Hydrogen Mixing in Large Enclosures

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Firexplo

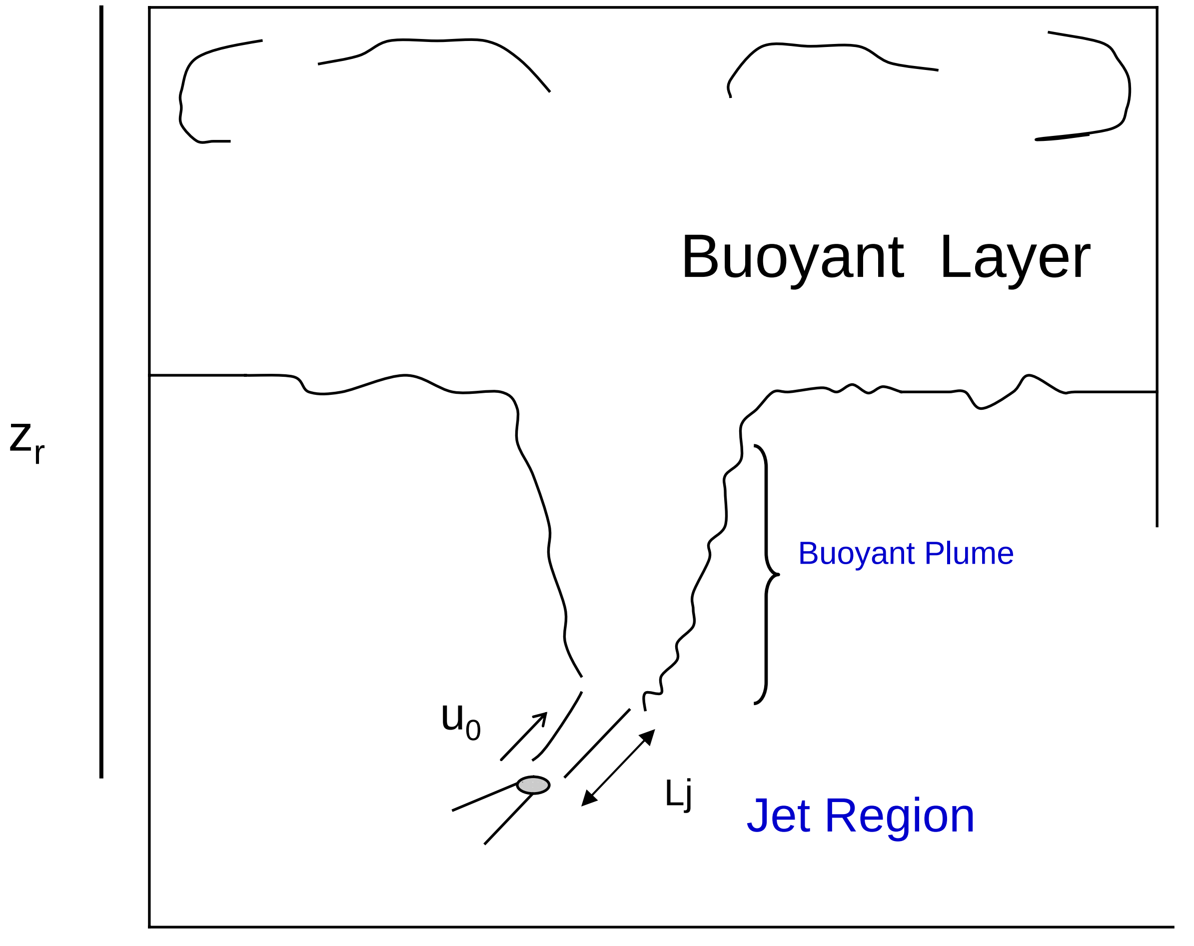
Objectives

1. What are the pertinent physical phenomena, theoretical models and experimental observations associated with a buoyant plume or puff formed from a hydrogen release in a simple, empty enclosure?
2. How do these phenomena, models, and empirical correlations vary with enclosure natural ventilation and forced ventilation parameters?
3. What happened during the hydrogen release in the 1979 Three Mile Island nuclear plant accident?

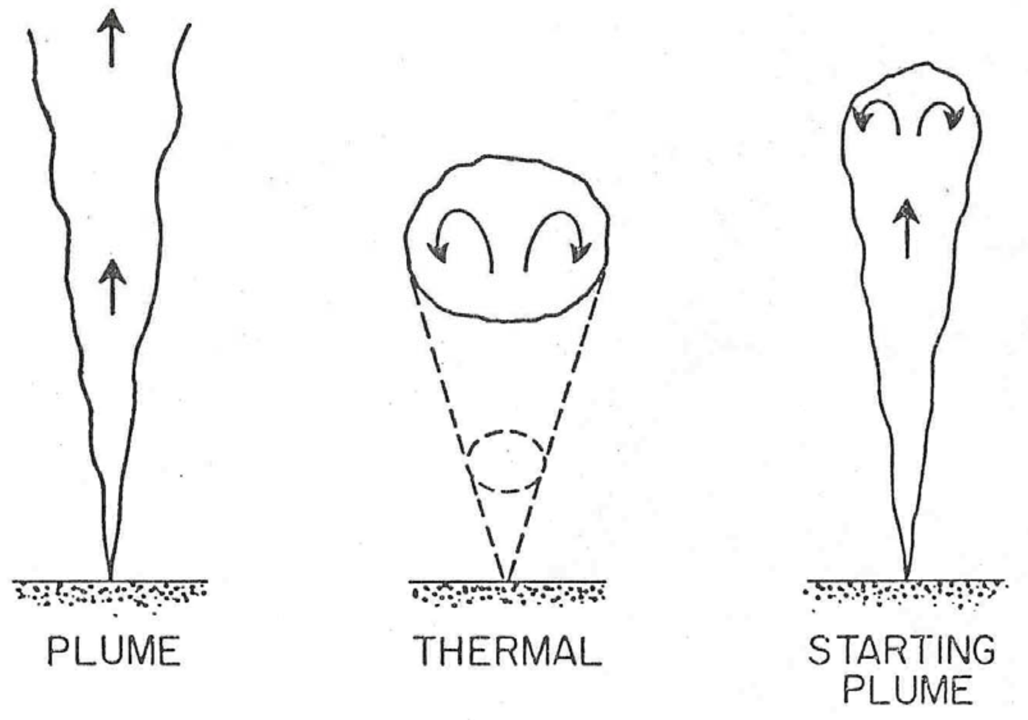
More Questions and Objectives

- Can lumped parameter models provide accurate estimates of average concentrations in multiple compartmented enclosures such as nuclear plant containment structures?
- When are Computational Fluid Dynamic (CFD) computer simulations needed, i.e. when do the lumped parameter models break down?
- What are the effects of major obstructions and other geometric complications?

Buoyant Plume and Ceiling Layer



Comparisons of steady-state plume, starting plume, and thermal (puff)



Selection of appropriate configuration requires comparison of hydrogen release duration to travel time for hydrogen to reach ceiling layer, and to potential time-to-ignition

Buoyant Plume Velocity Correlation

$$w = 4.7 F^{1/3} z^{-1/3} \exp(-96r^2 / z^2)$$

Buoyancy Flux, F:

$$F = w_0 \, g \frac{(\rho_a - \rho_{H2})}{\rho_a} \pi D_0^2 / 4$$

Travel time to reach ceiling:

$$t_{tr} = \frac{0.32 z_r^{4/3}}{F^{1/3}}$$

Example: D_0 = 10 cm, z_r = 5 m, w_0 = 10 m/s

t_{tr} = 1.8 sec

Length of Jet Momentum Region

$$L_j = 1.02 \frac{M_0^{3/4}}{F^{1/2}} = \frac{0.96 w_0 \sqrt{D_0}}{\sqrt{\frac{g(\rho_a - \rho_{H2})}{\rho_a}}}$$

For isothermal release:

$$L_j = 0.32 w_0 \sqrt{D_0}$$

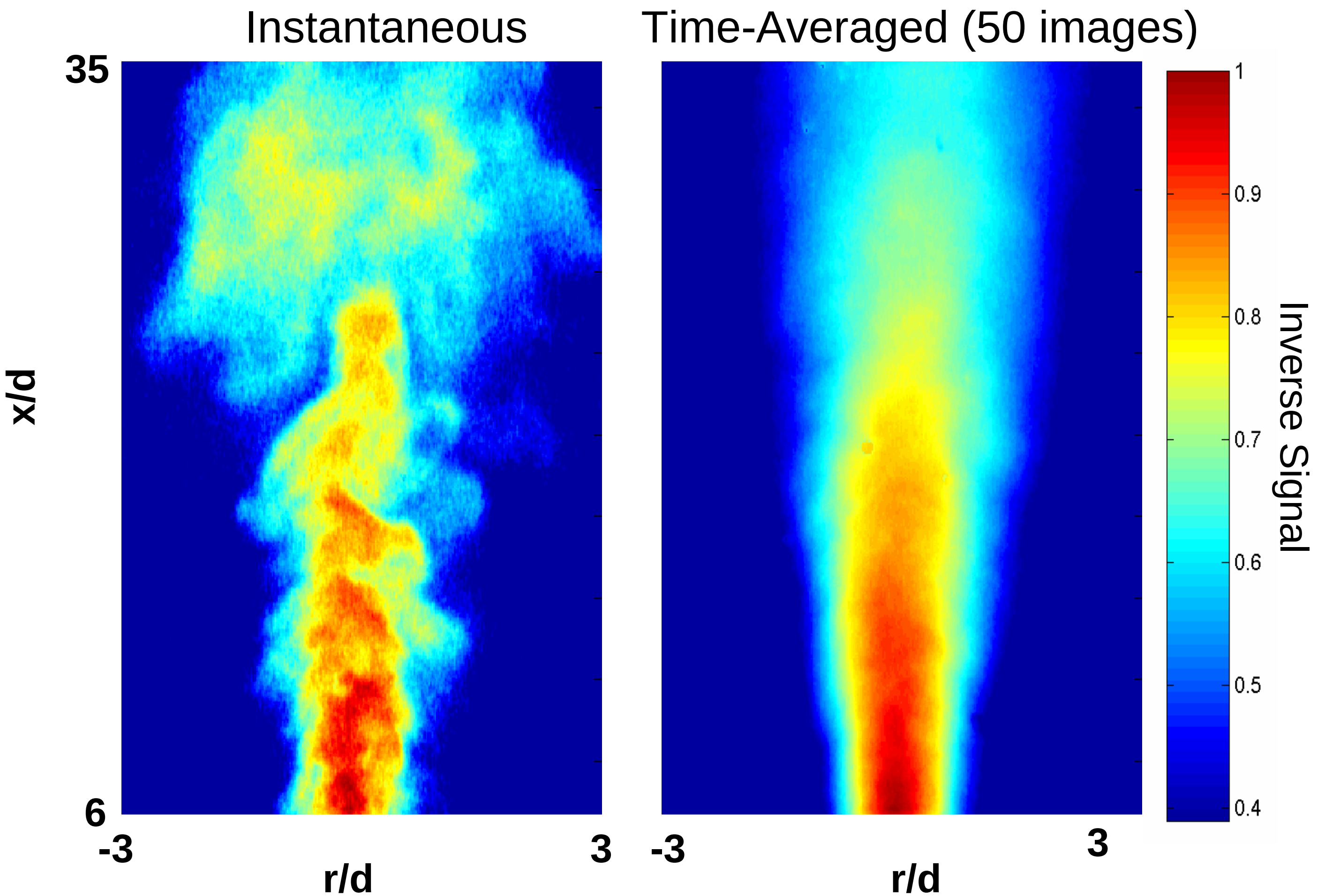
for SI units

Example: D_0 = 10 cm, w_0 = 10 m/s,

L_j = 1 m

H2 Concentration Distribution Measurements at Sandia Livermore

Rayleigh scattering images of unignited H_2 leak



Leak Geometry

Round Jet
d = 1.9 mm
Q = 10 slm
= 0.35 scfm
Re = 1044
Fr = 117

Images reveal instantaneous and time-averaged leak structure.

Plume Hydrogen Concentration and Density Defect Correlations with virtual source

$$\Delta = \frac{11}{g} N F^{2/3} (z - z_{v0})^{-5/3}$$

where

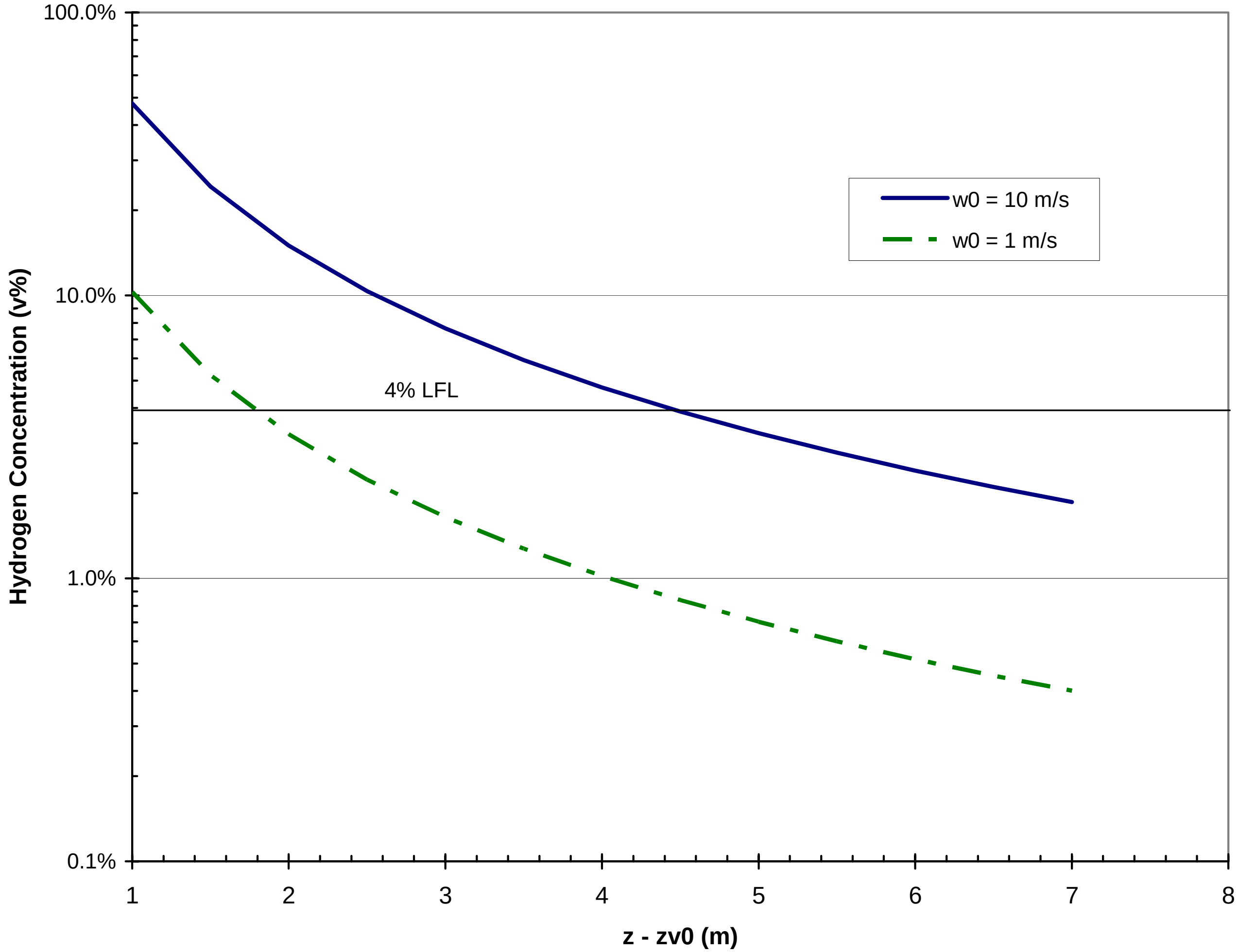
$$N = \left(\pi^{2/3} \frac{6\alpha}{5} (\frac{9\alpha}{10})^{1/3} \right)^{-1}$$

$$L = \sqrt{3N} \Big/ 2$$

. If α = 0.12, N = 5.43.

$$\chi_{H2} = \frac{\Delta}{(1 - \frac{2}{M_a})} = 1.075 \, \Delta$$

Example Axial Distribution for D_0 = 10 cm



Enclosure Effects

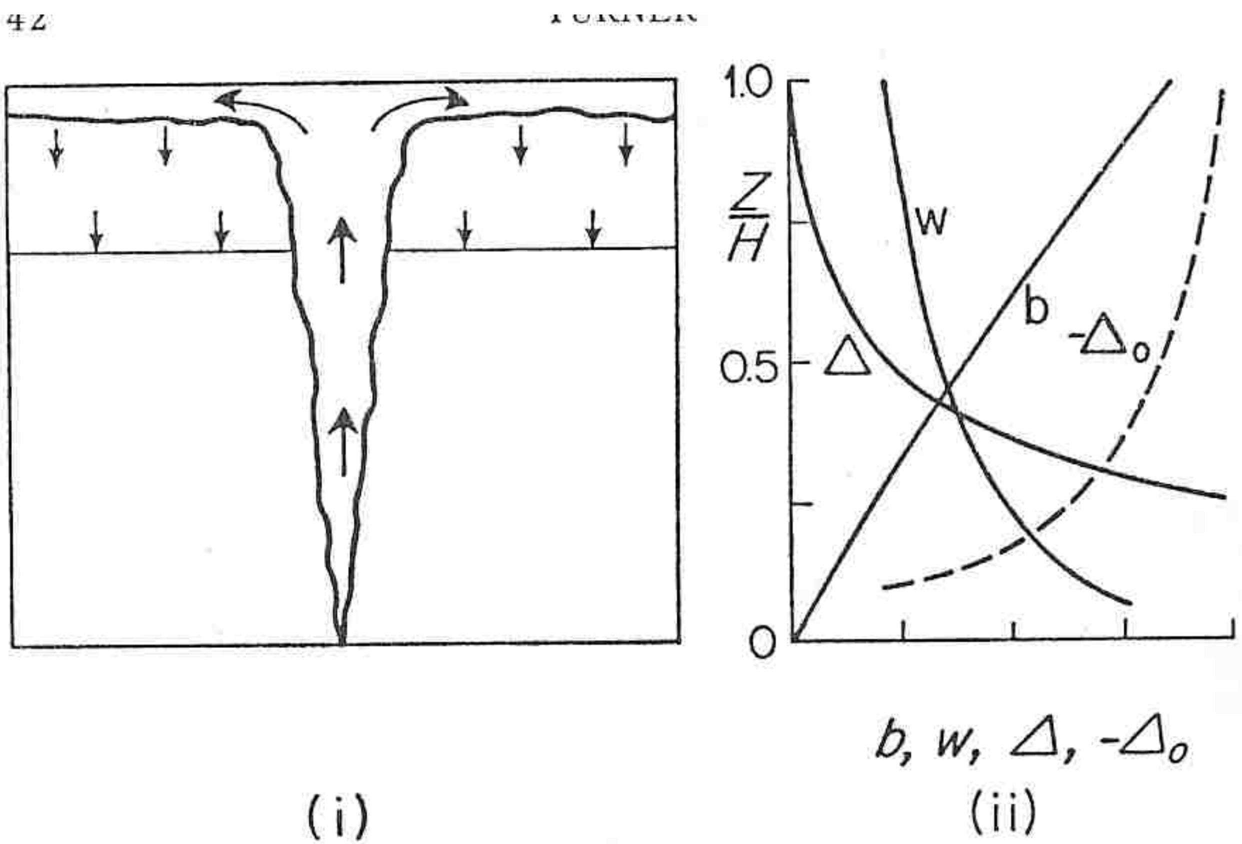
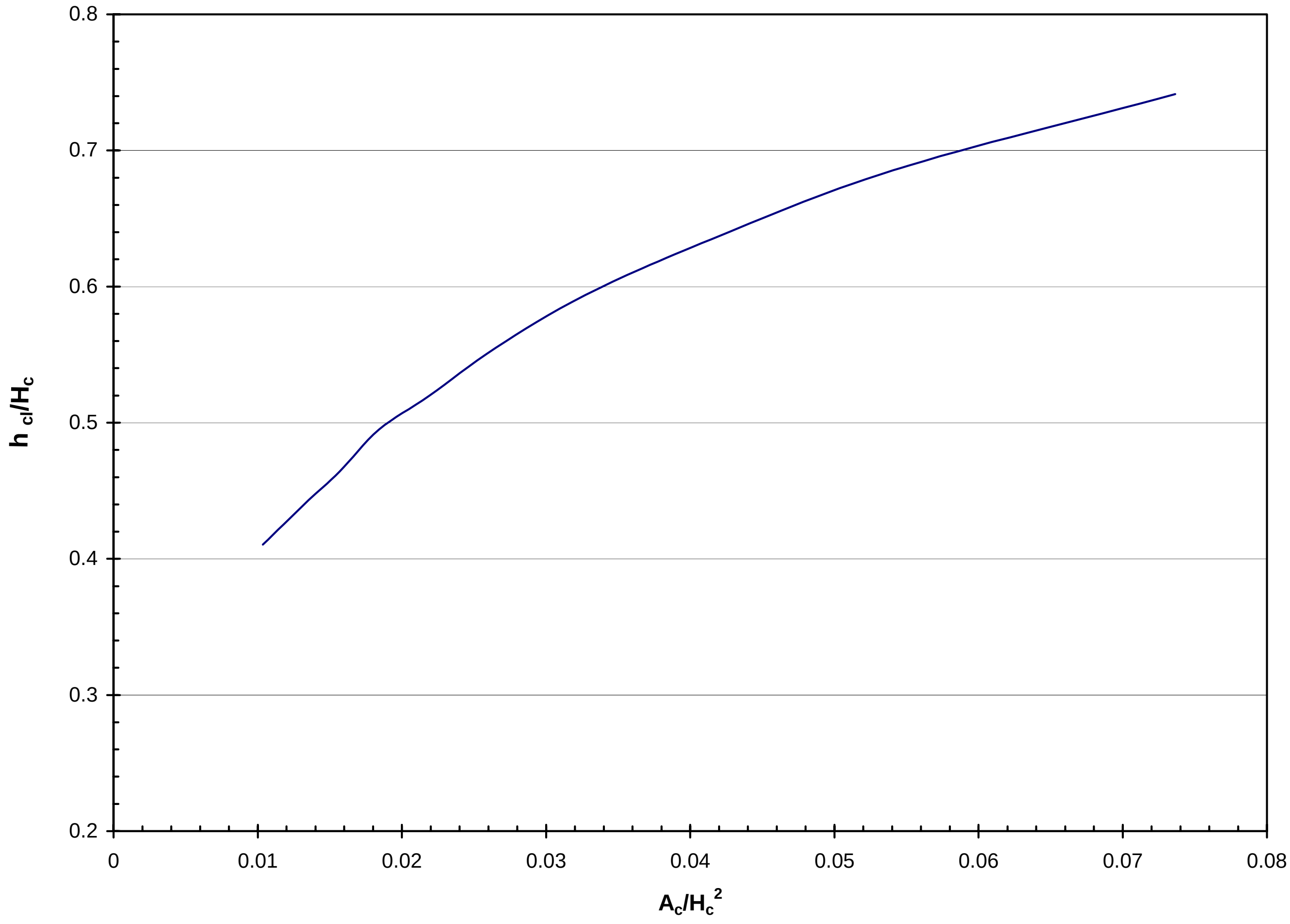


FIG. 3. The "filling-box" model of Baines & Turner (46). (i) Sketch of an early stage of the motion as the first front of light fluid is pushed downwards. (ii) The non-dimensional solutions at large times.

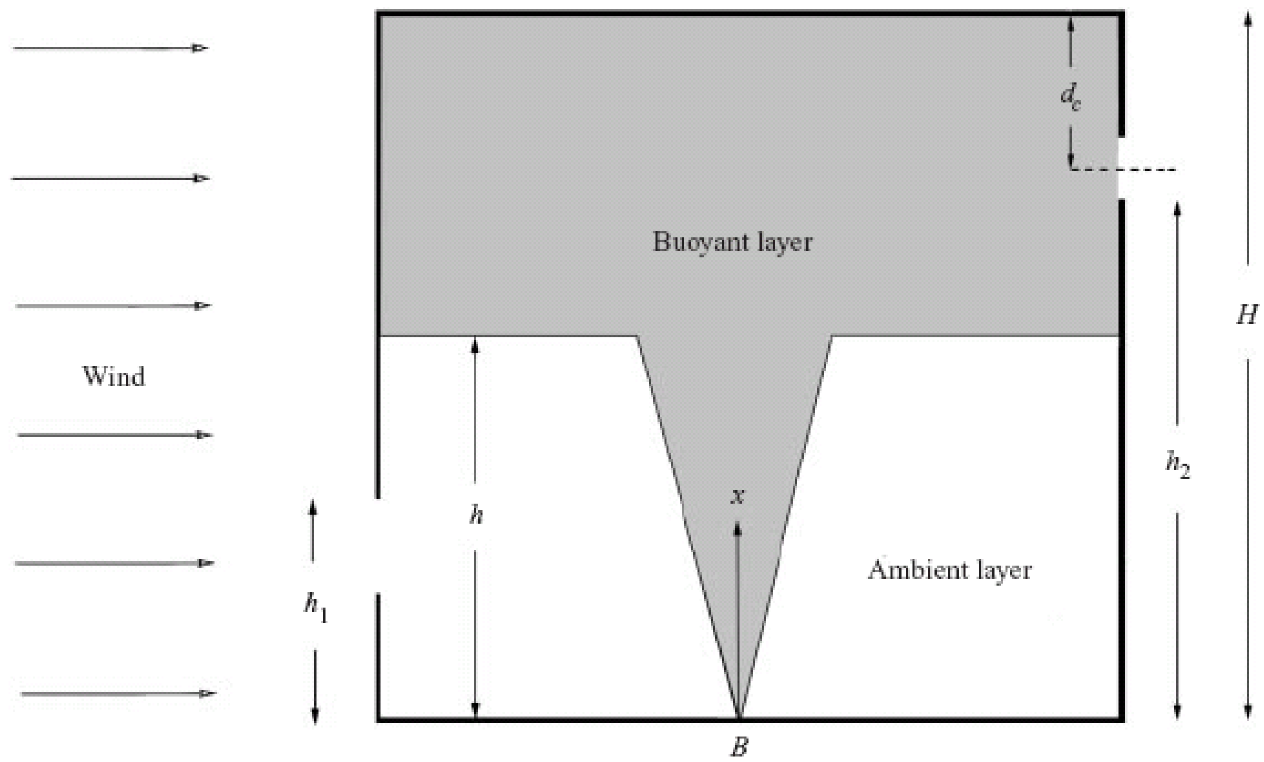
Well-Mixed Ceiling Layer Providing

$$z_r > 0.38\sqrt{A_c}$$

Ceiling Layer Elevation



Ceiling Layer Ventilation/Venting Effects



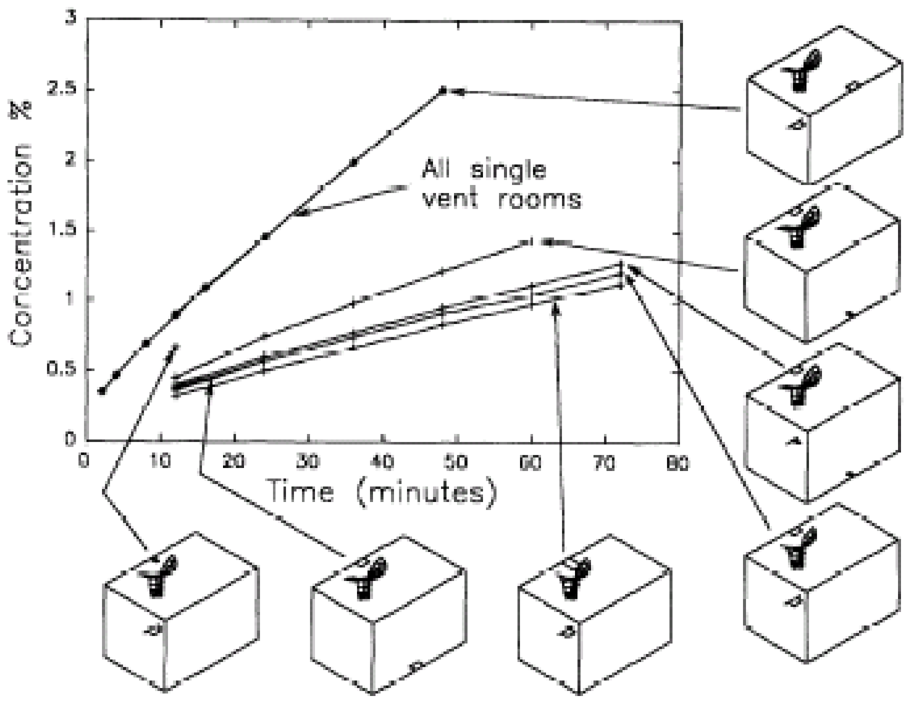
Layer Elevation Eqn:

$$\frac{A^*}{H_c^{\ 2}} = \frac{N^{3/2}\zeta^{5/3}}{\left(\left(1-\zeta-\frac{d_c}{H_c}\right)/\,\zeta^{5/3} + N\,Fr^2\right)^{1/2}}$$

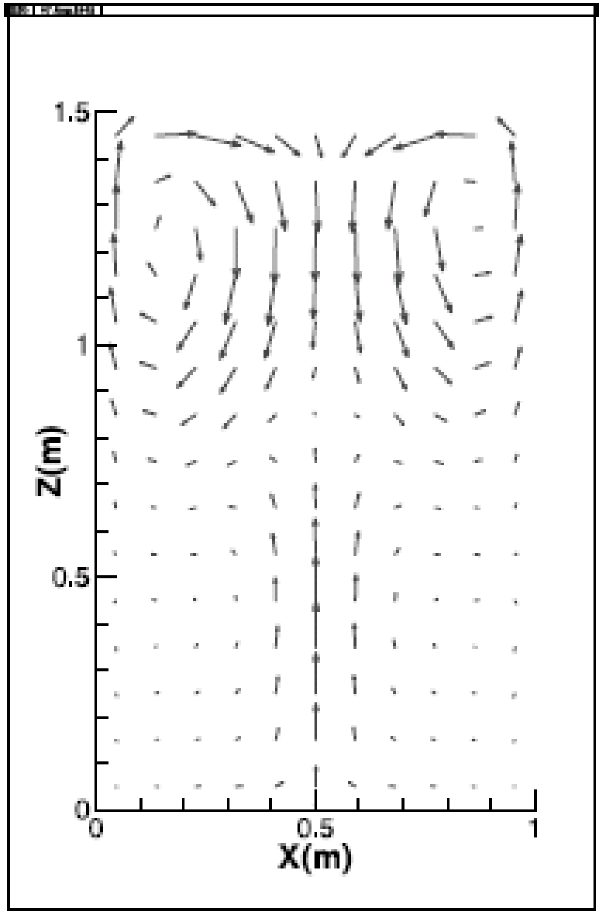
Time to Empty Filled Enclosure by Venting

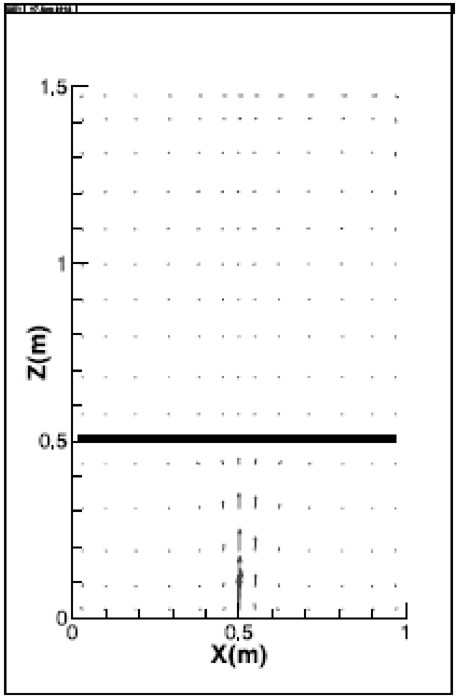
$$T_d = \left(\frac{A_c}{A}\right)\left(\frac{H_c}{g\,\Delta_p\big|_{z=H}}\right)$$

CFD Hydrogen Mixing Calculation

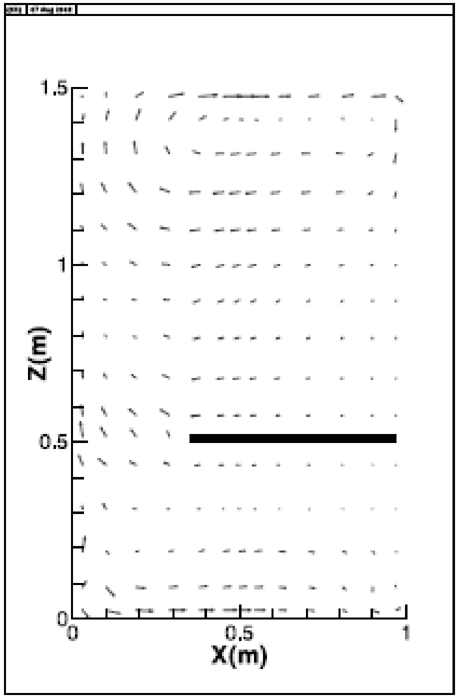


CFD Mixing Calculations for Simple Enclosures



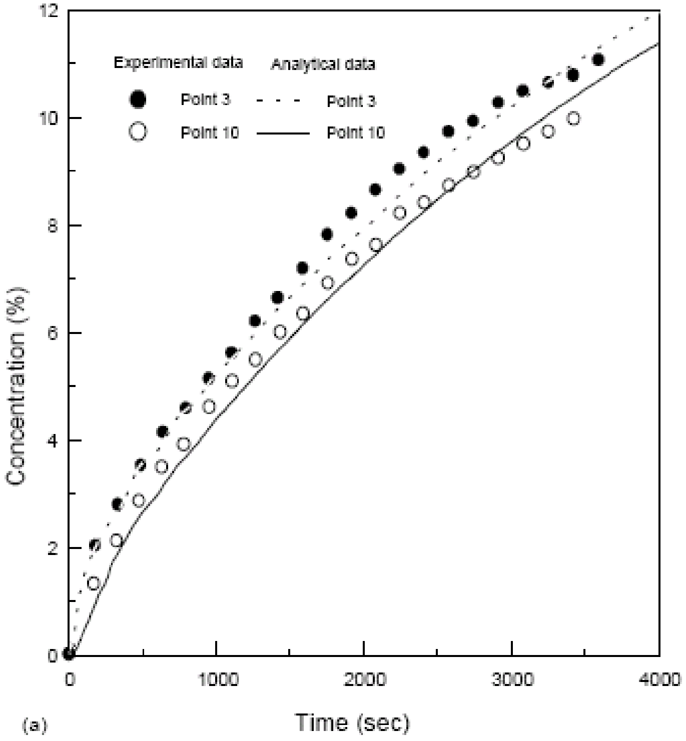


(a)

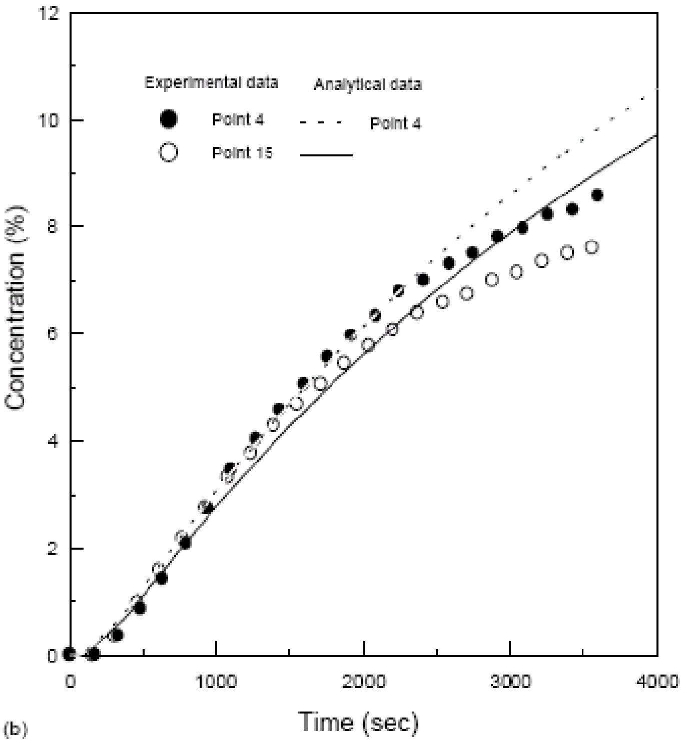


(b)

CFD Comparisons with Data for Simple Enclosures

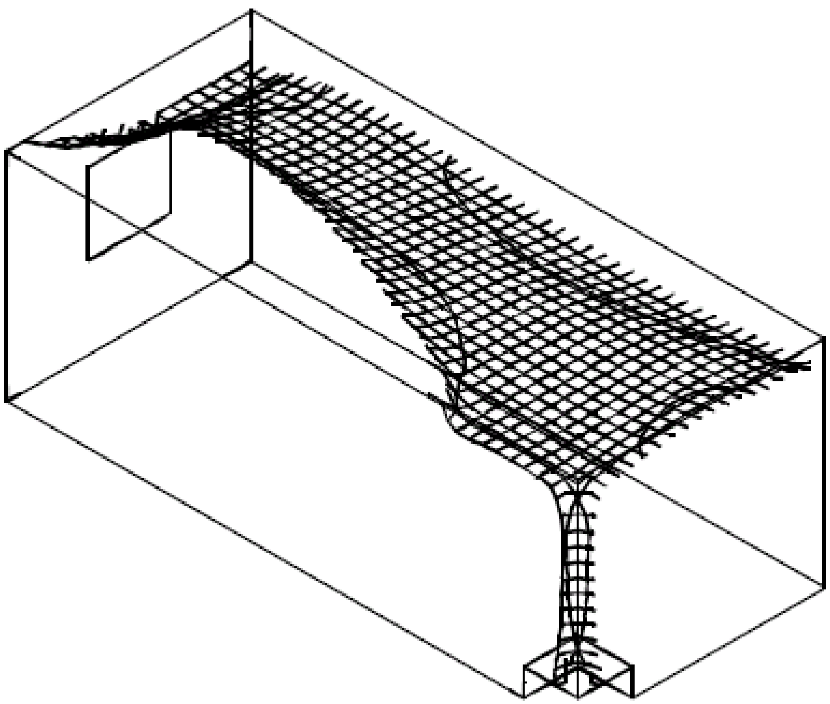


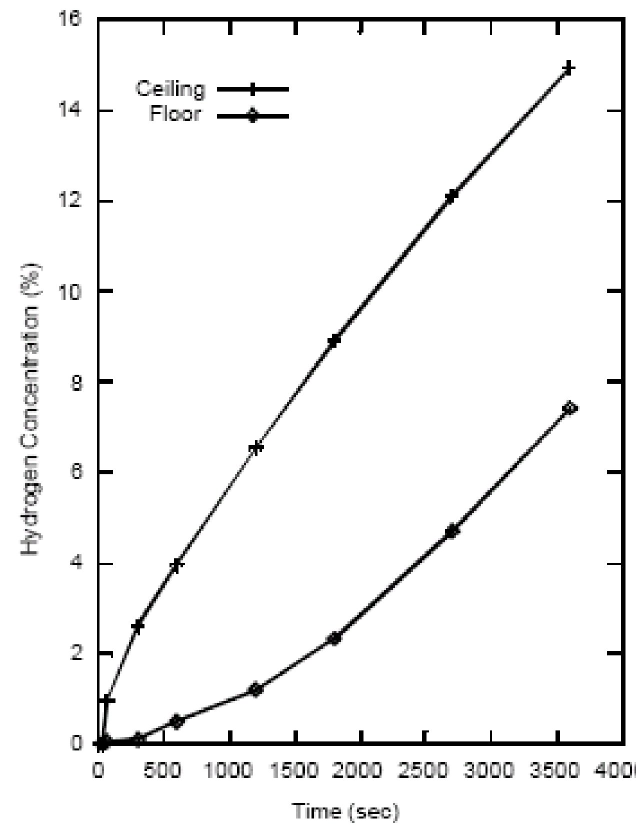
(a)



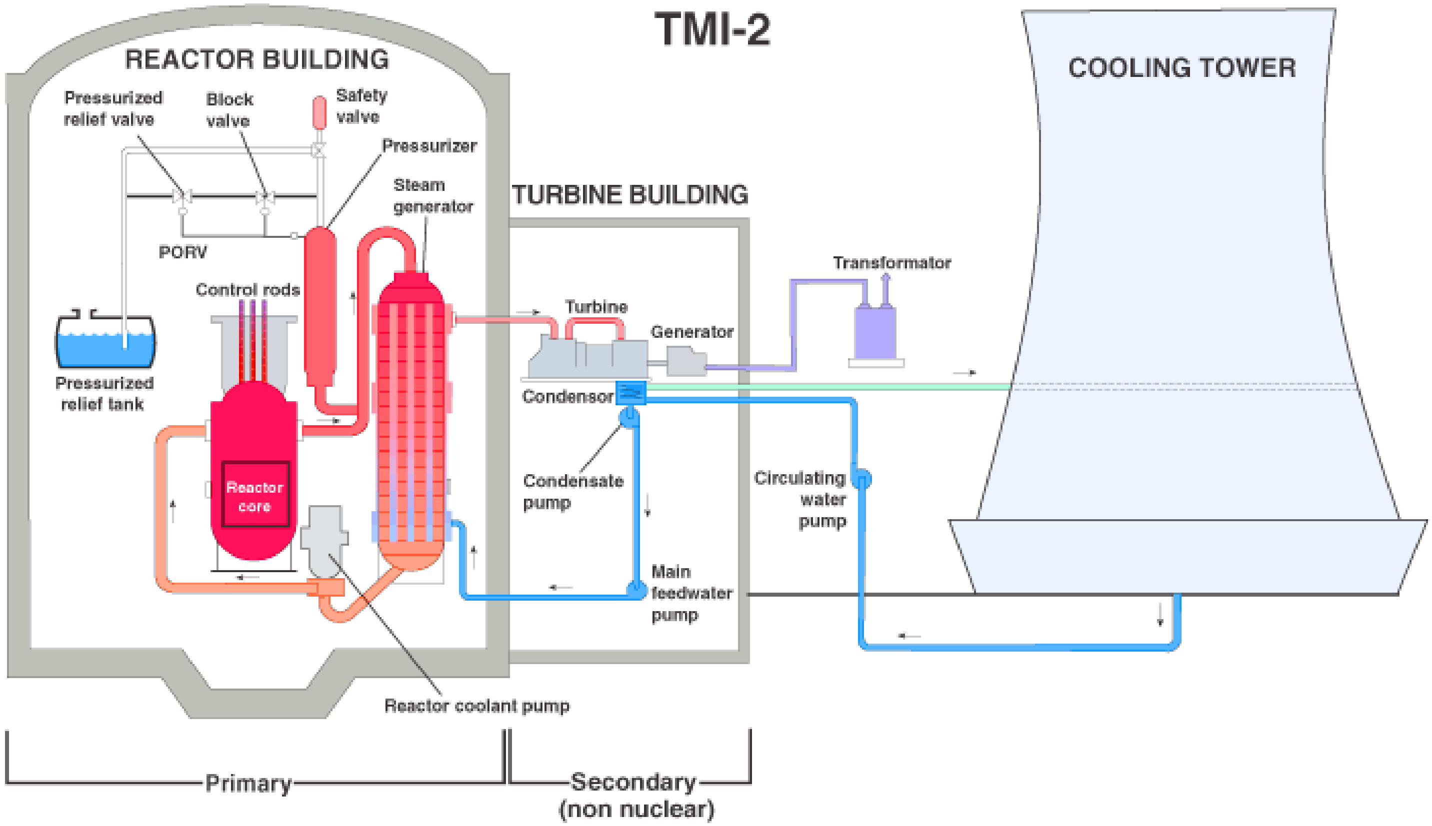
(b)

CFD Simulation of H2 Release in Corner from M. Swain

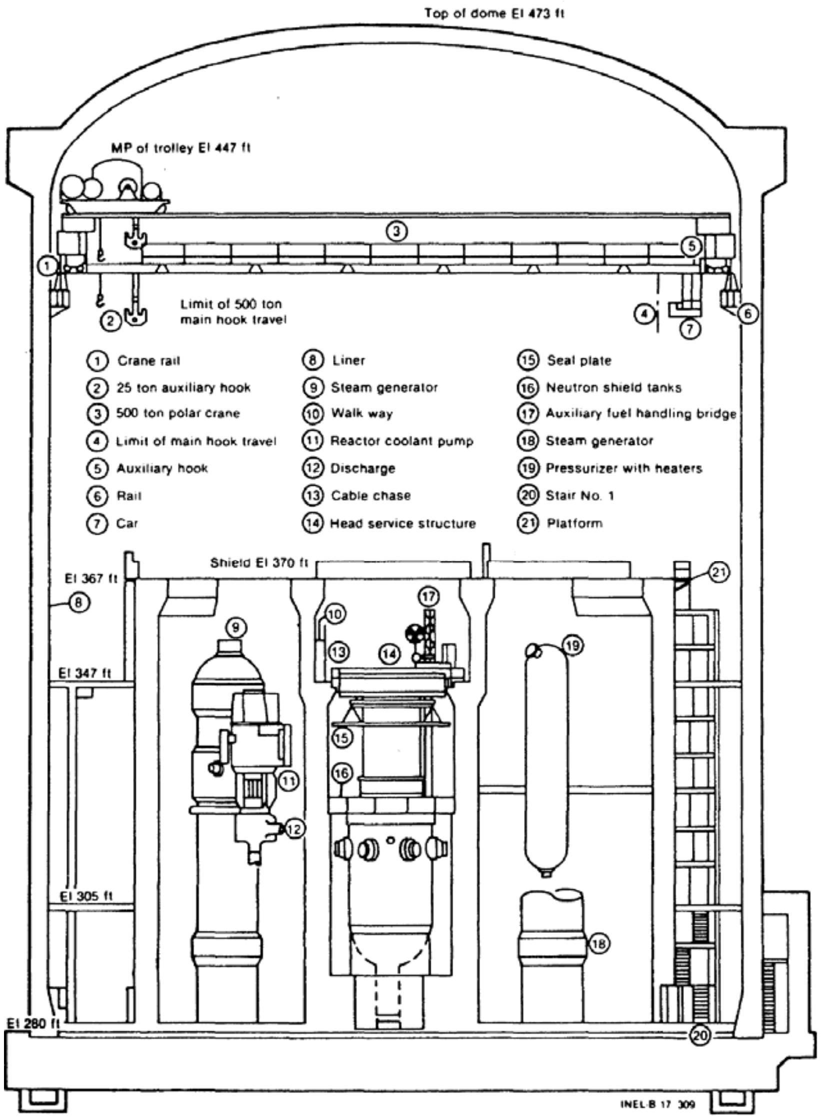


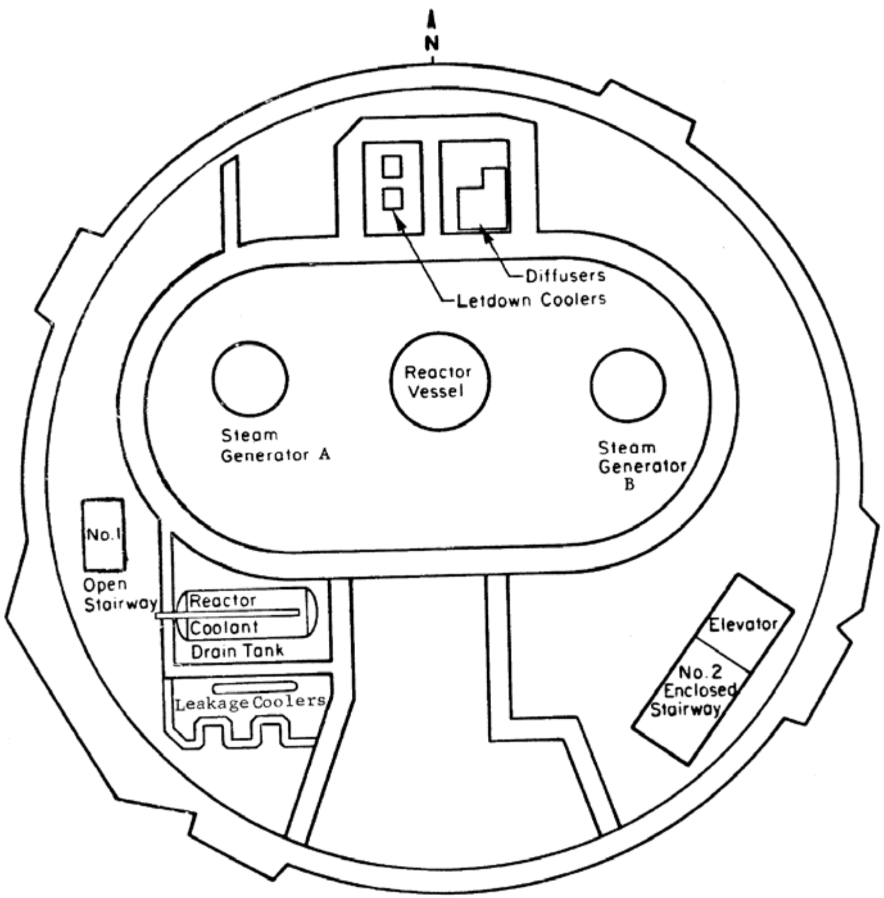


Hydrogen Phenomena During the Three Mile Island Accident

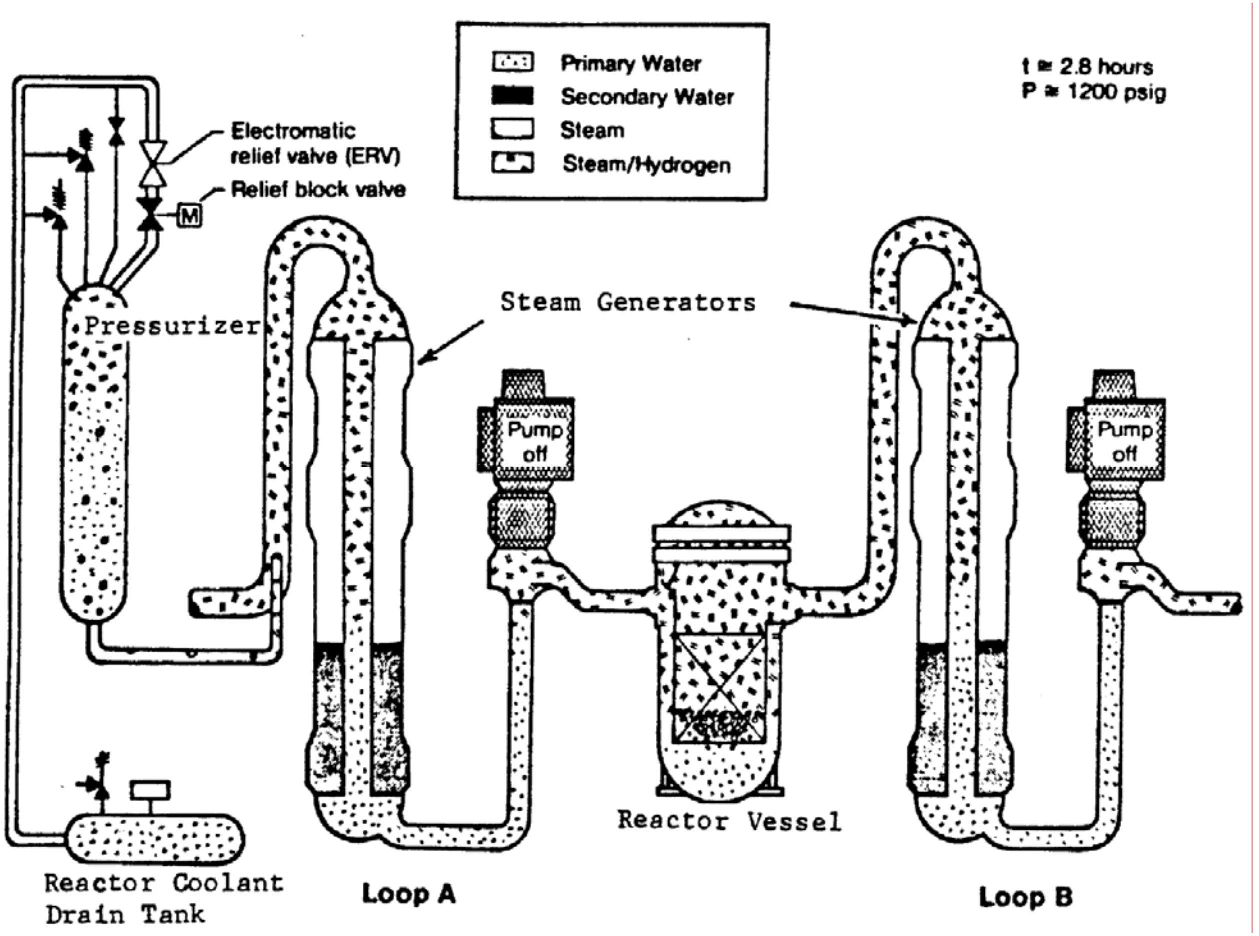


TMI Containment Cross-Sections

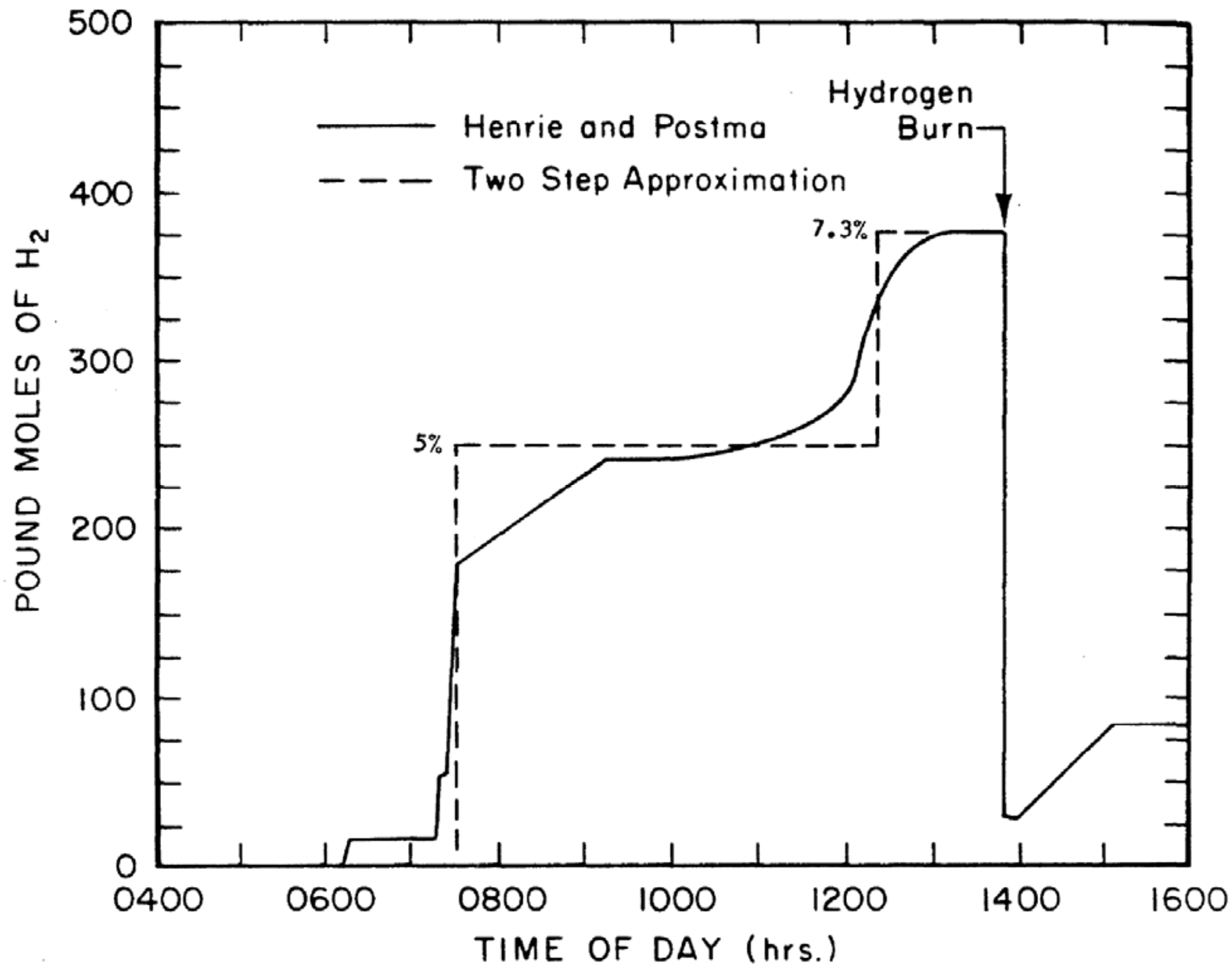




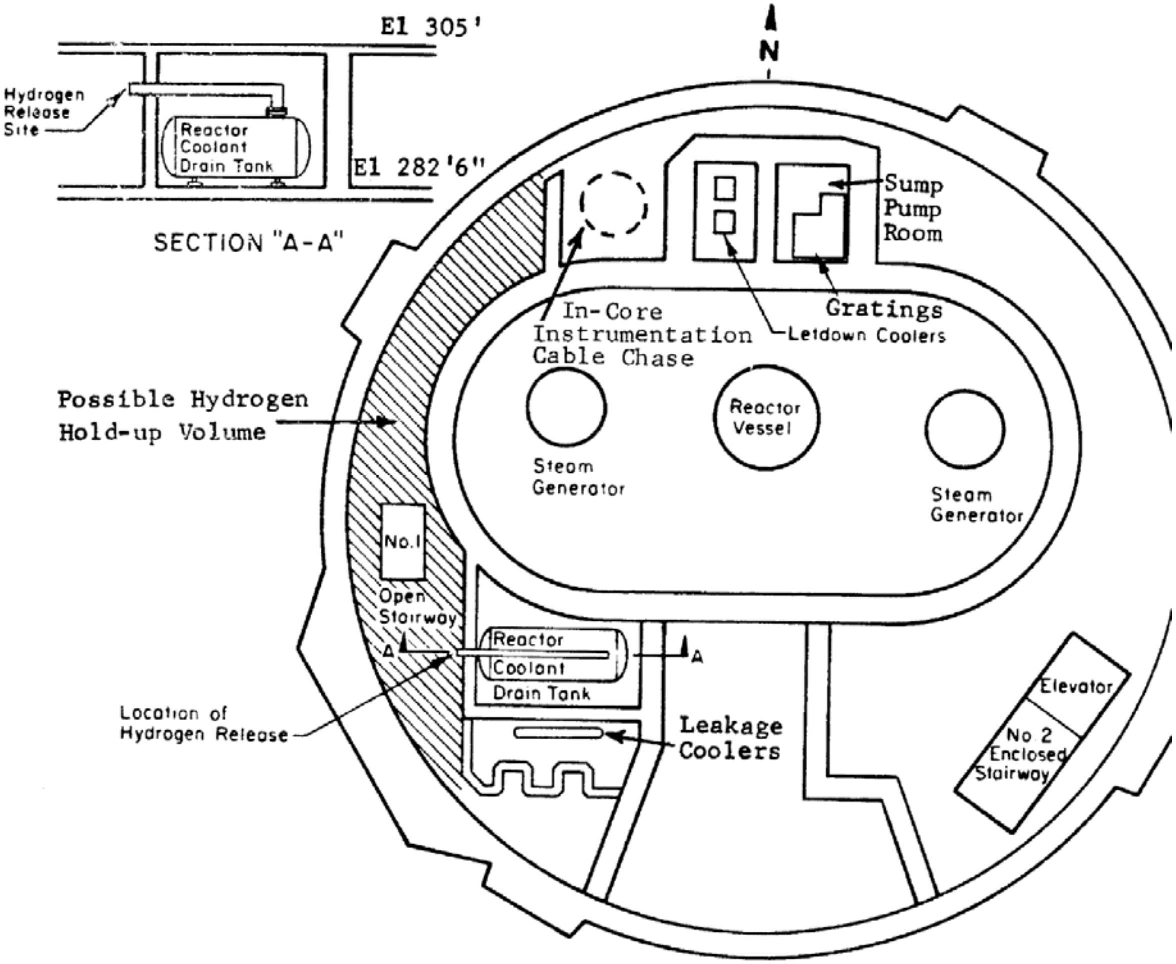
Hydrogen Generation & Release Path



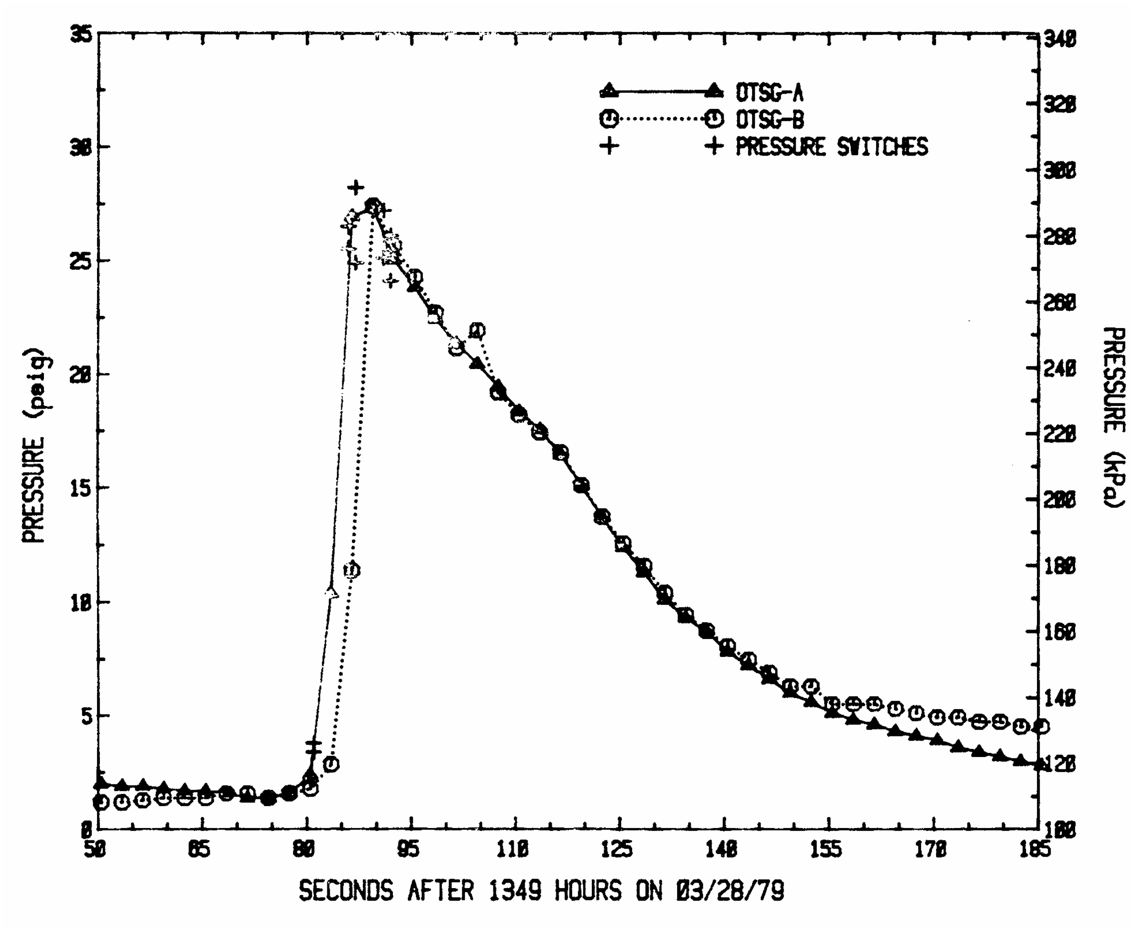
Hydrogen in Containment



Release Site



Hydrogen Deflagration Pressure Rise



Lumped Parameter Mixing Models

Standard lumped-parameter codes are able to predict H2 mixing and distribution phenomena when H2 is injected into a well-mixed atmosphere in lower zones of the containment with excellent agreement in most of the important quantities. 2. A few discrepancies remain, dependent on the codes' modeling methodologies and the impact of incorrect specifications. E11.2: 1. Accounting for the corrections substantially improves the agreements compared to the blind posttest predictions. 2. However, concerning the predictions of the thermal stratification pattern and the H2 distribution, more or less large discrepancies still remain.

CONCLUDING REMARKS

- Empirical correlations and analytical models work well for simple enclosures.
- Lumped parameter models work well for average concentration in multi-compartment enclosures.
- CFD calculations are suitable for large, obstructed enclosures, but gridding and time steps are difficult for problems with combinations of momentum jet releases, and large buoyancy regions.