**Presentation prepared by:**

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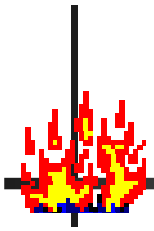
# The 21st Century COE Program

## The First International Symposium on
## *Wind Effects on Buildings and Urban Environment*

**March 8 and 9, 2004**

**Main Hall at Science Council of Japan**
**7-22-34, Roppongi, Minatoku Tokyo, Japan**

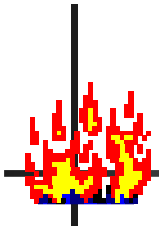
# Smoke and Fire in Building Atria



Robert N. Meroney, Hose Carrier
Wind Engineering and Fluid Mechanics
Civil Engineering Department
Colorado State University

# Costs of Fire to the USA

- America's fire death rate is one of the highest per capita in the industrialized world.
- Fire kills over 4,000 and injures more than 23,000 people each year.
- Firefighters pay a high price for this terrible fire record as well; approximately 100 firefighters die in the line of duty each year.
- Direct property losses due to fire exceed $8.5 billion a year.
- Most of these deaths and losses can be prevented!



# Special characteristics of Atria

- Atria, covered shopping malls, convention centers, airport terminals, sports arenas, and warehouses are examples of large spaces for which conventional fire-model approaches are not always effective.
- Challenges
  - No way to maintain blocking pressure differences without barriers (doors, vents)
  - Large communicating spaces present so smoke moves unimpeded

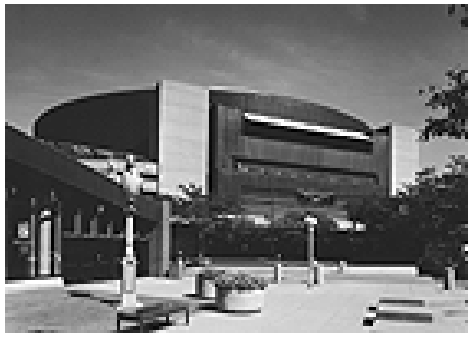
# Actual Atria Fires

- *" There are plenty of examples of fire tests in large spaces, but few actual events of note. Hotel fires occur all the time, but few are serious. Smoke management is the most important aspect of these fires."*

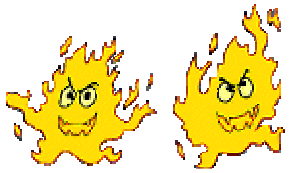
- Kevin McGrattan, NIST, noted in an email (24 September 2002)

# Market Square Arena 1974

- May 6, 1974: Fire in Market Square Arena, Indianapolis set during installation of gutters on the roof during construction.
- "*Arriving fire companies were greeted by the sight of flames and smoke rolling from the roof of the still under construction arena*." Fire caused by construction workers.



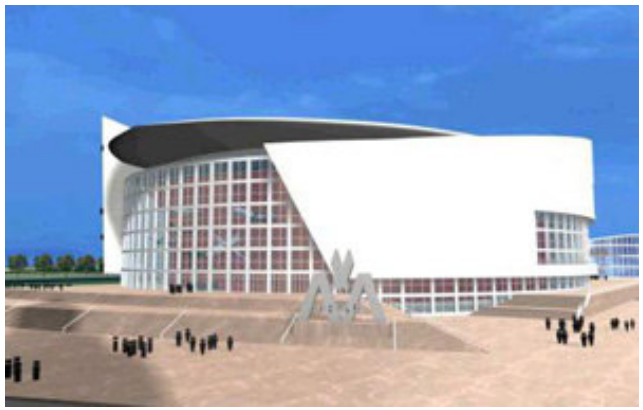
# Market Square Arena 1991



- Market Square Burns Again!
- *"INDIANAPOLIS, Ind. (5-14-01) – A demolition crews' cutting torch ignited a two-alarm fire at Market Square Arena in downtown Indianapolis today."*

# American Airlines Arena 1998

- November 13, 1998: The new downtown arena for the NBA's Miami Heat caught fire at the $165 million American Airlines Arena.
- Fire caused by construction workers.



# Alamo Dome 2001

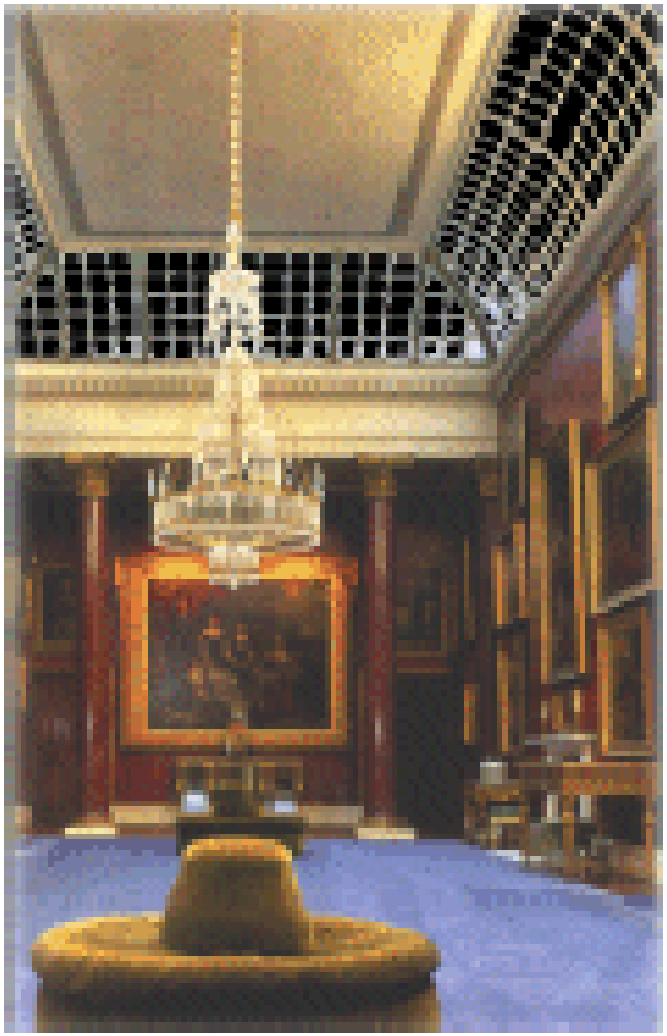
- December 25, 2001: San Antonio, TX...a three-alarm fire at the Alamo-Dome caused an estimated $100,000 damage.

# Evolution of the Atria

- Roman house with central space open to sky
- Included grand entrance space, focal courtyard, and sheltered public area.
- Facade blank

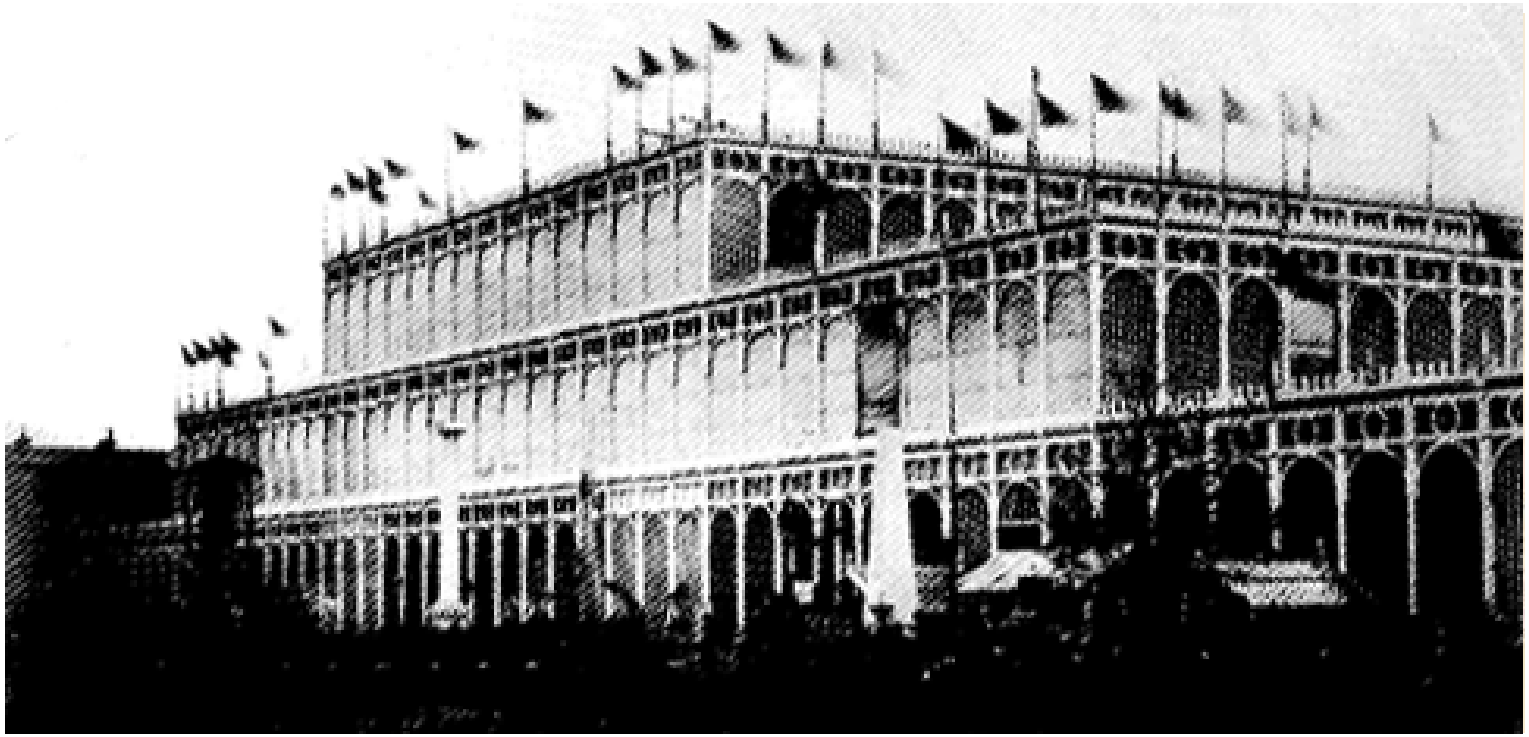
# Early 19th Century Atria

- Roof over picture gallery at Attingham Park, Shropshire
- John Nash, 1806
- Use of iron and glass technology in houses

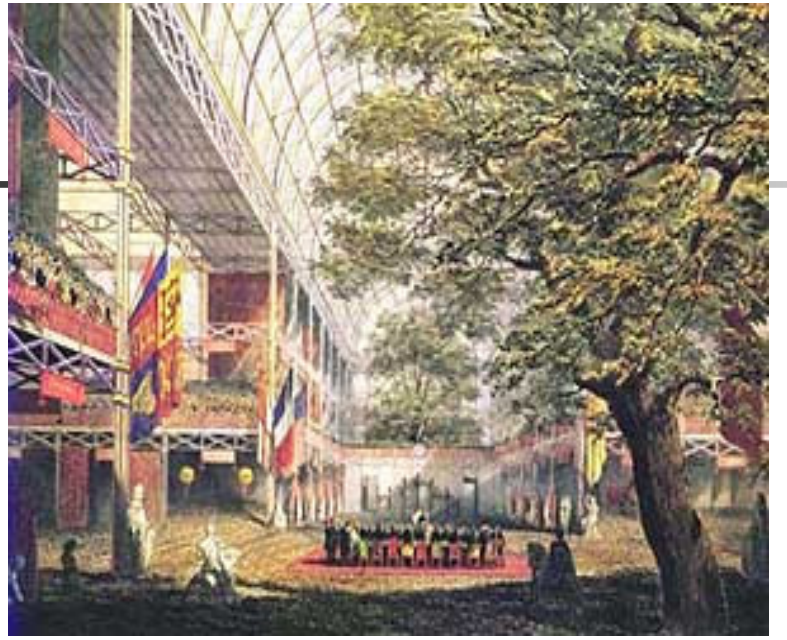


# Crystal Palace Exhibition Hall

- John Paxton (1850-51) in London



# Crystal Palace (contd)

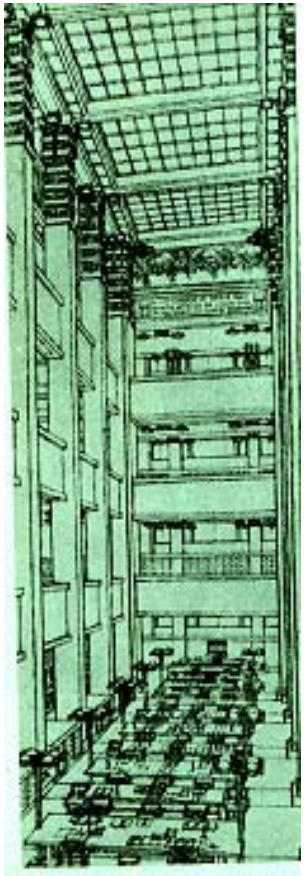


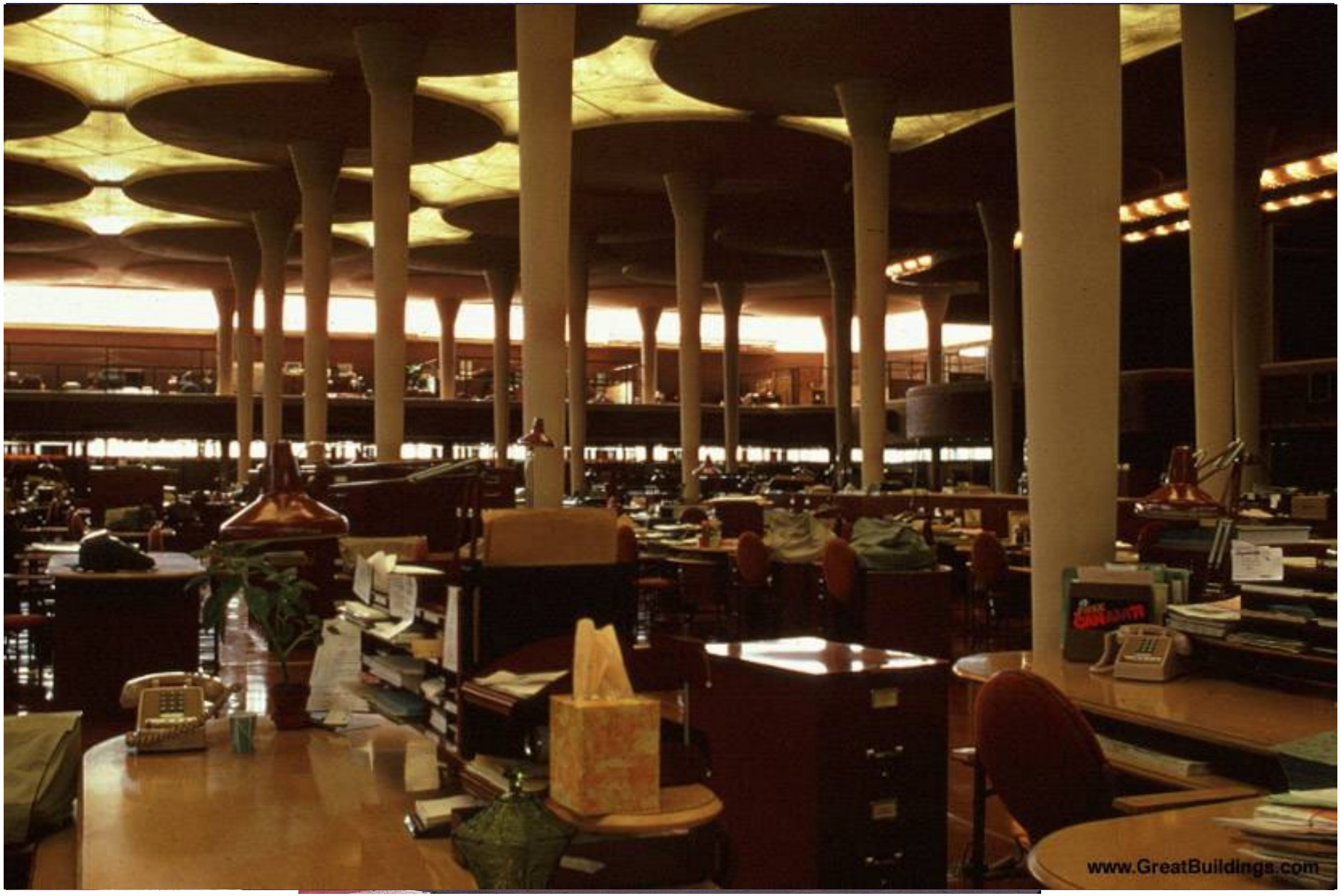
BROOKS BROTHERS
BROOKS BROTHERS

# Early 20th Century Atriums

- Larkin Building, Buffalo NY 1905
- Frank Lloyd Wright
- Four open sided levels around a sky lit court with filtered air.

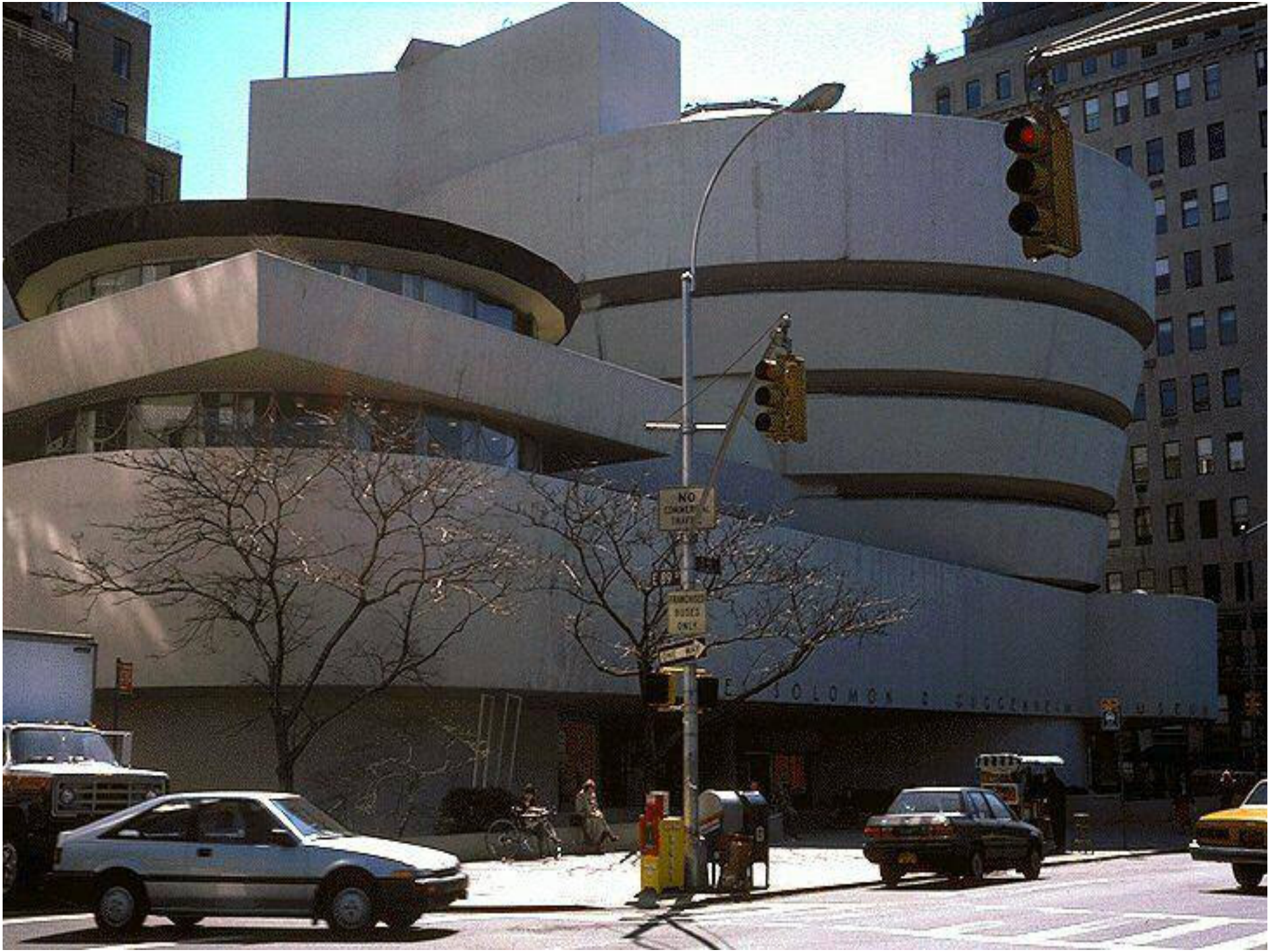
# Larkin Atrium



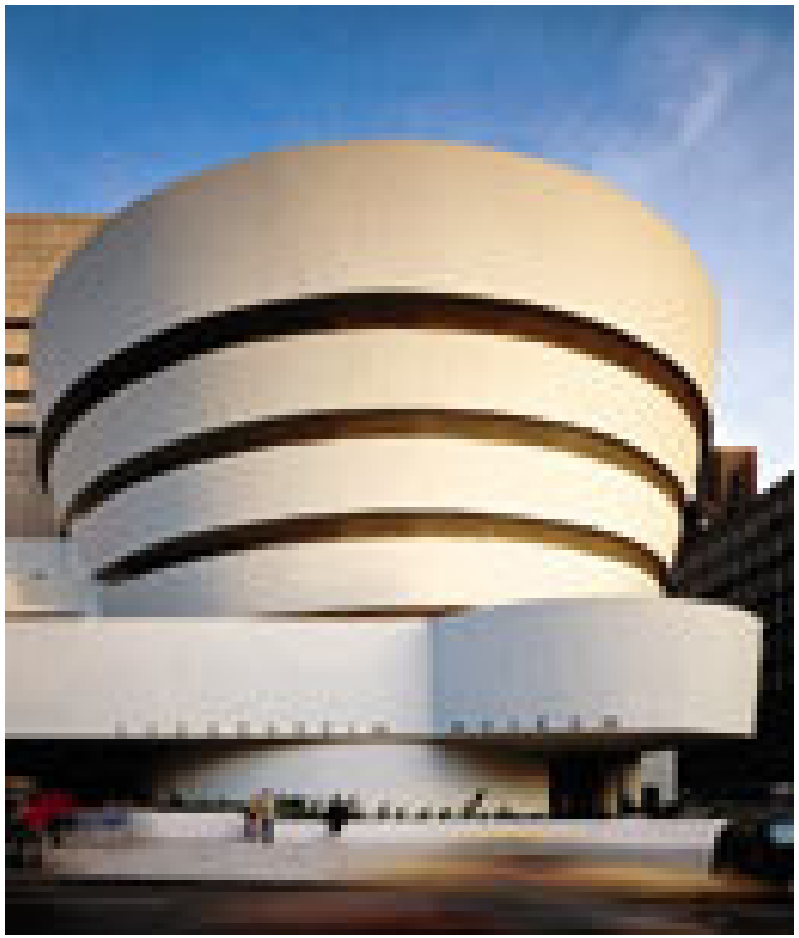

www.GreatBuildings.com

# VC Morris Store

- Built in 1949 in San Francisco, CA
- Frank Lloyd Wright
- Top-lit building with focal central court


NO
BUSES
ONLY

# Views



# Hyatt Regency, Atlanta

- Built in 1968 by John Portman. Its covered central court was first called an "atrium"
- Note balconies and outside elevators

# Chicago Board of Trade

# State of Illinois Center

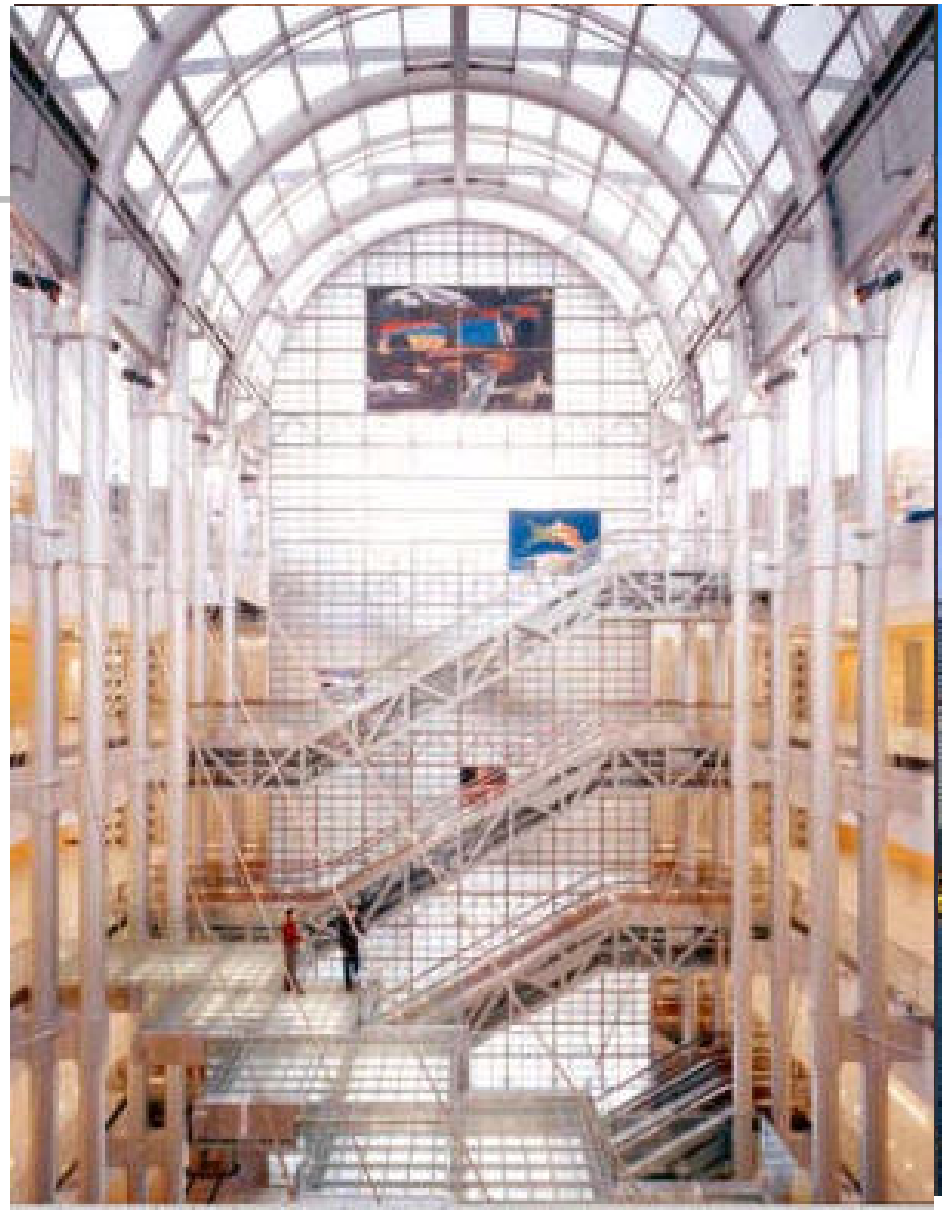
- Murphy/Jahn (1984) built State of Illinois Center in Chicago.
- Rotunda is transparent at 18th story.
- Elevators are kinetic sculpture.

# Skyscraper Atriums

- Hong Kong Shanghai Bank Tower
  - Sir Norman Fosters & Partners, 1985
  - 43 stories with 10 story atrium
- Hong Kong Bank
  - E.M. Pei, 1989
  - 70 stories with 17 story atrium from 3rd floor
  - Very bad Fung Shui!

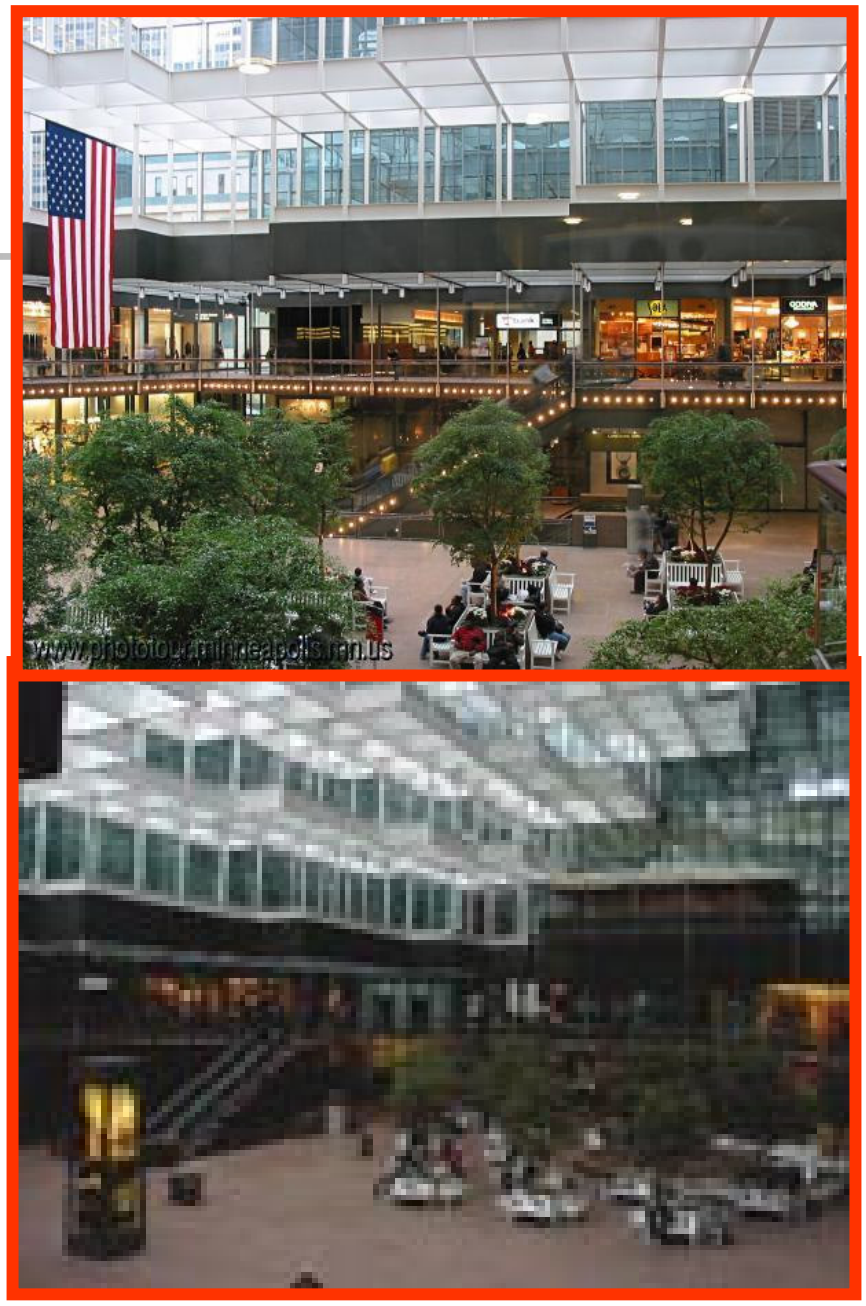
# Jin Mao Tower

- Skidmore, Owings & Merrill Architects (1999)
- Shanghai, China



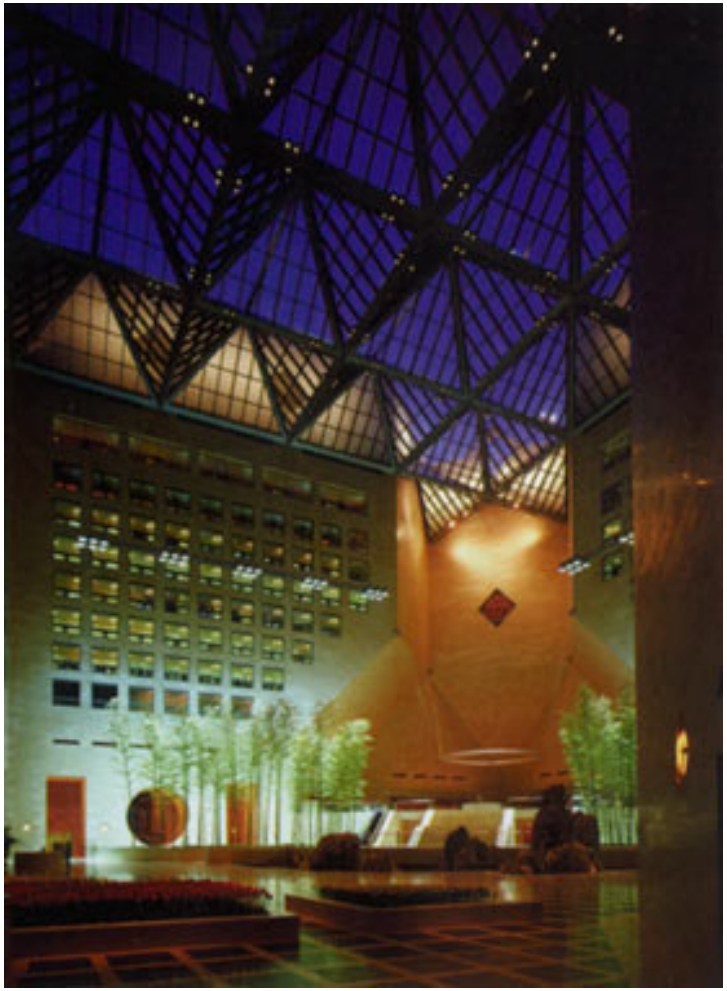
# IDS Center

- Crystal Court, Minneapolis/St Paul MN
- 42,614 panes of reflective glass in lobby of 775 ft high building
- 51 stories tall



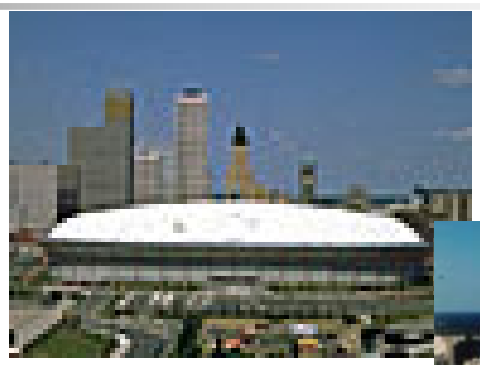
# Modern Atriums

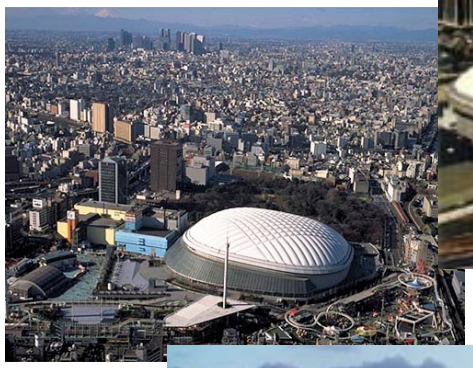
- Bank of China, Beijing, PRC
- E.M. Pei, 2001



# Sports Domes

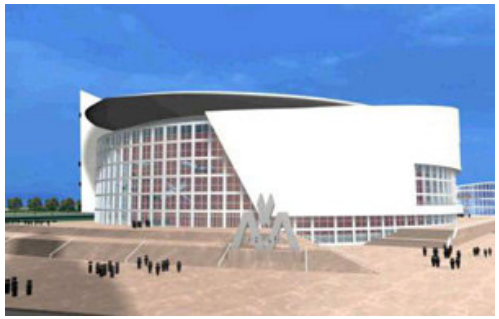
- Hubert Humphrey Dome, Minneapolis
- RCA Dome
- "Big Egg", Tokyo
- Millennium Dome, London



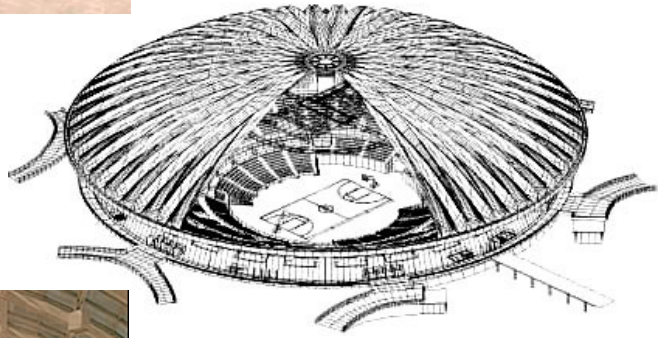


# Arenas and Halls

- American Airlines



- Assembly Hall, U. of Illinois, Champaign

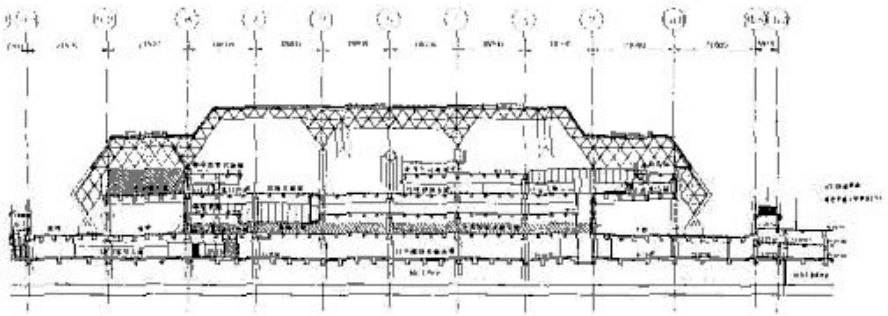


- Ice Palace, Edmonton

# Shopping Malls, Airports, Hangers, etc.

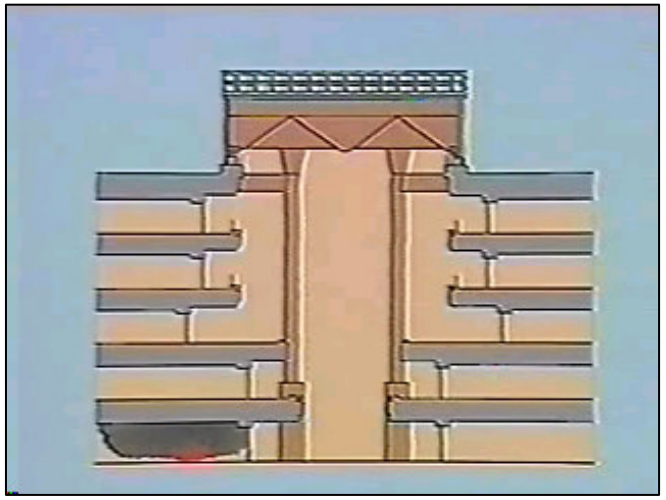
- Winter Garden, NY

- Chang Kai Chek Airport, Taiwan

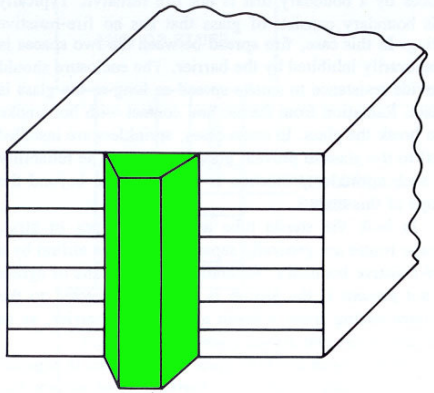


# Landmark Tower, Yokohama

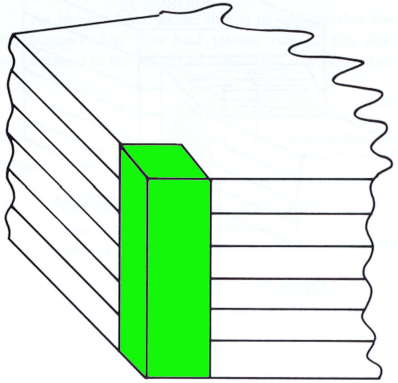
- Tallest building in Japan, built 1993
- Architects:  Stubbins Assoc.
- 297 m tall, 393,000 sq meters floor space
- 1-48 floors offices
- 49-70 floors hotel
- World's fastest elevator
- Atrium:  5 floors tall, 200m long



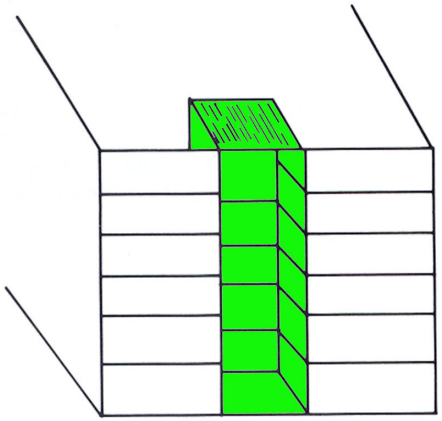
# Atria Classification



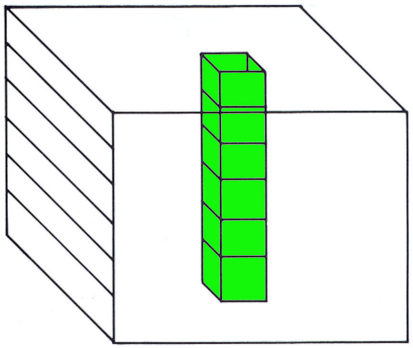
Conservatory



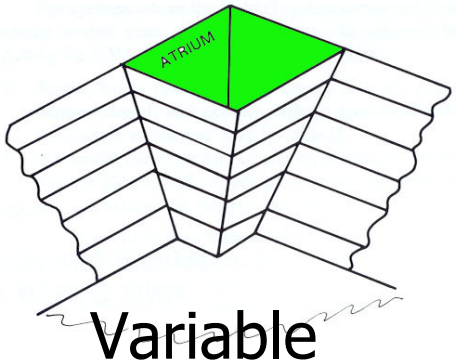
Two-sided atrium



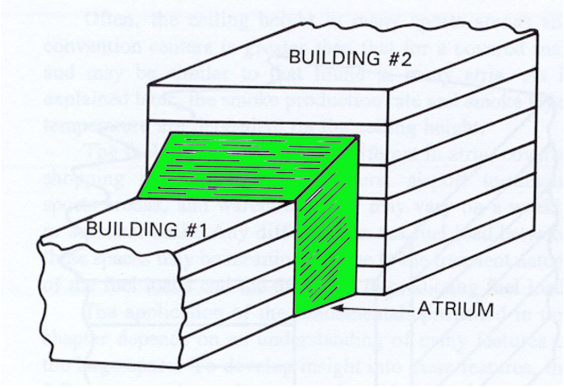
Three-sided atrium



Four-sided atrium

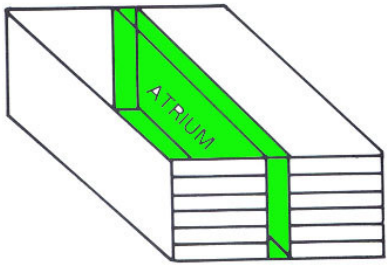



Variable cross-section

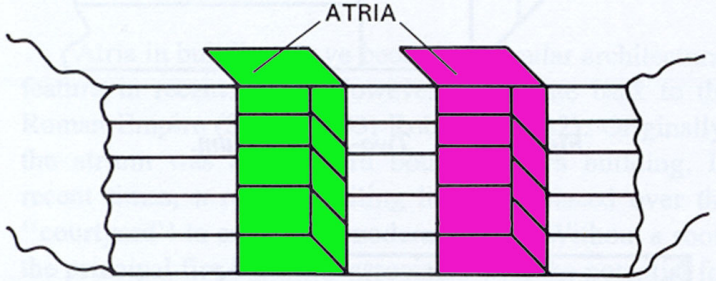



Bridging atrium

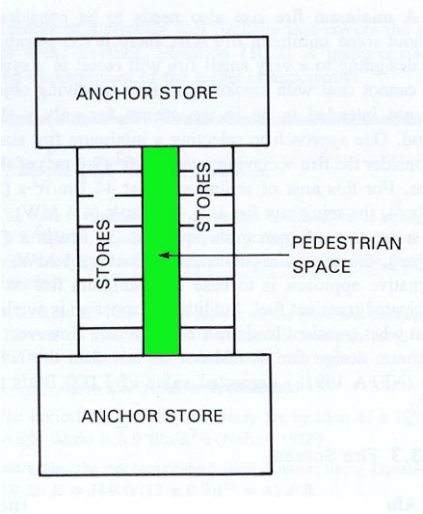
# Atria Classification (contd.)



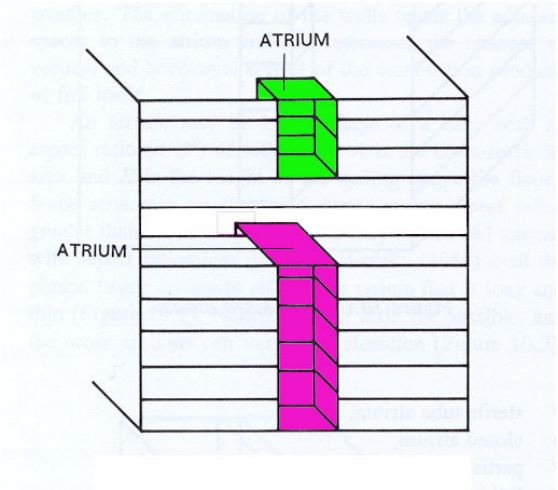

Linear atrium



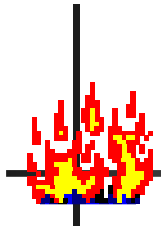

Side-by-side atria




Shopping mall atrium



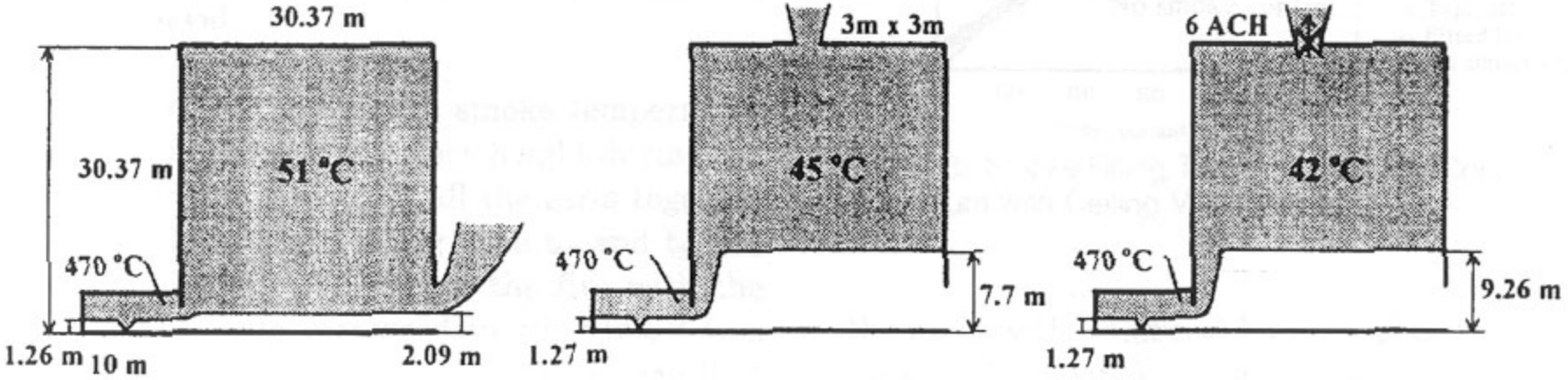

Multiple vertical atria



# Fire Management Methods

- Conventional wisdom uses sprinklers to suppress smoke and fire,
- Revised goal:  maintain a lower "smoke free layer" for evacuation
- Smoke management used in atria
  - Smoke filling…..let it burn and smoke rise
  - Gravity venting…let buoyancy remove smoke through vents
  - Smoke exhaust…use fans to exhaust smoke

# Fill, Natural Vent, Exhaust



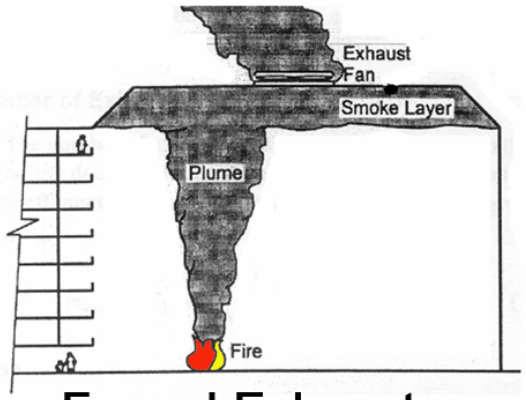

No Smoke Control
Smoke Filling

Natural Venting
=Gravity Venting

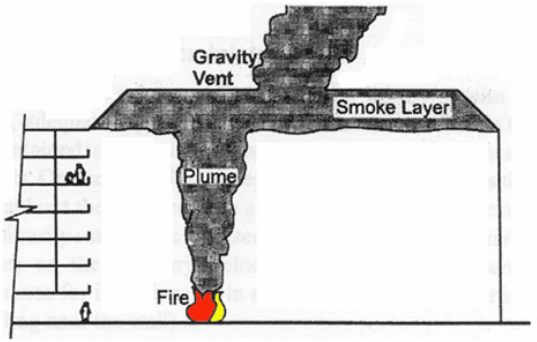
Forced Venting =
Smoke Exhaust

# Atrium Smoke Problems

***GOOD***

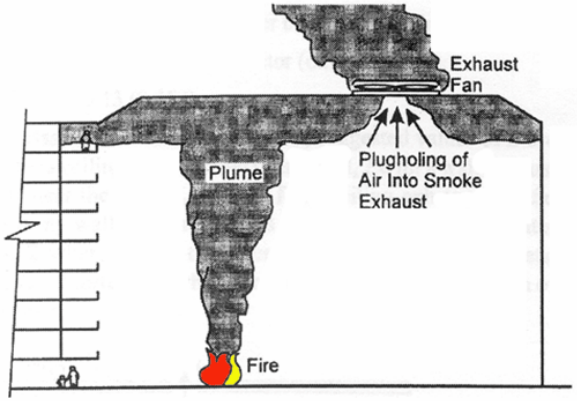



Forced Exhaust

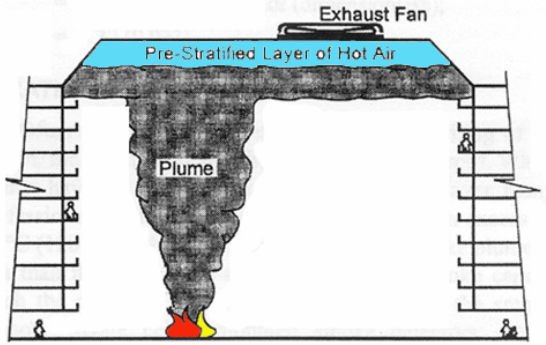



Gravity Venting

***BAD***

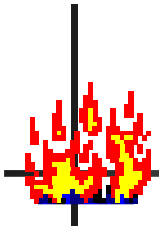



Plugholing




Stratification

# Evolution of Virtual Fire Control Concepts



- Physical and full-scale models
- Node & network models
- Zone models
- Field or CFD models

# Physical Modeling




- Actual fires can be simulated at full or partial scales
- Full scale hot smoke test in the Chang Kai-Chek Air Terminal Departure Hall

(a) Time 0:00, fire was set

(b) Time 04:00 (4 min.), clear height = 20m

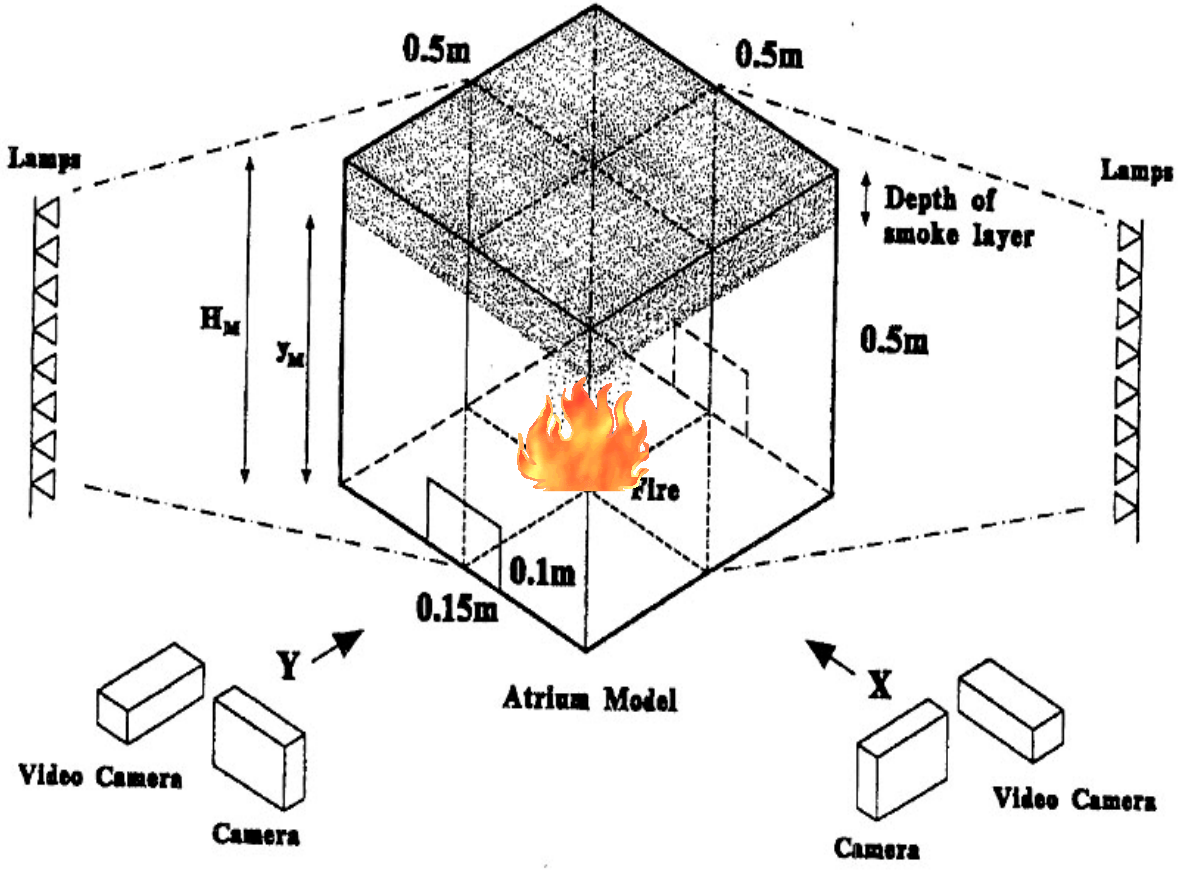
(c) Time 07:00 (7 min.), clear height = 18m

(d) Time 11:00 (11 min.), clear height = 11m

Yang & Lee (2000)

# Small-scale Physical Models

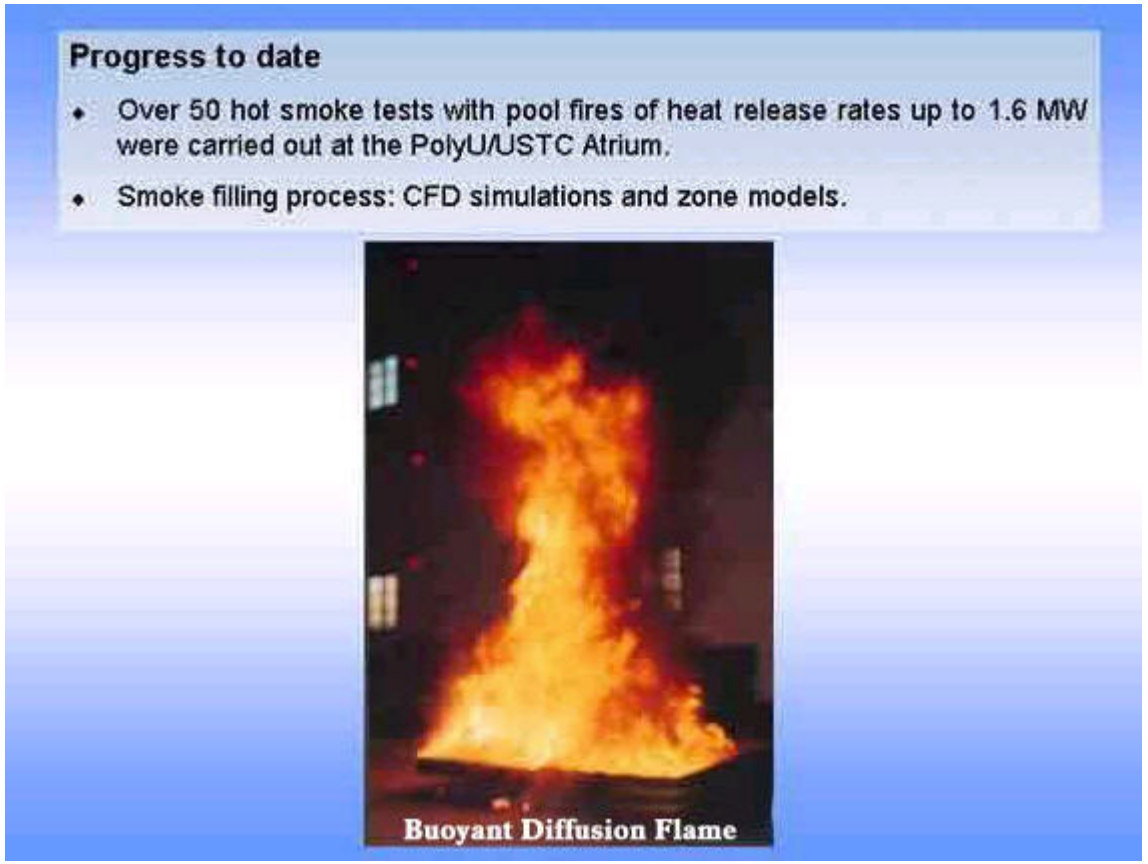
- Simulated fires can be studied at small scales with fire, heat, inert gases, smoke, or salt-water



Savanah River Laboratory
Auto-tunnel Ventilator Exhaust Plumes Boston

# Poly U/USTC Atrium Test Centre

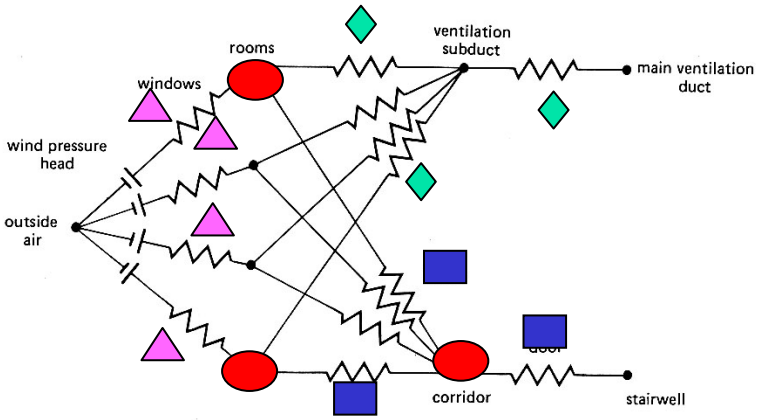
- Large space fire research
- L:W:H = 30:18:30 m
- 8 exhaust vents 1.2x 1.2 m sq on roof

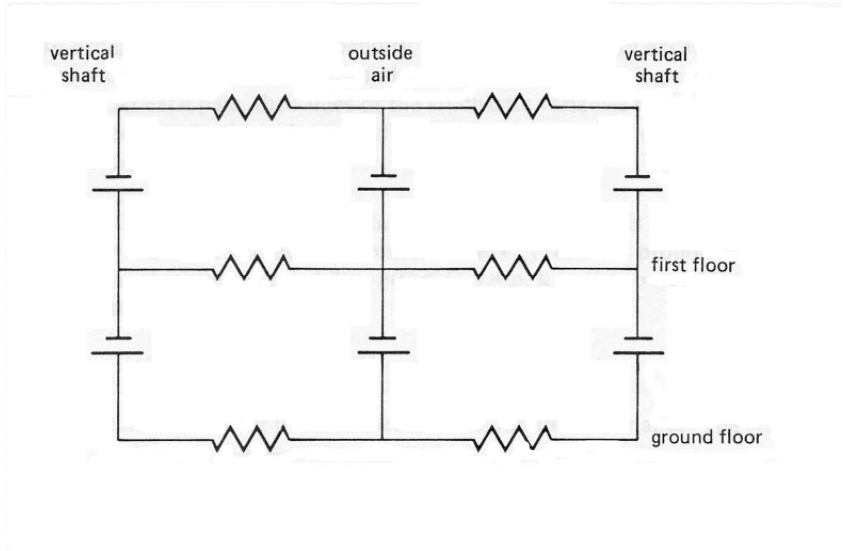


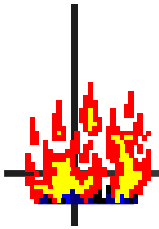
# Node & Network Modeling

- Essentially an electric analog to flow, it uses pressure drop formulae through doors, vents, windows & cracks to provide resistance and room volumes for capacitance

Vents
Windows
Doors
Rooms



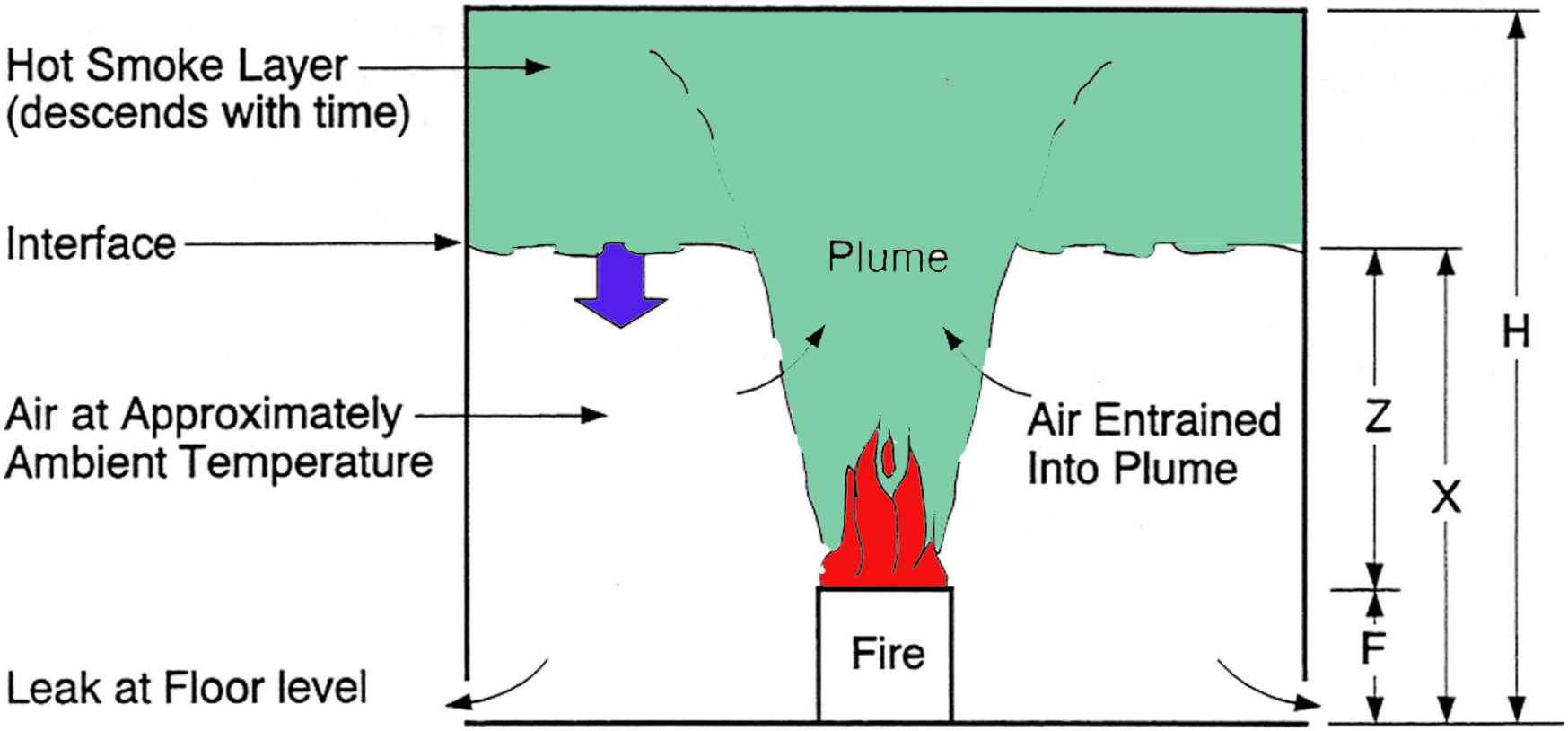





# Zone Models

- Zero, two & multiple zone fire models are idealizations that presume fire properties are constant over a specified region
- Mixing occurs across regions based on empirical algorithms
- Example models are ASET, ASME, BRI-model, and CFAST
- Output are temperatures, densities, concentrations, smoke visibility, and zone depths with time
- Does not handle unusual configurations or interior blockages well

# Basic Smoke Plume Behavior



# Field or CFD Modeling

- CFD often called "field modeling" in the fire community permits finer specification of geometry and fire physics.

FLUENT

CFX

STAR CD adapco Group

FDS-BRFL-NIST

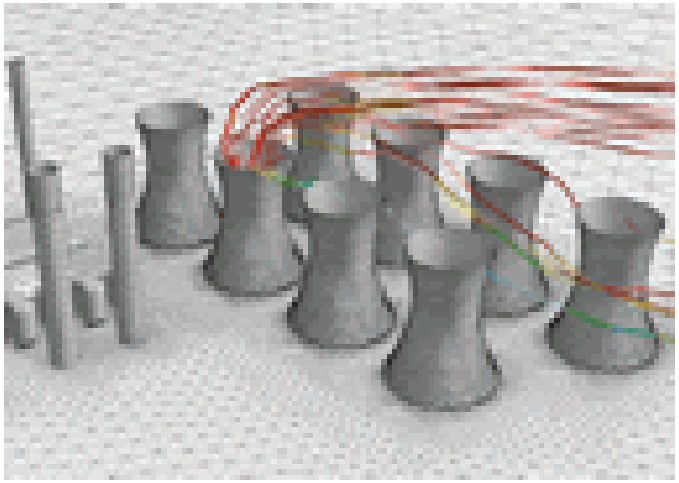
adaptive RESEARCH

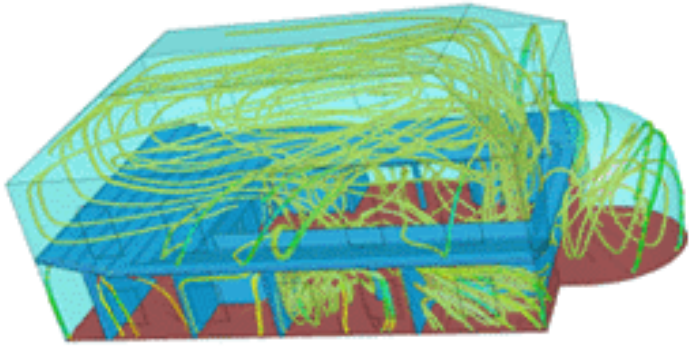
FLOMERICS

Pioneering Design-Class Analysis

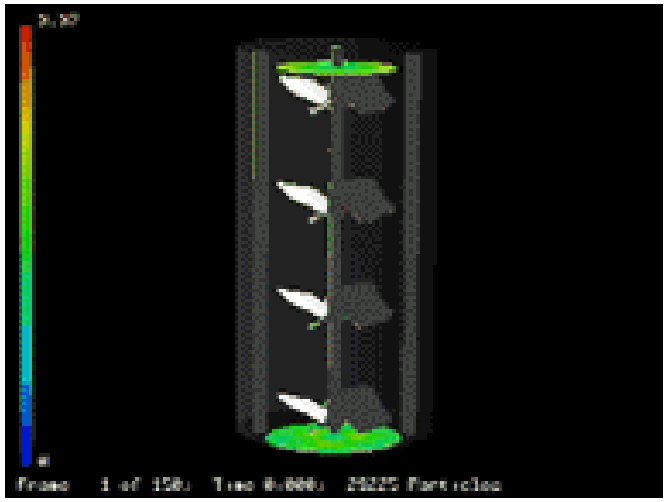
# Fluent 6.0

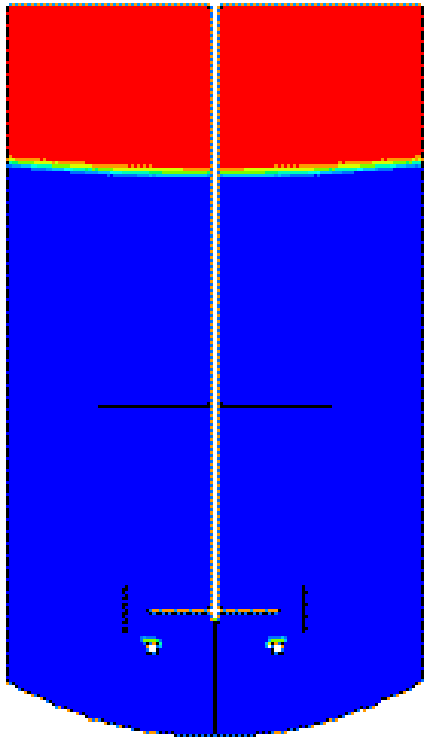
- An unstructured, finite volume based general solver which includes multiphase, combustion, heat transfer, phase change, radiation options, and a variety of RANS & LES turbulence models.
- CD-star, CFX, PHOENICS, and TASCflow offer similar options





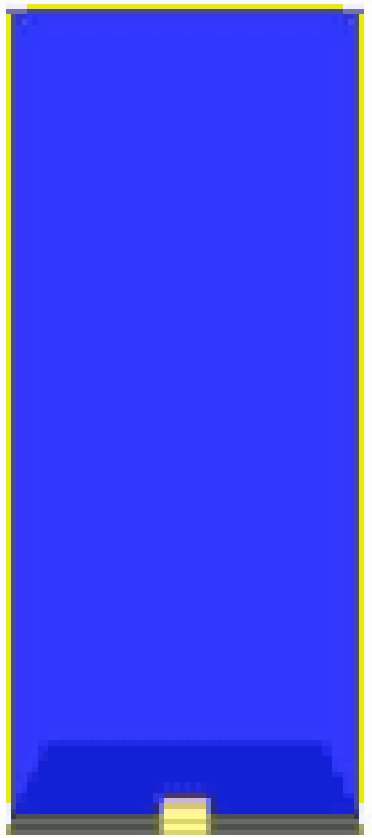
# Fluent Mixing Examples





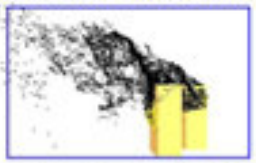
# FDS – Fire Dynamic Simulator

- CFD model of fire driven fluid flow that solves numerically the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with emphasis on smoke and heat transport from fires.
- Includes simple combustion model, ray tracing radiation transport algorithm, and sprinklers.
- Turbulence modeled by Large Eddy Simulation (LES)

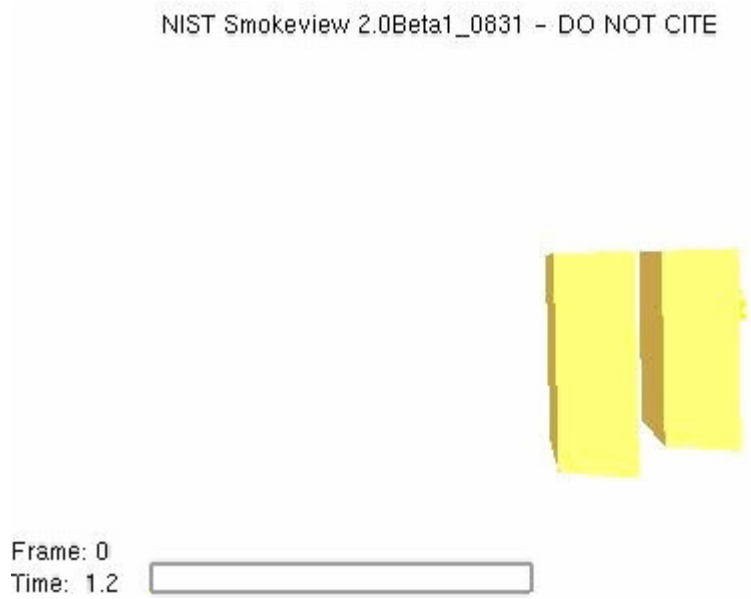


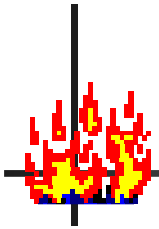
# FDS Simulation of World Trade Center Fire – 9-11

Frame of a Video of the World Trade Center Fire.



Simulation of the Smoke Plume of the WTC Fire.





# CFD as an Art

- "*Considering that application of CFD is an art and that the turbulence models are approximate, simulations need to (be) compared to experimental data. This is especially true of new applications, and it is why many of the projects above included such comparisons. If a simulation is similar in most respects to others that have been experimentally verified, further experimental verification is not necessary*."
- John H. Klote (1994) NISTIR 5516, p. 84.

# CFD Models Considered

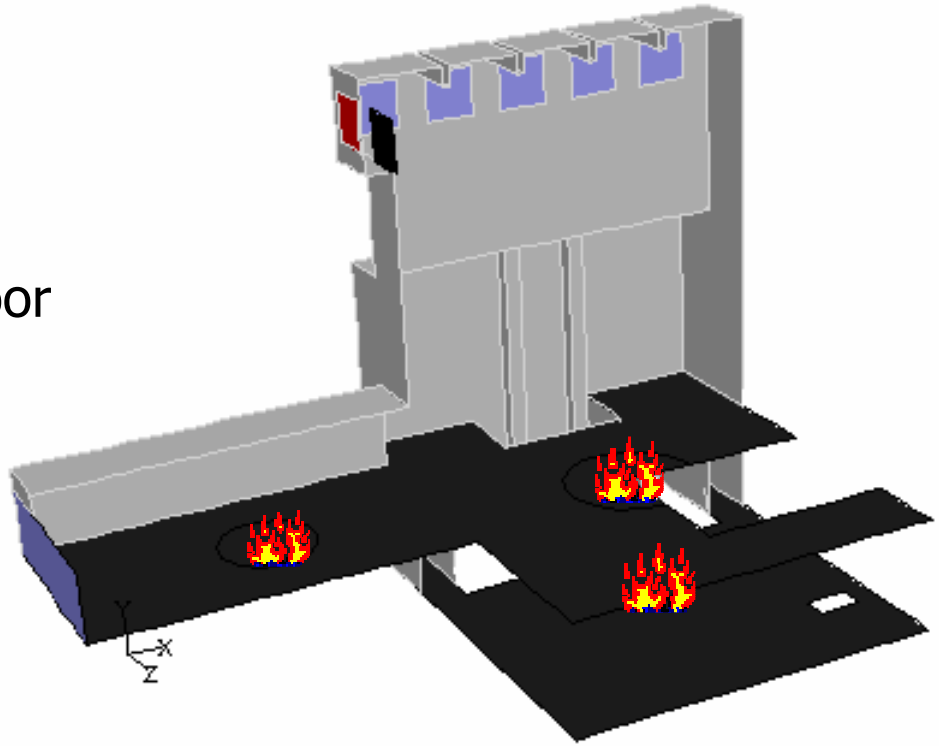
- ASMET
  - Simple zonal model
- FLUENT
  - Differential volume model
  - Structured or unstructured grids
  - RANS or LES turbulence
- FDS
  - Differential volume model
  - Structured grid only
  - LES turbulence

Models of Yamana & Tanaka (1985) test fires at BRI Full Scale Test Laboratory, Tsukuba, Japan

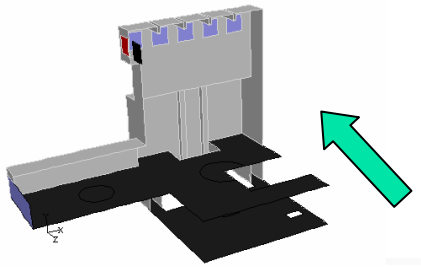
# Building Case Study

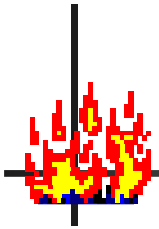


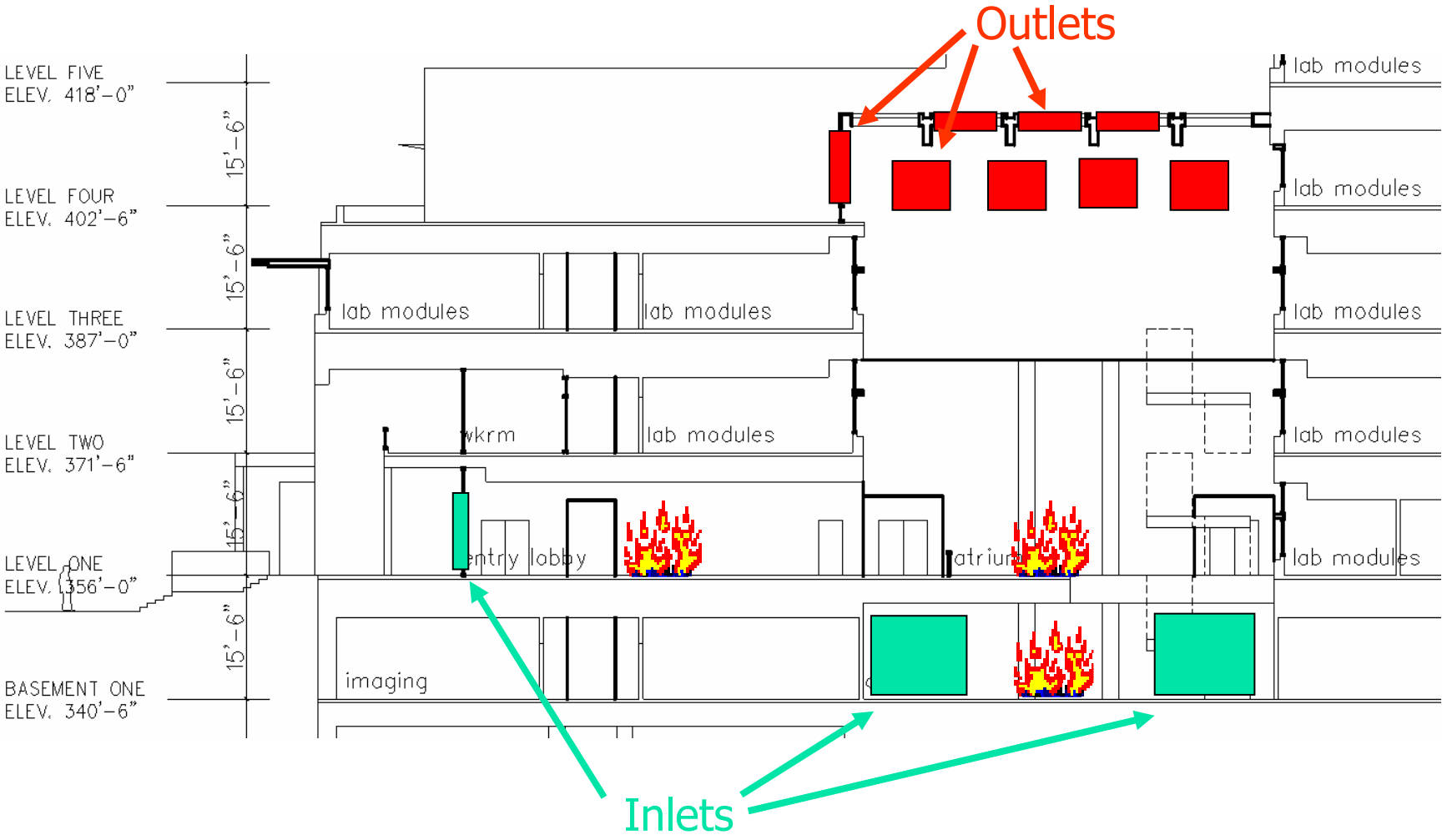

- Size ~17 m cube
- Fire sources
  - 5276 kw & 2100 kw
  - Lobby, ground & 1st floor regions
- Mitigation concepts
  - Gravity ceiling vents
  - Mechanical exhausts
- Effect of exterior wind



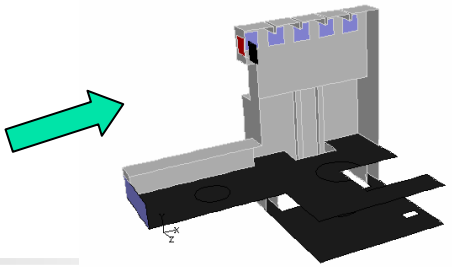
# Looking North

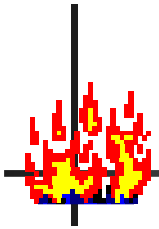


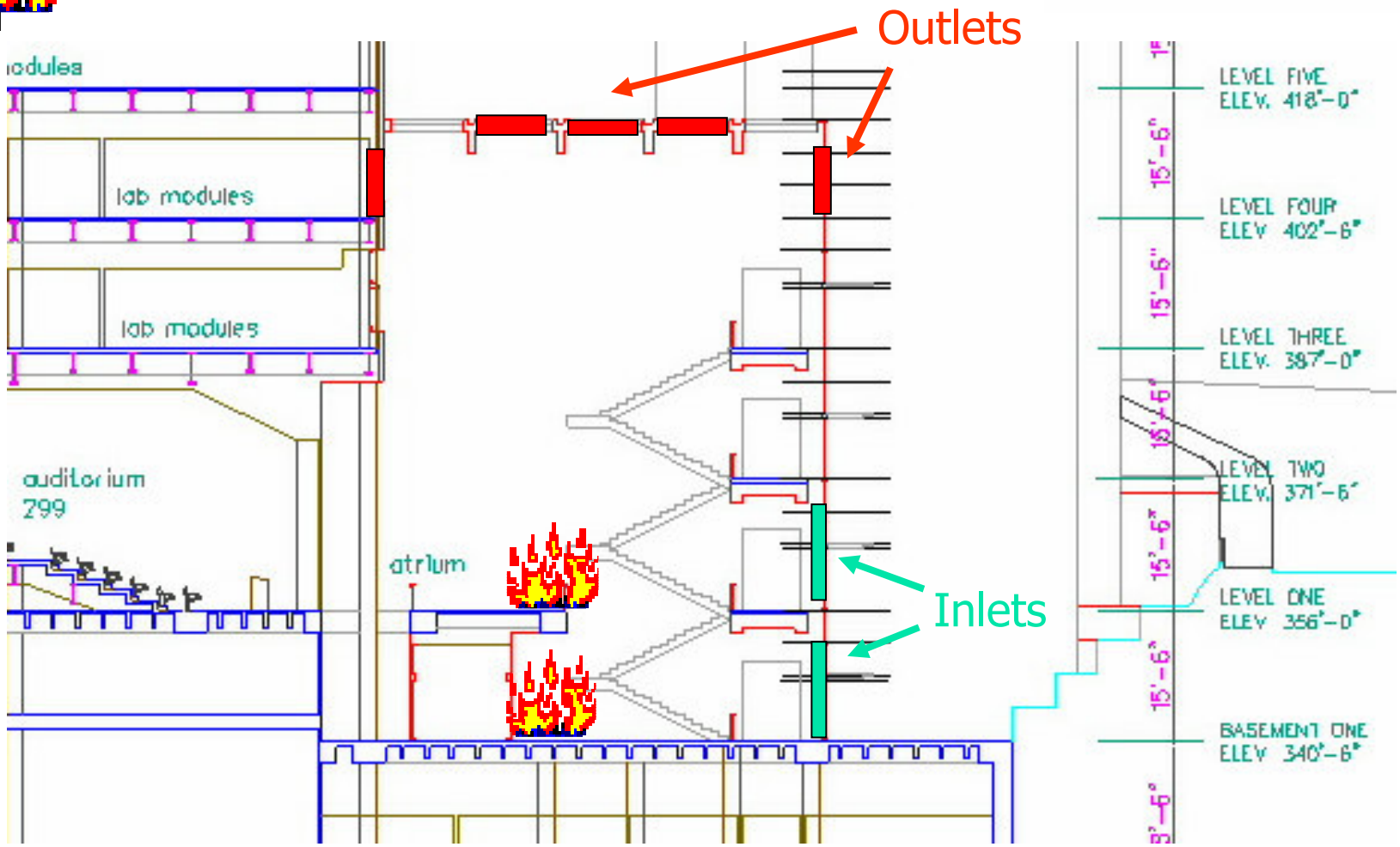




# Looking East

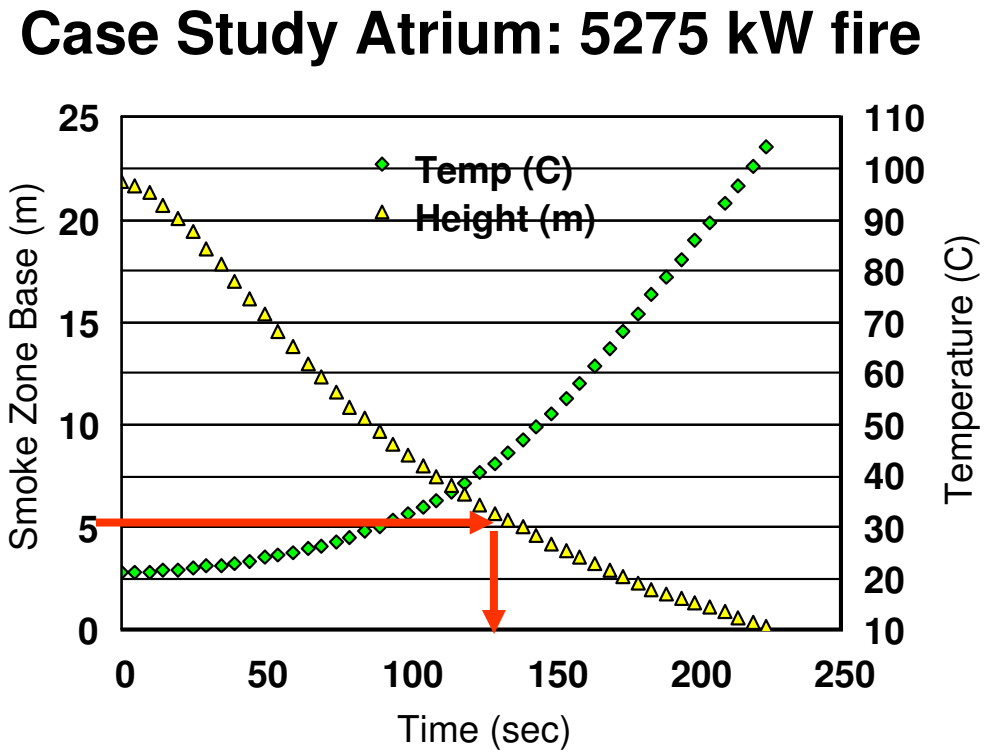






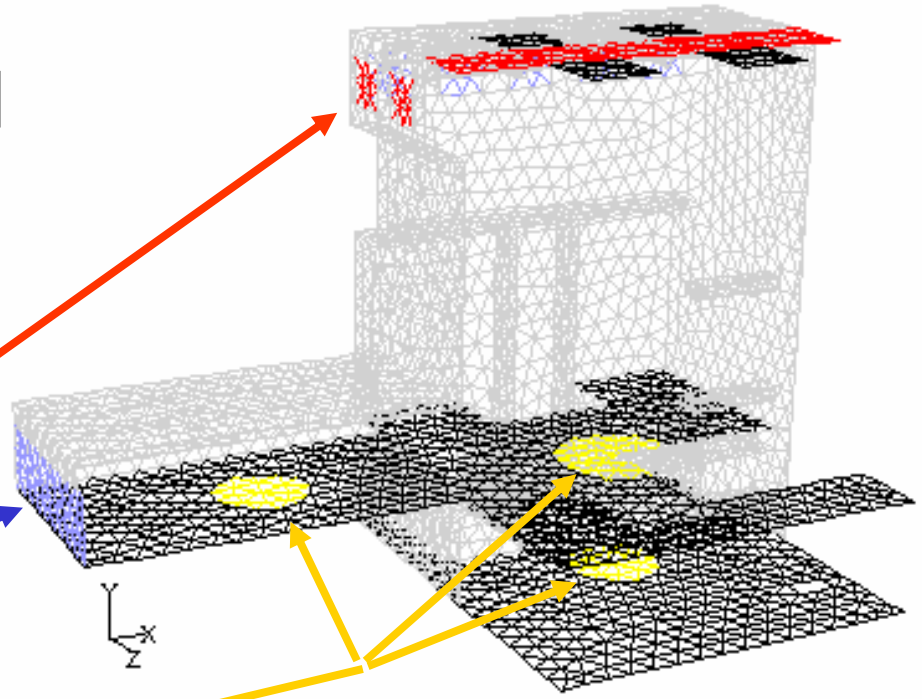
# Zone Model Results: No mitigation

- ASMET/ASET-C NISTIR 5516 (1994)
- Fire height 0.2m
- Room height 21.9m
- Floor area 252 sq m
- Growth rate ultra-fast (0.187 kW/sec$^2$)



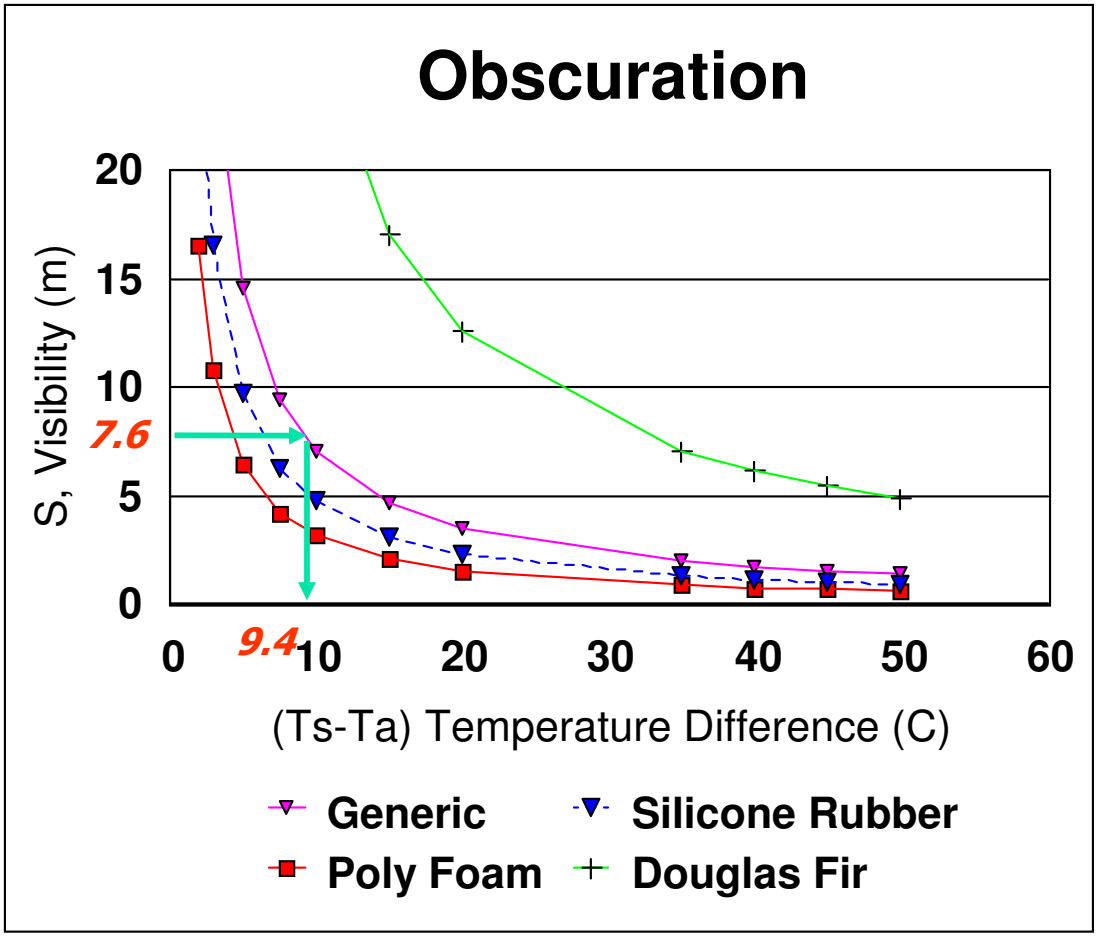
# FLUENT: Differential Volume Model

- 36,817 unstructured tetrahedral cells
- K-E & LES turbulent models
- Ceiling & wall exhausts
- Inlets
- Fire locations

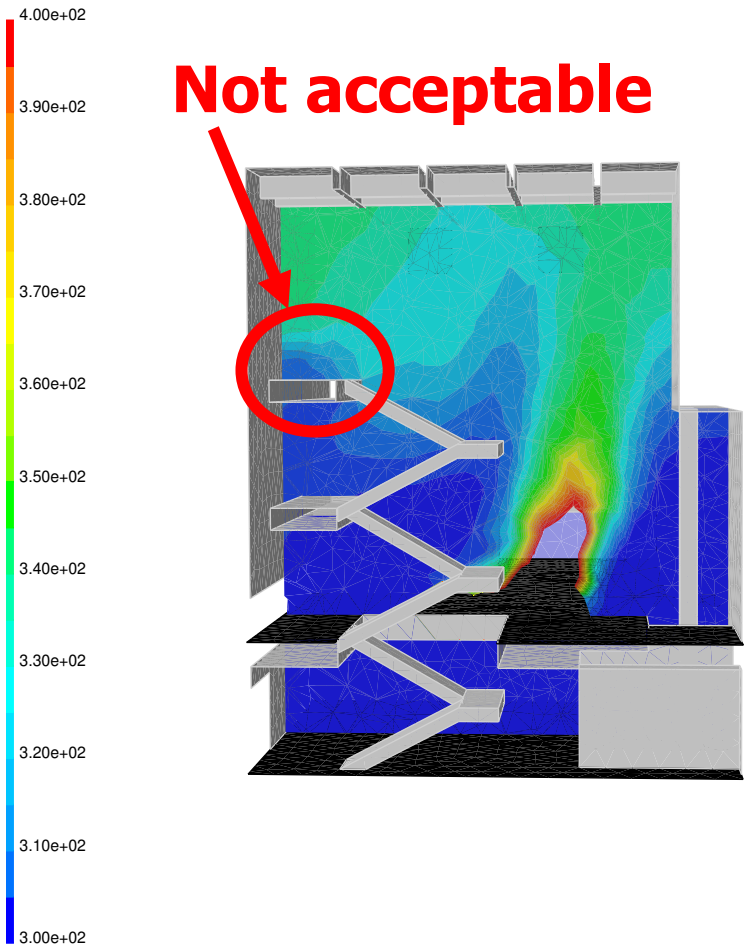


# Obscuration (S vs $T_{smoke}$)

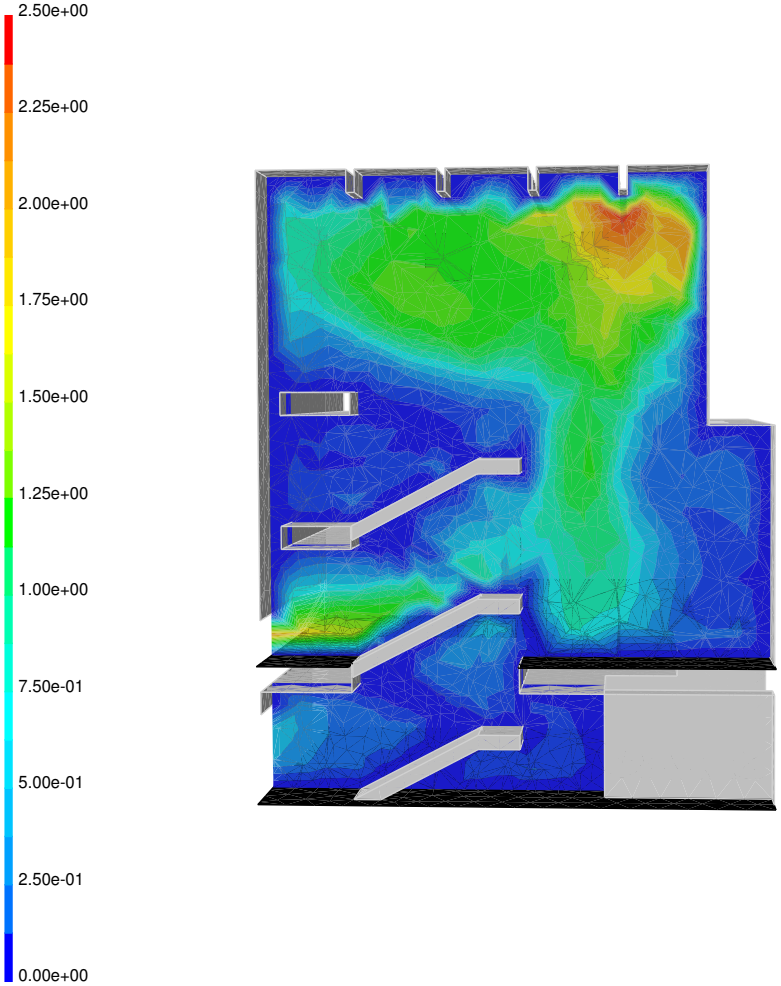
- Visibility is a function of smoke particle loading
- Particle density can be related to mass and type of fuel, HRR
- Typical criteria is visibility S > 25 ft (7.6 m)



# Fluent Results: Case 2: 200,000 cfm out ceiling via mechanical exhaust; 5275 kw fire

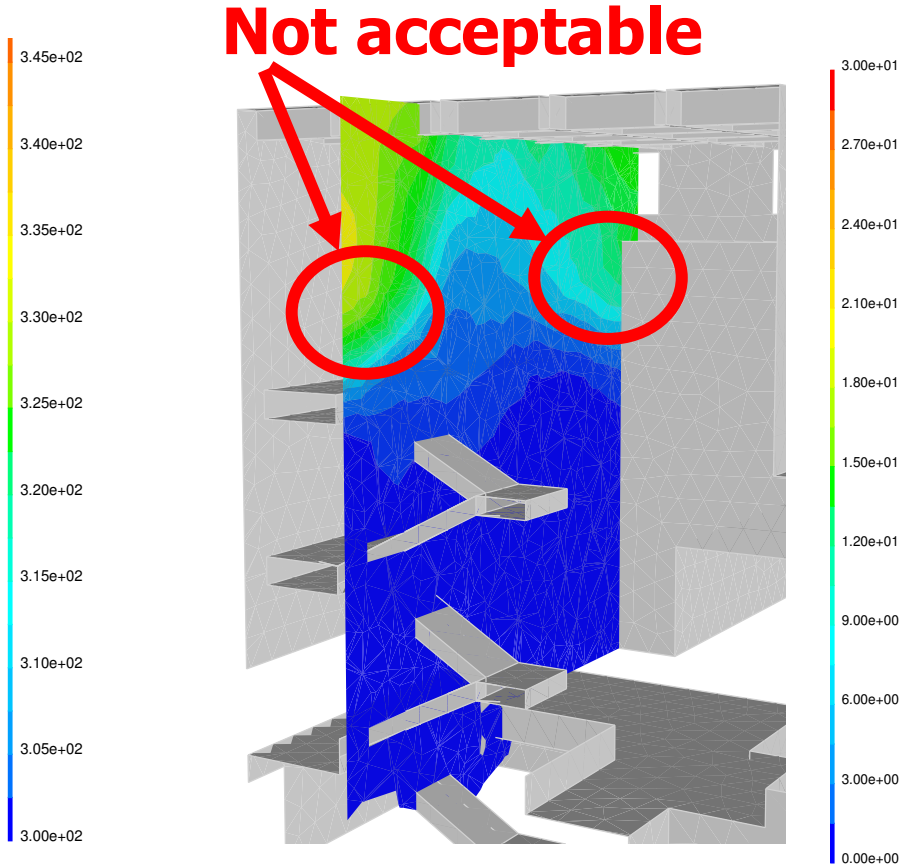



Temperature Contours, T $^{o}$K

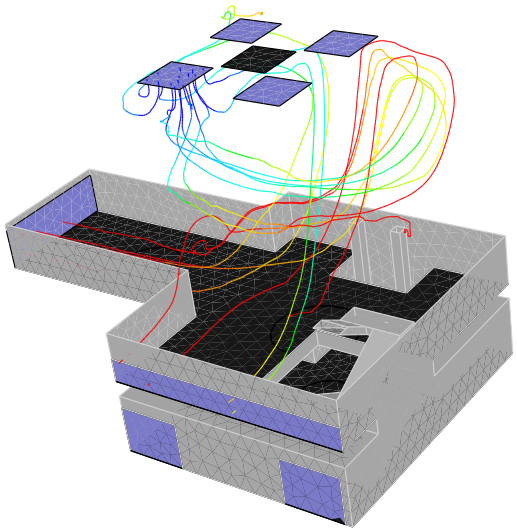



Velocity Magnitude (m/s)

# Fluent Results: Case 2b: 320,000 cfm out ceiling via mechanical exhaust; 5275 kW fire



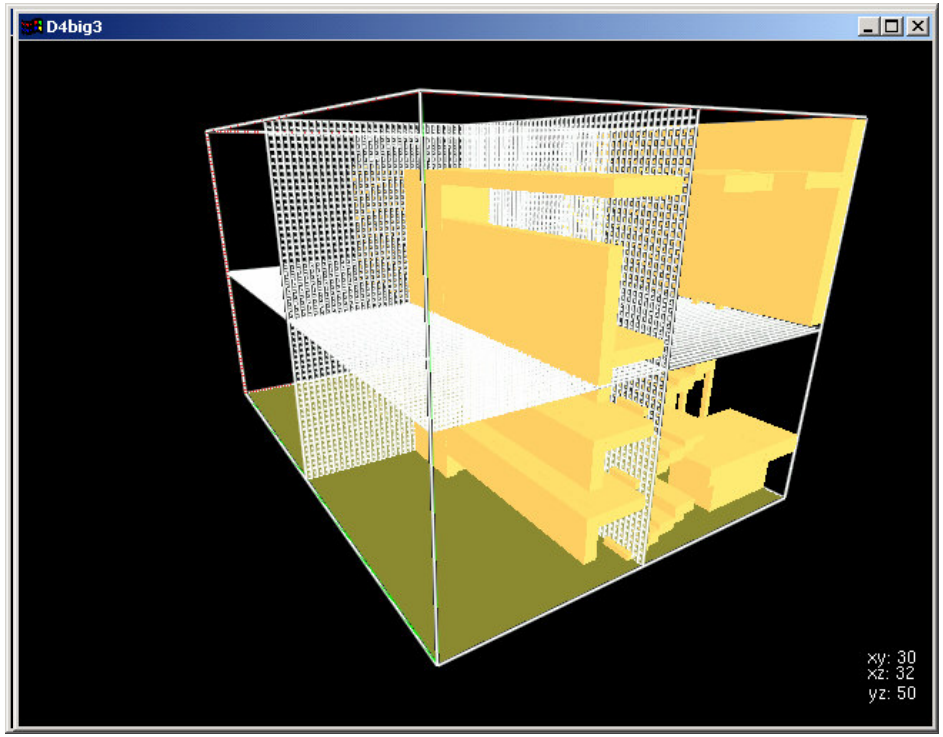

Temperature Contours, T $^{o}$K



Pathlines colored by time before exit, seconds

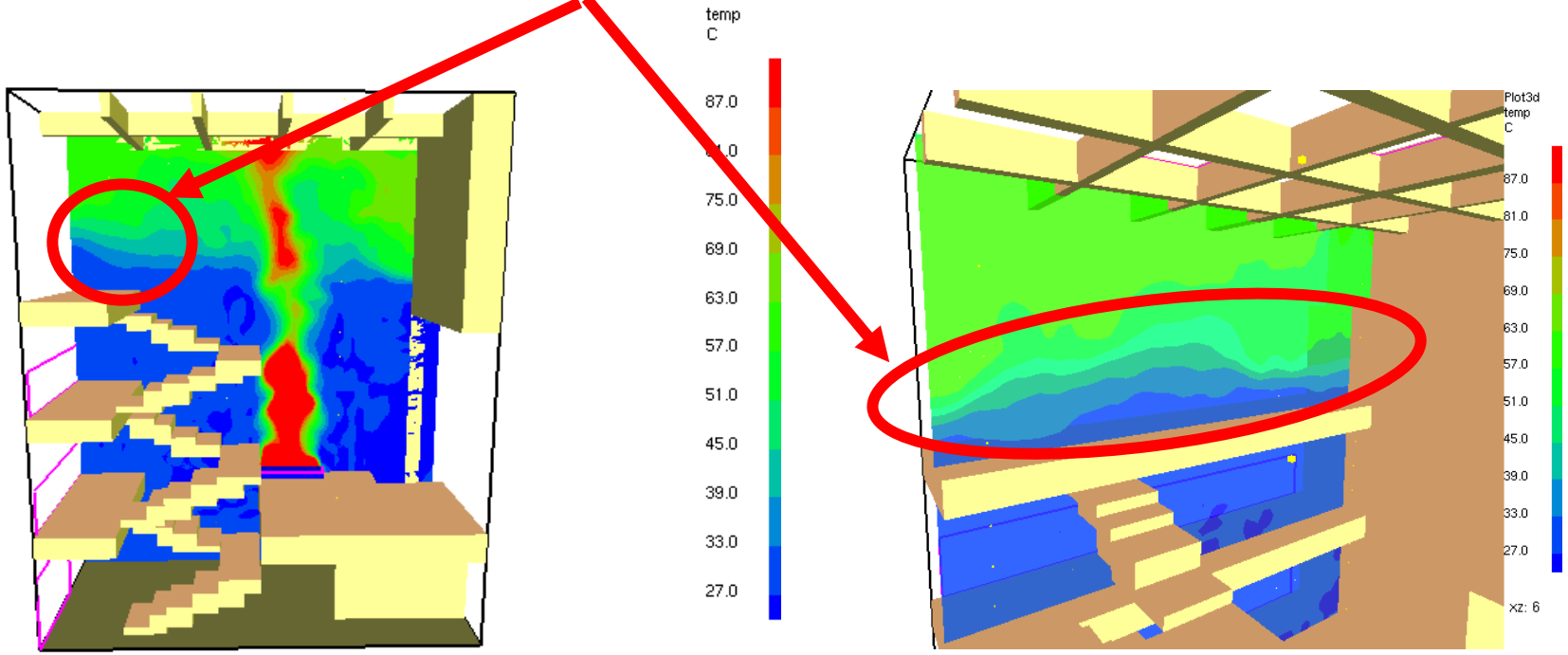
# FDS (Fire Dynamics Simulator): LES model)

- 259,200 structured hexagonal cells on a rectangular grid
- Elliptic formulation of NS Equations which permits solution with a fast Poisson solver
- LES turbulence model

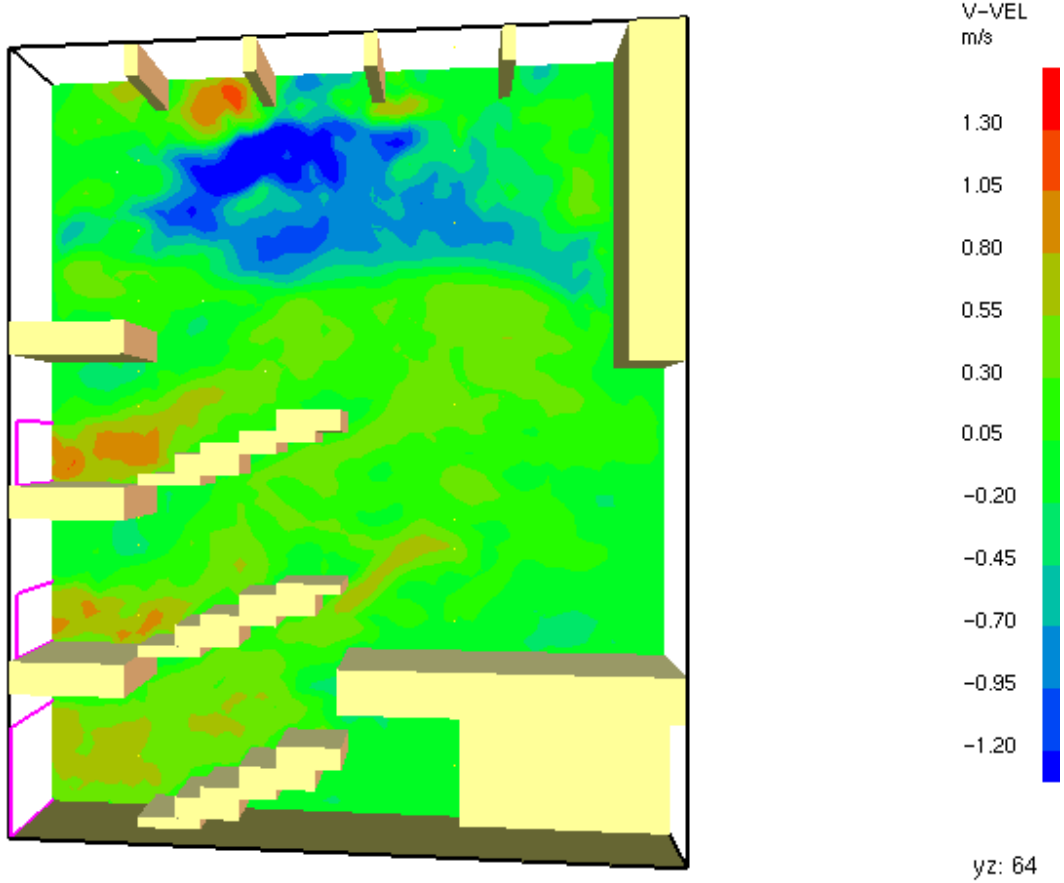


# FDS Results: Temperature

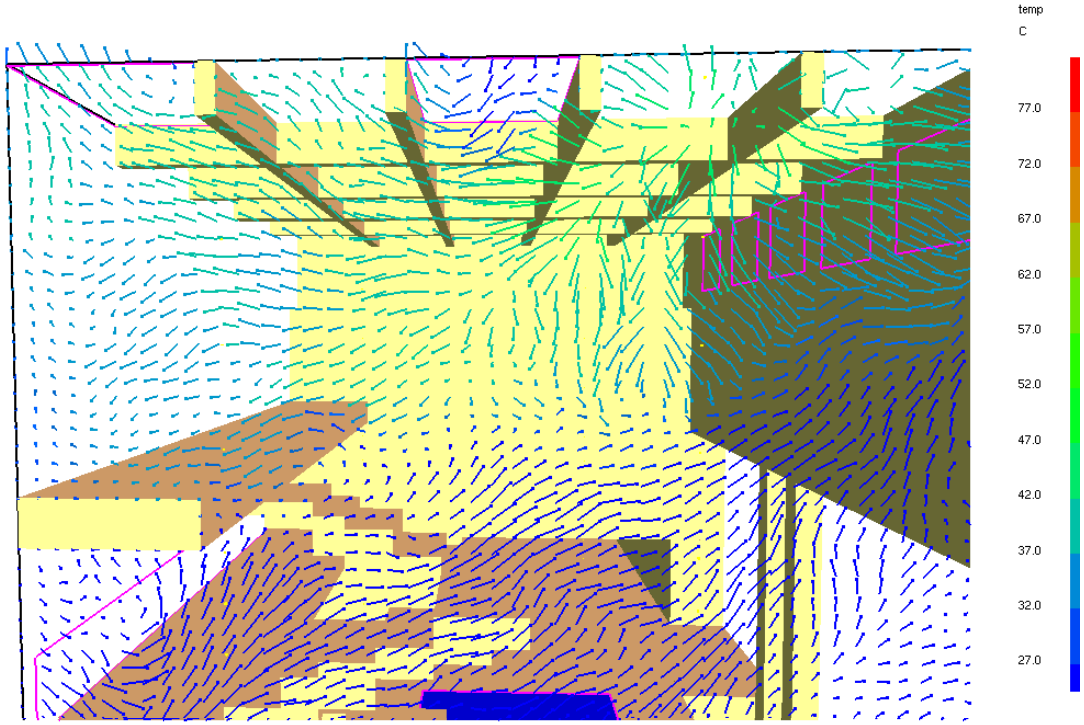
**Not acceptable**



# FDS Results: Speed Contours



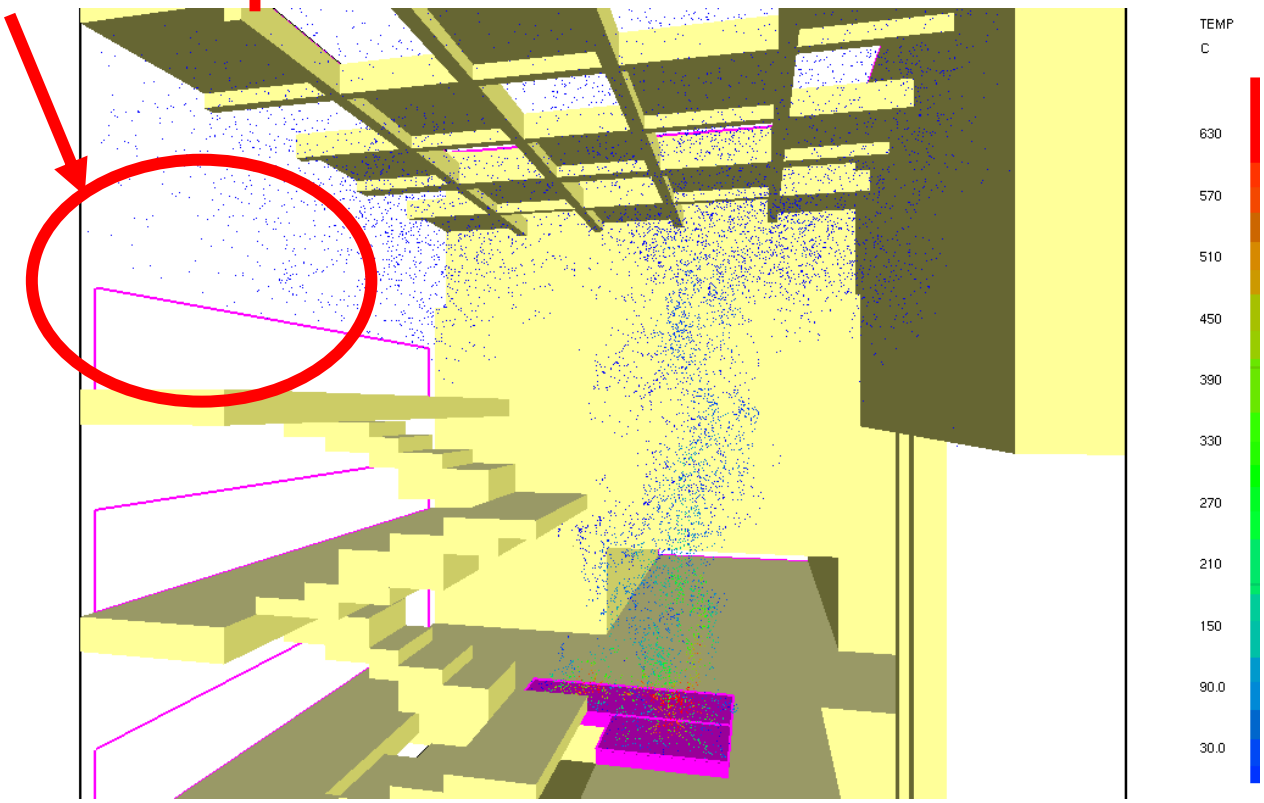
# FDS Results: Case 5: 300,000 cfm out north wall by mechanical exhaust & 1000 sq ft natural ventilation in ceiling; 5275 kW fire



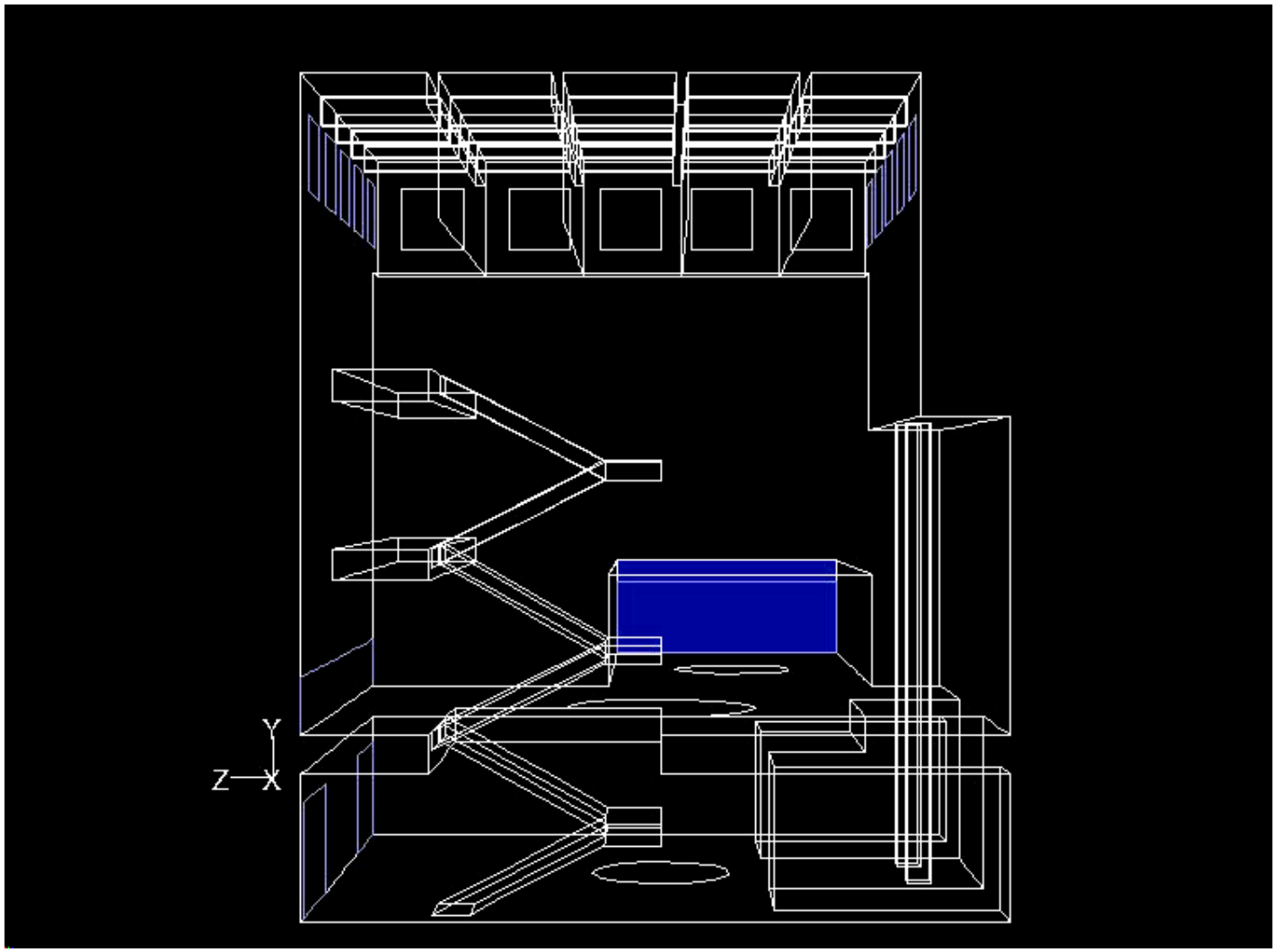

Flow vectors, east wall: t= 120 sec.

# FDS Results: Smoke Particles

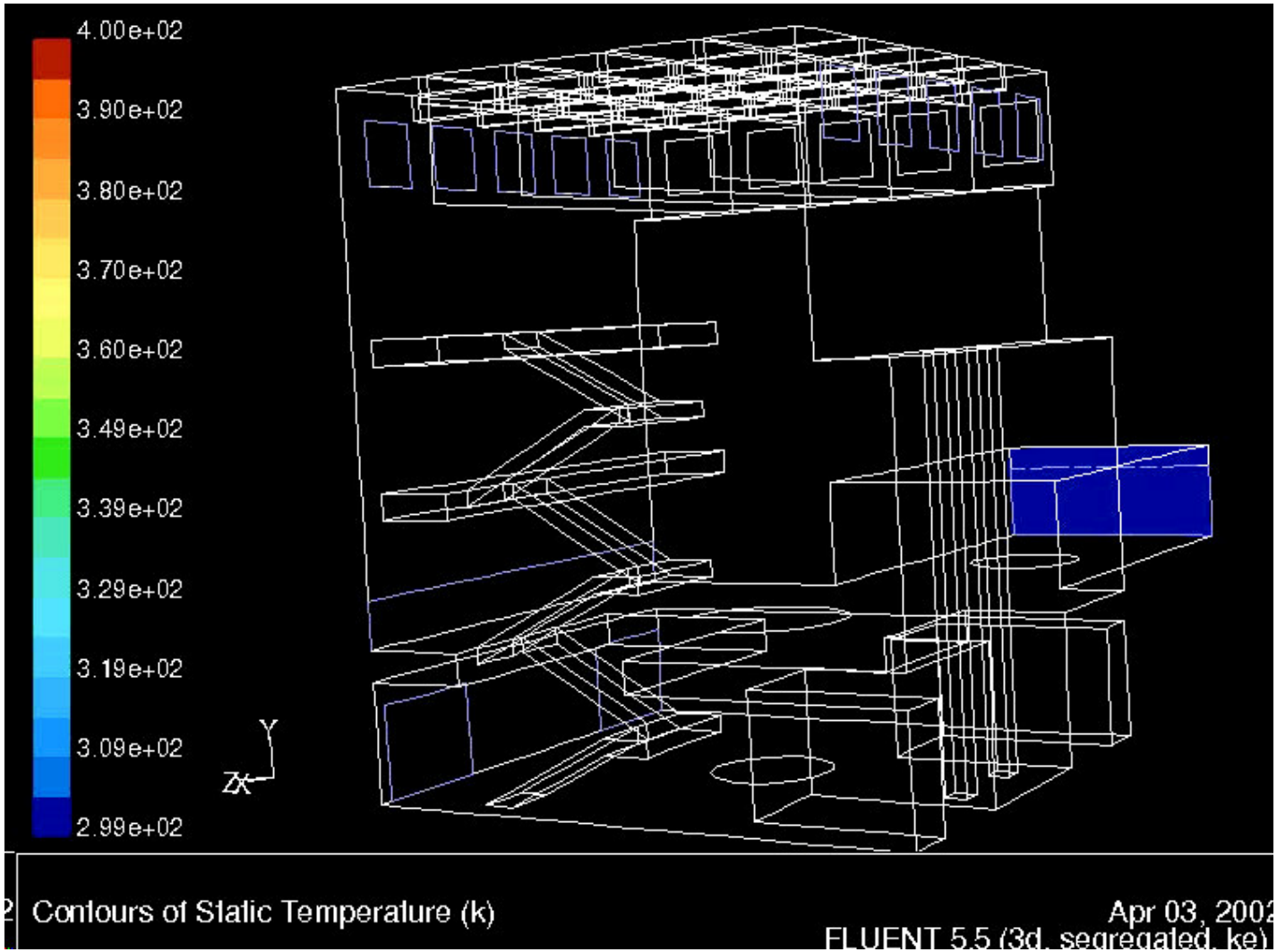
**Not acceptable**



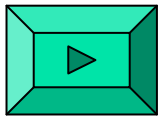
# Ceiling Curtains: Fluent



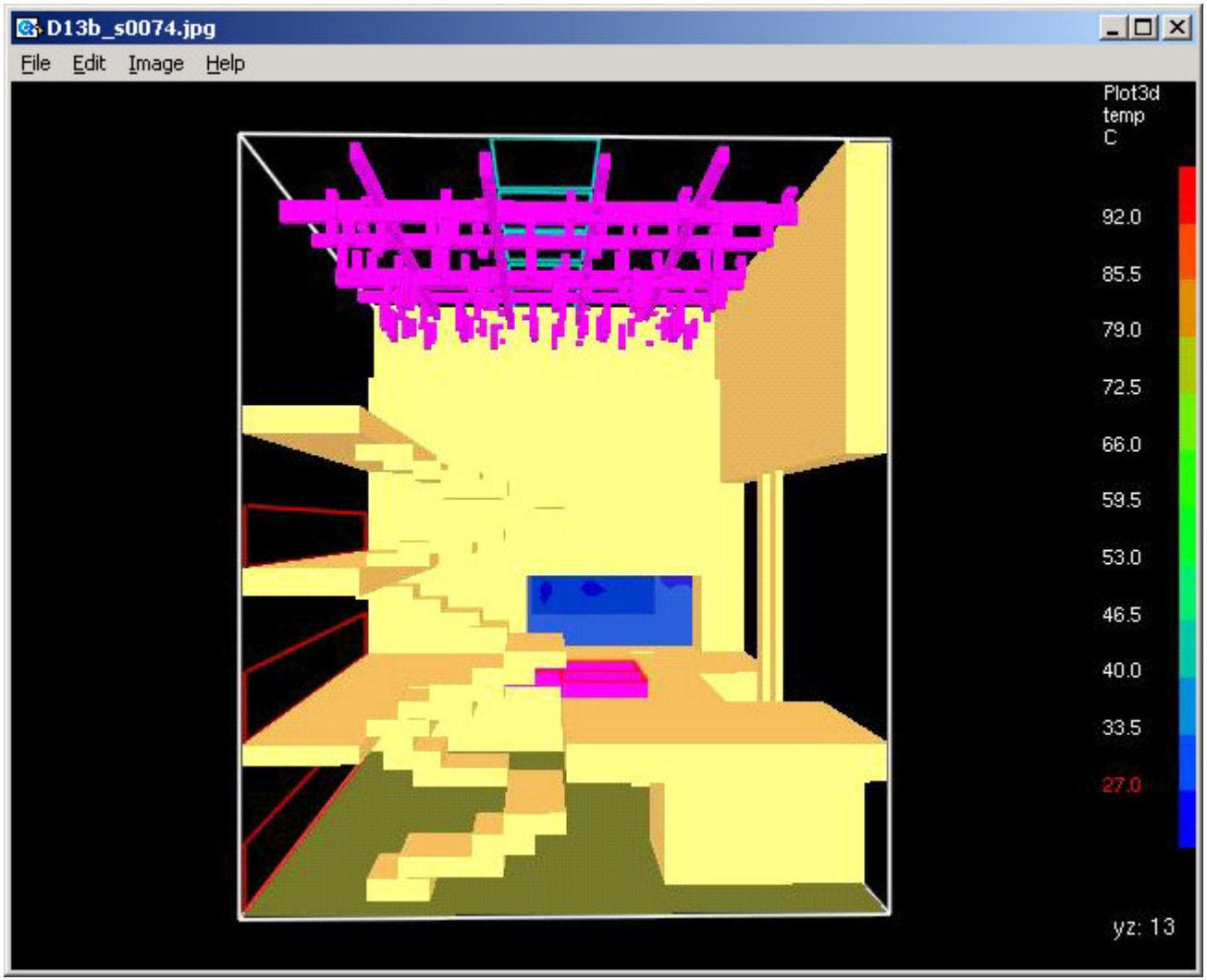
# Ceiling Curtains: Fluent



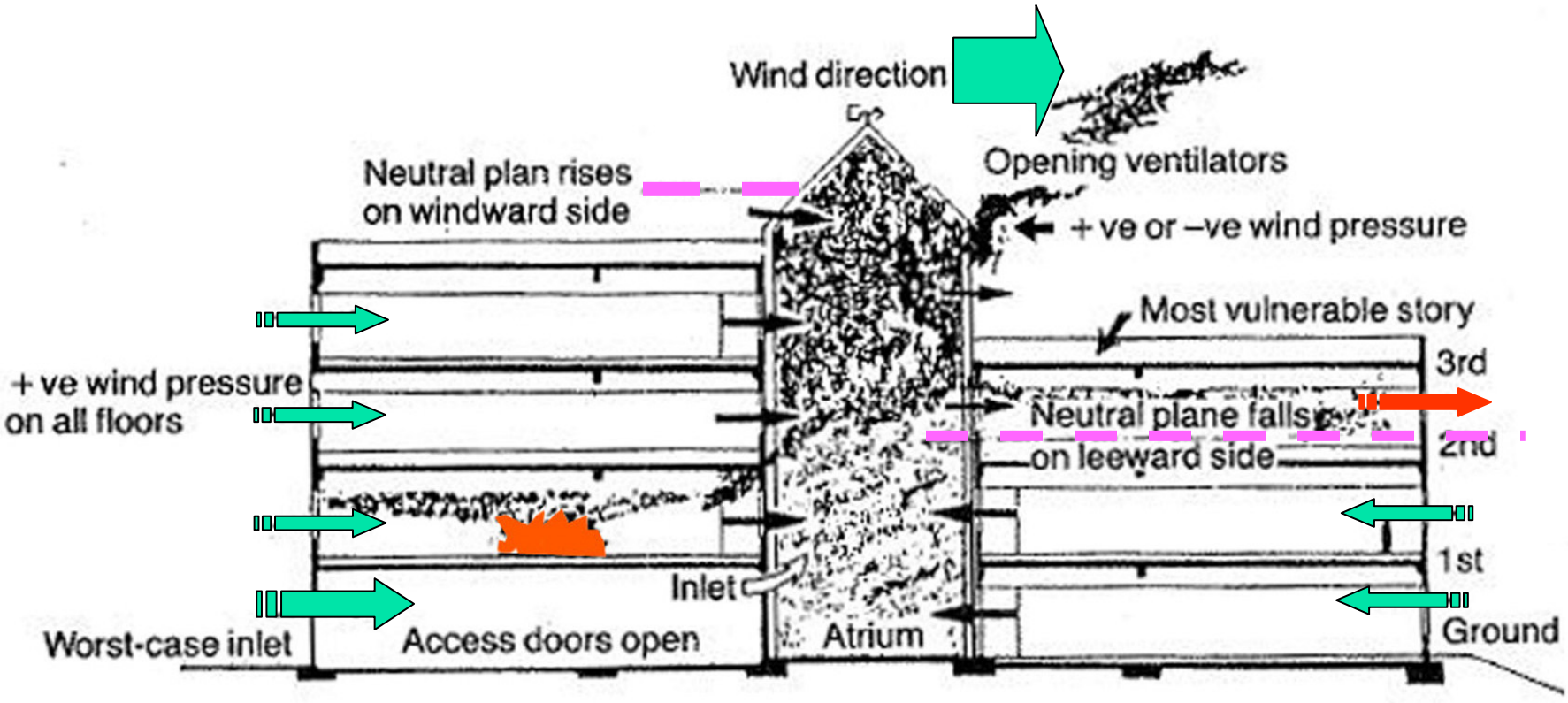
# Ceiling Curtains: FDS



t = 100 sec



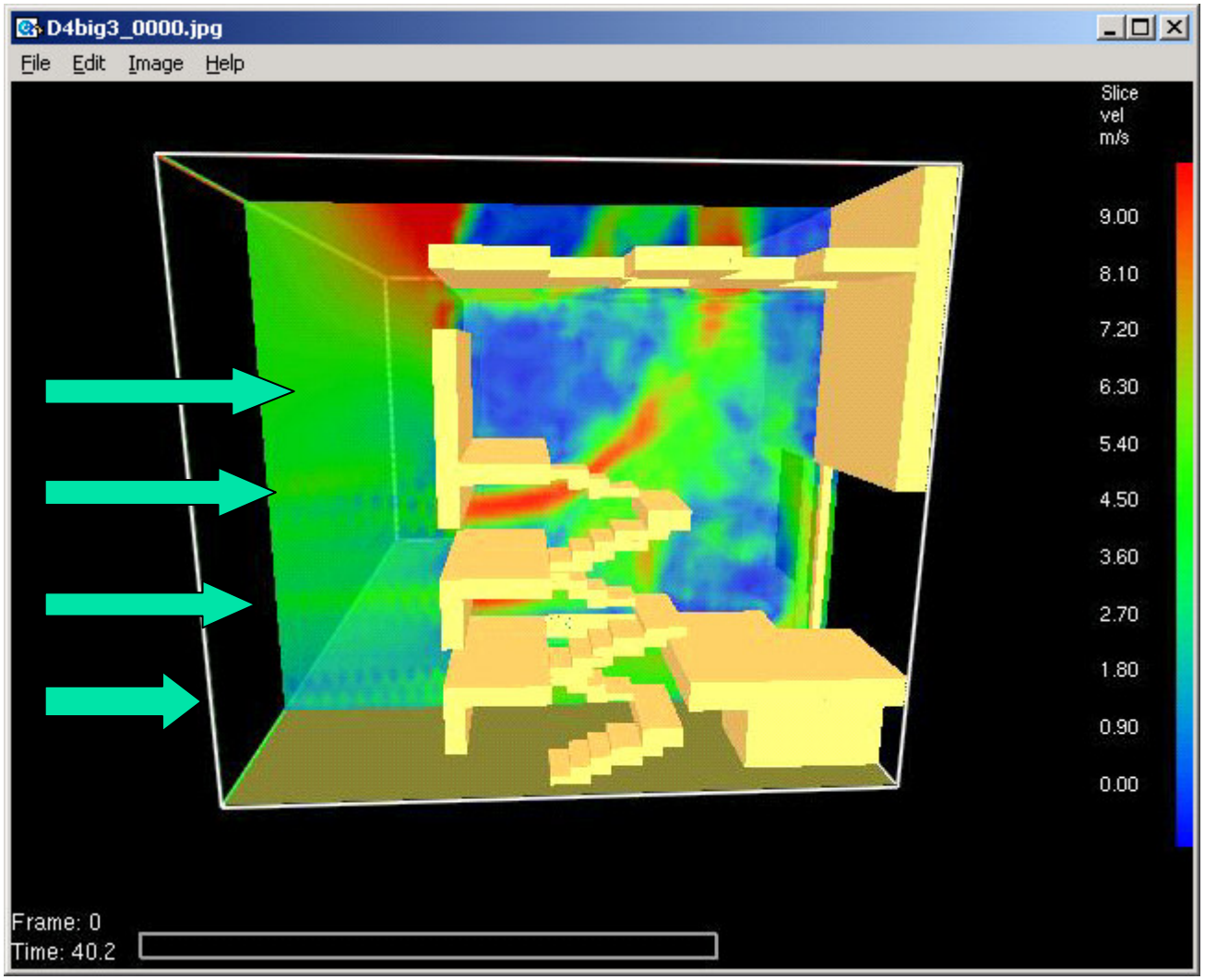
# Wind Effects on Smoke



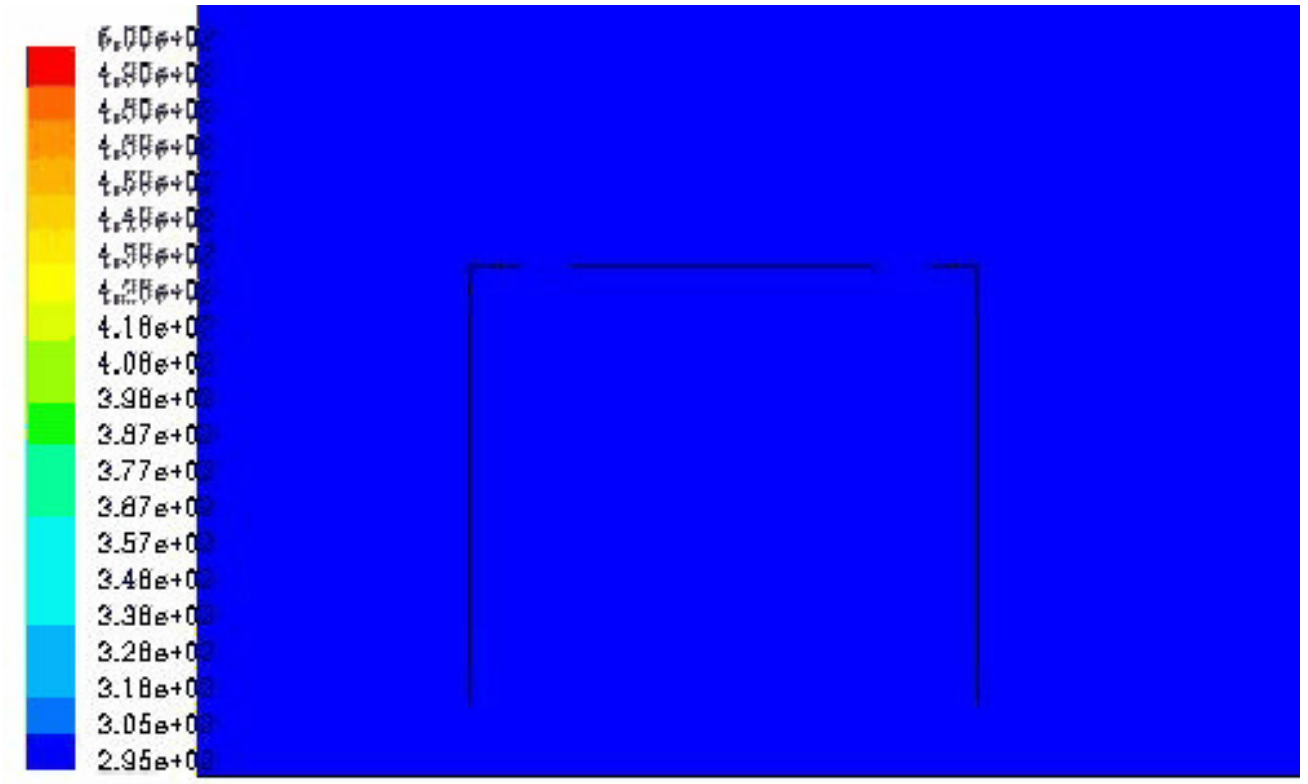

Wind-induced failure of design.

**Hansell, 1988**

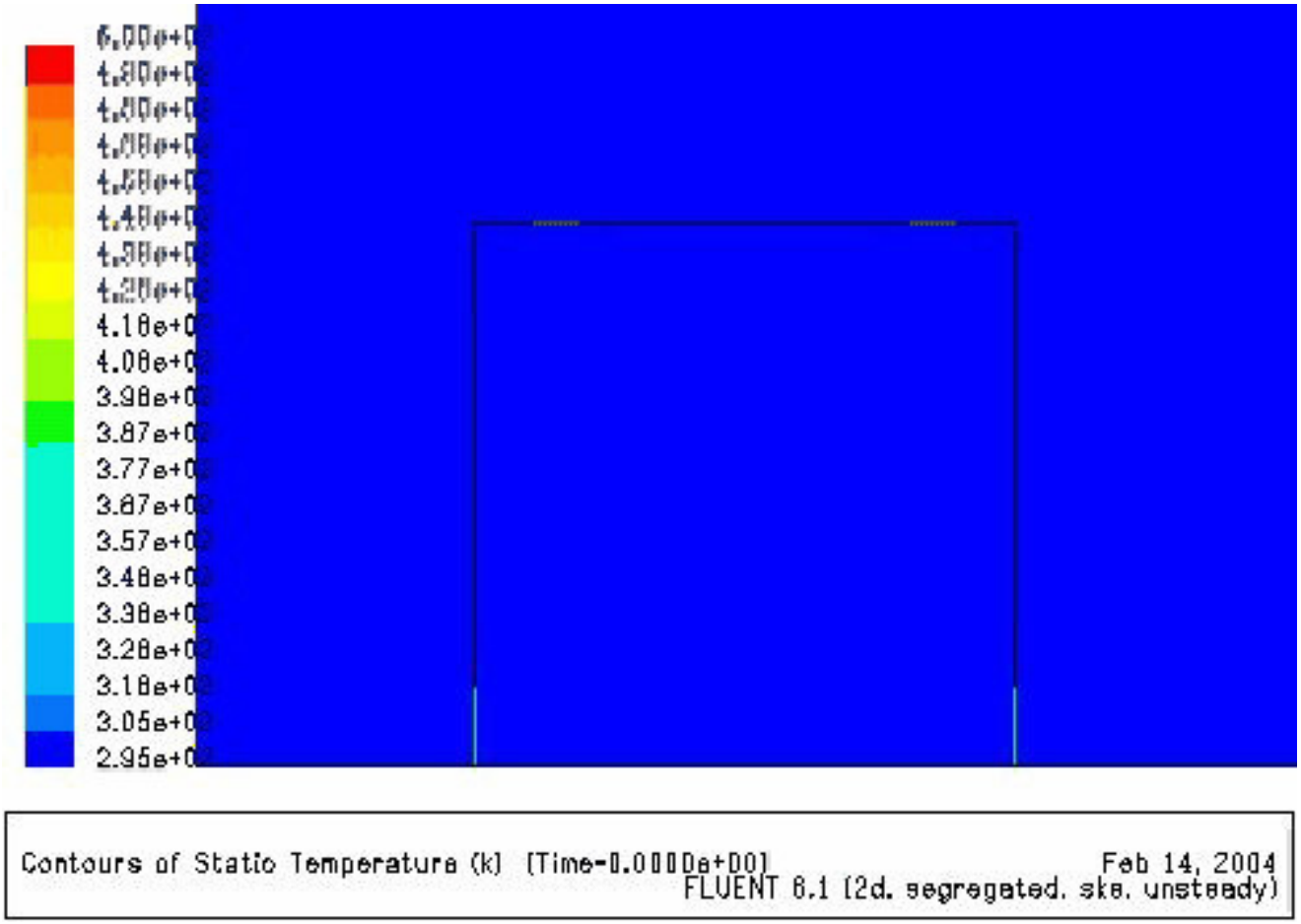
# Cross Wind Effects: FDS



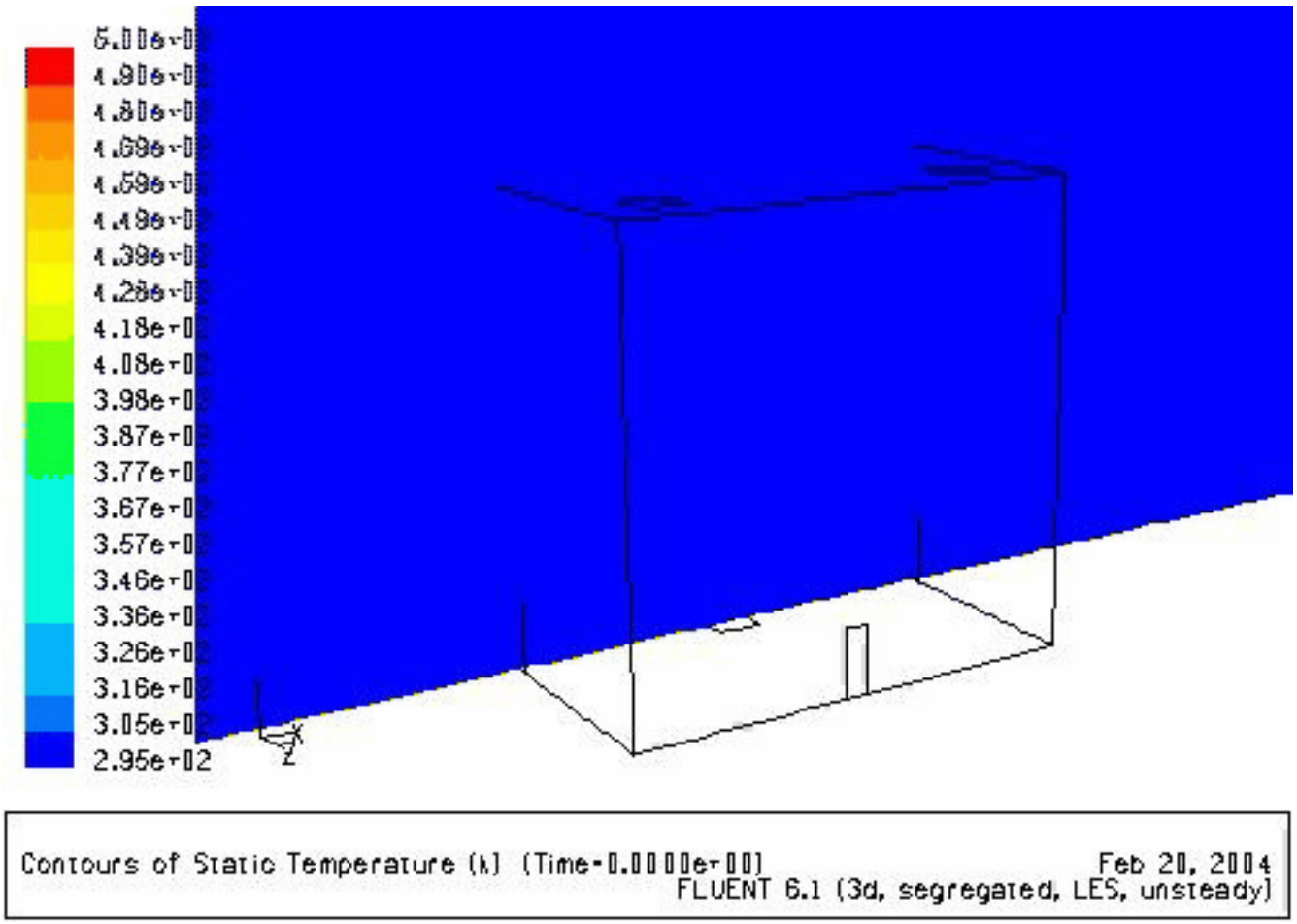
# Wind effects on generic 2d building
# No wind



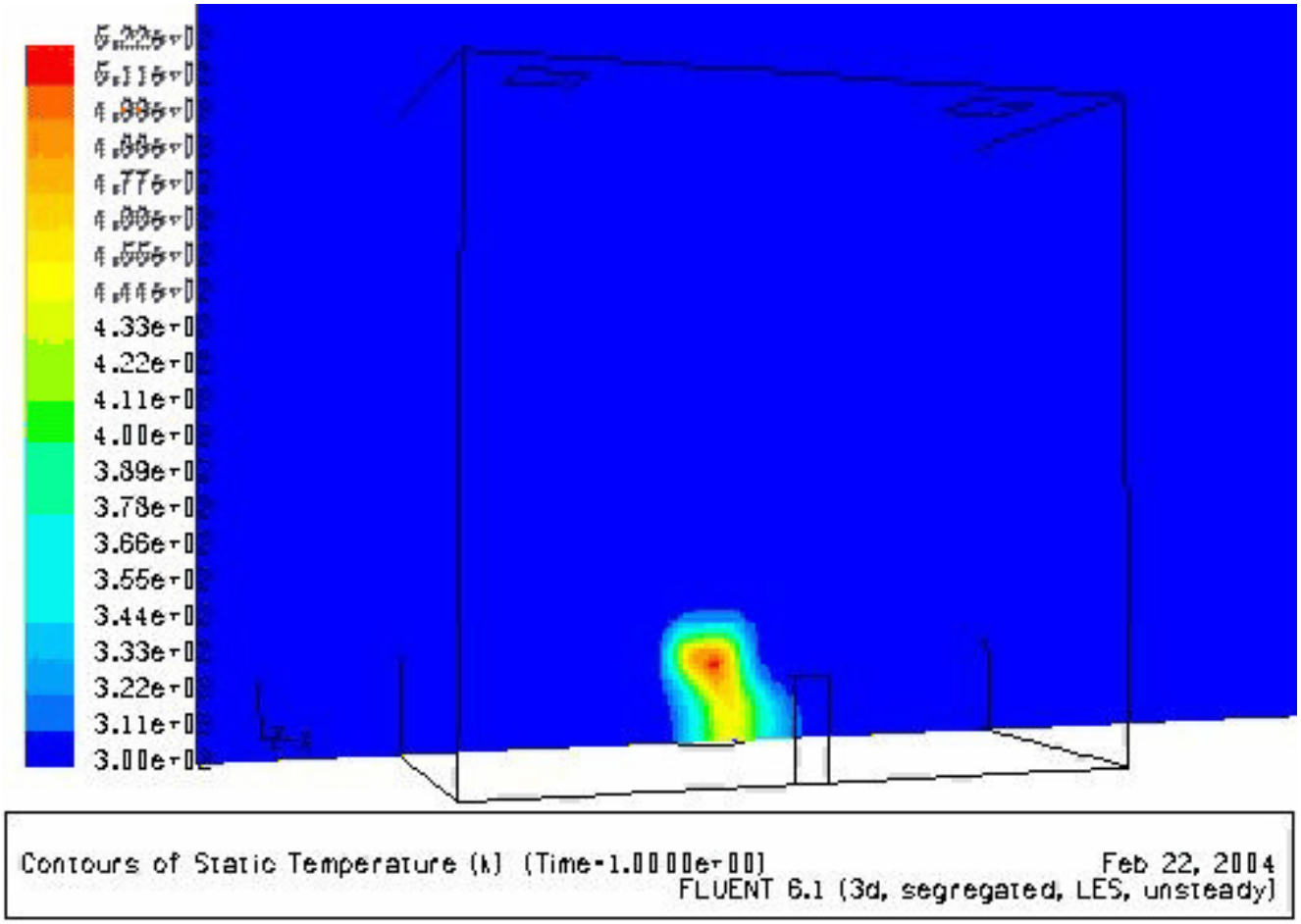
# Wind effects on generic 2d building
# Wind from left at U= 1m/s



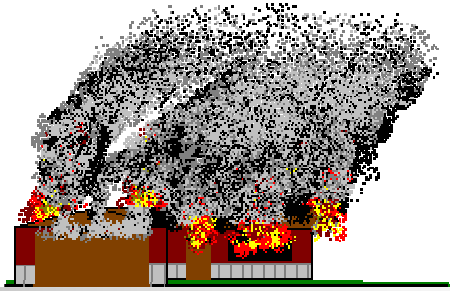
# Wind effects on generic 3d building
# No wind



# Wind effects on generic 3d building
# Wind from left at U= 2m/s



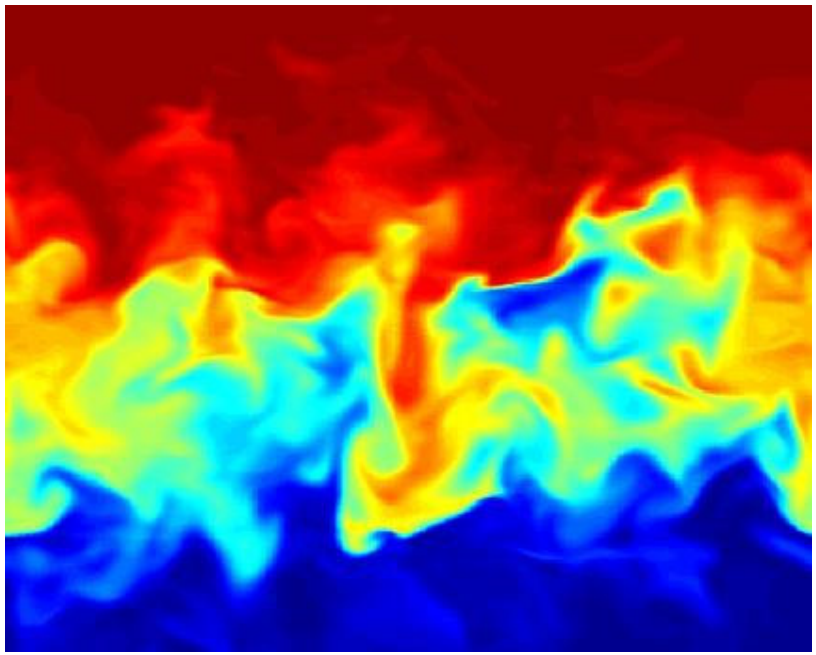
# Summary



- ASMET calculations suggest an exhaust rate of 200,000 cfm limits descent of smoke to regions 10 ft above any walking surface.
- But FLUENT steady state calculations suggest smoke plumes will descend below top walkway due to impingement of plume against ceiling and deflection downward by side walls.
- FDS unsteady calculations confirmed problem.
- Hanging porous curtains across the ceiling appears to mitigate the problem.
- Exterior winds which produce lateral jets through wall inlets can significantly alter the trajectory of plumes within the atrium itself and may complicate situation further.

# What we can't do yet for fires.

- Modeling over scales from molecular to building size to include flame dynamics ~$10^9$ length scale ratio range
- DNS simulation of mixing at molecular scales - S. M. de Bruyn Kops and J. J. Riley (2000).



# The End: Thank you for your attention

For good building health schedule
an annual appointment with the

Wind Doctors