Analysis of Buoyancy-Driven Ventilation of Hydrogen from Buildings

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Scope of Work

- Safe building design
- Vehicle leak in residential garage
- Continual slow leak
- Passive, buoyancy-driven ventilation (vs. mechanical)
- Steady-state concentration of H_2 vs. vent size

Prior Work

- Modeling and testing with H_2 and He
- Transient H_2 cloud formation

Swain et al. (1996, 2001, 2003, 2005, 2007)

Breitung et al. (2001)

Papanikolaou and Venetsanos (2005)

Our Focus / New Findings

- Slow continual leaks
- Steady-state concentration of H_2
- Algebraic equation for vent sizing
- Significant thermal effect (high outdoor temp)

Range of "Slow" Leakage Rates

- Low end: 1.4 L/min per SAE J2578 (vehicle manufacture quality control)
- High end: 566 L/min automatic shutdown (per Parsons Brinkerhoff for CaFCP)
- Consider: Collision damage or faulty maintenance
- Parametric CFD modeling: 5.9 to 82 L/min (12 hr to 7 days/5 kg)

Methods of Analysis

- CFD modeling (FLUENT)
- Simplified, 1-D, steady-state, algebraic analysis

Pulte Homes, Las Vegas, NV

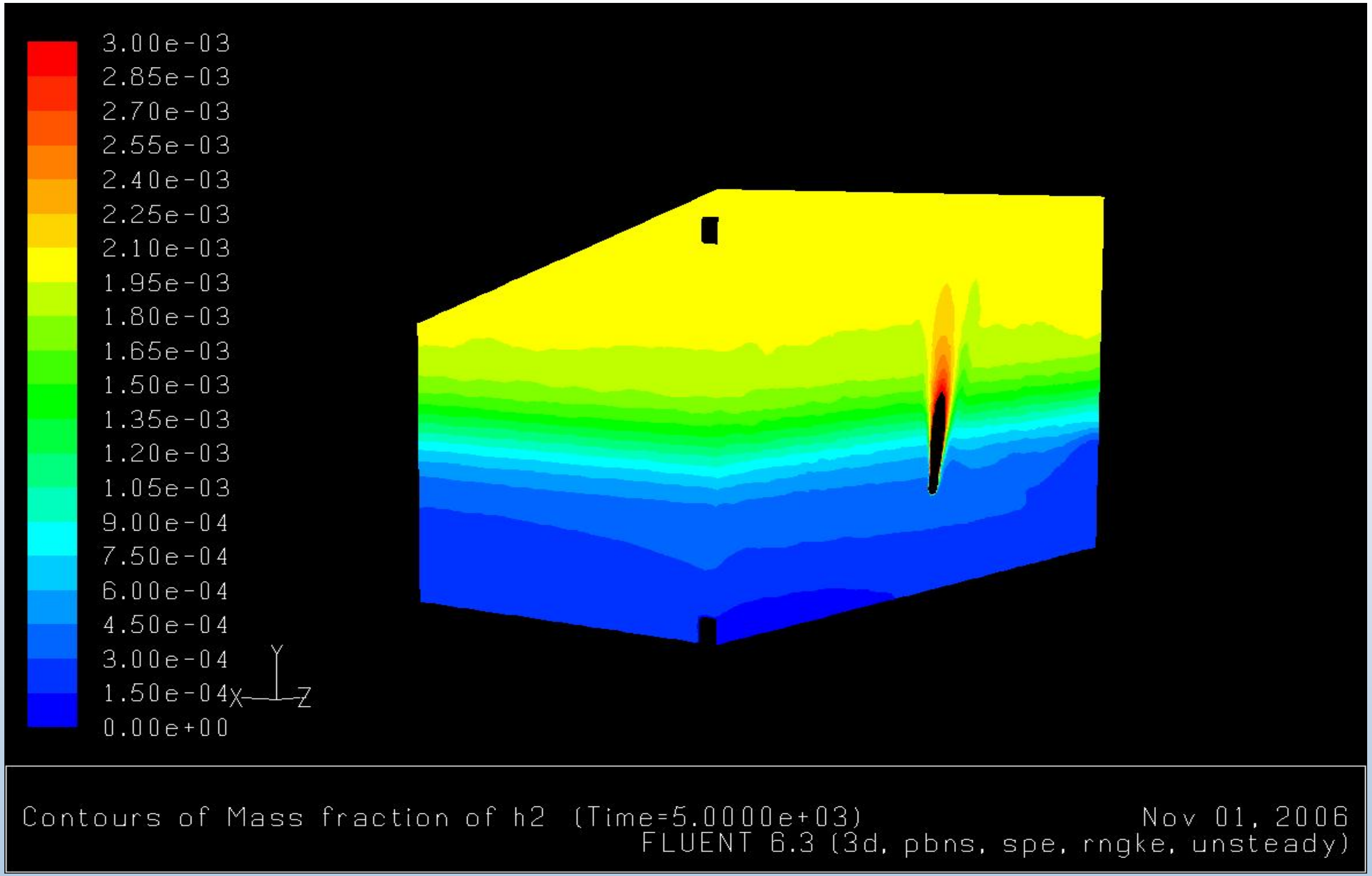
Volume of garage is 146 m^3

Volume of 5 kg of H_2 is 60 m^3

41% mixture is possible

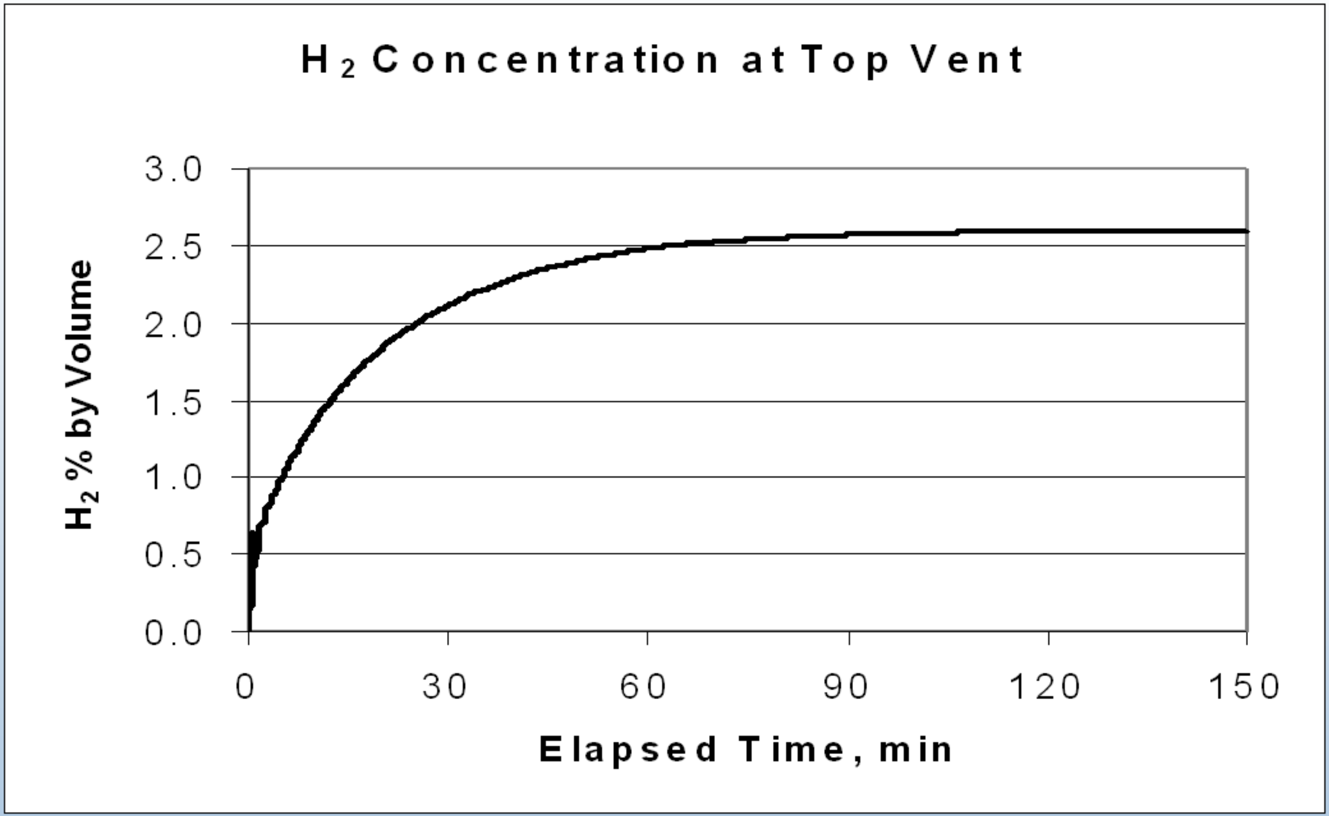
Well within flammable range

Sample CFD Model Result



CFD modeling used to study H_2 cloud. Half of garage is shown. Leak rate is 5 kg/24 hours (41.5 L/min). Vent sizes 790 cm^2. Elapsed time = 83 min. Full scale is 4% H_2 by volume.

Sample CFD Model Result



H_2 concentration at top vent increases monotonically and reaches a steady value in about 90 minutes. A flammable mixture does not occur in this case.

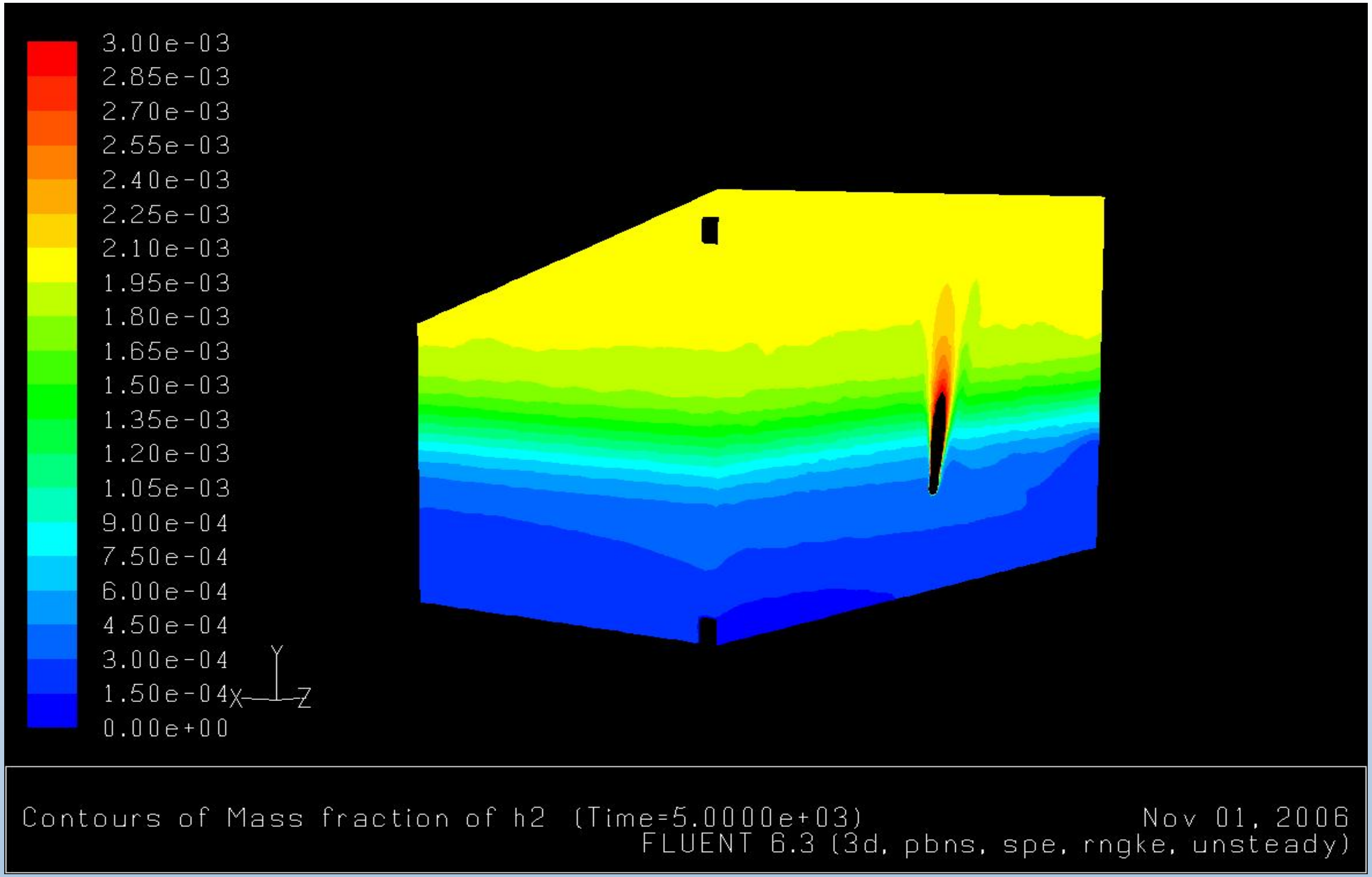
Simulation Setup

- FLUENT version 6.3
- Poly mesh for computational economy
- Grid density study showed solution invariant at approx. 40,000 cells (Avg. ~1.8 L/cell)
- High mesh density near inlet, outlet, gas leak
- Laminar flow model used (more conservative than turbulent models)
- No diffusion across vents at model boundary

Simulation Setup

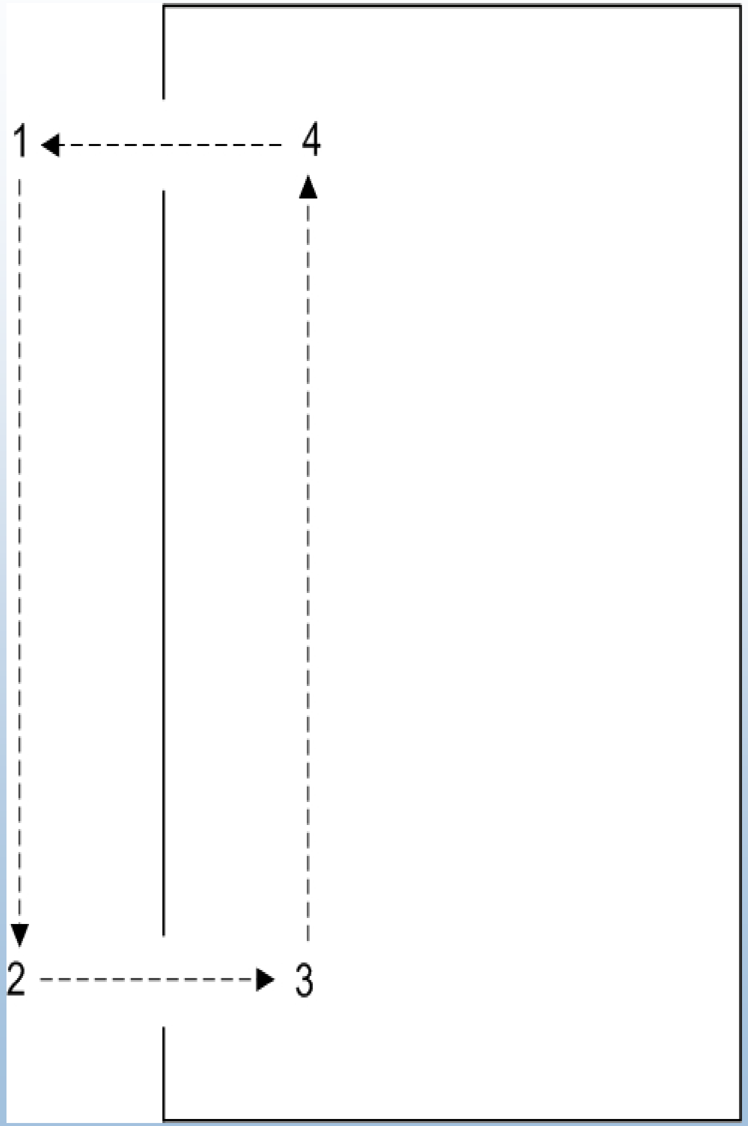
- Hydrogen concentration at outlet monitored to determine steady state
- 5 kg discharge times from 12 hours to 1 week
- Low speed leak from 8-cm-diameter sphere
- Leak ~1 m above floor, one model near ceiling
- Vent sizes and height varied

Concept of 1-D Model



Typical H_2 stratification determined by CFD model (steady-state condition)

1-D Parametric Analysis



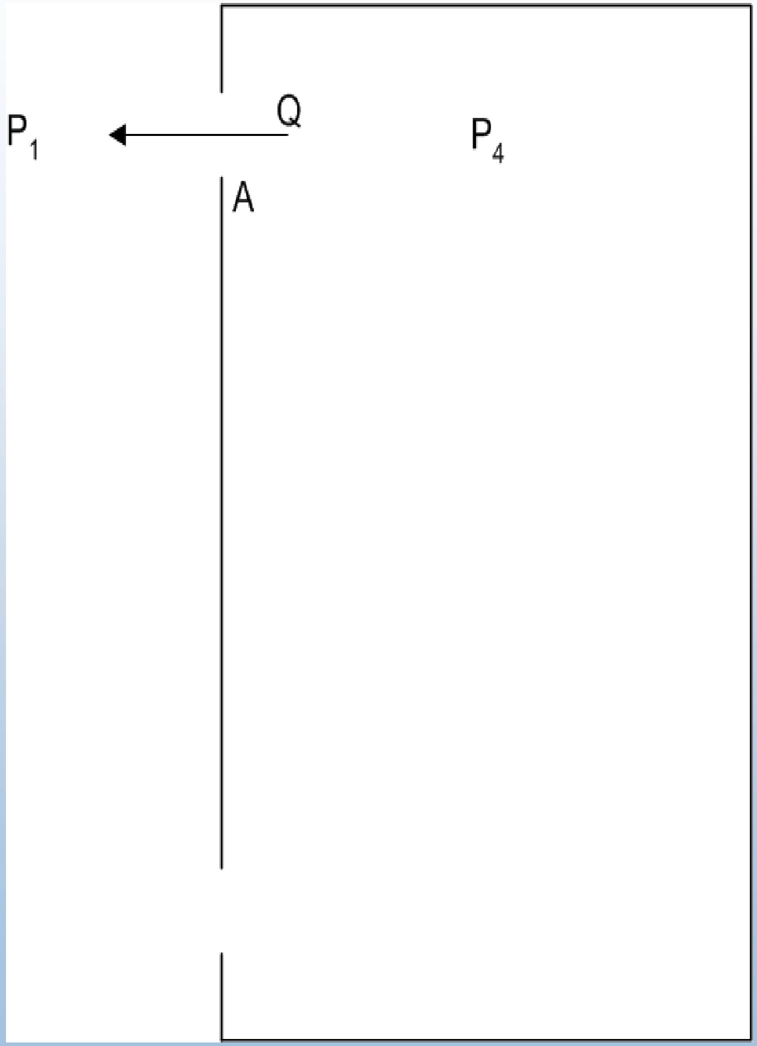
Pressure Loop / Buoyancy

$$\Delta P_{1\text{-}2} + \Delta P_{2\text{-}3} + \Delta P_{3\text{-}4} + \Delta P_{4\text{-}1} = 0$$

$$\Delta P_{1\text{-}2} + \Delta P_{3\text{-}4} = g\ h\ \rho_{air}\ c_{avg}\ (1\text{-}\delta)$$

P = Total pressure
h = Height between vents
c = Concentration of H_2, by volume
ρ = Density
g = Acceleration of gravity
δ = Density of H_2 / density of air

1-D Parametric Analysis



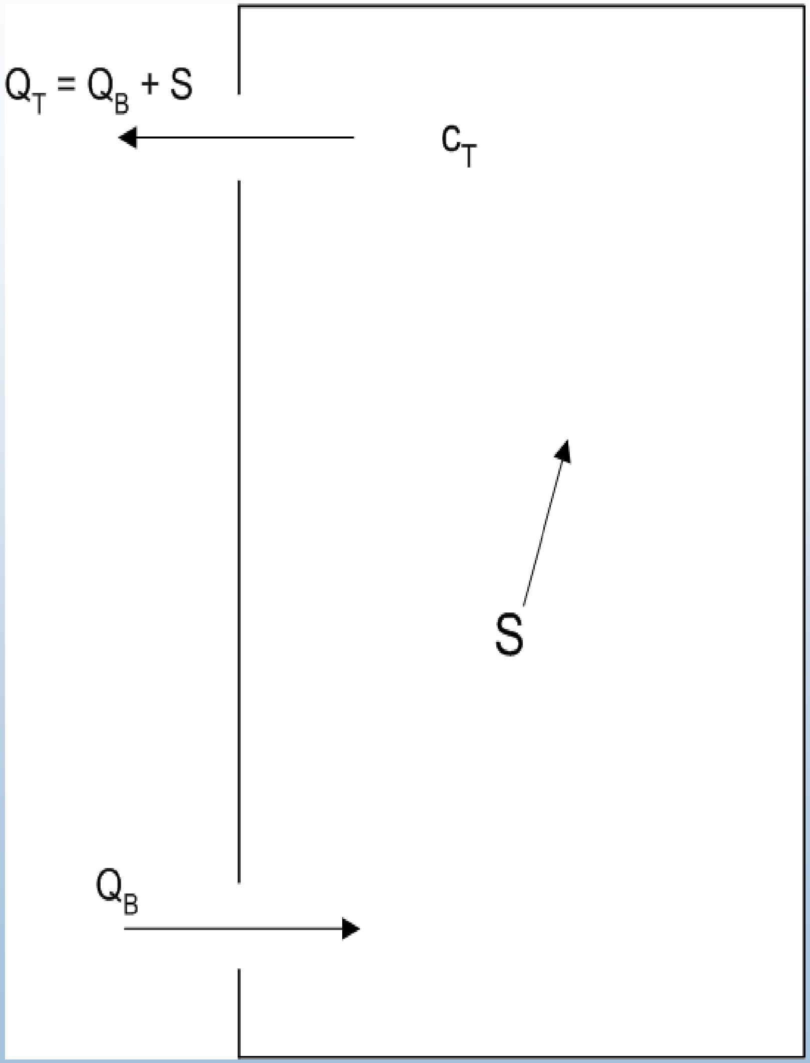
Vent Flow vs. Pressure

$$Q = AD\sqrt{\frac{2\Delta P_{4-1}}{\rho}}$$

Q = Volumetric flow rate
A = Vent area
D = Discharge coefficient

(Similar at bottom vent)

1-D Parametric Analysis



<u>Steady-State Mass Balances</u>

$$Q_T \, c_T = S$$

Q = Volumetric flow rate

c_T = H_2 concentration at top vent, by volume

S = Volumetric H_2 source rate

1-D Parametric Analysis

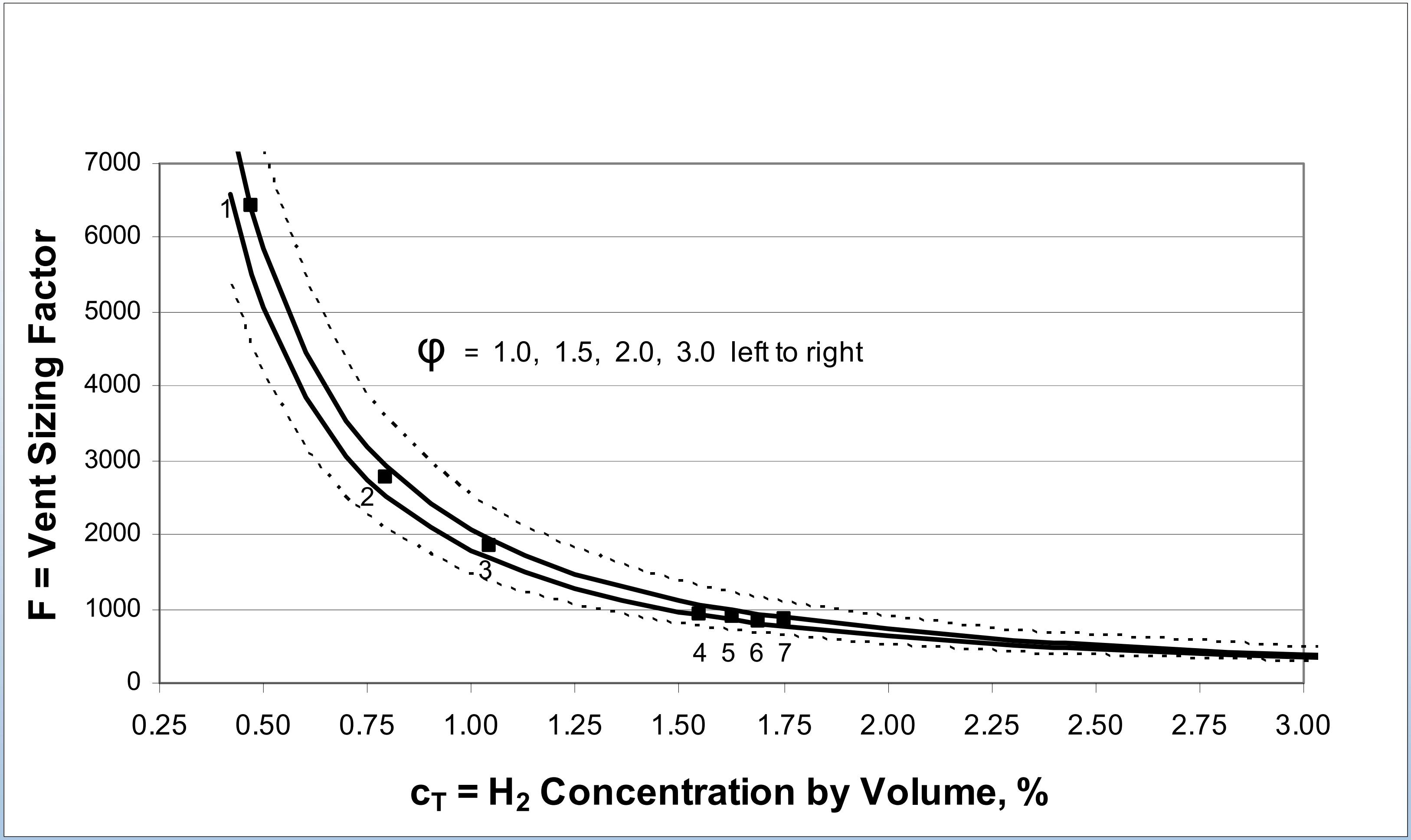
Isothermal Vent-Sizing Equation:

$$F \equiv \frac{AD}{S}\sqrt{2gh} = \phi^{\frac{1}{2}}\left[\frac{1 - C_T(1-\delta) + (1 - C_T)^2}{(1-\delta)\ C_T{}^3}\right]^{\frac{1}{2}}$$

where:

F	=	Vent sizing factor, dimensionless
A	=	Vent area (top = bottom), m^2
C_T	=	H_2 concentration at top vent, by volume (0-1)
D	=	Vent discharge coefficient (0-1)
S	=	Source rate of H_2 (leak rate), m^3/s
g	=	Acceleration of gravity = 9.81 m/s^2
h	=	Height between vents, m
δ	=	Ratio of densities of H_2/Air = 0.0717
φ	=	Stratification factor = C_T/C_{avg} (C_{avg} = average over height)

Comparison of Models



Curves illustrate isothermal vent-sizing equation.

Points 1-7 are CFD results.

Series of CFD Cases

Specifications, Results	CFD Case						
	1	2	3	4	5	6	7
Leak-Down Time, hr/5 kg	168	72	48	24	24	24	12
Vent Size, cm^2	788	788	788	788	788	788	1576
Vent Offset, cm	0.0	0.0	0.0	0.0	15.2	30.5	0.0
Vent Height, m	3.650	3.650	3.650	3.650	3.345	3.040	3.599
H_2 Conc. at top vent, % Vol	0.47	0.79	1.04	1.55	1.63	1.69	1.75
Straification Factor (φ)	1.65	1.67	1.67	1.52	1.58	1.59	1.88
Discharge Coeff. (D*)	0.952	0.952	0.952	0.965	0.948	0.944	0.903

Ranges of Parameters

- Stratification factor (φ):
  1.52 to 1.88
- Apparent discharge coefficient (D*):
  0.903 to 0.965

  D* higher than typical D (0.60 to 0.70)

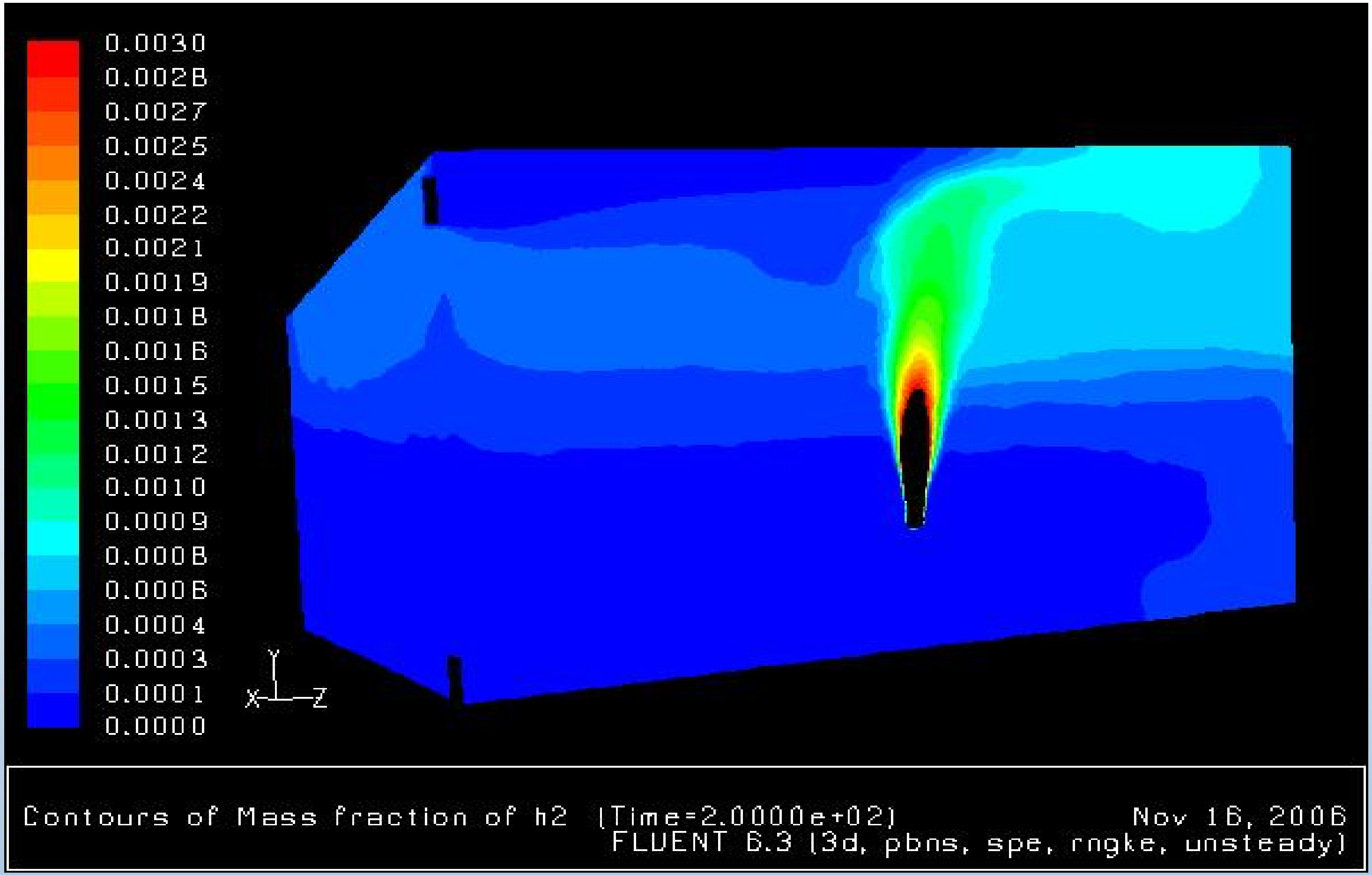
  D* includes momentum effects

  Further study needed (experimental)

Reverse Thermocirculation

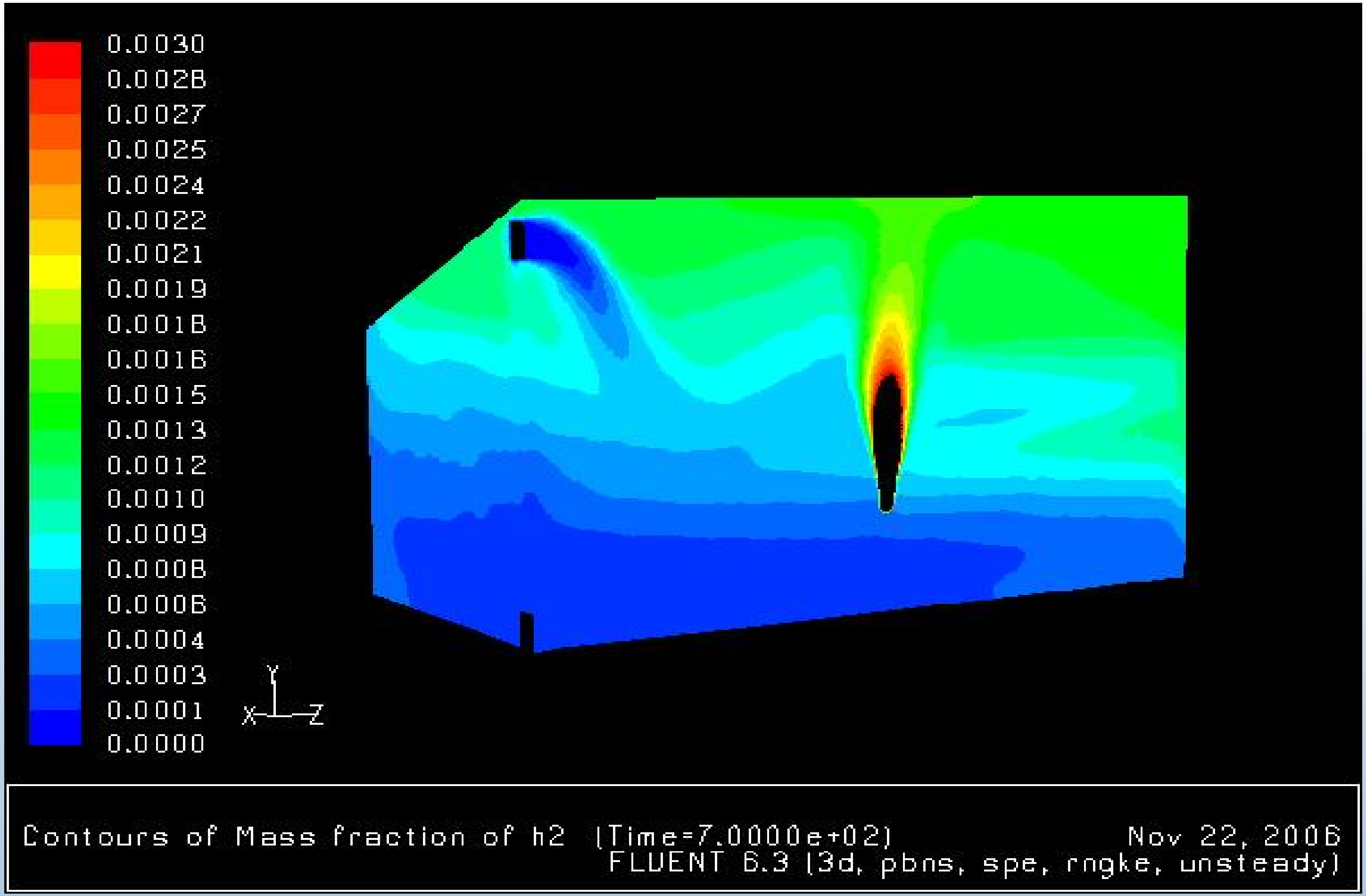
When outdoor temperature is higher than indoor (garage) temperature, thermal circulation opposes H_2-buoyancy-driven circulation.

Thermal Case Study



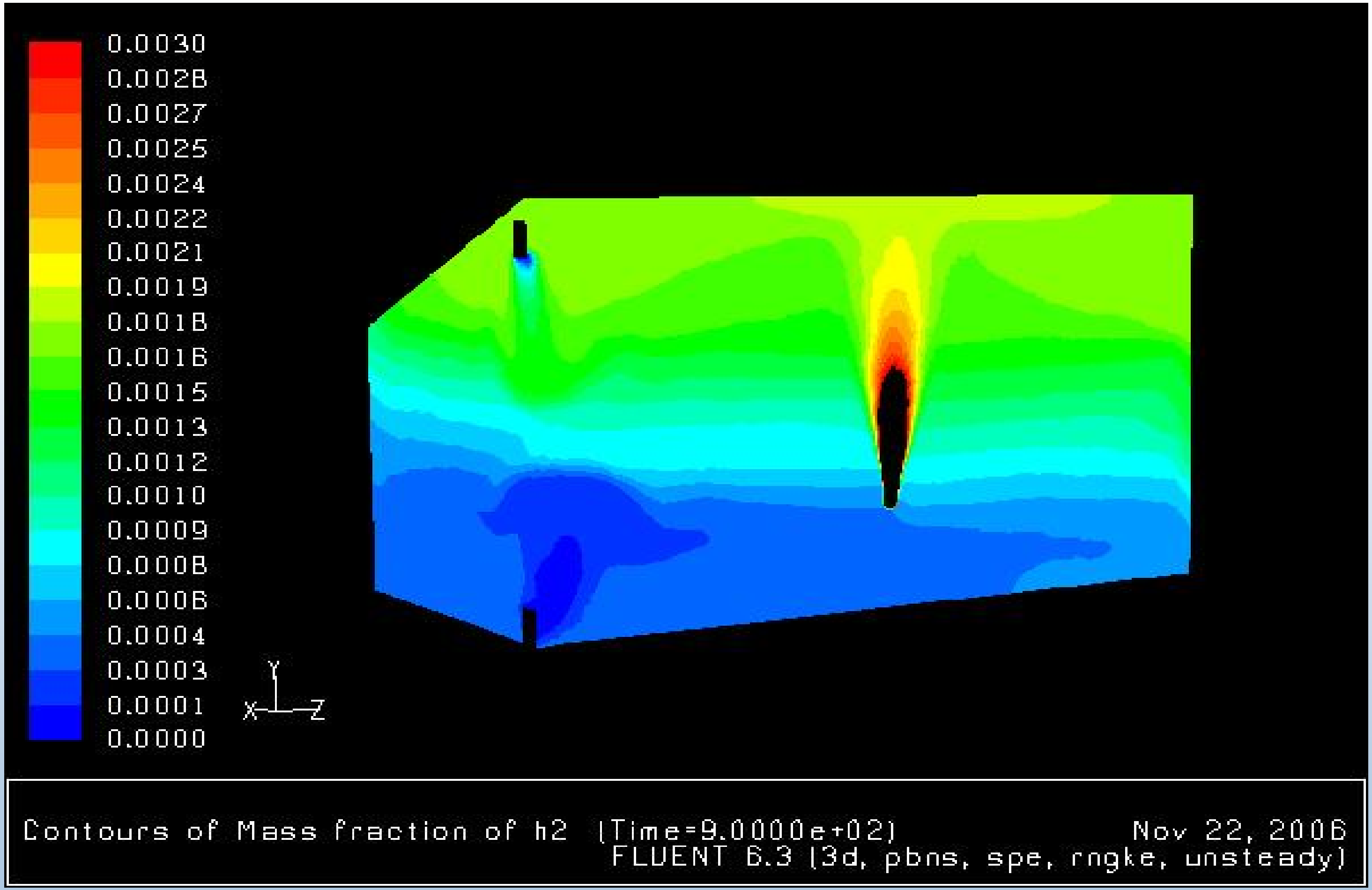
Leak rate = 5 kg/12 hours. Vent size = 1,580 cm^2.
T_{amb}-T_{cond} = 20°C. Elapsed time = 3.3 min.
Full scale = 4% H_2 by volume.

Thermal Case Study



Leak rate = 5 kg/12 hours. Vent size = 1,580 cm^2.
T_{amb}-T_{cond} = 20°C. Elapsed time = 11.7 min.
Full scale = 4% H_2 by volume.

Thermal Case Study

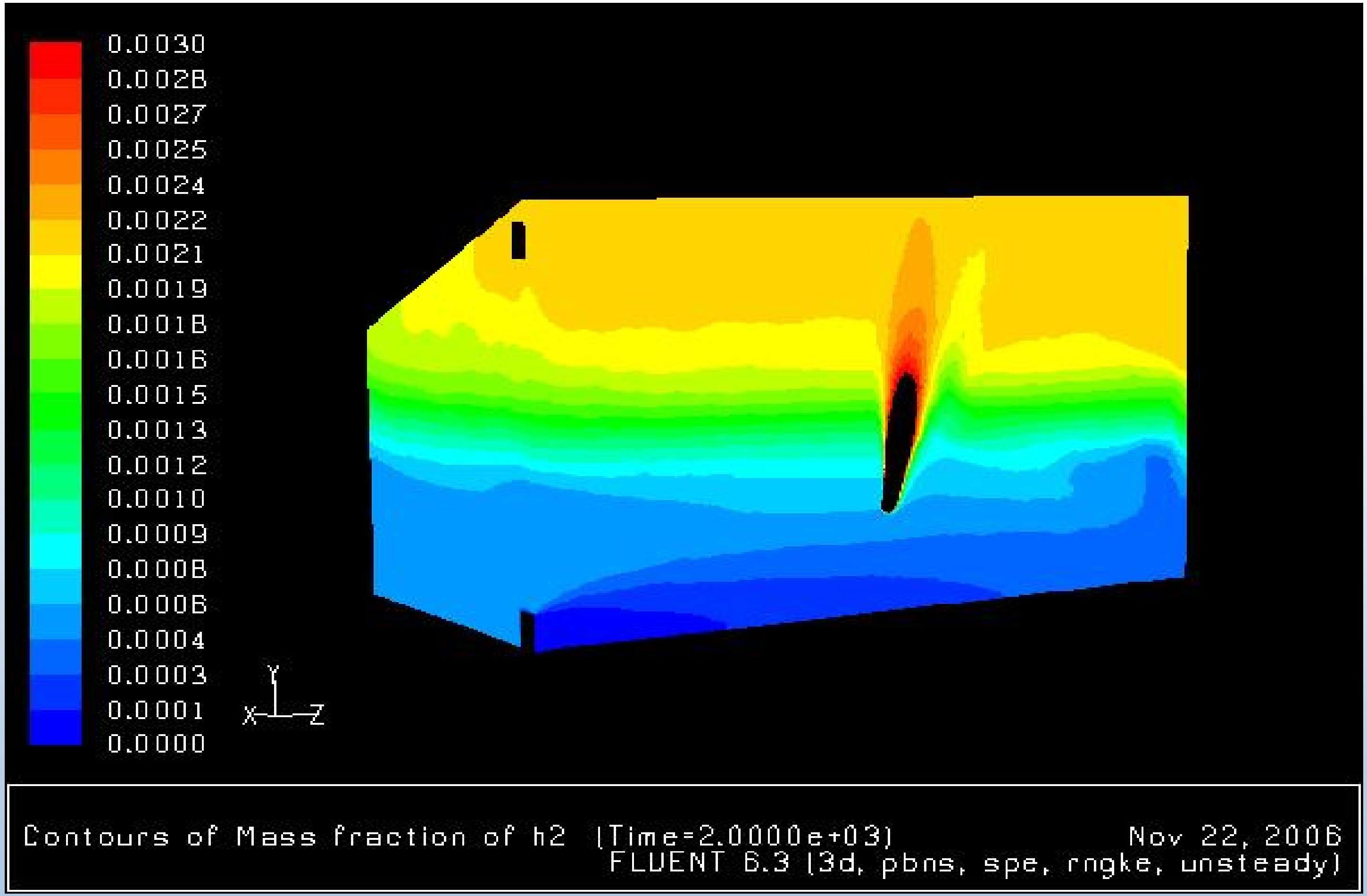


Leak rate = 5 kg/12 hours. Vent size = 1,580 cm^2.

T_{amb}-T_{cond} = 20°C. Elapsed time = 15 min.

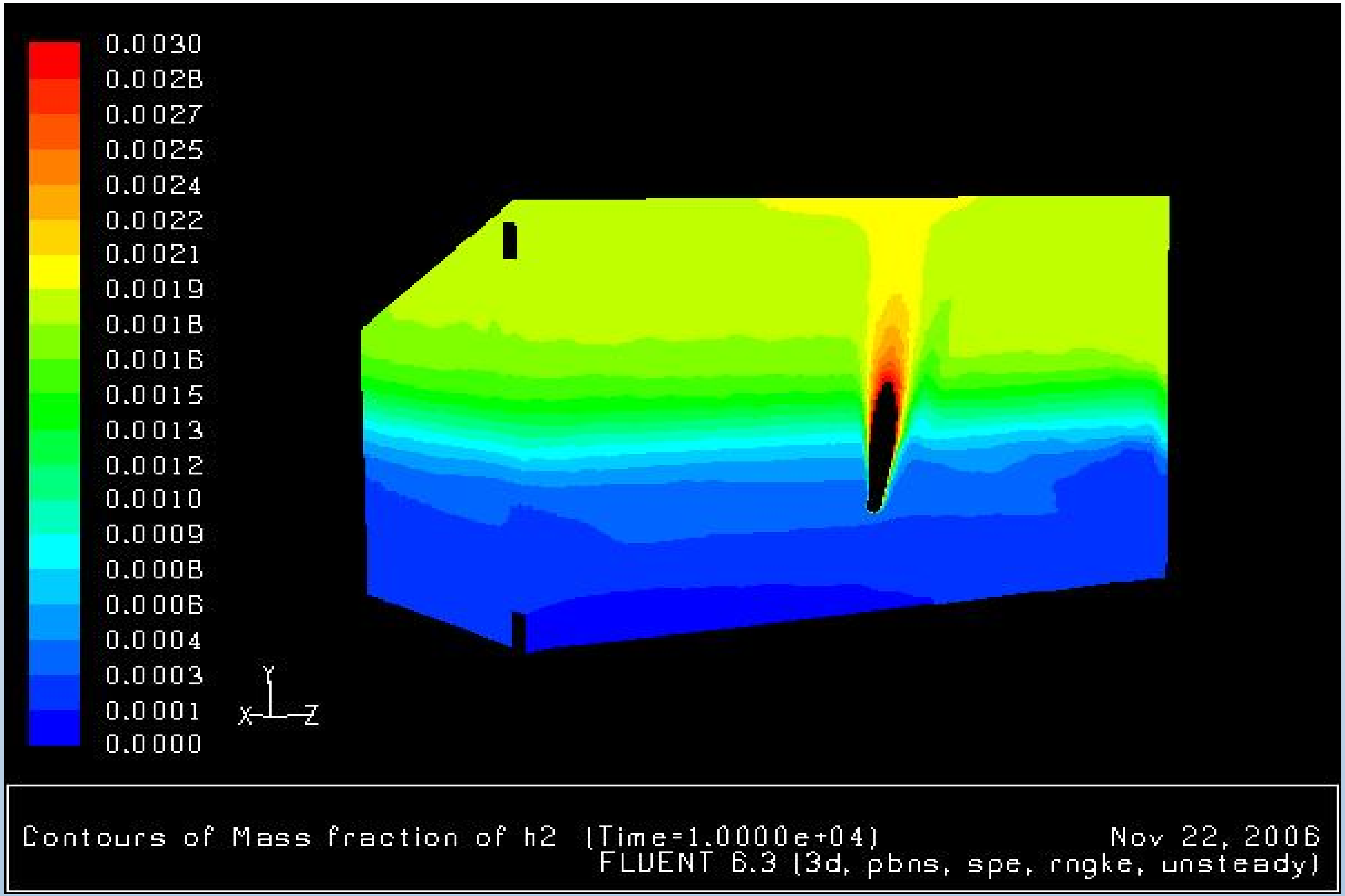
Full scale = 4% H_2 by volume.

Thermal Case Study



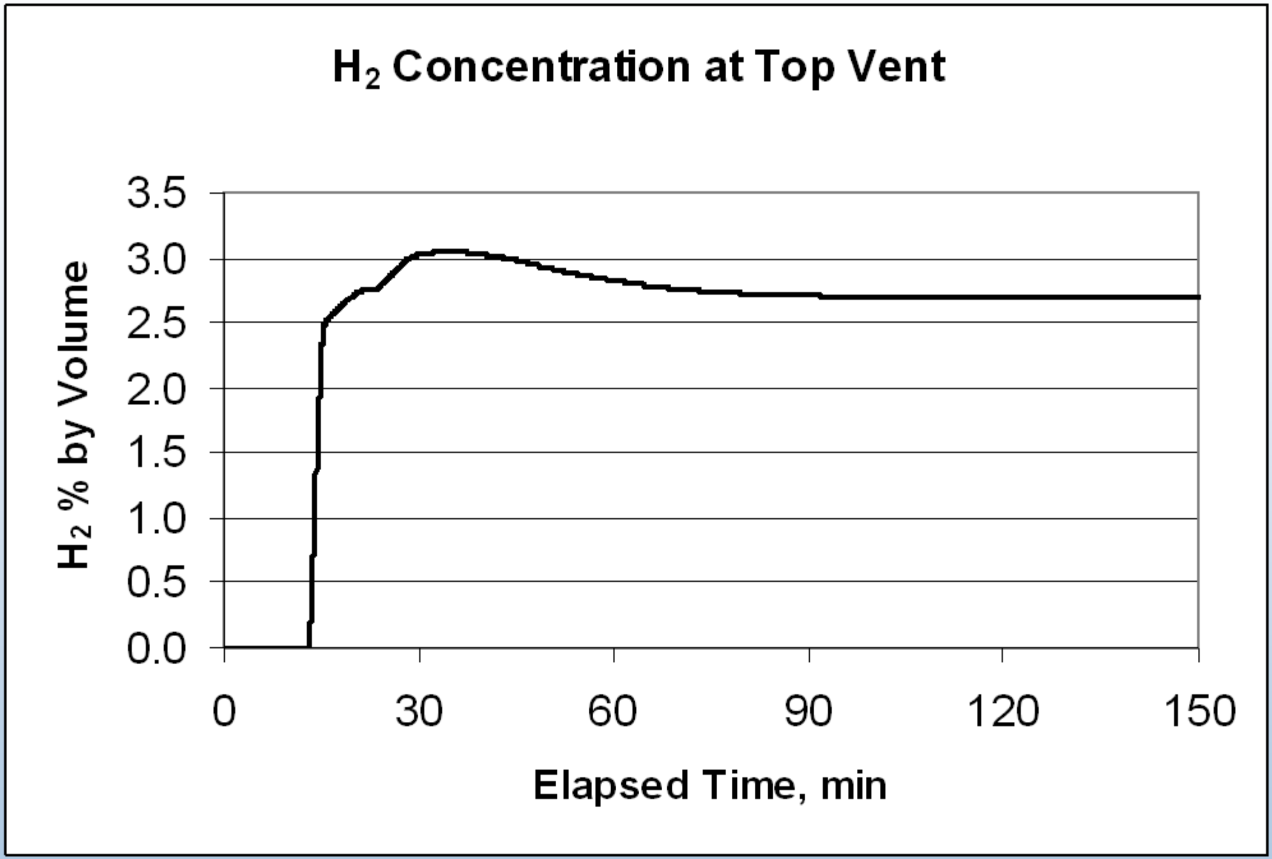
Leak rate = 5 kg/12 hours. Vent size = 1,580 cm^2.
T_{amb}-T_{cond} = 20°C. Elapsed time = 33 min.
Full scale = 4% H_2 by volume.

Thermal Case Study



Leak rate = 5 kg/12 hours. Vent size = 1,580 cm^2.
T_{amb}-T_{cond} = 20°C. Elapsed time = 2.8 hr (steady state).
Full scale = 4% H_2 by volume.

Thermal Case Study



Leak rate = 5 kg/12 hours. Vent size = 1,580 cm^2.
T_{amb}-T_{cond} = 20°C.

A Perfect Storm
Extreme thermal scenario

Garage strongly coupled to house & ground

Garage weakly coupled to ambient

Hot day, cool ground, low A/C setpoint

Small vents—sized for 2% H_2 max with 1-D model

A Perfect Storm

Heartland Homes, Pittsburgh, PA

Building AMERICA
U.S. Department of Energy

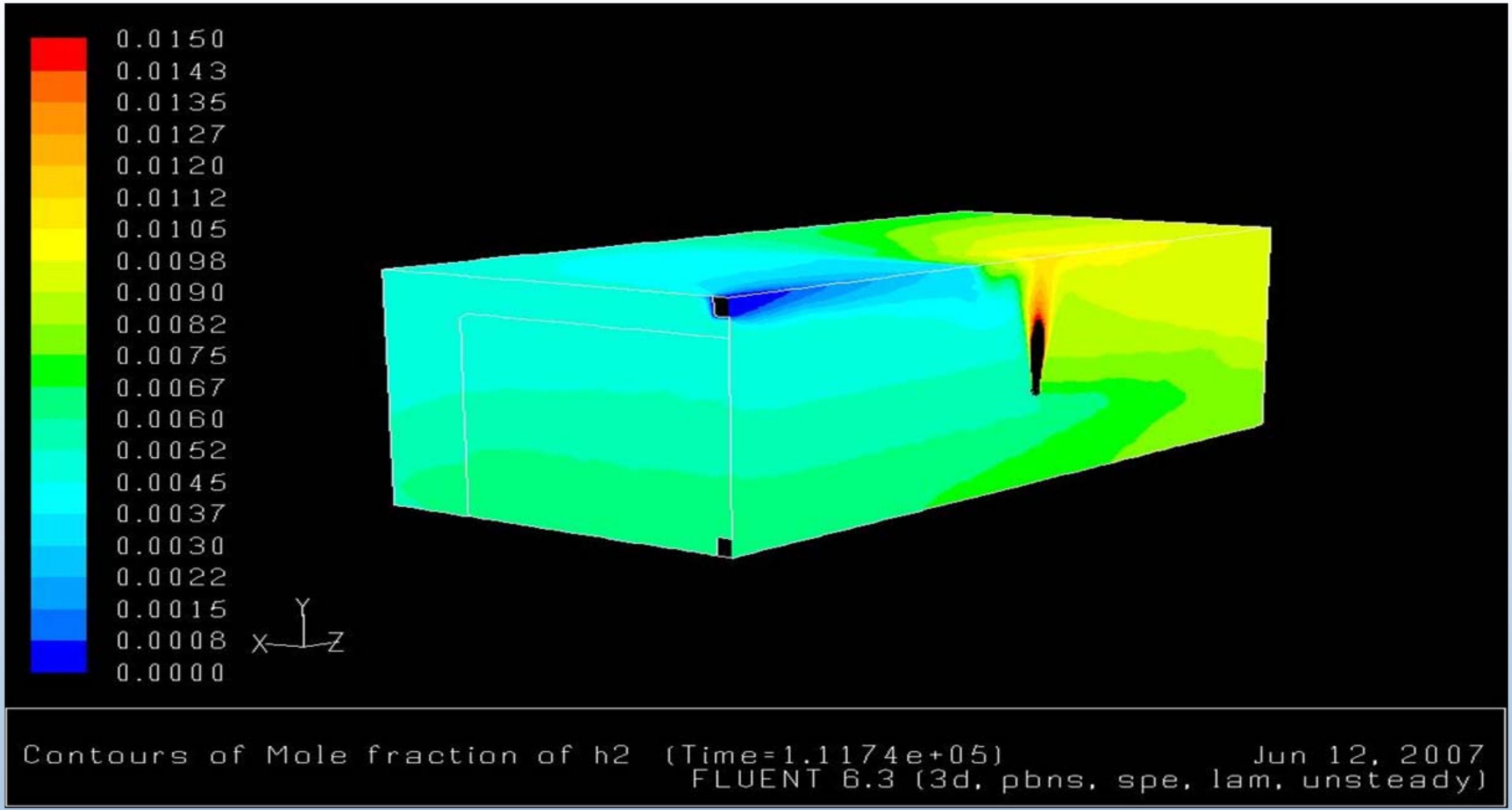
NREL National Renewable Energy Laboratory

A Perfect Storm
Ambient conditions modeled

- Ambient temp. = 40.6°C (Approx. max. in Denver)
- Ground temp = 10°C (Denver, mid-April)
- A/C setpoint = 21.1°C (Rather low)

Reverse Flow Scenario

H_2 exiting through bottom vent



Case 9. Leak rate = 5 kg/7 days. Vent size = 494 cm^2.
Elapsed time = 31 hr (steady state).
Full scale = 1.5% H_2 by volume.

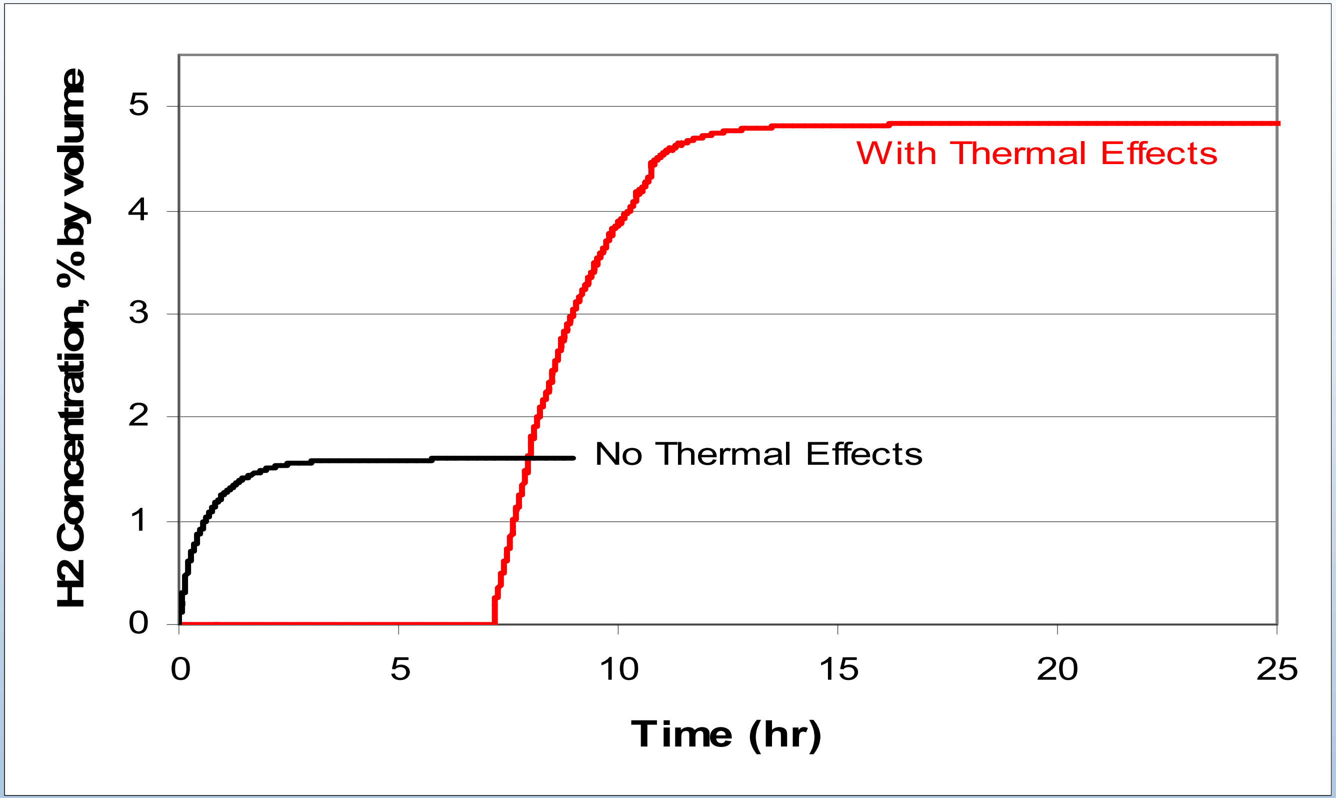
A Perfect Storm

Results

- Case 8 (1-day leak):
  Vents from top, 2.3% max
- Case 9 (7-day leak):
  Vents from bottom, 1.0% max
- Case 10 (3-day leak):
  Vents from top, 4.8% max

A Perfect Storm

Worst thermal case we modeled



Case 10. Leak rate = 5 kg/3 days. Vent size = 405 cm^2.

Conclusions

1. The leakage rates that will occur and their frequencies are unknown.

   Further study of leakage rates is needed to put parametric results into perspective.

2. Our CFD model has not yet been validated against experimental data.
   - Uncertainty in results
   - Future work

Conclusions

3. The 1-D model ignores thermal effects, but otherwise provides a safe-side estimate of H_2 concentration by ignoring momentum effects (pending model validation).
4. Indicated vent sizes would cause very low garage temperatures in cold climates, for leak rates of roughly 6 L/min and higher (leak-down in 1 week or less).

Conclusions

5. Reverse thermocirculation:

- Can occur in nearly any climate
- The worst case we modeled increased the expected H_2 concentration from 2% to 5%. This is a significant risk factor,
- Likelihood of occurrence may be low, judging by the lengths we went to in order to identify a significant example.

Conclusions

6. Mechanical ventilation is alternative approach to safety.

- H_2-sensing fan controller is recommended.
- Research is needed to develop a control system that is sufficiently reliable and economical for residential use.