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Computer-aided Halon 1301 Piping Calculations

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SUMMARY

The design of Halon 1301 fire suppression systems often requires difficult hydraulic calculations. With the aid of a computer, the hydraulic calculations can be performed effectively and efficiently. Based on the theory of Halon 1301 system discharge, it is possible to consider fundamental programing concepts and examine different programing alternatives.

INTRODUCTION

Halon 1301 is a proven safe and effective fire extinguishing agent when used in a properly designed system. It is most important that every system be carefully engineered in order to fully exploit the performance characteristics of the agent. The most difficult part of the design process is frequently the hydraulic calculations. Since it is not practical to manually perform these calculations, the only effective method of design is through the aid of a computer program which will realistically model the discharge process.

When used in total flooding extinguishing systems, Halon 1301 is especially attractive for a combination of reasons: low vision obscuration, rapid mixing with air, compact storage volumes, ready access to blocked or baffled spaces, lack of particulate residue, and low toxicity of the extinguishing atmosphere. Even though Halon 1301 vapor has a low toxicity when applied in accordance with NFPA 12A, its decomposition products can be hazardous. The amount of decomposition can be held to insignificant levels by early detection and rapid extinguishment. To minimize decomposition, NFPA 12A (1980) mandates that the liquid Halon 1301 in the storage container be substantially discharged in a nominal 10 seconds. This period is measured as the interval between the first appearance of liquid at the nozzle and the time when the discharge becomes predominantly gaseous.

The requirement for rapid discharge, coupled with the necessity for uniform agent distribution, highlights the need for accurate agent flow calculations and for properly sized nozzles. Accurate flow calculations not only predict discharge times and agent distribution, but they also minimize the overall system cost by identifying the smallest possible pipe sizes which can adequately deliver the required quantities of agent. Since it is not practical to manually calculate the system hydraulics, a computer program is used to determine pressure drops and orifice areas. For a given piping system, as defined by an input data file, the program is required to calculate flow rates, pipeline pressures, and nozzle orifice areas such that an acceptable design may be achieved.

AGENT CHARACTERISTICS

At standard temperature and pressure, Halon 1301 is a colorless, odorless, and electrically non-conductive gas. With an approximate boiling point of −57.8 °C (−72 °F), the gas is compressed and stored as a high density, low viscosity liquid. Once discharged out of the nozzle and into the hazard area, the agent changes almost instantly to its gaseous phase. Referring to Fig. 1, Halon 1301 is stored as a liquid at 21.1 °C (70 °F) and has a vapor pressure of approximately 1379 kPa (200 psig). This pressure is sufficient to discharge the agent from the container at 21.1 °C (70 °F), but the vapor pressure decreases rapidly with lower temperatures. To compensate for lower temperatures, the storage container is superpressurized with dry nitrogen to either 2482.2 kPa (360 psig) or 4137 kPa (600

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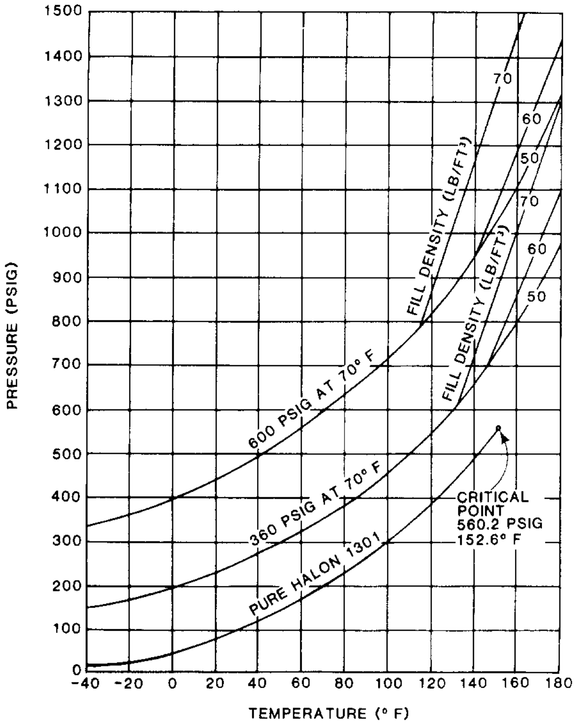

Fig. 1. Temperature–pressure relationship for pure Halon 1301, Halon 1301 superpressurized to 2482.2 kPa (360 psig) at 21.1 °C (70 °F), and Halon 1301 superpressurized to 4137 kPa (600 psig) at 21.1 °C (70 °F). (*Chemetron Design Manual*, April 1978, p. 6.)

psig) at 21.1 °C (70 °F). Figure 1 shows how superpressurization insures adequate performance of the system over the expected temperature range. For the purpose of simplification, this paper will focus on containers of the more common 2482.2 kPa (360 psig) category.

Superpressurization acts as a propellant, resulting in rapid discharge of the extinguishing agent. Interestingly, nitrogen is to some extent soluble in liquid Halon 1301. The solubility is related both to the temperature and the degree of superpressurization. Prior to discharge, the container has a gas phase of nitrogen vapor and Halon 1301 vapor, and a liquid form of Halon 1301 and dissolved nitrogen. As the container is discharged there is an initial pressure drop followed by a recovery in pressure, from which the pressure recedes in a linear manner until all the liquid has been discharged. The pressure recovery is caused by the dissolved nitrogen vigorously boiling out of the Halon 1301/nitrogen solution, thus intensifying the discharge of the container contents. It is assumed for the purpose of calculations that all the vapor formed by boiling in the container will remain in the container and only the liquid phase enters the pipeline. Recognizing this, the typical container design either has its discharge port on its liquid side or a dip tube extending below the liquid level.

FORMULATION OF THEORY

As with sprinkler systems or other systems involving fluid flow, the methodology for solving Halon 1301 piping calculations involves seeking terminal characteristics based on both initial conditions and the property changes encountered due to the movement of the fluid. Because the flow of Halon 1301 is non-steady and has a change in phase as one of its inherent hydraulic properties, the calculations become highly complex. The traditional approach to this problem is to determine the average discharge conditions of the system such that they might generally represent the system operation. With the understanding that the average conditions will focus on an average point in time (reasonably representing the entire calculation time span), the first mode of the calculation process is to determine the average conditions at the storage container. Once these are determined, they can then be used for the second mode of the calculation process, which is to determine the pressure changes encountered due to the movement of the fluid. The third and final mode is to determine the characteristics at the systems terminal points, or for Halon 1301 systems, the nozzle orifice. This approach is analogous to calculating sprinkler system pressures where one would first determine the starting supply pressure, then solve for pressure losses, and finally determine the pressures at the sprinkler heads. For Halon 1301 extinguishing systems, the final objective concerning hydraulic calculations is to determine the nozzle and nozzle orifice required for a specified set of starting and flow conditions.

SYSTEM ASSUMPTIONS

Calculations for Halon 1301 flow involve sophisticated hydraulic theory. In the storage container, the agent is primarily a liquid, yet it is a gas upon discharge from the nozzle. While traveling in the pipeline, the agent attempts to change from a liquid to a gas in a phenomena known as two phase flow. The hydraulic calculations must take into account two phase flow and the resulting non-steady characteristics of the process. Thus the flow of Halon 1301 in a piping system involves a change in phase and a change in density as well as variations in pressure.

To formulate the calculation method for Halon 1301 flow, certain assumptions must be made. To calculate the pressure conditions in the storage container and in the pipeline, the agent density must first be determined. This can be found by using general thermodynamic considerations, assuming that there is saturation equilibrium between the liquid and vapor states in the storage container and constant enthalpy expansion in the pipeline. Yet even with these basic assumptions, it is still not practical to provide a complete description of the discharge process from beginning to end. Hence, to simplify calculations, a time-independent model is required to properly approximate the non-steady discharge characteristics. This model is constructed from the conditions existing in the system when half the liquid phase of the agent has left the nozzle; all subsequent calculations are based on these conditions. The result is that critical characteristics that vary with discharge such as the storage container pressure and the pressure–density relationship in the pipeline are replaced with average time-independent values.

To illustrate the necessity of time-independent modeling, Fig. 2 represents an acceptable approximation of the receding container pressure as a function of time (or percent outage). It is necessary to replace the container pressure recession curve with an average time-independent value which properly represents the container pressure over the entire discharge process. This is referred to as the average container pressure and is determined when half of the liquid phase of the agent has left the nozzle. The manner in which the pressure recedes is affected by the initial fill density of the container. The initial container fill density is different from the actual agent density needed for the calculation of the pipeline

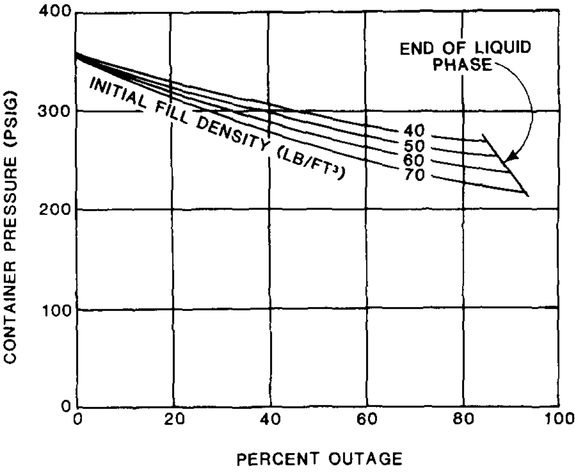

Fig. 2. Calculated pressure recession for a container superpressurized to 2482.2 kPa (360 psig) at 21.1 °C (70 °F). (*NFPA 12A*, 1980, pp. 12A-68.)

pressure. The definition of the initial container fill density is the total weight of agent per volume of container, while the pipeline agent density is the weight per volume of liquid agent. The initial container fill density is a condition existing prior to discharge which affects the subsequent recession of container pressure. Once discharge begins, the agent density in the piping network continually changes with respect to time, yet it does so based on the starting conditions at the container which include the initial container fill density.

The pressure–density relationship of the agent traveling in the pipeline, like the storage container pressure, is also a function of percent outage. Figure 3 illustrates this relationship based on an initial container fill density of 640.8 kg/m^3 (40 lb/ft^3). Due to the superpressurization of the storage container, the density of the fluid flowing into the piping network is constantly changing. As previously stated, the opening of the container valve releases liquid into the pipeline, causing an initial pressure drop. Rapidly following this is a recovery in pressure due to the nitrogen evolving from the liquid, from which the pressure recedes in a linear manner until all the liquid has been discharged. Because of the loss of nitrogen from the solution, there is a temperature drop which increases the density of the liquid as it leaves the container. Hence, as the liquid Halon 1301 leaves the agent storage container, its density continually increases. Since the

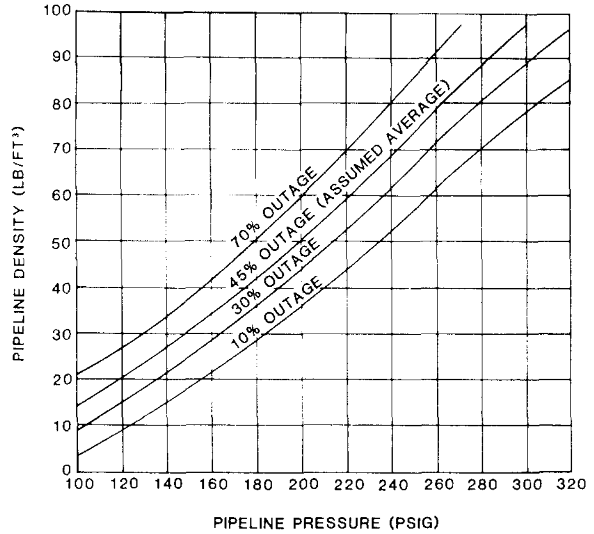

Fig. 3. Density–pressure relationship in the pipeline for selected stages of Halon 1301 leaving the storage container during discharge based on an initial container fill density of 640.8 kg/m^3 (40 lb/ft^3). (*Fenwal Publication 273*, July 1982, p. 11.)

density of agent increases over the entire discharge time span, it is necessary to determine a time-independent representation of the pressure–density relationship. Between 85 percent and 93 percent of the container contents is discharged as liquid, with the remaining agent following as a residual vapor. Thus, the 45 percent outage point is assumed to be the most reasonable estimation of the pressure–density relationship of the fluid as it travels from the container to the nozzle.

THE STORAGE CONTAINER

Before any nozzle or pipeline pressures can be calculated, a starting pressure must be determined at the storage container. The average storage container pressure is calculated based on the original pressurization level, the container fill density, and the percent of agent in the pipe. The first two factors are simply derived. The original pressurization level is either 2482.2 kPa (360 psig) or 4137 kPa (600 psig) and the container fill density is the ratio of the total agent poundage in the container to the volume of the storage container.

The percent of agent in pipe has a significant effect on the average storage container pressure. It is defined as the ratio of the weight of agent in the pipe under flow conditions to the total weight of agent for the system. The amount of agent in the pipe under flow conditions is initially an estimate since the calculations for pipeline densities and pressures have yet to be determined. If a high degree of calculation accuracy is desired, the initial estimated percent in pipe should be compared to the final calculated percent in pipe, and if their difference exceeds a pre-set criterion, the average of the two should then be used as the new percent in pipe with the entire calculation process being reiterated.

The percent in pipe is important in determining the average storage container pressure because it accounts for the agent that has left the container but has not yet discharged from the nozzle. This has a significant effect on the value chosen for the average container pressure. Since the characteristics of the system are defined when half the agent has left the nozzle, to determine the amount of agent still in the container requires that the agent residing in the pipeline be considered. Consider Fig. 4, which represents a system with a container fill density of 640.8 kg/m^3 (40 lb/ft^3) and a percent of agent in pipe of 25%. The amount of agent residing in the pipeline when half the agent has left the nozzle reduces the average container pressure from approximately 2068.5 kPa (300 psig) to 1896.1 kPa (275 psig). This demonstrates how the average container pressure is a function of the percent of agent in pipe. Simple

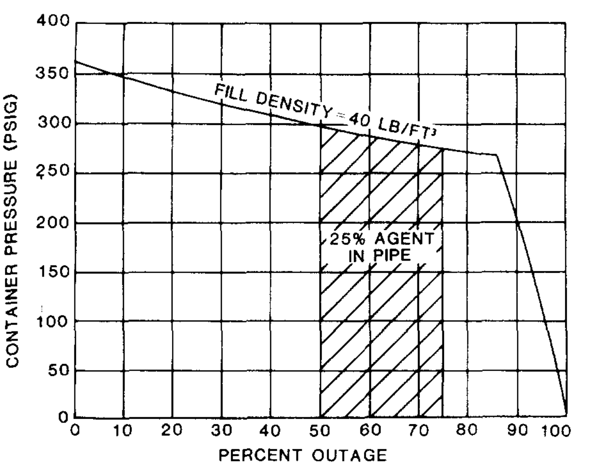

Fig. 4. Average container pressure consideration for a 2482.2 kPa (360 psig) system with a fill density of 640.8 kg/m^3 (40 lb/ft^3) and a calculated percent of agent in pipe of 25%, (*NFPA 12A*, 1980, pp. 12A-69.)

extrapolation of this relationship makes the average container pressure available over a wide range of values for percent of agent in pipe.

PIPELINE FLOW

As the liquid Halon 1301 is discharged from the container, it flows through the piping system and experiences a pressure drop due to friction. This, along with the cold liquid coming in contact with the piping at ambient temperature, creates additional vapor and intensifies the two phase flow of liquid and vapor. Since the volume of the vapor phase increases with decreasing pressure, the density decreases while the velocity of flow increases so as to maintain a constant mass flow rate. The result is that the rate of pressure drop is not proportional to the length traveled, but is instead a variable quantity dependent on the fluid density in the pipeline. This is demonstrated in Fig. 3, based on an initial container fill density of 640.8 kg/m^3 (40 lb/ft^3). The increase in density at any one location over the entire time span should not be confused with the decrease in density that occurs when the fluid flows from one location to the other.

The three factors which determine the pressure change during pipeline flow are: elevation head, friction losses, and velocity head. The elevation head is simply the result of the work done by or against gravity. The friction loss, perhaps the most complex segment of the entire calculation process, is indirectly solved by first calculating the fluid density. The reason for this is that the pressure drop due to friction is a variable dependent on the fluid density and is not directly proportional to the length of pipe. Beside the normal losses due to fluid viscosity and interaction with the pipe walls, there are also friction losses associated with the changing properties of the fluid as it flows in the pipeline. Friction losses are based upon the assumption that heat losses are negligible, the mixture behaves as a compressible fluid, and the liquid and vapor flow with equal velocities. Finally, the velocity head is accounted for when there is a velocity change in the fluid flow, such as at a flow split or a changing pipe diameter. The calculations for elevation head and velocity head are typical considerations common to all fluids, while the friction loss calculations are unique for Halon 1301.

Since the friction loss calculations require a homogeneous mixture of vapor and liquid, the flow rate must be sufficient to maintain turbulent flow. This constraint insures accurate flow calculations and inhibits unwanted phase separation. To insure turbulent flows in pipe with a specific flow rate, the pipe diameter must not exceed a pre-set maximum size. Thus, for Halon 1301 hydraulics, there is a definite range of acceptable pipe diameters. If pipe diameters are too large, turbulent flows will be lost; if pipe diameters are too small, pressure losses will be too great.

NOZZLES

The primary objective of Halon 1301 hydraulic calculations is to solve for the required nozzle orifice area. It is the function of the nozzle not only to properly disperse the agent throughout the enclosure, but more importantly to provide through the orifice area a limiting factor which will guarantee that the system will discharge as calculated. The availability of a physical nozzle to match a calculated orifice area is the final factor in determining system acceptability. Equipment manufacturers carry nozzles with a wide selection of orifice areas for this reason. The determination of the orifice area for each nozzle is based on the flow rate, the agent density, and the terminal pressure, with an allowance factor made for the nozzle efficiency. The calculated nozzle pressure must always be greater than a pre-set minimum value to insure proper agent dispersal from the nozzle. Since the nozzle is the primary element in controlling the hydraulics, good design should always limit the nozzle orifice area to a certain percentage of the feed-pipe area.

PROGRAM CONSTRAINTS

The theory of Halon 1301 hydraulics provides the vehicle by which computer aided calculations may be accomplished. To aid in the development of an accurate calculation process, certain fundamental limitations are necessary to insure proper system design. In general, these limitations are:

1. Good design practice reflected in the actual piping layout.
2. Discharge time less than or equal to 10 seconds.
3. System temperature within a range which causes favorable container pressure.
4. Initial container pressure equal to 2482.2 kPa (360 psig) or 4137 kPa (600 psig).
5. Initial container fill density less than or equal to 1121.4 kg/m^3 (70 lb/ft^3).
6. Percent of agent in pipe less than an established maximum value.
7. Turbulent flow maintained in all pipelines.
8. Nozzle pressure greater than an established minimum value.
9. Actual nozzle area less than a certain percentage of the feed pipe area.
10. Actual nozzle area equal to the calculated nozzle area within ± 5%.

The values for some of these constraints are determined by the individuals developing the computer program, which eventually are verified by approval agencies through actual discharge tests. For any calculation process to be effective, good engineering judgement must always be used on the original Halon 1301 system design. If possible, a balanced system should be favored so that flows and pressure losses to each nozzle are relatively equal. A secondary limitation supporting this would be an established maximum value for the degree of imbalance at flow splits. Likewise, piping practices which may separate the Halon gas/liquid mixture should not be used, examples of this being vertically installed tee's and nozzles on different floors of a building. Unrealistic distribution networks fail to perform to specifications and are difficult if not impossible to predict from a calculation standpoint. The more unrealistic a piping system, the more unreliable the calculations; thus, the justification for the previously mentioned set of constraints.

PROGRAM MODEL

It is the pursuit of computer aided Halon 1301 piping calculations to determine acceptable output based on specific input. Basically, the input covers the piping system characteristics by defining the container, the pipeline, the nozzle and the discharge time. The output consists primarily of the nozzle orifice area which the calculation process requires. Figure 5 represents the input–output relationship in a typical flow of logic for computer aided Halon 1301 piping calculations.

The input needed for the container requires the initial pressurization level, the characteristics of the container (such as the equivalent length of the valve), and the fill density, which is based on the container volume and the weight of the agent in the container. The definition of the pipeline includes the pipe length, the equivalent length of fittings, any elevation change, the type of piping material, and the pipe diameter (which can be determined by the computer program itself through systematic reasoning). Pipeline calculations are performed for each segment of pipe having both a constant flow rate and a uniform pipe diameter; therefore, the piping network is commonly input in segments. The information required for the nozzle is the flow out of the nozzle along with a factor which allows for the nozzle efficiency. Finally, it is necessary to provide the discharge time, this being the most flexible of all the data used in the calculation process.

Based on the pressure calculated at the nozzle, the required orifice area can be determined from this input. Yet due to the efficiency of computer aided calculations, it's possible to have both the discharge time and the pipe diameter as output also. This is accomplished by letting the program calculate pipe diameters based on turbulent flow rate limits and then performing the calculations at descending time intervals until an acceptable nozzle orifice can be found. The initial choice of diameters for each pipe in the piping network is selected by reducing down a pre-set number of pipe sizes from the maximum allowable size of each pipe as indicated by the turbulent flow rate limits. Due to the cost of pipe, it is preferable to use the smallest possible sizes; however, pipe which is too small will have unacceptably high pressure losses. Once initial pipe diameters have been selected, the quest for an

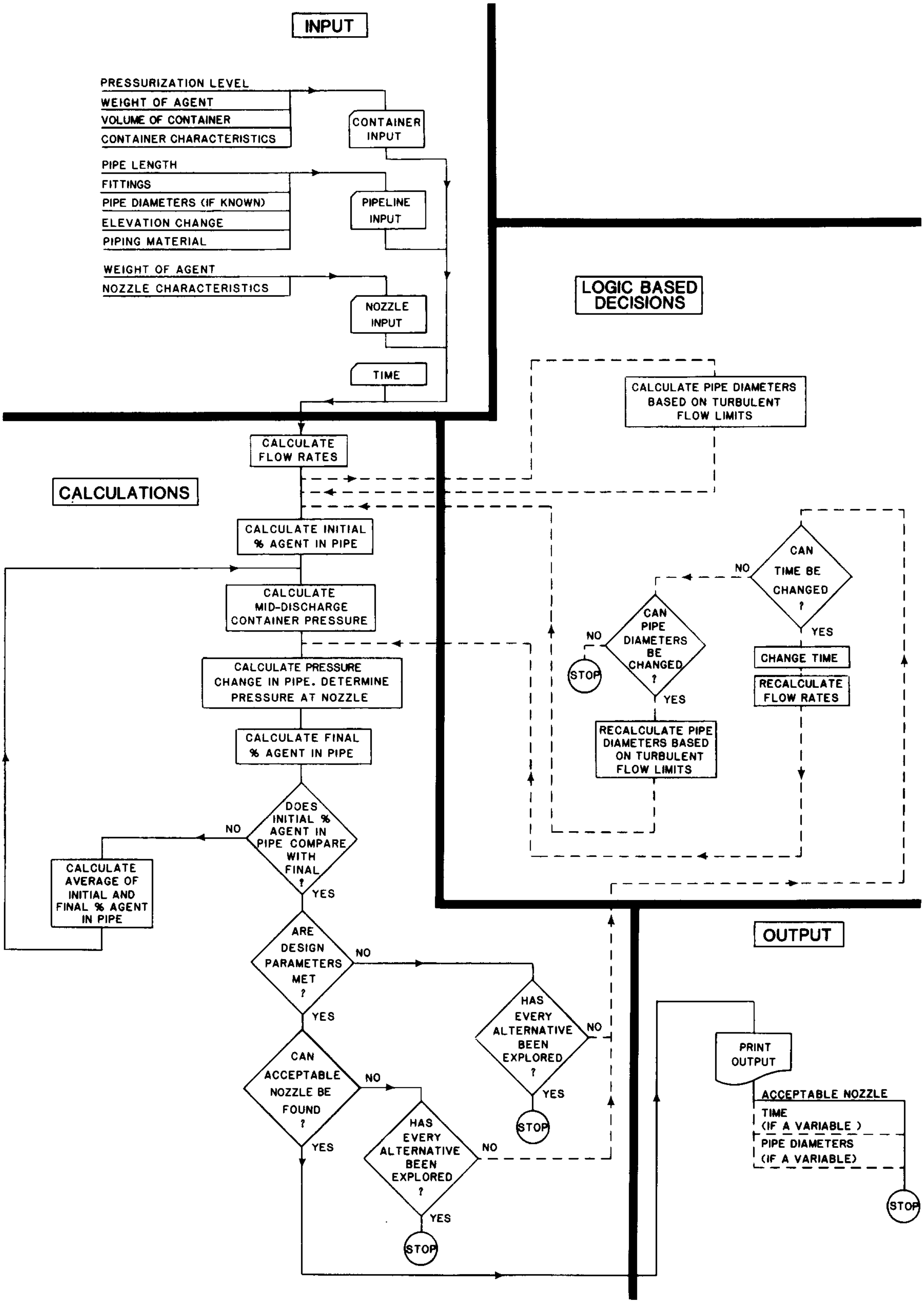

Fig. 5. Logic flow for computer-aided Halon 1301 piping calculations.

adequate orifice area is most logically performed by calculating the hydraulics at descending time intervals. Only after the acceptable range of discharge times has been exhausted should a change in pipe size be considered. As outlined in Fig. 5, it is not mandatory to have the calculations select the discharge time and pipe diameters; the option to input this information manually should always be available to the program user. However, the convenience of allowing the computer program to perform these logic based decisions is an asset not to be overlooked. This approach is especially effective for large or unbalanced systems.

The caliber of the hardware needed to perform Halon 1301 piping calculations varies significantly with the number of options which the program employs. An exhaustive calculating program with an elaborate input–output scheme can use up to 400 kilobytes worth of on-line storage, thus justifying hardware as large as minicomputers. Yet there are packaged programs available for small office calculators which will perform the skeleton calculations at the sacrifice of numerous options. These smaller programs are simply an extension of basic hand calculations and are usually not completely reliable for unbalanced piping systems. Equipment manufacturers typically make their programs available through timesharing networks, thus gaining the advantage of operating their software on very powerful computers as well as allowing user access over large geographic areas.

PROGRAM VERIFICATION

Computer programs that model the Halon 1301 discharge process lack true credibility unless verified by experimental data. In a competitive Halon industry where the hazards protected are often worth millions of dollars, it is important that the modeling of the actual discharge process be authentic. Currently, the recognized method for substantiating computer-aided Halon 1301 piping calculations is through approval agencies such as the Factory Mutual System or Underwriters Laboratories Inc.

Because of the complexity of computer aided Halon 1301 piping calculations, it is not feasible for an approval agency to verify actual software programing. Instead, it is the methodology used in the calculation process which receives agency approval, once proven with actual discharge tests. A typical test program includes a series of discharges each involving separate volumes protected by a single unbalanced piping system. The piping system design is based on computer program predictions of agent distribution, discharge time, and pressure at nozzles. Along with other criteria, test results should show the Halon 1301 concentrations measured in each separate test volume to be within plus 10% and minus 5% of the concentrations called out in the original design. It is during the test process that the developer of the computer program verifies his program constraints such as minimum allowable nozzle pressure, maximum allowable percent agent in pipe, maximum allowable percent of nozzle area to feed pipe area, and maximum allowable degree of imbalance at flow splits.

CONCLUSION

As stated earlier, the most difficult part of designing Halon 1301 fire suppression systems is frequently the hydraulic calculations. Because it is not practical to perform these calculations manually, the only effective method of design is with the aid of a computer program. Today the fire protection community has at its disposal a variety of qualified computer programs, each rapidly and effectively performing Halon 1301 piping calculations. These programs assist the fire protection engineer with the complex requirements typically associated with unbalanced Halon 1301 piping systems. In a world of flourishing high technology, Halon 1301 is providing an answer to the growing need for modern methods of fire protection. So too is high technology providing an answer to the needs of Halon 1301 fire suppression system design.

BIBLIOGRAPHY

Ansul Company, *The Design of Halon 1301 Systems*, Marinette, WI, May 1979.

Chemetron Corporation, *Design Manual — Halon 1301 Systems*, Monee, IL, April 1978.

Crane Company, *Flow Of Fluids, Technical Paper No. 410*, Chicago, IL, 1969.

Du Pont Company, *Du Pont Halon 1301 Fire Extinguishant, Technical Bulletin B-29E*, Wilmington, DE.

Du Pont Company, *Du Pont Halon Fire Extinguishant — Thermodynamic Properties, Technical Bulletin T-1301*, Wilmington, DE.

Du Pont Company, *'Freon' FE 1301 Fire Extinguishing Agent — Handling And Transferring, Technical Bulletin FE-2*, Wilmington, DE, 1969.

John E. Echternacht, Halon extinguishing systems design criteria, *Fire J.*, *65* (6) (Nov.) (1971).

Factory Mutual Research, *Draft Copy Of Approval Standard For Halogenated Agent Type Fire Extinguishing Systems — II*, Norwood, MA, Class No. 5214, June 1983.

Fenwal Incorporated, *Halon 1301 Piping Calculation Methodology, Publication 273*, Ashland, MA, July 1982.

Fenwal Incorporated, *Halon 1301 Piping Program User Guide, Publication 274*, Ashland, MA, Sept. 1983.

Charles L. Ford, Halon 1301 update: research, application, new standard, *Specifying Engineer*, May 1977.

J. Graham Forrester, Halon 1301 liquid discharge — sustained by self-chilling, *Fire Technol.*, *18* (2) (May) (1982).

James C. Hesson, *Pressure Drop For Two-Phase Carbon Dioxide Flowing In Pipelines*, Illinois Institute of Technology, Chemical Engineering Dept., Chicago, IL, January 1953.

National Fire Protection Association, *NFPA 12A — Halon 1301 Fire Extinguishing Systems*, Quincy, MA, 1980.

National Fire Protection Association, *NFPA Handbook*, 14th edn., Quincy, MA, 1982.

Produits Chimiques Ugine Kuhlmann, *Flow In Pipes — Halon Pyroforane 1301*, 92400 Corbevoie, Paris, France.

Underwriters Laboratories Incorporated, *Appendix A — Proposed First Edition Of The Standard For Halogenated Agent Extinguishing System Units, UL 1058*, Subject 1058, Northbrook, IL, May 1983.

Steve J. Wiersma, Flow characteristics of Halon 1301 in pipelines, *Fire Technol.*, *14* (1) (Feb.) (1978).

H. V. Williamson, *Halon 1301 Flow Calculations — An Analysis Of A Series Of Tests Conducted By FEMA At The Fenwal Test Sites Using Two-Phase Calculation Methods Including An Analysis Of The Linear Approach With Suggestions For Improvement*, Chemetron Corporation, Hanover, PA, March 5, 1975.

H. V. Williamson, Halon 1301 flow in pipelines, *Fire Technol.*, *12* (1) (Feb.) (1976).