# HALON ALTERNATIVES: RECENT TECHNICAL PROGRESS

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## *ABSTRACT*

Recent progress in the development of Halon alternatives at Great Lakes Chemical Corporation is presented. Large scale fire test results are presented for the extinguishment of n-heptane pool fires by **FM-100** (bromodifluoromethane), **FM-200** (1,1,1,2,3,3,3-heptafluoro-propane) and **HFC-23** (trifluoromethane). Critical properties, vapor pressures, and liquid and vapor molar volumes have been measured for **FM-100** and **FM-200**, and the experimental data fit to the Carnahan-Starling-DeSantis (CSD) equation of state. Tables of saturation and superheated vapor properties are generated for FM-100 and **FM-200**, and pressure-enthalpy diagrams constructed for both agents. **A** complete set of thermodynamic properties is thus made available for use in the design of fire suppression systems employing these new agents.

## INTRODUCTION

Regulations on the production and use of the Halon fire suppression agents Halon 1301 (bromotrifluoromethane) and Halon **1211** (**bromochlorodifluoromethane**) have resulted in intensive efforts in both the industrial and academic sectors to find environmentally acceptable replacements for these agents.

**FM-100** (bromodifluoromethane) and **FM-200 (1,1,1,2,3,3,3-heptafluoropropane)** are environmentally superior fire suppression agents developed by Great Lakes Chemical Corporation [1,2]. **FM-200** has an ozone depletion potential (ODP) of zero, and hence presents no threat to the stratospheric ozone layer. **FM-100** is also an environmentally superior fire suppression agent, providing a greater than 90% reduction in ODP compared to Halon **1301. A** selection of properties of **FM-100** and **FM-200** of interest in fire suppression applications *are* summarized in Table 1.

## TABLE 1: PROPERTIES OF FIRE SUPPRESSION AGENTS

| | FM-100 | FM-200 | HALON 1301 | HALON 1211 |
|---|---|---|---|---|
| Chemical Formula | $CF_2HBr$ | $CF_3CHFCF_3$ | $CF_3Br$ | $CF_2BrCl$ |
| Molecular weight | 130.92 | 170.03 | 148.91 | 165.37 |
| Boiling point | 4.14 °F | 2.55 °F | -71.95 °F | 24.80 °F |
| | -15.48 °C | -16.36 °C | -57.75 °C | -4.00 °C |
| Melting point | -229 °F | -204 °F | -270 °F | -256.00 °F |
| | -145 °C | -131 °C | -168 °C | -160.00 °C |
| critical Temperature | 281.89 °F | 215.02 °F | 152.60 °F | 308.84 °F |
| | 138.83 °C | 101.68 °C | 67.00 °C | 153.80 °C |
| critical Pressure | 744 psia | 422 psia | 575 psia | 595 psia |
| | 5.132 MPa | 2.912 MPa | 3.964 MPa | 4.102 MPa |
| critical Density | 49.0 $lb/ft^3$ | 38.7 $lb/ft^3$ | 46.5 $lb/ft^3$ | 44.4 $lb/ft^3$ |
| | 0.784 kg/L | 0.62 1 kg/L | 0.745 kg/L | 0.7 13 kg/L |
| Extinguishing Concentration, cupburner, % v/v (n-heptane) | 3.9 | 6.0 | 3.5 | 3.7 |
| Inerting Conc %v/v (Stoichiomemc) | | | | |
| Methane | 6 | 8 | 4 | - |
| Propane | 8 | 12 | 8 | |
| (Reference 3) | | | | |
| $LC_{50}$ (4 hour) | 108,000 | >800,000 | 800,000 | 131,000 |

Requirements for a viable Halon alternative include good fire suppression characteristics, low toxicity, minimal formation of decomposition products during extinguishment, and compatibility with materials of construction. In addition, to properly evaluate the performance of a Halon alternative in a fire suppression system and to enable the design of a suppression system for a given application, a complete set of thermodynamic properties is required. This study reports on the extinguishing efficiency of FM-100, FM-200 and HFC-23, and the decomposition products produced upon extinguishment of n-heptane pool fires by these agents in a 1440 cubic foot test facility. Also *reported* is the determination of a complete set of thermodynamic properties for the agents FM-100 and FM-200 by the fitting of experimentally measured critical properties, vapor pressure, and liquid and vapor volumes to the Carnahan-Starling-DeSantis equation of state.

## LARGE SCALE FIRE TESTING

It is well known that the presently employed Halon fire extinguishing agents produce both hydrogen fluoride (HF) and hydrogen bromide (HBr) in the combustion environment [4-9]. Due to the toxic and corrosive nature of these halogen acids, it is important to ascertain the concentrations of these products formed upon extinguishment of a fire with a particular agent.

Agent efficiencies and decomposition products were determined employing the test facility shown schematically in Figures 1 and 2. The facility consists of a plywood structure of internal dimensions 12 ft (length) x 10 ft (width) x 12 ft (height), corresponding to an internal volume of 1440 cubic feet. The facility is constructed from 2x4 lumber and 3/4" plywood, and the inside surfaces are painted with an oil-based primer (KILZ). A 3 ft x 3 ft hinged "trap door" was located on the ceiling to allow venting in the event of overpressurization.

The agent delivery system consisted of 1 1/2" carbon steel pipe, a single lateral dispersion type nozzle (FIKE 80-029) located in the center of the ceiling, and a FIKE Halon 1301 cylinder fitted with a 1" pyrotechnic assembly or a manually activated ball valve. The delivery system was fitted at the nozzle with an Omega series PX302-500GV pressure transducer to allow determination of the agent discharge time. Fuel and flame temperatures were monitored with Type K exposed junction thermocouples with Inconel sheaths. Data acquisition was accomplished with a Rustrak Ranger datalogger (Gulton-Rustrak) with a Pronto Release 3 software package.

A metal fire pan (3.5" x 3.5" x 4" deep or 11.5" x 11.5" x 4" deep) was located in the center of the test facility and filled with two inches of water, followed by one inch of commercial grade n-heptane. The fuel was ignited and allowed a 30 second preburn period with both doors open. The doors were then closed and the agent discharged. Extinguishment times were determined by visual observation employing a stopwatch, and discharge times were determined from the variation of the nozzle pressure with time.

An all plastic collection system located inside the test facility was employed for the determination of halogen acid decomposition products. This system consists of a 250 cc polypropylene gas washing bottle equipped with a 70 micron porosity polyethylene disk. In the case of Halon 1301 and FM-100, the gas washing bottle was filled with 100 cc of deionized water and the acid halides determined by ion chromatography (IC) on a Dionex Ionpack AS4A column with 2 mM sodium carbonate/2 mM sodium bicarbonate eluent. For FM-200 and HFC-23, HF was determined via IC as described above, and also by ion selective electrode (ISE), employing

FIGURE 1. FIRE TEST FACILITY

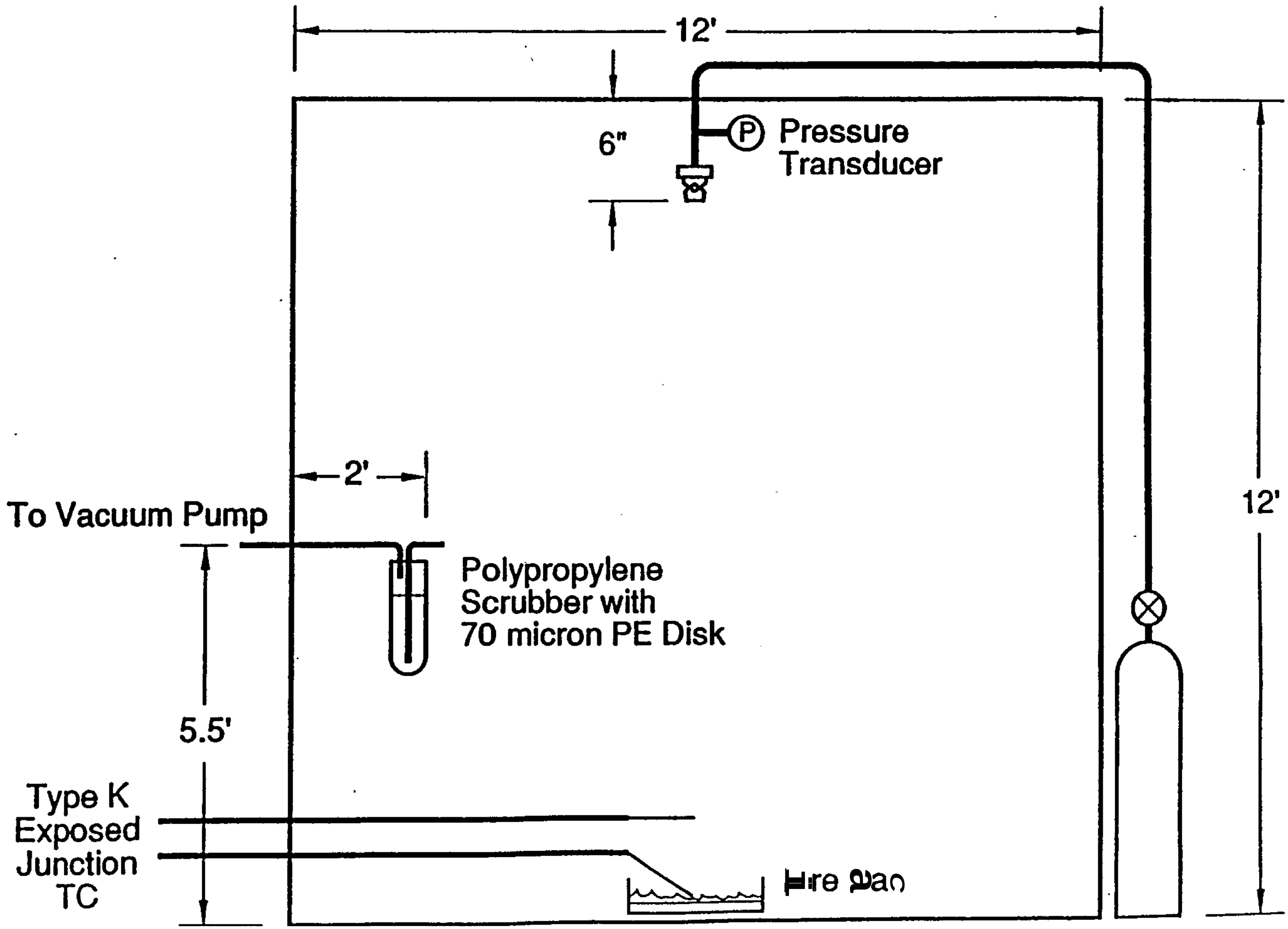
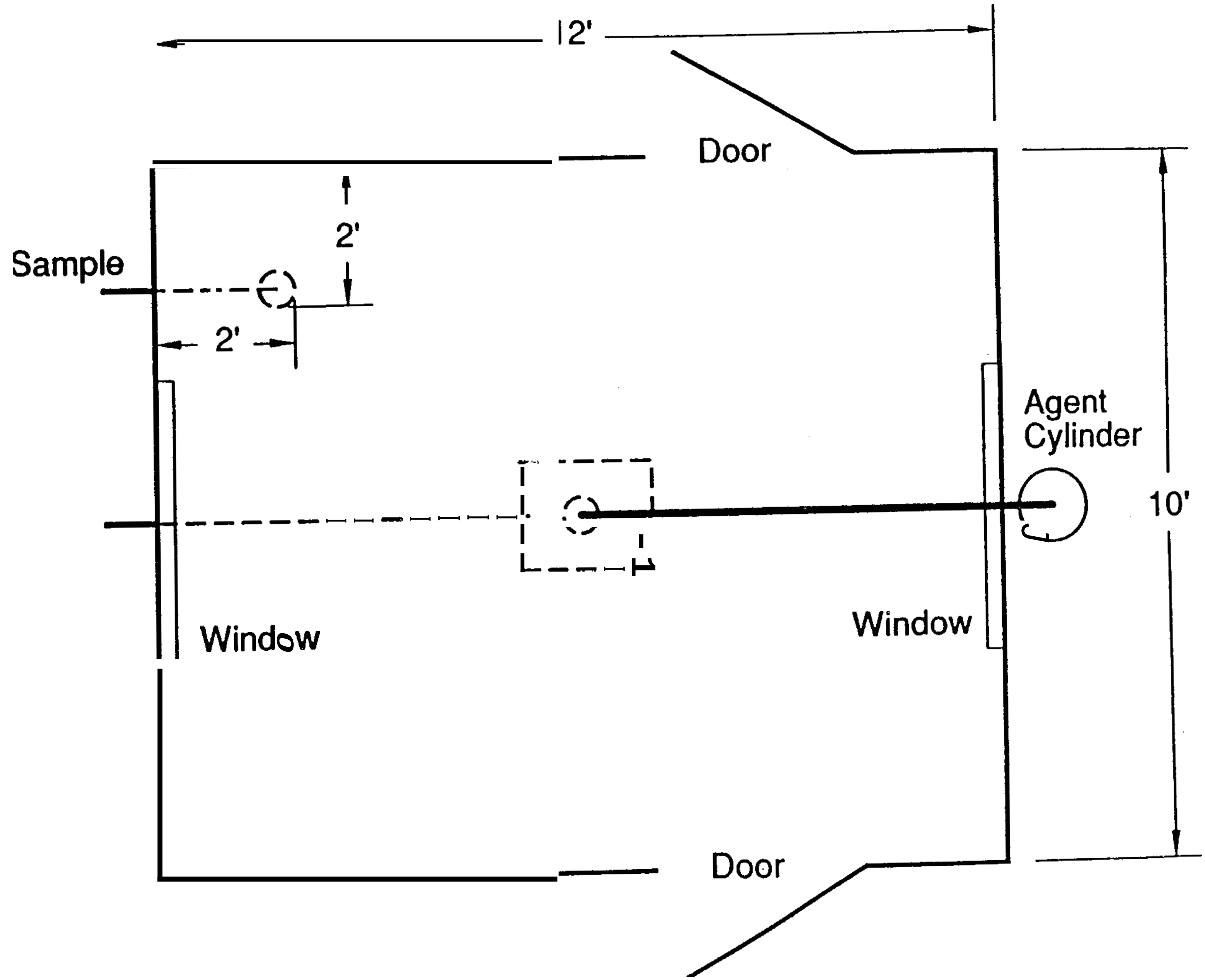


FIGURE 2. FIRE TEST FACILITY



110 cc of an ionic strength adjusting solution (TISAB IV, Orion) in place of the deionized water. Either method produced similar results for the concentrations of HF. Halogen acid samples were collected beginning 30 seconds after agent discharge by pulling enclosure air through the gas washing bottles with calibrated vacuum pumps for a total of 10 minutes. Based upon the amount of halogen acids collected in the gas washing bottle, the concentration of halogen acids produced in the test facility volume can be calculated. Additional details of the sampling procedure have been presented elsewhere [10].

The experimentally measured concentrations of hydrogen fluoride and hydrogen bromide produced from Halon 1301, FM-100, FM-200 and HFC-23 are summarized in Tables 2 and 3 for small (0.06 $ft^2$ fuel surface area per 1000 ft3 enclosure volume) and large (0.60 $ft^2$ fuel surface area per 1000 ft3 enclosure volume) n-heptane pool fires, respectively. For each agent, at least five tests were conducted for each fire size.

TABLE 2. COMPARISON OF FIRE SUPPRESSION AGENTS
Small fires (0.06 $ft^2$/1000 $ft^3$)

| Agent | Concentration % v/v | Discharge Time, s | HF (ppm) | HBr (ppm) |
|---|---|---|---|---|
| H-1301 | 5 | 4.5 | 3.9 +/- 1.2 | 2.6 +/- 1.3 |
| FM-100 | 5 | 6.0 | 3.9 +/- 1.0 | 14 +/- 10 |
| FM-200 | 8 | 6.5 | 25 +/- 10 | - |

1.5" pipe, 1.5" nozzle (FIKE 80-029)

TABLE 3. COMPARISON OF FIRE SUPPRESSION AGENTS
Large Fires (0.60 $ft^2$/1000 $ft^3$)

| Agent | Concentration % v/v | Discharge Time, s | HF (ppm) | HBr (ppm) |
|---|---|---|---|---|
| H-1301 | 5 | 4.5 | 78 +/- 48 | 25 +/- 6 |
| FM-100 | 5 | 6.0 | 53 +/- 23 | 32 +/- 9 |
| FM-200 | 10 | 6.5 | 503 +/- 123 | - |
| HFC-23 | 16 | 8.0 | 1259 +/- 159 | - |
| HFC-23 | 18 | 9.0 | 805 +/- 209 | - |

1.5" pipe, 1.5" nozzle (FIKE 80-029)

For the results presented in Tables 2 and 3 the delivery system was constructed of 1 1/2" carbon steel with a 1 1/2" standard nozzle (FIKE 80-029). Since no changes were made to the system (i.e., no attempts were made to optimize the system for a particular agent), the tests serve to evaluate the alternatives when employed as "drop-in" agents. The design concentrations given in the tables are the lowest concentrations of agent which result in extinguishment of the fire in a time period less than or equal to the agent discharge time.

For the small fires, FM-100 at 5 % by volume produced similar levels of HF and HBr compared to those produced from Halon 1301 at 5 % by volume. The halodifluoromethanes are known to readily decompose at elevated temperatures via elimination of HX [11], and this may explain the somewhat increased levels of HBr observed with FM-100 compared to Halon 1301. For the large fires, FM-100 at 5 % by volume again produced similar levels of HF and HBr compared to those produced from Halon 1301 at 5 % by volume. Extinguishment of both small and large fires with FM-100 was rapid and clean (no residues). The results demonstrate that on a weight basis FM-100 is equal in efficiency to Halon 1301. Replacement of Halon 1301 with FM-100 provides equal fire extinguishing efficiency and cleanliness, with a significant decrease in ozone-depleting properties.

For the small fires, FM-200 at 8 % by volume produced rapid and clean extinguishment with the production of HF levels in the range of 15 to 35 ppm, approximately six times the amount produced by Halon 1301 at 5 % by volume in the same fire scenario. For the large fires, 8 % by volume FM-200 was sufficient to rapidly extinguish the fire, but the levels of HF produced were excessive (> 1000 ppm). At a concentration of 10 % by volume, FM-200 provided rapid and clean extinguishment of the large fires, and produced HF levels in the range of 380 to 626 ppm; these HF levels are again approximately six times those produced by Halon 1301 at 5 % by volume in an identical fire scenario. At these HF levels no etching of the observation windows was observed. Electronic circuits exposed to the fire environment were operational following exposure, and showed no signs of residues or other adverse affects, other than a slight tarnishing of solder joints.

At a concentration of 16 % by volume, HFC-23 was able to extinguish the large fires, but HF levels were in excess of 1000 ppm. At a concentration of 18 % by volume, HFC-23 provided rapid and clean extinguishment, producing HF levels ranging from 596 to 1014 ppm. These HF levels are approximately ten times those produced by Halon 1301 at 5 % by volume in an identical fire scenario. It should be noted that at these high concentrations, overpressurization of the test facility can become a problem if the leakage rate of the facility is not great enough to prevent excessive pressure buildup.

It is of interest to compare the above results with literature citations concerning the toxicology of HF. Purser [12], in the SFPE Handbook of Fire Protection, cites a 30 minute mammalian $LC_{50}$ for HF of 900 - 3600 ppm and Taylor [13], in the NFPA Handbook of Fire Protection, indicates a 10 minute ALC50 for HF of 2500 ppm. It is noteworthy that the levels of HF observed during extinguishment with FM-100 and FM-200 are below these $LC_{50}$ values.

## THERMODYNAMIC PROPERTIES

Measurement of the properties of FM-100 and FM-200 were performed under the direction of Professor W. Alexander Van Hook of the Department of Chemistry, University of Tennessee. Sample purities for both FM-100 and FM-200 were in excess of 0.9995 mole fraction, determined by gas chromatographic analysis. Complete details of the determination of the PVT properties of FM-100 and FM-200 have been described elsewhere [14], as have details of the PVT apparatus and techniques employed in these studies [15]. Critical temperatures were determined by visually noting the loss of meniscus in sealed capillaries. Critical pressures were obtained by extrapolating the vapor pressure expression to $T_c$, and critical densities were determined from the law of rectilinear diameters. Table 1 summarizes the critical properties and other properties of FM-100 and FM-200, as well as properties for Halon 1301 [16] and Halon 1211 [17] from the literature.

The experimental vapor pressure data for FM-100 and FM-200 were smoothed by least-squares fitting to the vapor pressure equation shown in Table 4, and experimental liquid molar volumes were smoothed by least-squares fitting to the expression shown in Table 5. Vapor molar volumes were calculated from the experimental critical properties employing the generalized virial-coefficient correlation of Pitzer and Curl [18].

## TABLE 4. VAPOR PRESSURE CORRELATION

$$\ln P = A_0 + \frac{A_1}{T} + A_2 T + A_3 \ln T$$

P = Pa; T = Kelvin

| | $A_0$ | $A_1$ | $A_2$ | $A_3$ |
|---|---|---|---|---|
| **FM-100** | **110.8260** | **-5264.060** | **2.21845E-2** | **-15.23629** |
| **FM-200** | **124.7789** | **-5672.184** | **2.605601E-2** | **-17.63847** |

## TABLE 5. LIQUID MOLAR VOLUME CORRELATION

$$\ln V_0 = E_0 + E_1 T + E_2 T^2 + E_3 T^3$$

$V_0 = m^3$/mole; T = Kelvin

| | $E_0$ | $E_1$ | $E_2$ | $E_3$ |
|---|---|---|---|---|
| **FM-100** | **-15.4705** | 5.4755E-2 | -1.7354E-4 | 1.9033E-7 |
| **FM-200** | **-20.5100** | **0.11550** | -3.9393E-4 | 4.5585E-7 |

The experimental data was fit to the Carnahan-Starling-DeSantis (CSD) equation of state and the fitted parameters are detailed in Table 6. Also included in Table 6 are the CSD coefficients for Halon 1301 and Halon 1211, determined by fitting the CSD equation to literature values for the properties of the agents [16,17]. The CSD equation of state has been shown to accurately describe the properties of fluorinated molecules such as the commonly employed refrigerants (R11, R12, R13, R22, R23, R113, R114) as well as the properties of the more recently developed CFC replacements, including R123, R134a, R152a and R125 [19-21]. The CSD equation of state is applicable to both the liquid and vapor phases, its principle limitation being its failure to accurately describe properties in the critical region [19]. However, since in the vast majority of practical applications operation in the critical region is avoided, this limitation does not pose a problem.

TABLE 6. CARNAHAN-STARLING-DESANTIS COEFFICIENTS

$$\frac{pV}{RT} = \frac{1+(b/4V)+(b/4V)^2-(b/4V)^3}{[1-(b/4V)]^3} - \frac{a}{RT(V+b)}$$

$$a = a_0 \exp(a_1 T + a_2 T^2)$$

$$b = b_0 + b_1 T + b_2 T^2$$

$$c_p = c_0 + c_1 T + c_2 T^2$$

| | FM-100 | FM-200 | H-1301 | H-1211 |
|---|---|---|---|---|
| $a_0$ | 1772.01 | 5124.05 | 2503.14 | 4749.90 |
| $a_1$ | 0.127422E-2 | -0.209572E-2 | -0.215184E-2 | -0.333938E-2 |
| $a_2$ | -0.685486E-5 | -0.370377E-5 | -0.273976E-5 | 0.810944E-6 |
| $b_0$ | 0.656975E-1 | 0.194429 | 0.142871 | 0.175794 |
| $b_1$ | 0.257243E-3 | -0.888528E-4 | -0.205155E-3 | -0.255102E-3 |
| $b_2$ | -0.671013E-6 | -0.462247E-6 | -0.353784E-7 | 0.841644E-7 |
| $c_0$ | 26.5716 | -17.0985 | 22.5312 | 22.0184 |
| $c_1$ | 0.125052 | 0.575753 | 0.195767 | 0.235464 |
| $c_2$ | -0.569902E-4 | -0.369941E-3 | -0.135512E-3 | -0.198691E-3 |

Tables 7 and 8 compare the experimentally observed values for the vapor pressure and liquid densities of FM-200 with those calculated from the CSD equation of state, and it is seen that the agreement between the calculated and experimental values is excellent.

The temperature dependence of the ideal gas heat capacity is required in addition to the PVT equation of state to completely express the thermodynamic properties of a fluid. The ideal gas heat capacity for FM-100, derived from spectroscopic data [22] was fit to a simple polynomial as shown in Table 6. Due to the increased complexity of FM-200, derivation of the ideal gas heat capacity from IR or Raman spectra was not possible. In this case the temperature dependence of the ideal gas heat capacity was estimated by the method of Rihani and Doraiswamy [23].

TABLE 7. FM-200 VAPOR PRESSURE: EXPERIMENTAL VS. CSD EQUATION OF STATE

| T(K) | P (kPa) observed | P (kPa) calculated | Difference % |
|---|---|---|---|
| 237.65 | 40.86 | 40.67 | 0.47 |
| 243.60 | 55.12 | 54.98 | 0.26 |
| 248.16 | 68.61 | 68.47 | 0.20 |
| 252.39 | 83.25 | 83.23 | 0.02 |
| 260.92 | 120.44 | 120.60 | -0.13 |
| 268.31 | 161.53 | 162.63 | -0.68 |
| 275.69 | 216.08 | 215.19 | 0.41 |
| 283.20 | 281.68 | 281.23 | 0.16 |
| 290.57 | 359.18 | 360.12 | -0.26 |
| 298.22 | 458.72 | 458.69 | 0.01 |
| 305.58 | 576.29 | 571.46 | 0.84 |
| 313.08 | 707.05 | 706.45 | 0.08 |
| 320.66 | 864.81 | 865.48 | -0.08 |
| 328.60 | 1057.90 | 1058.64 | -0.07 |
| 335.24 | 1242.42 | 1242.69 | -0.02 |
| 343.45 | 1503.39 | 1500.64 | 0.18 |

TABLE 8. FM-200 LIQUID DENSITY: EXPERIMENTAL VS CSD EQUATION OF STATE

| T(K) | Density ($kg/m^3$) observed | Density ($kg/m^3$) calculated | Difference % |
|---|---|---|---|
| 257.55 | 1521.6 | 1526.4 | -0.32 |
| 273.15 | 1488.2 | 1475.8 | 0.83 |
| 273.16 | 1489.0 | 1475.8 | 0.89 |
| 303.07 | 1372.1 | 1370.3 | 0.13 |
| 303.15 | 1367.0 | 1370.0 | -0.22 |
| 322.93 | 1281.4 | 1290.4 | -0.70 |
| 343.38 | 1188.7 | 1194.3 | -0.47 |

Employing the equation of state and ideal gas heat capacity constants shown in Table 6, tables of the thermodynamic properties of the agents were generated. As an example, saturation and superheated vapor properties for FM-200 are shown in Tables 9 and 10, respectively. Saturation and superheated vapor properties are conveniently summarized in a pressure-enthalpy (Mollier) diagram, and a series of computer routines were devised which allowed calculation of the pressure-enthalpy diagram. The pressure-enthalpy diagram for FM-200 is reproduced in Figure 3. The availability of reliable superheated vapor propexties also allows the construction of total flooding quantity tables, and the total flooding quantity table for FM-200 is shown in Table 11.

## CONCLUSIONS

For both small and large fires, the extinguishing efficiency of FM-100 on a weight basis was observed to be equal to that of Halon 1301 for similar fire scenarios. FM-100 provided rapid and clean extinguishment, and produced HF and HBr at levels similar to that produced by Halon 1301.

Small fires were rapidly and cleanly extinguished by 8 % by volume FM-200 and the HF produced was approximately six times that produced by Halon 1301 at 5 % by volume. The low levels of HF produced from FM-200 (16-35 ppm) are likely insignificant when consideration is given to the potential hazards presented by the fire itself. These results suggest that if fire detection systems of sufficient sensitivity are employed to allow detection and agent release in the early stages when the fire size is minimal, FM-200 can serve as a viable, environmentally acceptable substitute for Halon 1301 in total flooding applications. Large fires were rapidly and cleanly extinguished by FM-200 at a concentration of 10% by volume and produced HF in levels ranging from 380 to 626 ppm. These levels compare to cited values for the 30 minute mammalian $LC_{50}$ for HF of 900 - 3600 ppm, and a 10 minute $ALC_{50}$ of 2500 ppm.

At concentrations of 16 to 18 % by volume HFC-23 provided rapid and clean extinguishment of large fires. However, HF levels produced were approximately ten times those produced by Halon 1301 in a similar tire scenario, and overpressurization of the test enclosure at these high concentrations also occurred.

TABLE **9.** SATURATION PROPERTIES FOR **FM-200**

| TEMP | PRESSURE | DENSITY | | ENTHALPY | | | ENTROPY | | CV | | CP | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LIQ | VAP | LIQ | EVAP | VAP | LIQ | VAP | LIQ | VAP | LIQ | VAP |
| (F) | (PSIA) | (LB/FT**3) | | --- (BTU/LB) ---- | | | | | (BTU/LB F) | | | |
| -40 | 4.639 | 100.03 | 0.1787 | 0.0 | 61.1 | 61.1 | 0.0000 | 0.1456 | 0.1985 | 0.1248 | 0.2172 | 0.1375 |
| -35 | 5.388 | 99.50 | 0.2056 | 1.1 | 60.7 | 61.8 | 0.0026 | 0.1454 | 0.2005 | 0.1264 | 0.2192 | 0.1393 |
| -30 | 6.231 | 98.97 | 0.2356 | 2.2 | 60.2 | 62.4 | 0.0052 | 0.1453 | 0.2025 | 0.1280 | 0.2211 | 0.1410 |
| -25 | 7.178 | 98.43 | 0.2691 | 3.3 | 59.7 | 63.1 | 0.0077 | 0.1452 | 0.2044 | 0.1296 | 0.2231 | 0.1428 |
| -20 | 8.237 | 97.89 | 0.3062 | 4.4 | 59.3 | 63.7 | 0.0103 | 0.1451 | 0.2063 | 0.1312 | 0.2250 | 0.1445 |
| -15 | 9.418 | 97.35 | 0.3473 | 5.6 | 58.8 | 64.4 | 0.0128 | 0.1451 | 0.2082 | 0.1328 | 0.2270 | 0.1463 |
| -10 | 10.730 | 96.81 | 0.3927 | 6.7 | 58.3 | 65.0 | 0.0154 | 0.1451 | 0.2101 | 0.1344 | 0.2289 | 0.1481 |
| -5 | 12.183 | 96.27 | 0.4427 | 7.8 | 57.8 | 65.7 | 0.0179 | 0.1451 | 0.2120 | 0.1359 | 0.2308 | 0.1500 |
| 0 | 13.788 | 95.72 | 0.4977 | 9.0 | 57.3 | 66.3 | 0.0205 | 0.1452 | 0.2139 | 0.1375 | 0.2328 | 0.1518 |
| 5 | 15.556 | 95.17 | 0.5579 | 10.2 | 56.8 | 67.0 | 0.0230 | 0.1452 | 0.2157 | 0.1391 | 0.2347 | 0.1537 |
| 10 | 17.497 | 94.62 | 0.6237 | 11.4 | 56.3 | 67.6 | 0.0255 | 0.1454 | 0.2175 | 0.1406 | 0.2367 | 0.1556 |
| 15 | 19.624 | 94.06 | 0.6956 | 12.5 | 55.8 | 68.3 | 0.0280 | 0.1455 | 0.2193 | 0.1422 | 0.2386 | 0.1575 |
| 20 | 21.947 | 93.50 | 0.7739 | 13.7 | 55.2 | 69.0 | 0.0305 | 0.1456 | 0.2211 | 0.1438 | 0.2405 | 0.1595 |
| 25 | 24.480 | 92.93 | 0.8591 | 15.0 | 54.7 | 69.6 | 0.0330 | 0.1458 | 0.2228 | 0.1454 | 0.2425 | 0.1615 |
| 30 | 27.233 | 92.36 | 0.9516 | 16.2 | 54.1 | 70.3 | 0.0355 | 0.1460 | 0.2246 | 0.1469 | 0.2444 | 0.1635 |
| 35 | 30.221 | 91.78 | 1.0518 | 17.4 | 53.5 | 70.6 | 0.0380 | 0.1462 | 0.2263 | 0.1485 | 0.2464 | 0.1656 |
| 40 | 33.456 | 91.20 | 1.1603 | 18.6 | 52.9 | 71.6 | 0.0405 | 0.1464 | 0.2280 | 0.1501 | 0.2484 | 0.1677 |
| 45 | 36.951 | 90.61 | 1.2776 | 19.9 | 52.3 | 72.2 | 0.0429 | 0.1467 | 0.2296 | 0.1517 | 0.2503 | 0.1699 |
| 50 | 40.720 | 90.02 | 1.4042 | 21.2 | 51.7 | 72.9 | 0.0454 | 0.1469 | 0.2313 | 0.1533 | 0.2523 | 0.1722 |
| 55 | 44.775 | 89.42 | 1.5406 | 22.4 | 51.1 | 73.5 | 0.0479 | 0.1472 | 0.2329 | 0.1549 | 0.2543 | 0.1745 |
| 60 | 49.132 | 88.81 | 1.6876 | 23.7 | 50.5 | 74.2 | 0.0503 | 0.1475 | 0.2345 | 0.1565 | 0.2563 | 0.1769 |
| 65 | 53.804 | 88.20 | 1.8458 | 25.0 | 49.8 | 74.8 | 0.0528 | 0.1477 | 0.2361 | 0.1581 | 0.2583 | 0.1793 |
| 70 | 58.804 | 87.58 | 2.0157 | 26.3 | 49.2 | 75.4 | 0.0552 | 0.1480 | 0.2377 | 0.1597 | 0.2604 | 0.1819 |
| 75 | 64.148 | 86.95 | 2.1982 | 27.6 | 48.5 | 76.1 | 0.0577 | 0.1483 | 0.2392 | 0.1614 | 0.2625 | 0.1846 |
| 80 | 69.850 | 86.31 | 2.3941 | 28.9 | 47.8 | 76.7 | 0.0601 | 0.1486 | 0.2407 | 0.1630 | 0.2646 | 0.1873 |
| 85 | 75.925 | 85.66 | 2.6041 | 30.2 | 47.1 | 77.3 | 0.0625 | 0.1489 | 0.2422 | 0.1647 | 0.2667 | 0.1902 |
| 90 | 82.386 | 85.00 | 2.8291 | 31.6 | 46.3 | 77.9 | 0.0649 | 0.1492 | 0.2436 | 0.1664 | 0.2689 | 0.1932 |
| 95 | 89.249 | 84.33 | 3.0700 | 32.9 | 45.6 | 78.5 | 0.0674 | 0.1495 | 0.2451 | 0.1680 | 0.2711 | 0.1964 |
| 100 | 96.528 | 83.65 | 3.3279 | 34.3 | 44.8 | 79.1 | 0.0698 | 0.1498 | 0.2465 | 0.1698 | 0.2734 | 0.1997 |
| 105 | 104.239 | 82.95 | 3.6039 | 35.7 | 44.0 | 79.7 | 0.0722 | 0.1501 | 0.2478 | 0.1715 | 0.2757 | 0.2034 |
| 110 | 112.395 | 82.25 | 3.8990 | 37.0 | 43.2 | 80.3 | 0.0746 | 0.1504 | 0.2492 | 0.1733 | 0.2781 | 0.2069 |
| 115 | 121.011 | 81.53 | 4.2145 | 38.4 | 42.4 | 80.8 | 0.0770 | 0.1507 | 0.2505 | 0.1750 | 0.2806 | 0.2108 |
| 120 | 130.103 | 80.79 | 4.5518 | 39.8 | 41.5 | 81.4 | 0.0794 | 0.1510 | 0.2518 | 0.1768 | 0.2832 | 0.2150 |
| 125 | 139.684 | 80.04 | 4.9122 | 41.3 | 40.7 | 81.9 | 0.0818 | 0.1513 | 0.2530 | 0.1787 | 0.2859 | 0.2194 |
| 130 | 149.768 | 79.28 | 5.2975 | 42.7 | 39.8 | 82.5 | 0.0842 | 0.1516 | 0.2543 | 0.1805 | 0.2887 | 0.2242 |
| 135 | 160.371 | 78.50 | 5.7092 | 44.1 | 38.9 | 83.0 | 0.0866 | 0.1519 | 0.2554 | 0.1824 | 0.2916 | 0.2293 |
| 140 | 171.505 | 77.69 | 6.1493 | 45.6 | 37.9 | 83.5 | 0.0889 | 0.1522 | 0.2566 | 0.1844 | 0.2948 | 0.2349 |
| 145 | 183.184 | 76.87 | 6.6198 | 47.0 | 37.0 | 84.0 | 0.0913 | 0.1524 | 0.2577 | 0.1864 | 0.2981 | 0.2409 |
| 150 | 195.422 | 76.03 | 7.1230 | 48.5 | 36.0 | 84.5 | 0.0937 | 0.1527 | 0.2588 | 0.1884 | 0.3017 | 0.2474 |
| 155 | 208.231 | 75.16 | 7.6614 | 50.0 | 35.0 | 85.0 | 0.0961 | 0.1529 | 0.2598 | 0.1904 | 0.3056 | 0.2546 |
| 160 | 221.625 | 74.27 | 8.2377 | 51.5 | 33.9 | 85.4 | 0.0985 | 0.1532 | 0.2608 | 0.1925 | 0.3099 | 0.2625 |

TABLE 10. SUPERHEATED VAPOR PROPERTIES FOR FM-200

PRESSURE = 14.70 PSIA

| | TEMP (F) | DENSITY (LB/FT**3) | ENTHALPY (BTU/LB) | ENTROPY | CV (BTU/LB F) | CP |
|---|---|---|---|---|---|---|
| SAT LIQ | 2.6 | 95.4325 | 9.6 | 0.0218 | 0.2148 | 0.2338 |
| SAT VAP | 2.6 | 0.5286 | 66.7 | 0.1452 | 0.1383 | 0.1528 |
| | 10.0 | 0.5190 | 67.8 | 0.1476 | 0.1405 | 0.1549 |
| | 20.0 | 0.5065 | 69.4 | 0.1509 | 0.1435 | 0.1577 |
| | 30.0 | 0.4947 | 71.0 | 0.1542 | 0.1465 | 0.1605 |
| | 40.0 | 0.4835 | 72.6 | 0.1575 | 0.1494 | 0.1633 |
| | 50.0 | 0.4728 | 74.2 | 0.1607 | 0.1523 | 0.1660 |
| | 60.0 | 0.4626 | 75.9 | 0.1640 | 0.1551 | 0.1688 |
| | 70.0 | 0.4529 | 77.6 | 0.1672 | 0.1579 | 0.1715 |
| | 80.0 | 0.4436 | 79.3 | 0.1705 | 0.1607 | 0.1742 |
| | 90.0 | 0.4348 | 81.1 | 0.1737 | 0.1635 | 0.1768 |
| | 100.0 | 0.4263 | 82.9 | 0.1769 | 0.1662 | 0.1795 |
| | 110.0 | 0.4181 | 84.7 | 0.1801 | 0.1689 | 0.1821 |
| | 120.0 | 0.4103 | 86.5 | 0.1833 | 0.1715 | 0.1846 |
| | 130.0 | 0.4028 | 88.4 | 0.1865 | 0.1742 | 0.1872 |
| | 140.0 | 0.3956 | 90.3 | 0.1896 | 0.1767 | 0.1897 |
| | 150.0 | 0.3886 | 92.2 | 0.1928 | 0.1793 | 0.1922 |
| | 160.0 | 0.3819 | 94.1 | 0.1960 | 0.1818 | 0.1947 |
| | 170.0 | 0.3755 | 96.1 | 0.1991 | 0.1843 | 0.1971 |
| | 180.0 | 0.3693 | 98.0 | 0.2022 | 0.1868 | 0.1995 |
| | 190.0 | 0.3633 | 100.0 | 0.2053 | 0.1892 | 0.2019 |
| | 200.0 | 0.3575 | 102.1 | 0.2084 | 0.1916 | 0.2042 |
| | 210.0 | 0.3519 | 104.1 | 0.2115 | 0.1940 | 0.2065 |
| | 220.0 | 0.3464 | 106.2 | 0.2146 | 0.1963 | 0.2088 |
| | 230.0 | 0.3412 | 108.3 | 0.2177 | 0.1986 | 0.2111 |
| | 240.0 | 0.3361 | 110.4 | 0.2207 | 0.2009 | 0.2133 |
| | 250.0 | 0.3312 | 112.6 | 0.2238 | 0.2031 | 0.2155 |
| | 260.0 | 0.3264 | 114.7 | 0.2268 | 0.2053 | 0.2177 |
| | 270.0 | 0.3218 | 116.9 | 0.2298 | 0.2075 | 0.2198 |
| | 280.0 | 0.3173 | 119.1 | 0.2328 | 0.2096 | 0.2219 |
| | 290.0 | 0.3129 | 121.4 | 0.2358 | 0.2117 | 0.2240 |
| | 300.0 | 0.3086 | 123.6 | 0.2388 | 0.2138 | 0.2260 |
| | 310.0 | 0.3045 | 125.9 | 0.2418 | 0.2158 | 0.2280 |
| | 320.0 | 0.3005 | 128.2 | 0.2447 | 0.2178 | 0.2300 |
| | 330.0 | 0.2966 | 130.5 | 0.2477 | 0.2198 | 0.2320 |
| | 340.0 | 0.2928 | 132.8 | 0.2506 | 0.2218 | 0.2339 |
| | 350.0 | 0.2891 | 135.2 | 0.2535 | 0.2237 | 0.2358 |
| | 360.0 | 0.2855 | 137.5 | 0.2564 | 0.2256 | 0.2376 |
| | 370.0 | 0.2820 | 139.9 | 0.2593 | 0.2274 | 0.2395 |
| | 380.0 | 0.2786 | 142.3 | 0.2622 | 0.2292 | 0.2412 |
| | 390.0 | 0.2752 | 144.7 | 0.2651 | 0.2310 | 0.2430 |
| | 400.0 | 0.2720 | 147.2 | 0.2679 | 0.2328 | 0.2447 |

TABLE 11. FM-200 **TOTAL** FLOODING QUANTITY

| ***TEMP*** -t- (€9 [2] | FM-200 **Specific Vapor Volume** -S- (cu.ft./lb) [3] | FM-200 **Weight Requirements of Hazard Volume W/V (lb/cu.ft.)** [1] / FM-200 **Concentration (% by volume)** [4] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 1.9264 | 0.0331 | 0.0391 | 0.0451 | 0.0513 | 0.0577 | 0.0642 | 0.0708 | 0.0776 | 0.0845 | 0.0916 |
| 20 | 1.9736 | 0.0323 | 0.0381 | 0.0441 | 0.0501 | 0.0563 | 0.0626 | 0.0691 | 0.0757 | 0.0825 | 0.0894 |
| 30 | 2.0210 | 0.0316 | 0.0372 | 0.0430 | 0.0489 | 0.0550 | 0.0612 | 0.0675 | 0.0739 | 0.0805 | 0.0873 |
| 40 | 2.0678 | 0.0309 | 0.0364 | 0.0421 | 0.0478 | 0.0537 | 0.0598 | 0.0659 | 0.0723 | 0.0787 | 0.0853 |
| 50 | 2.1 146 | 0.0302 | 0.0356 | 0.0411 | 0.0468 | 0.0525 | 0.0584 | 0.0645 | 0.0707 | 0.0770 | 0.0835 |
| 60 | 2.1612 | 0.0295 | 0.0348 | 0.0402 | 0.0458 | 0.0514 | 0.0572 | 0.0631 | 0.0691 | 0.0753 | 0.0817 |
| 70 | 2.2075 | 0.0289 | 0.0341 | 0.0394 | 0.0448 | 0.0503 | 0.0560 | 0.0618 | 0.0677 | 0.0737 | 0.0799 |
| 80 | 2.2538 | 0.0283 | 0.0334 | 0.0386 | 0.0439 | 0.0493 | 0.0548 | 0.0605 | 0.0663 | 0.0722 | 0.0783 |
| 90 | 2.2994 | 0.0278 | 0.0327 | 0.0378 | 0.0430 | 0.0483 | 0.0538 | 0.0593 | 0.0650 | 0.0708 | 0.0767 |
| 100 | 2.3452 | 0.0272 | 0.0321 | 0.0371 | 0.0422 | 0.0474 | 0.0527 | 0.0581 | 0.0637 | 0.0694 | 0.0752 |
| 110 | 2.3912 | 0.0267 | 0.0315 | 0.0364 | 0.0414 | 0.0465 | 0.0517 | 0.0570 | 0.0625 | 0.0681 | 0.0738 |
| 120 | 2.4366 | 0.0262 | 0.0309 | 0.0357 | 0.0406 | 0.0456 | 0.0507 | 0.0560 | 0.0613 | 0.0668 | 0.0724 |
| 130 | 2.4820 | 0.0257 | 0.0303 | 0.0350 | 0.0398 | 0.0448 | 0.0498 | 0.0549 | 0.0602 | 0.0656 | 0.0711 |
| 140 | 2.5272 | 0.0253 | 0.0298 | 0.0344 | 0.0391 | 0.0440 | 0.0489 | 0.0540 | 0.0591 | 0.0644 | 0.0698 |
| 150 | 2.5727 | 0.0248 | 0.0293 | 0.0338 | 0.0384 | 0.0432 | 0.0480 | 0.0530 | 0.0581 | 0.0633 | 0.0686 |
| 160 | 2.6171 | 0.0244 | 0.0288 | 0.0332 | 0.0378 | 0.0425 | 0.0472 | 0.0521 | 0.0571 | 0.0622 | 0.0674 |
| 170 | 2.6624 | 0.0240 | 0.0283 | 0.0327 | 0.0371 | 0.0417 | 0.0464 | 0.0512 | 0.0561 | 0.0611 | 0.0663 |
| 180 | 2.7071 | 0.0236 | 0.0278 | 0.0321 | 0.0365 | 0.0410 | 0.0457 | 0.0504 | 0.0552 | 0.0601 | 0.0652 |
| 190 | 2.7518 | 0.0232 | 0.0274 | 0.0316 | 0.0359 | 0.0404 | 0.0449 | 0.0496 | 0.0543 | 0.0592 | 0.0641 |
| 200 | 2.7954 | 0.0228 | 0.0269 | 0.0311 | 0.0354 | 0.0397 | 0.0442 | 0.0488 | 0.0535 | 0.0582 | 0.0631 |

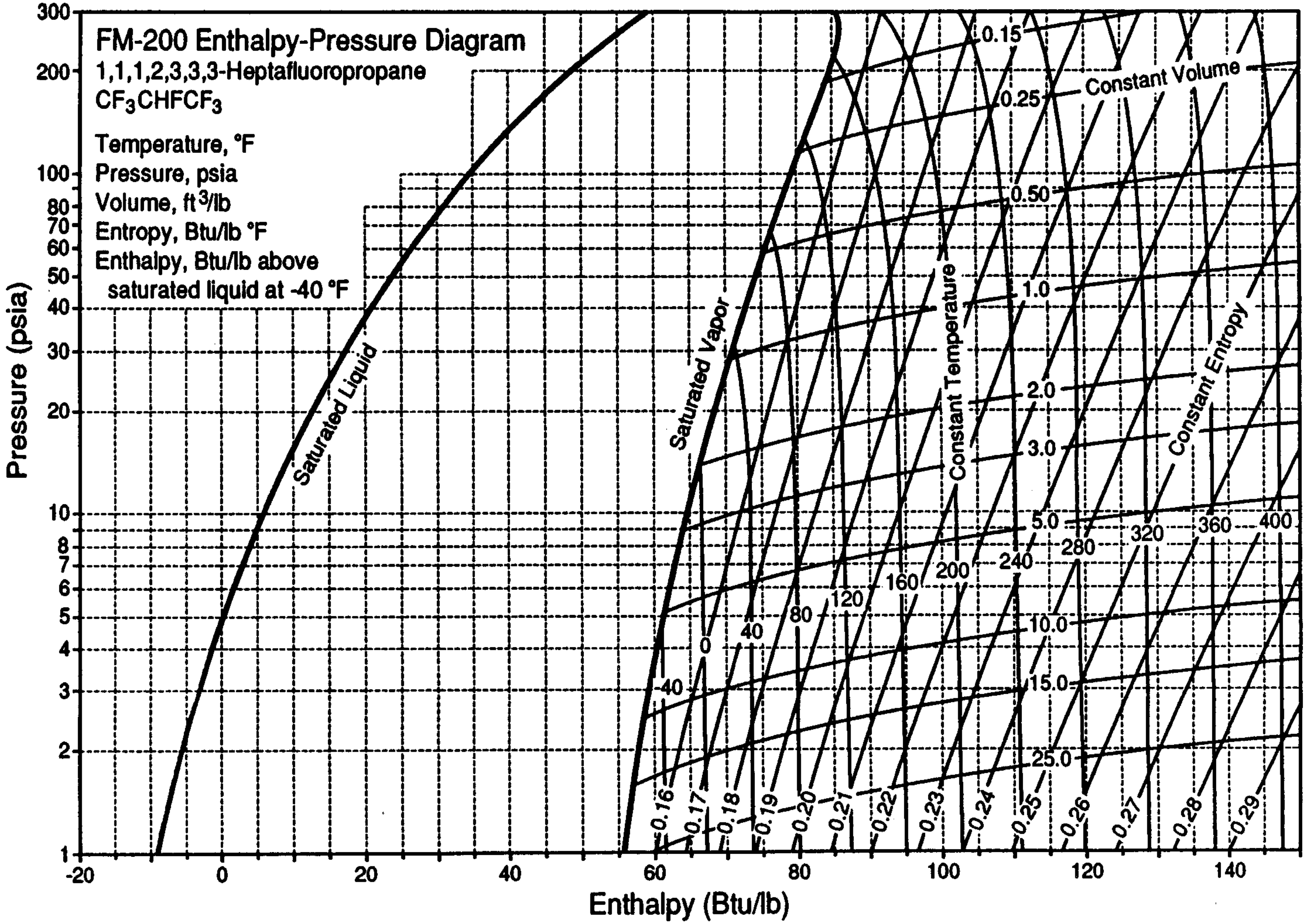
[1] - **W/V [Agent Weight Requirements (lb/cu.ft.)] - Pounds of agent per cubic foot of protected volume to produce indicated concenmtion at temperature specified.**

$$W = \frac{V}{s}\frac{C}{100 - C}$$

[2] t **[Temperature** (F)] **- The design temperature in the hazard area.**

[3] s **[Specific Volume (cu.ft./lb)] - Specific volume of superheated** FM-200 **vapor may** be **approximated by the formula:**
s = 1.8854 + 0.004574t
**where t = temperature (F)**

[4] C **[Concentration** (%)] **- Volumetric concentration of** FM-200 **in** air **at *the* temperature indicated.**


FM-200 Enthalpy-Pressure Diagram
1,1,1,2,3,3,3-Heptafluoropropane
$CF_3CHFCF_3$
Temperature, °F
Pressure, psia
Volume, ft$^3$/lb
Entropy, Btu/lb °F
Enthalpy, Btu/lb above saturated liquid at -40 °F
Saturated Liquid
Saturated Vapor
Constant Temperature
Constant Volume
Constant Entropy
Pressure (psia)
Enthalpy (Btu/lb)
300
200
100
80
70
60
50
40
30
20
10
8
7
6
5
4
3
2
1
-20
0
20
40
60
80
100
120
140
-40
0
40
80
120
160
200
240
280
320
360
400
0.15
0.25
0.50
1.0
2.0
3.0
5.0
10.0
15.0
25.0
0.16
0.17
0.18
0.19
0.20
0.21
0.22
0.23
0.24
0.25
0.26
0.27
0.28
0.29

Experimental data for FM-100 and FM-200 were fit to the Carnahan-Starling-DeSantis equation of state. Tables of saturation properties and superheated vapor properties were generated, and pressure-enthalpy diagrams constructed. More details of this work were not included due to space constraints. Other properties of interest such as saturated and superheated vapor properties of FM-100 and Halons 1301 and 1211, transport properties, etc., are available upon request.

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