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EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Module V – Advanced Fire Modeling

Fire Modeling Tools

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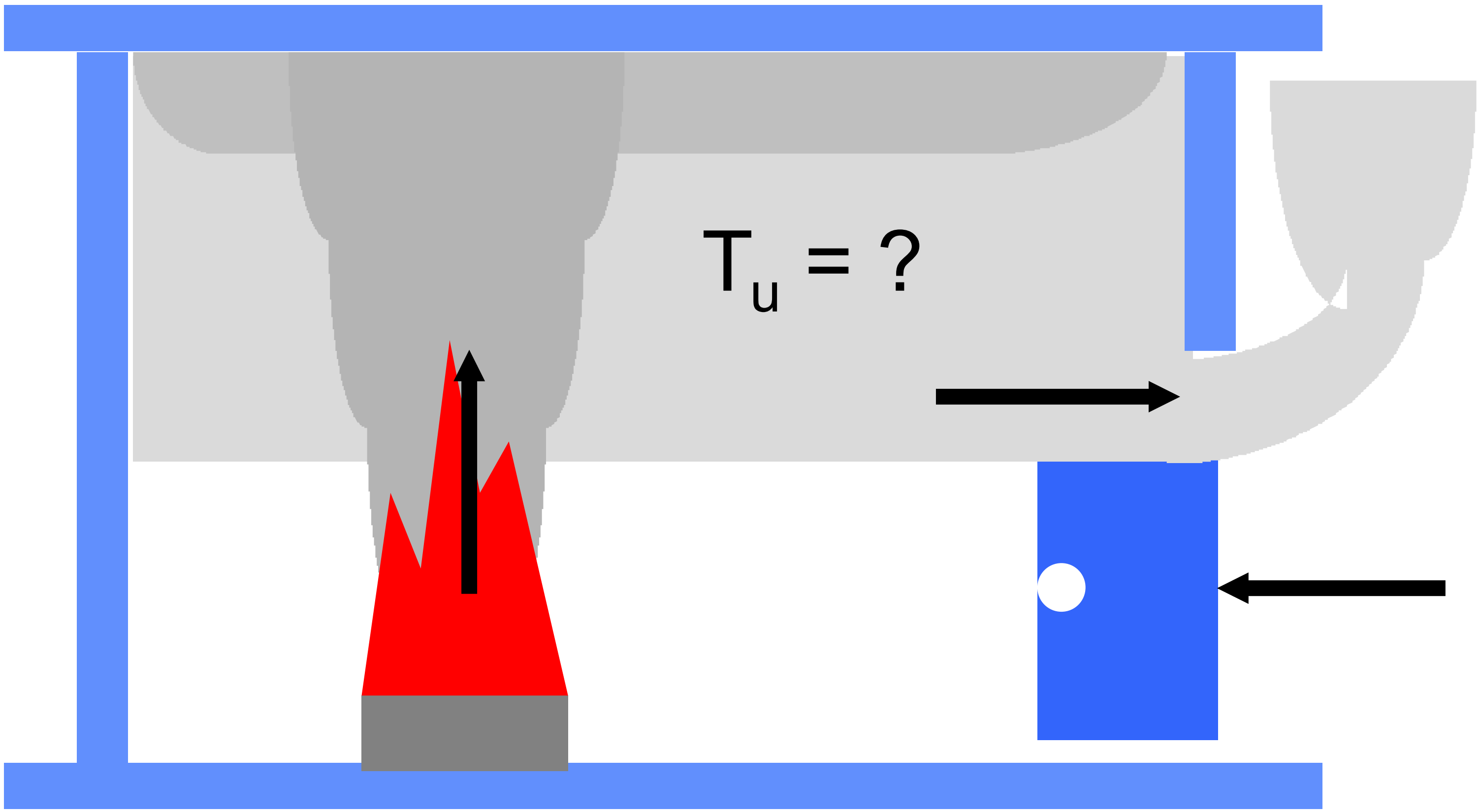
A Collaboration of the Electric Power Research Institute (EPRI) & U.S. NRC Office of Nuclear Regulatory Research (RES)

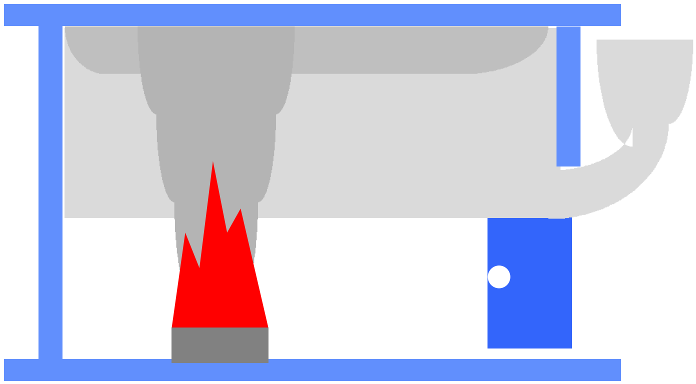
Empirical Compartment Models

- Purpose is to calculate average HGL temperature

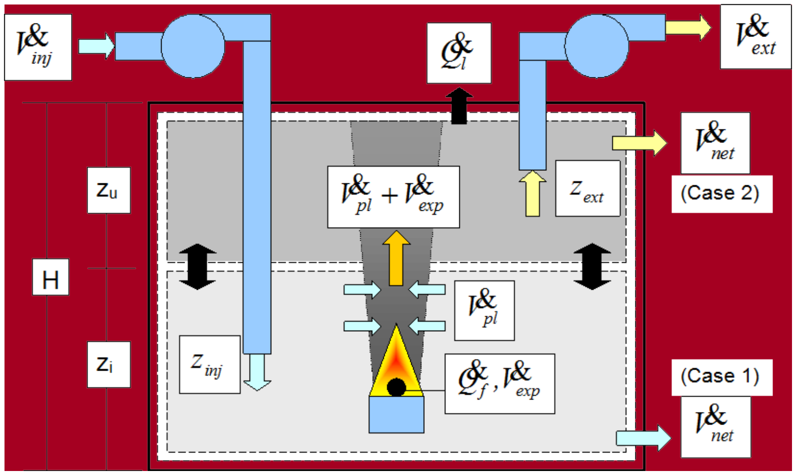


Empirical Compartment Models

- Naturally ventilated enclosures
  - MQH correlation



- Mechanically ventilated enclosures
  - FPA correlation



The MQH Correlation – Basic Concepts

- Upper layer energy balance

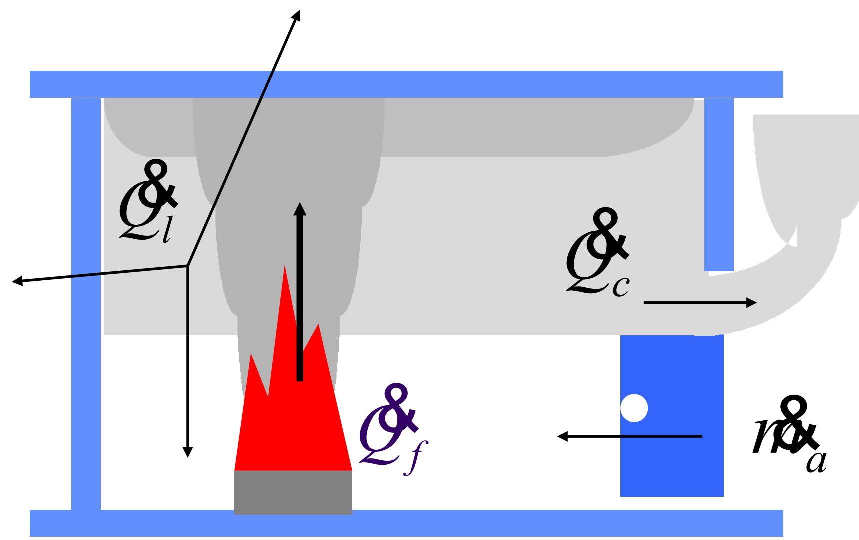
$$\dot{Q}_f = \dot{Q}_l + \dot{Q}_c$$

- Boundary heat loss term

$$\dot{Q}_l = h_k A_s \Delta T$$

- Convective heat loss term

$$\dot{Q}_c = \dot{m}_a c_p \Delta T$$



- Solve for ΔT:

$$\Delta T = \frac{\dot{Q}_f}{\dot{m}_a c_p + h_k A_s}$$

The MQH correlation

- Non-dimensionalize variables (by dividing by T_o)

$$\frac{\Delta T}{T_o} = \frac{\dot{Q}_f}{\dot{m}_a c_p T_o + h_k A_s T_o} = \frac{\left(\dot{Q}_f / \dot{m}_a c_p T_o\right)}{1 + \left(\dfrac{h_k A_s}{\dot{m}_a c_p}\right)}$$

- Assume that $\dot{m}_a \sim \rho_o A_o \sqrt{g H_o}$

$$\frac{\Delta T}{T_o} = f\left[\frac{\dot{Q}_f}{\sqrt{g}\,\rho_o c_p T_o A_o \sqrt{H_o}}, \frac{h_k A_s}{\sqrt{g}\,\rho_o c_p A_o \sqrt{H_o}}\right]$$

The MQH correlation

- Statistical correlation of the form:

$$\frac{\Delta T}{T_o} = C\left(\frac{\dot{Q}_f}{\sqrt{g}\,\rho_o c_p T_o A_o \sqrt{H_o}}\right)^N \left(\frac{h_k A_s}{\sqrt{g}\,\rho_o c_p A_o \sqrt{H_o}}\right)^M$$

- Over 100 sets of room fire data
  - Fuels: Gas, wood, plastics
  - Range of room sizes, thermal properties
  - Bias towards low fires in center of room

The MQH correlation

- Values for C, N and M from regression:

$$\frac{\Delta T}{T_o} = 1.63\left(\frac{\dot{Q}_f}{\sqrt{g}\,\rho_o c_p T_o A_o \sqrt{H_o}}\right)^{2/3}\left(\frac{h_k A_s}{\sqrt{g}\,\rho_o c_p A_o \sqrt{H_o}}\right)^{-1/3}$$

- For conventional values, this reduces to:

$$\Delta T = 6.85\left(\frac{\dot{Q}_f^2}{A_o\sqrt{H_o}\,h_k A_s}\right)^{1/3}$$

Heat transfer coefficient (h_k)

- Early stage - transient semi-infinite solid

$$\dot{q}'' = \frac{1}{\sqrt{\pi}}\sqrt{\frac{k\rho c}{t}}(T_g - T_o) \sim \sqrt{\frac{k\rho c}{t}}(T_g - T_o)$$

- Late stage - steady one-dimensional slab

$$\dot{q}'' = \frac{k}{\delta}(T_g - T_o)$$

- Effective heat transfer coefficient

$$h_k = MAX\left(\sqrt{\frac{k\rho c}{t}}, \frac{k}{\delta}\right)$$

Representative thermal properties

MATERIAL	k kW/m/K	ρ kg/m^3	c kJ/kg/K	α m^2/s	$k\rho c$
Aluminum (pure)	2.06E-01	2710	0.895	8.49E-05	5.00E+02
Concrete	1.60E-03	2400	0.75	8.89E-07	2.88E+00
Aerated concrete	2.60E-04	500	0.96	5.42E-07	1.25E-01
Brick	8.00E-04	2600	0.8	3.85E-07	1.66E+00
Concrete block	7.30E-04	1900	0.84	4.57E-07	1.17E+00
Cement-asbestos board	1.40E-04	658	1.06	2.01E-07	9.76E-02
Calcium silicate board	1.25E-04	700	1.12	1.59E-07	9.80E-02
Alumina silicate block	1.40E-04	260	1	5.38E-07	3.64E-02
Gypsum board	1.70E-04	960	1.1	1.61E-07	1.80E-01
Plaster board	1.60E-04	950	0.84	2.01E-07	1.28E-01
Plywood	1.20E-04	540	2.5	8.89E-08	1.62E-01
Chipboard	1.50E-04	800	1.25	1.50E-07	1.50E-01
Fiber insulation board	5.30E-05	240	1.25	1.77E-07	1.59E-02
Glass fiber insulation	3.70E-05	60	0.8	7.71E-07	1.78E-03
Expanded polystyrene	3.40E-05	20	1.5	1.13E-06	1.02E-03

MQH correlation example

- Calculate the quasi-steady smoke layer temperature rise in the FMSNL enclosure based on the following assumptions:
  - Lining material is 2.54 cm thick gypsum wallboard
  - Fire burns at a steady HRR of 500 kW
  - There is a single 0.8 m wide by 2.0 m high door in one of the walls
  - There is no mechanical ventilation

MQH correlation example

- Solution:
  - Lining material is 2.54 cm thick gypsum wallboard
    - Want quasi-steady solution, so need k and d
    - k = 1.7 x 10^{-4} kW/(m·K) and d = 0.0254 m
    - h_k = k/d = 6.7 x 10^{-3} kW/(m^2·K)
  - Heat transfer surface area

$$A_s = 2 \cdot \left[(18.3 \times 12.2) + (18.3 \times 6.1) + (12.2 \times 6.1) \right] - (0.8 \times 2.0)$$
$$= 817 \quad \mathrm{m}^2$$

  - Ventilation factor

$$A_o \sqrt{H_o} = 1.6\sqrt{2.0} = 2.26 \quad \mathrm{m}^{5/2}$$

MQH correlation example

- Solution:

$$\Delta T = 6.85\left(\frac{\dot{Q}_f^2}{A_o\sqrt{H_o}\,h_k A_s}\right)^{1/3}$$

$$= 6.85\left(\frac{500^2}{(2.26)(6.7\times10^{-3})(817)}\right)^{1/3}$$

$$= 187 \text{ C}$$

MQH correlation example

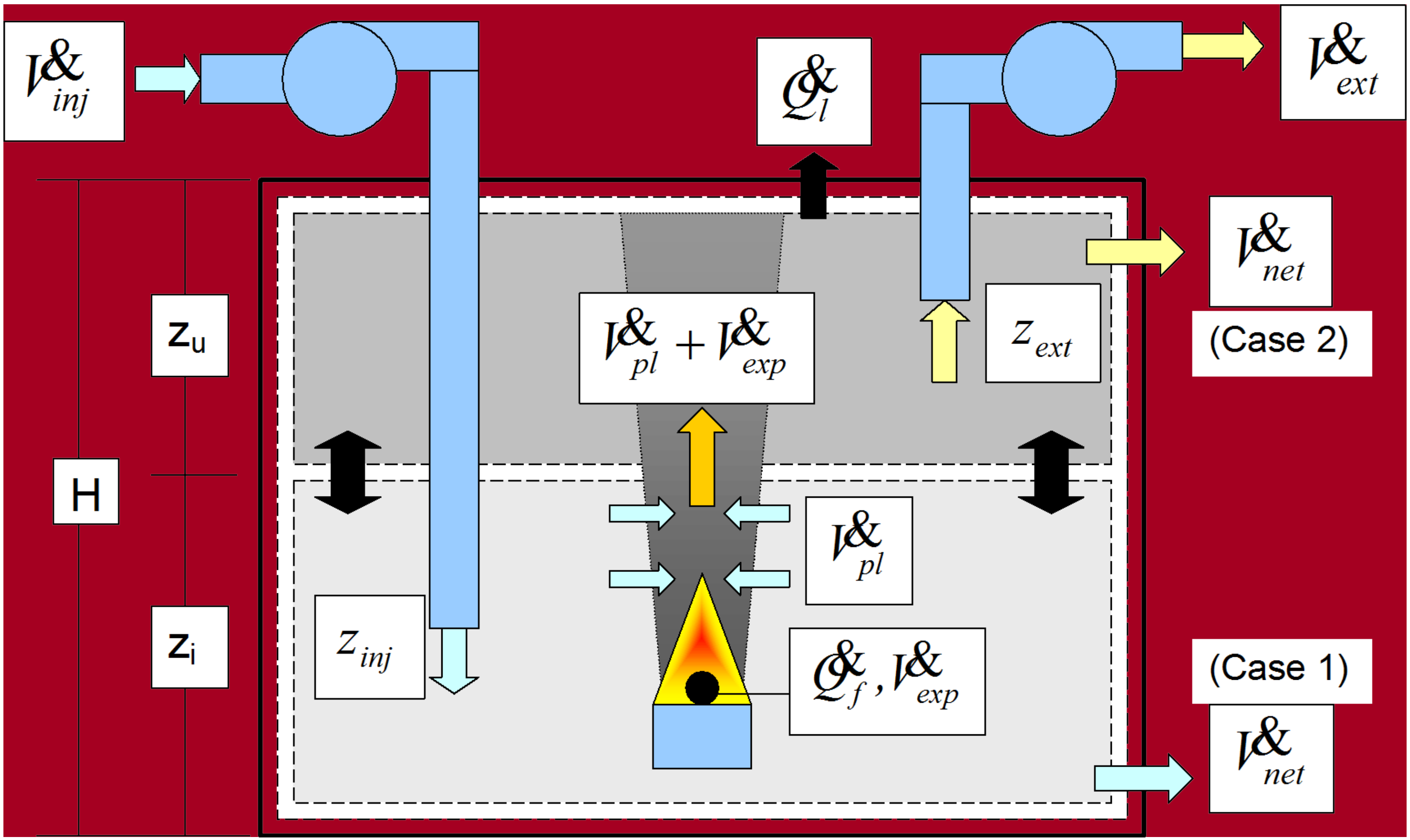
- Repeat the previous example calculation, but assume the fire only burns for 10 minutes
  - For this case, need to calculate the transient h_k:

$$h_k = \sqrt{\frac{k\rho c}{t}} = \sqrt{\frac{0.18}{600}} = 0.017 \quad \mathrm{kW/(m^2 \cdot K)}$$

$$\Delta T = 6.85\left(\frac{500^2}{(2.26)(0.017)(817)}\right)^{1/3}$$

$$= 137C$$

Mechanically ventilated spaces



Mechanically ventilated spaces

- Foote-Pagni-Alvares (FPA) correlation
  – Analogous to MQH correlation
  – Based on limited data in single enclosure
  – Quasi-steady temperature rise

$$\frac{\Delta T}{T_o} = 0.63\left(\frac{\dot{Q}_f}{\dot{m} c_p T_o}\right)^{0.72}\left(\frac{h_k A_s}{\dot{m} c_p}\right)^{-0.36}$$

Mechanically ventilated spaces

- Foote-Pagni-Alvares correlation example
  - Calculate the temperature rise in the FMSNL enclosure for a HRR of 500 kW and a mechanical ventilation rate of 10 ach
  - Solution
    - T_0 = 293 K (remember to use absolute temperature)
    - h_k and A_s as in the MQH example
    - Mass flow rate calculated as

$$\dot{m} = \rho \dot{V} = (1.2\ \text{kg}/\text{m}^3)(3.8\ \text{m}^3/\text{s}) = 4.6\ \text{kg/s}$$

Mechanically ventilated spaces

- Foote-Pagni-Alvares correlation example
  - Solution

$$\frac{\Delta T}{T_o} = 0.63\left(\frac{\dot{Q}_f}{\dot{m} c_p T_o}\right)^{0.72}\left(\frac{h_k A_s}{\dot{m} c_p}\right)^{-0.36}$$

$$= 0.63\left(\frac{500}{(4.6)(1.0)(293)}\right)^{0.72}\left(\frac{(0.017)(817)}{(4.6)(1.0)}\right)^{-0.36}$$

$$= 0.21$$

$$\Delta T = 0.21\,T_o = 0.21\,(293) = 61\ \text{K}$$

Smoke and visibility

- Light attenuation and visibility through smoke can be estimated based on the soot mass concentration within the smoke layer
- The light extinction coefficient, K, is directly proportional to the soot mass concentration as:

$$K = K_m \rho Y_s$$

  – where K_m is the specific extinction coefficient and Y_s is the soot mass fraction in the smoke

Smoke and visibility

- Seader and Einhorn suggested values for K_m
  - K_m = 7,600 m^2/kg for flaming combustion and
  - K_m = 4,400 m^2/kg for pyrolysis smoke.
  - These values have been widely used for light attenuation and visibility calculations in the past
- Mulholand and Croarkin have suggested a value of K_m = 8,700 m^2/kg for flaming combustion of wood and plastic fuels
  - This value is now more widely used (e.g., default value in FDS)

Smoke and visibility

- Light attenuation is calculated in accordance with Bougher's Law for monochromatic light:

$$I / I_o = e^{-KL}$$

- Visibility through smoke varies inversely with the light extinction coefficient:

$$S = C / K$$

  - where S is the visibility distance (m) and C is a constant related to the illumination of the object being viewed

Smoke and visibility

- Mulholand gives the following values for C:
  - C = 8 for light-emitting signs $$I / I_o = e^{-8} = 3.35 \times 10^{-4}$$
  - C = 3 for light-reflecting signs $$I / I_o = e^{-3} = 0.05$$
- These values should be used with caution because they will depend on the ambient light levels

Smoke and visibility

- To calculate smoke obscuration and visibility, the soot mass fraction, Y_s, is calculated
- First, the soot generation rate is calculated

$$\dot{m}_{s,gen} = f_s \dot{m}_f = \frac{\dot{Q}_f}{(\Delta H_c / f_s)}$$

  – where f_s is the soot yield of the fuel (g soot / g fuel)
  – Representative soot yields are tabulated in the SFPE Handbook (Tewarson chapter) for a large number of fuels
    - Some values have been copied into Table 18-3 of NUREG 1805

Smoke and visibility

- Representative soot yields

Table 18-3. Smoke Particulate Yield (Klote and Milke, 2002)

Material	Particulate Yield - y_p
Wood (Red Oak)	0.015
Wood (Douglas Fir)	0.018
Wood (Hemlock)	0.015
Fiberboard	0.008
Wool (100-percent)	0.008
Acrylonitrile-Butadiene-Styrene (ABS)	0.105
Polymethylmethacrylate (PMMA; Plexiglas™)	0.022
Polypropylene	0.059
Polystyrene	0.164
Silicone	0.065
Polyester	0.09
Nylon	0.075
Silicone Rubber	0.078
Polyurethane Foam (Flexible)	0.188
Polyurethane Foam (Rigid)	0.118

Smoke and visibility

- Soot mass concentration
  - Unventilated rooms:

$$\rho Y_s = \frac{\left(Q_f / V\right)}{(\Delta H_c / f_s)}$$

  - Ventilated rooms:

$$Y_s = \frac{\dot{m}_s}{\dot{m}_{tot}} = \frac{\left(\dot{Q}_f / \dot{V}\right)}{\rho(\Delta H_c / f_s)} \qquad \rho Y_s = \frac{\left(\dot{Q}_f / \dot{V}\right)}{(\Delta H_c / f_s)}$$

Smoke and visibility

- Unventilated room example
  - Estimate the average mass concentration of soot and the visibility distance within the 18.3 m by 12.2 m by 6.1 m FMSNL enclosure at 240 s and 600 s after ignition
    - Assume the enclosure is unventilated
    - Assume propylene (C_3H_6) is the fuel
    - Assume the fire grows as a t-squared fire to a HRR of 500 kW in 240 s, then burns at a constant HRR of 500 kW for another 360 s.

Smoke and visibility

- Unventilated room example
  - For propylene (C_3H_6)

$$\Delta H_c = 46.4 \text{ MJ/kg}_\text{f}$$

$$f_s = 0.095 \text{ kg}_\text{s}/\text{kg}_\text{f}$$

$$\Delta H_c / f_s = 488.4 \text{ MJ/kg}_\text{s}$$

  - Fire heat release

$$Q_f(@240\ s) = \int_o^{240} \left(\frac{500}{(240)^2} \right) t^2 dt = \left(\frac{500}{(240)^2} \right) \left(\frac{(240)^3}{3} \right) = 40{,}000 \text{ kJ}$$

$$Q_f(@600 \text{ s}) = Q_f(@240 \text{ s}) + \int_{240}^{600} 500 \text{ d}t = 40{,}000 \text{ kJ} + 180{,}000 \text{ kJ} = 220{,}000 \text{ kJ}$$

Smoke and visibility

- Unventilated room example
  - Heat release per unit volume

$$Q_f / V(@240\ s) = 40{,}000\,kJ / 1{,}382\,m^3 = 28.9\,kJ / m^3$$

$$Q_f / V(@600\ s) = 220{,}000\,kJ / 1{,}382\,m^3 = 159.2\,kJ / m^3$$

  - Soot mass concentration

$$\rho Y_{soot}(@240\,s) = \frac{28.9\,kJ / m^3}{488.42 \times 10^3\ kJ / kg_{soot}} = 5.92 \times 10^{-5}\,kg_{soot} / m^3$$

$$\rho Y_{soot}(@600\,s) = \frac{159.2\,kJ / m^3}{488.42 \times 10^3\ kJ / kg_{soot}} = 3.26 \times 10^{-4}\,kg_{soot} / m^3$$

Smoke and visibility

- Unventilated room example
  - Extinction coefficient

$$K(@240\,s) = K_m \rho Y_{soot} = (8{,}700\,m^2/kg_{soot})(5.92\times10^{-5}\,kg_{soot}/m^3) = 0.52\,m^{-1}$$

$$K(@600\,s) = K_m \rho Y_{soot} = (8{,}700\,m^2/kg_{soot})(3.26\times10^{-4}\,kg_{soot}/m^3) = 2.83\,m^{-1}$$

  - Visibility of light-reflecting sign through smoke

$$S(@240\,s) = 3/0.52\,m^{-1} = 5.8\,m\,(19\,ft)$$

$$S(@600\,s) = 3/2.83\,m^{-1} = 1.1\,m\,(3.6\,ft)$$

Smoke and visibility

- Ventilated room example
  - Estimate the average mass concentration of soot and the visibility distance within the 18.3 m by 12.2 m by 6.1 m FMSNL enclosure under quasi-steady conditions assuming the enclosure is mechanically ventilated at 10 ach
    - Assume propylene (C_3H_6) is the fuel burned in the FMSNL fire tests
    - Assume the fire burns at a constant HRR of 500 kW

Smoke and visibility

- Ventilated room example
  - Volumetric flow rate

$$\dot{V} = \frac{10 \cdot (18.3\ \text{m} \times 12.2\ \text{m} \times 6.1\ \text{m})}{3{,}600\ \text{s}} = 3.8\ \text{m}^3/\text{s}$$

  - HRR/Volumetric flow rate

$$\dot{Q}_f / \dot{V} = \frac{500\ \text{kW}}{3.8\ \text{m}^3/\text{s}} = 131.6\ \text{kJ/m}^3$$

Smoke and visibility

- Ventilated room example
  - Soot mass concentration

$$\rho Y_s = \frac{\left(\dot{Q}_f / \dot{V}\right)}{(\Delta H_c / f_s)} = \frac{131.6\, kJ / m3}{488.4 \times 10^3\, kJ / kg_s} = 2.7 \times 10^{-4}\, kg_s / m^3$$

  - Extinction coefficient

$$K = K_m \rho Y_{soot} = (8{,}700\, m^2 / kg_s)(2.7 \times 10^{-4}\, kg_s / m^3) = 2.35\, m^{-1}$$

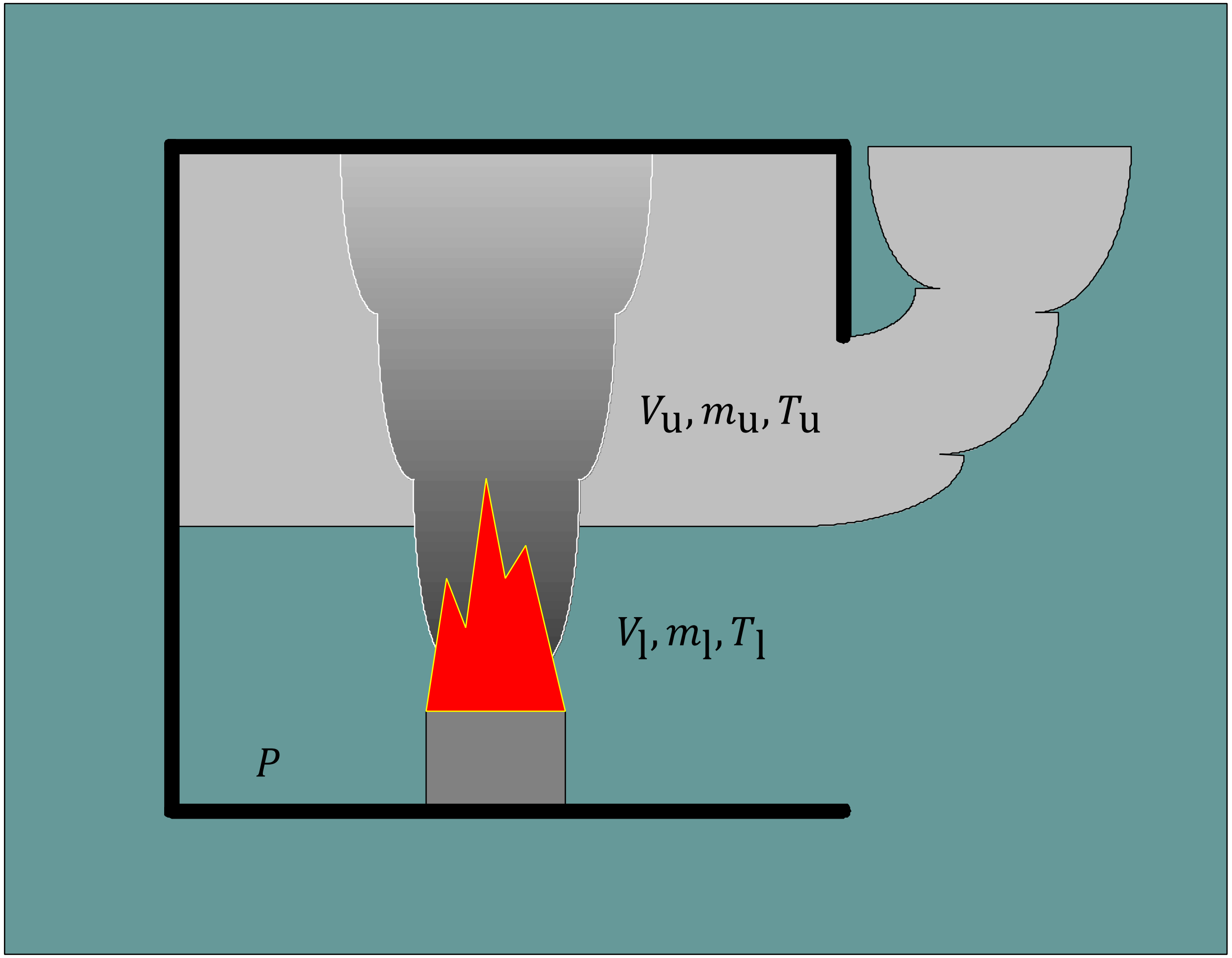
  - Visibility of light-reflecting sign through smoke

$$S = 3 / 2.35\, m^{-1} = 1.3\, m\,(4.2\, ft)$$

Overview of zone models

- Conservation equations and the hot gas layer
- Pressure profiles and vent flows
- Mechanical ventilation effects
- Thermal Radiation

Zone model nomenclature



$$\rho = \frac{m}{V}$$

Equation of State

$$P\,V = m\,R\,T$$

(Pa) x (m^3) = (kg) x (J/kg/K) x (K)

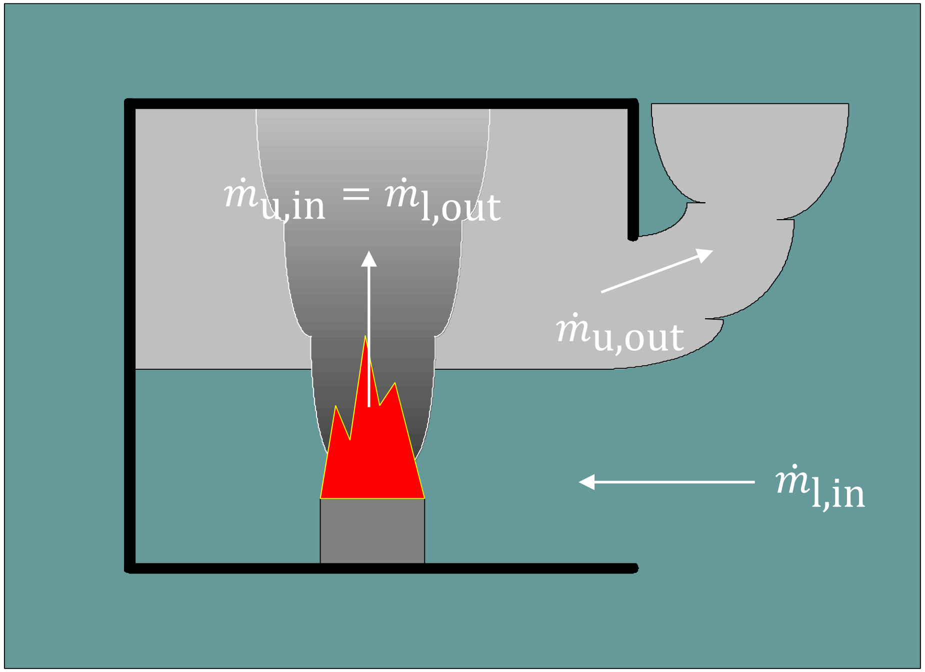
Ideal gas, constant properties

$$R = c_p - c_v \;\; ; \;\; \gamma = \frac{c_p}{c_v} \;\; ; \;\; c_p = 1012\ \mathrm{J/kg/K} \;\; ; \;\; \gamma = 1.4$$

Mass conservation

$$\frac{dm}{dt} = \frac{\rho V}{dt} = \dot{m}_{\text{in}} - \dot{m}_{\text{out}}$$

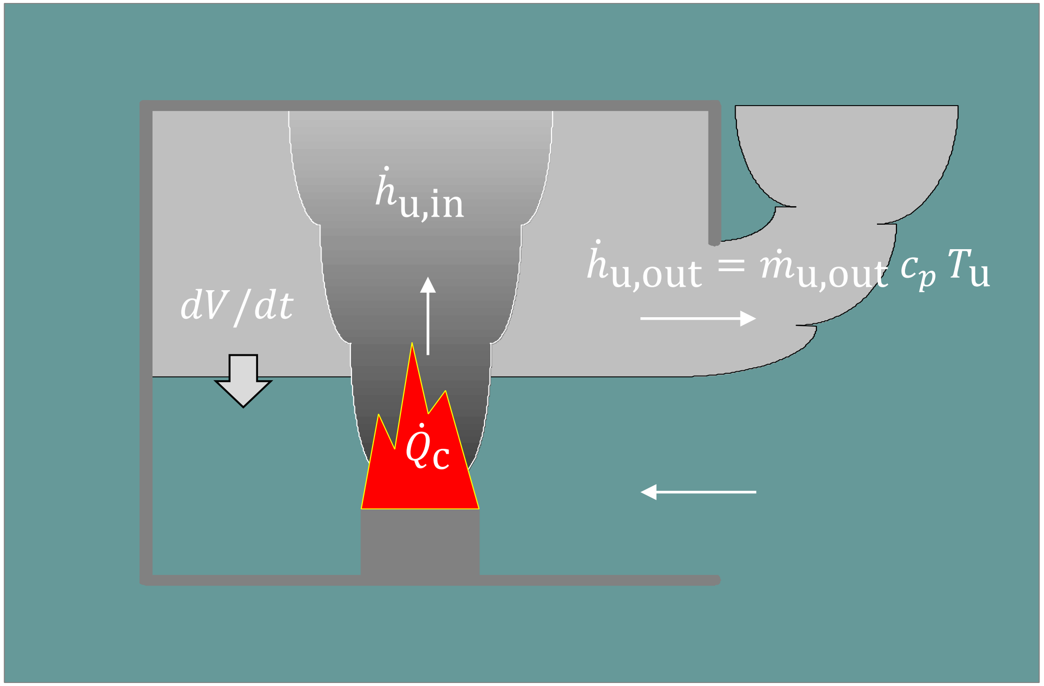
change in mass = mass in – mass out



Energy conservation

$$\frac{d}{dt}(c_v m T) = \dot{h}_{\mathrm{in}} - \dot{h}_{\mathrm{out}} - P\frac{dV}{dt} + \dot{Q}_{\mathrm{c}}$$

increase in internal energy = enthalpy in – enthalpy out – pressure work + fire HRR



CFAST Equation Set

$$
\begin{aligned}
\frac{\mathrm{d}P}{\mathrm{d}t} &= \frac{\gamma - 1}{V}\left(\dot{h}_{\mathrm{l}} + \dot{h}_{\mathrm{u}}\right) \\
\frac{\mathrm{d}V_{\mathrm{u}}}{\mathrm{d}t} &= \frac{1}{P\gamma}\left((\gamma - 1)\,\dot{h}_{\mathrm{u}} - V_{\mathrm{u}}\frac{\mathrm{d}P}{\mathrm{d}t}\right) \\
\frac{\mathrm{d}T_{\mathrm{u}}}{\mathrm{d}t} &= \frac{1}{c_p\, m_{\mathrm{u}}}\left(\dot{h}_{\mathrm{u}} - c_p\,\dot{m}_{\mathrm{u}}\,T_{\mathrm{u}} + V_{\mathrm{u}}\frac{\mathrm{d}P}{\mathrm{d}t}\right) \\
\frac{\mathrm{d}T_{\mathrm{l}}}{\mathrm{d}t} &= \frac{1}{c_p\, m_{\mathrm{l}}}\left(\dot{h}_{\mathrm{l}} - c_p\,\dot{m}_{\mathrm{u}}\,T_{\mathrm{l}} + V_{\mathrm{l}}\frac{\mathrm{d}P}{\mathrm{d}t}\right)
\end{aligned}
$$

Combustion (CFAST)

CFAST converts a user-specified fuel molecule to user-specified products, assuming that the oxygen concentration is greater than 10%:

$$\mathrm{C}_{n_\mathrm{C}}\mathrm{H}_{n_\mathrm{H}}\mathrm{O}_{n_\mathrm{O}}\mathrm{N}_{n_\mathrm{N}}\mathrm{Cl}_{n_\mathrm{Cl}} \quad + \quad \nu_{\mathrm{O_2}}\,\mathrm{O_2} \rightarrow$$

$$\nu_{\mathrm{CO_2}}\,\mathrm{CO_2} \quad + \quad \nu_{\mathrm{H_2O}}\,\mathrm{H_2O} + \nu_{\mathrm{CO}}\,\mathrm{CO} + \nu_{\mathrm{S}}\,\mathrm{Soot} + \nu_{\mathrm{HCl}}\mathrm{HCl} + \nu_{\mathrm{HCN}}\mathrm{HCN}$$

The user species the atoms of the fuel molecule plus the yields, *y*, of soot and CO:

$$\nu_\mathrm{S} = \frac{M_\mathrm{F}}{M_\mathrm{S}}\, y_\mathrm{S}$$

$$\nu_\mathrm{CO} = \frac{M_\mathrm{F}}{M_\mathrm{CO}}\, y_\mathrm{CO}$$

All Cl and N in the fuel molecule go to HCl and HCN.

Vent (Orifice) flow

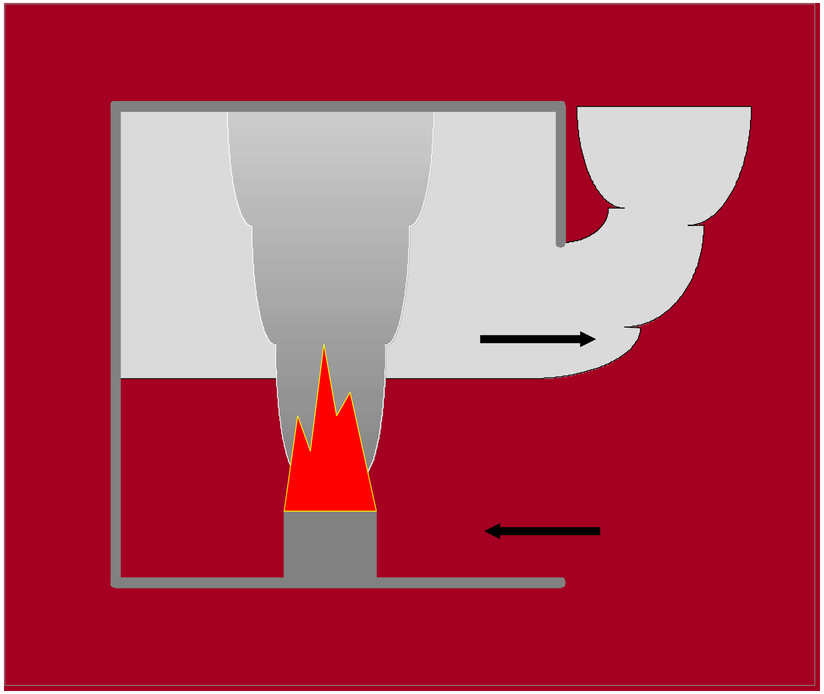
Mass flow through a relatively small vent:

$$\dot{m} = C\,A\,\sqrt{2\,\rho\,\Delta p} \quad ; \quad C \cong 0.7$$

When the pressure varies with height:

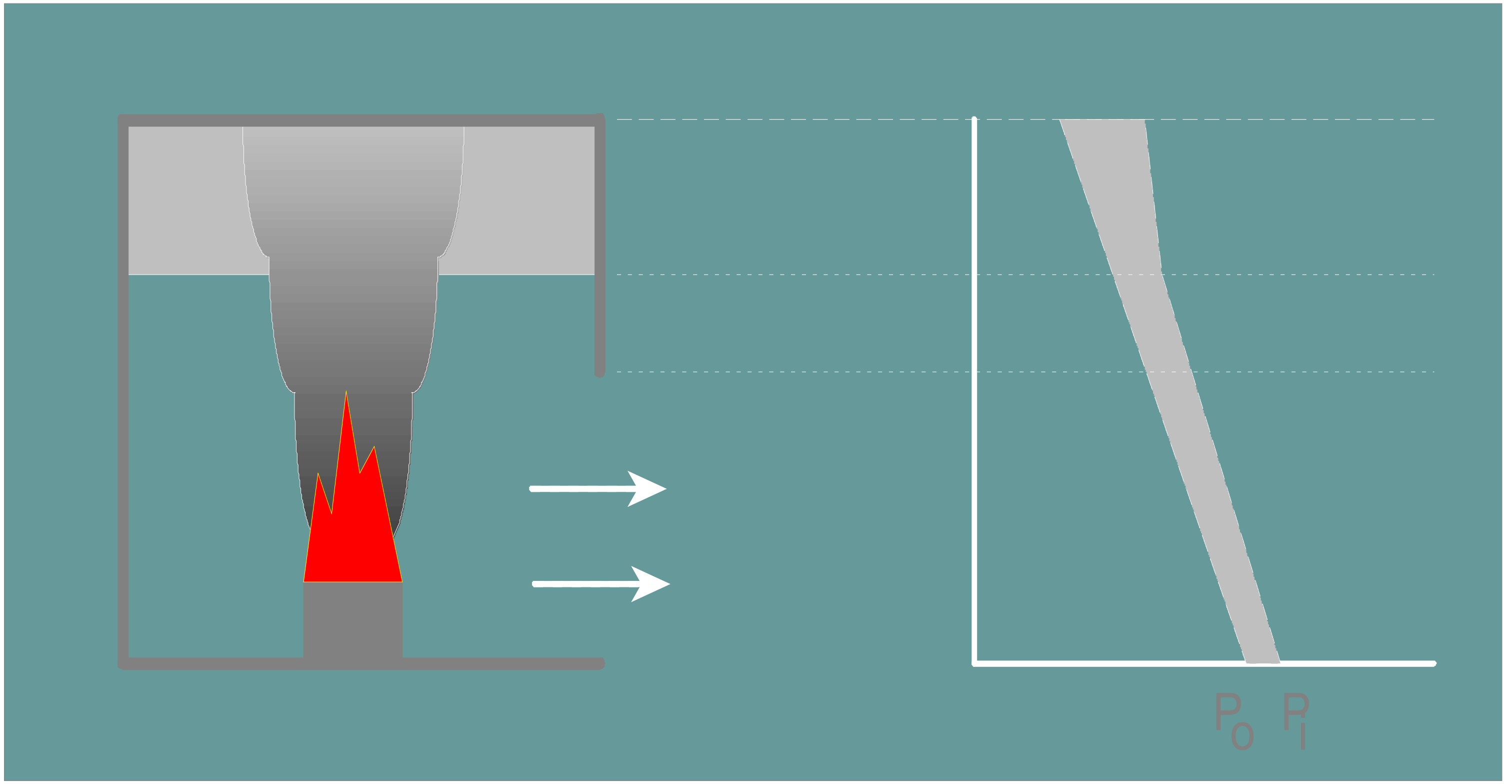
$$p(z) = p_0 - \rho(z) g\, z$$

$$\dot{m} = \int_{\mathrm{b}}^{\mathrm{t}} C\sqrt{2\rho\,\Delta p(z)}\; w\, dz$$



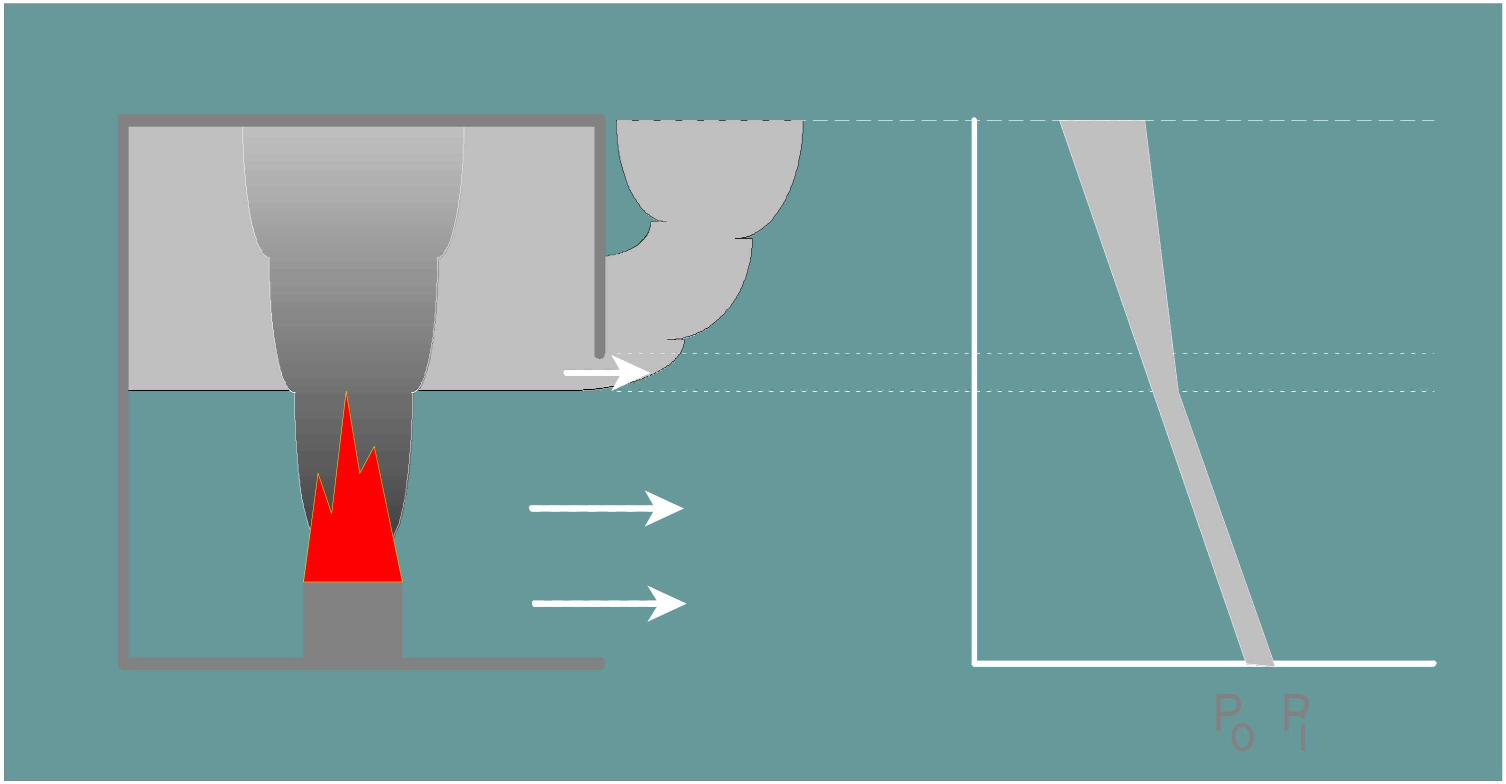
Pressure profile

PHASE 1



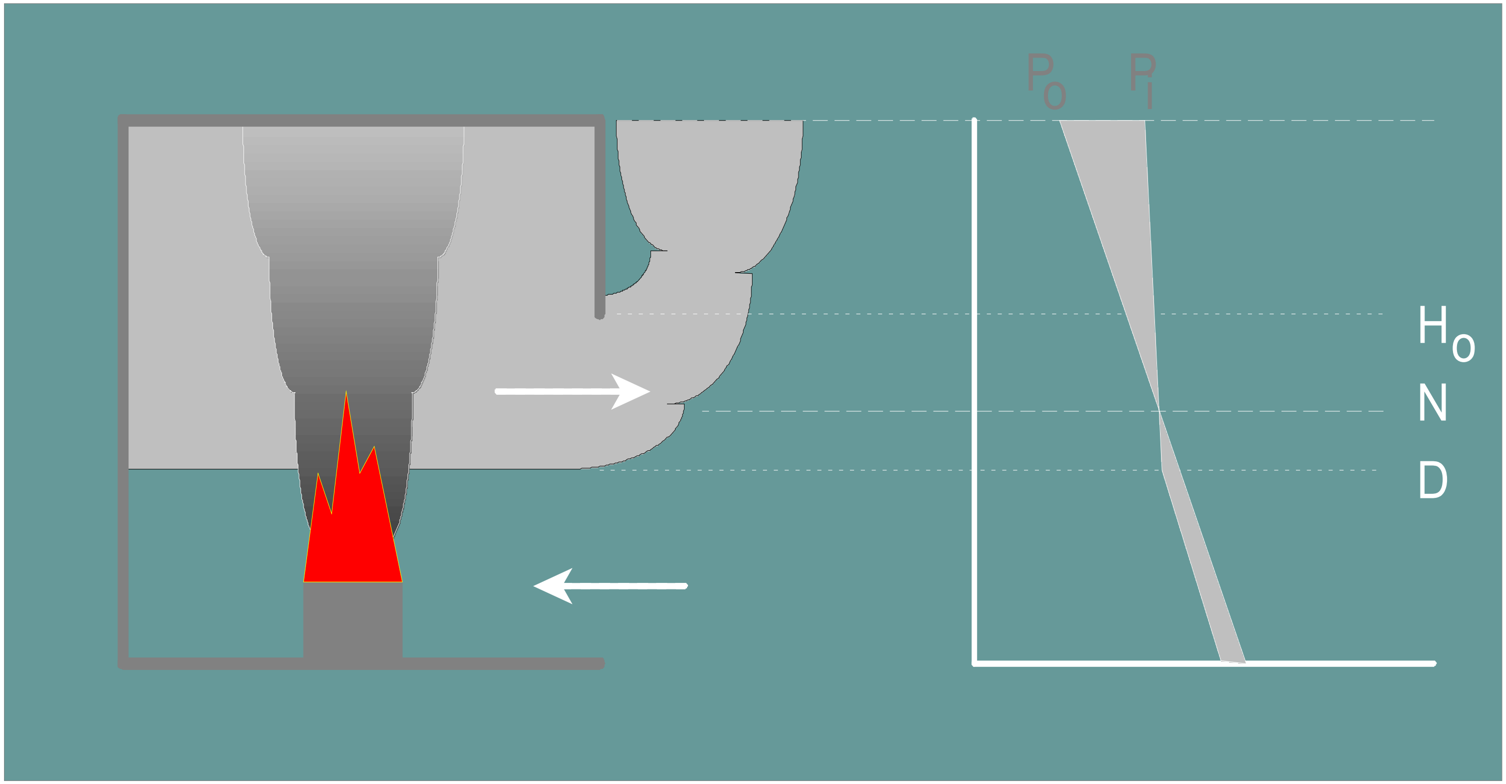
Pressure profile

PHASE 2

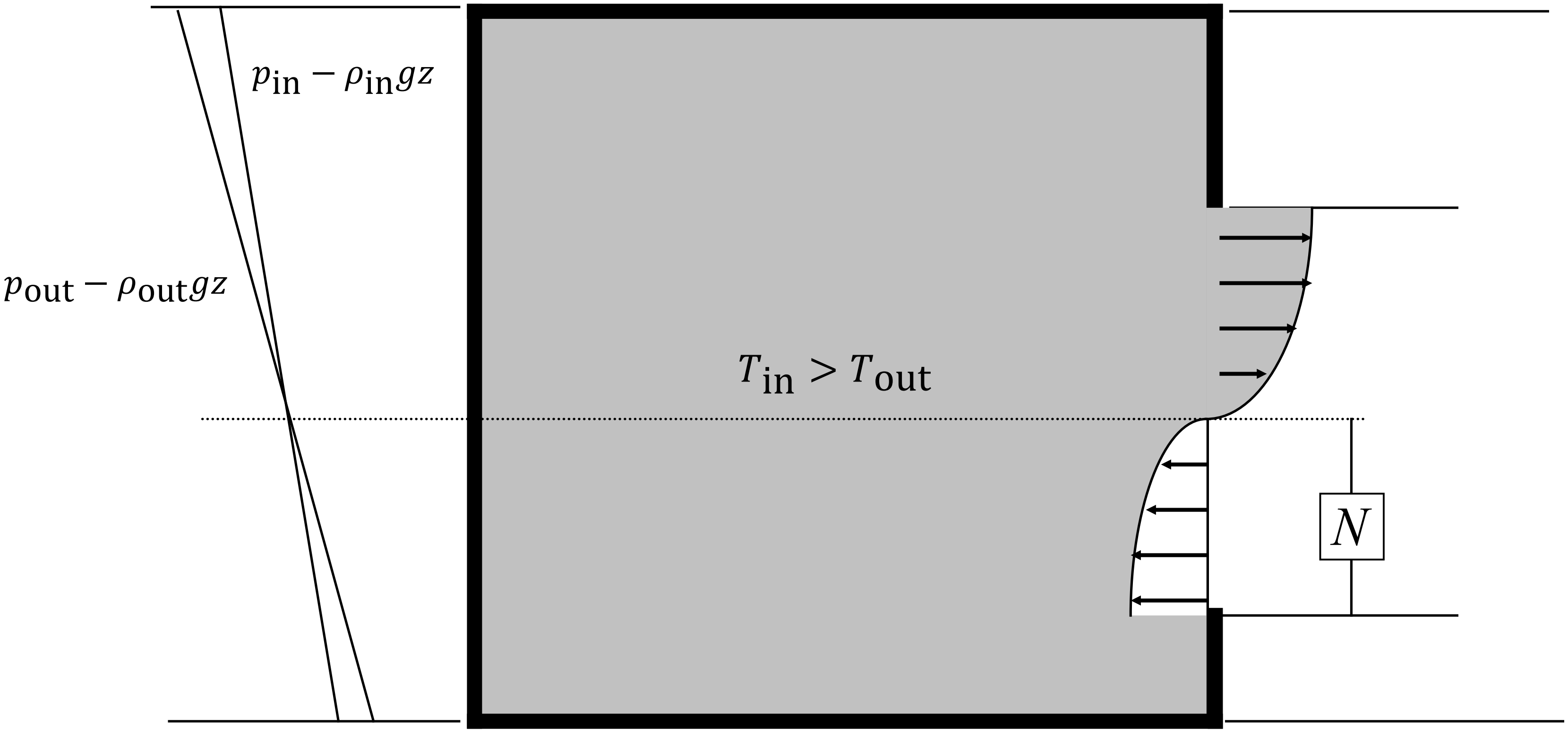


Pressure profile

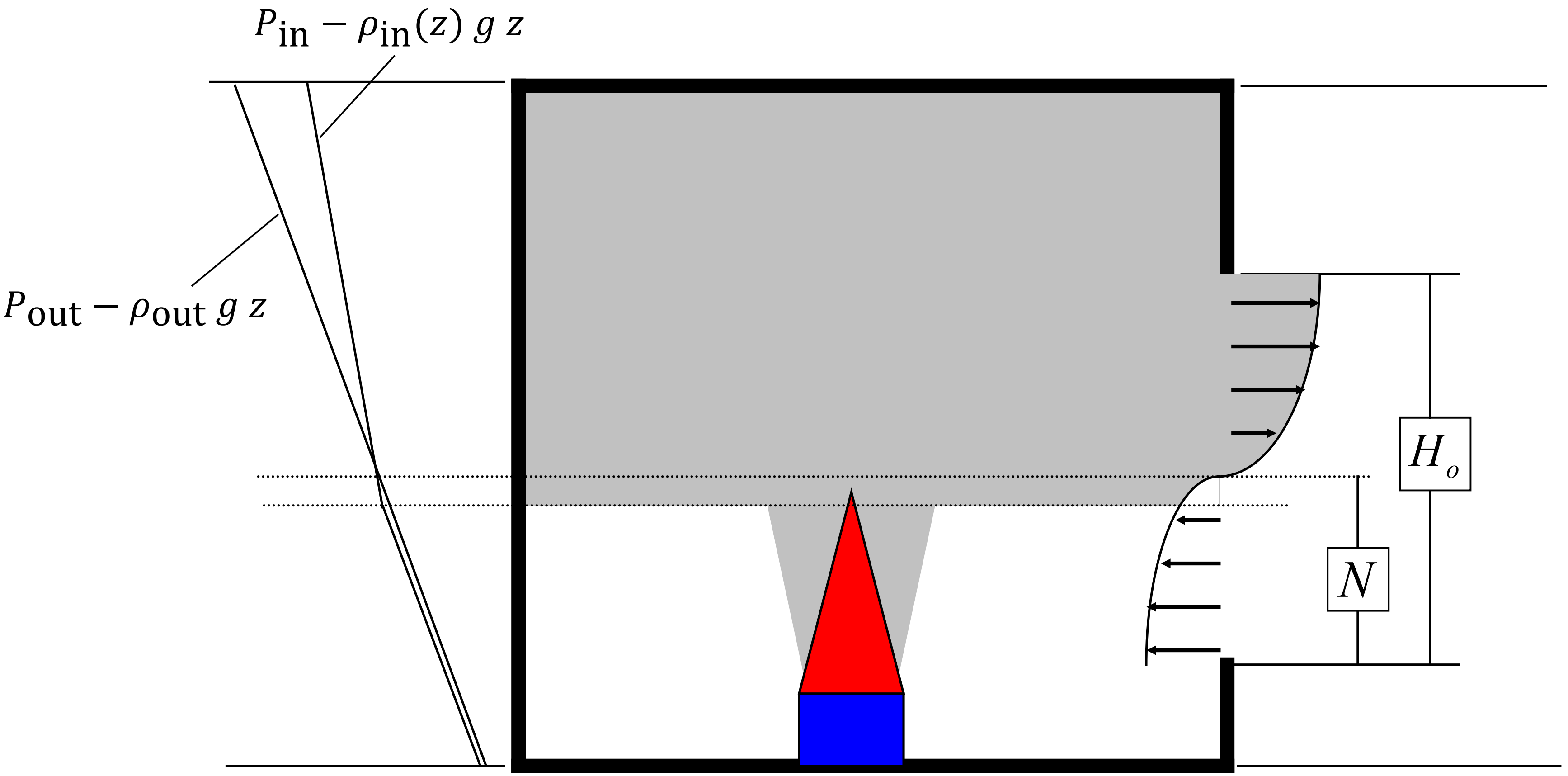
PHASE 3



Wall vents – one zone ($T_{in} > T_{out}$)

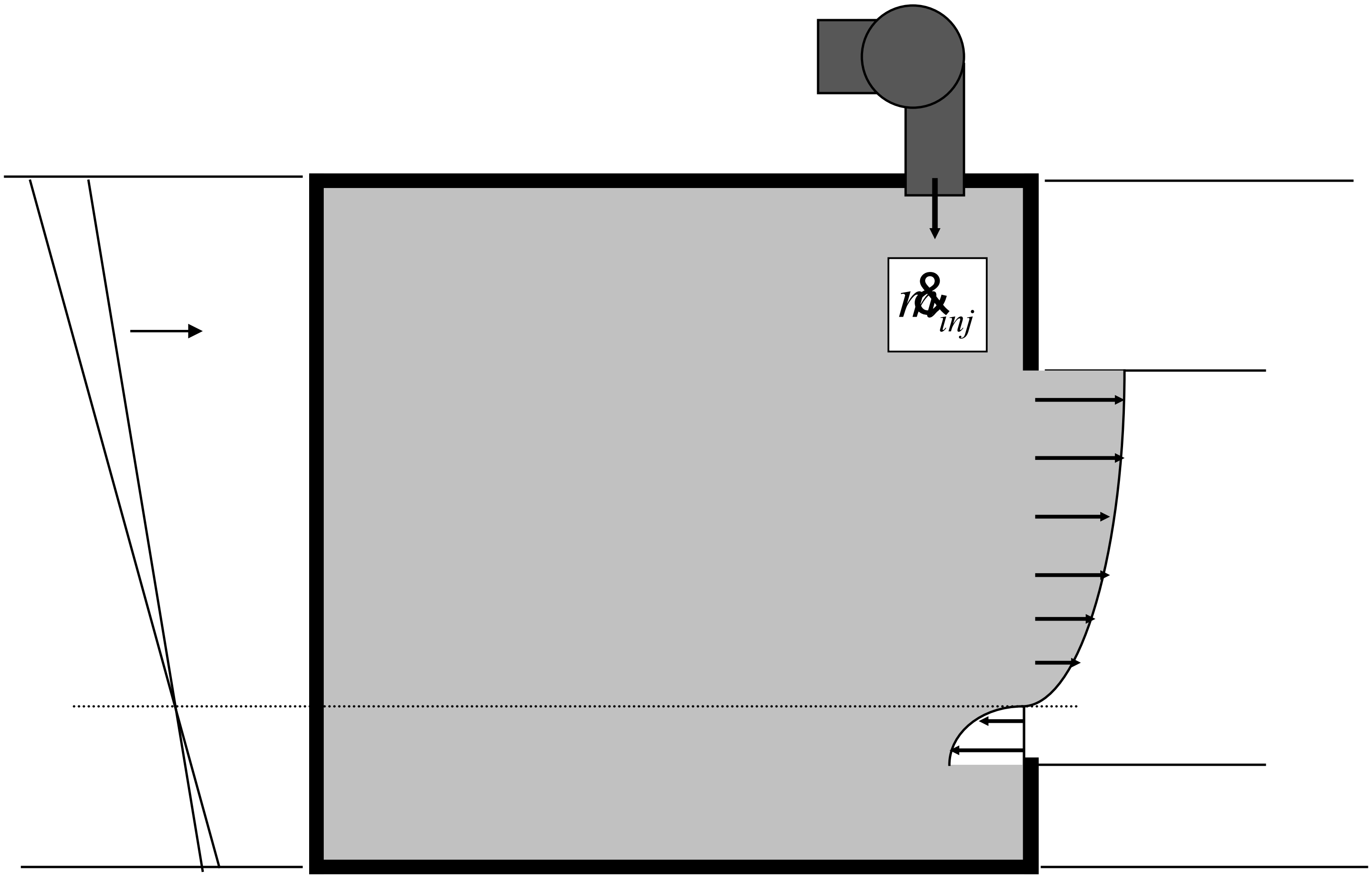


Wall vents – two zone ($T_u > T_{out}$)



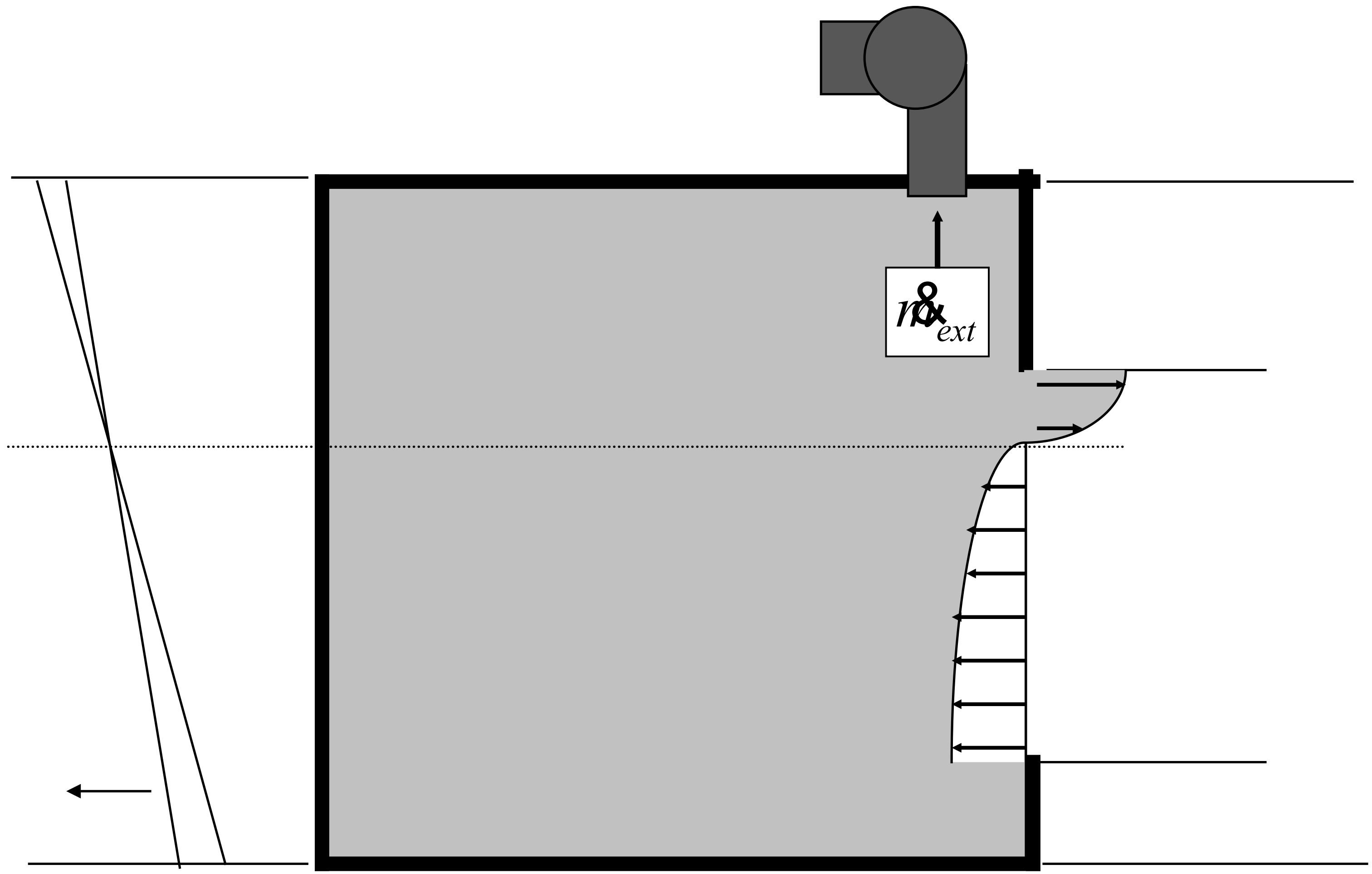
Mechanical ventilation

- Injection – increases P_{in}



Mechanical ventilation

- Extraction – decreases P_{in}



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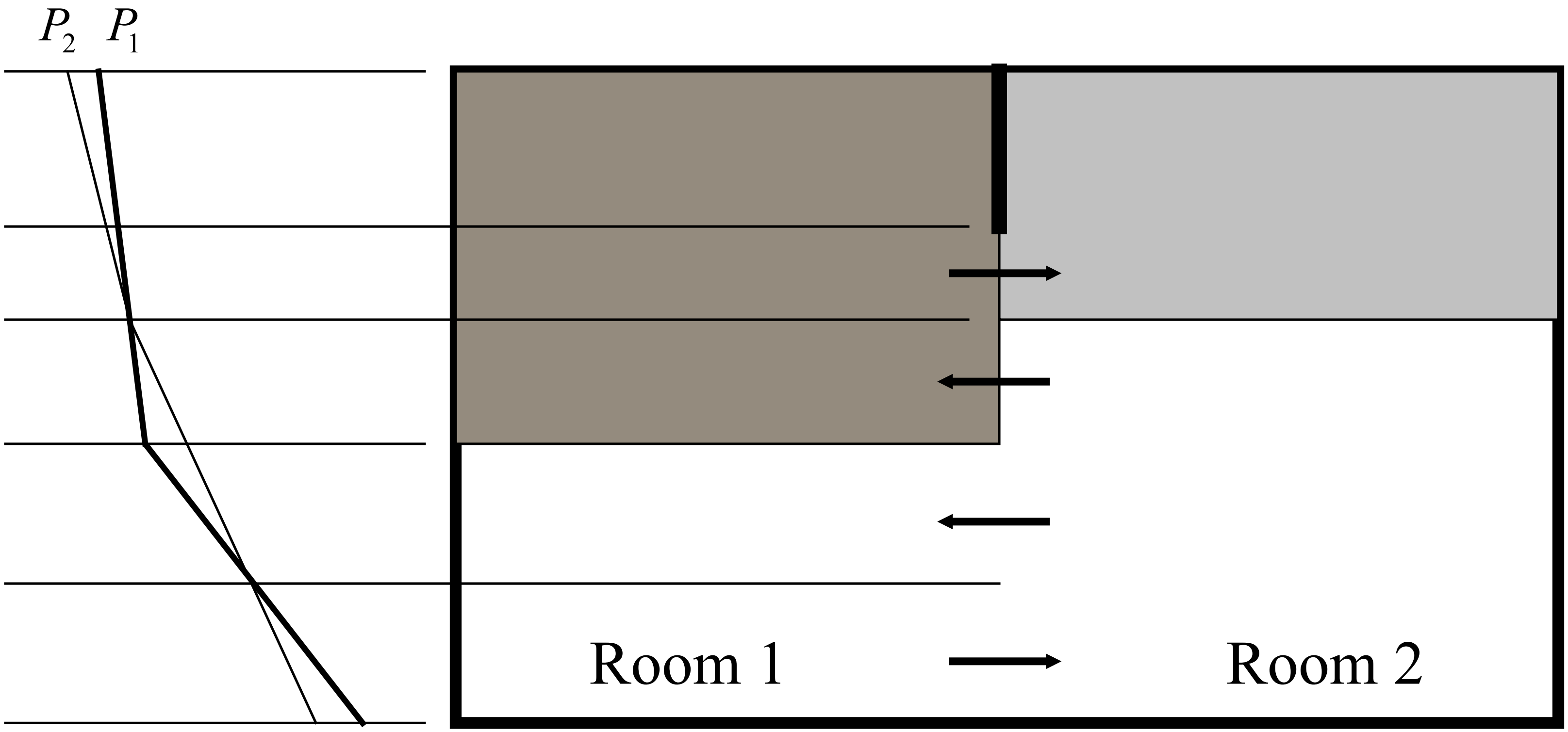
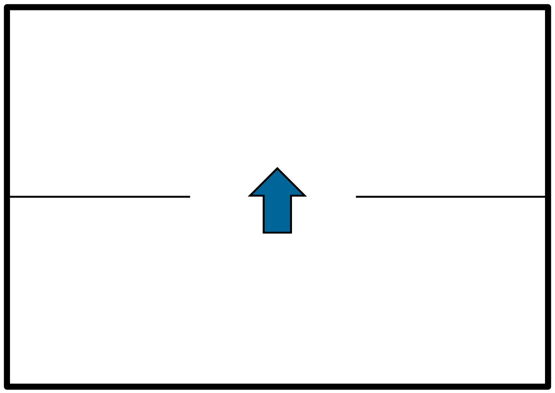
Multiple rooms with hot gas layers



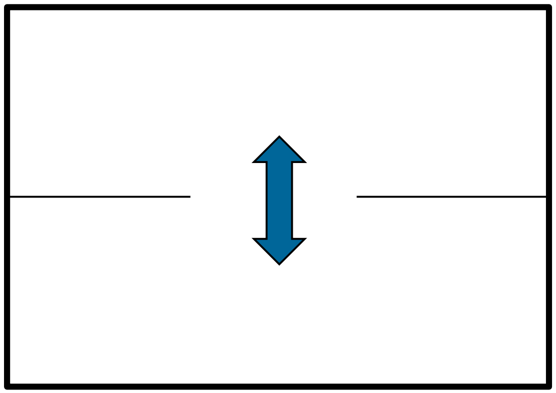
Ceiling Vents (Cooper's Theory)

$$\dot{V}_{up} = 0.68\,A_v\,\sqrt{2\,|\max(\Delta P, 0)|/\rho_{bot}} + \dot{V}_{ex}$$

$$\dot{V}_{down} = 0.68\,A_v\,\sqrt{2\,|\min(\Delta P, 0)|/\rho_{top}} + \dot{V}_{ex}$$



$$\dot{V}_{ex} = 0$$



$$|\Delta P| < |\Delta P_{flood}| \equiv \frac{C_s^2\, g\, \Delta\rho\, D^5}{2\,A_v^2}$$

$$\dot{V}_{ex} = 0.10 \left(\frac{g\,\Delta\rho\,A_v^{5/2}}{\rho_{avg}} \right)^{1/2} \left(1 - \frac{|\Delta P|}{|\Delta P_{flood}|} \right)$$

Thermal Radiation

Net heat flux to wall surface *k*

Transmissivity of gas between surfaces *k* and *j*

$$-\frac{\dot{q}''_{\mathrm{r},k}}{\varepsilon_k}+\sum_{j=1}^{N}\frac{1-\varepsilon_j}{\varepsilon_j}F_{k-j}\,\tau_{k-j}\,\dot{q}''_{\mathrm{r},j}=\sigma T_k^4-\sum_{j=1}^{N}\left(F_{k-j}\,\tau_{k-j}\,\sigma T_j^4\right)-\sum_{j=1}^{2}\varepsilon_j F_{k-j}\,\sigma\,T_{\mathrm{u}}^4-\frac{\omega_{k-\mathrm{f}}}{A_k}\frac{\chi_{\mathrm{r}}\dot{Q}}{4\pi}$$

View factor of surface *k* onto surface *j*

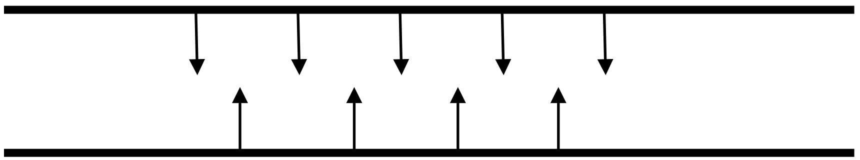
Emissivity of wall surface *k*

Radiation from fire distributed evenly over an entire wall

Contribution of radiation from upper and lower layer gases

Stefan-Boltzmann constant, $\sigma = 5.67 \times 10^{-11}\ \mathrm{kW/(m^2 \cdot K^4)}$

Radiation – Simple Example



$$-\frac{\dot{q}_1''}{\varepsilon_1} + \frac{1-\varepsilon_2}{\varepsilon_2}\dot{q}_2'' = \sigma T_1^4 - \sigma T_2^4$$

$$-\frac{\dot{q}_2''}{\varepsilon_2} + \frac{1-\varepsilon_1}{\varepsilon_1}\dot{q}_1'' = \sigma T_2^4 - \sigma T_1^4$$

$$\Rightarrow$$

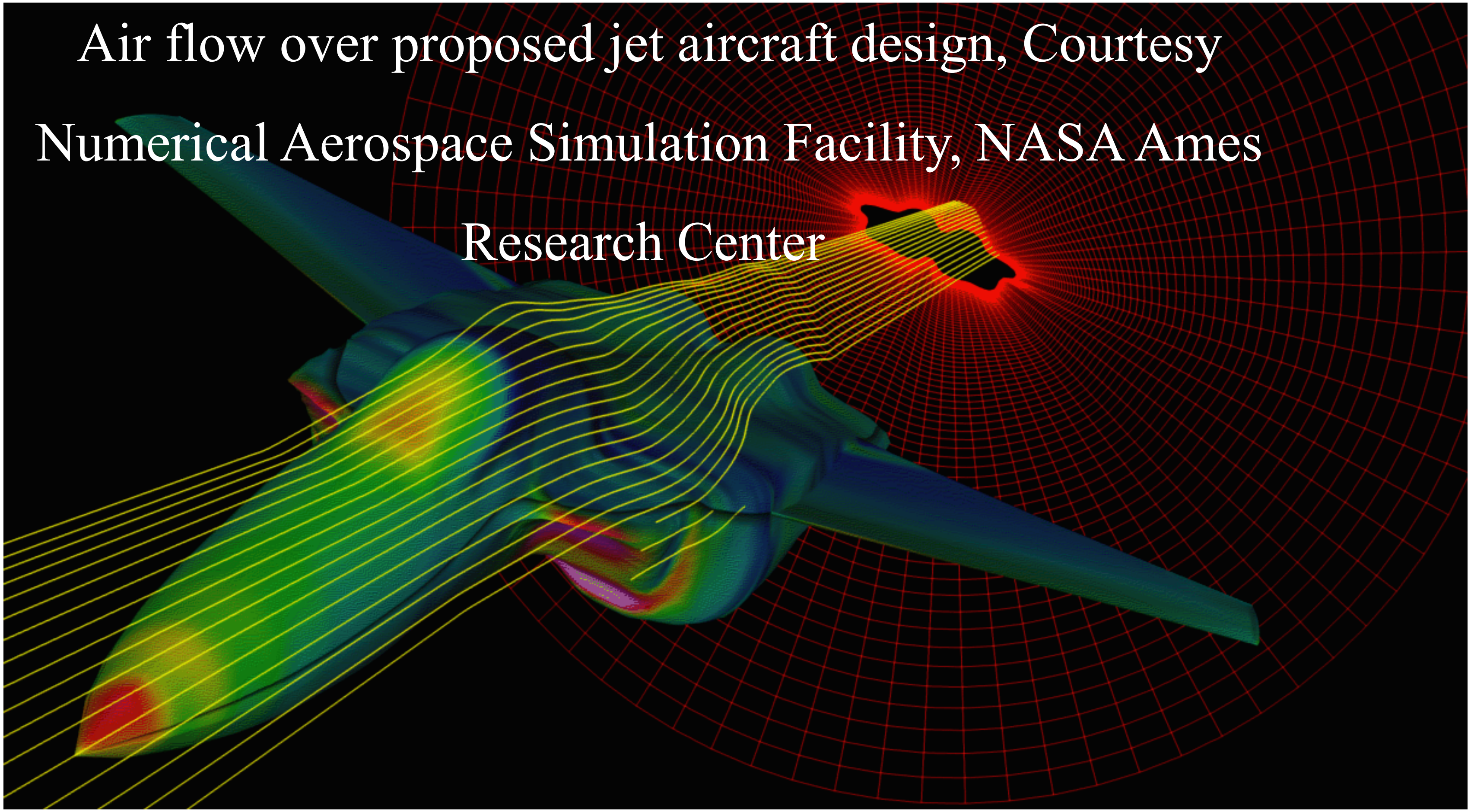
$$\dot{q}_1'' = \frac{\sigma T_2^4 - \sigma T_1^4}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

$$\dot{q}_2'' = -\dot{q}_1''$$

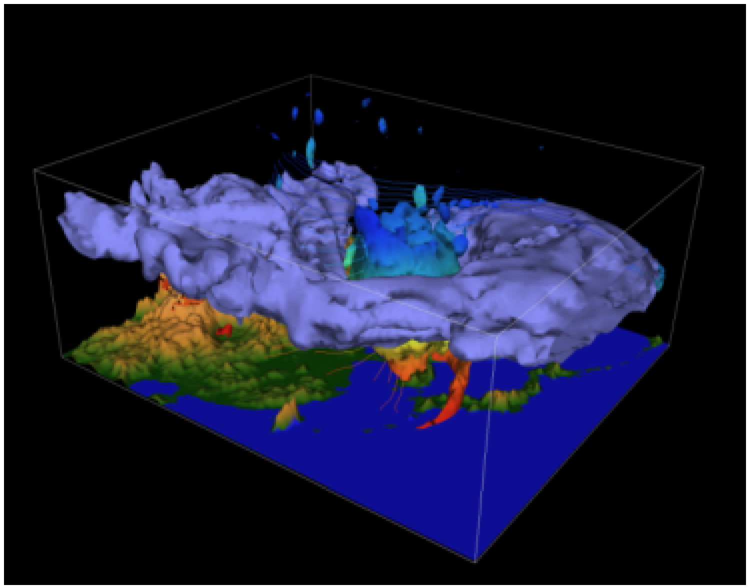
Overview of FDS

- Basic Assumptions of FDS
  - Low Mach Number Approximation
  - Large Eddy Simulation
  - Fire and Combustion Approaches
- Plume Simulations
- Verification and Validation
- Fire Modeling for FPE Design
- Fire Modeling for Fire Forensics and Reconstructions

Aerodynamics



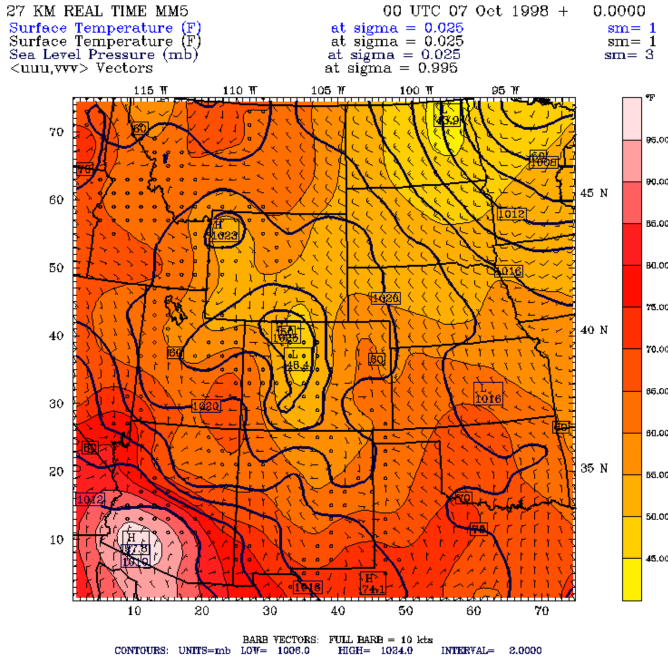
Weather Prediction



Development of a Cyclone in the Sea of Japan, Courtesy National Center for Atmospheric Research (NCAR)

Regional Weather Prediction, US Midwest and Mountain States,

Courtesy NCAR



Basic Conservation Equations for Single Species

Conservation of Mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0$$

Conservation of Momentum

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot \rho \mathbf{u}\mathbf{u} = -\nabla p + \rho \mathbf{g} + \nabla \cdot \tau$$

Conservation of Energy

$$\frac{\partial (\rho h)}{\partial t} + \nabla \cdot \rho h \mathbf{u} = \frac{Dp}{Dt} + \dot{q}''' + \nabla \cdot k \nabla T$$

Equation of State

$$p = \mathcal{R} \rho T$$

Turbulence

Large Eddy Simulation

Fire/Combustion

Low Mach Number

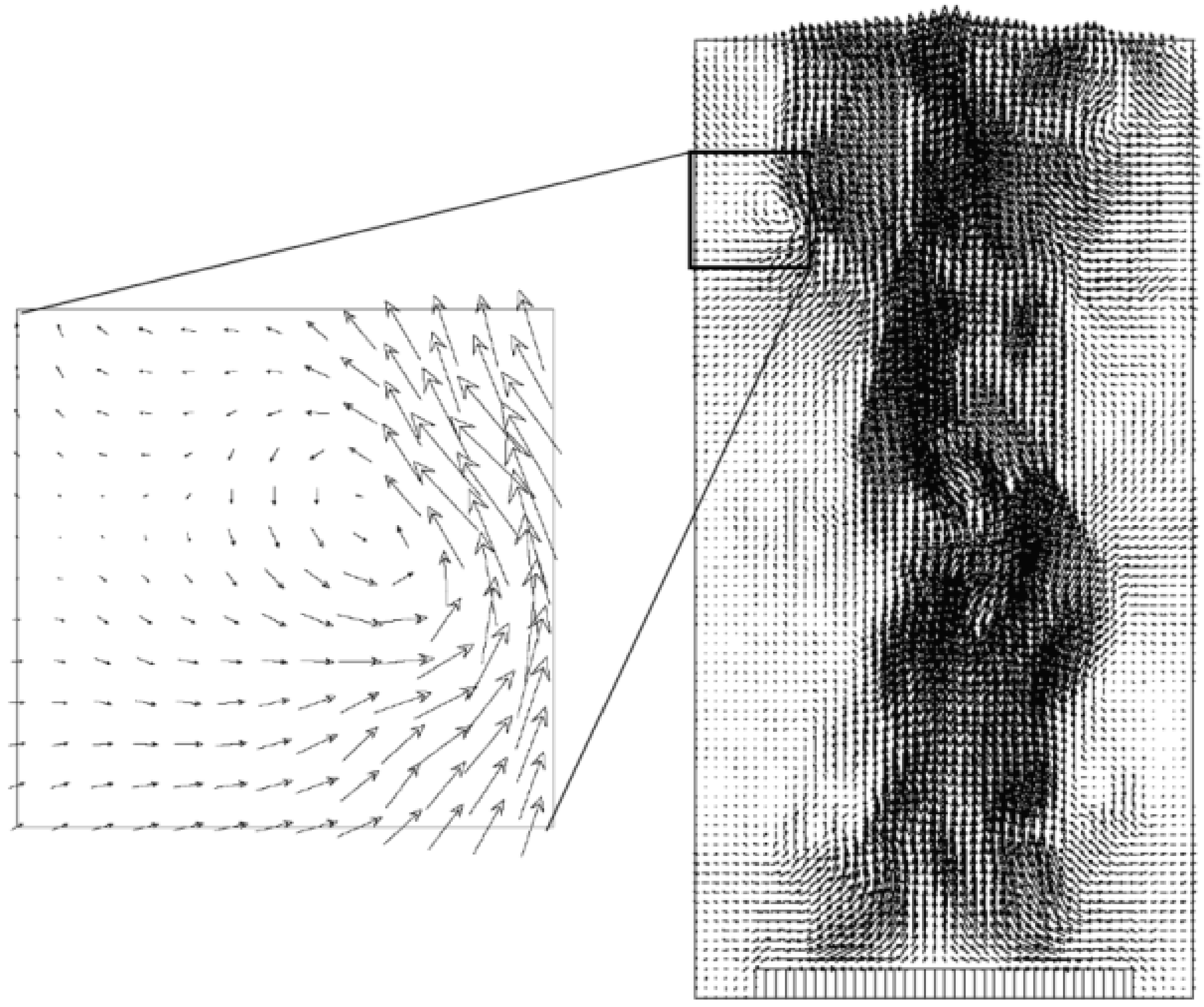
Approximation

$$p_0 = \mathcal{R} \rho T$$

What are the unknowns? Density ρ; Velocity Components u, v, w; Enthalpy h, Pressure p

What needs to be provided? $\dot{q}'''$, the fire; τ, the (turbulent) viscous stresses, $\nabla \cdot k \nabla T$, thermal conductivity

Large Eddy Simulation



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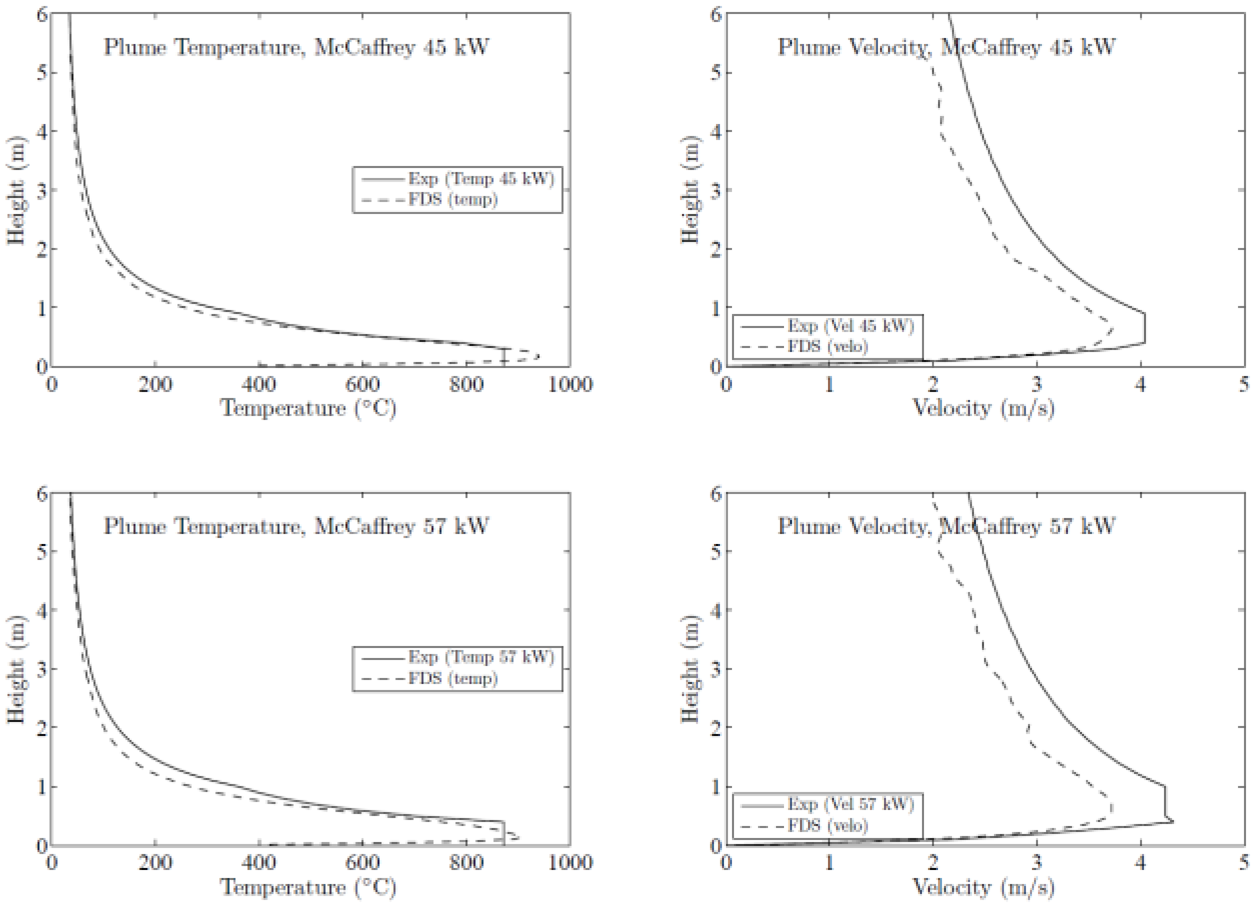
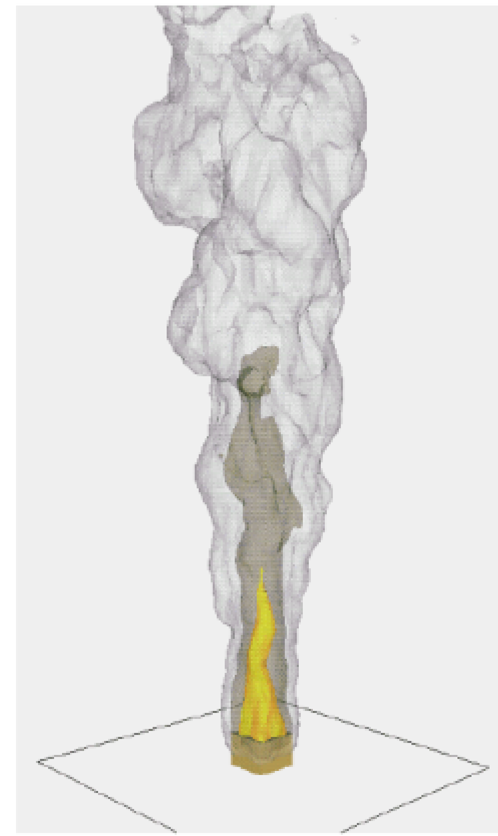
McCaffrey's Plume Measurements

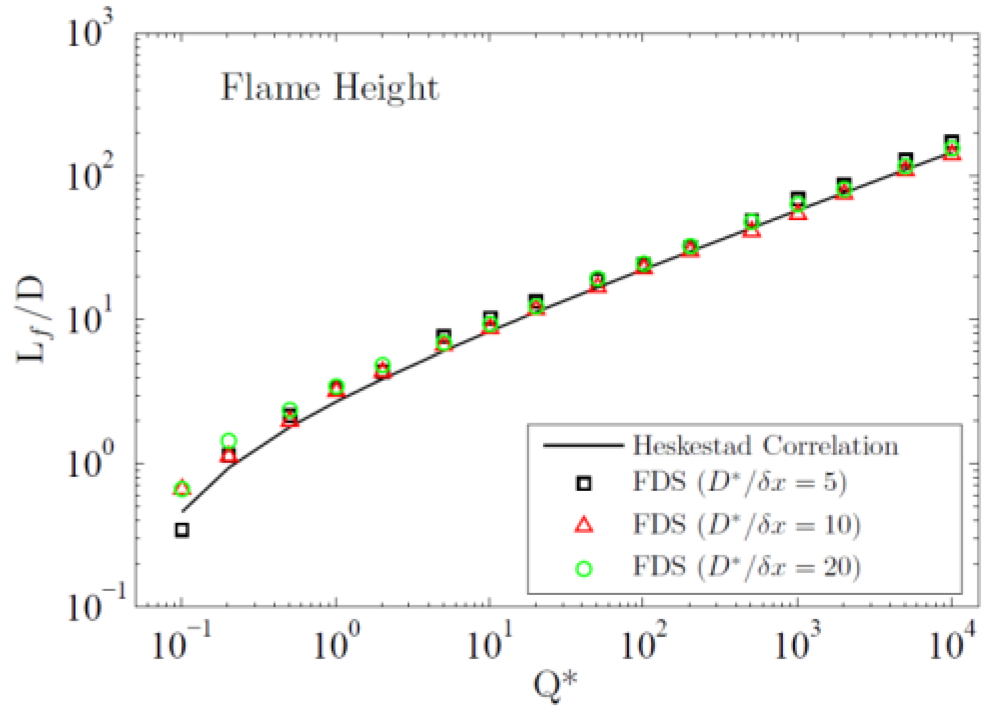




Heskestad Flame Height Correlation

$$\frac{L_f}{D} = 3.7\,(Q^*)^{2/5} - 1.02$$

$$Q^* = \frac{\dot{Q}}{\rho_\infty\, c_p\, T_\infty \sqrt{g}\, D^{5/2}}$$



Grid Resolution

Characteristic length scale for fire plume correlations:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{2/5} \quad ; \quad Q^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}\, D^{5/2}} \quad ; \quad Q^* = \left(\frac{D^*}{D}\right)^{5/2}$$

Where does this characteristic length come from? Consider the Energy Conservation equation

$$\rho c_p \frac{DT}{Dt} = \dot{q}''' + \nabla \cdot k \nabla T + \quad \ldots$$

Non-dimensionalize according to

$$\mathbf{x}^* = \mathbf{x}/D^* \quad ; \quad \mathbf{u}^* = \mathbf{u}/\sqrt{gD^*} \quad ; \quad t^* = t/\sqrt{D^*/g} \quad ; \quad \rho^* = \rho/\rho_\infty \quad ; \quad T^* = T/T_\infty$$

The Energy equation is now written in non-dimensional form

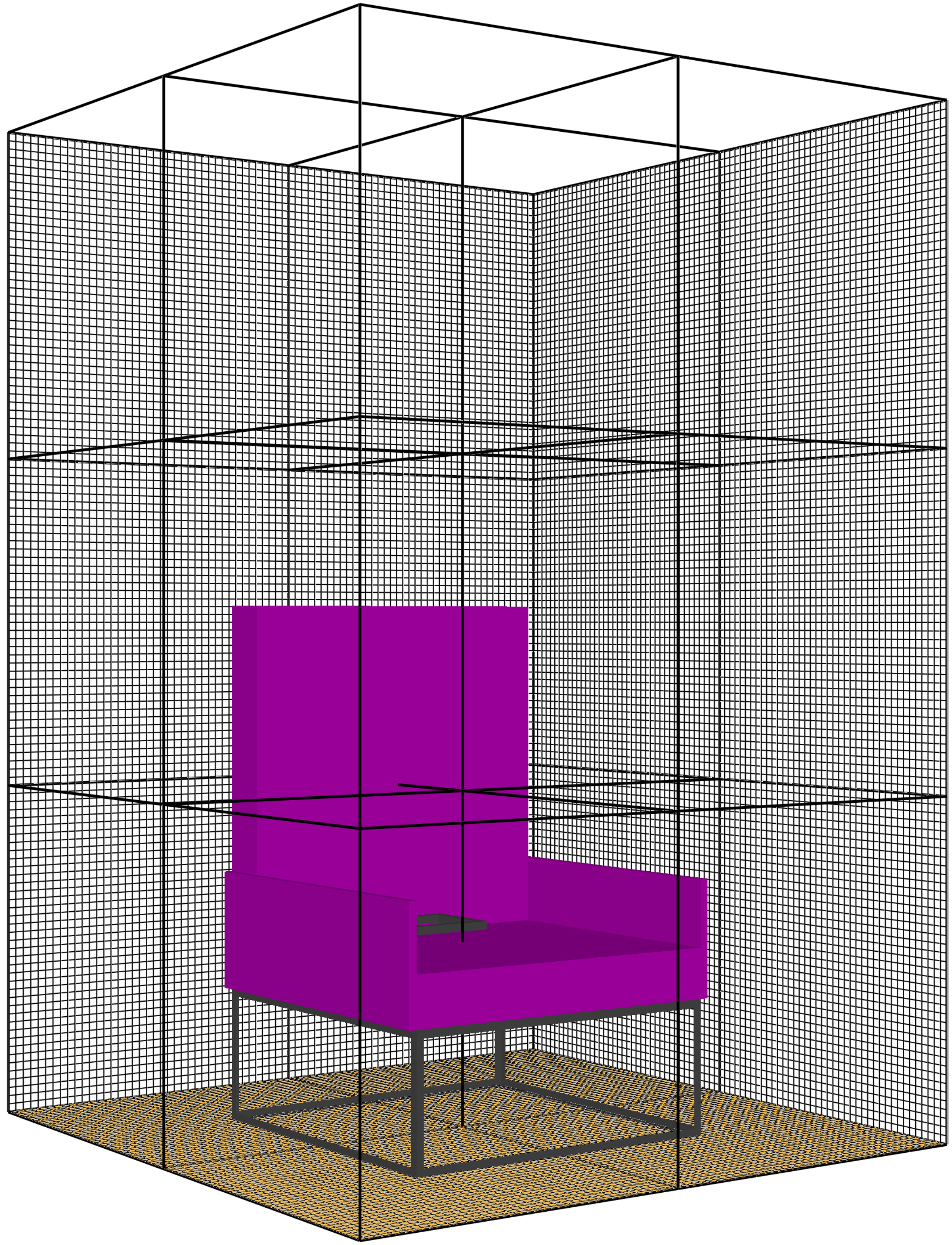
$$\rho^* \frac{DT^*}{Dt^*} = \dot{q}'''^* + \nabla \cdot k^* \nabla T^* + \quad \ldots$$

where

$$\dot{q}'''^* = \frac{\sqrt{D^*}}{\rho_\infty c_p T_\infty \sqrt{g}}\, \dot{q}'''$$

Integrating the local HRR over the entire domain

$$\int \dot{q}'''^* \, dV^* = \frac{\int \dot{q}''' \, dV}{\rho_\infty c_p T_\infty \sqrt{g}\, D^{*5/2}} = 1$$



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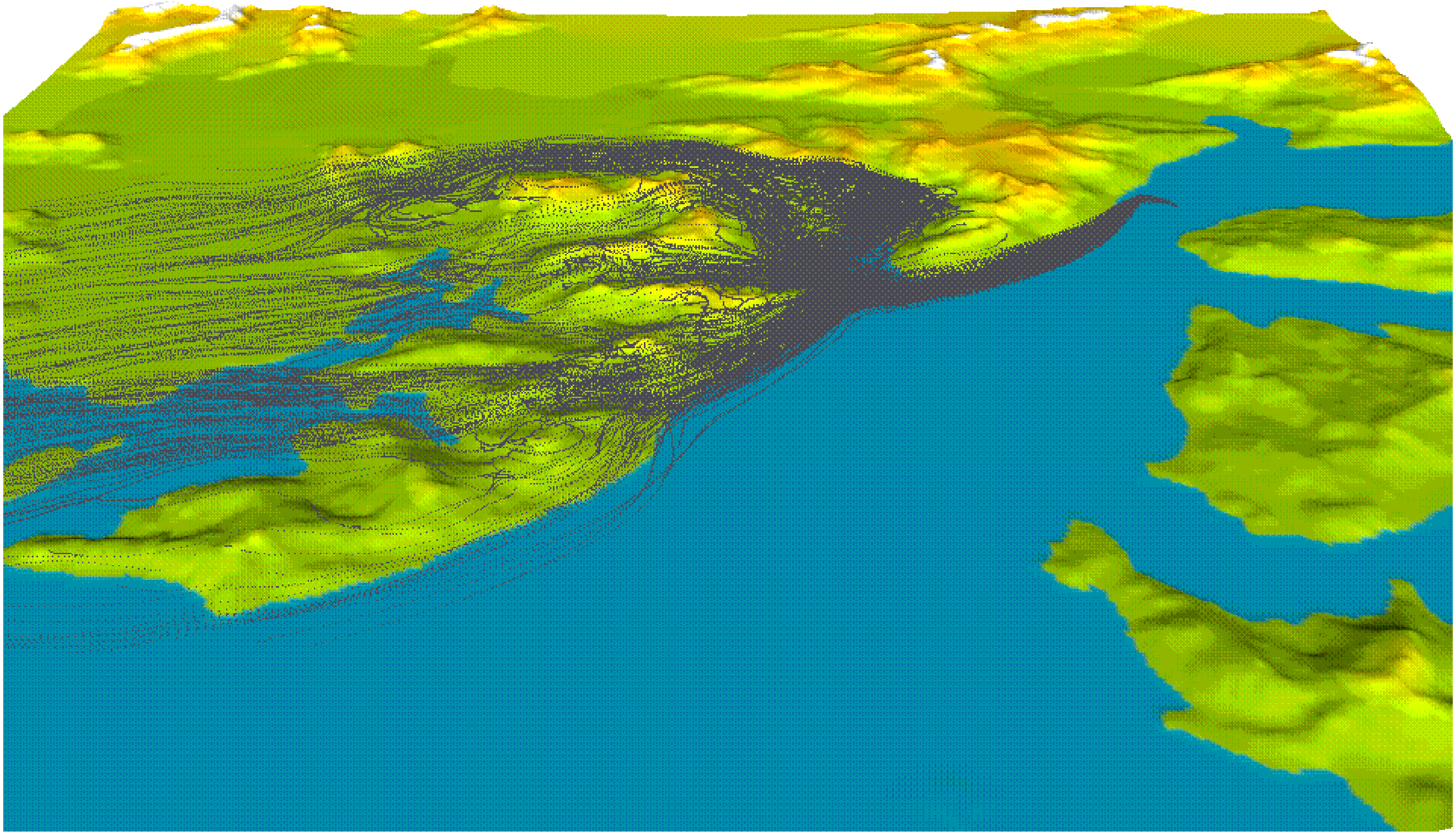
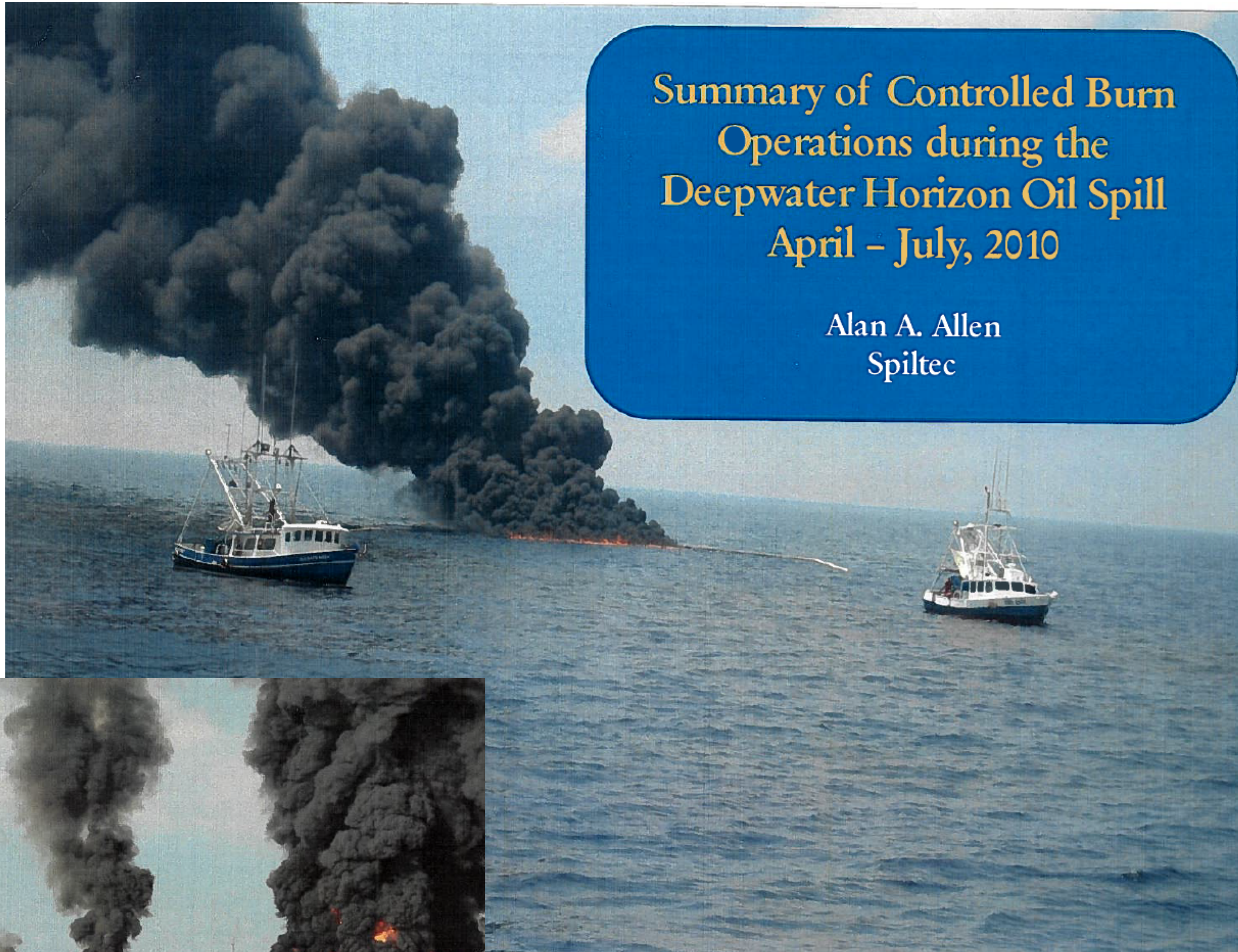
15 m diesel fuel fire, Little Sand Island, Mobile Bay. Courtesy Doug Walton, NIST

Smoke Trajectory from hypothetical burn, Valdez, Alaska



Terrain data courtesy US Geological Survey, Digital Elevation Maps


Summary of Controlled Burn
Operations during the
Deepwater Horizon Oil Spill
April – July, 2010
Alan A. Allen
Spiltec

NFPA Research Foundation, Sprinkler, Vent and Draft Curtain Project. Full-Scale experiments, Underwriters Labs, Chicago

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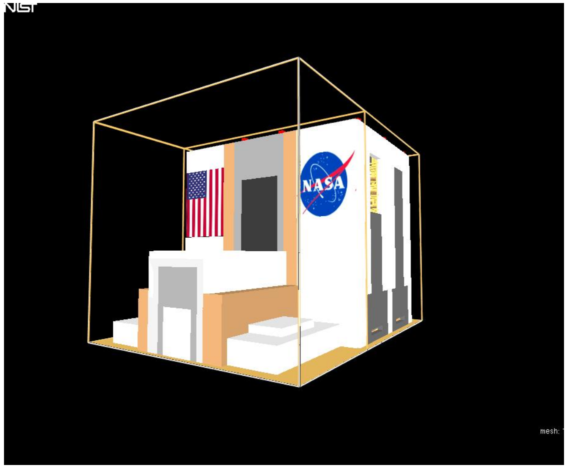
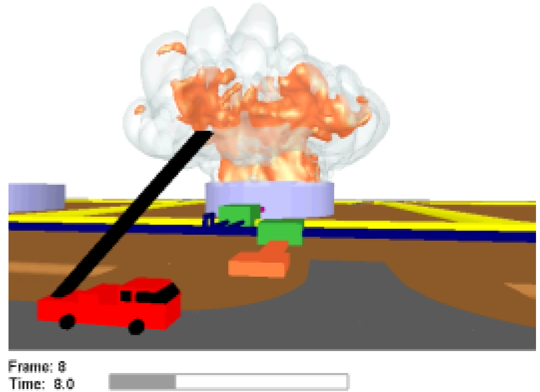


NASA Vehicle Assembly Building

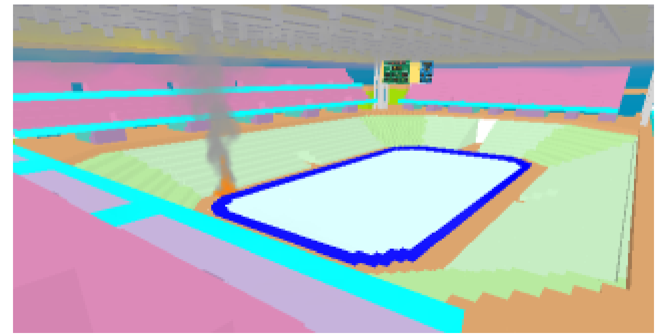
Kennedy Space Center

courtesy Rolf Jensen



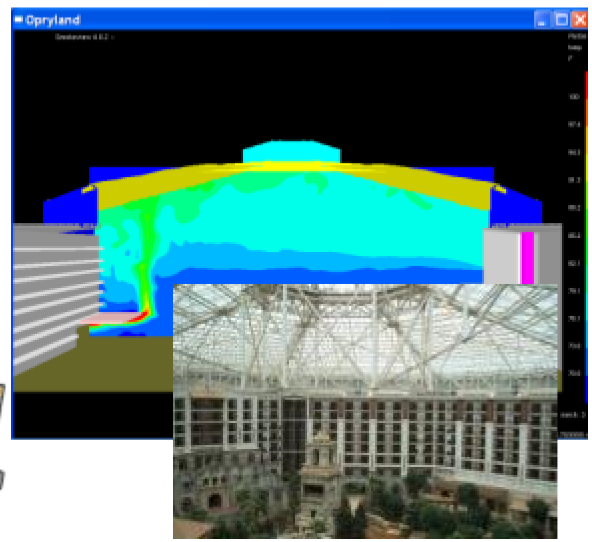
Tank Fire Analysis, courtesy

Combustion Science and Engineering

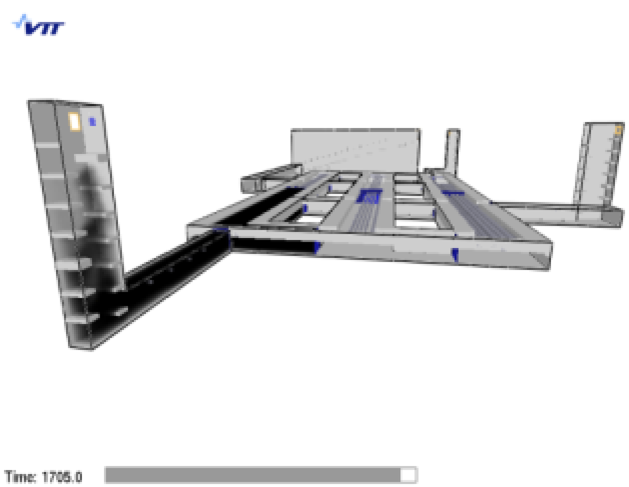


2006 Olympic Ice Hockey Stadium,

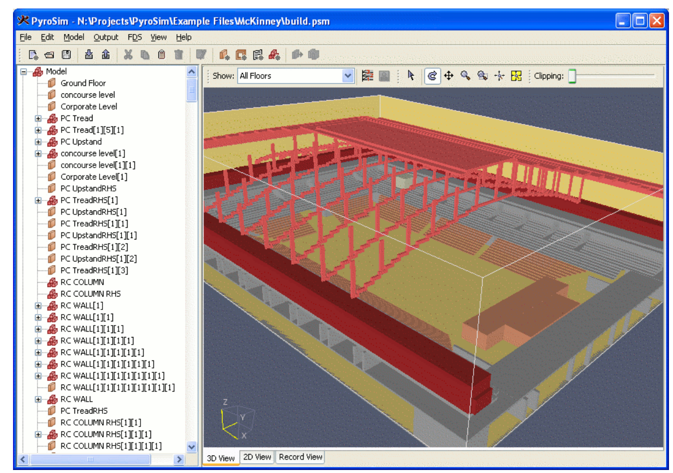
Turin, Italy, courtesy Arup



Courtesy, Schirmer Engineering



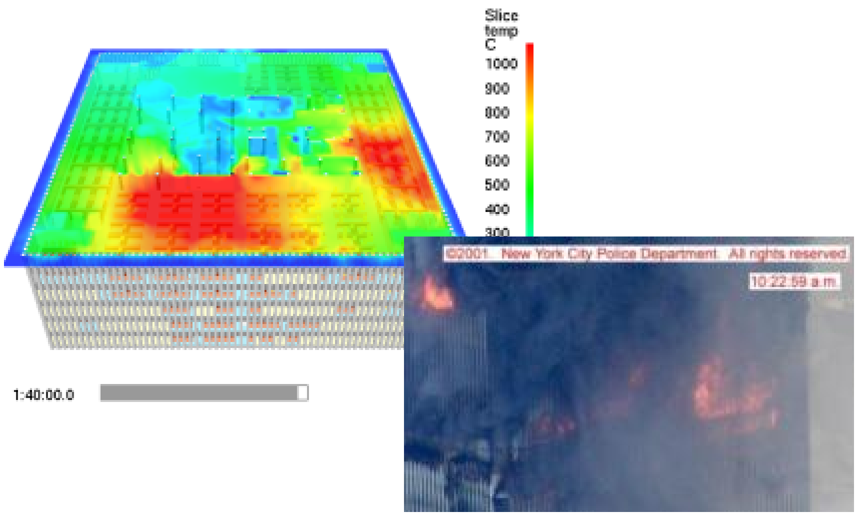
Parking Garage, courtesy VTT, Finland



PyroSim, courtesy Thunderhead

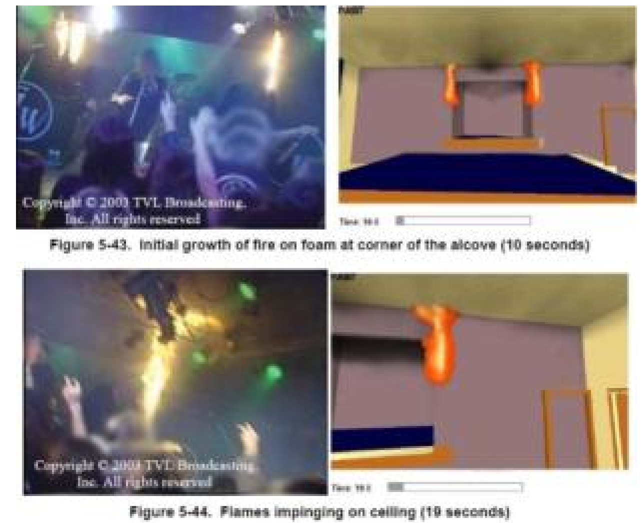
Engineering Consultants, Manhattan, Kansas

Fire Reconstructions



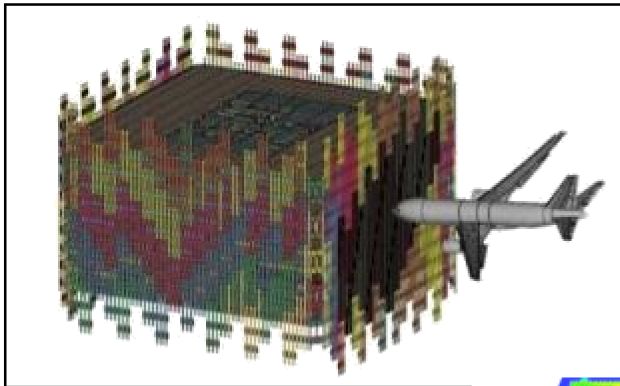
World Trade Center Investigation

NIST



The Station Nightclub Fire
Dan Madrzykowski and Steve Kerber

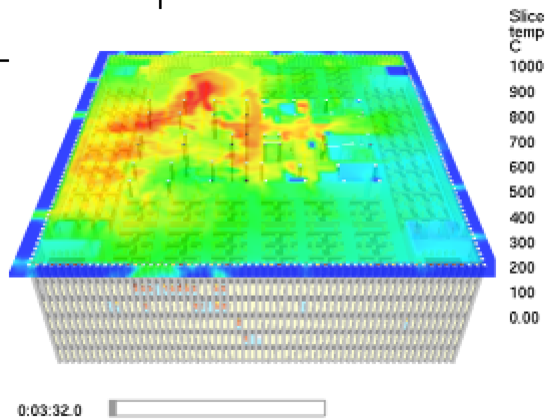
Cook County Administration Building Fire
69 West Washington, Chicago, Illinois, October 17, 2003
Doug Walton and Dan Madrzykowski



Aircraft Impact Analysis

Applied Research Associates

Program: LS-DYNA



Fire Analysis

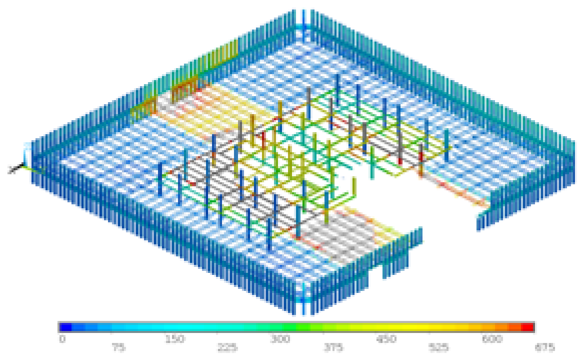
NIST

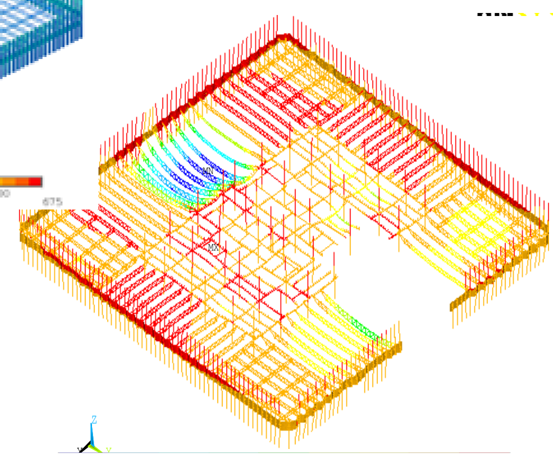
Program: Fire Dynamics Simulator

Thermal Analysis

NIST

Program: ANSYS

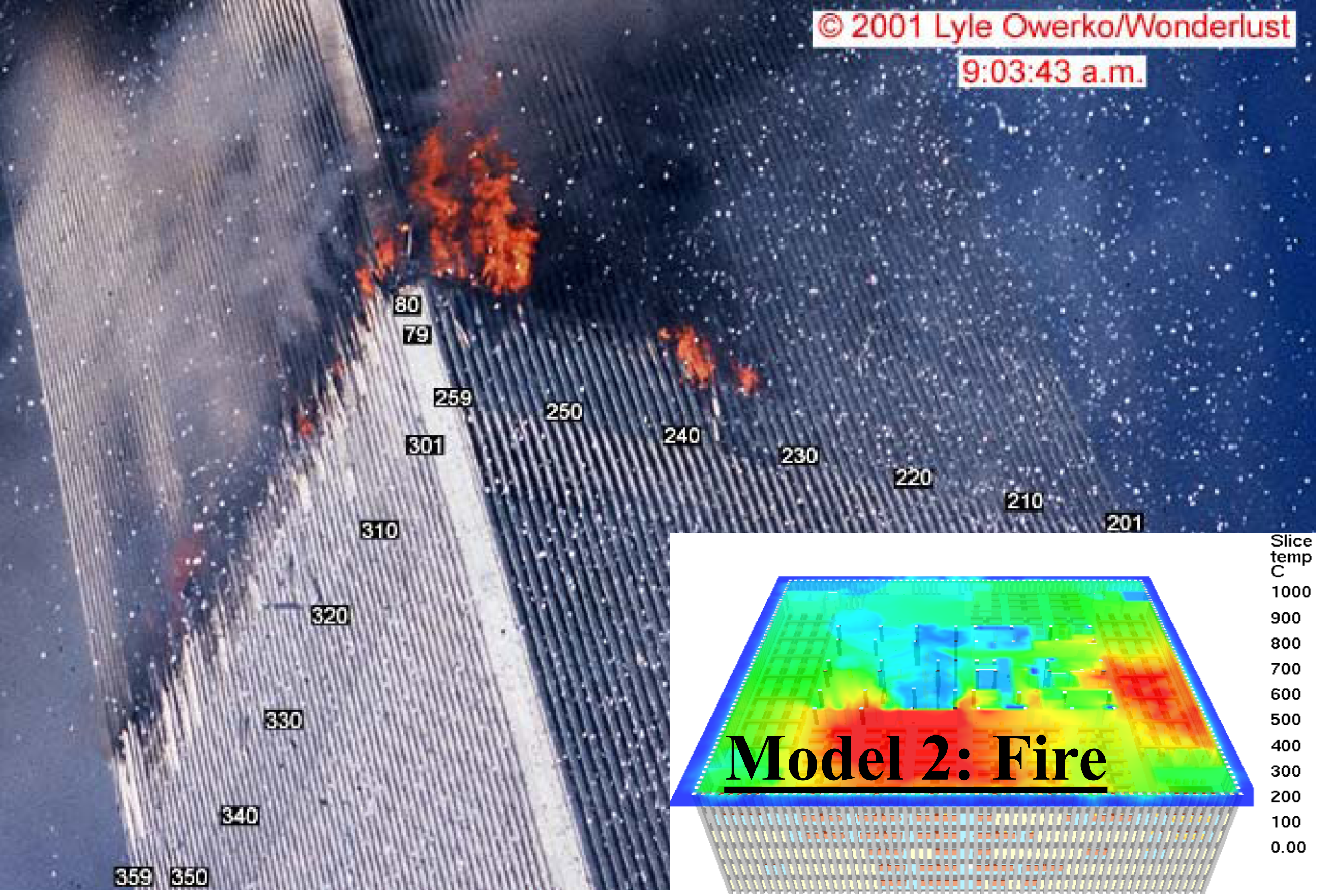




Structural Analysis

Simpson Gumhertz & Heger

Program: ANSYS


© 2001 Lyle Owerko/Wonderlust
9:03:43 a.m.
80
79
259
250
240
230
220
210
201
301
310
320
330
340
359
350
Slice temp C
1000
900
800
700
600
500
400
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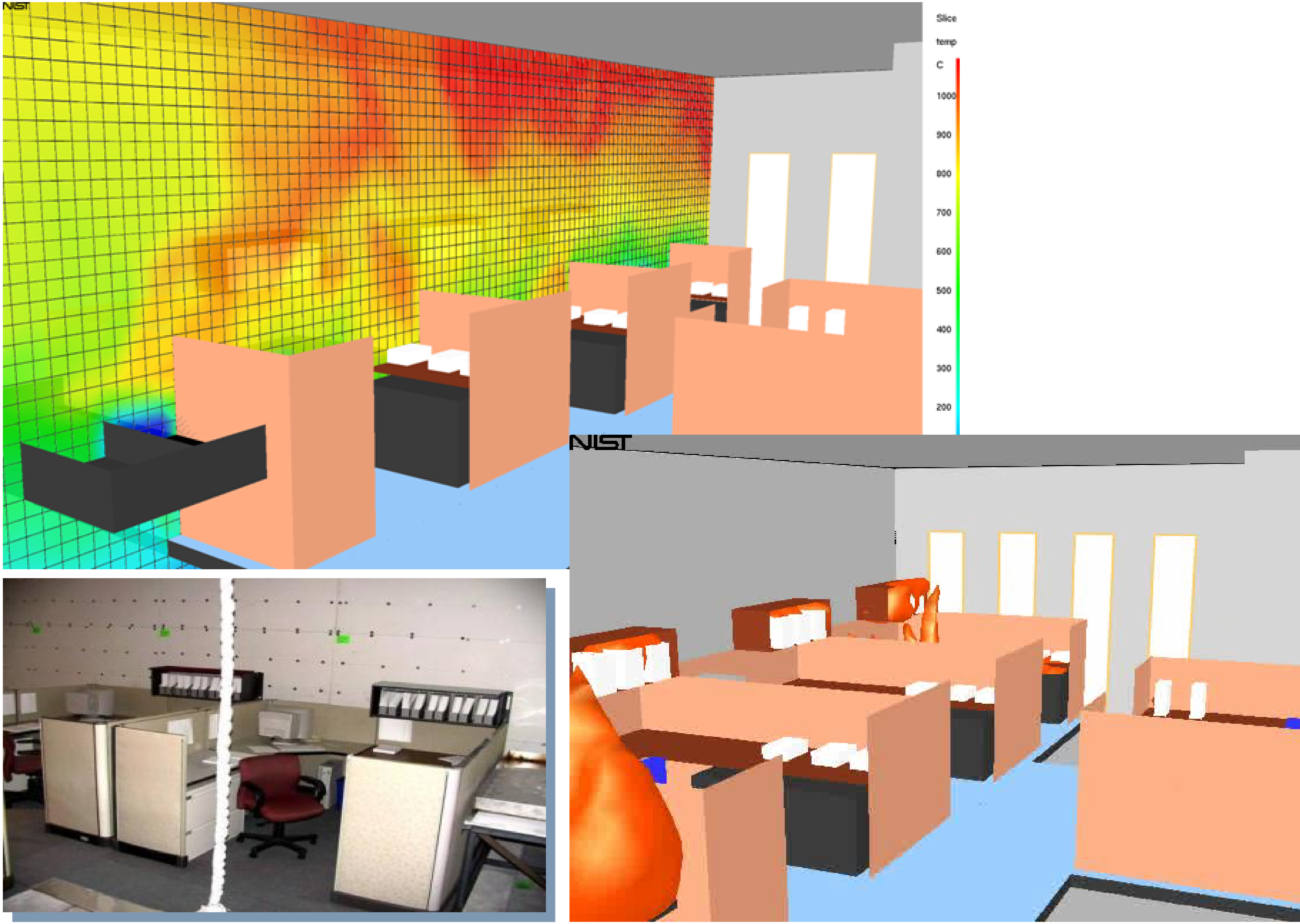
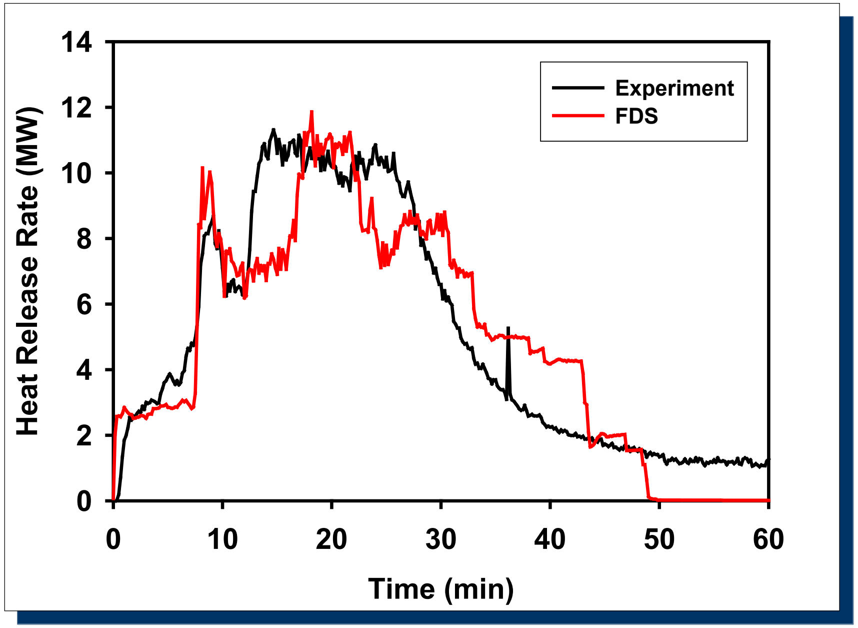
200
100
0.00
Model 2: Fire

Photos courtesy of the Port Authority

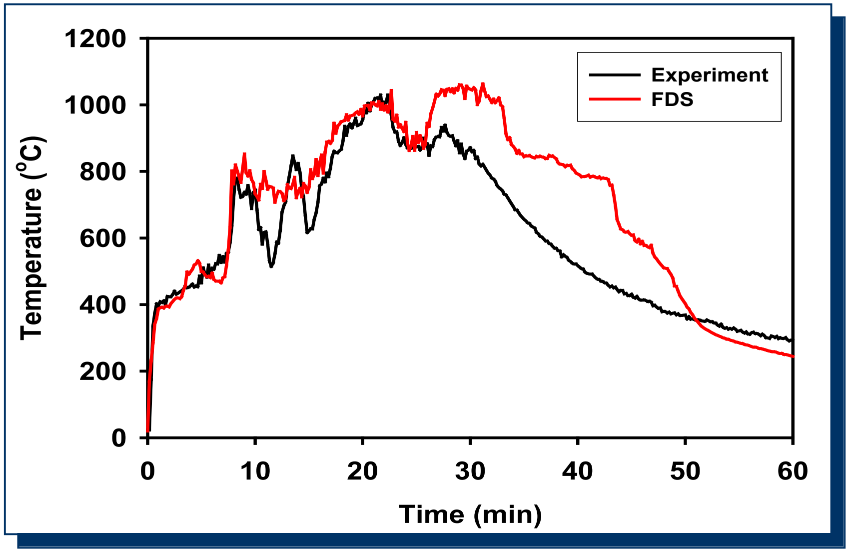

NIST
Slice
temp
C
1000
900
800
700
600
500
400
300
200
NIST

Video courtesy of Alex Maranghides, Anthony Hamins, NIST

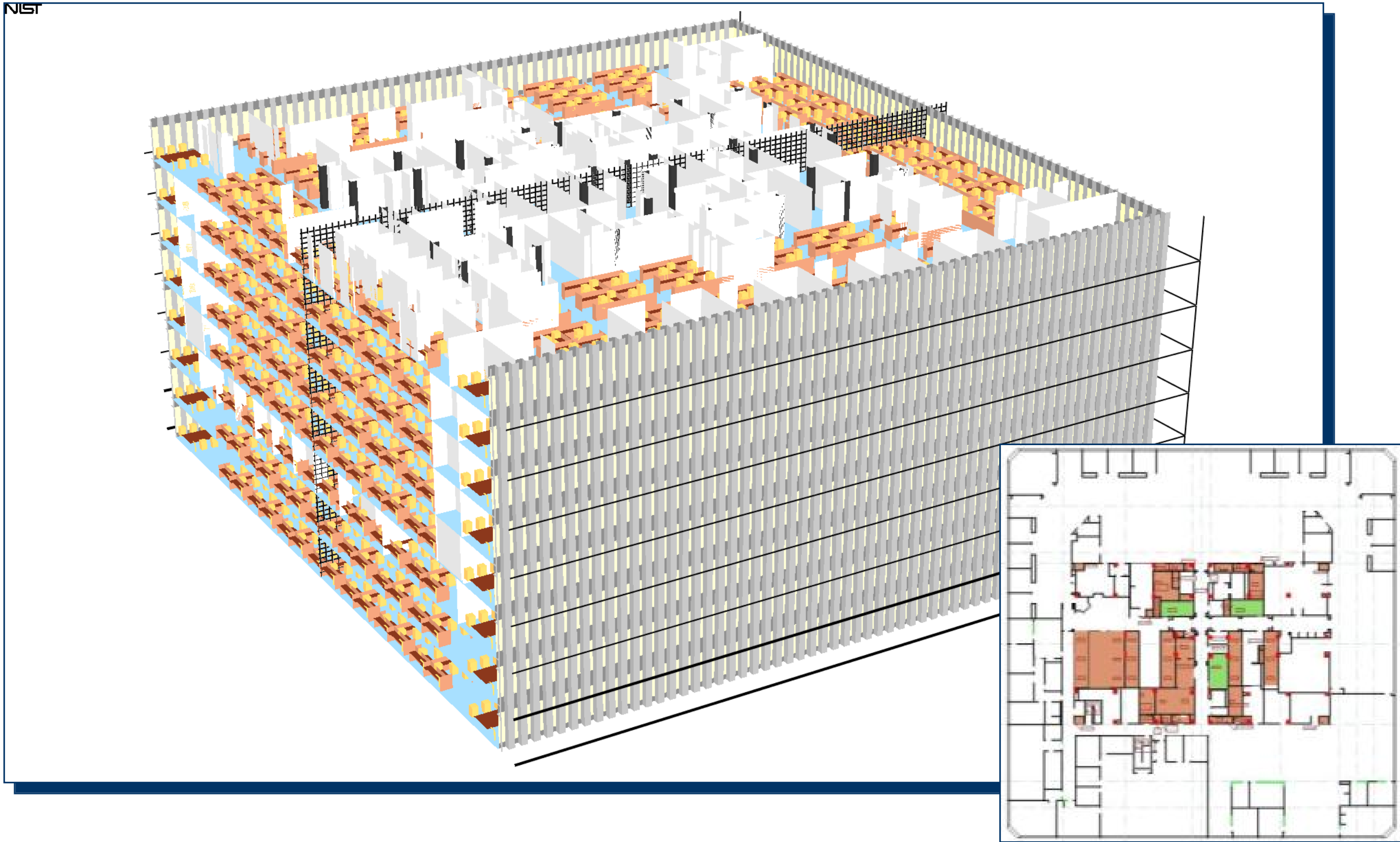
Heat Release Rate



Temperature

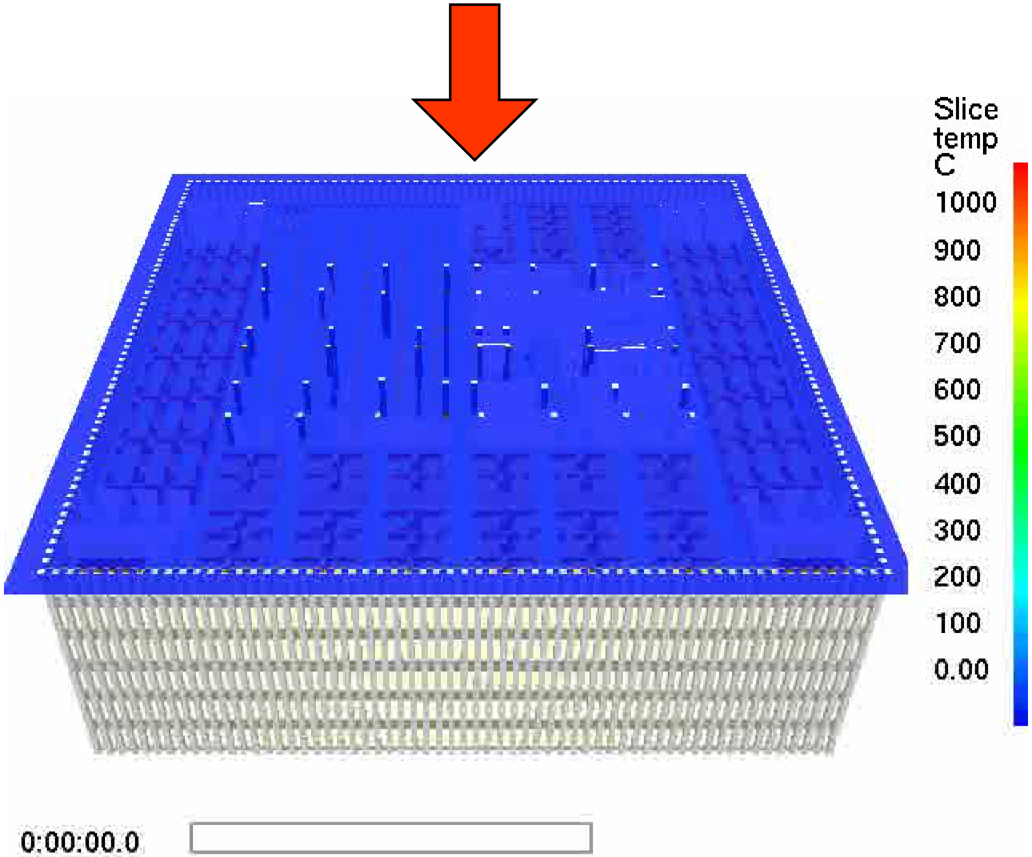


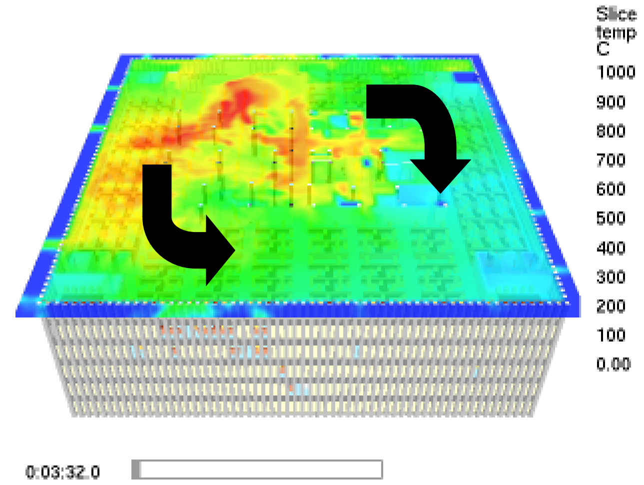
Multi-Floor WTC Geometry

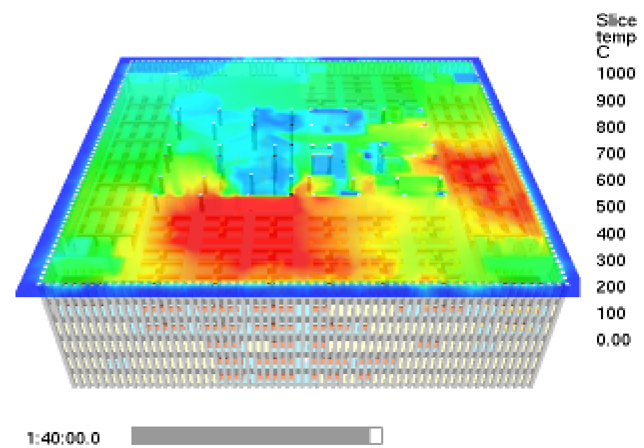


Upper Layer Gas Temperatures

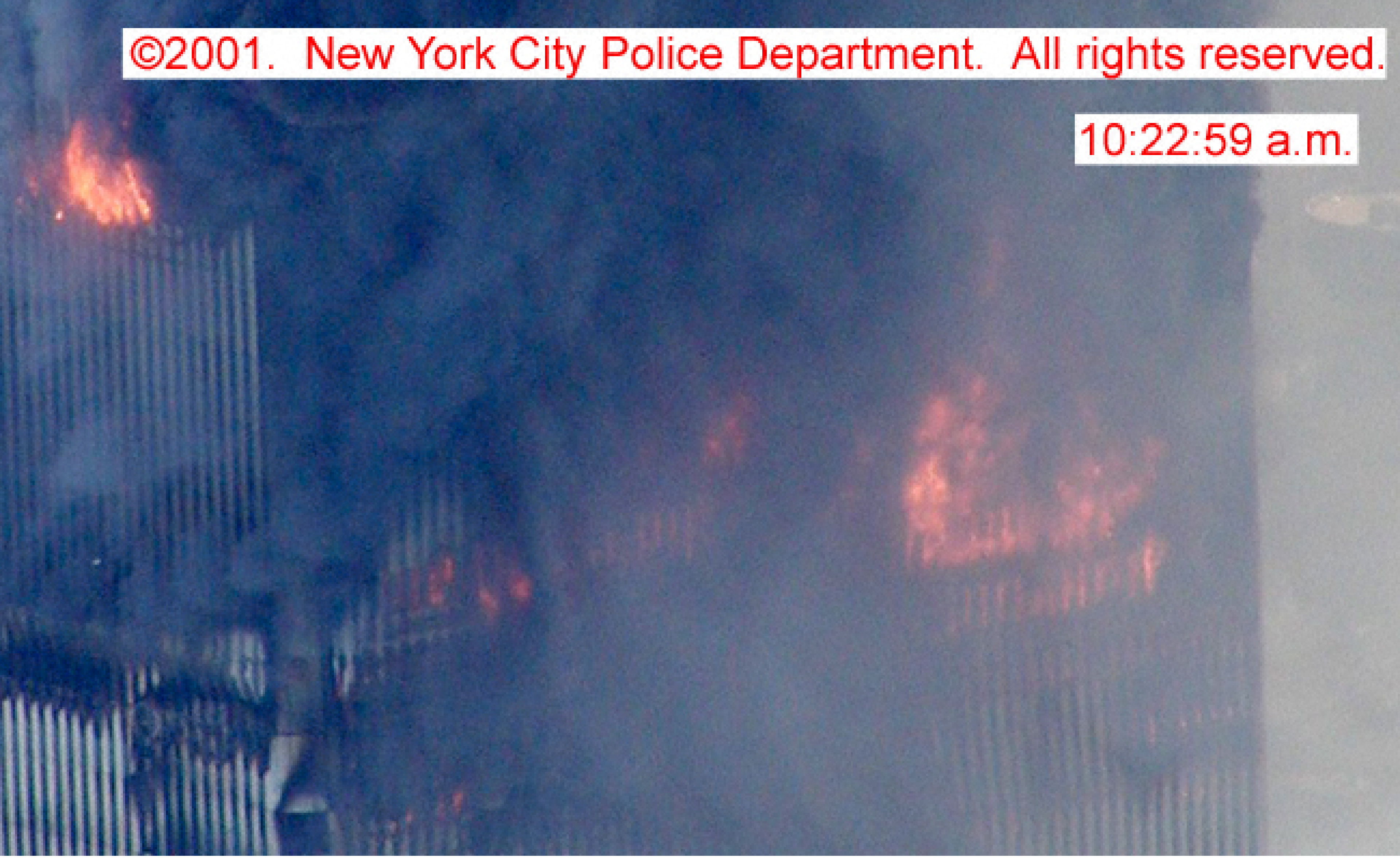
WTC 1 - Floor 97







Graphics courtesy of Glenn Forney, NIST



South Face of WTC 1 at 10:23

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