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Division of Fluid Dynamics

The Fluid Mechanics of Fires

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TOPICS

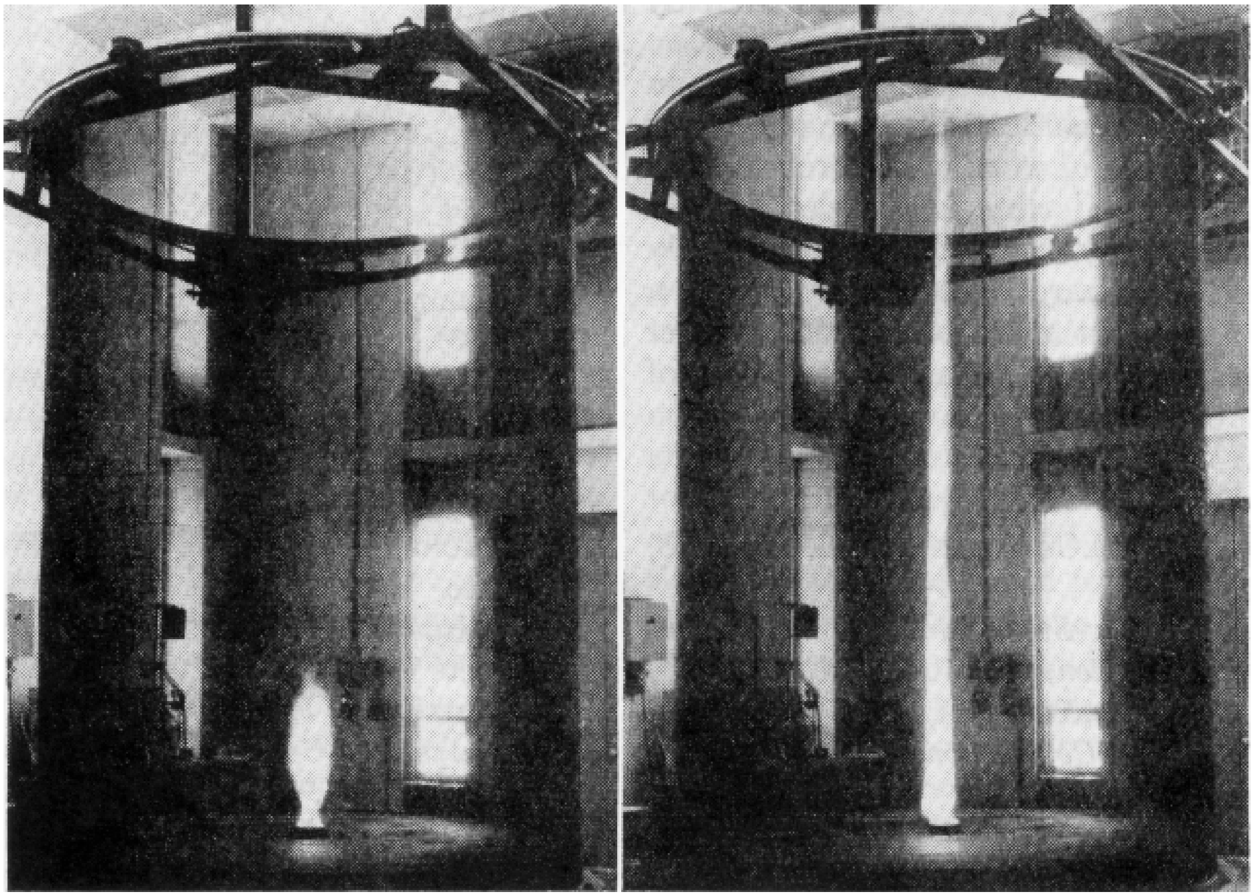
- Plume entrainment dynamics
- Mass fire induced flow fields
- Dispersion of smoke plumes
- Fire whirl dynamics
- World Trade Center fires

FIRE WHIRLS

Courtesy F. Battaglia

- Externally maintained circulation interacts with fire induced vorticity
- Fire concentrates vorticity along nominal plume centerline reducing entrainment
- Dramatically enhanced flame height

EMMONS - YING (1966)



- Burning acetone pool inside rotating screen
- Flame height reached $\sim$ 30 pool diameters
- Flame stable for long periods of time

INVISCID MODEL

- Low Mach number thermally expandable fluid
- Steady, axially symmetric flow
- No combustion or entrainment

$$\nabla \cdot (\rho \vec{u}) = 0$$

$$\rho \left(\nabla \left(\vec{u} \right)^2 / 2 - \vec{u} \times \vec{\omega} \right) + \nabla \tilde{p} - \rho \vec{g} = 0$$

$$\rho \vec{u} \cdot \nabla T = 0$$

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

$$p = p_0 + \tilde{p}$$

ANALYSIS

- Yih Transformation

$$\vec{u} = \mathbf{u}'\sqrt{T/T_0} \qquad \frac{\partial \psi}{\partial z} = -ru' \qquad \frac{\partial \psi}{\partial r} = rw'$$

- Partial Integrals

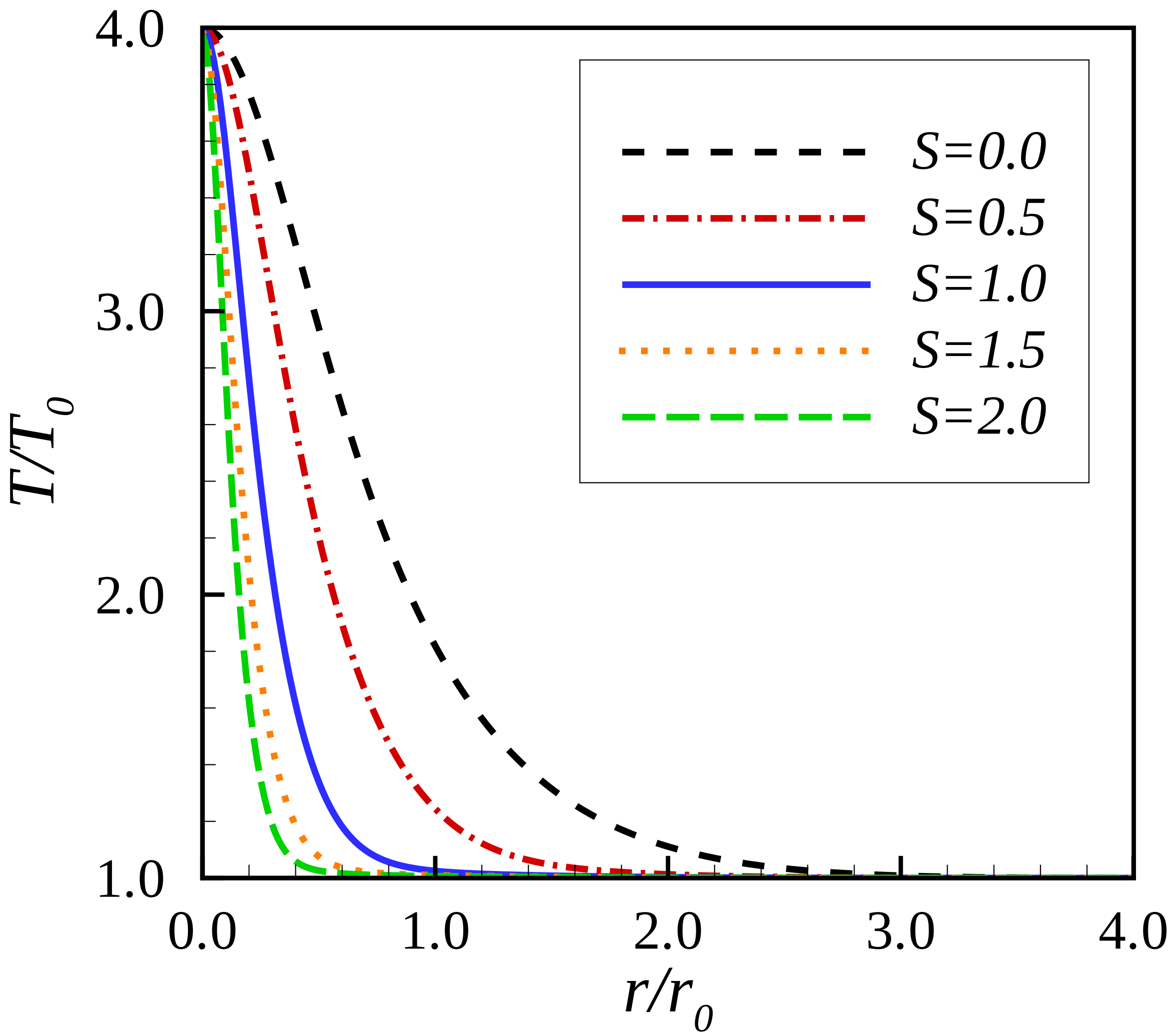
$$\left(T - T_0\right)/T \equiv \theta_0\left(\psi\right) \quad \Gamma \equiv 2\pi r v' = \Gamma_0\left(\psi\right)$$

$$\tilde{p}/\rho_0 + \left(\mathbf{u}'\right)^2/2 + gz \equiv \mathcal{H}_0\left(\psi\right)$$

- Stream function equation

$$r\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial \psi}{\partial z}\right) + \frac{\partial^2 \psi}{\partial z^2} = r^2\left(\frac{d\mathcal{H}_0}{d\psi} + gz\frac{d\theta_0}{d\psi}\right) - \Gamma_0\frac{d\Gamma_0}{d\psi}$$

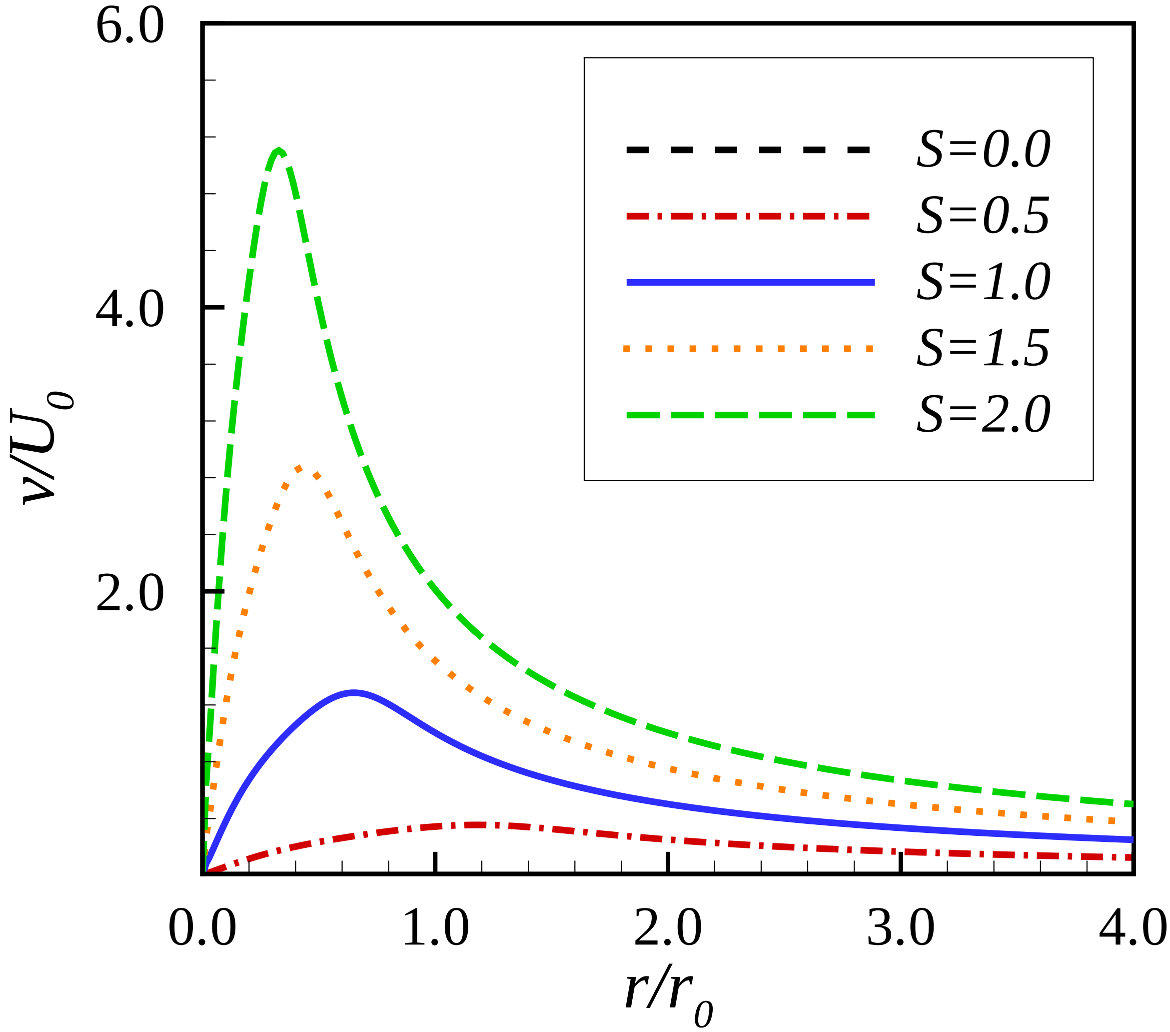
TEMPERATURES



Courtesy F. Battaglia

$$S = \Gamma_\infty / (2\pi r_0 U_0) \qquad U_0 = \sqrt{2 g r_0 \left(\frac{T_m - T_0}{T_0}\right)}$$

SWIRL VELOCITY



Courtesy F. Battaglia

$$S = \Gamma_\infty / \left(2\pi r_0 U_0\right) \qquad U_0 = \sqrt{2 g r_0 \left(\frac{T_m - T_0}{T_0}\right)}$$

WORLD TRADE CENTER TOWER COLLAPSE ANALYSIS - A SYNOPSIS -

TECHNICAL COMPONENTS

Fire Scenario *Descriptions of building geometry, materials, and initiating event(s).*

$\Updownarrow$

Fire Dynamics *Simulations of combustion, fluid mechanics, heat and mass transport in gas.*

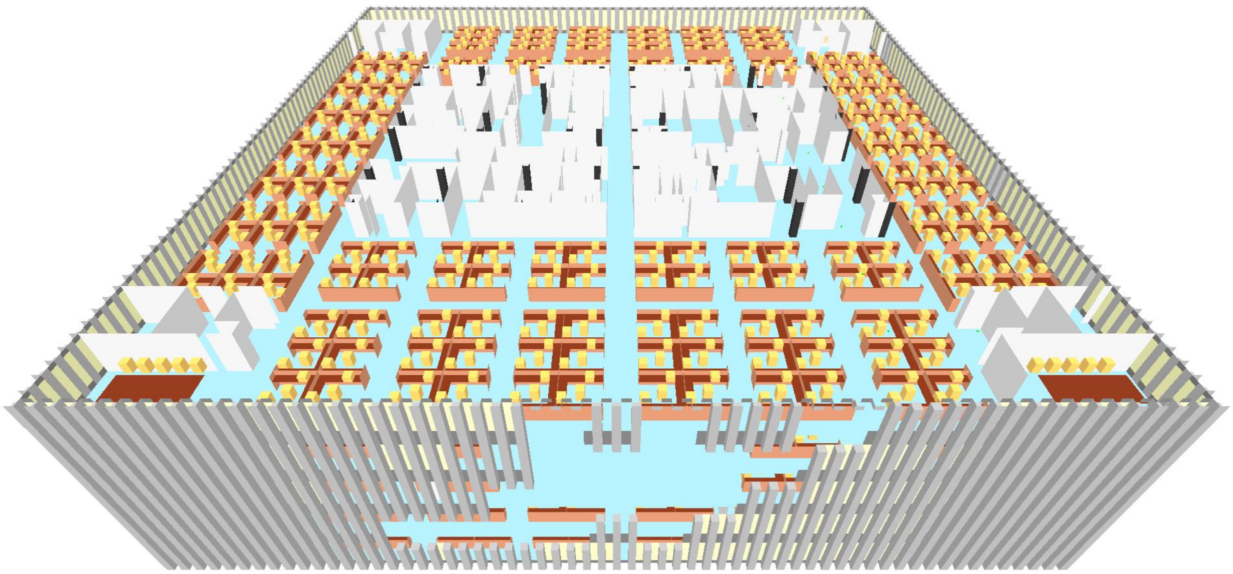
$\Updownarrow$

Thermal Analysis *Simulations of heating and cooling of condensed phase materials.*

$\Updownarrow$

Structural Analysis *Calculation of displacements, stresses, and loss of capacity of load bearing structure.*

FIRE DYNAMICS



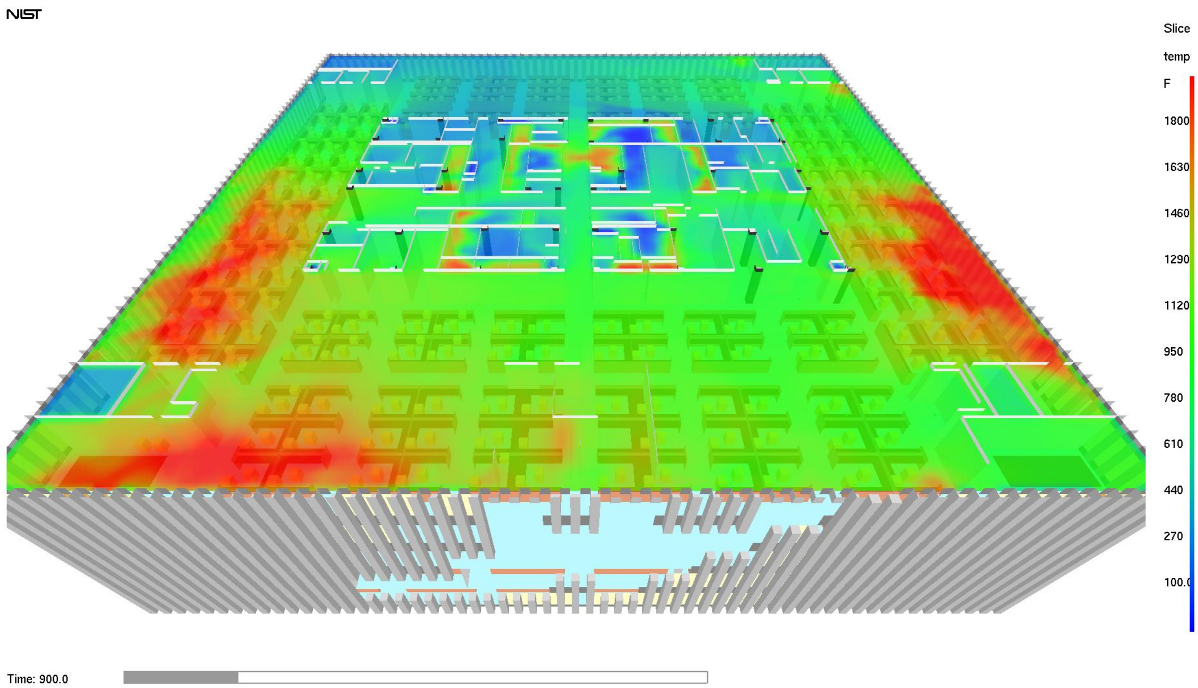
From *McGrattan and Bouldin* 2004

- All fire simulations performed with NIST Fire Dynamics Simulator (FDS).

- Geometry model as used by FDS based on architectural rather than structural features.

- Window breaking times and locations obtained from photographic and video data.

FIRE DYNAMICS (2)



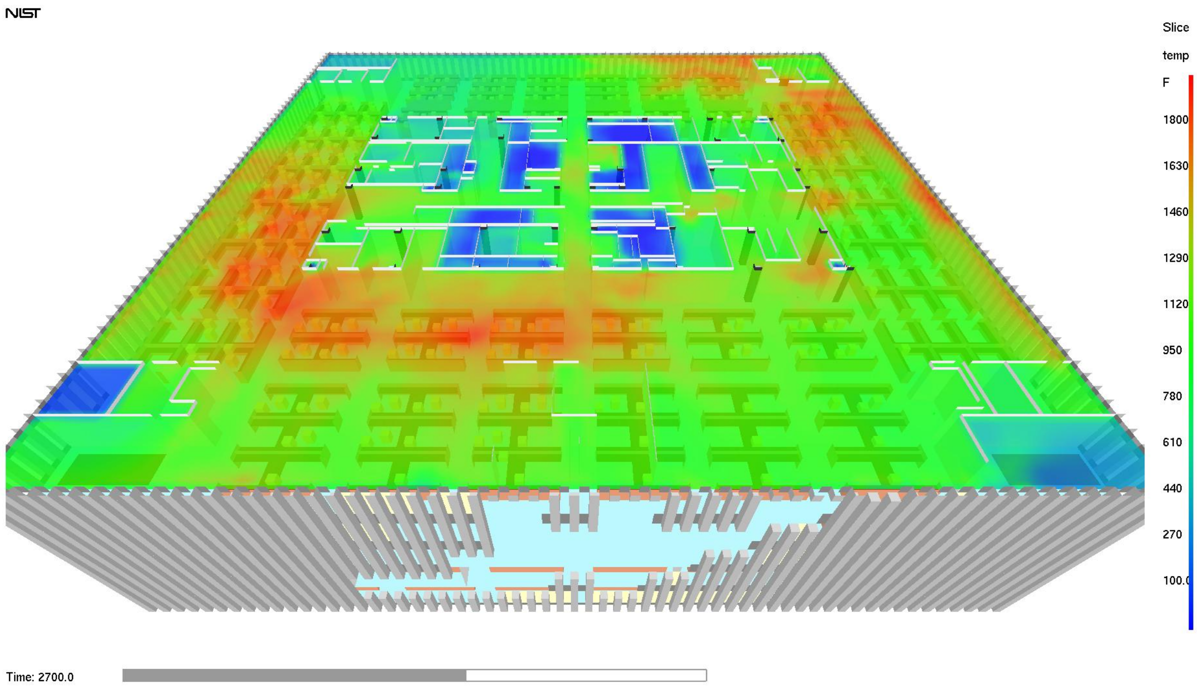
From *McGrattan and Bouldin* (2004)

- Predicted temperatures and heat release rates compared with experiments.

- Experiments burned paper laden work stations in limited ventilation compartments.

- Actual contents and completeness of burning are sources of uncertainty.

FDS SIMULATIONS



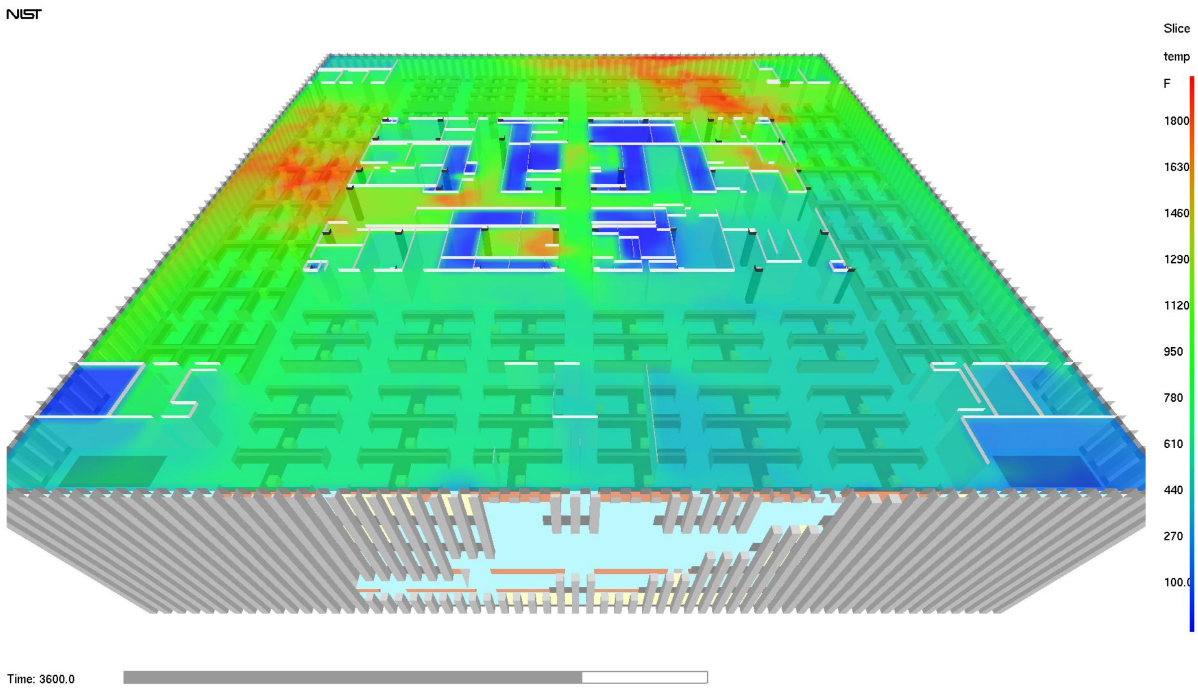
From *McGrattan and Bouldin* (2004)

- North tower 96th floor ceiling temperatures at 15 minute intervals.

- At 50 cm resolution, 150,000 cells per floor and 500,000 time steps required for 6000 seconds simulated time.

- Parallel processing reduces computing time to 2 days (8 processors/floor). 6-12 GBytes memory required.

FDS SIMULATIONS (2)



From *McGrattan and Bouldin* (2004)

- Heating *and* cooling at any location as fires migrate.

- FDS time step $10^2 - 10^3$ times smaller than thermal time scales. Allows simultaneous fire and thermal calculations if desired.

- Further details in (*McGrattan and Bouldin* 2004).