Mathematical Modeling of FM-200™ Discharge and Leakage From an Enclosure

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ABSTRACT

A mathematical model has been developed to calculate the concentration history of FM-200™ (C_3F_7H) during and following discharge into a leaky enclosure. Equations representing conservation of **mass, agent(FM-200)**, and energy are solved with assumed distributions of agent and temperature in various regions of the enclosure, and with turbulent mixing between regions. Enclosure pressure history and leakage into and out of the enclosure are calculated along with agent concentrations.

Calculated results obtained with the model have been compared to data obtained by the Naval Research Laboratory (NRL) in the 56 m^3 test enclosure at the Chespeake Bay Detachment (CBD). In one test the standard four-orifice, horizontal discharge Navy nozzle was used; in another test a eight-orifice, 8 degree downward centerline, commercial nozzle was used. The design concentration in both test were 6 vol. % and the discharge time was 10 seconds. The leakage area is not know accurately but has been estimated to be 0.092 m^2. The calculated concentration histories in the upper region and lower region ofthe enclosure agree well with the data. The FM-200 concentration in the upper region is higher than the concentration in the lower region during discharge, but the concentration distribution is uniform and steady for at least one minute following discharge because of the relatively small leakage area and the residual turbulent mixing in the enclosure to minimize concentration stratification.

INTRODUCTION

An important consideration in the design and installation of a total flooding fire suppression system is the amount of leakage from the enclosure. Some leakage is necessary to prevent over pressurization of the enclosure during agent discharge. However, the leakage area should be kept to a minimum in order to:(1) allow the design concentration to be achieved, and (2) ensure adequate hold time of the design concentration.

The NFPA 2001 [1] specifications for the amount of suppression agent needed to achieve the design concentration are said to "include an allowance for normal leakage from a tight enclosure," without quantifying this normal leakage. Appendix B of NFPA 2001 describes a procedure for evaluating enclosure integrity and its effect on agent hold time, but the analysis is based on a questionable model of agent-air mixture leakage after discharge. The basic assumption in the NFPA 2001 agent hold time model is that there is a sharp descending interface between the agent-air mixture and the air that enters the enclosure due to leakage after discharge. There has not been any evidence of such an interface in the large-scale shipboard discharge tests conducted to date by the Naval Research Laboratory [2] or the Coast Guard [3].

The purpose of this paper is to describe a new mathematical model that has been developed to determine pressure and agent concentration histories during and after discharge in a leaky enclosure. The model is conceptually similar to a recent model of CO, discharge tests [4], but accounts for the non-uniform agent concentration distributions generated during the discharge of agent from a user specified nozzle configuration. It also utilizes the residual turbulence associated with the nozzle discharge to determine the extent of mixing between the upper and lower regions of the enclosure after discharge. The model has been implemented for FM-200™ (C_3F_7H), which has been perhaps the most widely used of the first generation of halon replacement agents.

MATHEMATICAL MODEL

Since spatial distributions and dominant phenomena differ during and following FM-200 discharge, separate formulations are developed for the two different stages of a discharge test.

Model Formulation During Discharge

FM-200 is assumed to be discharged at a specified rate through a multi-orifice nozzle located near the ceiling in a rectangular enclosure. The flow field formed in the enclosure may be divided into four regions as depicted in Figure 1. The four regions are: Region 1) the turbulent two-phase jets emitted from the nozzle orifices at an angle θ from the horizontal; Region 2) the wall jets formed when the nozzle jets impinge on the enclosure wall or some equipment in the path of the jets; Region 3) the upper layer above the elevation of the nozzle; and Region 4) the lower region of the enclosure outside the free and wall jet regions. Vertically stratified concentration distributions are assumed to exist in Regions 3 and 4. FM-200 concentration distributions in the two-phase jets and the wall jets are assumed to follow the empirical distributions described in References 5 and 6, respectively.

Governing equation used to simulate this representation of the discharge are conservation of mass, FM-200, and energy, and the associated mixture ideal gas law. Mass conservation for FM-200 and air in the different regions are written as follows.

1. MASS CONSERVATION

Region 2. FM-200

$$\frac{dM_{2,\ FM\text{-}200}}{dt} = 0.5(1-\sin\theta)Q_{discharge} - \dot{m}_{2L,\ FM200} - \dot{m}_{24,\ FM\text{-}200} \qquad (1)$$

Region 2, Air

$$\frac{dM_{2,\,air}}{dt} = 0.5(1-\sin\theta)Q_{entrain,\,air} - \dot{m}_{2L,\,air} - \dot{m}_{24,\,air} \qquad (2)$$

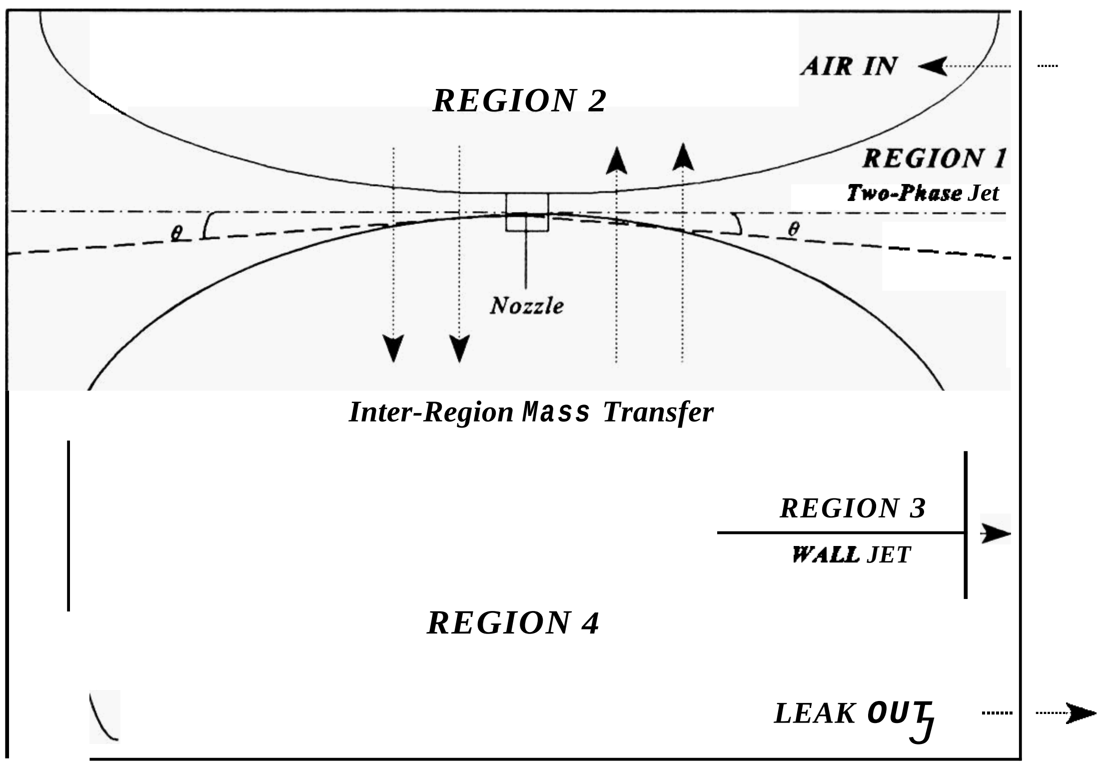

Figure 1 Schematic representation of four **region model during discharge.**

Region 4, FM-200

$$\frac{dM_{4,\,FM-200}}{dt} = 0.5(1+\sin\theta)Q_{discharge} - \dot{m}_{4L,\,FM200} + \dot{m}_{24,\,FM-200} \qquad (3)$$

Region 4, Air

$$\frac{dM_{4,\,air}}{dt} = 0.5(1+\sin\theta)Q_{entrain,\,air} - \dot{m}_{4L,\,air} + \dot{m}_{24,\,air} \qquad (4)$$

where $Q_{discharge}$ **is the discharge rate of FM-200;**

$\dot{m}_{2L, FM200}$ is the leakage rate of **FM-200** from enclosure to outside;
$\dot{m}_{24, FM200}$ is the mass transfer rate of **FM-200** from region **2** to Region **4;**
$Q_{entrain, air}$ is the rate of air entrained into the jet;
$\dot{m}_{2L, air}$ is the air leakage rate from the enclosure to the outside;
$\dot{m}_{24, air}$ is the mass transfer rate of air from Region 2 to Region **4.**

From Papadourakis et al [5], the rate of air entrained into a flashing liquefied gas jet is given by:

$$Q_{entrain,\ air} = 0.32 \frac{q_0 x}{D_{jet}} \sqrt{\frac{\rho_{air}}{\rho'}} \tag{5}$$

where D_{jet} is the diameter of the jet after initial flash; q_0 is the **FM-200** discharge rate ($Q_{discharge}$); ρ' is the density of the jet after flashing; ρ_{air} is the density of air; and **x** is the axial distance downstream from the orifice to the enclosure wall.

Since the pressures in both Region **2** and Region **4** are changing with time, the direction and magnitude of the mass transfer between regions will depend upon the instantaneous pressure differences. The following equations are used to describe this mass transfer for both FM-200 and air flow.

If $P_2 > P_4$, the flow will be from Region **2** to Region **4,** as given by:

$$\dot{m}_{24,\ FM200} = x_2\ A_{transfer} \sqrt{2\ (P_2 - P_4)\ \rho_2} \tag{6}$$

$$\dot{m}_{24,\ air} = (1 - x_2)\ A_{transfer} \sqrt{2\ (P_2 - P_4)\ \rho_2} \tag{7}$$

where x_2 is the mass fraction of **FM-200** in the Region **2;** $A_{transfer}$ is the area for mass transfer between Region **2** and Region **4,** i.e. the enclosure horizontal cross-sectional area; and ρ_2 is the density of Region 2.

If $P_4 > P_2$, the flow will be from Region **4** to Region 2, as given by:

$$\dot{m}_{24,\ air} = -(1 - x_4)\ A_{transfer} \sqrt{2\ (P_4 - P_2)\ \rho_4} \tag{8}$$

$$\dot{m}_{24,\ FM200} = -x_4\ A_{transfer} \sqrt{2\ (P_4 - P_2)\ \rho_4} \tag{9}$$

The flashing of FM-200 during the discharge suddenly cools and reduces the pressures in the enclosure. The pressures in Region **2** and Region **4** tend to be less than atmospheric pressure early in the discharge, whereas the addition of more FM 200, the evaporation of residual liquid FM-200, and the gradual warming of the gas-air mixture cause the pressures to increase above atmospheric pressure towards the end of discharge. Thus, flow may be either into or out of the enclosure at various times during the discharge.

If P, $>P_A$, the mixture and air flow rates out of the enclosure are given by:

$$\dot{m}_{2L,\ air} = C_d(1-x_2)\ A_{2,\ leakage}\sqrt{2\ (P_2 - P_A)\ \rho_2} \qquad \textbf{(10)}$$

$$\dot{m}_{2L,\ FM\text{-}200} = x_2 C_d\ A_{2L,\ leakage}\sqrt{2\ (P_2 - P_A)\ \rho_2} \qquad \textbf{(11)}$$

If $P_2 < P_A$, the air outside will flow into the enclosure; the mass flow rates are given by:

$$\dot{m}_{2L,\ air} = -C_d\ A_{2L,\ leakage}\sqrt{2\ (P_A - P_4)\ \rho_A} \qquad \textbf{(12)}$$

$$\dot{m}_{2L,\ EM\text{-}zoo} = 0 \qquad \textbf{(13)}$$

where $A_{2L,leakage}$ is the leakage area of Region **2;** C_d is discharge coefficient; and ρ_A is the density of air outside the enclosure. Region **4** has analogous equations as Region **2.**

2. Energy Conservation Equations

The energy conservation equation can be derived as follows:

Rate of system energy change = Energy added by FM-200 discharge(E_{20})
+ Energy got from wall jet heat transfer(E_{21})
+ Energy got from air flow through the leakage (E,,)
- Energy change from Region 2 to Region **4** (E,)
+ Energy increment by entrained air (E_{24})
- Energy loss due to leakage flow (E_{25}) **(14)**

Since the enthalpy is a function of temperature, it is given by:

$$H_T = C_P\,(T - T_{ref}) \quad (15)$$

The discharge temperature of **FM-200** is **256 K,** thus, taking reference temperature T_{ref} as ***256*** K, the energy added by **FM-200** discharge E_{20} is equal to 0.

Donaldson et al [6] have determined that the heat transfer coefficient correlation for a wall jet with $R_e > 10^4$ and $z/D_{jet} > 30$, can be written as:

$$h_{walljet} = 0.128\, R_e^{0.8} \left(\frac{k}{D}\right) \quad (16)$$

where R_e is the Reynolds number; D is the characteristic length of wall jet; and k is the thermal conductivity. Hence, E,, in Eqn 14 is given by:

$$E_{21} = A_{walljet2}\, h_{walljet2}\, (T_w - T_2) \quad (17)$$

where T_w is the inside wall temperature of enclosure; $A_{walljet2}$ is the area of wall jet in Region **2;** and T_2 is the temperature of Region 2.

When the pressure of Region **2** is less then the ambient atmospheric pressure, air will flow into the enclosure through the leakage area and will bring energy to the enclosure as given by:

$$E_{22} = \dot{m}_{2L,\ leakage}\, C_{p,\ air}(T_A - T_{ref}) \quad (18)$$

where $C_{p,air}$ is the specific heat of air; and T_A is the temperature of air.

The energy transferred from Region **2** to Region **4** will be depend on the pressure of Region **2** and Region **4.** Here if P, $>P_4$ **,** The E_{23} is given by:

$$E_{23} = (\dot{m}_{24,FM-200} + \dot{m}_{24,air})C_{p,2}(T_2 - T_{ref}) \quad (19)$$

The energy gained by air entrainment into the FM -200 dischargejet is:

$$E_{24} = Q_{antrain,\ air}\, C_{p,\ air}(T_A - T_{ref}) \quad (20)$$

Ifthe pressure of region 2 is greater than the atmospheric pressure, the gas-air mixture flows out and the associated loss of energy by convection is given by:

$$E_{25} = (\dot{m}_{2L,\ FM-200} + \dot{m}_{2L,\ air})C_{p,\ 2}(T_2 - T_{ref}) \quad (21)$$

The rate of energy change of Region 2 is a function of time and temperature. It is written as:

$$\frac{d}{dt}(M_{2,FM200}H_{2,FM200}+M_{2,air}H_{2,air}) = (\frac{dM_2}{dt}C_{p,FM200}+\frac{dM_{2,air}}{dt}C_{p,air})(T_2-T_{ref}) + (m_{2,FM200}C_{p,FM200}+M_{2,air}C_{p,air})\frac{dT_2}{dt} \quad (22)$$

where $M_{2,FM200}$ and $M_{2,air}$ are the mass of FM200 and air in the Region *2;* $H_{a,FM200}$ and $H_{2,air}$ are enthalpy of FM200 and *air* in the Region 2. In order to simplify the energy equation, we set the first item on the right side of Eqn. (26) equal to E„ and the second term equals to E_{27} (dT/dt). Finally, we have the energy equation for Region 2.

If $P_2>P_A$, $E_{22}=0$, $E_2=E_{21}-E_{23}+E_{25}-E_{26}$
If $P_2<P_A$ E„ $=0$, $E_2=E_{21}-E_{22}-E_{23}+E_{24}-E_2$

$$\frac{dT_2}{dt} = \frac{E_2}{E*}, \quad (23)$$

Equation (1), (2), **(3), (4),** (23), and their counterparts for Region **4** constitute a model describing the discharge process in Region *2* and Region **4.** From now on, this model will be referred as the Four-Region model. It must be emphasized that this four-region model only has the mass and energy equations in Region *2* and Region **4** because the free jet Region 1 and the wall jet Region **3** is comparatively small, thus the FM-200 discharged from then nozzle comes into Region 2 and Region **4** at the rate given by the reflection of the jets off the nearest wall such that if the jets are horizontal the energy is equally partitioned into regions *2* and **4.**

Model Formulation After Discharge

The following assumptions are adopted for the post-discharge distributions in the enclosure:

1. Linear distribution of density with elevation.
2. Uniform distribution of temperature.
3. No variations in the horizontal directions.
4. Ideal gas law applicable locally.
5. Hydrostatic pressure distribution based on density distribution.

The post-discharge model corresponding to these assumptions is illustrated in Figure 2. The conservation equations are the same as those derived for the CO, discharge model [4], and will not be repeated here because of page number limitations.

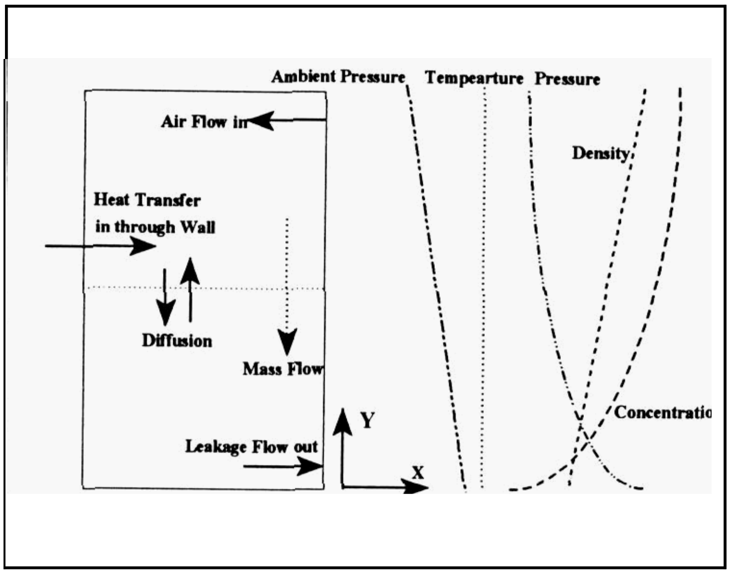

Figure 2 Post-Discharge Model Schematic

The CO_2 model has been modified to include the turbulent diffusive mixing that occurs between the upper and lower regions as illustrated in Figure 2. Even after discharge, there is still a turbulent mixing because of the residual turbulent flow associated with the discharge. Based on the turbulent wall jet model proposed by Launder and Rodi [7], the turbulent viscosity is given by

$$v_t = C_\mu k^{1/2} L$$

where k =local turbulent kinetic energy,
L=representation length scale,
C_μ= constant.

Inserting this equation into the momentum balance equation and using the jet mixing velocity decay correlation of Moodie [8], the turbulent residual velocity after discharge is given by

$$v_m = v_{m0} \exp(-t/\tau)$$

where v_{m0} is the initial turbulent jet orifice velocity, and v_m is the turbulent velocity at time t. τ is defined as

$$\tau = \frac{4.57x}{v_j[1-\exp(\frac{1}{0.074\frac{x}{r_I}})]}$$

v_j is the jet velocity,
r_j is the jet diameter, and
x is the distance from nozzle to the wall of the enclosure.

Assuming that turbulent mass transfer has the analogous correlation as heat transfer for this flow geometry, the Sherwood number Sh (defined as the ration of the total mass transfer to the purely diffusive mass transfer) is given by

$$Sh = CRe_D^m S_c^{1/3}$$

where Re is Reynolds number, and Sc is Schmidt number. C and m are constant dependent upon the flow geometry of the enclosure.

Using this approach, the turbulent mass transfer rate between upper region and lower region is given by

$$\dot{m}_{u-l} = k_g A(\rho_{lower} - \rho_{upper})$$

where k_g is mass transfer coefficient, defined by Sh D_{A-B}/L,
D_{A-B} is diffusion coefficient, m^2/s
L is diffusion length, m
A is the horizontal cross section area of the enclosure, m^2 and
ρ_{lower}, ρ_{upper} are the mixture density in the lower region and upper region, respectively

This representation of turbulent diffusive mass transfer between upper region and lower region provided a more uniform concentration in the enclosure after discharge and correspondingly better agreement with data than the molecular diffusion formulation described in [4].

NUMERICAL METHODS FOR SOLUTIONS

The Runge-Kutta method of order four is used for the solution of the during discharge model because it is quite accurate, stable, and easy to program. The Runge-Kutta Fehlberg method is chosen for the solutions of post discharge because the time step is adjustable according to a specified error limit. Before the Runge-Kutta-Fehlberg method can be applied to solve the variables on pressure, temperature and density,, it is necessary to solve the set of simultaneous algebraic equations describing the transition from the discharge to post-discharge models [3]. The method of Gauss-Jordan Elimination Method is adopted for its simplicity in computer programming and its characteristics of stability.

Thermal properties of air, FM-200, and agent-air mixture vary with temperature. The polynomial equations for FM-200 properties built into the computer code are those recommended by Robin [9]. Other thermodynamic and transport property values are taken from a variety of handbooks.

Input data include the enclosure dimensions, elevations and areas of discharge openings, enclosure wall thickness and thermal properties, surface area of any internal structures or equipment, nozzle characteristics, FM-200 discharge rate as a function of time, and outside and inside air properties. The chemical and thermal properties of discharge agent are built into the computer code for convenience, but the user can change them easily by editing a second data input file. Parameters controlling the numerical solutions and the code output are also included in the this data file.

RESULTS AND DISCUSSION

Calculations have been conducted with our FM-200 discharge/retention zone model to simulate two cold discharge tests conducted at the Naval Research Laboratory's (NRL) Chesapeake Bay Detachment (CBD) test facility. The 56 m^3 test enclosure and test methods used for the discharge and fire suppression tests were described by Sheinson et al [10,11] in previous Conference papers. The specific tests simulated employed a standard 4-orifice Navy 3/16" nozzle (Test J2), and an 8-orifice 1/8" node (Test K2). Test data were provided by NRL. In both tests, a total of 25.9 kg FM-200 was discharged within 10 seconds.

The modeling and NRL test results for CBD Test J2 are shown in Figure 3. The test data in Figure 3 show the FM-200 concentration is slightly higher near the roof of the enclosure than near the enclosure deck during discharge, but the concentration is virtually uniform by about 8 s after the 10 s discharge. The modeling results also showed this trend and are in close agreement with data for at least 40 s from

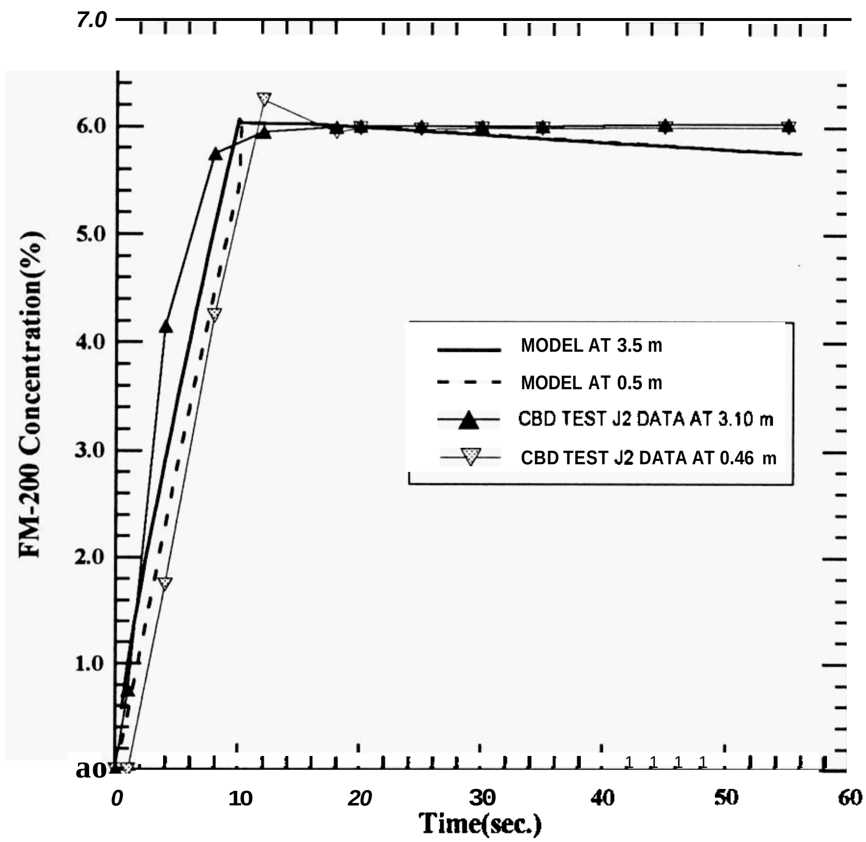

Figure 3, FM-200 Concentration vs Time for Navy 3/16" Standard Nozzle the beginning of discharge. Beyond this time these is a tendency for the model to predict a slight decrease in concentration whereas the measured concentrations remain constant.

The estimated enclosure leakage area around the door and roof panels in the CBD test enclosure is roughly 0.092 m^2 (141 in^2), which is the value used for the calculated results shown in Figure **3.** Sensitivity calculations were conducted with this area increased, and then decreased by a factor of two. This variation produced negligible differences in the calculated concentration histories.

Calculated and measured results for CBD Test K2 (1/8" 8-orifice nozzle) are shown in Figure **4.** This nozzle has a small downward angle (about **8** degrees) between the horizontal line and nozzle discharge centerline. The result is that more FM-200 is discharged into the lower region of the enclosure. Consequently, both the data and calculated concentrations are more uniform during discharge than in test J2 (Fig. **3)** with the horizontal nozzle discharge. Sheinson et al [10] have shown the performance of FM-200, as measured by fire extingusihment time, to be quite sensitive to agent concentration distribution during discharge.

Although the calculated concentrations are slightly higher (about *0.25* v%) than the test results at the completion of discharge, there is good agreement at about 60 sec, which is the duration of the test data. The extrapolated trend would indicate that there is more calculated leakage from the enclosure than measured.

The pressure variation with time in the enclosure during discharge and after discharge is also calculated by the model. Results for CBD Test K2 are shown in Figure ***5. As*** the discharge began, the cold FM-200 (boiling point of -16.4 C at one atmosphere) reduced the enclosure pressure to about *-550* Pa g. **As** the

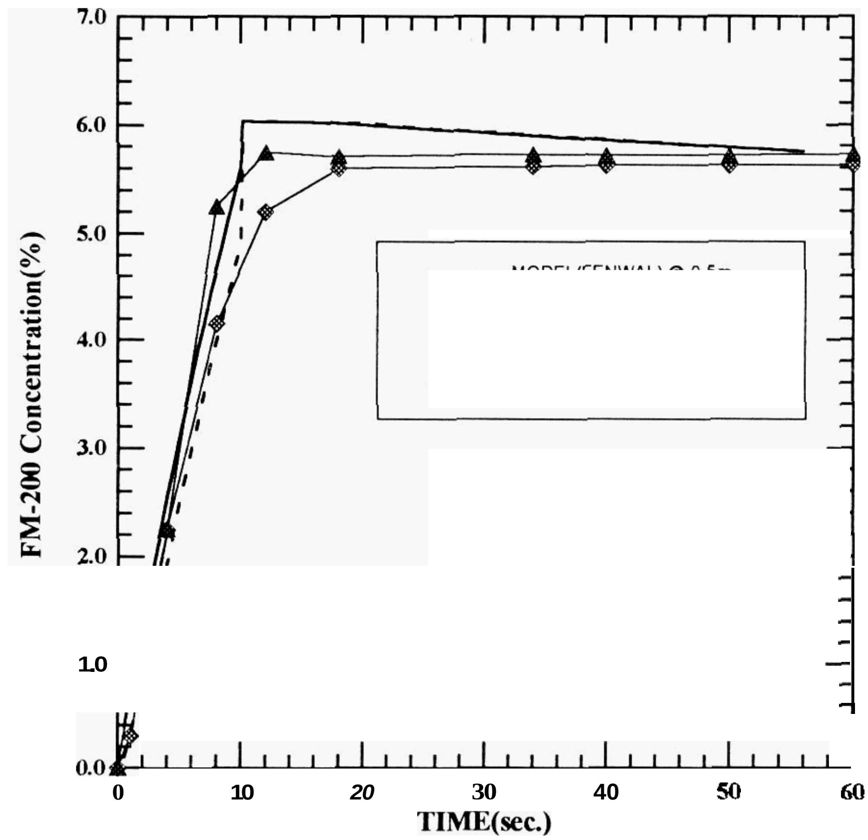

Figure *4* FM-200 Concentration vs Time for **NRL.** CBD Test K2 using 8-orifice 1/8" Nozzle agent-air mixture gradually warmed (partially due to ambient air in leakage), the calculated enclosure pressure increased to about 900 Pascal above the ambient pressure. When the discharge terminated, the calculated pressure sharply decreased to equilibrate with the ambient pressure.

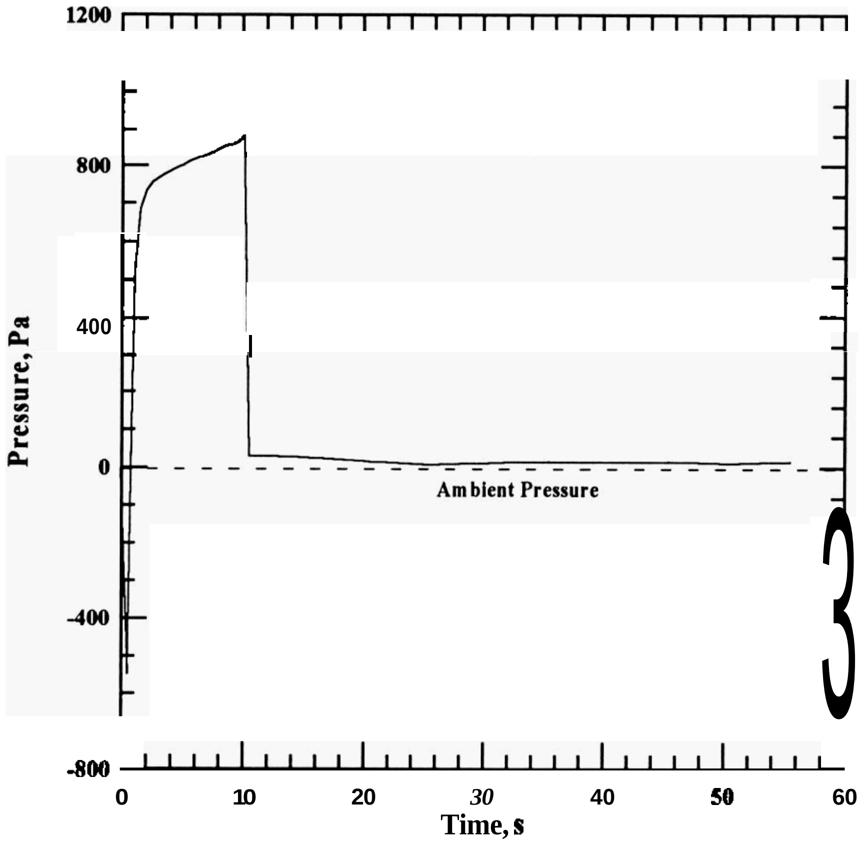

Figure 5 Calculated Pressure Variation with Time During and After Discharge for NRL CBD Test K2

CONCLUSIONS

Calculated FM-200 concentration histories obtained with the new model agree well with data for at least two cold discharge tests in the NRL 56 m^3 test enclosure. Concentration non-uniformities during discharge are dependent on the discharge nozzle employed. The almost uniform concentration distribution after discharge in the empty enclosure is simulated in the model with the turbulent mixing induced by the residual turbulence from the nozzle discharge. Calculated concentration histories for these tests are not sensitive to the leakage area specified as input to the model.

Calculated enclosure pressures show a sudden decrease in pressure below ambient at the beginning of discharge, followed by a more gradual increase in pressure to a peak at the completion of discharge. The calculated peak in at least one test simulation is about 900 Pa

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