FM-200™ Suppression Systems: **A** Conservative Discharge Test **Method** and In-Room Pressure Variance **Upon** Discharge

by

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Abstract

Total flooding fire protection systems employing FM-200 will; in many cases, serve as the preferred substitute technology where systems based on Halon 1301 would have been previously specified. State of the art fluid dynamic modelling techniques have been brought to bear in developing new piping system design routines which are able to predict nozzle pressures and flow rates with the accuracy required to meet listing and approval standards. Substantial numbers of discharge tests have been conducted to provide the necessary validation data for a wide variety of simulated system conditions. **A** discharge test methodology has been developed which permits direct and unambiguous verification of agent flow splits in complex agent distribution networks. The basis of the method is direct agent collection and weighing. Weight accuracy of 98% is achieved in accounting for agent assuring a highly reliable nozzle-to-nozzle and overall analysis. Further, a simple and economic technique has been developed for agent recycle. Agent recovery efficiency is at least **84%** thus avoiding unnecessary emission of a chemical with an atmospheric lifetime of 31 years to the atmosphere. While the system designs resulting from the new computational techniques are the best possible, given the state of current technology, it is likely that discharge testing will be desired in some cases to provide a higher level of assurance that design criteria have been met. Thus, the method described would have clear economic benefits while offering an environmentally responsible method of validating system designs.

The minimum design requirements for total flooding fire protection systems employing new clean agents are set forth in NFPA-2001[1] in a manner analogous to those defined for Halon 1301 in NFPA 12a[2]. The lower fire extinguishing efficiency of all halon replacement agents has necessitated that substantially larger quantities of agent be employed relative to halon. In the case of the discharge of any of the halogenated agents, all of which are essentially refrigerants, there are complex variations in the temperature and pressure profiles in the room environment[3].

The pressure effects in particular are highly time variant and have a direct impact on the actual room-average and localized agent-air ratios during the critical fire extinguishing period. These effects have been analyzed from a theoretical stand point using thermodynamic, heat transfer, and fluid dynamic consideration which were confirmed by numerous observations made during discharge tests of FM-200. That is, there occurs in a tight protected room pressure swings which would tend initially to cause intrusion of air during and immediately subsequent to the completion of agent discharge. Heat transfer from the surroundings leads to pressure rise and eventually to development of a net positive differential pressure relative to the exterior environment and agent-air out-gassing. The effects of "room breathing" during the discharge period include formation of agent-air mixtures on a localized basis which may be substantially off-average. Careful analysis of these effects can serve as a basis for design adjustments in critical applications to improve system reliability.

Part I. In-Room Pressure Variance Upon Discharge

Upon discharge of a gaseous fire extinguishing agent into a room there will occur changes in average air temperature and pressure. The magnitude and rate of change of variations in T and P will depend on the amount, thermodynamic properties and rate of delivery of the stored agent, the dimensions of the room, its contents, and size of leakage area to the outside. The simplified analysis given herein considers two limiting conditions, an estimate of the dynamic aspect of the situation, and a look at some full-scale pressure response data obtained on discharge of an FM-200 system into a 1200 ft^3 enclosure.

Case **1.** Equilibrium Discharge into a Tight Enclosure: Maximum Pressure Potential

This case considers the maximum pressure developed in a tight enclosure on discharge of an FM-200 total flooding system Consider the the following example:

Room volume = 1200 ft^3
Temperature = 70°F = 294.1 K
Pressure = **14.7** psia
FM-200 concentration = C = 7 vol%
Agent specific volume = 2.2075 ft^3/lb at 70"F
Cylinder fill density = 70 lb/ft^3
Cylinder volume = 0.585 ft^3 = 0.0165 m^3
Pipe: 20 ft 3/4" Sch. 40 steel. Internal volume = 0 **074** ft^3 = 0.0021 m^3
Total system volume after discharge = 1200 66 ft^3 = 34 00 m^3
The agent quantity is calculated as W = (V/S) C/(100-C) = 10.9 lb = I09 **3** mol
Quantity of nitrogen (typical) used to pressurize agent is 0 097 mol N_2/mol FM-200 = 10.6 mol
Quantity of air initially in room = PV/RT = 1408 6 mol
Total mols gas after discharge = 1528 5 mol
The pressure attained in the closed system is then P = nRT/V = 15 95 psia = 1.25 psig

Values of equilibrium pressure as a function of delivered agent concentration are shown in Figure 1. These values may be well above the strength of normal room construction. Therefore, a room so protected must be able to leak gas to the ambient in order to avoid damage. The key factor here is that the leak characteristics of the protected volume must be designed in such a way as to maintain agent at the design concentration but permit pressure relief

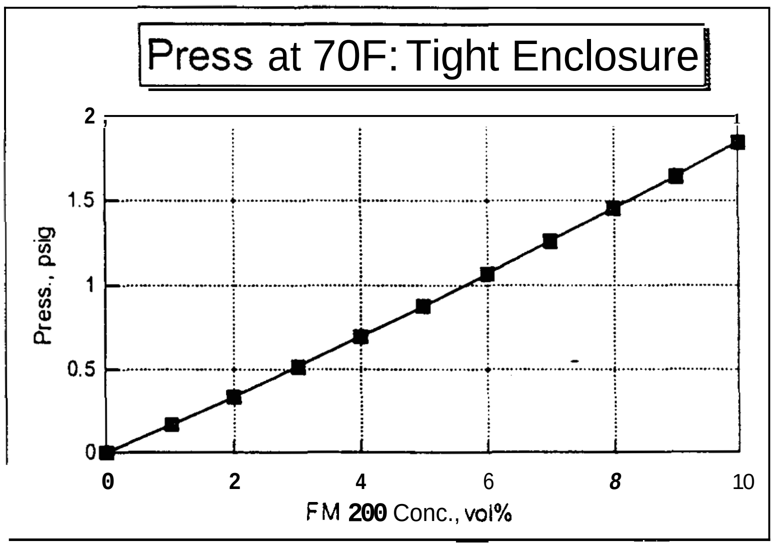

Figure 1. Pressure attained in a tight enclosure as a fbnction of added gas concentration at 70°F.

Case 2. Adiabatic Discharge to a Control Volume: Minimum Pressure Potential

A lower bound for possible temperature and pressure attainment in an enclosure is calculated by adiabatically expanding the agent into the enclosure air. The constant-enthalpy process results in a temperature reduction as the agent liquid evaporates at the lower room pressure. The relevant energy balance is

$$m\,h_l = m\,h_v + M\,C_A\,(T_1 - T_2) \qquad \text{where} \qquad (1)$$

m = amount of agent, kg
h_l = enthalpy of saturated liquid agent in the bottle at T_1, 61,094 J/kg at 70F (**294.4** K)
h_v = FM-200 vapor enthalpy = $h_0 + h_1 T$ over the temperature range of interest
= $-46{,}451 + 789.82\,T$, J/kg where temperature is in Kelvin
M = amount of air initially in the enclosure, kg
C_A = specific heat of air, ~1000 J/kg/K
T_1, T_2 = initial and final temperatures, K

See reference **4** for thermodynamic data for FM-200. The effect predicted by the adiabatic expansion of agent into air initially at 70" F (294.4 K) is shown in Figure 2. For all agent amounts

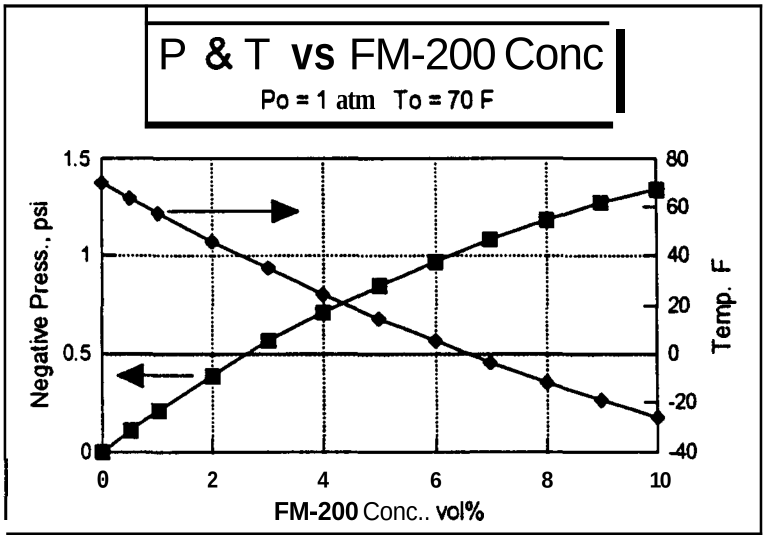

Figure 2 Temperature and pressure minima upon discharge to room with no heat absorbed from walls, contents, tec.

greater than zero the room pressure and temperature drop. The minimum pressure, if achieved, would cause many structures to suffer implosion damage. The actual state of affairs lies in between. Heat is transferred fiom the warmer walls (and objects in the room) to the cooled room air at a rate dependent on the room air temperature and the governing heat transfer coefficients. The latter is a time dependent function dictated by the state of turbulence in the room.

Case 3. Dynamic Analysis: Heat Transfer During and After Discharge

Upon discharge of an actual system in a tight enclosure the temperature and pressure behaviors will lie between the equilibrium and adiabatic limits of Cases 1 and 2. *An* enthalpy balance, Eq. 2, on the enclosure includes enthalpy addition by the delivered agent and by heat transfer to the cooled air from the warmer walls and enthalpy accumulation in the room air by temperature change. A dynamic analysis was made using the following simplifying assumptions:

1. The rate of agent delivery, w, is constant during the period of liquid phase delivery, $0 < t < t_L$
2. Bottle gas blow down occurs during the period $t_L < t < t_G$
3. The overall heat transfer coefficient, U, has a constant value during liquid delivery and has a decaying value for $t > t_L$.
4. The floor, walls, and ceiling remain at the initial temperature, T_o.

$$w\,h_L + UA(T_o - T) = d(mh_V)/dt + MC_v\,dT/dt \quad \text{where} \qquad (2)$$

w = agent delivery rate, kg/s
U = overall heat transfer coefficient, $J/m^2/s/K$
A = heat transfer area, m^2, and other terms are as previously defined

Eq.2 is solved as follows.

a. $0 < t < t_L$

The average air temperature is

$$T = \{ (b_o + b_1 t)^{-1/\alpha} - a, \}/ a, \quad \text{where} \qquad (3)$$

$a, =$ $w (h, -h_o) + UA\ T_o$
$a, =$ $- (w\ h, + UA)$
$b_o =$ $w (h_L - (h, + h_1 T_o)$
$b, =$ $b_o\ w\ h, / MC,$
$\alpha =$ $w\ h, /(w\ h, + UA)$

The value of U during this period was taken as constant and selected to give the best match between the calculated and observed minimum pressure in the actual test shown in Figure 3.

b. $t > t_L$

The value of U was taken as variable, decreasing, during the period $t > t_L$. Logic here is that during the blow down of the agent cylinder the turbulence intensity in the room decreases leading to a decrease in U. During this period U(t) was modelled as

$$U(t) = U_{LAMINAR} + U_{TURB}(t) = U_{LAMINAR} + U_{TURB,0} \cdot \exp(-\lambda \{t - t_L\}) \qquad (4)$$

The values of $U_{LAMINAR}$, $U_{TURB,0}$ and λ were taken to give the best fit to the observed P-t behavior after the end of liquid discharge.

For w = 0 Eq. **2** becomes

$$UA(T_o - T) = (m_R h_l + M\ C_A) dT/dt \quad \text{where} \qquad (5)$$

m_R = total amount of agent added to the room

The solution of (5) is

$$T = T_o - (T_o - T_{ELD}) \exp(-\beta t) \quad \text{where} \qquad (6)$$

T_{ELD} = room temperature at end of liquid discharge
$\beta = UA / (m_R h_l + M\ C,)$

A central, and unknown, factor in this analysis is the value of the overall heat transfer coefficient, U. Its magnitude can be estimated for the case of a quiescent environment. Also, an upper bound can be estimated based on assumptions of the mean air velocity swirling around an enclosure during agent discharge.

Shown in Figure 3 is a pressure-time profile measured during a closed-room discharge using sufficientFM-200 to attain a 5.9 vol% concentration. The room, as designed, was nominally leak free against negative pressure but a one-way vent arrangement opened when the internal pressure exceeded ambient allowing the room to "exhale". Thus, this pressure experiment ended when ambient pressure was attained. Also shown in Figure 3 is an estimate of the P-t behavior obtained using Eq. 3 for $t < t_l = 9.4$ s ($U = 7.4$ J/m²/K/s) and Eq. 4 values of $U_{LAMINAR}$, $U_{TURB,0}$ and λ of 0.6, 6.5, and 0.5, respectively.

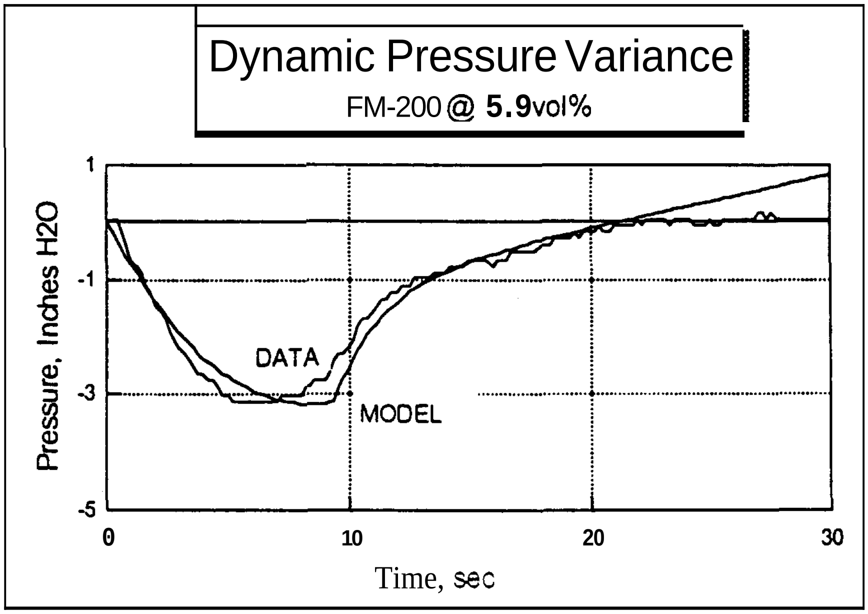

Figure 3 Actual and estimated pressure-time behavior in a tight 1200 **ft3** room upon FM-200 discharge to yield 5.9 vol%.

Both the qualitative and quantitative P-t behavior is modelled with good agreement to the observed result using values of U quite close to an a priori estimate[5,6] of 10 J/m²/K/s. In particular, the minimum pressure and the time at which the room pressure goes positive are in good agreement with test results.

These results are based on the use of empirically fitted constants. Nonetheless, the model should be useful in estimating P-t behaviors at other operating conditions. Calculations were performed at several delivered agent concentrations the results being shown in Figure 4. Liquid discharge time was held at 9.4 s in each case.

Useful insights can be gained from the foregoing analysis. Heat transfer is fast enough that full droplet agent vaporization is assured even at high delivered concentrations. Pressure reductions during and just after discharge are relatively modest compared to the adiabatic case. In a room with internal objects heat transfer would be expected to be faster leading to even lower net pressure fluctuations.

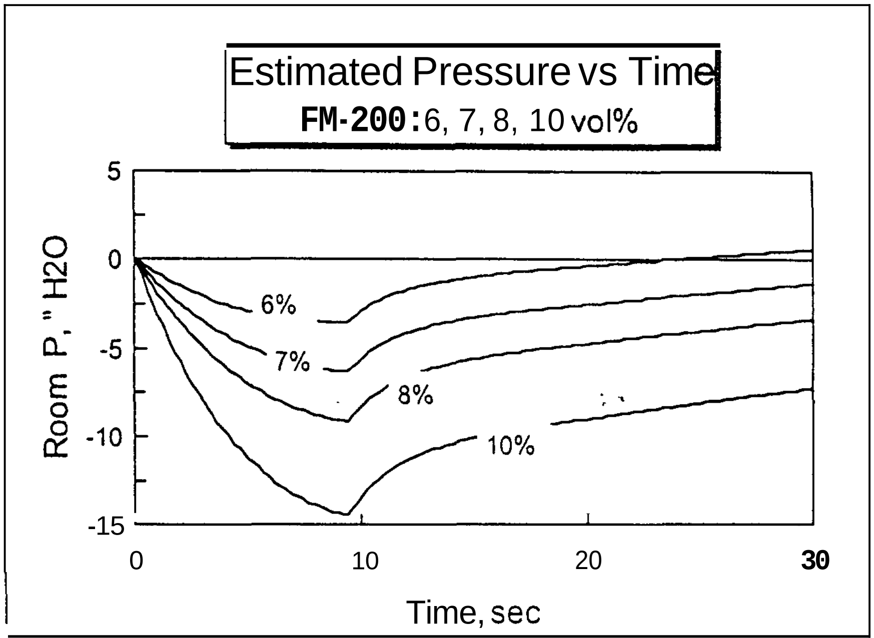

Figure 4 Estimates of P-t behavior in a tight 1200 ft3 room vs FM-200 concentration.

Part B: A Conservative Discharge Test Method of FM-200 Systems

Extensive fluid dynamic studies of transient two phase flow of FM-200 are the result of a non-polluting method with vapor recovery. It has enabled us to study the fluid mechanics of FM-200 with great precision, for reasonable cost, with minimal environmental impact. Kidde-Fenwal has conducted over 125 full scale discharge tests with multiple nozzle unbalanced systems to generate the precise data embedded in the engineered systems software. The savings in agent exceeds 20,000 pounds, and there has been a comparable reduction in release of agent to the atmosphere. Because the test method is economical we have been empowered to obtain test data covering virtually all combinations of system parameters, from largest to smallest cylinders. The very large data base assures Kidde Fenwal's customers of the highest levels of accuracy in calculating system performance. The test program is ongoing.

Elimination of Mixing in the Enclosure

The single basic requirement for the method to permit recovery of agent is that mixing of the FM-200 with air must be prevented during discharge. As a result, traditional methods of determining mass flows by concentration measurement are not useful, and it is not possible during flow distribution tests to observe mixing behavior of the nozzles It is, however, possible to measure the mass of agent which has flowed through each nozzle with high accuracy

Prior Practice

In prior laboratory test methods[1] actual wood frame enclosures were normally constructed, generally in three or more sizes. The accuracy of system calculations were verified by measurement of concentration of agent discharged into each of the enclosures using thermal conductivity instrumentation. The amount of agent was then back calculated from the total flooding factors given in **NFPA 12A**, Table A-3-5.1. Diluted in the enclosure air, the agent was then vented into the atmosphere. Enclosure leakage and thermodynamic effects introduced uncertainty into the measurements, and required scme assumptions about mixing. The new method provides direct measurement of agent mass discharged at each nozzle.

Before the environmental costs of Halon 1301 discharges were recognized, many installed systems were discharge tested in accordance with NFPA 12A Appendix A, paragraph A-4 -7 . The tests led to very direct observation of all aspects of the system, including mixing behavior of nozzles and enclosure integrity. The method eliminates the concerns of enclosure integrity or nozzle mixing and has been supplemented by separate nozzle and enclosure tests.

Method and Analysis

Capturing the Agent. Agent from each nozzle is collected in a large bag. Each nozzle is provided with a shroud to prevent direct impingement of the agent stream against the bag. The bag consists of 0.004 " thick polyethylene tubing which when flat is 48" wide, and is provided in a roll several hundred feet long. The bags are carefully identified and weighed prior to the test. Each bag is secured to the pipe with wire ties and closed at the opposite end. It is installed with care to minimize entrapment of air. The required length of bag is calculated using the quantity of agent to be collected and an FM-200 vapor specific volume of 2.2 cubic feet per pound. See reference 1, Table 3-5.1(e). During discharge no air is entrained by the stream of agent. Therefore the bag will contain, after discharge, all of the agent and the nitrogen with which it was super-pressurized plus the air which was in the piping through which it flowed.

After the discharge is complete the FM-200 in each bag will be composed of gas and boiling liquid. Since the FM-200 is not permitted to mix with air it is denied the heat ordinarily supplied by the air necessary for prompt vaporization. After a short wait to allow vaporization of the liquid by heat conduction through the bag fiom the floor and ambient air, the bags of gas are weighed on a special scale. It consisted of a 2.5' x 20' frame of aluminum pipe which was suspended fiom a load cell. The bags are cut into 20' lengths, much like sausages, and weighed in pieces. Careful record keeping of the weights of bag segments is required. The data are entered into a Microsoft Excel Spreadsheet where compensation for the buoyancy of air is made. Direct weight measurements have agreed with agent charge weights to an accuracy of better than 98% in our tests. It is our practice to apply a uniform buoyancy compensation factor to all weights.

Recovering FM-200. When weighing is complete, the bags are connected to the inlet of the vapor recovery system for the next step of the test process. The recovery system which we have used is simple, consisting of a compressor, condenser and a gas liquid separator with a level control valve. See Figure 5. The 5 hp oil-less gas compressor compresses about 2 pounds of FM-200 per minute. The condenser removes heat, cooling the gas nearly to ambient, causing most FM-200 to condense. A safety relief valve, SRV, is provided to protect the condenser. Nitrogen and FM-200 gas are drawn off at the separator to waste through a back pressure regulator, BPR. Liquid FM-200 is drawn off at the separator to a storage container through a level control valve, LCV. Suitable pressure and flow controls are provided

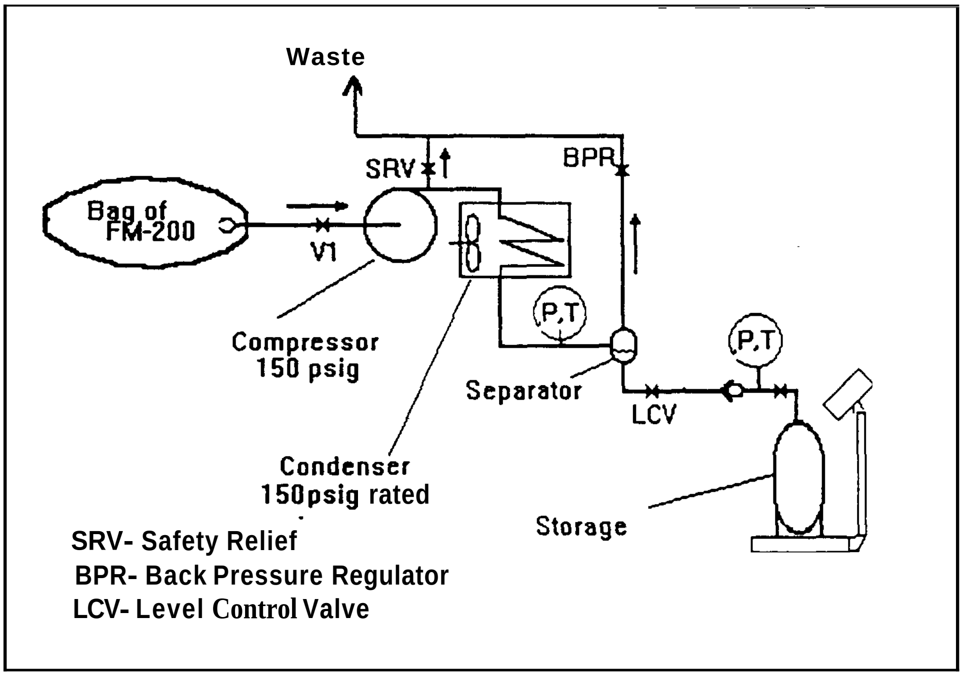

Figure 5. Schematic of single stage high pressure recovery unit.

Nitrogen Carried Away by FM-200. Because of the presence of the Nitrogen used for super-pressurization, not all of the FM-200 condenses. As nitrogen gas is removed at the liquid gas separator, it carries FM-200 vapor with it. The amount of loss of FM-200 is proportional to the total amounts of air entrained during discharge and of nitrogen used to super-pressurize the FM-200. The nitrogen added to pressurize cylinders of FM-200 has been carefully determined for the full range of fill density. It is maximum at low fill density. The amount of loss also depends on the temperature and pressure at the separator. The losses can be easily computed by applying Dalton's Law[8] and the ideal gas law to the waste gas stream, assuming perfect gases:

$P_{Total} = P_{FM\text{-}200\ Vap} + P_{N2}$ where

$P_{FM\text{-}200\ Vap}$ is the vapor pressure of FM-200
P_{N2} is the partial pressure of nitrogen.

Since $N_{FM\text{-}200} = P_{FM\text{-}200\ Vap} \bullet V/RT$, and

$$N_{N2} = P_{N2} \cdot V/RT$$

where N is the number of moles of FM-200 or nitrogen then

$$N_{FM\text{-}200} = N_{N2} \cdot P_{FM\text{-}200\,Vap} / (P_{Total} - P_{FM\text{-}200\,Vap})$$

The vapor pressure of FM-200 is given by Robin[9] as follows:

$$P_{FM\text{-}200\,Vap} = \exp(124.78 - 5672.2 / T + 0.02606\,T - 17.24\ln(T))$$

where P is in Pascals and T is in Kelvin.

The total amount of nitrogen present from super-pressurization, N_{N2}, was determined by test The results of the computation in customary units are shown in Figure 6. It can be seen that at moderate pressure (about 130 psia) good recovery is possible at 80F. Operating at 80 F permits use of ambient air for cooling the condenser, while the pressure is adequate for in-line transfer *to* an un-chilled storage cylinder without a pump. Using this method, it is feasible to recover about 84% at the worst case fill density of 30 lb./cubic foot. Recovery rates are much higher at high fill density when nitrogen content is reduced.

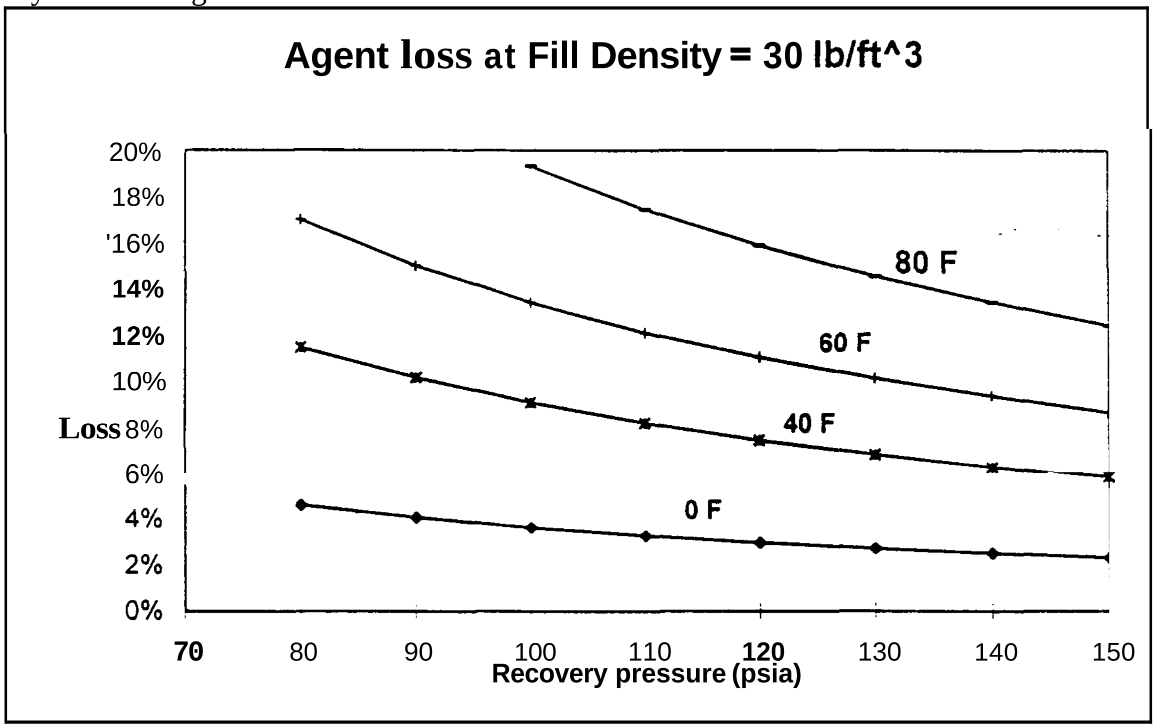

Figure 6. Agent loss as a hnction of recovery pressure and temperature

Contamination of Recovered Agent. There is a trade-off between recovery efficiency and nitrogen and other gases dissolved in the recovered agent. **At** higher pressure and lower temperature more FM-200 is recovered but the amount of gas dissolved in the agent increases. See Figure 7. Excessive nitrogen in the recovered agent causes some difficulties with handling and storage. A second stage recovery operating at lower temperature and pressure provided improvements in recovery but introduced equipment complexity, and is currently unused in our test program.

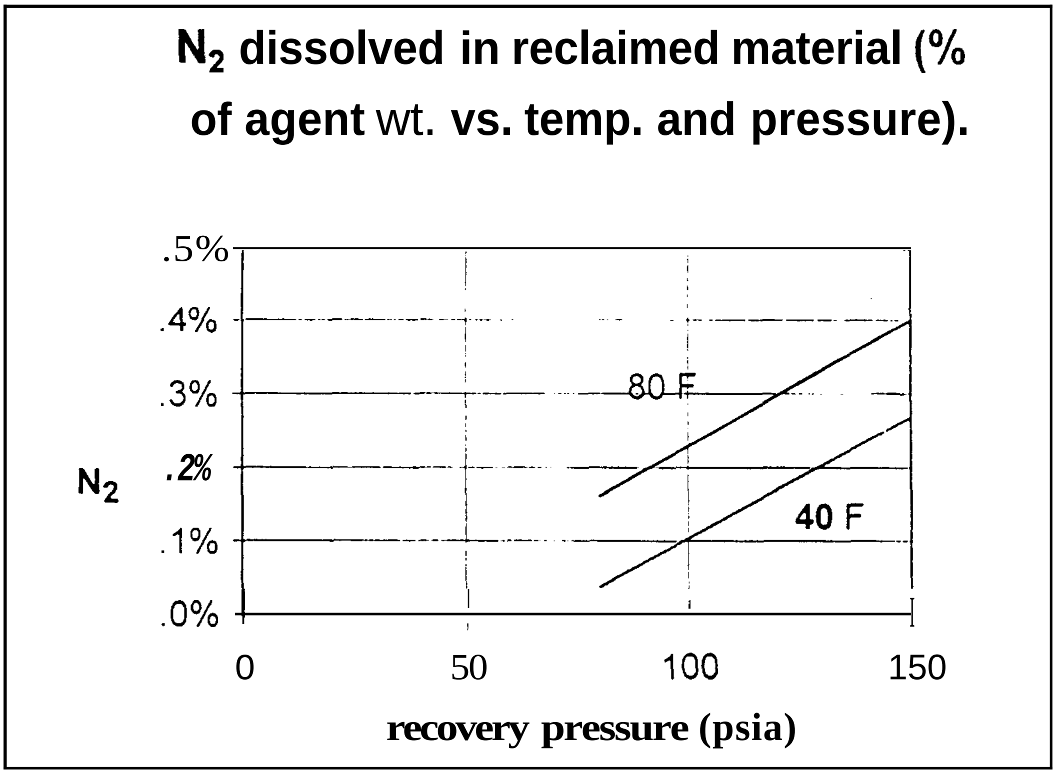

Figure 7. Dissolved nitrogen.

After recovery, the agent is contaminated with dissolved water, nitrogen, and oxygen present in the humid air found in the piping, and other volumes. However, non-volatiles and oils from the piping tend to remain in the bags which are discarded after use. Contaminated agent is not suitable for sale for fire protection. It is our practice to remove the water with a molecular sieve and to re-use the agent for flow testing only.

The use of the bag method of discharge testing has been limited to laboratory experiments in order to determine flow parameters of FM-200. It is apparent that the method offers a workable economical non-polluting opportunity for on site testing of total flooding systems. FM-200 thermodynamic properties are favorable for such tests. Improved second stage recovery would be useful to further reduce the amount of emissions and to further reduce cost.

Conclusions

1. The elementary heat transfer considerations have allowed reasonable estimates of dynamic temperature and pressure behaviors related to clean agent discharges into tight enclosures. Such analysis can be useful in critical design applications where temperature or pressure variations may be important.

2. **A** method for non-polluting and economical discharge tests has been developed for laboratory studies of FM-200 flow in unbalanced piping. **It** is economical, and provides simple direct measurement of the agent mass flowed through each nozzle. It eliminates uncertainties in prior test methods.

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10. *FM-200* is a trademark of the Great Lake Chemical Corporation, West LaFayette, IN 47906.