5-7 simply give ancillary information. It is, however, useful to recast the above fully in terms of design variables. It can be shown that Equation 4 can be given as

$$y = \exp\left(\frac{-0.4\,C_d Ht}{t_d\sqrt{A_n}}\right) \tag{3-8}$$

Equation 8 gives the nondimensional pure air layer height as a function of design parameters (C_d,H,A_n). Notice that the number of nozzles and the floor area do not appear. This occurs because the halon pipe and nozzle flow dynamics are not considered here. Once the nozzle area is established by Equation 8, the piping and nozzle flow dynamics along with Equation 6, which determine the halon discharge rate, will dictate how many nozzles will be required to discharge the halon in the specified time period. Equation 8 is an extremely simple way to choose a nozzle area. Rearranging and solving for A_n at $t-t_d$ yields:

$$A_n = \frac{-0.4\,C_d H}{\ln(y_d)} \tag{3-9}$$

where y_d is the nondimensional extent of the pure air layer remaining at the end of the discharge. This might be taken as 0.1 for design purposes. The nozzle area used here is a virtual nozzle size after flashing occurs and is in general much larger than the actual nozzle area.

We understand that the ability of the halon jet to entrain air and hence mix the compartment is central to successful mixing and filling. This ability is characterized by the average concentration of halon as the jet strikes the floor at the beginning of the discharge. From the entrainment given by

Equation 2 and the discharge rate of a single nozzle, the average concentration of halon in the jet as it strikes the floor prior to layer formation, C_{floor}, is given by:

$$C_{floor} = \frac{\dot{m}_n / \rho H}{0.4n \sqrt{K_n} H} \qquad (3\text{-}10)$$

Using Equations 3 and 10, and substituting into Equation 8, we find

$$Y = \exp(-C_d/C_{floor}) \qquad (3\text{-}11)$$

This implies that in design

$$C_{floor}/C_d < -1/1n(y_d) \qquad (3\text{-}12)$$

which for $Y_d = 0.1$, gives $C_{floor}/C_d < 9.43$. While this value is somewhat arbitrary and should be determined by experiments, the ability of the jet to entrain air (as indicated by the average concentration of halon in the jet as it strikes the floor) is the performance parameter of the jet which needs to be examined and specified in the design.

While the above analysis was performed using a forced jet entrainment law, the analysis can be carried out for any entrainment law. The solutions are particularly simple for devices whose entrainment is proportional to some power of the distance from the nozzle. With the availability of this wide range of entrainment laws, all halon discharge systems should be able to be modeled, analyzed, and designed using this framework.

Additional work needs to be done to experimentally validate the present model and to develop simple techniques for measuring the entrainment by halon discharge devices. Two particularly simple candidates for the measurement of entrainment are 1) an adaptation of Baines' transient technique [1983] for measuring entrainment from buoyant plumes and 2) an adaptation of the steady state method used by Cetegen et al [1984] and Beyler [1983] for buoyant plume entrainment. Also, a design value of the final extent of filling Y_d, needs to be established based on the results of the validation experiments.

3.3.3.b How This Can Be Used in Design

The use of this methodology in assuring adequate dispersion of the halon in design is quite simple. The design halon concentration (C_d) is determined in the usual way. The required extent of filling (Y_d) will be determined finally and specified in the design procedure. The required concentration at the floor as the jet reaches the floor prior to layer formation, C_{floor}, is given by Equation 12, restated as:

$$C_{floor} < C_d/[-1n(y_d)] \qquad (3\text{-}13)$$

Manufacturers of halon discharge equipment could produce tables which give C_{floor} for their equipment as a function of the room height and the discharge rate. The designer will select the appropriate size and number of nozzles required to satisfy Equation 12, the discharge time constraint, and the required design concentration. Nozzles will be uniformly spaced over the room floor plan.

3.4 Summary

The combination of the UL 1058 approval and the experienced judgement of designers and installers relative to position, orientation, and type of nozzle has apparently reduced but not eliminated the problems of initial agent distribution and mixing. The performance of discharge tests has provided the AHJ, specifier, and owner with the necessary confidence in these judgements.

Failures due to poor initial mixing have occurred particularly in complex enclosure geometries with high ceiling heights. The need for discharge tests, either with Halon 1301 or a test gas alternative, to confirm initial mixing is probably not required for rooms with ceiling heights no higher than 10-12 feet and modest aspect ratios of room length to width.

Longer term efforts aimed at eliminating the need for discharge tests in general would require substantial effort in the characterization of spray parameters for each nozzle type, the impact of obstructions, and a more generally applicable engineering design method. However, an analytical framework is presented which addresses the global enclosure issues of agent mixing and distribution from a nozzle, based on forced jet entrainment theory. It is well within the state of the art to fully develop this capability and the companion methods needed to measure and catalog appropriate nozzle characteristics. This has been done in several other areas. Such an effort would lead to relaxation of the need for discharge testing related to nozzle discharge and mixing. It would also have positive impact on reduction of halon emissions for research and development and in the design of local application Halon 1301 and 1211 systems.

An alternative means to reduce potential agent mixing problems is to install more nozzles at closer spacings and at several elevations. This approach complicates the flow network and hence the hydraulic calculation task.

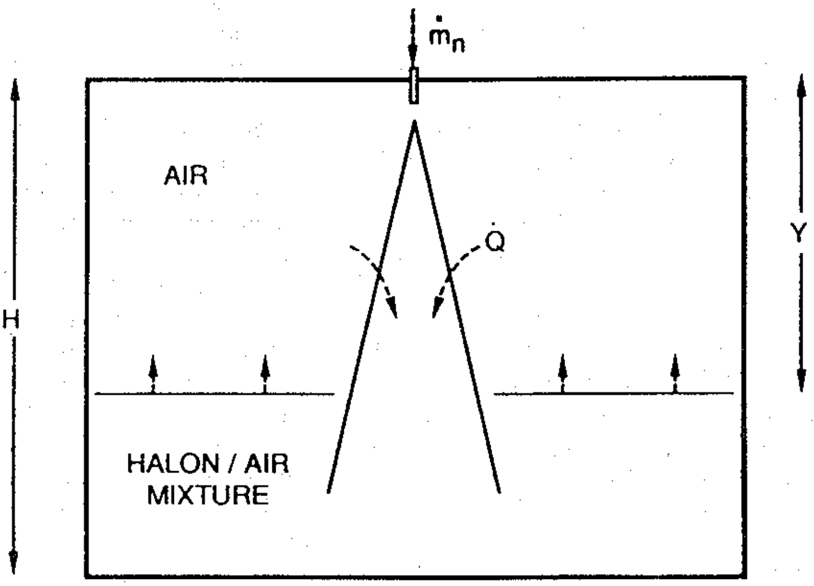

Fig. 3.3-1 – Model of halon dispersion in a compartment

4. ENCLOSURE LEAKAGE

4.1 General

As discussed in Section 1, NFPA 12A requires that 80 percent of the design concentration be maintained in the enclosure for a "hold" time of 10 minutes. While the basis for the time period is primarily one of engineering judgement, the results of experimental work indicate that a 10 minute hold time is effective in most cases in preventing reflash in an enclosure after initial suppression [Dietz (1973), Dube (1983), Ford (1972, 1975), Kay (1973), Klamerus (1980), DiNenno and Starchville (1987), Musick and Williams (1977), Sheehan (1972), Underwriters Laboratories (1972)].

Currently, time-dependent measurement of Halon 1301 concentration is a primary requirement in full scale discharge testing. The importance of such measurements is demonstrated in the discharge test failure data presented in Section 1; a substantial fraction of the failures can be attributed to the inability of the system (including the enclosure) to adequately maintain the required design concentration for a ten minute hold time. Generally, this failure has been attributed exclusively to leakage from the enclosure. Therefore, any alternative strategy to full discharge testing must include a dependable means for assessing the leakage characteristics of the enclosure and evaluating the impact of the leakage on retention of Halon 1301 design concentrations.

4.2 Causes of Enclosure Leakage

The principle causes for leakage are typically some combination of:

(1) hydrostatic pressure developed by the Halon 1301/air mixture in the compartment;

(2) induced pressure differentials across the enclosure boundary due to forced ventilation (e.g., HVAC); and/or

(3) environmental effects (i.e., wind or temperature gradient induced pressure differentials across enclosure boundaries).

The pressure differentials resulting from these effects cause flows through available leakage paths. The direction of flow depends on the pressures created, and may be inward or outward, depending on the conditions.

While barrier construction and air pressurization technology exists which renders enclosures "air tight", this technology is generally applied to highly specialized facilities such as clean rooms. In normal construction there are a myriad of inherent leakage paths. Some, such as door and window cracks, HVAC-air transfer grills and dampers, and cable or duct penetrations of the enclosure are obvious. However, significant leakage may also occur through suspended ceilings, construction cracks in building walls, and various other sources.

It is reasonable to assume that all enclosures will be characterized by some leakage. Attention must be given to assurance that leakage areas do not exceed a level which will result in failure to maintain the required Halon1301 concentrations. In isolating leakage areas and estimating their size, openings such as vents, windows, and doors can be readily identified, as can door undercuts and weather stripping. However, leakage due to construction porosity is more difficult to assess. Typical leakage areas for wall and floor construction are presented in Table 4.2-1, based on data compiled by Klote [ASHRAE, 1983]. ASHRAE has also published data on leakage rates for various building components [1986]. The data is compiled for doors, windows, dampers, and so forth.

The dependence of leakage rates on relatively minute details of construction has important implications for retaining some means of evaluating enclosure leakage relative to performance of Halon 1301 suppression systems. As an example, a 0.9 × 2.1 m door with an average crack width of 3.2 mm has a leakage area of .02m^2. However, if the door undercut is measured at 19 mm, the leakage area is increased by 50 percent to .03 m^2. If the pressure difference across the door due to hydrostatic pressure, forced ventilation, and temperature and wind effects is 75 Pa, the smaller leak area results in a leakage rate of .14 m^3/s; the larger area provides a significantly higher leakage rate of .22 m^3/s.

Table 4.2-1 Typical Leakage Areas For Building Construction [from Klote, 1983]

Construction Element	Wall Tightness	Area Ratio A/Aw
Exterior Building Walls (includes construction cracks, cracks around windows and doors)	Tight	0.70×10^{-4}
	Average	0.21×10^{-3}
	Loose	0.42×10^{-3}
Stairwell Walls (includes construction cracks but not cracks around windows or doors)	Tight	0.14×10^{-4}
	Average	0.11×10^{-3}
	Loose	0.35×10^{-3}
Elevator Shaft Walls (includes construction cracks but not cracks around doors)	Tight	0.18×10^{-3}
	Average	0.84×10^{-3}
	Loose	0.18×10^{-2}
		A/A_F
Floors (includes construction cracks and cracks around penetrations)	Average	0.52×10^{-4}

A = leakage area
Aw = wall area
A_F = floor area

Such variations in leakage rates, when compounded throughout the enclosure, can significantly affect the design concentrations of Halon 1301.

4.3 Leakage Fundamentals

4.3.1 Hydrostatic Pressure Effects

Essentially, hydrostatic pressure is the resultant pressure from a column of fluid of prescribed height and density. Hydrostatic pressure difference (ΔP) occurs when two columns of fluids with different densities exist adjacent to each other. Such a condition is created in an enclosure, relative to the outside, when an enclosure contains a mixture of Halon 1301 and air.

A 5 percent by volume mixture of Halon 1301 in air is approximately 30 percent heavier than air. In addition, the mixture is cooler than the air outside the enclosure. The resulting density difference causes a hydrostatic pressure differential to exist across the enclosure boundaries. The pressure differential is given by

$$\Delta P = gy(\rho_i - \rho_a) \qquad (4\text{-}1)$$

where: ΔP = pressure difference (P_a)
g = gravitational acceleration (9.80665 m/s^2)
y = height of column of fluid, or room height, distance from neutral plane (m)
ρ_i = density of 1301/air mixture (kg/m^3)
ρ_a = density of ambient air (kg/m^3)

The velocity of flow across a leak can be obtained by use of Bernoulli's equation:

$$V_e = \left[2gy \frac{\rho_i - \rho_a}{\rho_a} \right]^{1/2} \qquad (4\text{-}2)$$

where

V_e = mass outflow velocity (m/s)

The total volumetric flow rate of the Halon 1301/air mixture through a leak of area A_L is given by:

$$Q_e = 2/3\, C_d\, A_L\, V_e \qquad (4\text{-}3)$$

where: Q_e = volume flow rate (m^3/s)
A_L = area of leak (for outflow) (m^2)
V_e = velocity (m/s)
C_d = discharge coefficient of leak

Knowledge of the position of the leaks for both inflow of ambient air and outflow of 1301/air mixture is important. Figs. 4.3-1 and 4.3-2 illustrate potential leak patterns.

The first case shown in Fig. 4.3-1 consists of a leak in the upper part of the enclosure providing an inflow of ambient air, and a low level leak providing a vent for the Halon 1301/air mixture. In this case an interface is formed between the air flowing into the enclosure and the Halon 1301/air mixture. In some cases mixing may actually occur between the two layers. In the case depicted here, the volumetric flow rate of the Halon 1301/air mixture will decrease with time, due to the decrease in the hydrostatic pressure head of the Halon 1301/air mixture. This condition, which results in the most rapid decrease in halon concentration for a given leakage area, is a relatively typical case. Many enclosures have the highest leakage concentrated at the top and bottom of the enclosure.

The most rapid leakage scenario for a given leakage area, assuming the pressure difference is primarily due to the hydrostatic head caused by the Halon 1301/air mixture, occurs when approximately one-half the area is located near the ceiling and one-half the area near the floor. This may not be true where the primary combustible loading is near the ceiling and all of the leakage area is concentrated at or near the ceiling.

The second scenario involves a single leak located at a position in the lower part of the enclosure. The single leak forms a path for both inflow of ambient air and outflow of the Halon 1301/air mixture. The neutral plane location (e.g., the elevation where the inside pressure is the same as the outside pressure), fixes the area of each path. The neutral plane location can be specified by setting the inflow and outflow mass flow rates equal to each other and solving for the height of the neutral plane. This flow scenario is also more complex. As the ambient air flows into the top of the leak and rises through the Halon 1301/air mixture, the air entrains Halon 1301, resulting in an upper layer with a gas density greater than ambient air.

Actual leakage conditions in an enclosure will likely be some combination of the phenomena associated with these two extremes. For design purposes, splitting an overall leakage area between a leak high in the enclosure and a leak low in the enclosure will give a worst case estimation of the Halon 1301 concentration decay. Yao and Smith [1968] developed design nomographs to assist in estimating the leakage rate of Halon 1301/air mixtures from enclosures.

4.3.2 Forced Ventilation (HVAC) Effects

HVAC systems induce pressure gradients across enclosure boundaries. This problem may be exaggerated during Halon 1301 discharge due to isolation of the HVAC system or some portion of the system serving the protected enclosure while HVAC systems outside the enclosure continue to operate. These fan induced pressure differentials may cause a flow of air into the enclosure and Halon 1301/air mixture out of the compartment. The pressure differential conditions may vary with outside environmental conditions as heating and cooling systems are alternatively employed.

Whether or not such pressure differentials seriously degrade the halon concentration is a function of the design details of the fan systems and subsequent pressure differentials across all of the compartment boundaries. If, for example, the protected enclosure is at a uniform reactive pressure gradient on all sides and there is no source of make-up air, the net effect will be small. However, if two sides of the enclosure are at negative pressure with respect to the bounding space and the other two sides are at a positive pressure due to the enclosure forming a boundary between HVAC zones or the presence of an exterior wall, substantial leakage may occur. To further complicate the problem, such fan induced leakage could either complement or offset leakage due to hydrostatic effects.

4.3.3 Environmental Effects

Pressure gradients caused by stack effect (in relatively tall buildings) and wind conditions are common considerations in HVAC and smoke control system design.

Stack effect is in essence a hydrostatic buoyancy effect. The pressure differential caused by stack effect can be estimated as follows (ASHRAE, 1985):

$$\begin{aligned} \Delta P &= (\rho_o - \rho_i)\, g\, (y - y_N) \\ &= \rho_i\, g\, (y - y_N)(T_i - T_o)/T_o \end{aligned} \tag{4-4}$$

where ρ_o = outside air density (kg/m^3)
ρ_i = inside air density (kg/m^3)
P = pressure differential (P_a)
T_i = inside temperature (k)
T_o = outside temperature (k)
y = height of observation point (m)
y_N = height of neutral plane (m)

The position of the neutral plane is determined by the relative flow areas above and below the neutral plane, the building height, and the temperature difference between inside and outside. Under normal stack effect conditions, above the neutral plane air flows out of the building; below the neutral plane the net flow is into the structure. Reverse stack effect can also occur. The height of the neutral plane varies typically between .3 and .7 of the total height for tall buildings. Protected enclosures located near shafts or along exterior walls may be subjected to relatively high differential pressures depending upon their location relative to the neutral plane.

A second weather induced condition which can affect air flow through leakage areas is wind. Although wind effects are difficult to predict due to extreme variations in wind conditions, the pressure exerted due to wind on a surface can be estimated by the expression:

$$P_W = \frac{1}{2} C_W \rho_o V^2 \qquad (4\text{-}5)$$

where: P_W = pressure (P_a)
C_W = pressure coefficient
ρ_o = outside air density (kg/m^3)
V = wind velocity (m/s)

Typically, if the enclosure has one or more exterior wall surfaces, estimates of leakage due to construction porosity should be calculated for several wind conditions.

4.4 Enclosure Leakage Measurements

Methods other than full discharge testing are available to assess leakage rates from enclosures. These methods have been developed to assist mechanical engineers in evaluating enclosure tightness and building leakage rates for design of HVAC systems and smoke control systems. In addition to avoiding Halon 1301 discharge, such procedures could be used to routinely reassess an enclosure's integrity, providing long term assurance that an acceptable leakage rate has been maintained.

The pressure difference across an enclosure boundary can be directly measured by a manometer magnehelic gauge or other suitable low range pressure measurement device. A knowledge of this pressure gradient and of total leakage area enables one to calculate the flow rate across a leak.

A novel approach to measuring actual air leakage rates employs the use of sound transmission technology. Limited correlations of sound loss vs. leakage rate at specific sound frequencies are under development. Developmental work by Sonoda and Petersen [1986] indicates promise for the use of such sonic methods in conjunction with visual or thermal (IR) leak location methods to provide quantification information on specific leakage paths. However, the limited correlations developed so far restrict the application of this technique. Additional research is needed to investigate various leak geometries and to provide more generic correlations. If developed further, this technique could provide the capability to quantify leakage rates at specific locations in an enclosure.

There are two well-recognized methods of determining enclosure leakage: tracer gas dilution [ASTM E-741, 1983] and door fan pressurization [ASTM E-779, 1987]. Both methods have been used to evaluate air leakage characteristics of buildings under actual field conditions.

4.4.1 Tracer Gas Method(s)

The tracer gas dilution method incorporates known relationships for air change rates and volumetric purging to relate the time dependent change in a gas concentration within an enclosure. Essentially, a known concentration of a "tracer" gas is introduced into the enclosure, and the subsequent decay of this concentration is related to leakage rates through the use of a well established exponential relationship for air change rates (purging) and gas species concentrations. The air change rates are related to leakage rates based on the volume of the enclosure and the decay in tracer gas concentrations.

By measuring the tracer gas concentration continually, the air change rate can be determined to within 10 percent accuracy from the expression:

$$I = \frac{1}{t} \ln \left(\frac{C_0}{C} \right) \tag{4-6}$$

where:
I = air change rate (changes/min)
t = time (min)
C_0 = initial tracer gas concentration
C = concentration of tracer gas at time, t

The units for C_0 and C must be the same, and can be whatever is suitable (e.g., volume percent, ppm).

Two variations on the tracer gas dilution method are (1) the constant concentration technique, and (2) the constant flow technique. The constant concentration technique involves injection of a tracer gas into the enclosure at a *variable* rate that assures a constant concentration. In the constant flow technique, tracer gas is introduced at a *constant* rate and the change in tracer gas concentration is measured.

Various tracer gases have been used successfully in the employment of tracer gas dilution methods. Shaw (1984) evaluated five tracer gases (CH_4, CO, CO_2, N_2O, SF_6) and compared the results to actual air flow measurements. He concluded that all of the tracer gases gave acceptable results, although less scatter was noted with CH_4, CO and N_20.

4.4.2 Fan Pressurization Method

Door fan pressurization leakage test methods measure an effective leakage area. The typical method utilizes a fan unit, a flow or velocity measuring device, and a pressure measuring device. In essence, the enclosure under evaluation is artificially pressurized with the door fan unit. The air flow through the fan into the room is measured, and the pressure differential across the enclosure envelope is monitored. The test is performed over a range of induced pressure differentials in order to provide leakage rate data for a range of induced pressure conditions.

Fan pressurization techniques have been widely used for evaluating HVAC mechanical systems, in terms of enclosure overpressurization, air quality (e.g., air changes), and energy effects of air infiltration. The leakage (fan air flow rate) versus pressure differential may be fit to an equation of the form:

$$\dot{Q} = C \Delta P^N \tag{4-7}$$

where: $\dot{Q}$ is the volumetric flow rate, C is a constant equivalent to the flow at some fixed pressure (e.g. 1 in. water column), Δ P is the pressure difference across the leak or compartment boundary, and N is an exponent dependent on the type of leak. Typical values of N are given by Saum and Hupman [1987] as:

$N = .5$ for hole in thin wall
$N = .65$ typical building cracks
$N \approx 1.0$ thin cracks in thick walls

Shaw [1981] provides data on a series of fan pressurization tests on supermarkets and shopping malls. Exterior wall leakage and leakage through HVAC openings, shop windows, and doors were evaluated. He also [1980] conducted an experimental study to develop methods for partial building pressurization tests for multiple story apartment buildings where complete building air leakage tests were not practical. The method involved performing fan pressurization tests on isolated portions of the building (e.g., portions of exterior walls, window assemblies). Differences between induced positive and negative pressurization were then compared. In addition, leakage data were gathered on walls, windows, balcony doors, and ceiling/wall and floor joints.

Refinements in fan pressurization techniques have been introduced to improve the accuracy of field measurements. For example, Reardon et al [1986] refined a technique called "balanced fan depressurization" to evaluate leakage from single and multiple family dwellings. The method was originally developed by Shaw [1980] to avoid indirect air leakage when taking air flow and pressure difference measurements in buildings. Indirect air leakage occurs where air may flow through a partition between rooms or buildings when one space or a portion of a space is pressurized (or depressurized). These indirect leakage paths may cause erroneous results. The proposed method, which had been tested in multiple story apartment buildings, involves the use of balancing fans to balance the pressure between enclosures or compartments to and from which indirect leakage was expected.

4.4.3 Combined Use of Tracer Gas and Fan Pressurization Methods

Both techniques have been combined on a limited basis for field studies primarily directed at air infiltration relative to energy conservation. Blomsterberg et al [1981] report on a mobile infiltration test unit used to evaluate air infiltration using a fan pressurization system under a range of wind and weather conditions. They used a combination of tracer gas and fan pressurization techniques. Tests conducted over a range of leakage areas, wind conditions, and outside temperatures indicated that the fan pressurization and tracer gas dilution methods predicted infiltration to within ± 5 percent. However, in a study by Persily and Grot (1984) on a series of air infiltration studies on 50 solar energy heated residences, notable differences were found in the infiltration rate as measured by tracer gas dilution and those rates inferred from 50 Pa door fan tests. These tests were conducted under a wide range of environmental conditions.

4.4.4 Applications to Halon 1301 Systems

The use of these techniques for Halon 1301 system evaluation is a natural extension of their application to energy conservation and ventilation system analysis. There has been discussion of replacing discharge tests with door fan tests [Genge and Moffett, 1987; Genge, 1987]. It has also been proposed that fan pressurization techniques be used to isolate leaks above suspended ceilings and below raised floors. These procedures are under active development.

At least four firms manufacture door fan pressurization units and are actively involved in application of the techniques to halon system discharge tests. Saum and Hupman [1987] propose various applications of door fan pressurization in conducting halon system testing. These include:

(1) visual leakage inspection (with smoke tracers)
(2) measured leakage: combining weather and mechanical induced pressure differentials
(3) estimated discharge pressure: a method is provided to estimate the total overpressure on the enclosure walls during discharge
(4) estimated worst case leakage.

Fan pressurization methods have been used to measure leakage rates from enclosures as part of predischarge testing for Halon 1301 system acceptance testing. Hupman [1987] reports that no failures occurred during discharge tests for a number of Halon 1301 systems when fan pressurization techniques were employed to evaluate, and when necessary reduce, leakage rates in the enclosures.

Saum et al [1988] present the results of several combination door fan pressurization and Halon 1301 discharge tests. The analysis presented in this paper relating leakage data to halon concentration decay assuming worst case leak locations and discharge overpressure is an imperative first step in achieving acceptability of fan pressurization methods for evaluating leakage effects on maintenance of Halon 1301 design concentrations.

Results of door fan pressurization tests have been correlated on a limited basis to Halon 1301 concentration decay in a compartment with known leakage areas [DiNenno et al, 1988]. Provided that the elevation of the leakage area is known, the dilution rate of the Halon 1301/air mixture can be calculated and correlated to full scale experimental results.

One of the obvious applications of door fan pressurization methods is to use the procedure to find and seal leaks. Air leaks can be traced using visual techniques such as smoke candles, acoustic leak detectors, and even holographic interferometry. Leaks discovered by these methods and sealed prior to discharge testing minimize the chances of a discharge test failure.

4.5 Summary

Failure to maintain the design concentration for the specified time period is a major cause of discharge test failures and retests. The use of enclosure leakage measurements can assist in the identification of leakage paths, therefore reducing the likelihood of system failures. Mechanical and weather induced pressure differentials, as well as hydrostatic pressure differentials resulting from Halon 1301/air mixtures, should be addressed in any procedure to assess Halon 1301 leakage.

A disadvantage of the door fan pressurization technique is that it gives an indirect measurement of gross leakage area. That is, the method cannot predict Halon 1301 leakage based on inferred leakage areas without specific knowledge of leak locations. The difficulty is that the leakage rate is dependent on the *position* as well as the area of the leak(s). Defining a worst case maximum permitted leak area would be relatively straightforward for determining post-discharge leakage. However, potential leaks through suspended ceiling plenums and other leak locations at high elevations in the enclosure will often yield unacceptably large leakage areas by the "worst case" leak assumption criterion, but perform quite adequately in maintaining Halon 1301 concentrations.

Another consideration not directly accounted for in current fan pressurization methods is an accurate assessment of Halon 1301 discharge effects on leakage rates. However, leakage of Halon 1301/air mixtures during and immediately following system discharge can, in principle, be related to leakage area. Subsequently, corrections could be made to Halon 1301 storage requirements (e.g., quantity) to account for this leakage effect. A detailed examination of the technical basis for such a procedure is provided by Grant [1987] in his M.S. thesis work, and is under active development by Saum et al [1988].

Tracer gas dilution methods are limited in that: (1) as with fan pressurization methods a gross leakage rate is determined with no consideration for location, and (2) how well the tracer gas/air mixtures simulate a Halon 1301/air mixture is not well known. In addition, difficulties have been encountered in attaining agreement in results when both methods are deployed. Theoretically, gross leakage rates should be approximately equal, under similar test conditions, for the fan pressurization and tracer gas dilution methods.

Having recognized some important current limitations, it is important to note that leakage testing technology is well developed, and applications of these methods to Halon 1301 system evaluation have been conducted with encouraging results. While not a sufficient substitute for all aspects of discharge testing, successful application of these techniques could reduce the need for repeat testing, provide a means for routinely testing the enclosure, and perhaps in conjunction with other techniques, lead to reduction or elimination of total flooding discharge tests.

Since the degree of discharge test failures due to enclosure leakage and subsequent halon concentration decay is known to be significant, this could also lead directly to improved system reliability. This is in contrast to the relatively unknown impact of flow calculation and agent mixing and distribution problems.

Further development and testing of these techniques should be pursued. The key to successful use of door fan pressurization techniques in the *prediction* of halon leakage (other technical issues notwithstanding) is the ability to correlate leakage area with halon concentration decay. Various methods for scaling total leakage area have been proposed, including dividing total leakage area by the total floor area.

Ongoing work on development of simulant test gases is promising, demonstrating reasonable agreement with discharge concentrations and leakage for Halon 1301. This work should be continued in order to arrive at adequate correlations for agent mixing and leakage for Halon 1301 and substitute gases.

The technical feasibility of replacing total discharge testing of leakage affects with an alterative procedure appears attainable. Such a procedure must:

(1) determine leakage rates and locations (Note: If leak locations cannot be specified, a worst case location assumption may be used.)
(2) account for appropriate ranges of pressure differentials and flow directions
(3) provide accurate prediction of Halon 1301/air mixture concentrations relative to required design concentrations.

The most viable approach currently available involves some combined use of simulant test gases and fan pressurization. Such an approach should account for the primary physical processes influencing enclosure leakage and agent concentrations.

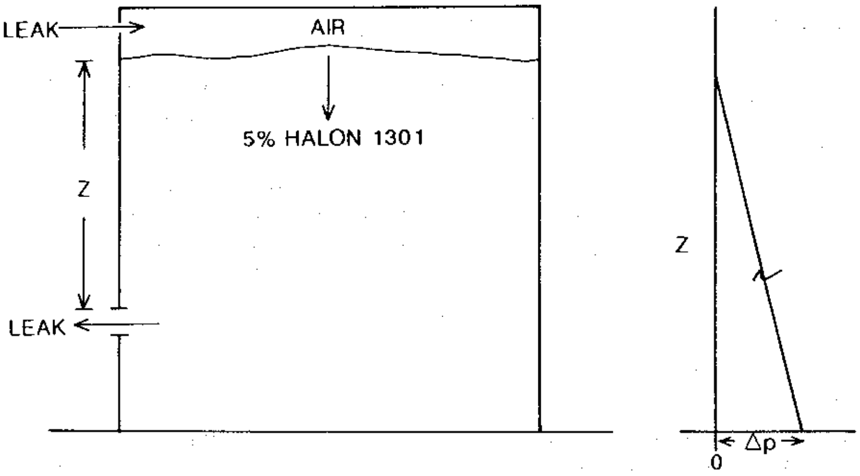

Fig. 4.3-1 – Schematic halon leak, hydrostatic pressure difference

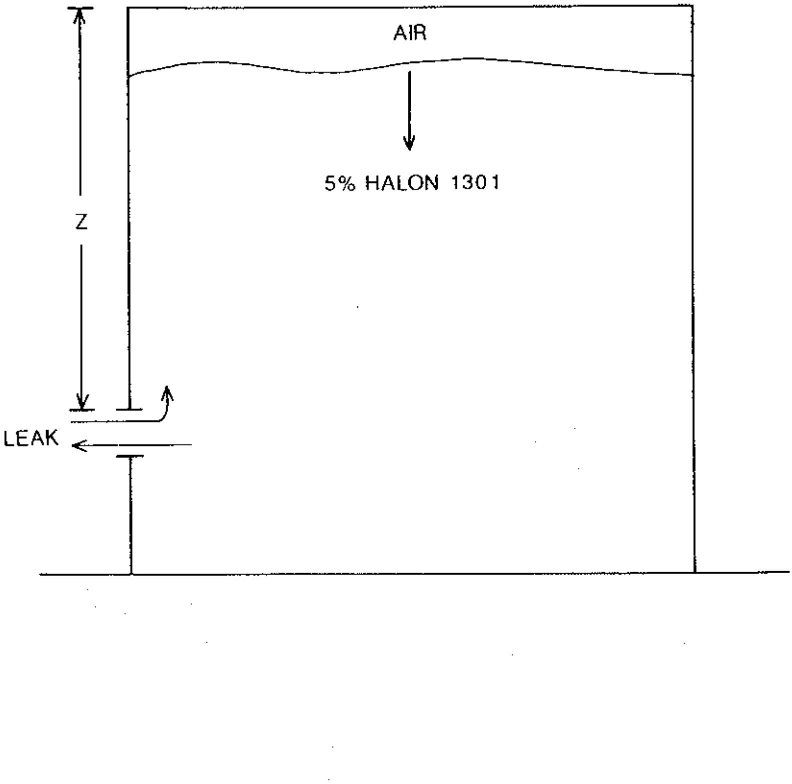

Fig. 4.3-2 — Single leak case

5. ALTERNATIVES TO HALON 1301 FULL DISCHARGE TESTS

In order to assess the viability of substituting alternative methods to full discharge testing, attention must be directed at the ability to accomplish the objectives implicit in such testing. As discussed in Section 1, the objectives of discharge testing include verification of:

(1) hardware integrity and absence of obstructions
(2) detection/actuation/alarm system operation
(3) adequate initial agent distribution and mixing
(4) design concentrations
(5) discharge time
(6) enclosure boundary integrity
(7) absence of hazard to contents and personnel.

These seven objectives are directly related to the performance objectives of the systems. They must be met for the systems to function as designed. Currently available test procedures not involving the discharge of Halon 1301 provide means for adequate assessment of piping integrity, piping structural mechanics, and mechanical and electrical hardware operability (e.g., objectives 1 and 2). However, technical uncertainties with regard to flow calculations, agent mixing and distribution, and enclosure leakage impact the ability to meet the remaining five objectives of discharge testing by alternative means.

5.1 Flow Calculations

The accuracy of flow calculations bears directly on the ability of the system to meet the discharge time requirement in NFPA 12A, and initial agent concentration. It also can influence initial agent distribution and mixing.

It is difficult to directly assess the relevance of flow calculation accuracy on system performance. While simplifying assumptions implicit in the procedures may or may not significantly affect the agent discharge, such issues have not been adequately addressed in the open literature. The impact of assumptions regarding flow regime characteristics and flow split and pressure drop at junctions on the accuracy of flow calculations requires attention. This is especially the case for unbalanced systems where inaccuracies could be particularly detrimental.

The uncertainty associated with current design programs and the UL 1058 listing process indicate the need for development of an independent method (in the absence of discharge tests) to check or verify design calculations. Such a procedure should reflect a consensus on the accuracy of acceptable assumptions, and limitations which are firmly rooted in experimental data and basic principles. It is not suggested or implied that current design methods listed in UL 1058 be discontinued or made open to the public domain. Rather, it is proposed that an independent effort be initiated in this regard.

It is desirable that any efforts to assess the accuracy of the flow calculation procedures provided in NFPA 12A be embraced in a broader effort to develop a generic, public domain flow calculation procedure. Models are available for similar problems in two phase flow and could be adapted for use in designing Halon 1301 systems. Various calculation procedures described in Section 2 could form the technical basis for this approach. Once a model is determined viable, work would focus on needed modifications, identification of calculation limits, and determination of statistical confidence (e.g., accuracy and repeatability).

5.2 Agent Mixing and Distribution

Agent mixing and distribution are influenced considerably by the spray characteristics of nozzles. Theoretical and empirical studies have been conducted on spray nozzles for fuel spray and spray drying technologies. However, due to the unique characteristics of the Halon 1301 spray phenomena, which results in a highly dense spray, direct application of these predictive techniques may not be possible. Therefore, in order to characterize the nozzle discharge for applications to Halon 1301 systems, experimental work will be required. Experimental correlations could be developed for specific nozzle designs which account for pressure, flow effect, and nozzle configuration on drop size distribution and velocity, as well as spray densities. Alternatively, a testing procedure embodying the approach described in Section 3 may be developed.

While research is necessary to establish correlations for Halon 1301 nozzle performance, experience indicates that current nozzle designs perform satisfactorily for many installations. Three primary conditions which appear consistent with inadequate nozzle mixing are (1) when ceiling heights exceed 10 - 12 feet, (2) when length to width aspect ratios approach extremes, and (3) when equipment and materials block the sprays.

5.3 Enclosure Leakage

Alternative test methods for evaluating enclosure leakage are well developed. Fan pressurization and tracer gas techniques can be readily used to provide a supplement or limited alternative to full discharge testing. Worst case limits for leakage can be readily determined from appropriate fan test data. However, such limits may be overly conservative.

A more attractive approach involves development of correlations for leak areas and agent concentration decay which account for both the size of leaks and their relative position in the enclosure. Continuation of research on development of simulant gases and an integrated procedure for leakage testing is a necessary but relatively near term task. The development and use of environmentally safe simulant gases as a substitute for Halon 1301 in total discharge testing would relax the priorities associated with improved flow calculations and nozzle mixing technology.

5.4 Strategies

Based on the available technical information and the necessary capabilities of any alternatives to total discharge testing, certain strategies can be formulated. Six such strategies are presented. These strategies are discussed in terms of (1) the necessary technical work to adequately develop the strategy, and (2) the estimated time required to implement them: that is, short term (<12 months), moderate term (1-3 years), and long term (3-5 years). The strategies include:

(1) Permit the use of Halon 1301 for full scale discharge tests.
(2) Selectively permit the use of Halon 1301 as a discharge test agent for specific conditions.
(3) Eliminate discharge testing, strengthen other test methods, and accept the associated risk of system failures, or uncertainty in design.
(4) Use an environmentally acceptable physically realistic test gas substitute.
(5) Limit the design flexibility of total flooding Halon 1301 systems.
(6) Develop improved, public domain design and evaluation procedures for flow calculation, mixing, distribution, and leakage assessment.

Of course several of these strategies could be pursued simultaneously. These six strategies are compared against the unresolved technical issues in Figure 5.5-1.

5.4.1 Continue the Use of Halon 1301 as a Discharge Test Gas.

This strategy, which can be implemented immediately, is one of the least attractive alternatives and is likely to be unacceptable due to issues associated with environmental risk. The use of Halon 1301 for discharge testing subsequently reduces the quantity of agent available for actual protection applications due to the production caps proposed under the Montreal Protocols. This alternative also stands squarely in the way of eventual potential emission based limits. Given new, more pessimistic estimates of environmental risk, this option may become completely unacceptable.

5.4.2 Selectively Permit the Use of Halon 1301 as a Test Gas.

This alternative, which also can be implemented immediately, would permit the use of Halon 1301 as a discharge agent in special application systems only. This option would be available primarily for cases where the flow distribution and agent mixing are expected to be especially critical and uncertain. It requires that owners, responsible engineers, and authorities having jurisdiction accept the risk and uncertainty associated with "average" or typical system designs.

5.4.3 Use Additional Test and Evaluation Techniques.

This strategy, which can be implemented in the short (<12 months) to moderate term (1-3 years), includes enclosure leakage testing as a surrogate for one aspect of full discharge tests. The use of fan pressurization techniques to identify and measure leakage coupled with a necessarily conservative maximum allowable leakage area would satisfy the discharge testing objective. The weakness in this approach is that certain systems may not meet the allowable leakage criteria but would pass a full scale discharge test. Additional techniques such as hydrostatic testing, hardware cycle testing, and non-destructive evaluation of piping (to ensure no obstructions exist) could be used to satisfy the less uncertain hardware oriented objectives of discharge testing. This strategy does not materially impact the issues of flow calculation verification and mixing/distribution.

5.4.4 Alternative Test Gas.

This strategy potentially satisfies all of the objectives of current discharge testing practice. The key to successful use of alternative test agents is that they be environmentally acceptable and physically realistic. Halon 122 has been and is widely used as a alternative test gas. It was originally used as a substitute due to the high cost of Halon 1301. However, it has fallen into disfavor because of allegations that it does not adequately simulate the flow or mixing of Halon 1301. NFPA 12A lists several known limitations of Halon 122 with respect to Halon 1301. Due to these limitations, other simulant gases have been proposed, including Halon 121 and Sulfur Hexafluoride (SF_6).

Table 5.4-1 gives comparison physical properties of Halon 1301, and three alternative simulants, Halon 121, Halon 122, and Sulfur Hexafluoride.

Moore and Waters [1987] presented comparison discharge test data for Halon 1301, Halon 121, and Halon 122 in a relatively complex piping geometry. Halon 121 adequately simulated the flow and mixing characteristics of Halon 1301. The leakage of Halon 121 was slower than that for Halon 1301, due primarily to the density difference between the 5 percent volumetric mixtures of each in air. This leakage differential could be scaled by requiring a longer hold time for the Halon 121 discharge.

The Halon Research Institute [Waters, 1988] has proposed a testing program of Halon 121 as an alternate test agent. The testing program consists of 150 direct comparison discharge tests of Halon 1301 and Halon 121. The results of this test program will potentially establish the efficacy of this approach.

Sulfur Hexafluoride (SF_6) was proposed as an alternative by DiNenno et al [1987] for the U.S. Navy. The U.S. Navy is testing both Halon 121 and Sulfur Hexafluoride as alternative test gases.

DiNenno et al (1988) report discharge test results comparing Halon 121, Halon 1301, and SF_6. This interim report summarizes twenty tests relating to enclosure leakage, modular systems flow, and compartment mixing. Figure 5.4-1 shows the height of the halon/air interface as a function of time for a 12 ft × 12 ft × 12 ft room with a 6 in. diameter leak at the floor and ceiling. The data show excellent agreement between SF_6 and Halon 1301. Figure 5.4-2 shows average density (or concentration) as a function of time for a 2.5 in. leak located at the floor and ceiling. The flow from a 30 lb. modular Halon 1301 cylinder pressurized to 350 psig was similar for each gas. Comparison tests between Halon 1301, Halon 121, and SF_6 in complex piping arrangements are underway.

Alternative test agents are under active testing and development. It appears that one or more acceptable simulants can be developed and verified in the moderate term (1-3 years).

5.4.5 Limit Design Conditions of Halon 1301 Systems.

This alternative refers to mandating simplifications of the design of Halon 1301 systems in an effort to remove the uncertainty of flow conditions in complex piping networks and in mixing/distribution of flow. Example limitations include:

(1) Required use of modular, balanced piping systems;
(2) Prohibited use in compartments over 20 ft. high or with complex nozzle flow obstructions; and/or
(3) Required mechanical mixing to eliminate uncertainty in initial distributions.

The disadvantages of this approach are obvious. The need for design flexibility and the flexibility that Halon 1301 systems provide as a protection alternative would be severely degraded. This approach also does not address post-discharge leakage of 1301, but could be used in conjunction with door fan testing under worst case leakage assumptions.

5.4.6 Improve Design and Evaluation Procedures.

The need for discharge testing could be eliminated if sufficient accuracy and confidence was available in the design procedures. Automatic sprinkler systems do not undergo full discharge tests, primarily because the design process and listing procedures are accepted with some confidence. The primary difference between the two systems from this standpoint is the degree of complexity of the phenomena.

An adequate technology base, both theoretical and experimental, exists to eliminate uncertainty and accuracy problems in flow calculation procedures in the moderate term (1-3 years). Additional "approval" tests and improved characterization of nozzle distribution and mixing coupled with improved design procedures for nozzle placement would eliminate the unnecessary empiricism and uncertainty in that regard. The remaining issue, enclosure integrity, could be partially accommodated through the use of leakage testing.

This strategy should be a long term objective of the fire protection industry, independent of the issue of discharge testing.

5.5 Summary

Figure 5.5-1 provides a comparison of the potential efficacy of each of the six strategies relative to their likely impact on the three areas of technical uncertainty discussed in this report. Additional constraints, including environmental and commercial acceptability, are also evaluated.

	Halon 1301	Sulfur Hexafluoride	Halon 122	Halon 121
Chemical Formula	$CBrF_3$	SF_6	CCl_2F_2	$CHClF_2$
Molecular Weight	148.93	146.05	120.9	86.48
Boiling Point	214°K	222.4°K	243.4°K	232.4°K
Vapor Pressure at 294°K	14.5 atm	21.3 atm	5.77 atm	9.26 atm
Critical Temp.	340.2°K	318.3°K	385.2°K	369.2°K
Critical Pressure	39.1 atm	37.2 atm	40.7 atm	49.1 atm
Liquid Density at 294°K	97.8 lbm/ft^3	86.0 lbm/ft^3	82.7 lbm/ft^3	75.5 lbm/ft^3
Vapor Density at 294°K, 1 atm	.391 lbm/ft^3	.382 lbm/ft^3	.319 lbm/ft^3	.227 lbm/ft^3
Viscosity of Liquid at 294°K	.16 cp	.29 cp	.22 cp	.20 cp
Viscosity of Vapor at 294°K	.016 cp	.015 cp	.012 cp	.013 cp
Thermal conductivity of vapor at 294°K	22 $\frac{\mu\text{cal}}{\text{cm s °K}}$	34 $\frac{\mu\text{cal}}{\text{cm s °K}}$	23 $\frac{\mu\text{cal}}{\text{cm s °K}}$	26 $\frac{\mu\text{cal}}{\text{cm s °K}}$
air 61 $\frac{\mu\text{cal}}{\text{cm s °K}}$				
Enthalpy of Vaporization				
at BP	4.23 kcal/gmole	4.50 kcal/gmole*	4.77 kcal/gmole*	4.83 kcal/gmole
at 294°K	2.94 kcal/gmole	2.30 kcal/gmole	4.05 kcal/gmole	3.86 kcal/gmole

*at Triple Point, 222.4°K+2.2 atm

Table 5.4-1 Selected Chemical and Physical Properties of Halon 1301 and Simulants

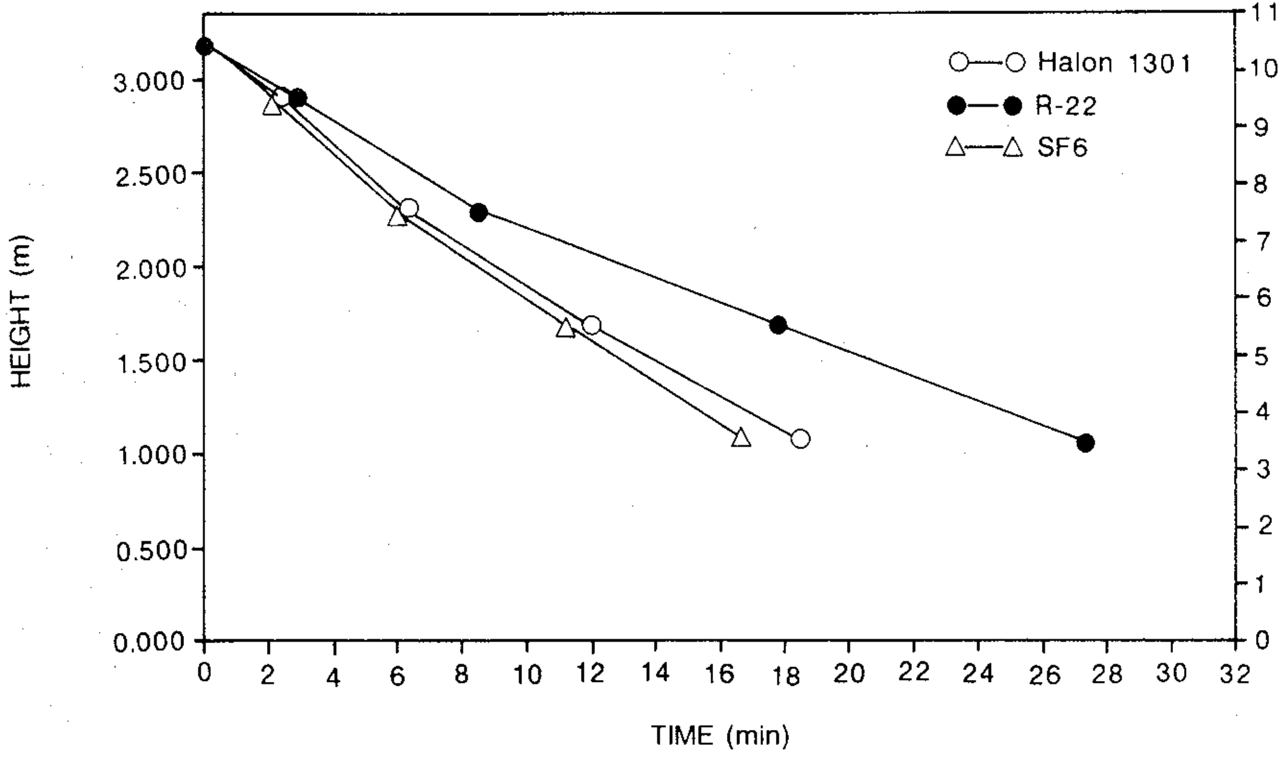

Fig. 5.4-1 – Experimental interphase height for 15.24 cm (6 in.) leak

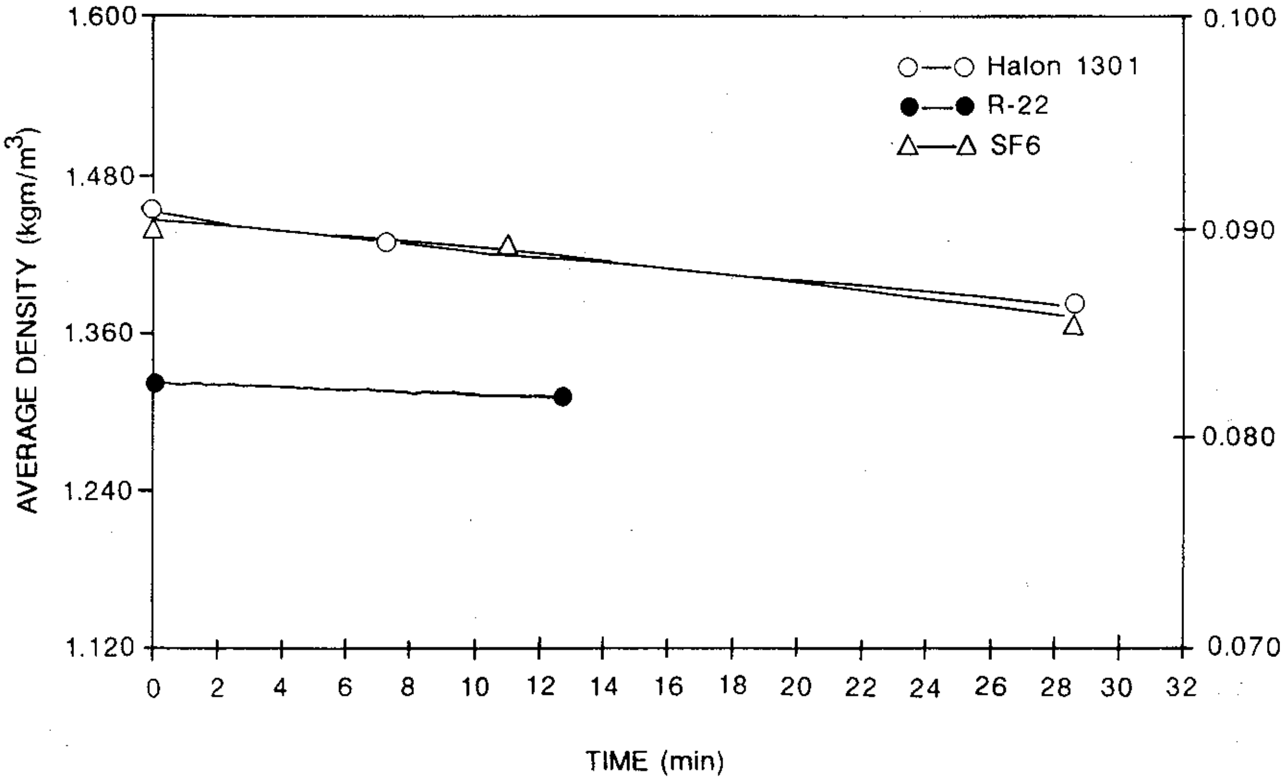

Fig. 5.4-2 – Experimental interphase height for 6 cm (2.5 in.) leak

	Strategy					
Issue	**1**	**2**	**3**	**4**	**5**	**6**
Flow Calculations	Y	P	N	Y	Y	Y
Nozzle Mixing	Y	P	N	Y	Y	Y
Enclosure Leakage	Y	P	Y	Y	N	P
Environmental Acceptable	N	N	Y	Y	Y	Y
Commercially Acceptable	?	?	?	Y	N	?

Y = yes - eliminate/substantially reduce problem
N = no - no appreciable impact
P = partial solution
? = unknown

Fig. 5.5-1 — Matrix of Technical Issues vs. Alternatives

6. SUMMARY AND CONCLUSIONS

6.1 Summary

A technical literature review and analysis was conducted to assess the need for Halon 1301 total discharge testing, and to identify and examine the technical feasibility of alternative strategies. The effort included consideration of information on Halon 1301 system performance (including discharge testing), an in-depth analysis of state-of-the-art Halon 1301 system design and installation, and a review of the technical basis embodied in NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems*. The study focused on identification of potential alternatives to full discharge testing, technical gaps which limit their viability, and means to reduce these gaps. An extensive review of technical literature outside the specific topic area of Halon 1301 fire suppression indicates that several technical uncertainties associated with Halon 1301 performance could be resolved in the near future. Particular areas of interest in the general technical literature include two phase flow, combustion fuel spray technology and spray drying technology.

The results of the literature review indicate that total discharge testing is an important element in Halon 1301 system performance verification. Although the historical information is considered sparse, the failure rate associated with discharge testing, actual performance, and false discharge incidents demonstrates a need for system performance confirmation. The single most dominant problem is the inability of systems to maintain Halon 1301 design concentrations. For the most part this problem is attributed to enclosure leakage – problems examined directly through discharge testing. In total, there are seven objectives implicit in discharge testing which should be preserved in the selection and development of alternative strategies. Elimination of full discharge testing without consideration for meeting these objectives would introduce additional risk in terms of system performance.

Three distinct areas of technical uncertainty have been identified. Gaps in our understanding of Halon 1301 flow characteristics, nozzle mixing, and enclosure leakage complicate efforts to replace full discharge testing. However, these uncertainties can be overcome through carefully focused research. A fundamental basis for two phase flow characteristics is well established in the general literature for similar problems outside the area of Halon 1301. Computer based generic two phase flow models are available which could be modified to address Halon 1301 flow characteristics. A theoretical basis and related experimental correlations exist for flow nozzle characterization for other fluids such as combustion fuels and paint sprays. A framework for providing an analytical approach to nozzle mixing and agent distribution is provided. Significant advancements have been made in enclosure leakage testing involving pressurization techniques and development of test gas simulants.

Relatively modest research efforts would be necessary to assess the applicability of available generic computer models to the problem of Halon 1301 flow characterization. A favorable assessment would most likely lead to necessary modifications to one or more available codes in order to address halon flow problems. Experimental work is required to establish correlations for nozzle discharge mixing. This effort requires relatively sophisticated measurement technology, but similar efforts have been successfully conducted in other industries. Ongoing work in development of pressurization techniques and test gas simulants should provide valuable insights in the short term.

To summarize, while elimination of Halon 1301 full discharge testing currently appears inappropriate, alternative strategies which address the performance objectives implicit in discharge testing are well within reach. Technical uncertainties require research in specific areas, but all of the areas are technically well supported in more advanced technologies reported in the open literature.

6.2 Specific Conclusions

The following specific conclusions were developed in support of the above arguments, based on the literature review and analysis.

(1) There are three primary areas of technical uncertainty in the design of Halon 1301 total flooding systems which form the basis of the need for discharge testing. These are flow calculation procedure, nozzle discharge and mixing characteristics, and enclosure leakage effects. Other objectives of discharge testing can be met through alternative test and evaluation techniques.

(2) The flow calculation programs used by halon system equipment manufacturers and their distributors are closed, proprietary design tools. While Underwriter's Laboratories does evaluate and list these programs, currently there is no acceptable procedure for authorities having jurisdiction, insurers, engineers, or facility owners or operators to judge the validity of the calculations, and hence the adequacy of a specific design.

(3) The adequacy of flow calculation programs is most uncertain when the piping networks are complex—comprised of long pipe lengths and involving numerous unbalanced flow splits. Appropriate limits are a function of each calculation program and cannot be determined in general.

(4) The approval standard for hydraulic flow calculation programs for Halon 1301 provides a useful indication of their accuracy. However, the approved version of a particular program does not validate or confirm the adequacy of the program in general.

(5) The technical literature on two phase flow and existing general two phase flow programs indicate that open non-proprietary calculation methods for Halon 1301 flow networks can likely be developed at reasonable cost.

(6) Provision of adequate agent mixing and initial distribution is largely an empirical art. Approval standards for halon nozzles provide useful but incomplete information to evaluate mixing and distribution a priori. The magnitude of the problem in terms of factors such as enclosure geometry is uncertain, but is likely limited to conditions of high ceiling heights and excessive obstructions to mixing.

(7) Technology exists for improved a priori evaluation of nozzle mixing and agent distribution, but extensive empirical work is required.

(8) The primary cause of halon system discharge test failures is excessive compartment leakage. Compartment leakage testing technology is sufficiently well developed to permit evaluation of compartment integrity. Correlations for halon system performance and enclosure leakage rates do not exist, but "worst case" limits on compartment leakage could be developed.

(9) Door fan pressurization techniques have demonstrated their value in eliminating the need for retests and in reducing discharge system failures.

(10) The most promising environmentally acceptable near term technology which meets all the objectives of current discharge testing practice involves alternative test agents. Test and evaluation work in progress will demonstrate the efficiency of various candidate alternative agents within twelve months.

(11) Elimination of discharge testing at the current time involves acceptance of some risk due to technical uncertainties in the design, installation, and approval process.

6.3 Proposed Areas for Research, Testing, and Analysis

The following proposals are predicated on the intent to replace full discharge testing of Halon 1301 suppression systems. They are based on the technical literature review and analysis.

(1) A near term priority should be the development and evaluation of test gas simulants for use in in situ Halon 1301 system testing. Ongoing research in this area should be encouraged, with the results being provided to the interested organizations associated with halon system design, installation, and approval (e.g., <12 months).

(2) Collection of data on door fan pressurization tests conducted during Halon 1301 system testing should be continued. Sufficient detail should be provided to enable the development and verification of halon decay/room leakage correlations.

(3) A special testing and development program should be instituted for door fan pressurization techniques and correlation with halon concentration decay. The need for differential pressure data, controlled leak conditions, humidity control, etc. to develop the necessary corre-

lation cannot, in general, be obtained by field tests during halon system approvals.

(4) Additional diagnostic test equipment should be considered for total flooding system tests. Bottle discharge pressure and nozzle pressure data during discharge should be taken. Potential benefits of this data include the determination of the cause of the test failure, if any, confirmation data for hydraulic calculation programs, and nozzle discharge and mixing.

(5) The magnitude of the problem of agent mixing and distribution needs to be established. Improved nozzle characterization in the form of jet geometry and decay as a function of position and nozzle pressure and fluid composition is required for a generic design basis.

(6) Development of a generic open hydraulic calculation program should be pursued. Existing public domain two phase flow programs should form the basis.

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