SINGLE POINT FLOW CALCULATIONS FOR LIQUEFIED COMPRESSED GAS FIRE EXTINGUISHING AGENTS

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HISTORY Whether the agent is water, dry chemical, inert gas or a liquefied compressed gas, engineered system design demands that we deliver a specified quantity of agent to the fire zone in a specified time. The science of hydraulics enables us to predict the flow of substances in networks of pipe and nozzles. Predicting the flow of liquefied compressed gases used for special fire fighting applications present a unique challenge.

The liquefied compressed gas which has had the longest history of continuous use for fire suppression is carbon dioxide. The NFPA Standard 12 on Carbon Dioxide systems gives a method of calculating flow of CO_2 based on the doctoral dissertation of Dr. James Hesson. This same basic methodology was adapted by Mr. Vic Williamson and later refined by the author to predict flow parameters for Halon 1301. In 1977, the Williamson/Hesson "two-phase" flow methodology was recognized in NFPA 12A, the Standard on Halon 1301 Systems.

During the 1970's and 1980's, numerous laboratory and countless field tests showed the Williamson/Hesson method of predicting Halon 1301 flow to be sufficiently accurate to design Halon 1301 pipe and nozzle systems. Nonetheless there has been considerable debate over the validity of the approach. As with most every mathematical model of physical reality, there are limits which must be recognized.

The approach has been successfully applied to predict flow of Halon 1301, carbon dioxide, HFC227ea, and HFC23. In this paper, we will review the flow theory for liquefied compressed gases. We will also present the enhancements which must be incorporated in order to use the Williamson/Hesson method for complex pipe networks.

"FLOW EQUATIONS"

Bernoulli's equation is a fundamental equation of hydrodynamics.   A qualitative statement of this equation is that the sum of any changes in pressure head, velocity head, friction head and elevation head in a system is zero assuming no heat input or loss from the system. In its basic form, this equation can calculate hydraulic parameters for substances whose density is essentially constant with changes in pressure -- in other words, for non-compressible flow.

$$Z + \frac{144\,P}{\rho} + \frac{v^2}{2g} = H$$

Figure 1 Bernoulli's Equation

Hesson's adaptation of Bernoulli's equation permits calculations for substances whose density changes with changing pressure.

$$43.5 \cdot Q^2 \cdot f \cdot L - 7.97 \cdot Q^2 \cdot D \cdot \int_{P_o}^{P_f} \rho \, dP + D^5 \cdot \int_{\rho_o}^{\rho_f} \frac{d\rho}{\rho} = 0$$

Both of these equations relating pressure, flow rate, pipe diameter, and pipe length <u>require knowledge of the density of the flowing media as a function of the pressure</u> in the pipe.

LIQUEFIED COMPRESSED GAS DISCHARGE

Liquefied compressed gases exhibit the characteristics of compressible flow. In other words, the density of the agent changes considerably as the pressure in the pipeline decreases. These agents also exhibit "two-phase" flow in that the flowing agent is comprised of a mixture of liquid and vapor.

One of the major problems in predicting pressure drop and flow rate in such a system is deriving an accurate relation between agent density and pressure. Depending on the degree of accuracy needed for the type of fire suppression system, a more or less rigorous approach will be required to calculate the pressure-density relationship.

For high pressure carbon dioxide system work, the pressure in the storage container is set to 750 PSI. Density as a function of pressure is calculated by assuming that the carbon dioxide liquid will expand from a saturated condition at 750 PSI with the enthalpy held constant.

This approach provides the required degree of accuracy for calculating flow rates and system pressures for CO_2. For large complex carbon dioxide systems, transient conditions at the start and end of discharge may also need to be considered.

Halon system work and Halon alternative system work generally require much greater accuracy. We are working toward quite accurate predictions of the amount of agent which will be discharged from individual nozzles in a system. ANSI Standard limits require we predict the quantity per nozzle to within -5% and +10%. Discharge times may vary by no more than 1 second predicted to actual.

To start out our calculation of density as a function of pressure, we first consider the discharge of the agent from the storage container. We assume that the agent leaves the storage container as pure liquid with appropriate amounts of nitrogen in solution. We assume constant entropy conditions as each increment of liquid leaves the storage container. Pressure recession curves such as those shown for FE13 (HFC23) or FM200 (HFC227ea) may be calculated.

FE13 PRESSURE RECESSION IN CYLINDER ASSUMING
CONSTANT ENTROPY
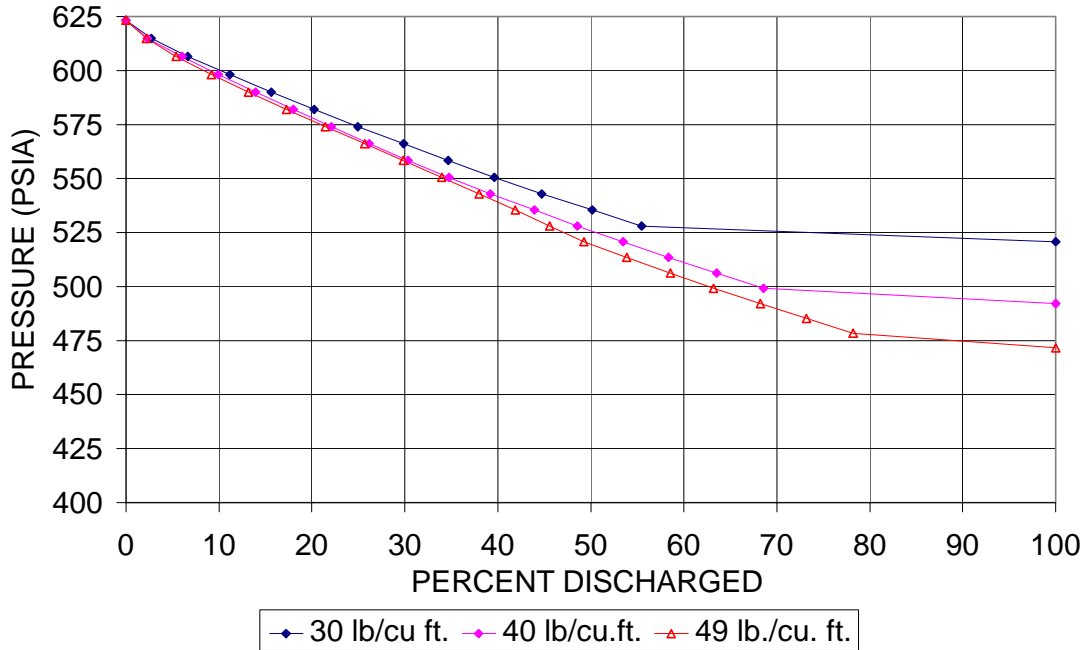
Here we see a theoretical cylinder pressure recession based on constant entropy condition for FE 13 (HFC23) discharge. Cylinder fill density affects the recession. Fill densities of 30, 40 and 49 pounds per cubic foot are shown.

NITROGEN SUPERPRESSURIZED FM200
CYLINDER PRESSURE RECESSION CONSTANT ENTROPY
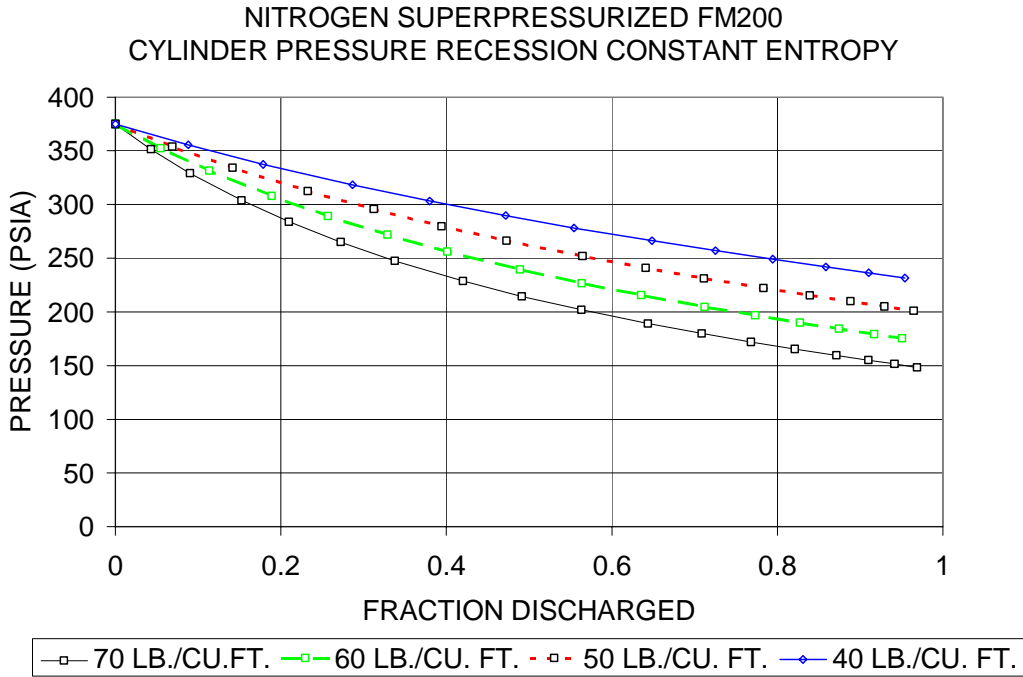
Here we see similar theoretical curves for FM200 superpressurized with nitrogen.

HFC227ea (FM200) DISCHARGE TEST 1
70 LB/CU FT FILL DENSITY
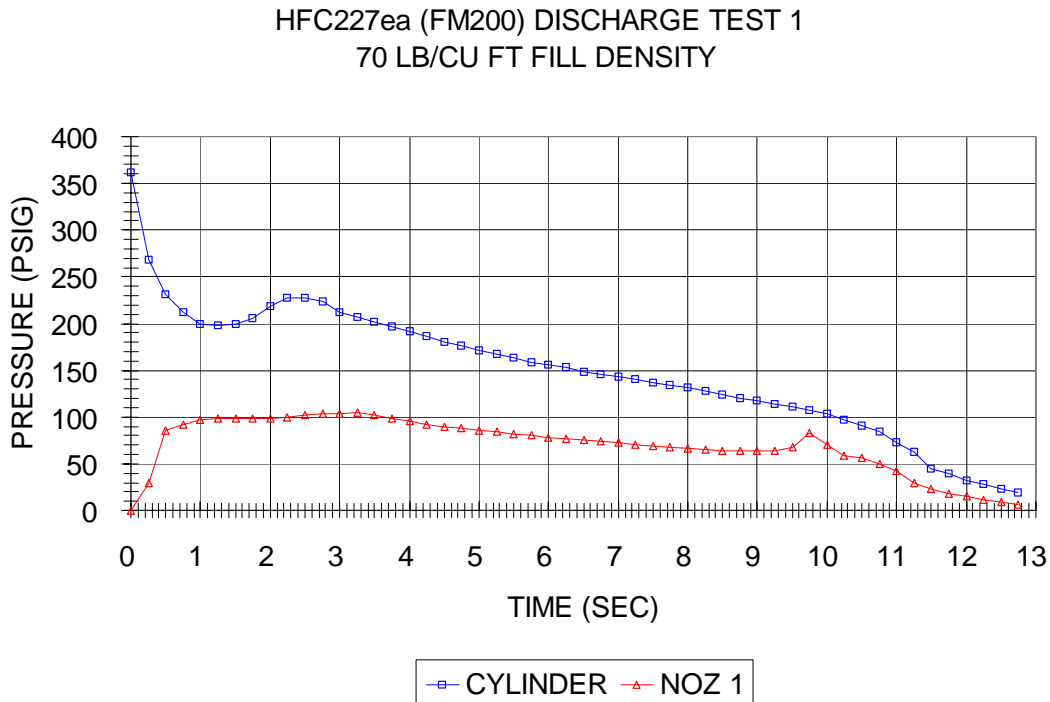
This pressure versus time tracing taken during a FM200 discharge shows the continual variation in cylinder pressure and a lesser variation in pressure at the

nozzle during the course of discharge. The peak in the nozzle pressure trace at 9.6 seconds indicates a change from two-phase flow to vapor flow.

Both the theoretical and experimental data indicate that pressure in the storage cylinder will vary considerably from the start of discharge until the end. Two basic approaches were considered and tested for calculating the essential hydraulic parameters of flow rate and pressure drop. One approach is to do multiple calculations for increments of agent leaving the cylinder. Any number of increments could be chosen -- for example, a calculation could be done for each 10% increment to leave the cylinder. The other approach is to work toward an "average" condition during the discharge and do a single calculation based on the "average" condition.

Intuitively one would expect that doing multiple calculations for increments leaving the cylinder would yield more accurate results. This is true for relatively simple systems -- yet for simple systems, the accuracy achieved by doing a single calculation is extremely good -- much better than that required by the ANSI standard. For complex systems, involving unbalanced flow splits at tees, a difficulty with any theoretical approach surfaces -- and this difficulty obviates any advantage in the accuracy which might be gained by the multiple increment approach.

PIPELINE PRESSURE AND AGENT DENSITY   In determining a single point in the discharge which approximates an overall "average" condition of flow, consider that in a well designed system the conditions at the discharge nozzle will control the agent flow rate. A good "average" condition would be approximated by the "mid discharge" condition at the nozzles. Neglecting initial transient conditions, the "mid discharge" condition will be the point in time at which ½ of the agent has been discharged from the nozzle.

The reference point on the cylinder pressure recession curve for the mid discharge condition will vary depending on the amount of agent which the pipeline contains.

FM200 CYLINDER PRESSURE RECESSION 70 LB/CU FT FILL DENSITY
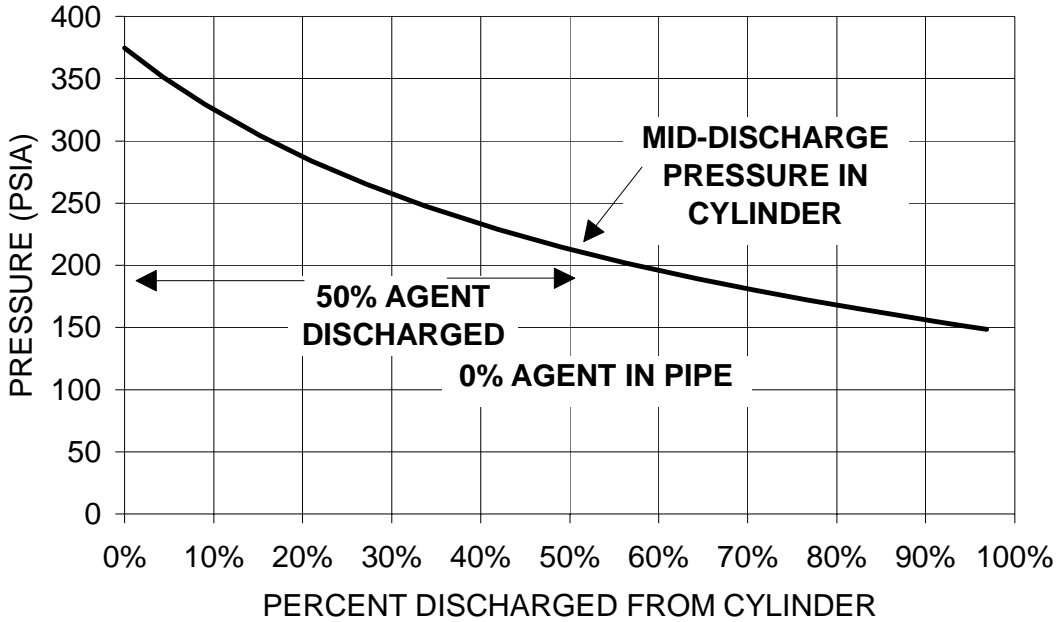
If the discharge nozzle is close coupled to the storage cylinder outlet, the pipe will hold "zero" agent during discharge. 50% of the agent will have left the nozzle basically when 50% of the agent leave the cylinder. This graph shows "mid discharge" storage cylinder pressure for such an arrangement..

### FM200 CYLINDER PRESSURE RECESSION 70 LB/CU FT FILL DENSITY
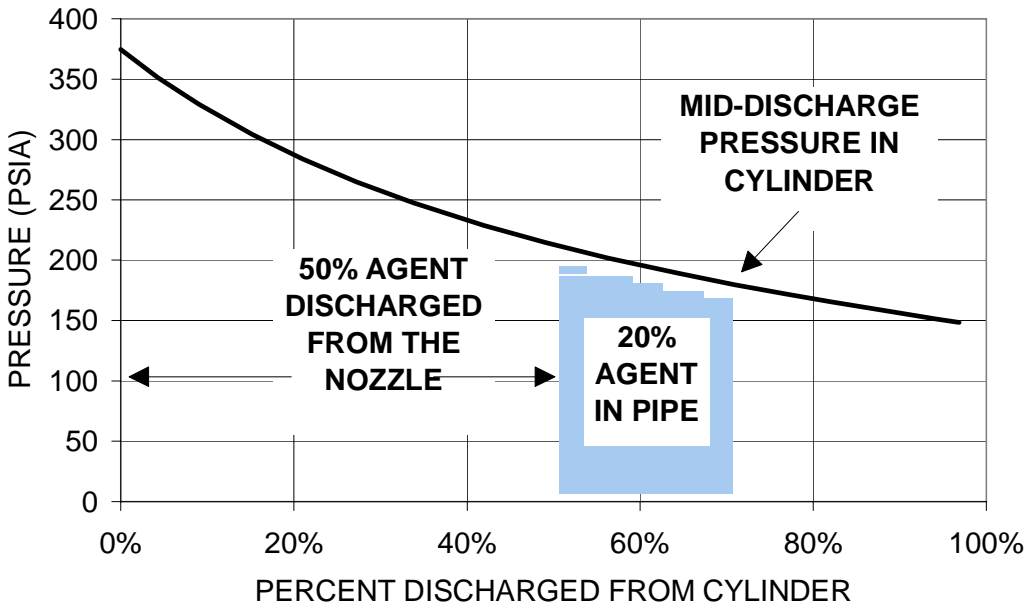
Most often there will be considerable pipe between the cylinder outlet and the discharge nozzles. The graph shows the "mid discharge" condition for a system where the pipeline holds 20% by weight of the agent under flowing conditions. 50% will have left the nozzle at the point in time when 70% of the agent has left the storage container.

PIPELINE DENSITY

For very rapid discharges and relatively short pipelines, heat exchange between the flowing agent and the pipe is usually negligible. An exception might be the initial increment of cold liquid flowing into a relatively warm pipe. The initial increments are often vaporized before they reach the discharge nozzle. Once the initial flow of agent has cooled the pipe, relatively little heat will be exchanged between the agent and its surroundings. For purposes of calculating density as a function of pressure in the pipe, we can assume no heat exchange or a constant enthalpy condition of the saturated agent.

PIPELINE DENSITY VS PRESSURE
NITROGEN SUPERPRESSURIZED FM200 60 LB/CU FT FILL DENSITY
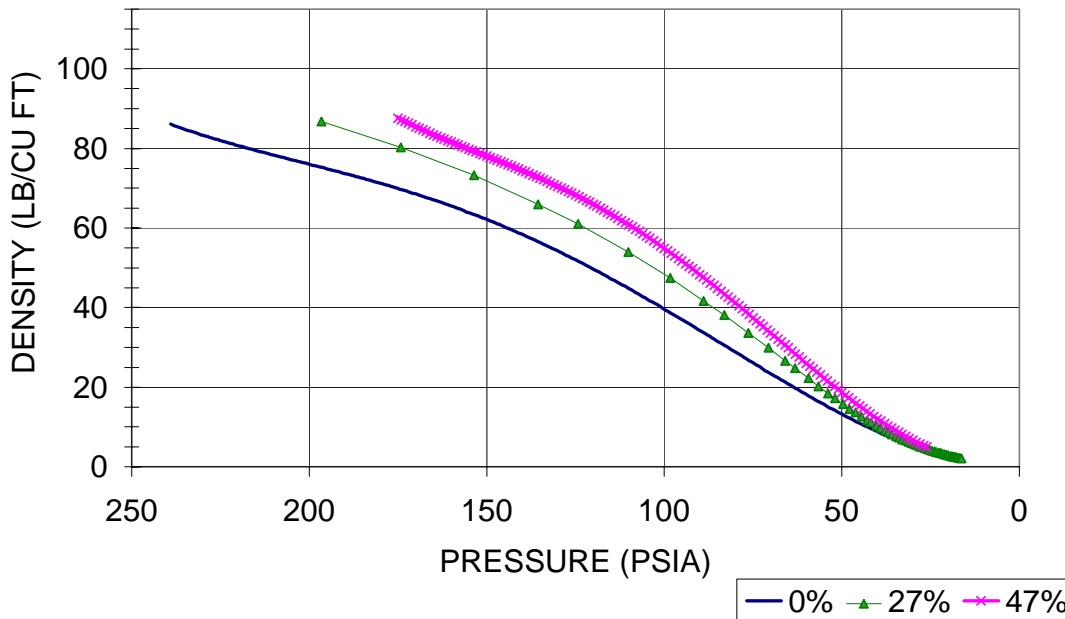
The graph shows theoretical agent densities in the pipe for FM200 (HFC227ea) based on constant enthalpy conditions. The calculation is shown for systems containing "0%" (close coupled nozzle cylinder), 27% and 47% of the agent in the pipe.

CORRELATION OF PRESSURE DROP CALCULATION WITH EXPERIMENT

PRESSURE DROP VERIFICATION HFC227ea (FM200)
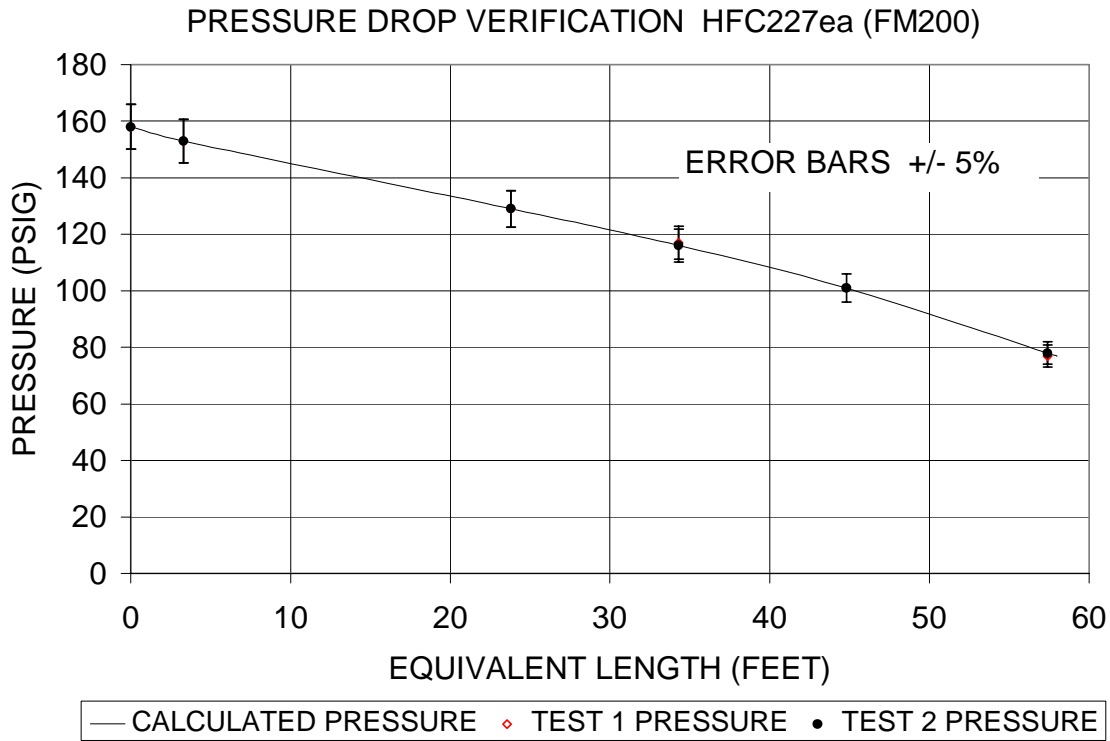
Experimental verification of the pressure drop predicted using the constant enthalpy assumption for density has been done for many agents. The figure shows the results for two test done with FE13. The system consisted of 60 equivalent feet of ½" pipe. Agreement of calculated and experimentally measured pressure and discharge time was excellent. The ANSI Standard which United States approval and testing laboratories apply to such flow calculations requires that predicted nozzle pressures be within 10% of measured nozzle pressures at the specified design reference point. Test results for single nozzle and balanced systems typically agree to within 5% for the liquefied compressed gases tested.

ADDITIONAL THEORETICAL CONSIDERATIONS The example we have seen is typical of the correlation between calculated and predicted pressures for single nozzle systems. More complex systems can be accurately calculated with additional theoretical considerations.   The following must be considered:

Flow regime -- turbulent, laminar, transition zone flow
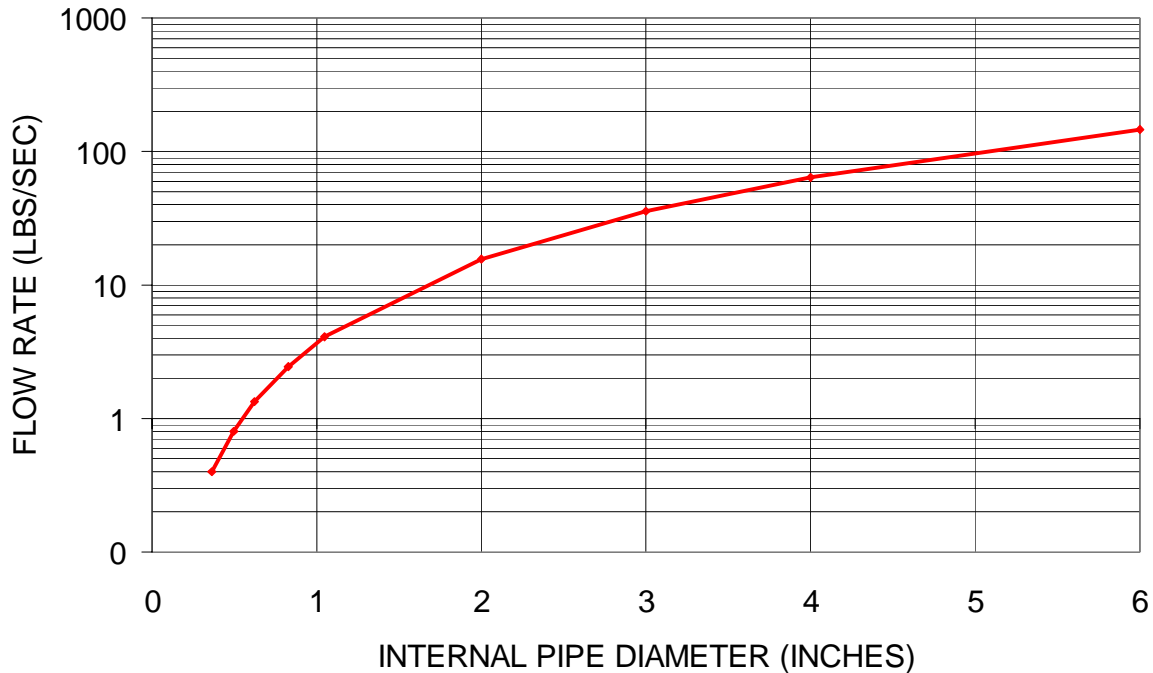
Velocity changes

Transient conditions

TURBULENCE   When using the Williamson/Hesson method for pressure drop calculation, it is important to maintain flow densities which will result in a fully turbulent mixture of the liquid and vapor phases of the agent as it flows through the pipe. The Moody friction factor varies with Reynolds number until flow reaches a fully turbulent state. For flow densities above the fully turbulent threshold, the Moody friction factor becomes a constant.

Although it is possible to vary the friction factor in the calculation with Reynolds number, there are a number of practical difficulties in system performance which occur at low flow densities. The major difficulty is unpredictable liquid-vapor phase separation when flow splits at tee junctions.

FE13 MINIMUM FLOW RATE FOR COMPLETE TURBULENCE

The graph shows theoretical minimum flow rates for FE13 to give complete turbulence.

VELOCITY CHANGES Conversions of energy between static pressure head and velocity head must be calculated when flow density (lbs./sec./cross sectional area of pipe) changes.

TRANSIENTS Transient effects such as compensation for initial heat entry into the agent and time delays for the agent to travel from cylinder outlet to various nozzles in the system must be considered. If systems are unbalanced, additional considerations must be made for transient conditions which occurs as the last increment of liquid agent leaves the cylinder and the trailing vapor expands into the

pipe. All of these considerations can be made on the basis of standard thermodynamic and hydraulic theory. All of these consideration must likewise be done if a multiple increment approach to pressure drop calculation is used.

MECHANICAL EFFECTS A phenomenon which has been noted for various multi-phase flow regimes is that of "mechanical" separation of phases which occurs when flow changes direction. As a mixture of heavier particles or liquid drops and lighter vapor moves into a bend in a pipe, the heavy particles because of their greater inertia tend to continue in a straight line toward the outer radius of the bend. Assuming turbulent flow and that the flow stream is not split near the outlet of the bend, any phase separation quickly is eliminated and the density of the flowing mixture behaves essentially as predicted by thermodynamics.

"Mechanical" Effects on Density

Flow direction

Liquid droplet
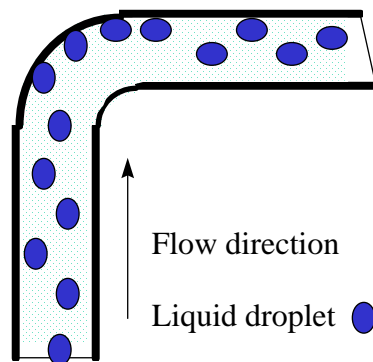
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Although this potential was recognized as a possibility for agents such as CO_2 compensation for the effect was not considered necessary. In 1973, Williamson and Wysocki documented the effect for Halon 1301. They developed empirical corrections to produce more accurate calculations of pressure drop and quantity of agent discharged from nozzles.

In recent work on unbalanced system calculations with HFC227ea, the effect was again noted.

When liquid and vapor mechanically separate at a tee junction, the density just downstream of the tee departs from the density predicted by thermodynamics. All pressure drop and flow downstream of the tee is affected by this density change.

BULLHEAD TEE
"Mechanical" Effects on Density
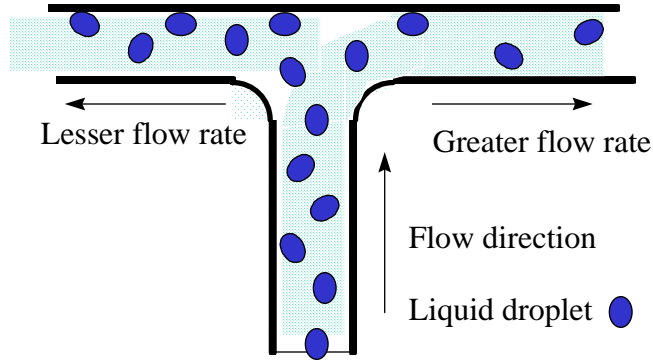
For a bull head tee configuration more liquid tends to flow into the outlet branch carrying the lesser flow rate.

BULL HEAD TEE TESTS
NO CORRECTION FOR MECHANICAL SEPARATION EFFECT
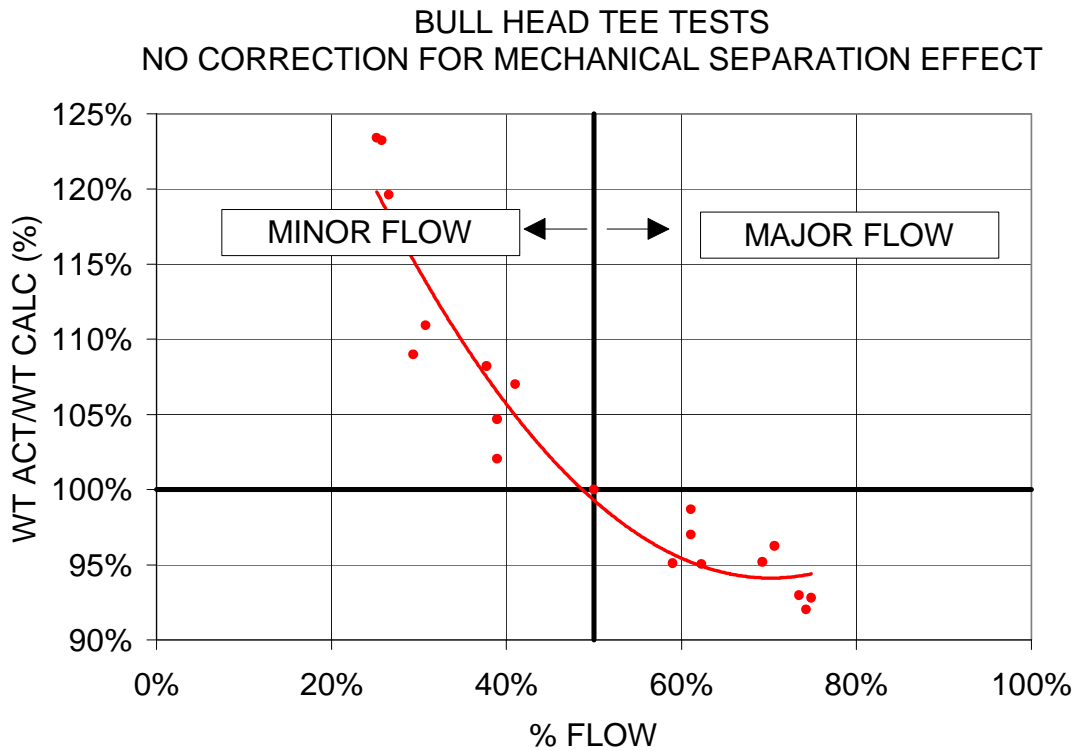
Since the density entering the minor flow branch is greater than that predicted by

thermodynamics, the flow rate from nozzles supplied by that branch tends to be higher than predicted by standard theory.

A large amount of the error introduced can be eliminated by empirically based corrections to the density downstream of the tee. The empirical correction factors tend to be complex. The amount of density variation introduced at a tee junction depends on

1. the velocity of the agent entering the tee

2. the ratio of flow exiting each branch of the tee

3. the relative amounts of liquid and vapor which enter the tee.

4. a degree of randomness inherent in the phenomenon.

Nonetheless, use of carefully developed empirical corrections permit calculation of some very complex systems with accuracy which is within the limits required by the listing and approval agencies.

DENSITY CORRECTION AT BULL HEAD TEE
30% MINOR FLOW 70% MAJOR FLOW
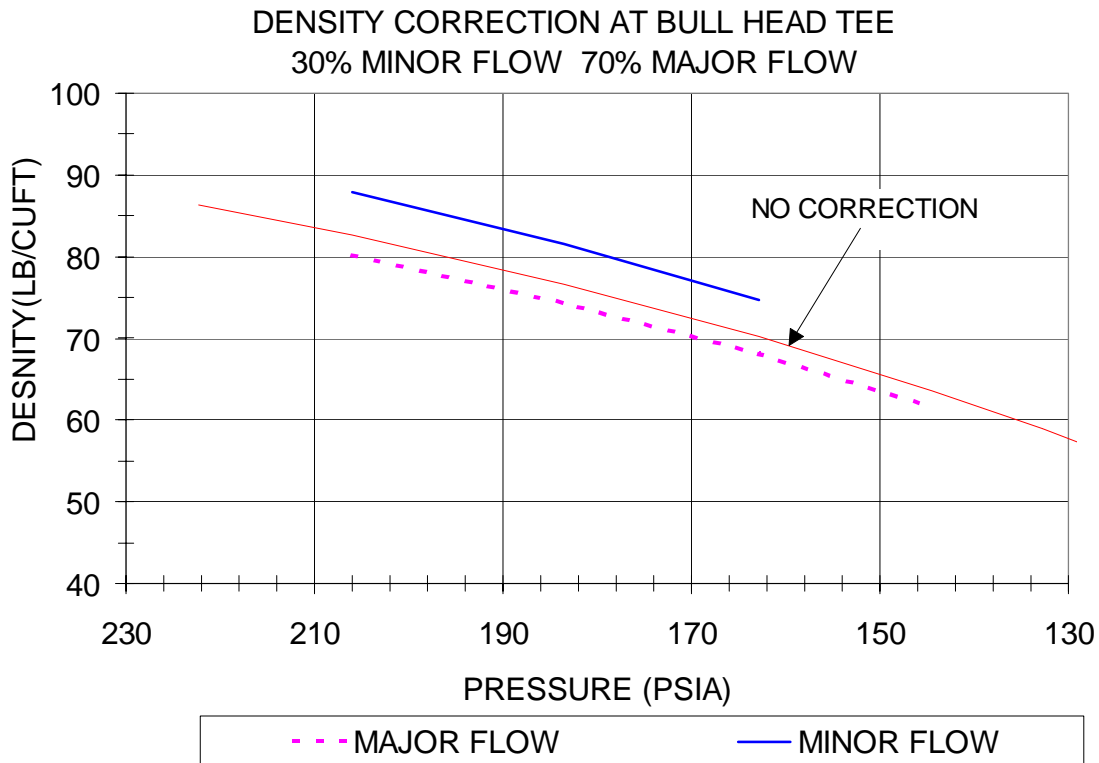
This graph shows a typical correction to the density exiting a bull head tee. The density in the branch carrying the "Minor Flow" becomes greater than the theoretical density. The "Major Flow" branch density is commensurately decreased.

BULL HEAD TEE TESTS HFC227ea
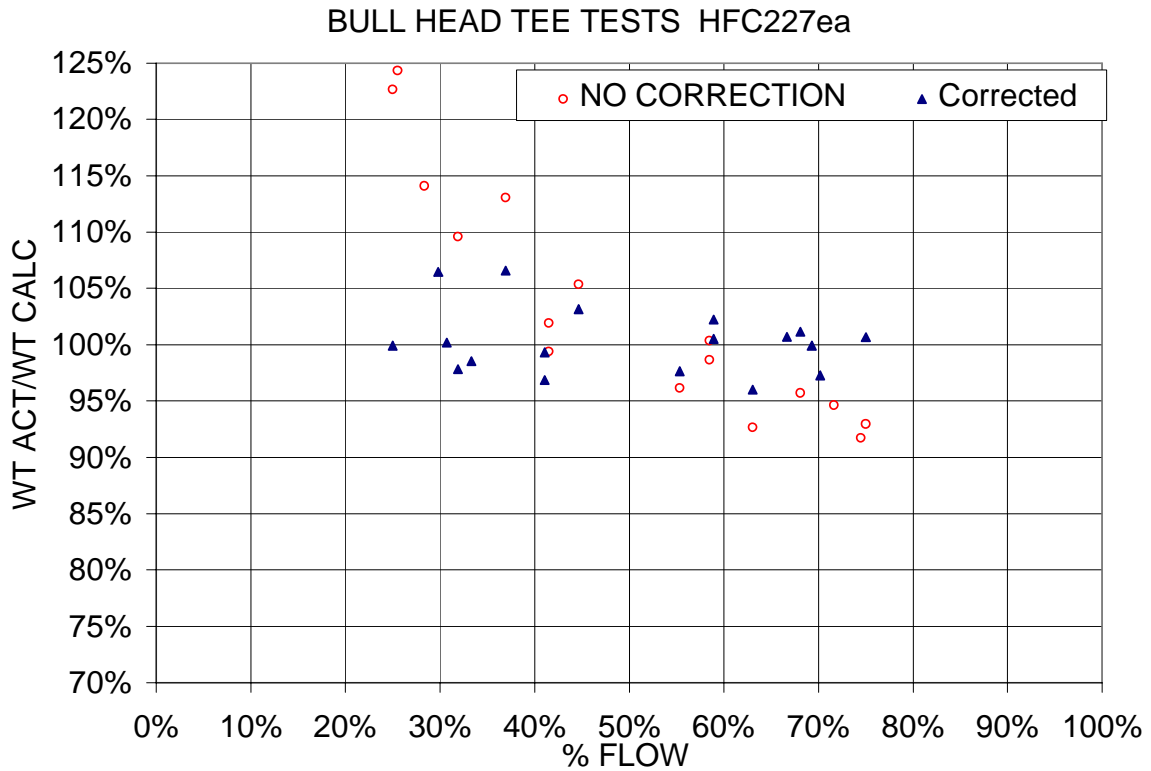
And this curve illustrates the effect of the density correction on the predicted quantity discharged from nozzle fed from a bull head tee.

The same phenomenon is apparent at "side-thru" tee junctions. Side-thru tee tests were conducted with the side branch receiving from 9% to 37% of the incoming flow. Over the range of splits which was tested, the side branch received a higher proportion of vapor than the thru branch.
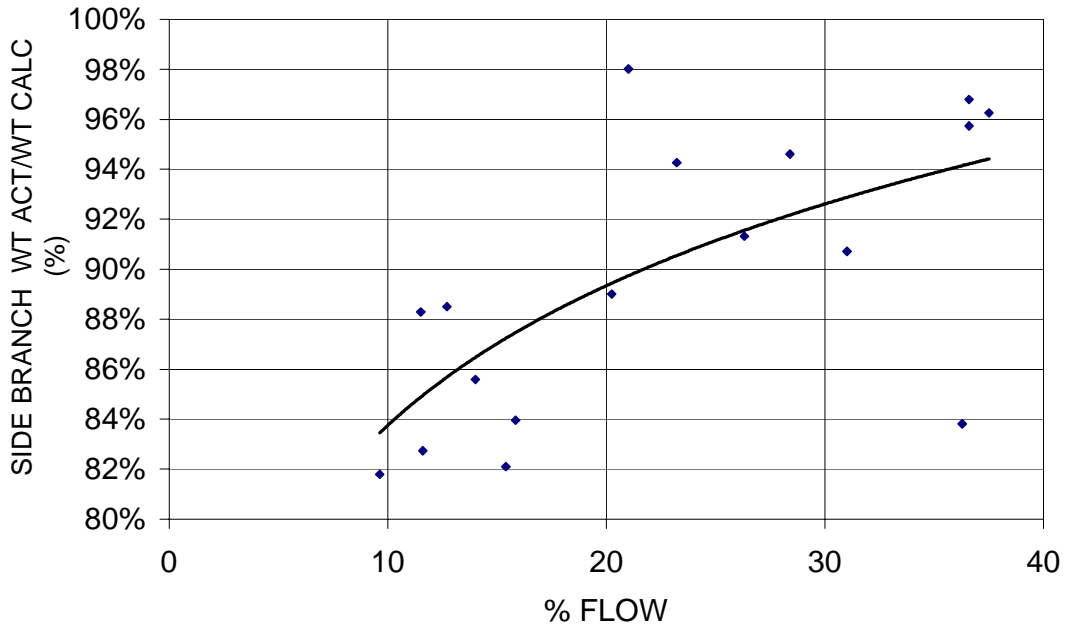
SIDE-THRU TEE
# "Mechanical" Effects on Density
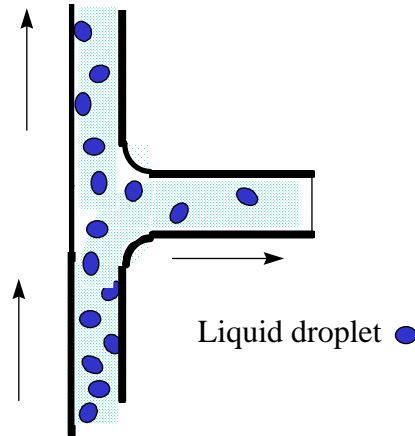
Liquid droplet ●

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The heavier liquid droplets tend to pass straight through the tee producing a density in the through branch greater than the thermodynamically predicted density. The side branch density is less than the thermodynamically predicted density.

HFC227ea SIDE-THRU TEE TESTS
EFFECT OF MECHANICAL PHASE SEPARATION ON SIDE
BRANCH DISCHARGE

The graph shows the deviation of predicted quantities from measured quantities discharged from nozzles fed from the side branch of a side-thru tee. These calculations were done using the thermodynamically predicted densities.

The density deviations resulting from flow splits at side-thru tees appear to have a greater random component than those exhibited at bull head tees. As such, the effects of predictable variables at a side-thru tee must be rigorously addressed if the required degree of accuracy is to be attained.

HFC227ea SIDE-THRU TEE TESTS
EFFECT OF DENSITY CORRECTION ON SIDE BRANCH
DISCHARGE
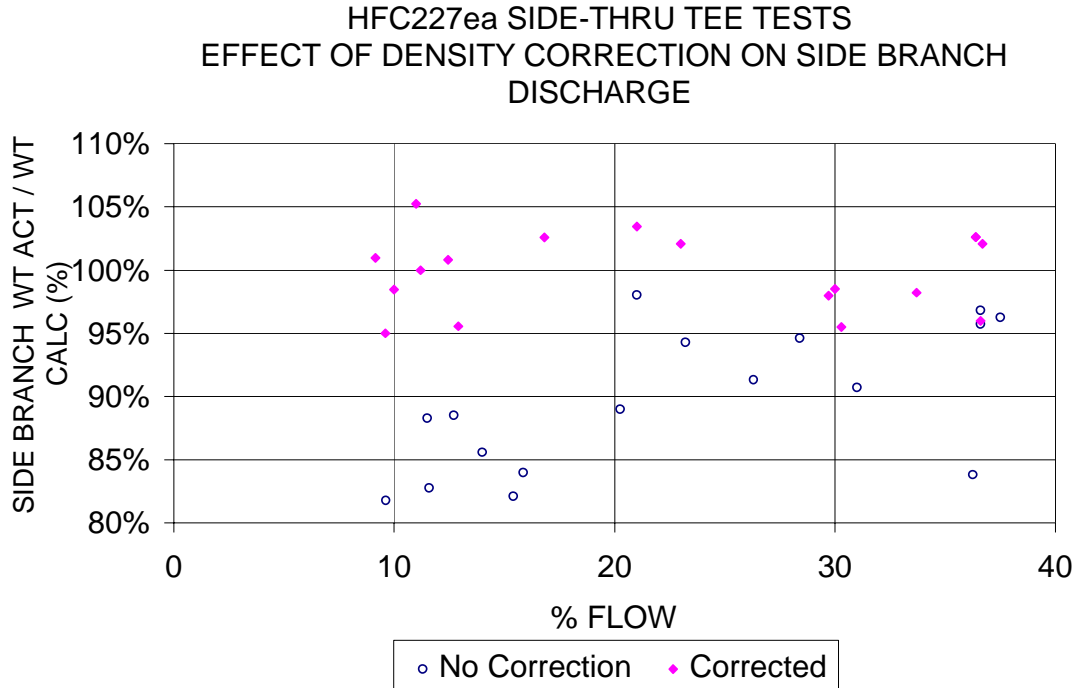
The empirical correction brings the predicted quantities within 5% of the experimental measurements for nozzles fed from the side outlet of the side-thru tee.

PRACTICAL LIMITS

There are some practical limits, not yet fully explored, that affect the predictability of flow. Some examples follow:

The relative roughness of pipe can vary considerably. During testing of single nozzle HFC227ea systems, flow through new ¾" black steel A53 pipe gave pressure drops 15% greater than predicted. The inside of the pipe was found to be unusually rough to the touch. The system was reinstalled using A53 pipe from a different manufacturer -- predicted pressures matched measured pressures within +/- 2 PSI.

Burrs on the inlet of a nozzle orifice have been shown to reduce flow as much as 10% from the affected nozzle. Nozzle orifices drilled by conventional means may have variations in diameter of 5% from the nominal size.

Such physical characteristics can be controlled in laboratory testing. Rarely, if ever, are such characteristics controlled or even considered in the field.   If a deviation in pipe roughness or nozzle orifice diameter is missed when constructing a laboratory system, it may be costly and inconvenient.   A similar deviation in a field installation could have more serious consequences.

The capability of calculating complex systems with flow calculation methodology such as we have discussed is admirable and should be considered a "safety factor." In field installations, pipe should be kept as simple as possible. If multiple enclosures must be flooded simultaneously, it is best done with dedicated agent storage and discharge pipe networks. There are too many uncontrolled physical variables in field installations to make simultaneous flooding of multiple enclosures from a single, complex, unbalanced pipe system advisable -- regardless of what flow calculation method is used.

In conclusion, the "two-phase" flow equation derived by James Hesson in the early 1950's still is quite useful for predicting pressure and flow in fire systems. The laws of energy conservation have not changed. The enhancements developed by Vic Williamson in the 1970's for Halon 1301 flow calculations can be successfully applied to the Halon alternatives. Single point calculations can provide the accuracy needed for practical design.