FOG INERTING CRITERIA FOR HYDROGEN/AIR MIXTURES

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ABSTRACT

A distributed ignition system has been proposed to ignite hydrogen at low concentration in the ice condenser containment during severe accidents. The post-accident containment atmosphere could be misty due to fog generation from the break flow and condensation in the ice bed. Thus it is important to establish a fog inerting criterion for effective performance of the ignition system. This paper presents such a criterion that specifies the necessary fogging conditions, i.e., fog concentration and drop size, for inerting a hydrogen/air mixture. The criterion shows that the minimum fog inerting concentration varies with the square of the volume mean fog drop size. The present fog inerting criterion is shown to be in general agreement with the Factory Mutual test data.

1. INTRODUCTION

A distributed ignition system has been proposed to ignite hydrogen at low concentration in the ice condenser containment during severe accidents. The post-accident containment atmosphere may be misty because of fog generation by the break flow and condensation in the ice bed. Thus it is of important to establish a fog inerting criterion for effective performance of the ignition system.

Zalosh and Bajpai(1) have recently conducted hydrogen flammability tests to determine the effect of water fogging on the hydrogen lower flammability limit. In the tests, the minimum fog inerting concentrations for various volume mean drop sizes and hydrogen concentrations were measured. It was found that an 8 vol percent hydrogen mixture could be inerted at high fog concentration. Fog formation may also have been responsible for failure of the two Lawrence Livermore tests(2) at high steam concentrations to ignite hydrogen during the test vessel cool-down period.

The capability of fog droplets in inhibiting combustion or quenching flames is due to their heat absorbing capability - high heat of vaporization and small drop sizes (on the order of 10 μ). Due to the small drop sizes, fog droplets could vaporize rapidly (on the order of miliseconds) within a propagating flame front (~ 1 mm thick). If a substantial amount of these droplets are present, the flame may be quenched.

The critical droplet diameter for quenching a hydrogen flame has been estimated by Sandia National Laboratories(3). It was assumed that the measured "quenching distance" for a hydrogen flame propagating through a

tube or between plates could be used for fog droplets. This model does not consider heat transfer and combustion occurring between the burned gas and the suspended droplets.

This paper presents a fog inerting criterion that specifies the necessary fogging conditions, i.e., fog concentration and drop size, for inerting a hydrogen/air mixture.

2. FOG INERTING CRITERIA

Recent hydrogen burn experiments[2] conducted at Lawrence Livermore Laboratory indicated that substantial fog formation could occur when saturated steam is discharged into an unheated vessel. It appeared that this fog prevented a glow plug igniter from successfully igniting the hydrogen mixture in the vessel. The ability of fog in inhibiting and quenching a hydrogen combustion can be explained as follows. The fog droplets suspended in the hydrogen-air-steam mixture act as a heat sink that could absorb a large amount of combustion heat by vaporization, greatly reducing the pressure and temperature rises resulting from hydrogen combustion. If droplets are sufficiently small such that they could vaporize inside the thin (1mm) flame front, the flame may be quenched or inhibited. For a flame speed of 2 m/s, the drop residence time is of the order of 0.5×10^{-3} seconds.[3] In such a short period of time, the droplets of initial radius less than about 4 μ will vaporize entirely in the flame front.

The quenching of a propagating flame is also governed by the distance between droplets. As the droplets become closely packed, the total droplet surface area available for energy loss increases. A critical spacing between droplets exists such that a large fraction of the heat released is absorbed, Thus preventing flame propagation. This critical spacing is known as the "quenching distance", which is usually determined by propagating flames in tubes.

2.1 PREVIOUS WORK

The effectiveness of fog droplets in inhibiting or quenching a flame depends on its quenching distance, which was determined by Berman et al.[3] as

$$d_q = [4V/S]_{crit} \tag{1}$$

where V is the gas volume and S is the heat transfer surface area.

In the suspended fog droplets, this volume-to-surface ratio (i.e., V/S) is equal to $d\,(1-\eta)/6\eta$, where d is the mean droplet diameter and η is the volume fraction of the droplets. When four times this ratio approaches the quenching distance, a critical droplet diameter can be obtained as

$$d_c = \frac{3}{2}\,\frac{\eta d_q}{1 - \eta} \tag{2}$$

Using the quenching distance data for a given volume fraction of water and gas composition, the critical droplet diameter can be determined from Equation (2). The drop sizes less than the critical drop size are capable of quenching a flame.

2.2 PRESENT THEORY

The previous theories do not model the heat transfer and combustion processes occurring between the burned gas and the suspended droplets. A new theory has been developed, which models the heat loss and combustion within a thin flame front.

Consider a hydrogen/air/steam/mist droplets mixture in which a flame is propagating. The flame may be divided into three zones: heating zone, reaction zone, and post-reaction zone as shown in Figure 1. The unburned gas at temperature T_u moves in the reaction zone with the laminar burning velocity S_u. If the unburned gas density is ρ_u, then the constant mass flow rate m is equal to $\rho_u S_u$. The unburned gas is heated to ignition temperature T_i and burned in the reaction zone to reach the flame temperature T_f. The fog droplets will act as a heat sink that reduces the flame temperature. The problem has been formulated and solved by von Karman[4]. In his formulation, three energy equations, which incorporate the heat loss terms, were written for the three zones described above. The solution to these equations yields the following relationship

$$2K\theta_i = \left\{ 1 - \exp\left(-\frac{1}{2}\mu^2\right) (Y_u - Y_f) \times \left[1 + \sqrt{1 + (4\,K/\mu)^2}\right] \right\} \times \left\{ 1 - \frac{1}{\sqrt{1 + K/\mu^2}} \right\} \qquad (3)$$

where $\theta_i = \overline{C}_p\,(T_i - T_u)/q$

$\mu = \sqrt{\overline{C}_p / \overline{\lambda} w}\;\; m$

$K\theta_i = (S/\overline{C}_p w)\;\theta_i$

= the ratio of heat loss rate per unit volume to the heat release rate by chemical reaction per unit volume

q = heat of combustion

$\overline{C}_p$ = mean specific heat

$\overline{\lambda}$ = mean heat conductivity

w = reaction rate (mass of fuel consumed per unit time per unit volume)

Y_u = hydrogen mass fraction in the heating zone

Y_f = hydrogen mass fraction in the reaction zone

m = $\rho_u S_u$

A plot of Eq. (3) is shown in Figure 2. It is seen that for a given $K\theta_i$, there is a minimum value of $(Y_u - Y_f)/\theta_i$. Below this minimum value, there is no solution for the $\sqrt{\theta_i}\ \mu$. Therefore, this value is considered as the flammability limit. At the flammability limit, the value of $K\theta_i$ can be determined from Figure 2 or from Eq. 3 as

$$(K)_{crit}\ \theta_i = f\left((Y_u - Y_f)/\theta_i\right) \tag{4}$$

A plot of $(K)_{crit}\ \theta_i$ as a function of $(Y_u - Y_f)/\theta_i$ is shown in Figure 3. Equation 4 may be expressed as

$$\frac{n}{d^2} = \frac{q\ \overline{C}_p\ \rho_u^2\ Su^2\ (Y_u - Y_f)\ f\left(\frac{Y_u - Y_f}{\theta_i}\right)}{12\ \overline{\lambda}^2 (T_i - T_u)} \tag{5}$$

Detailed derivation procedure for Eq. (5) is given in Appendix A. Using the data on S_u from Reference (5) we can calculate the right hand side of Eq. (5) for a given composition and initial gas temperature.

3. VERIFICATION OF THEORIES BY EXPERIMENTS

Experiments have been conducted at Factory Mutual to study the effects of water fog density, droplet diameter, and temperature on the lower flammability limit of hydrogen-air-steam mixtures(2). The results indicated that most of the fog nozzles tested at 20°C only changed the limit from 4.03 volume percent to 4.76 percent, corresponding to fog concentration in the range of 0.028-0.085 volume percent, and volume mean drop size ranging from 45-90 microns. For the 50°C case, the lower flammability limit increases to 7.2 percent, corresponding to 0.01-0.04 volume percent of fog and 20-50 micron volume mean drop sizes. The results demonstrated that the fog inerting effect is more pronounced at reduced drop sizes and increased temperature.

Figures 4 through 6 show the comparison between the test data and the theoretical predictions. For this comparison, the present theory used the free stream temperature to calculate the thermodynamic properties used in Equation (5). This yielded somewhat higher fog concentrations than those calculated by use of the mean of the flame and free stream temperatures. In Figures 4 and 5, the data suggests a linear relationship between the volume concentration and volume mean drop size on the log-log plot. It also suggests that the minimum fog inerting concentration varies approximately with the square of the volume mean drop size.

The present theory is in good agreement with the Factory Mutual data at 4.76 percent H_2; however, it overpredicts the minimum fog inerting concentration at 7.2 percent H_2. The cause of this discrepancy is still unknown. The discrepancy may be caused by the uncertainty of the data. The following discussion supports this view. The fog droplets are very small and they vaporize very fast in a flame. Therefore, the fog droplets behave as steam except for their larger heat absorption capability. When the fog droplets vaporize, they absorb the heat of vaporization which is much larger than the steam sensible heat. Typically, the heat of vaporization of water is about 1000 Btu/lb and the average specific heat of steam in the temperature range of interest is about 0.48 Btu/lb. It is well known that a hydrogen flame cannot propagate in steam higher than about 64 percent in a steam-air mixture. At 7.9 percent H_2, the adiabatic flame temperature is about 1240°F and therefore the increase of the steam sensible heat is about 540 Btu/lb. Consequently, for the same amount of fog droplets and steam, the fog droplets heat absorption capability is about 1.9 times higher. This means that the fog concentration which is equivalent to 22.1 percent steam in a steam-air mixture is capable of inerting 7.9 percent H_2. This fog inerting volumetric concentration was calculated to be 1.61×10^{-4} ft^3 H_2O/ft^3 mix for 7.9 percent H_2. To inert 7.2 percent H_2, a minimum fog concentration of 1.56×10^{-4} ft^3 H_2O/ft^3 mix equivalent to about 21.3 percent steam in a steam-air mixture is required. These estimates show that the present predictions are reasonable and conservative. The estimates are consistent with Factory Mutual data on 7.9 percent H_2 but not on 7.2 percent H_2.

It should be noted that in the tests three fog concentration measuring techniques were used. These three techniques gave substantially different results. The discrepancy is at least one order of magnitude difference. The fog concentration data presented in Figures 4 through 6 were obtained from one of the techniques. In view of the uncertainty of the data, care must be exercised in using them for fog inerting analysis purposes. They should be used in conjunction with the present fog inerting criterion in the assessment of fog inerting potential in the ice condenser plants. Some uncertainty also exists in the present fog inerting theory. The maximum uncertainty associated with the underprediction of the heat loss and temperature dependence of the thermophysical properties is estimated to be ±63 percent.

4. SUMMARY AND CONCLUSIONS

A fog inerting criterion has been developed to predict the minimum fog concentration required to inert a given hydrogen concentration and volume mean fog drop size. The present fog inerting criterion has been shown to be in general agreement with the Factory Mutual test data. The criterion shows that the minimum fog inerting concentration varies with the square of the volume mean fog drop size.

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APPENDIX A

DERIVATION OF EQUATION (5)

This appendix gives detailed procedures to derive Eq. (5), starting from Eq. (4)

$$(K)_{crit}\ \theta_i = f\ ((Y_u - Y_f)/\theta_i) \qquad (4)$$

where the ratio of heat loss rate per unit volume to the heat release rate by chemical reaction per unit volume, $(K)_{crit}$, is defined as

$$K_{crit} = S/C_p W \qquad (A-1)$$

and the ratio of sensible heat to heat of combustion, θ_i, is defined as

$$\theta_i = C_p\ (T_i - T_u)/q \qquad (A-2)$$

To arrive at Eq. (5), it is necessary to assume that all the heat loss is attributed to convection heat transfer to fog droplets of only one drop size. Under this assumption, the rate of heat loss per unit volume per degree, S, may be expressed as

$$S = n\pi d^2 h \qquad (A-3)$$

where n = number of drops per unit volume
d = volume mean drop size
h = heat transfer coefficient

It is further assumed that the relative velocity between the droplets and the mixture flow is so small that heat transfer coefficient, h, can be approximated by the conduction limit. In fact, it can be shown that for small drop sizes, convection and radiation are unimportant heat transfer mechanisms at the drop surface. Under this assumption, Eq. (A-3) reduces to

$$S = \frac{12\eta\bar{\lambda}}{d^2} \qquad (A-4)$$

where $\bar{\lambda}$ = mean heat conductivity

η = volume fraction of mist droplets $(\frac{n}{6}\pi d^3)$

The of heat generation per unit volume, w, is related to the laminar buring velocity, S_u, and the thickness of the reaction zone, ℓ, by

$$w = \frac{\rho_u \; S_u \; (Y_u - Y_f)}{\ell} \qquad \text{(A-5)}$$

The thickness of the reaction zone may be approximated by

$$\ell = \frac{\bar{\lambda}}{\rho_u \; S_u \; \bar{C}_p} \qquad \text{(A-6)}$$

Combining Eqs. (A-1), (A-4), (A-5), and (A-6), we have

$$K_{crit} = \frac{12n \; \bar{\lambda}^2}{\rho_u^{\;2} S_u^{\;2} \bar{C}_p^{\;2} \; (Y_u - Y_f) \;\; d^2} \qquad \text{(A-7)}$$

Substituting Eqs. (A-2) and (A-7) into Eq. (4), we have

$$\frac{n}{d^2} = \frac{q \; \bar{C}_p \; \rho_u^{\;2} \; S_u^{\;2}}{12 \; \bar{\lambda}^{\;2} \; (T_i - T_u)} \; (Y_u - Y_f) \; f \; (\frac{Y_u - Y_f}{\theta_i}) \qquad \text{(5)}$$

Q.E.D.

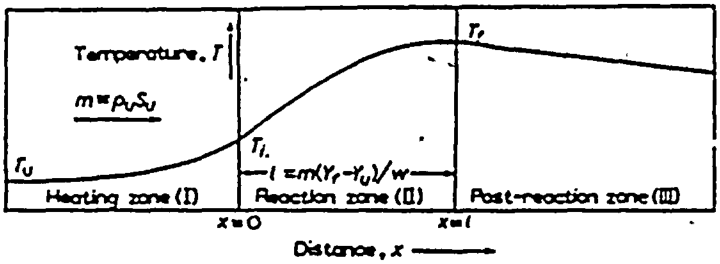

FIGURE 1 SCHEMATIC REPRESENTATION OF TEMPERATURE PROFILE THROUGH THE FLAME FRONT

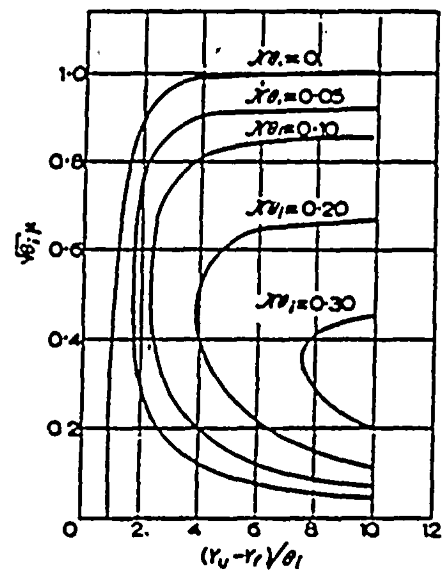

FIGURE 2 THE PARAMETER $\sqrt{\theta_i}\ \mu$ AS A FUNCTION OF $(Y_u - Y_f)/\theta_i$ FOR DIFFERENT VALUES OF $K\theta_i$

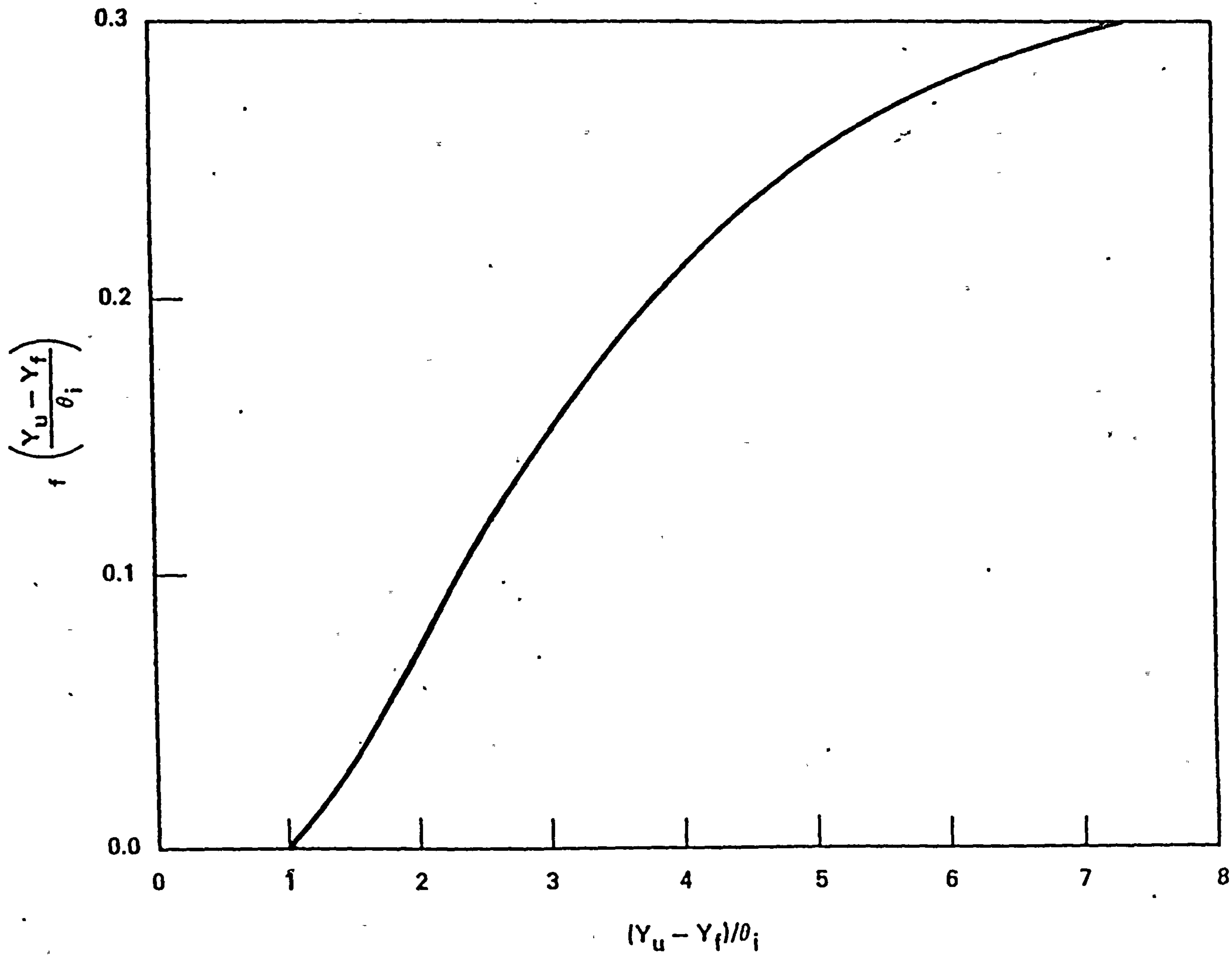

FIGURE 3 $(K)_{crit}\ \theta_i$ AT THE FLAMMABILITY LIMIT AS A FUNCTION OF $(Y_u - Y_f)/\theta_i$

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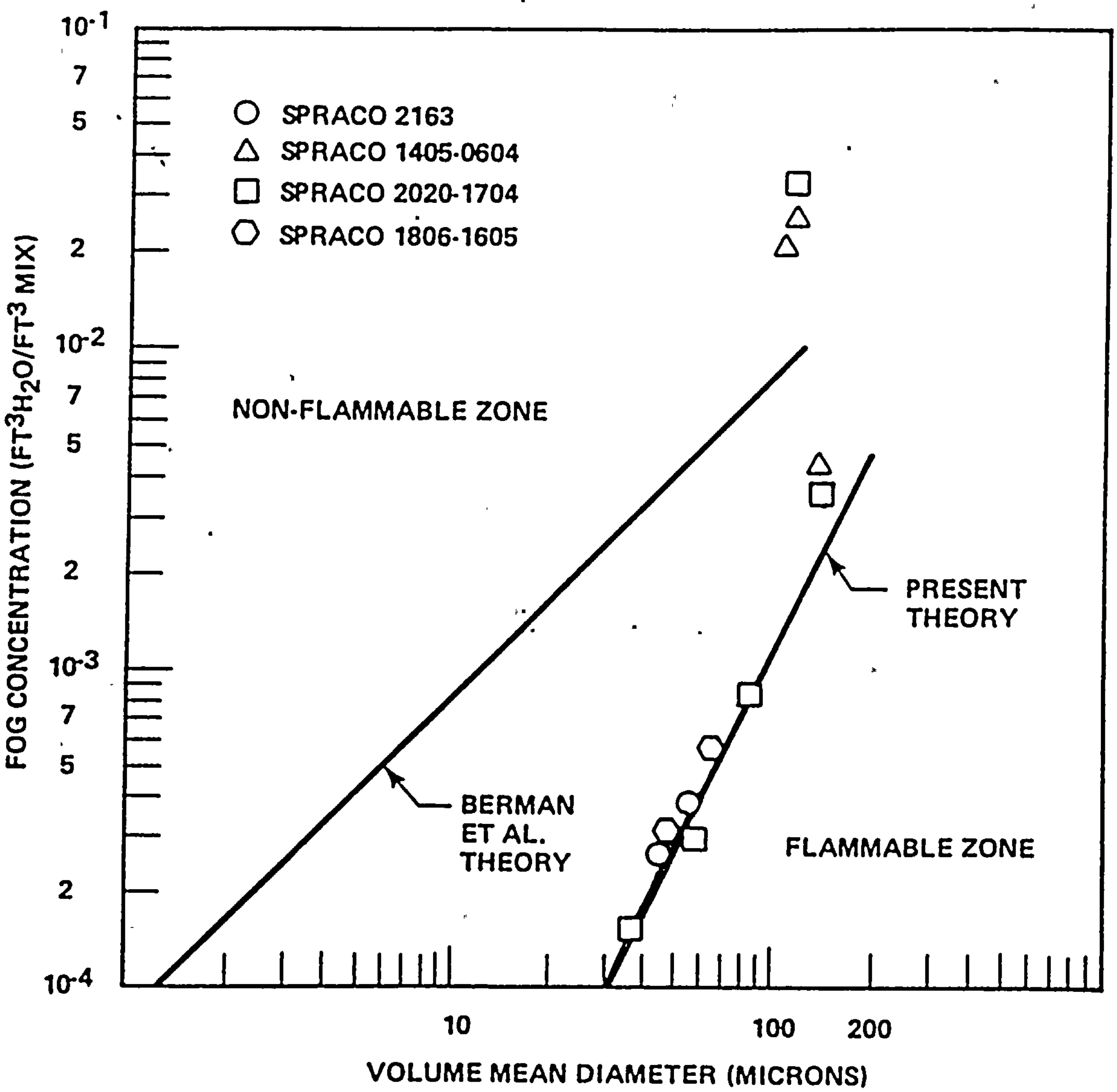

Figure 4. Comparison between Theories and Factory Mutual Fog Inerting Experiments on 4.76 Percent H_2

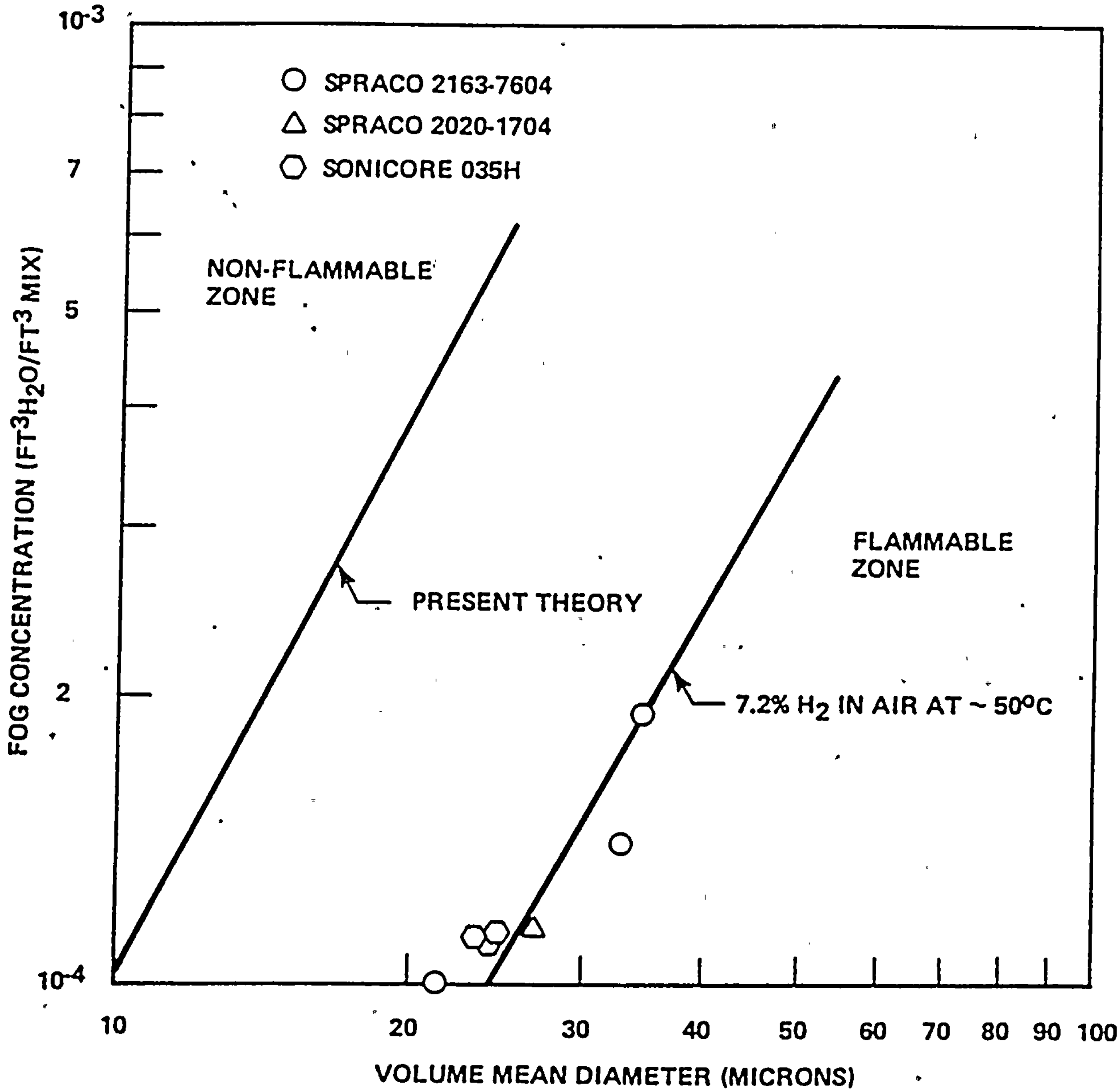

Figure 5. Comparison between the Present Theory and Factory Mutual Fog Inerting Experiments on 7.2 Percent H_2

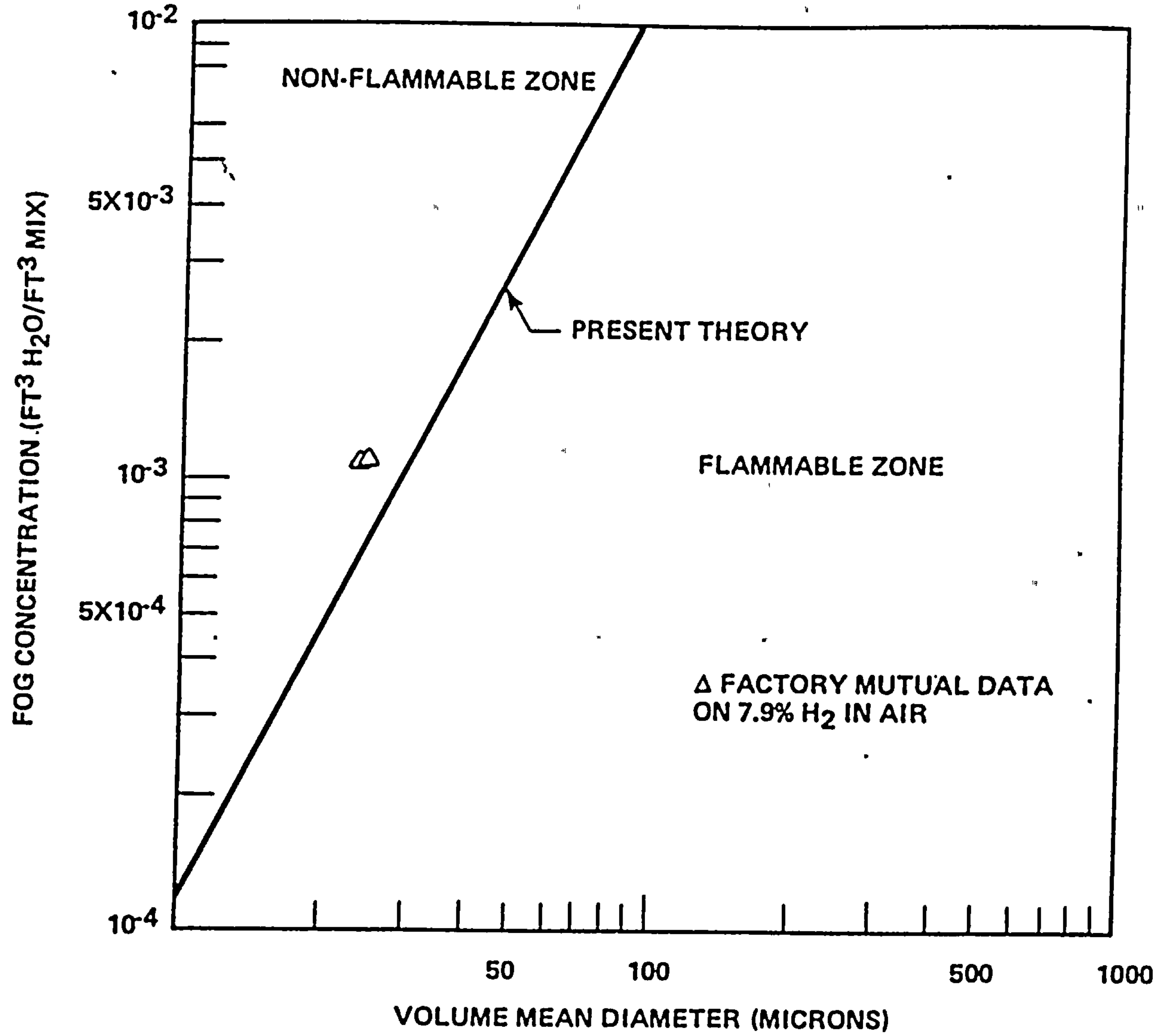

Figure 6. Comparison between the Present Theory and Factory Mutual Fog Inerting Experiments on 7.9 Percent H_2