Halon 1301 Flow in Pipelines

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An understanding of the mechanism of flow of Halon 1301 is necessary for the proper design of piping systems.

FROM THE time that Halon 1301 showed promise of being an effective and safe total flooding fire extinguishing agent, industry has been struggling with the problem of properly designing piping systems with predicatable performance. The problem is not a simple one. A rigid mathematical analysis is like opening Pandora's box to release a multitude of interrelated phenomena. The main objective of this paper is simply to describe the characteristics of Halon 1301 flow so that the reader will have a better understanding of the nature of the problem.

TWO-PHASE FLOW

Surely there is no doubt that the flow of nitrogen-pressurized Halon 1301 is, in fact, a two-phase flow phenomenon; that is, the fluid flowing in the pipeline consists of a mixture of liquid and vapor. Furthermore, the ratio of vapor to liquid increases as the pressure drops due to frictional loss in the pipeline.

The phenomenon of two-phase flow can be detected in various ways by means of test data or sheer mathematical deduction. The direct approach would be to install a transparent section in the discharge pipeline. If there are no gaseous bubbles in the fluid, the transparent pipe section would remain clear, as it would be if it contained water. In an actual test, the transparent section does not remain clear, but rather becomes opaque and foggy. The velocity of fluid flow is too fast to make out anything but a white fog that fills the pipeline. It takes high-speed flash photography to effectively freeze the flow in a photograph so that the mixture of bubbles and liquid can be seen.

Figure 1 is a photograph of Halon 1301 flowing through a transparent section of pipe. It was made with an electronic flash having a flash duration

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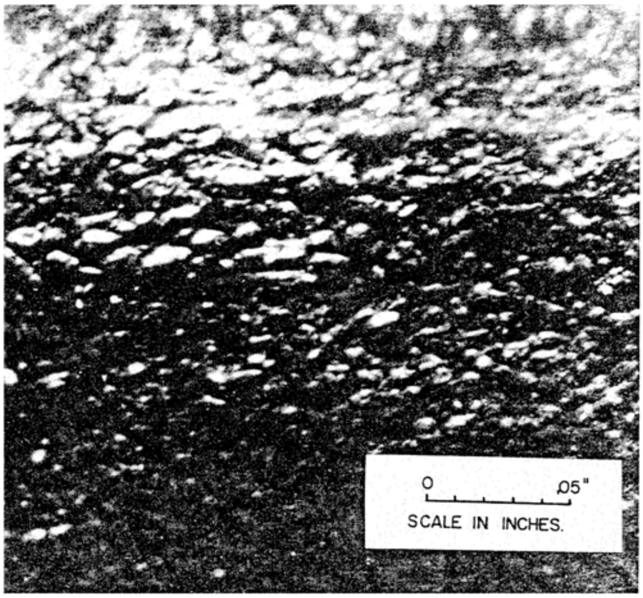

Figure 1. Enlarged view of bubble formation in flowing Halon 1301.

of not more than about 0.5 microsecond. The bubbles in this view are probably no more than about 0.01 inch in diameter. If the flash were sustained for much more than about 10 microseconds, the bubbles would have become blurred and elongated by movement during the exposure.

NONLINEAR PRESSURE DROP

The main characteristic of two-phase flow is that the rate of pressure drop increases as the fluid progresses through the pipeline because the velocity of flow must increase as the volume of fluid expands. In the fall of 1974, the Fire Equipment Manufacturers' Association (FEMA) conducted a series of tests to verify the pressure drop characteristics of Halon 1301. The tests were made with relatively long pipelines having pressure transducers located at a number of points between the storage container and the end of the pipeline. The data from Test No. 6, which is somewhat typical of all the testing, is plotted in Figure 2.

In this test, the storage container was charged with 46 pounds of Halon 1301 and pressurized to 360 psig with nitrogen. The filling density of the storage cylinder was 70 lbs/ft,[3] the maximum that is permitted by the *Standard on Halogenated Fire Extinguishing Agent Systems — Halon 1301*, NFPA No. 12A. The pipeline consisted of approximately 86 ft of ¾-inch Schedule 40, seamless steel pipe. The discharge was from the open end of the pipe with no restricting nozzle.

In Figure 2, the horizontal scale represents the equivalent length of the pipeline from the storage container to the end of the pipe. The vertical

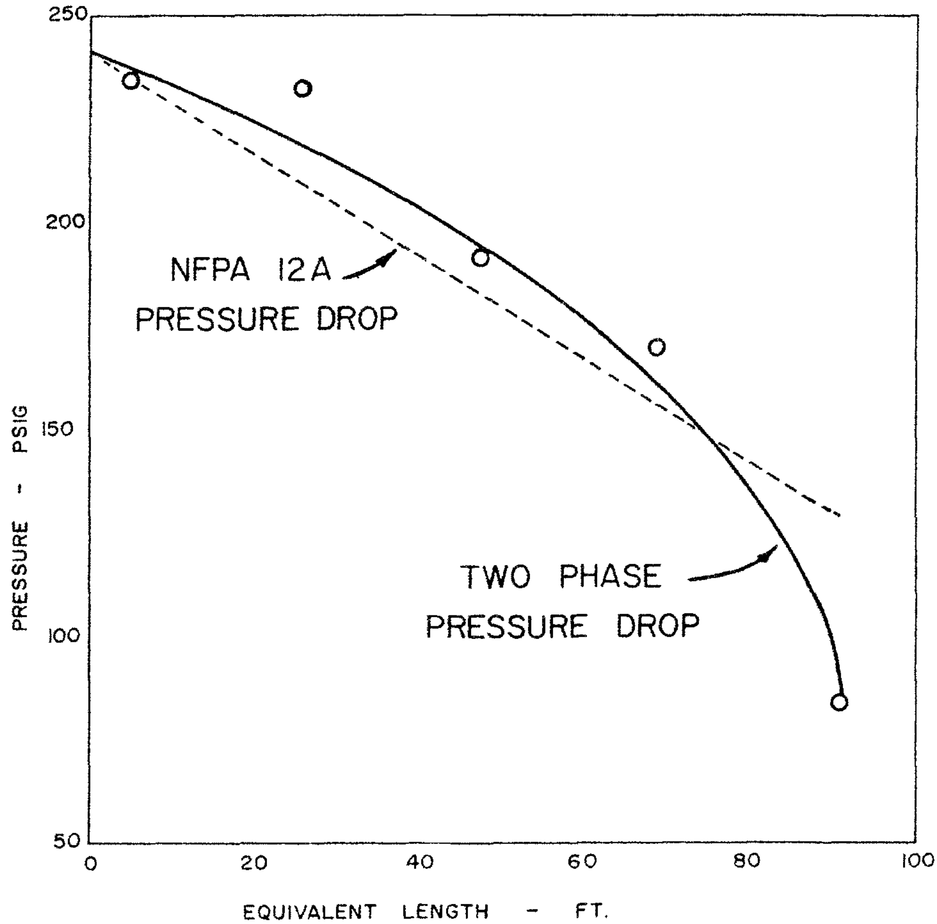

Figure 2. Actual pressure drop through a long pipe is not linear as illustrated by test data from FEMA Test No. 6.

scale represents the pressure in the storage container at various points down the pipeline at a time about halfway through the discharge. Test data, plotted as open circles, clearly follow the curve, which was obtained by calculations using two-phase flow equations. The average flow rate in this test was slightly less than 5 lbs/sec. The straight line sloping downward from the starting point represents the rate of pressure drop that would have been determined using the pressure drop chart presently in NFPA No. 12A.

PRESSURE RECESSION IN CYLINDER

Figure 3 is a pressure recording of a typical discharge test with pressure transducers located at the storage cylinder and at the end of the pipeline just ahead of the discharge nozzle. This was a simple, single-nozzle

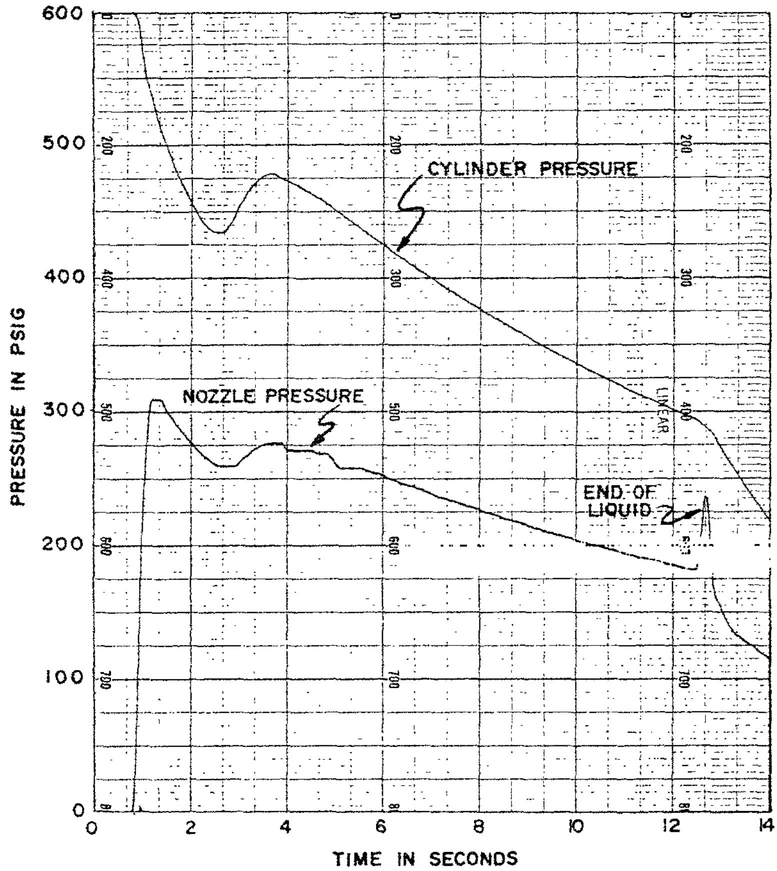

Figure 3. Container and nozzle pressure during discharge of a simple 600-psig system.

system using a storage container pressurized to 600 psig. The discharge started at about 1 second on the time scale.

Several interesting characteristics are illustrated on this recording. First, the pressure in the cylinder dropped rapidly when the valve was opened and then partially recovered at about the 3-second point. This initial rapid pressure drop was due to a super saturation effect in which the liquid in the container did not boil immediately, even though the pressure was well below the saturation level. When the liquid did begin to boil, the effective surface area was greatly increased by the bubbles, so that the pressure quickly recovered to near saturation level. Cylinder pressure then followed the saturation curve until the last of the liquid phase had been expelled at about 12.5 seconds, dropping off more rapidly as the remaining vapor was discharged.

This was a small system; therefore, nozzle pressure built up quickly and then proportionately followed cylinder pressure until the last bit of liquid reached the nozzle. At this point, the pressure suddenly rose at the nozzle because the pressure drop for the portion of the pipe filled with vapor was much less than when the pipe was completely filled with liquid. Liquid in this sense means, of course, a mixture of liquid and vapor, rather than all liquid.

Most important, this pressure recording illustrates the fact that pressure conditions were continually changing from beginning to end of the discharge. Obviously, the pressure in the storage container did not stay at 600 psig; therefore, this pressure cannot be used as a starting point for flow calculations. The problem is to select an average cylinder pressure that corresponds to the average flow rate when calculating pipeline pressure drop. In this case, the average pressure in the cylinder at the mid-point in discharge appears to have been about 400 psig on the recording. It would be difficult, however, to use test data to arrive at average starting pressures for the many different flow conditions that are encountered.

Fortunately, pressure recession in the cylinder can be calculated with the help of suitable tables of thermodynamic data. Du Pont has provided such data in its Bulletin T-1301, giving thermodynamic properties of Halon 1301. Du Pont has also provided information on the solubility of nitrogen in Halon 1301 at various temperatures and pressures.

Calculated pressure recession curves for the 600 psig system are plotted in Figure 4. The filling density of the storage container is an important factor because it influences the average pressure during discharge. Similar curves have been calculated for 360-psig systems. Using these curves, it is reasonable to select, as the average storage pressure during discharge, the calculated cylinder pressure when half of the contents have been expelled into the pipeline. However, this does not represent average container pressure for actual discharge from the end of the piping system.

PERCENT OF AGENT IN PIPING

In Halon 1301 systems designed for 10-sec discharge time, the internal volume of the piping may be relatively large as compared to the volume of the storage container. The ratio of pipe volume to agent volume has a substantial effect on the average flow rate. For example, in the FEMA test work, the piping system of Figure 2 was tested with three different sizes of storage containers. With 27 lbs of Halon 1301, the measured flow rate was 4.5 lbs/sec. With 105 lbs of agent, the measured flow rate was 5.4 lbs/sec. This was a 20 percent increase in average flow rate that can be credited only to a lower ratio of pipe volume to agent volume.

The ratio of pipe volume to agent volume can best be expressed in terms of percent of agent in piping. It is not the simple ratio of piping volume to storage volume because the agent expands to fill the piping system. This is an important concept that exerts a controlling influence on several aspects of flow calculation.

STARTING PRESSURE

Figure 5 is a repeat of the pressure recession curve in Figure 4 with some additional points of information. If the 50 percent discharge point is selected as the average pressure during discharge, the starting pressure for a short pipeline consisting entirely of equivalent lengths without volume would then be 403 psig. If the pipeline is large enough to hold 20 percent of the total supply during equilibrium flow, we could consider that half of this quantity left the storage container after the 40 percent point, with the remainder leaving the storage container before the 60 percent point. The average storage pressure for 20 percent in the pipeline would then be 377 psig, which is the 60 percent discharge point on the pressure recession curve.

Proceeding in this way, one can logically relate percent of agent in the pipe to a fixed starting pressure, based on the calculated pressure recession curves. Figure 6 is a plot of starting pressures or average storage pressures

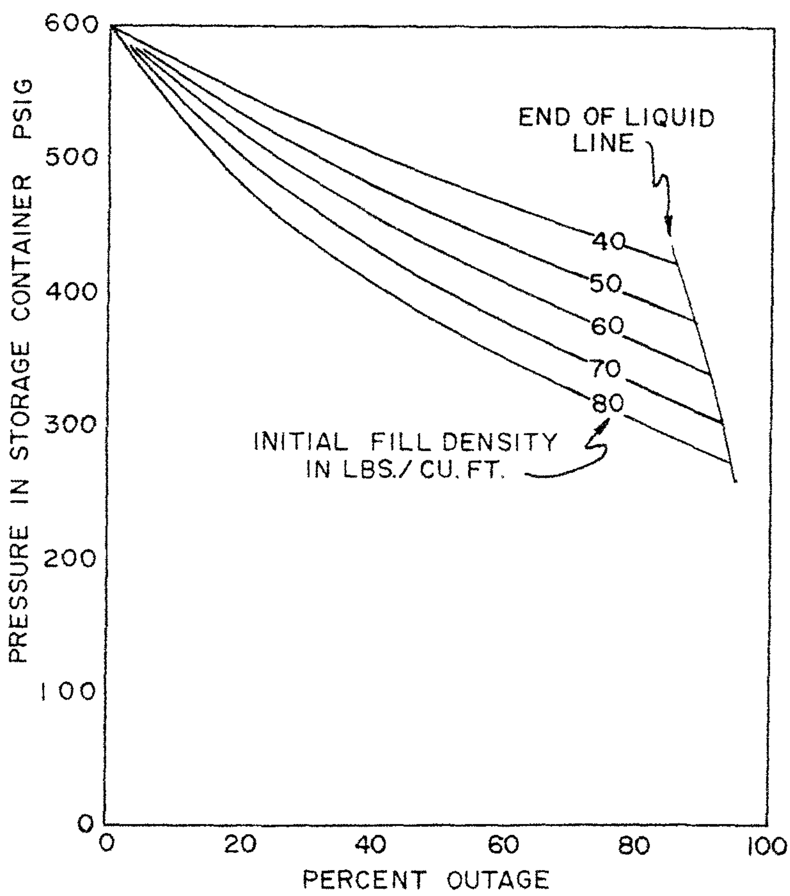

Figure 4. Calculated pressure recession for the 600-psig storage system.

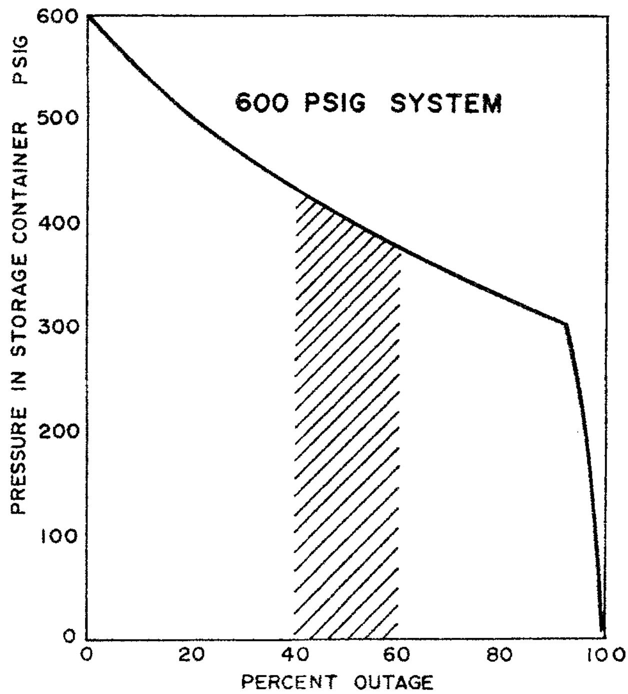

Figure 5. Shaded area represents percent of agent in the piping system at mean container pressure.

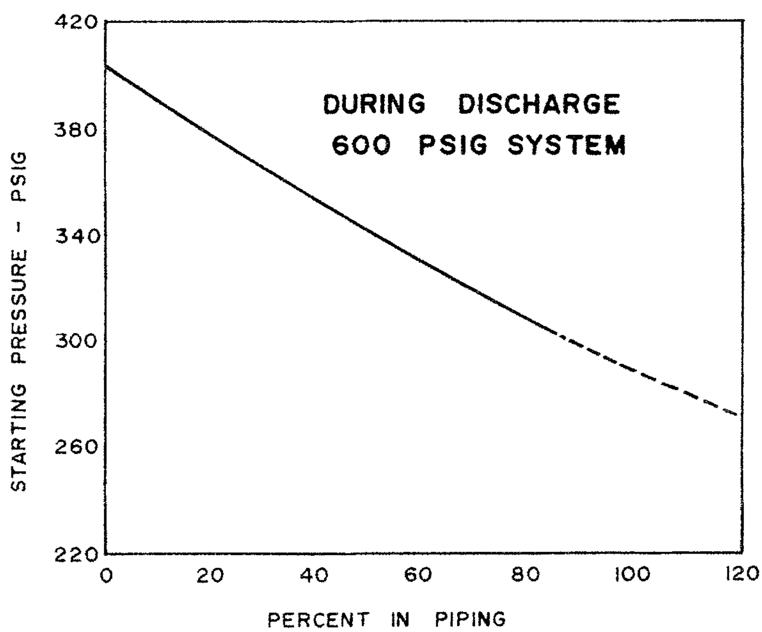

Figure 6. Average container pressure vs percent of agent in piping.

for the 600 psi storage system with a filling density of 70 lbs/ft.[3] This information holds up to the point where about 86 percent of the agent is calculated to be in the pipeline during the discharge. At this point, the last of the liquid has left the storage container, and the pipeline begins to fill with vapor. It then becomes more difficult to calculate the actual quantity of agent in the pipeline because of the need to consider the portion that is filled with vapor. If the starting pressure curve is simply extrapolated, as indicated by the dashed extension, we find the seemingly anomalous condition where the calculated quantity of agent in the pipeline is greater than 100 percent or the total quantity in storage. Of course, the fact of the matter is that part of the pipeline is filled with vapor, and the amount of agent in the pipeline does not reach 100 percent.

PRESSURE DROP IN PIPELINE

The most accurate method of calculating pressure drop in pipelines is the two-phase equation developed by Hesson. This is the same equation that is used for carbon dioxide flow. The Y and Z factors depend on the relationship between line pressure and density. The equation becomes specific for Halon 1301 when the Y and Z factors are derived from Halon 1301 density data.

$$Q = \frac{1.013\ D^{5.25}\ Y}{L + 8.08 D^{1.25}\ Z}$$

where Q = flow rate in lbs/sec, D = inside pipe diameter (actual) in inches, L = equivalent length of pipeline in feet, and Y and Z = factors depending upon density and line pressure.

The change in density for Halon 1301 can be calculated from suitable tables of thermodynamic data. The assumption is made that the expansion in the pipeline takes place at constant enthalpy. This simply means that no heat is added to, or removed from, the fluid as it flows through the pipeline.

Figure 7 is a plot of calculated density vs pipeline pressure for the 600 psig system with a filling density of 70 lbs/cu ft of cylinder volume. This is based on a starting pressure of 403 psig, as obtained from the pressure recession curve at the 50 percent outage point. It is assumed that only liquid leaves the container, and therefore, the density will be about 97 lbs/cu ft. As the pressure drops in the pipeline, some of the liquid will evaporate, so that the volume expands and the density of the mixture of liquid and vapor is reduced.

The curve in Figure 7 is valid only for storage containers charged to 70 lbs/cu ft of cylinder volume and pressurized with nitrogen to 600 psig at 70° F. Different curves will be obtained with the 360 psig system and with lower filling densities. In general, lower filling densities provide higher average pressures and thus higher flow rate capabilities.

It should be pointed out that the effect of percent of agent in piping is to start at lower pressures in the storage container. This also means lower density fluid entering the pipeline. While this is not strictly true, this procedure compensates for transient conditions in high volume systems, where the initial flow into the piping is at a much higher rate through the first part of the piping than the average through the system.

LIQUID-VAPOR SEPARATION

In the normal Halon 1301 piping system, the first objective is usually to achieve the highest possible flow rate with the smallest pipe size that can be used. This is the economical approach, and it is also the best approach. Under these conditions, the flow will be in a state of turbulence, and the liquid and vapor phases will be thoroughly intermixed. If the pipeline is oversized, the heavier liquid phase will tend to flow along the bottom, while the lighter bubbles will tend to accumulate along the top side of the pipe. Thus, a branch line connected to the bottom of a main line will tend to draw off a more dense mixture compared to that drawn off by a branch line connected to the top side.

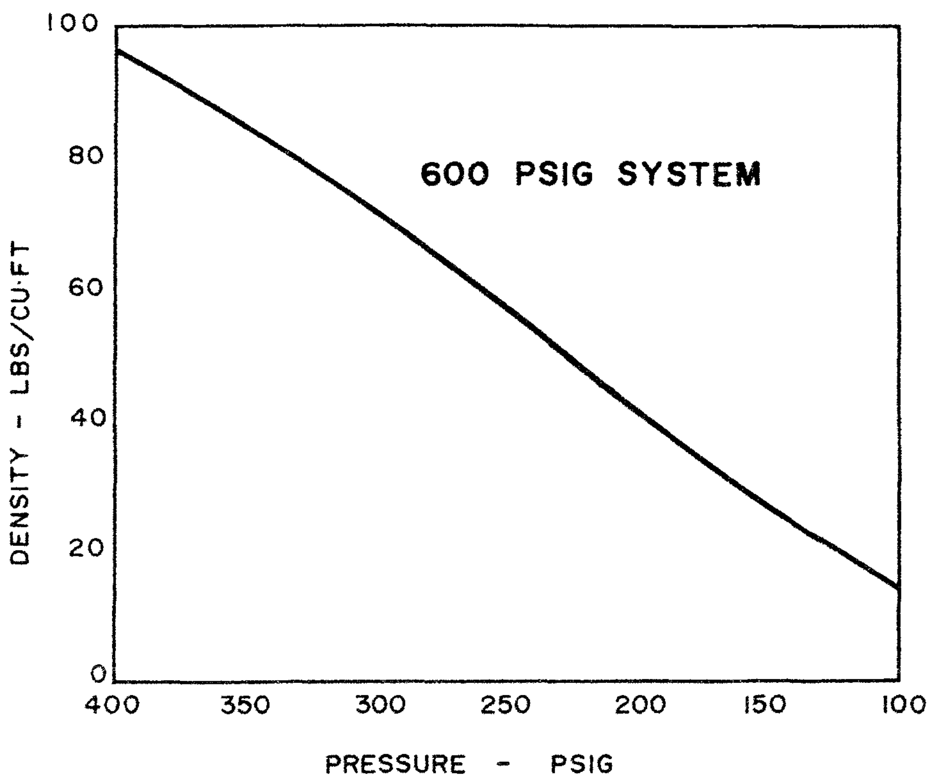

Figure 7. Average pipeline density vs. pressure for the 600-psig storage system.

Even with turbulent flow, the liquid and vapor phases do not divide proportionately at junction points under all conditions. Figure 8 is a plot of a series of tests using a bullhead tee configuration. If the system is designed to divide the flow evenly in each branch line, there is no problem, and the anticipated quantity of agent is discharged through each nozzle. On the other hand, if the system is designed to discharge only 20 percent through one branch line with the remaining 80 percent going to the other, the flow does not divide as expected. The 20 percent branch line receives nearly 15 percent more than expected, while the 80 percent branch line receives about 4 percent less than expected. This is due to the fact that a greater than proportionate share of liquid is forced into the 20 percent branch, so that more of the vapor is forced into the 80 percent branch. This changes the average density in each branch line so as to change the rate of pressure drop as well as the flow rate through the discharge nozzles.

Figure 9 is a plot of a similar series of tests using a through tee configuration. In this case, the flow through the branch line connected to the side outlet of the tee is less than expected, while the through flow is greater than expected. Again, the difference is due to a tendency for the heavier liquid portion to follow the through path, while more of the vapor, having lower density, is forced out of the side outlet. These conditions can be compensated for in the calculations so as to more accurately predict the flow rate in each branch line.

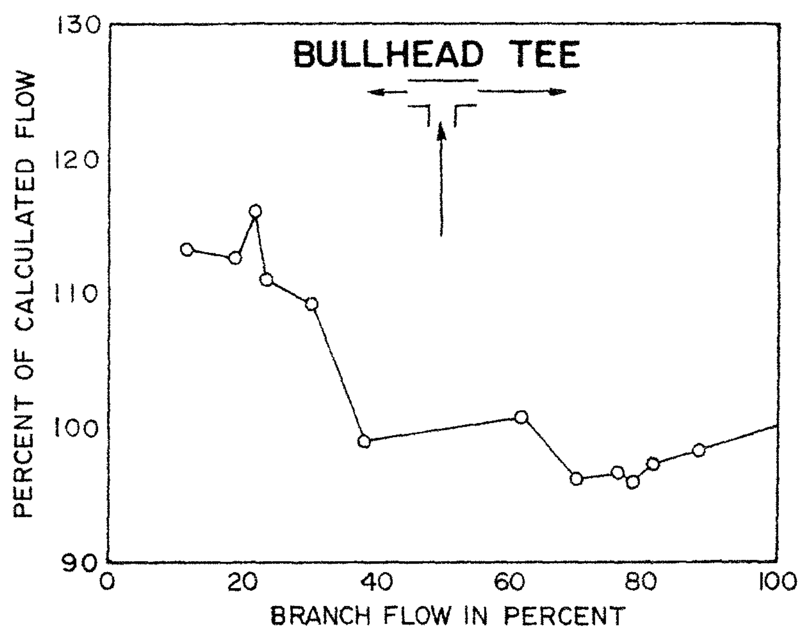

Figure 8. Deviation of flow from a bullhead tee due to liquid-vapor separation.

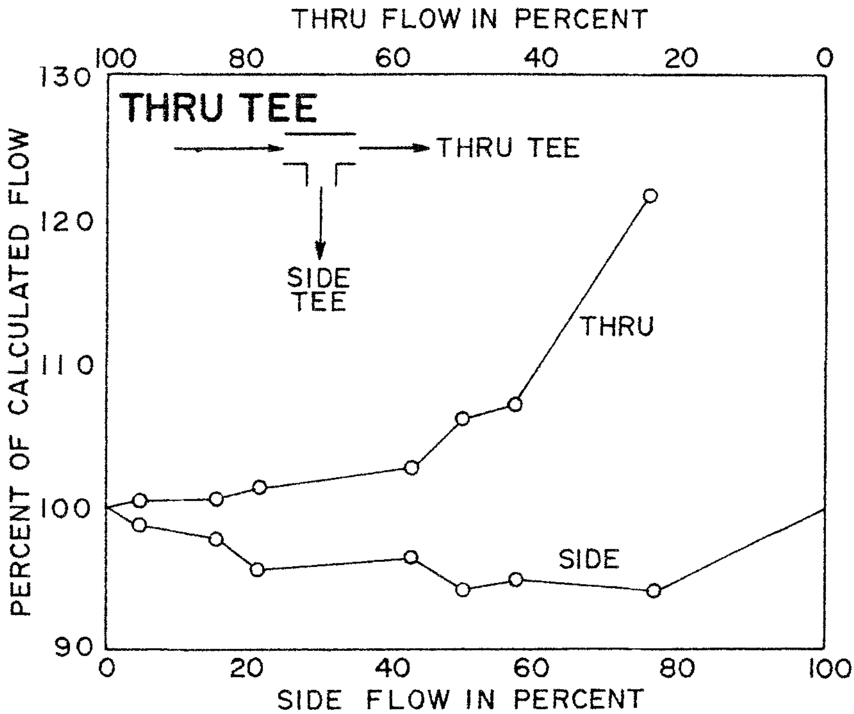

Figure 9. Deviation of flow from a through tee due to liquid-vapor separation.

TERMINAL PRESSURE

In the FEMA test illustrated in Figure 2, the minimum pipe pressure within 2 inches of the open end was about 85 psig. This was obtained with a flow rate of about 5 lbs/sec through a ¾-inch diameter, Schedule 40 pipe. The minimum possible pipeline terminal pressure tends to be directly proportional to the flow rate. The flat 200 psig minimum pressure allowed by the present edition of NFPA No. 12A is not realistic. On the other hand, to set a minimum terminal pressure based on flow rates in each pipe size would be unnecessarily complicated.

From a practical viewpoint, minimum terminal pressure can be expressed as a percentage of the starting pressure. This indirectly relates to the design flow rate as influenced by the storage pressure and also the effect of percent of agent in the pipeline. Under practical conditions, short pipelines will be designed for higher flow rates where the percentage of agent in the pipeline is small and the starting pressure is high. Long pipelines must necessarily be designed for lower flow rates, where the percentage of agent in the pipeline is high and the starting pressure is low. A terminal pressure limit of even 40 percent of the starting pressure would provide a suitable margin of safety above the minimum possible pressure.

BALANCED AND UNBALANCED PIPING SYSTEMS

The importance of accurate pressure drop calculations depends partly upon the nature of the piping system. In a balanced system, as illustrated in Figure 10, the main function of the calculation of pressure drop is to ensure that the system will discharge within the required time limit. In this system, each branch line would be exactly the same length and pipe size, and each nozzle would have the same size orifice. Whether the system will discharge in exactly 10 seconds or require a little more time is highly overemphasized for most total flooding systems. The important point is that both nozzles will discharge exactly the same total quantity.

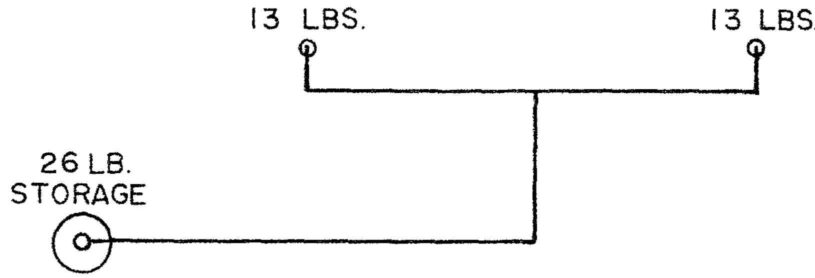

Figure 10. In a perfectly balanced piping system, the same quantity of agent is discharged from each nozzle.

Figure 11 represents a system that has the same length and size of pipe in each branch line; however, the piping is unbalanced by virtue of the tee configuration. In this system, the straight through branch of the tee will discharge a greater portion of the agent supply. This may not be too important if both nozzles are in the same room; however, if the nozzles are used to flood two adjacent rooms of the same size, the results may be completely unacceptable.

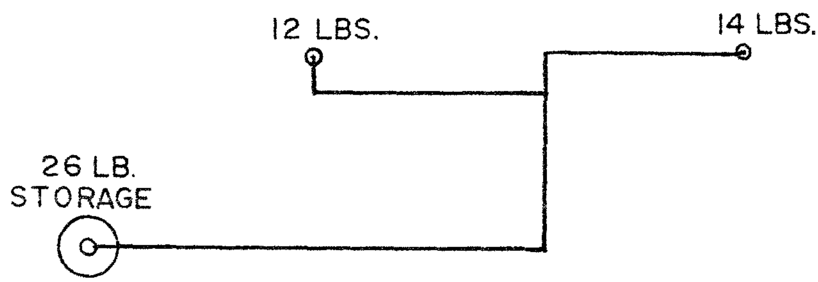

Figure 11. In an otherwise balanced system, the use of a through tee configuration will cause a greater portion to discharge through the favored nozzle.

Figure 12 represents a highly unbalanced system in which a different quantity of agent is desired from each nozzle. In this event, the nozzle orifice sizes must be different and the pipe sizes, and lengths may also be different. This system requires accurate calculations to make certain that the desired quantity will be discharged from each nozzle.

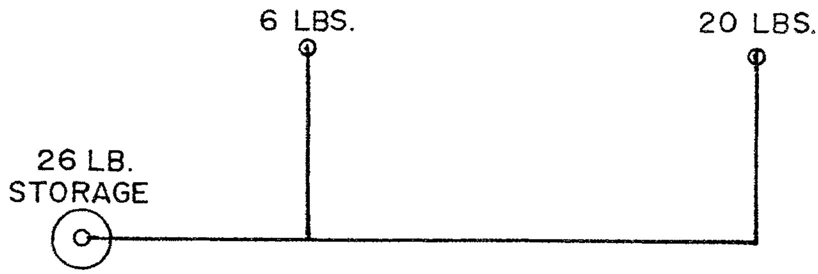

Figure 12. In a completely unbalanced system, the pipe and orifice sizes must be designed to discharge the desired quantity through each nozzle.

METHOD OF CALCULATION

For balanced piping systems, it is reasonable to use a simplified method of calculating pressure drops. For unbalanced systems, a full two-phase analysis should be made for the greatest possible accuracy in predicting the final quantities of agent to be discharged at each nozzle.

The basic linear pressure drop approach presently in NFPA No. 12A is a suitable basis for a simplified piping calculation. Modifications are required, however, because both methods must be based upon the same general principle. For example, the rate of pressure drop is heavily dependent on the percent of agent in the pipeline as illustrated in Figure 13.

A linear approximation would be the slope of a straight line between the starting point at the storage container and some minimum acceptable terminal pressure for the end of the line. In this graph, the terminal pressure was selected as 55 percent of the starting pressure, so as to minimize the deviation between the straight line and the actual curve. By this method, the equivalent linear rate of pressure drop can be determined for different storage conditions and for short and long pipelines. When these are plotted against percent of agent in the pipeline, we find that the rate of pressure drop in long pipelines, under some conditions, can be greater than two times the rate of pressure drop in short pipelines for the same flow rate.

A simple linear approach to system design along the following lines would be compatible with the basic facts and would approximate the results of complete two-phase calculations.

- Determine volume of piping system. Pipe sizes must, of course, be estimated at the outset on the basis of past experience.

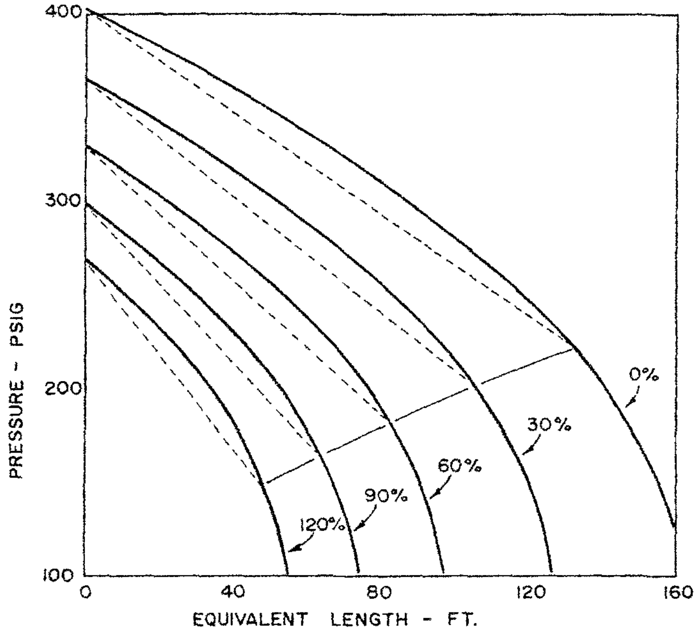

Figure 13. Family of curves illustrating the change of slope of the equivalent linear pressure drop as a function of percent of agent in the piping.

• Estimate percent of agent in piping. In the present edition of NFPA No. 12A, it is assumed that the agent remains a liquid in the piping. Since it does expand, the average density will be substantially less than the liquid density. Nevertheless, with the help of suitable curves or tables, it will not be difficult to estimate the average density and total quantity in the piping.

• Determine starting pressure. Since the starting pressure is a function of percent of agent in the piping, it will be a simpler matter to select the correct starting point from a suitable curve or table for the type of storage facility used in the system.

• Determine rate of pressure drop. This will have to be a two-step process because pressure drop is dependent upon both flow rate and percent of agent in the piping. A base rate of pressure drop would be obtained from a chart similar to the one presently in NFPA No. 12A. This would then be multiplied by a correction factor, based on the estimated percent of agent in the piping.

• Calculate terminal pressures. Using the adjusted rate of pressure drop and the starting pressure determined earlier, the pressure drop to each point in the piping system can be determined as it has been in the past. If any terminal pressure is too low, or if all pressures are too high, it may be necessary to change some pipe sizes and repeat the process.

- Determine nozzle orifice size. Nozzle orifice sizes must be compatible with the calculated nozzle pressure and design flow rate. The specific discharge rate tables used for this must be based on average storage pressure conditions as used in the pressure drop calculations.

At this point it should be evident that it is not practical to attempt complete two-phase calculations by any manual method, but it could be done conveniently by a computer. In general, the same basic steps would be followed as in the simple linear approach. The computer, however, would try different pipe sizes by reiteration and would take into account other variables, such as liquid-vapor separation at branch line, the initial vapor time for each nozzle, and the end of liquid time for each nozzle. The purpose, of course, is to arrive at the best possible prediction of the total quantity of agent that will be discharged at each nozzle to satisfy the requirements of an unbalanced system.

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