Experimental and Computational Evaluation of the Importance of Molecular Diffusion at Buncefield

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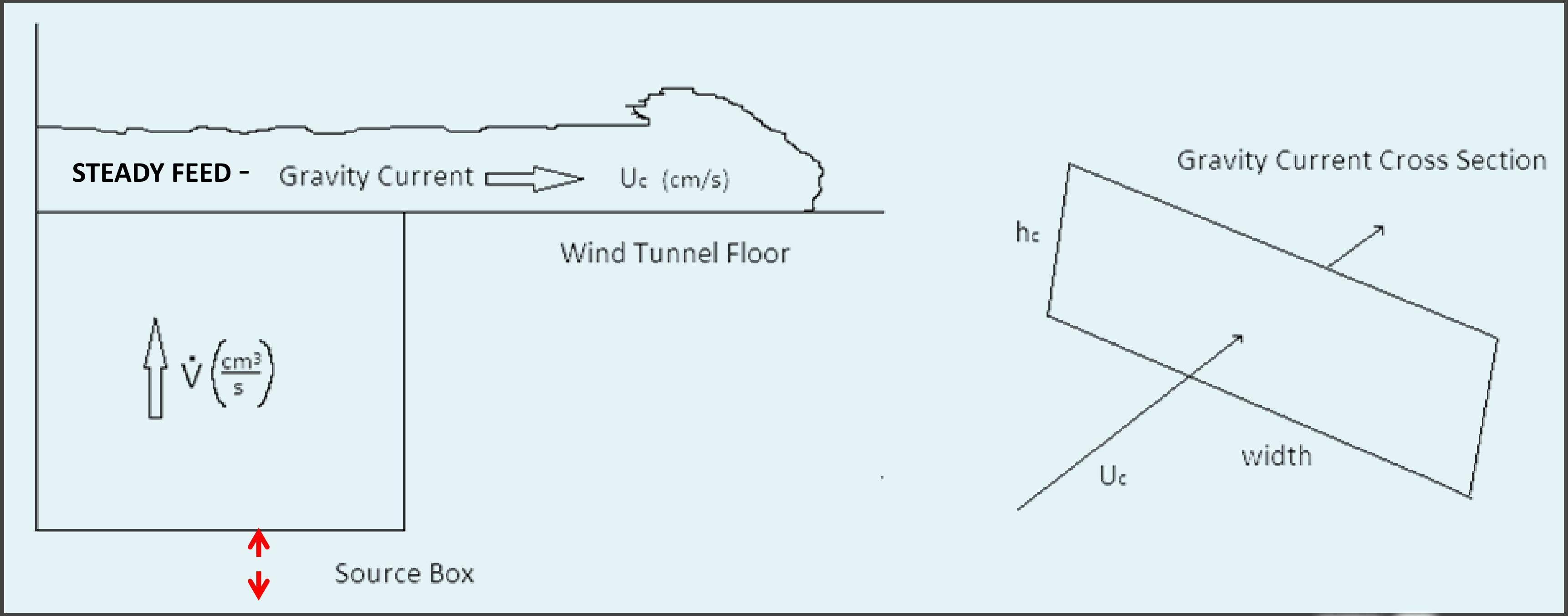
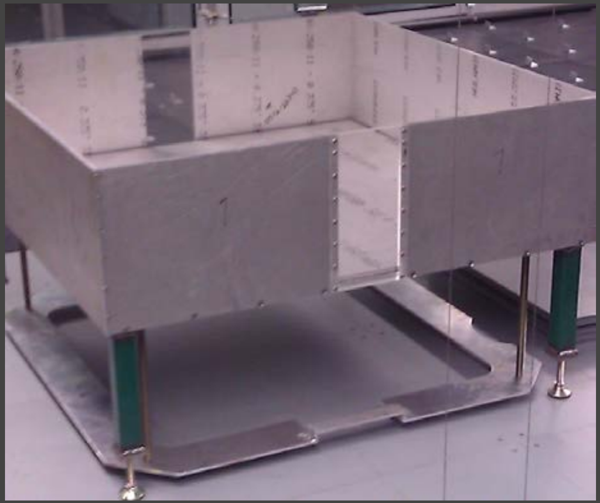
Assumed 2D Flow Area – Parking Lot
Concentration Decreasing Right to Left

If we can understand and predict this approximately 2-D section's concentration dependence with time, can proceed numerically …..

Experimental Design





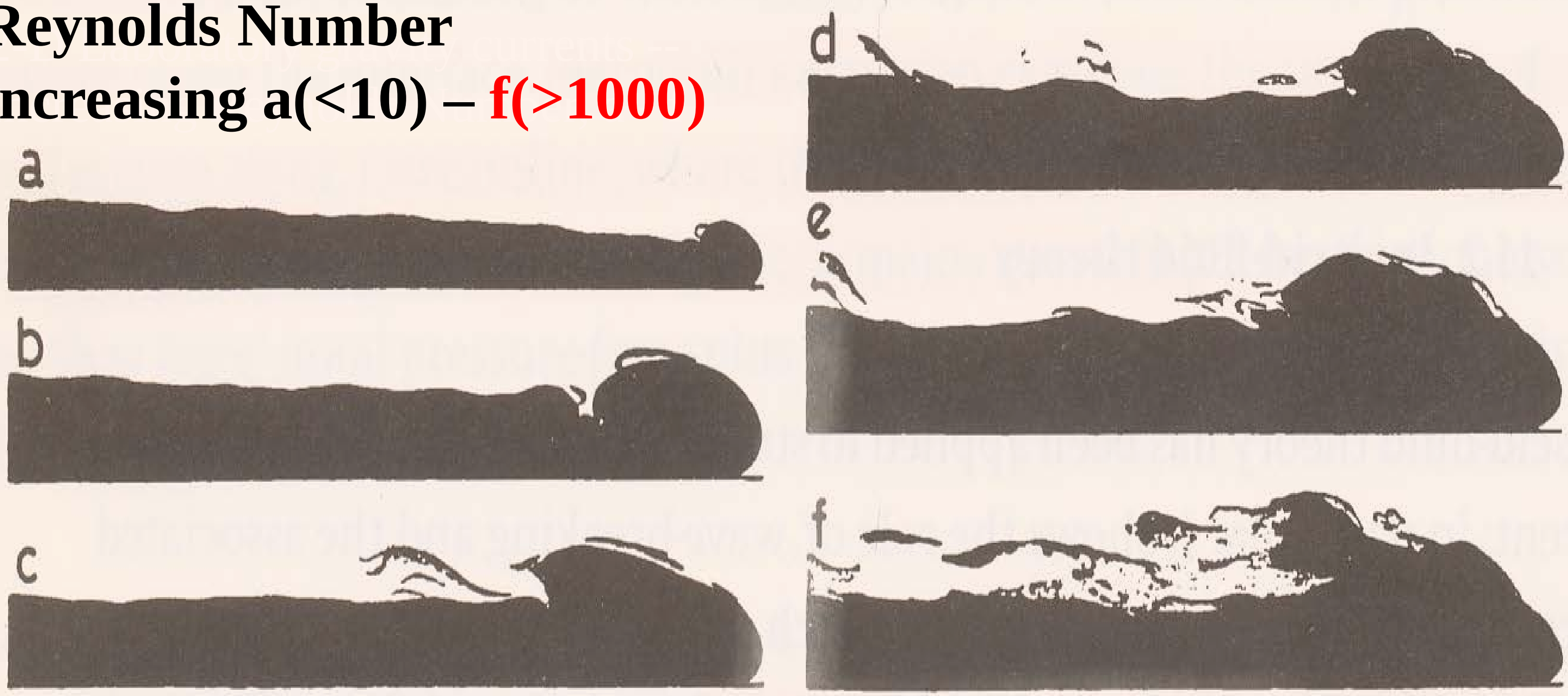
- Reynolds Number $\frac{U_c h_c}{\nu}$
- Froude Number $\frac{U_c^2}{g' h_c}$

ν = kinematic viscosity, m^2/s
$g' = g((\rho - \rho_{air})/\rho_{air})$, m/s^2

Original Idea was to Investigate Reynolds Number Independence

- Model as steady-feed 2-D Gas Gravity Current (zero wind)
- Primary goal: measure gas concentration in the flow field
- Secondary goal: model a 2-D section of the Buncefield gas flow

Liquid Gravity Currents
Reynolds Number
increasing a(<10) – f(>1000)



Schmidt (1911) - Indicating "N_{re} Independence"

Original Idea

- Determine the Reynolds number required for N_{Re} independence and verify N_{Re} independence with concentration measurements.

- Measure the resulting non-dimensional concentration distribution in the “indicated” section of the Buncefield flow.

BAD IDEA - ABANDONED

Path Forward

For the no-wind, density-stratified gas-gravity-currents under study, there appeared to be little, if any, meaning to the concept of Reynolds Number Independence except (possibly) as applying to the gravity current head. The gas gravity current behind the head appears to be essentially turbulence-free, in our experiments AS WELL AS IN THE BUNCEFIELD EVENT.

Laminarization Criteria (from published literature)

Authors	Criterion	
McQuaid (1976)	$U_m/(g \times g_o)^{1/3}$	< 3
Stretch (1986)	$(g \times g')/U^3$	> 0.005
Britter (1989)	$(g' \times Q_o)/(U_*^3 \times W)$	> 0.1
Hall & Waters (1989)	$(g' \times Q_o^{1/2})/U^{2.5}$	> 1000

where

- g = gravitational acceleration, m/s^2
- g' = reduced gravitational acceleration, m/s^2
- Q_o = volumetric flow rate, m^3/s
- U = fluid velocity, m/s
- U_* = friction velocity, m/s
- W = bund perimeter, m

Revised Plan

Lab Expt
and
Buncefield
Laminarization
Criteria values

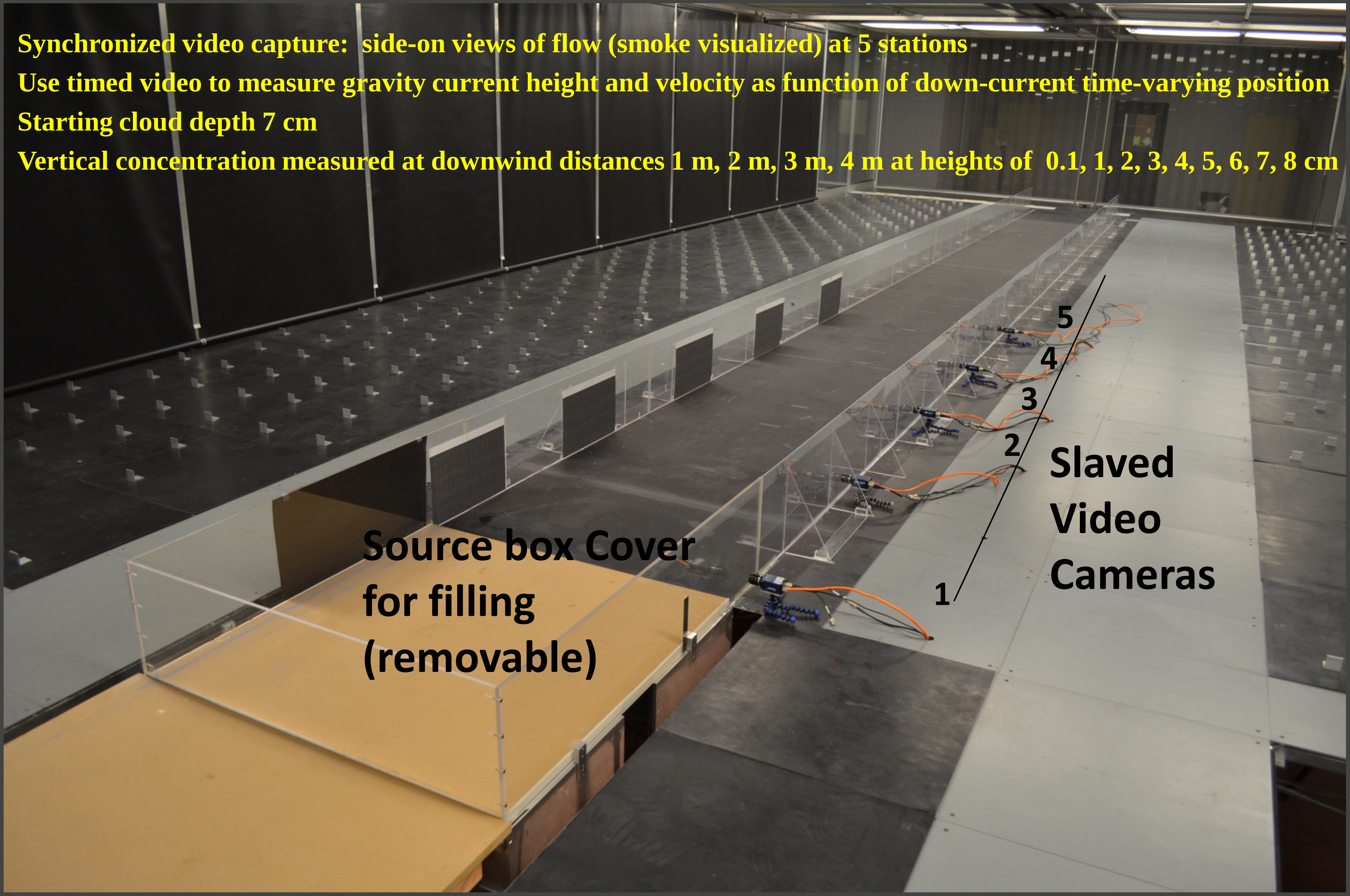
Authors	Criterion		Expt/Buncefied
McQuaid (1976)	$U_m /(g \times g_o)^{1/3}$	< 3	0.79/0.73
Stretch (1986)	$(g \times g')/U^3$	> 0.005	2.0/2.5
Britter (1989)	$(g' \times Q_o)/(U^3 \times W)$	> 0.1	2.0/2.3
Hall & Waters (1989)	$(g' \times Q_o^{1/2})/U^{2.5}$	> 1000	16329/87885

Design laboratory experiment for air mixing into the moving cloud by molecular diffusion only (minimize entraining head formation).

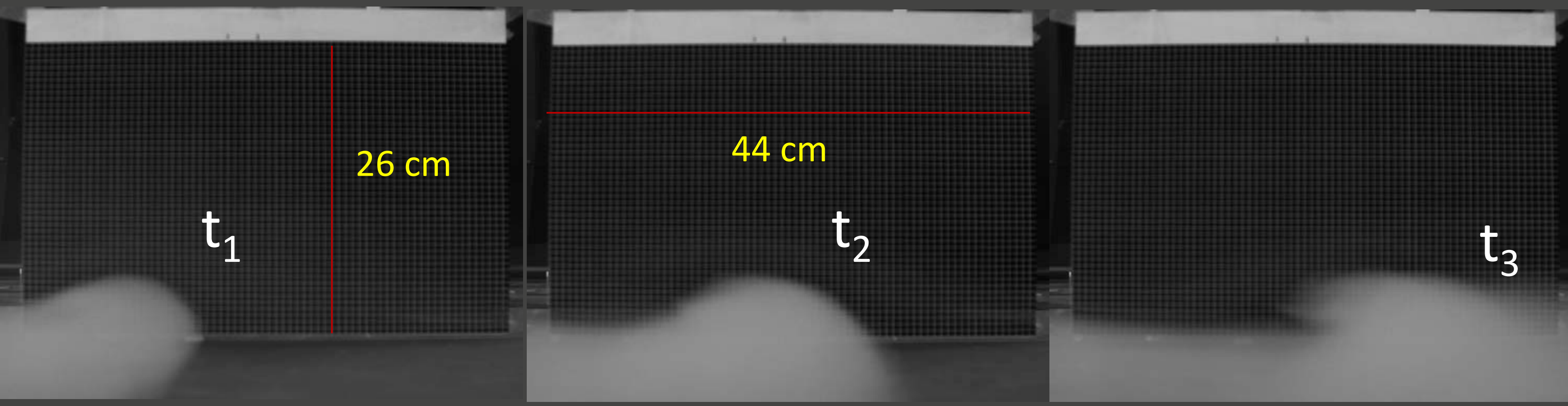
Develop and verify a model of the concentration field in the laboratory experiment

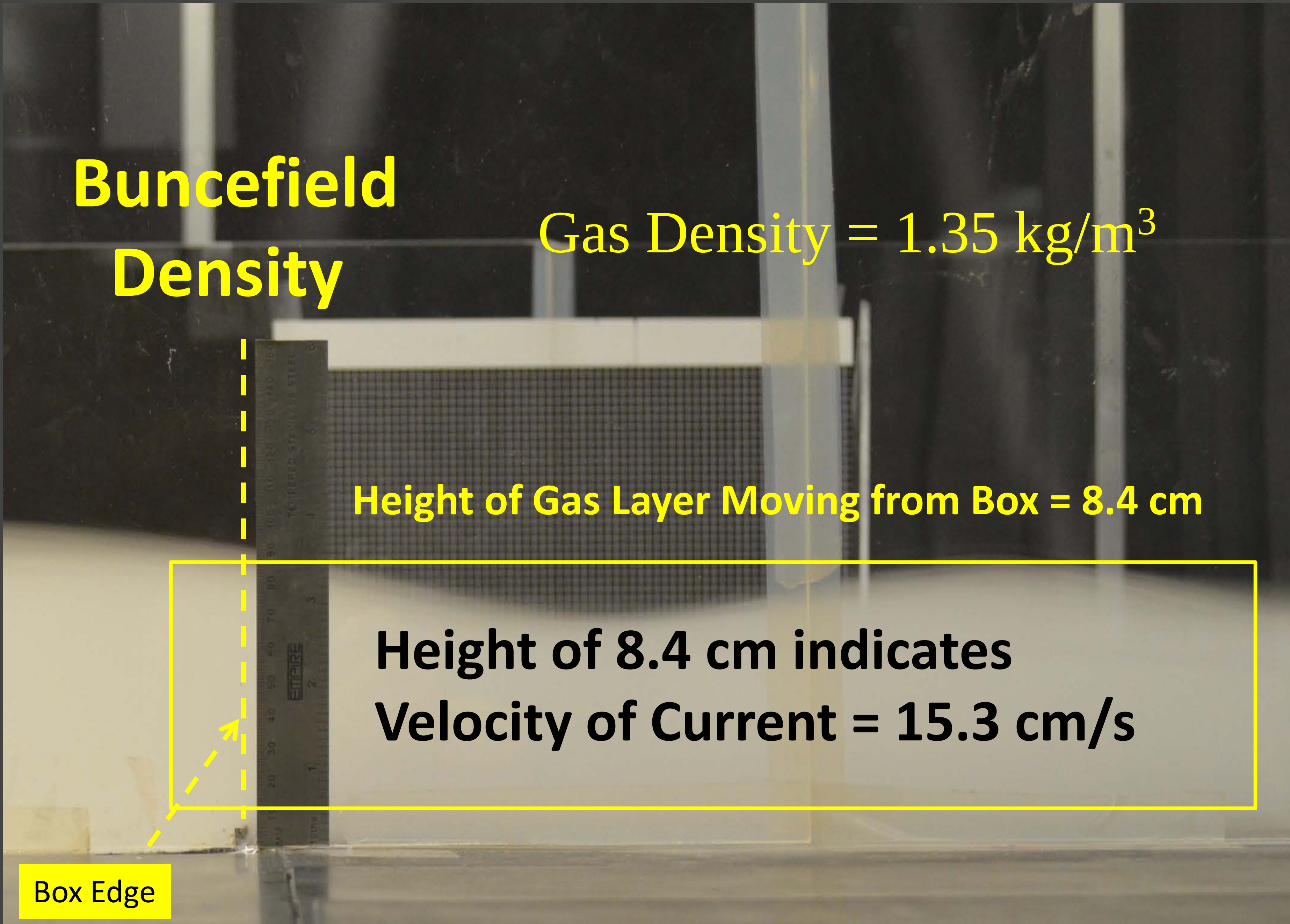
Predict concentration in the Buncefield flow (2D section of parking lot) assuming air mixing into the cloud limited to molecular diffusion

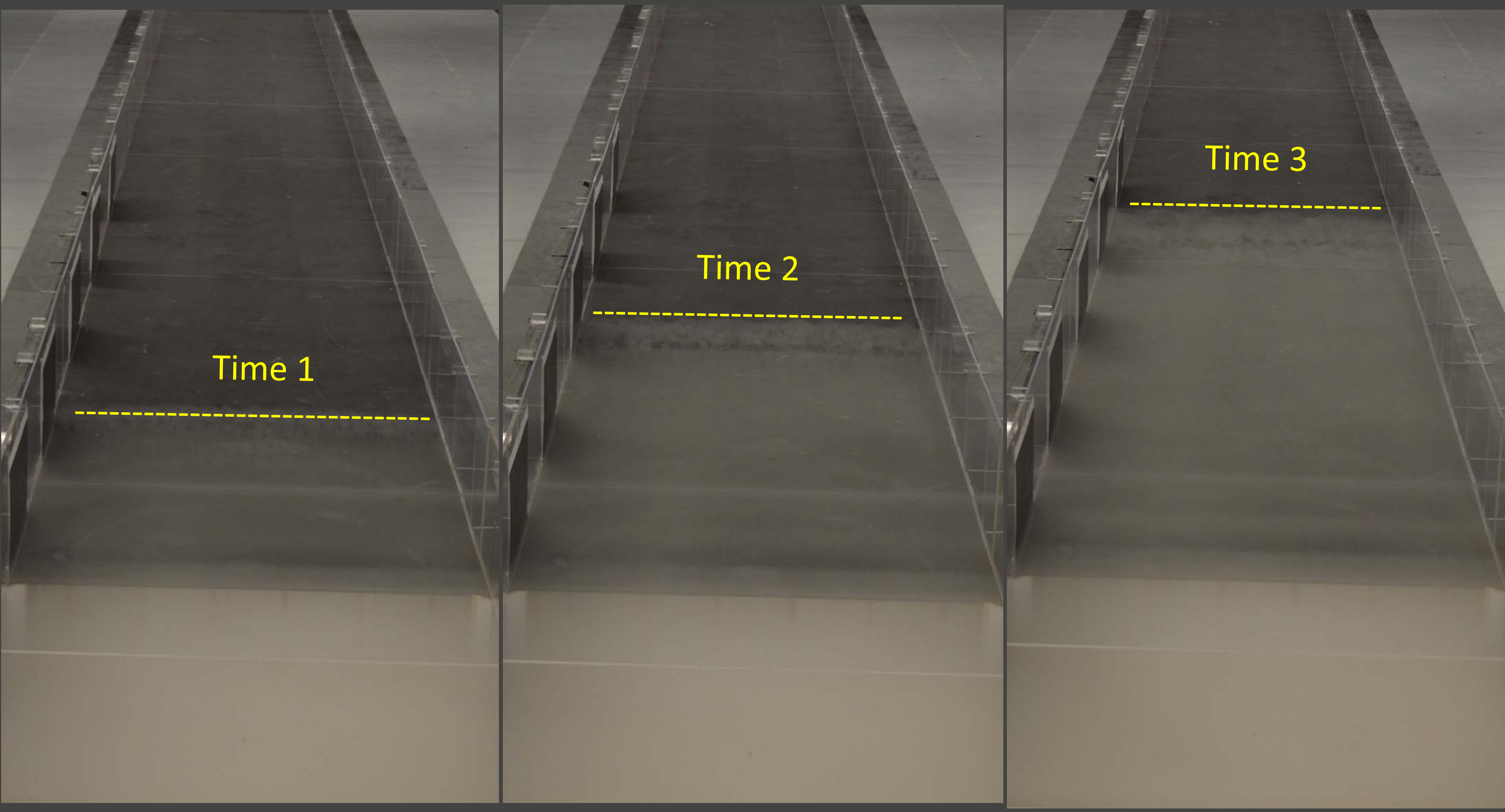
Experiment Design



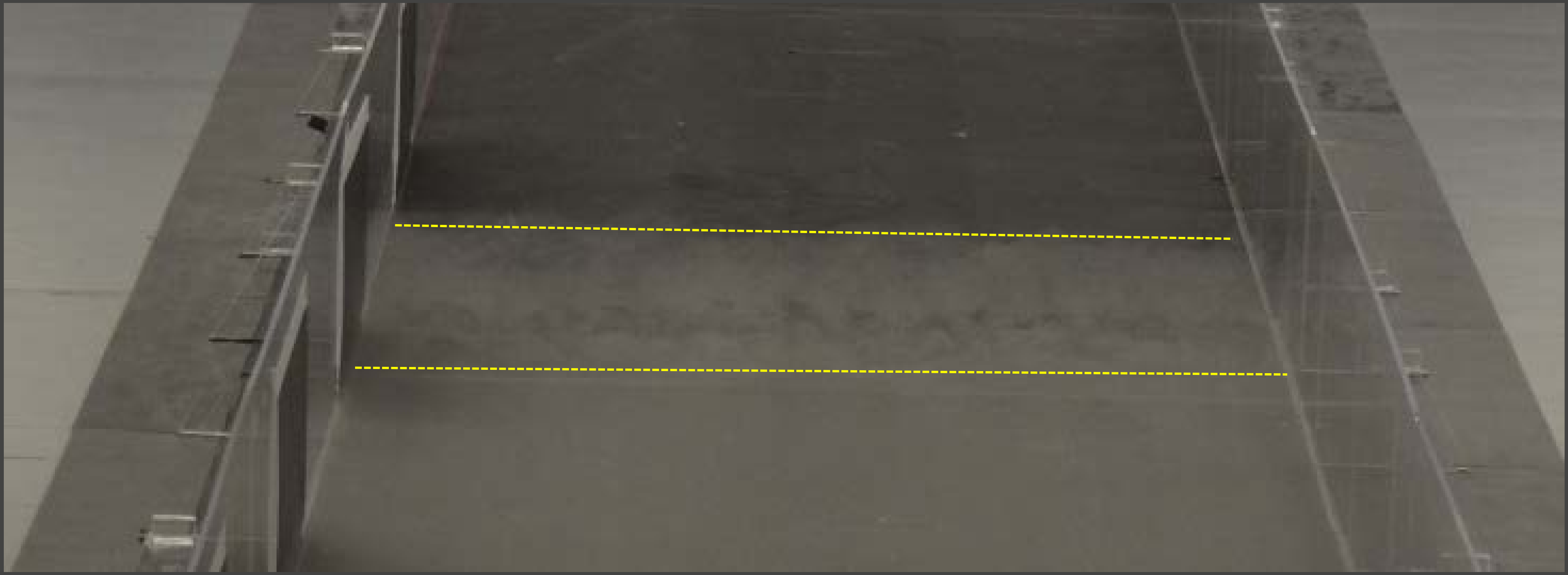
Typical Timing Camera Frames Indicating Head Development




Buncefield
Density
Gas Density = 1.35 kg/m3
Height of Gas Layer Moving from Box = 8.4 cm
Height of 8.4 cm indicates
Velocity of Current = 15.3 cm/s
Box Edge


Time 1
Time 2
Time 3

Front Structure



Lab Experiment Design

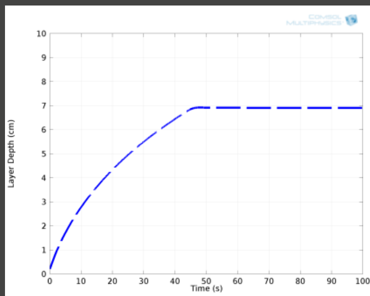
Density 1 = 1.77 kg/m^3 "CO_2" ($g' = 4.87\ m/s^2$)

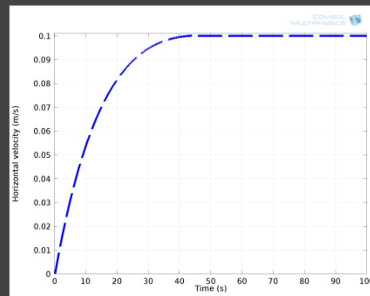
- For illustration, checks for consistency

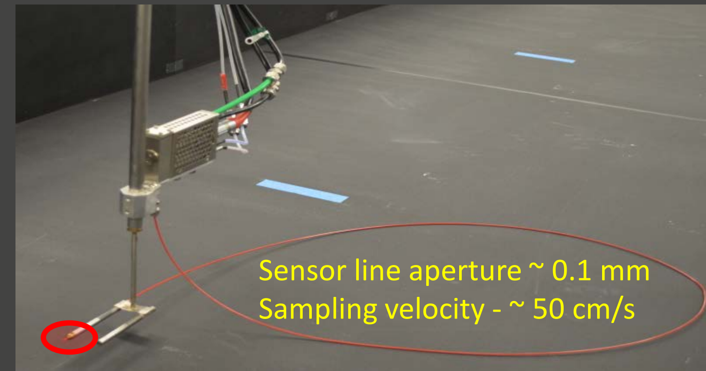
Density 2 = 1.35 kg/m^3 "Buncefield" ($g' = 1.40\ m/s^2$)

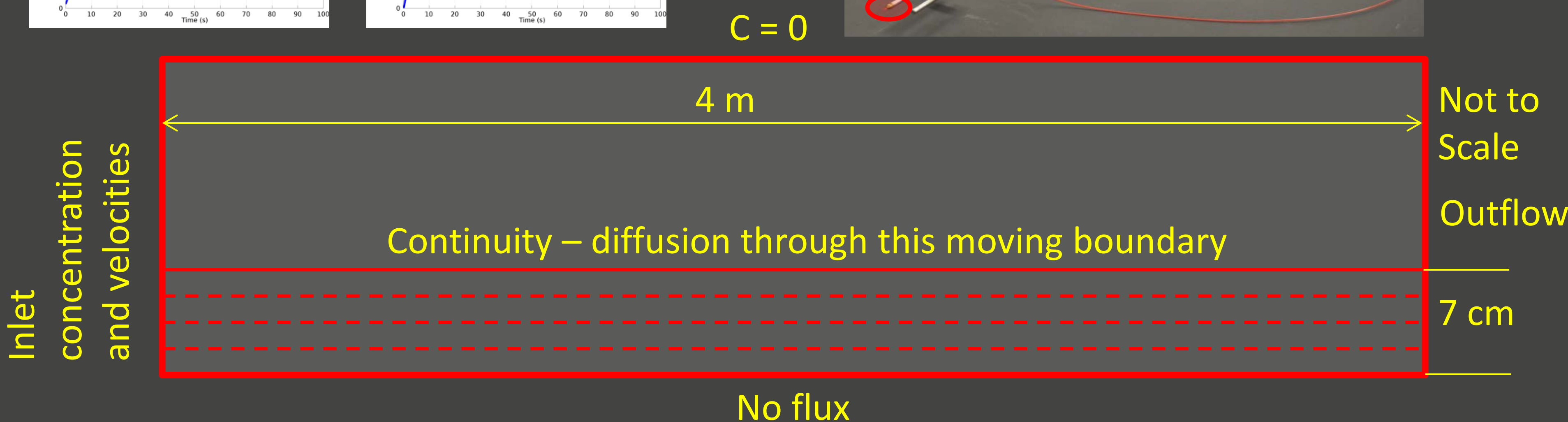
- Video records to measure timing
- Concentration measurements to define time-varying cloud concentrations - Measure gas concentrations with FID at specific heights and down-channel locations

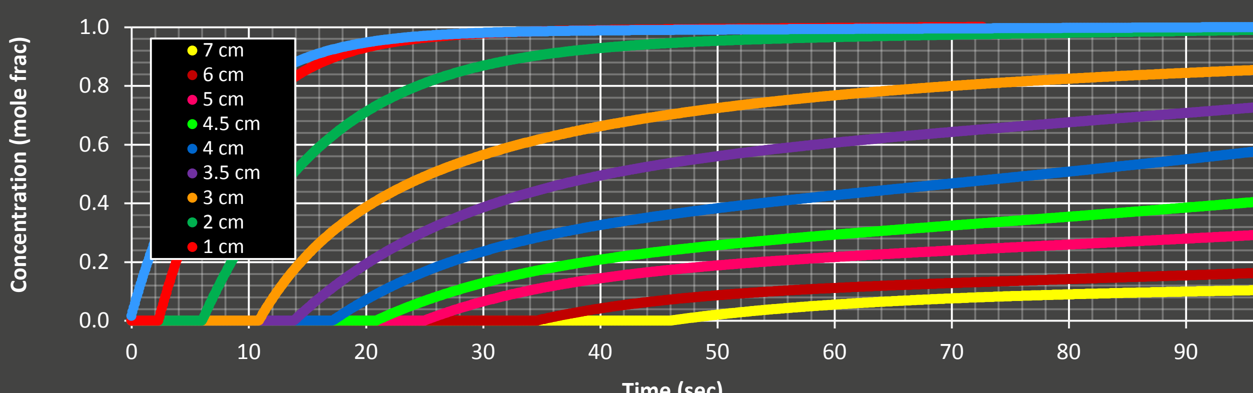
Lab Experiment - Computational domain and boundary conditions

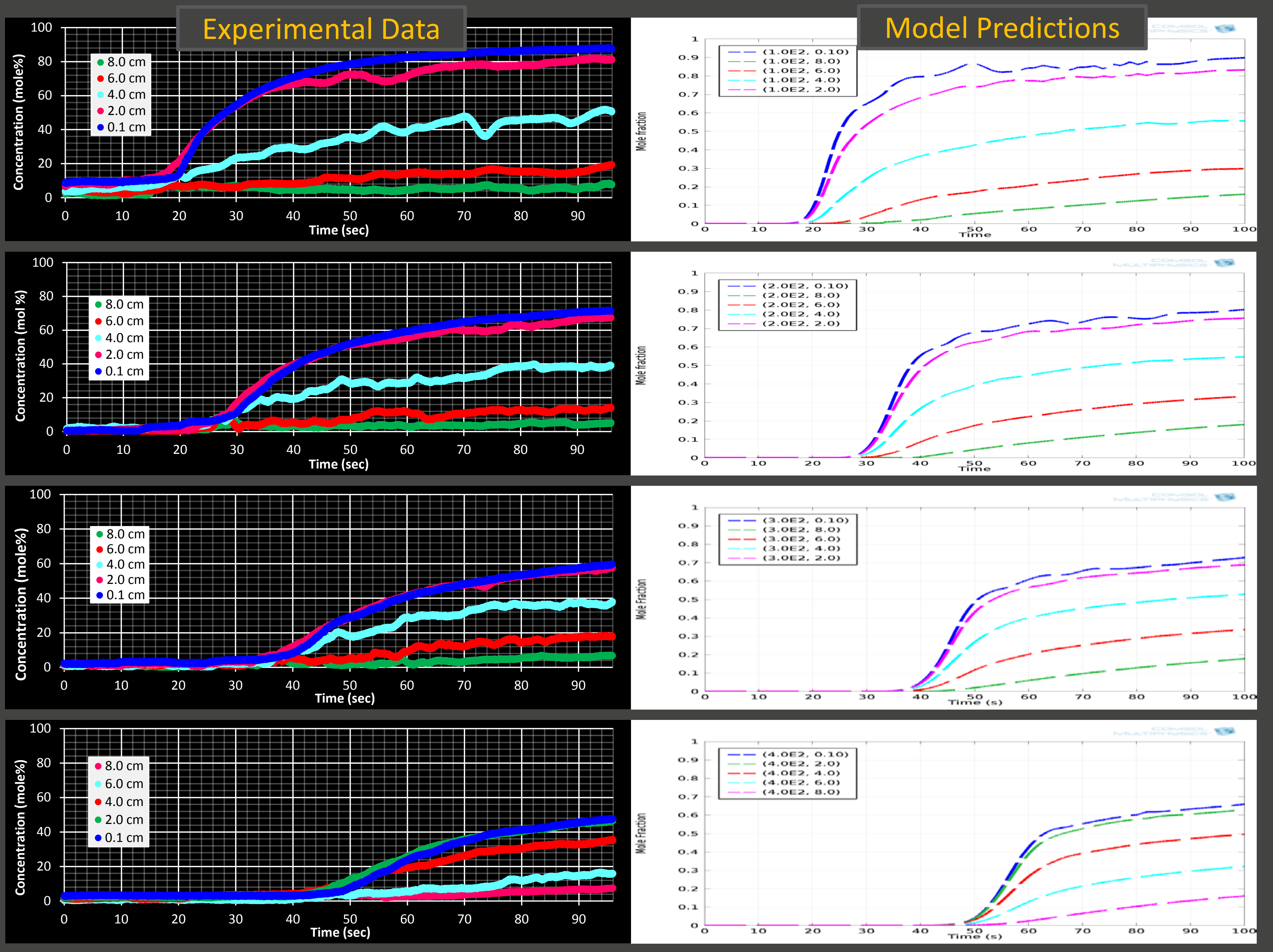






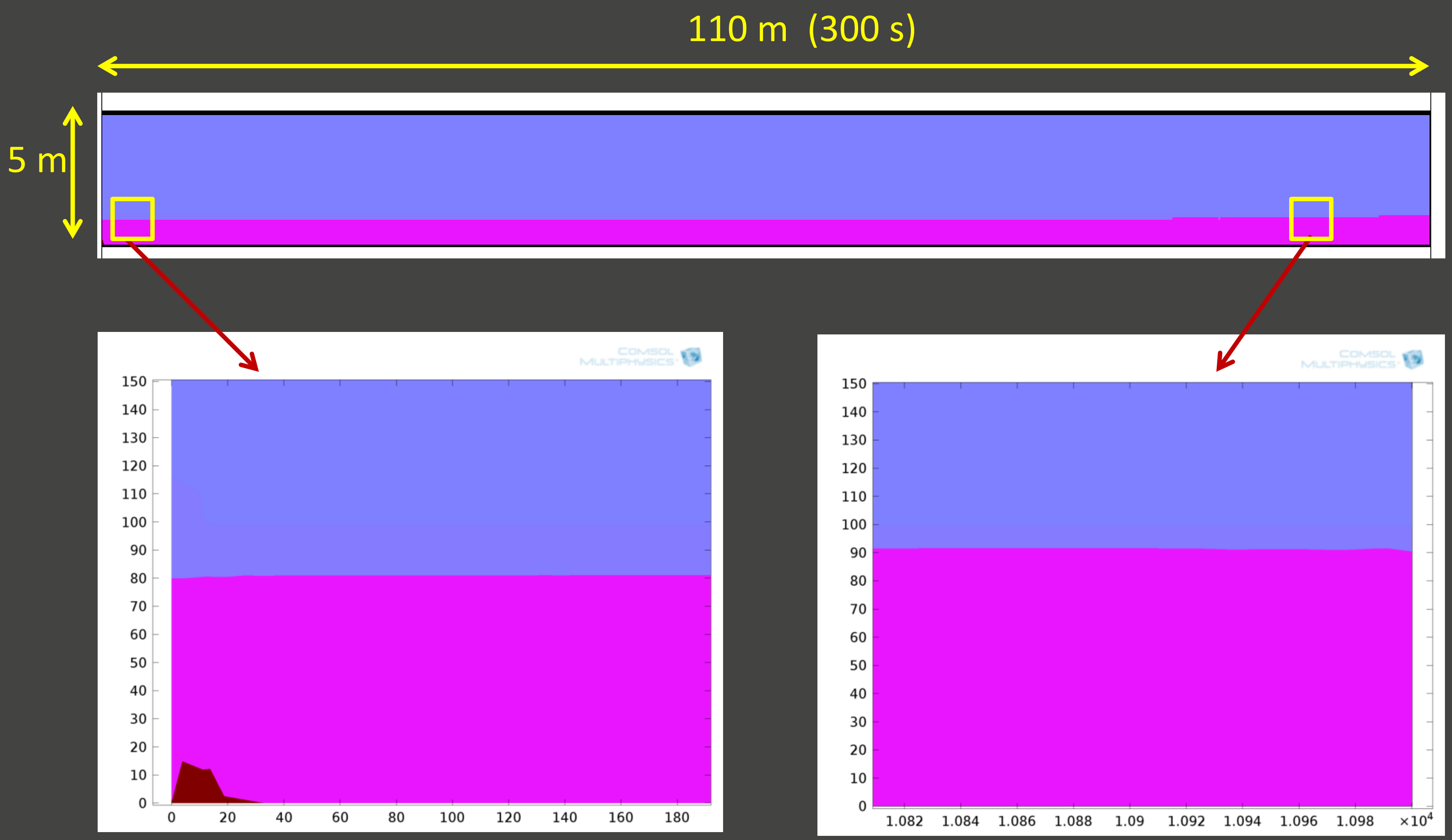





Experimental Data
Model Predictions
Concentration (mole%)
Concentration (mol %)
Time (sec)
8.0 cm
6.0 cm
4.0 cm
2.0 cm
0.1 cm
Mole fraction
Time
Time (s)
(1.0E2, 0.10)
(1.0E2, 8.0)
(1.0E2, 6.0)
(1.0E2, 4.0)
(1.0E2, 2.0)
(2.0E2, 0.10)
(2.0E2, 8.0)
(2.0E2, 6.0)
(2.0E2, 4.0)
(2.0E2, 2.0)
(3.0E2, 0.10)
(3.0E2, 8.0)
(3.0E2, 6.0)
(3.0E2, 4.0)
(3.0E2, 2.0)
(4.0E2, 0.10)
(4.0E2, 2.0)
(4.0E2, 4.0)
(4.0E2, 6.0)
(4.0E2, 8.0)

Implications for Buncefield

Diffusion can act to increase the explosive volume!



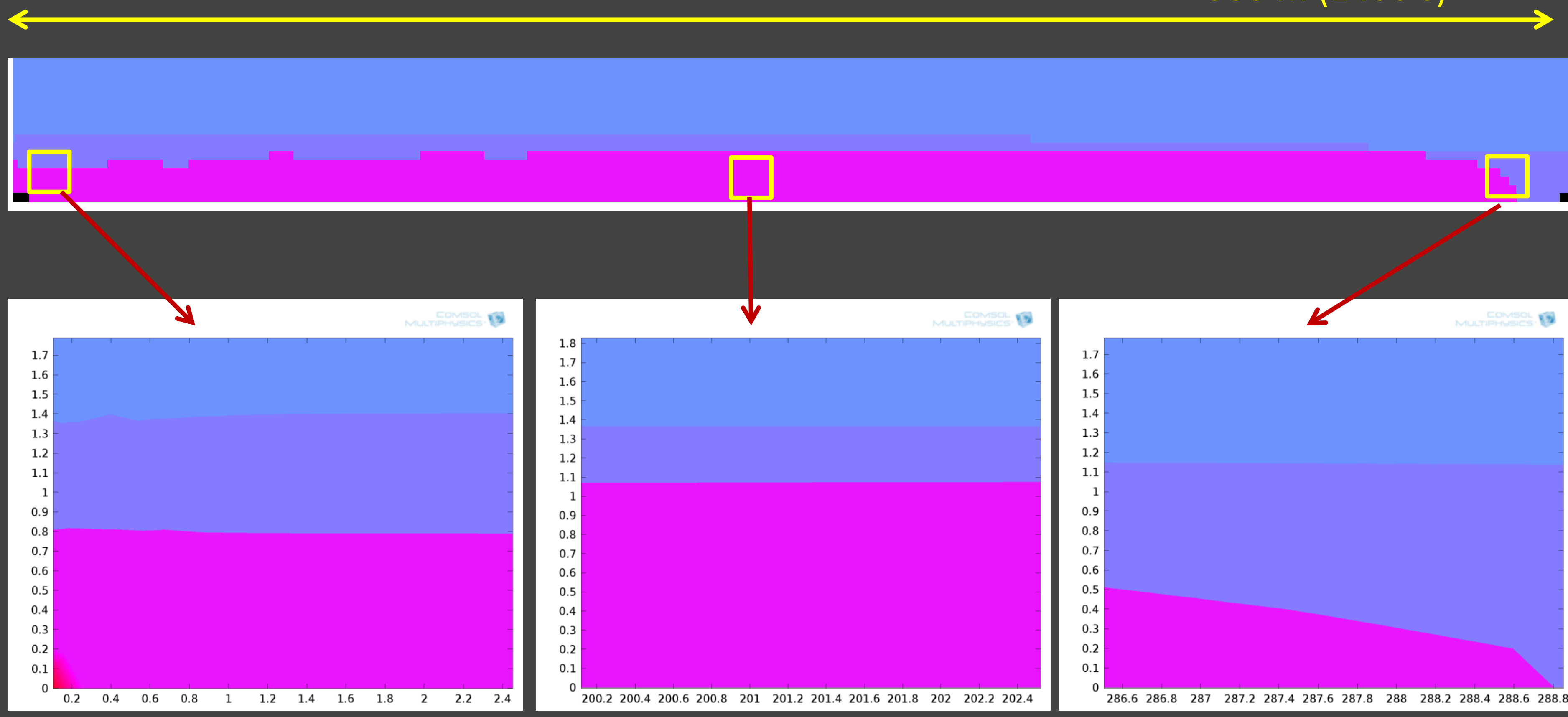
Implications for Regulatory Modeling

HSE Considering model for determining range to which a circular cloud could be ignited.

$$R_{ignition} = [\ 1/Pi\ V_{cloud}\ T]^{1/2}$$

For the example problem offered by HSE, we have calculated the effect of diffusion that would occur at the top of the cloud; the HSE model, which assumes no dilution, is conservative, but not overly so. However the explosive volume is indicated to increase.

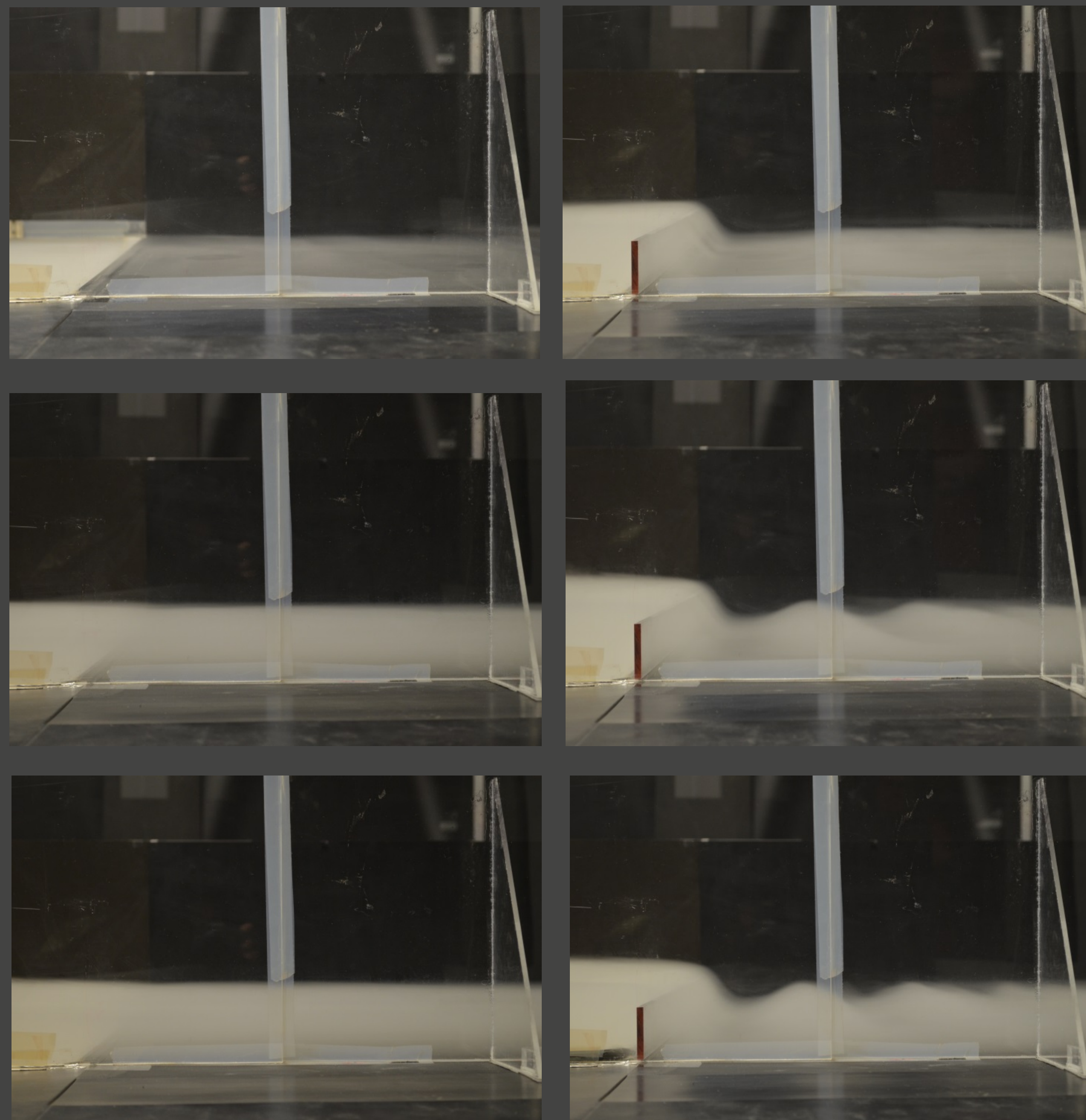
300 m (1400 s)



Speculations Regarding Effect of Dikes

- Layer thickness develops faster without dike
- Thinner, but faster, layer resulting from overflow of dike, results in greater diffusion
- Complex wave effects probably not important

No Fence | Fence



Conclusions

1. No-wind, shallow cloud depths, and long time scales indicate potential for important molecular diffusion effects.
2. Transient development of cloud thickness, starting concentration, and spreading velocity should be considered.
3. There is potential for diffusion effects to make concentrations more uniform and possibly increase potential for explosion.
4. Control measures for avoidance of such potential increases in hazard appear practical and worthy of consideration.