Virtual Fires via Computers

Robert N. Meroney
Wind Engineering Software
Wind Engineering and Fluid Mechanics
Colorado State University

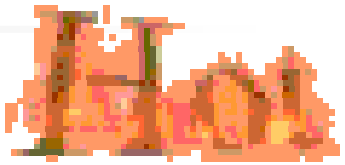
Introduction

- Fire Statistics
- Rational Analysis and Fire Prediction Tools
  - Algebraic equations
  - Scale or Physical Modeling
  - Network Modeling for Pressurized Systems
  - CFAST (Consolidated Model of Fire Growth and Smoke Transport)
  - FDS (Fire Dynamic Simulator)
- Example calculation

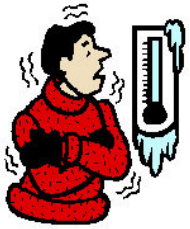
Costs of Fire to the USA

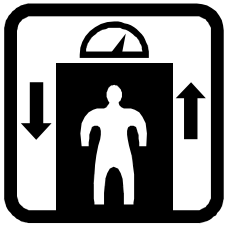
- America's fire death rate is one of the highest per capita in the industrialized world.
- Fire kills over 4,000 and injures more than 23,000 people each year.
- Firefighters pay a high price for this terrible fire record as well; approximately 100 firefighters die in the line of duty each year.
- Direct property losses due to fire exceed $13 billion a year.
- Most of these deaths and losses can be prevented!

Rational Analysis



- 2006 IBC code requires consideration of specific effects on smoke control operation
  - Stack or buoyancy effects
  - Characteristics of design fire
  - Wind effects
  - HVAC system
  - Climate
  - Room to room and floor to floor variations
  - Elevator and stairwell effects
  - System activation sequence

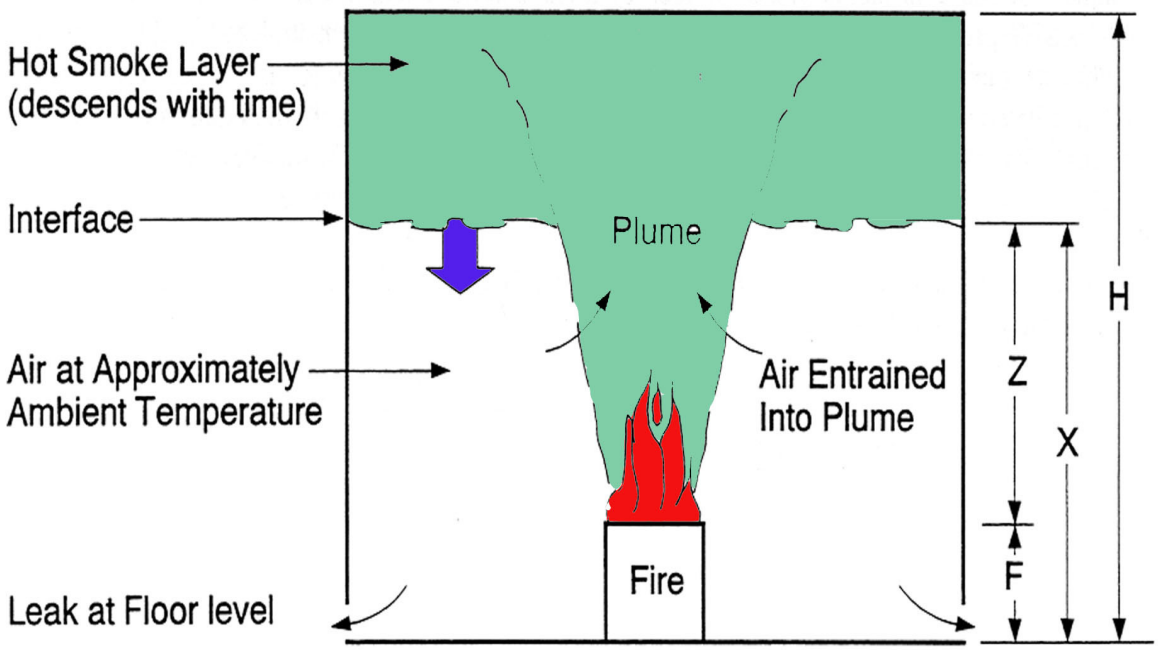


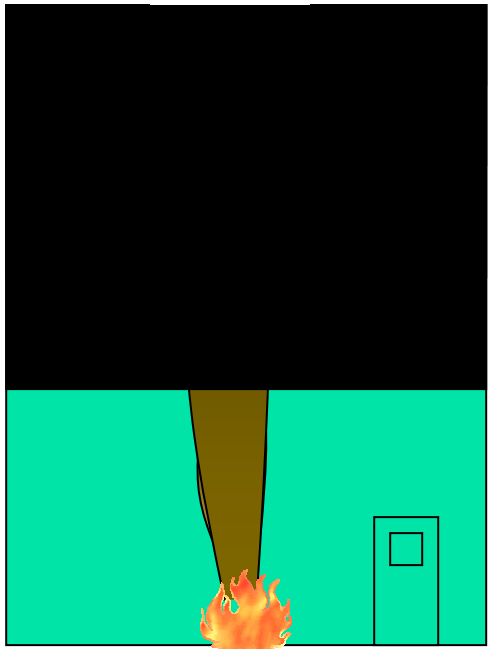


Rational Analysis Methods

- Algebraic equations
  - ASMET or ASETC

$$\frac{z}{H} = 0.67 - 0.28 \ln\left(\frac{tQ^{1/3} / H^{4/3}}{A / H^{2}}\right)$$





Rational Analysis Methods

- Algebraic equations
  - ASMET or ASETC
- Scale modeling

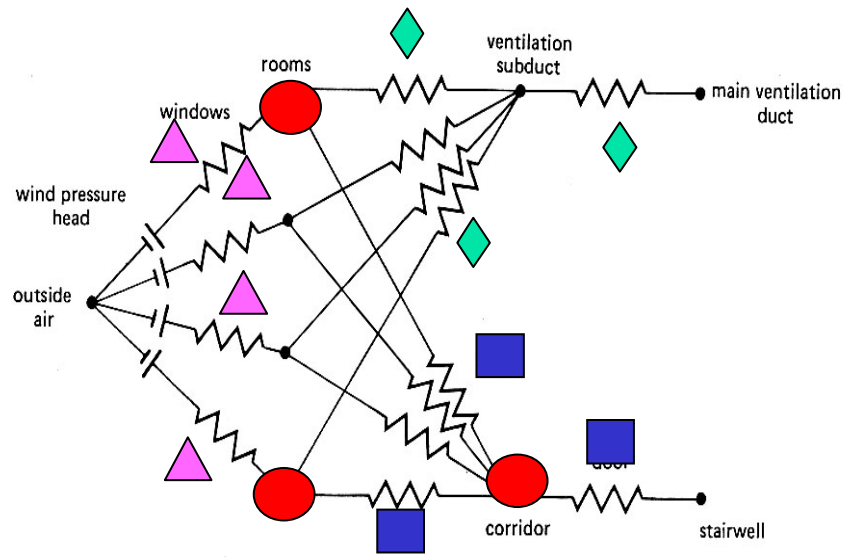
NIST 4-story stairway fire model

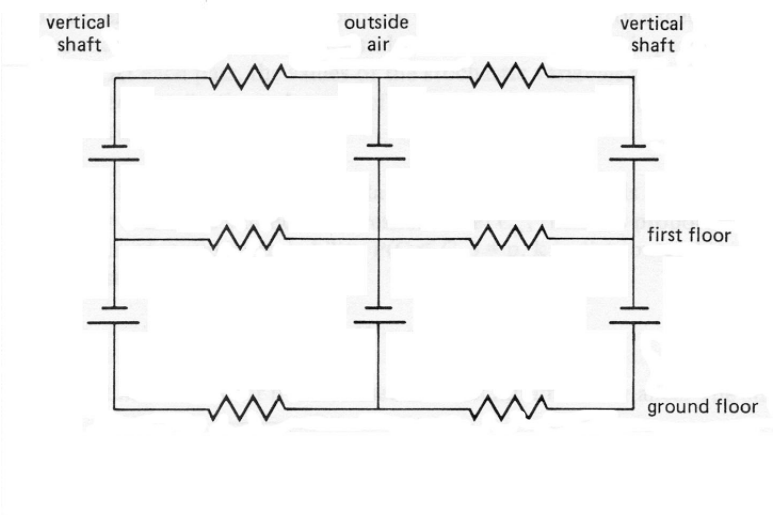
Before fire

During fire

Rational Analysis Methods

- Algebraic equations
  - ASMET or ASETC
- Scale modeling
- Node and network modeling
  - CONTAM

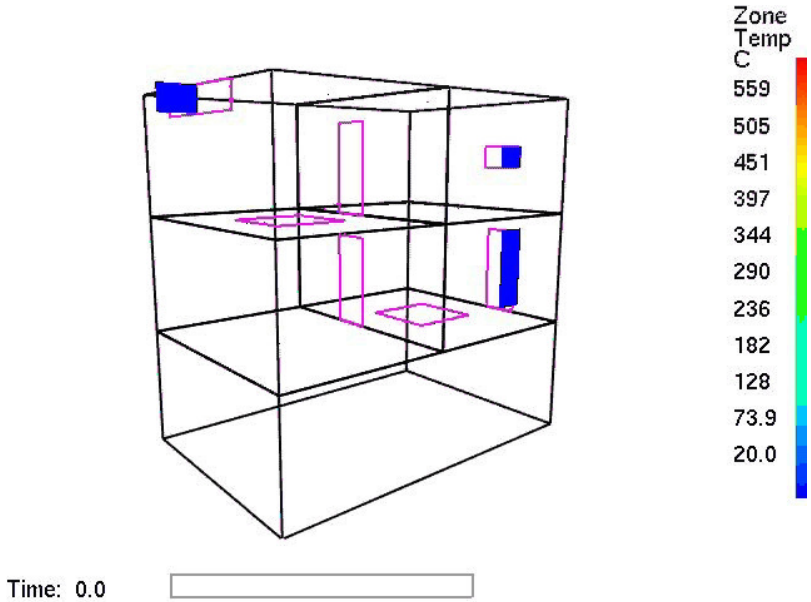




Vents
Windows
Doors
Rooms

Rational Analysis Methods

- Algebraic equations
  - ASMET or ASETC
- Scale modeling
- Node and network modeling
  - CONTAM
- Zone Models
  - CFAST



Why CFAST?

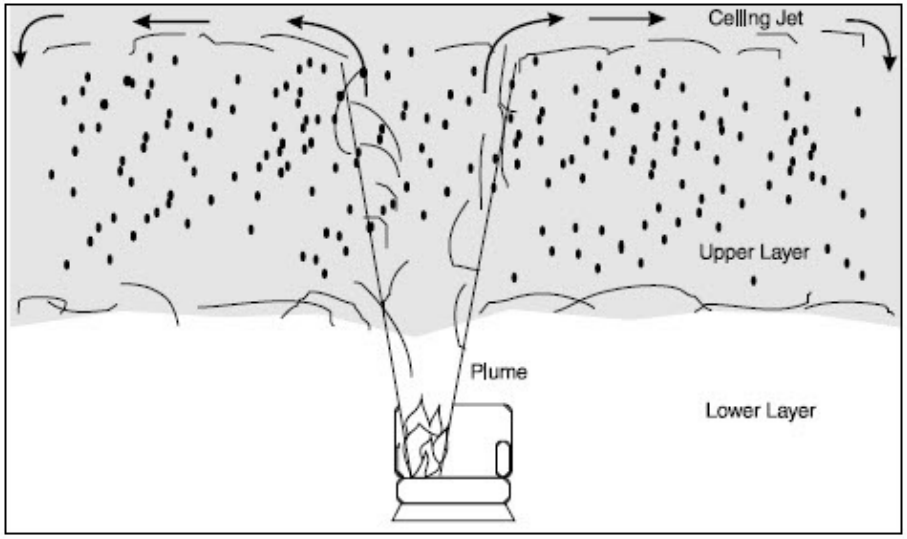
- Program specifically designed for unsteady fire simulation in compartments.
- Program designed for fast execution.

How did they do it?

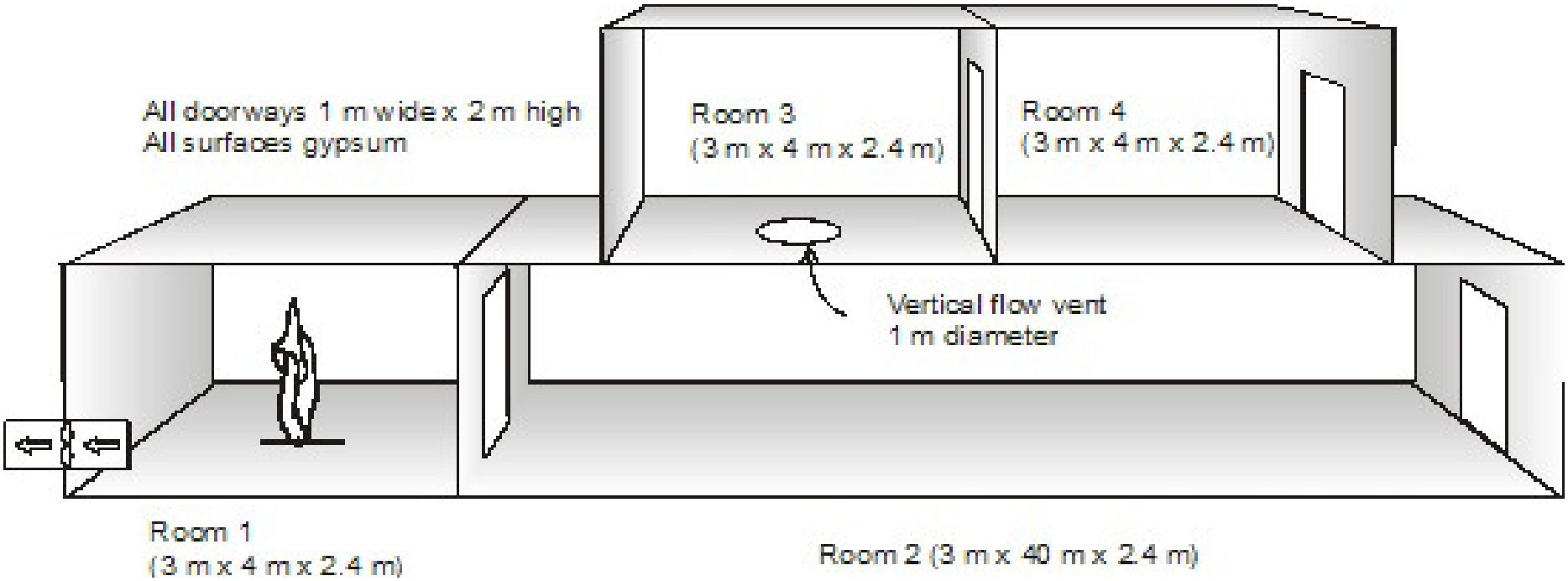
- Focus on the simplicity of the problem,
- Extensively use experimental data, and
- Focus on solving sets of ordinary differential equations (ODE).

Recognize simplicity of problem

- Divide flow regime into distinct zones (2 to 4),
- Assume flow within zones are well mixed,
- Replace complex processes with empirical algorithms.

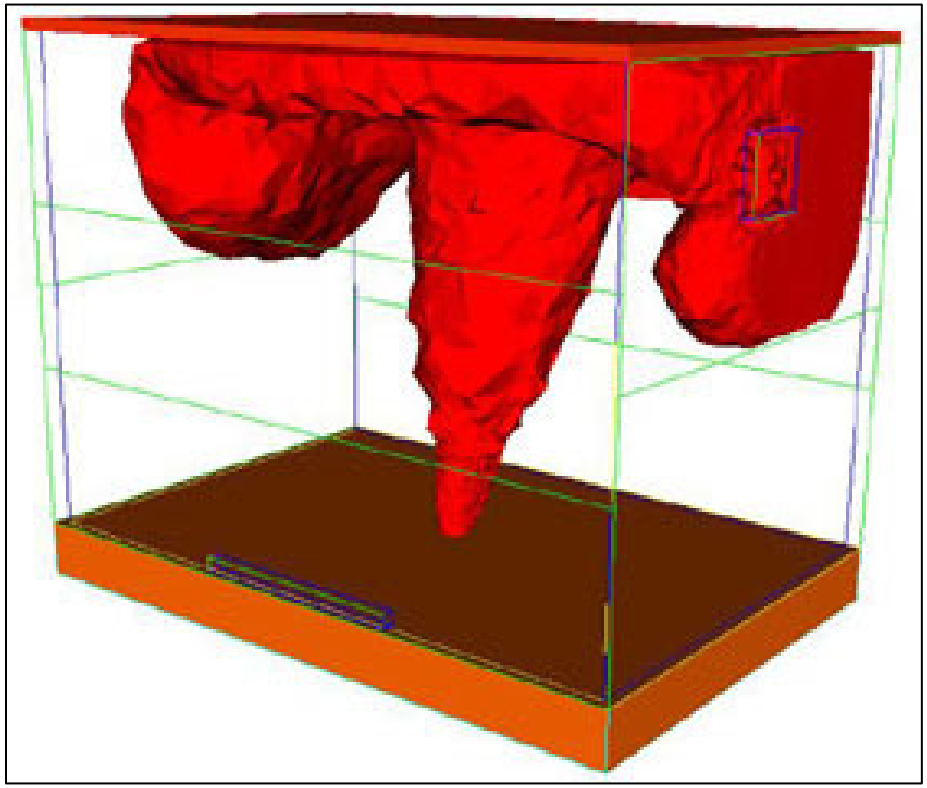


Typical Building Geometry



Simplify physical processes

- Assume few zones per compartment is adequate to model physical situation,
- Solve for conservation of mass and energy over zone,
- Momentum equation only solved through Bernoulli equation for vent flows.
  - This eliminates acoustic waves and gravity waves.

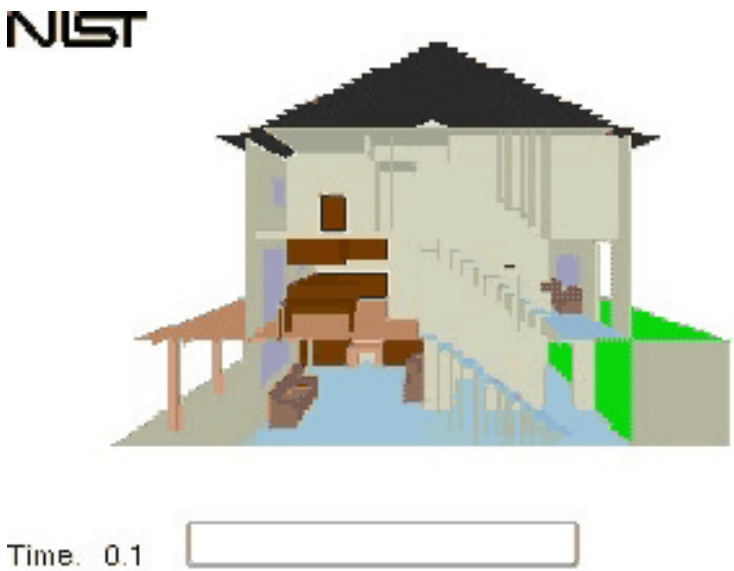


Focus on very fast numerical solvers

- Equations formed by integrating conservation expressions over volume of zone, resulting in ODE,
- Solve sets of coupled ODE, no finite difference expressions,
- Use algebraic algorithms to describe fire processes,

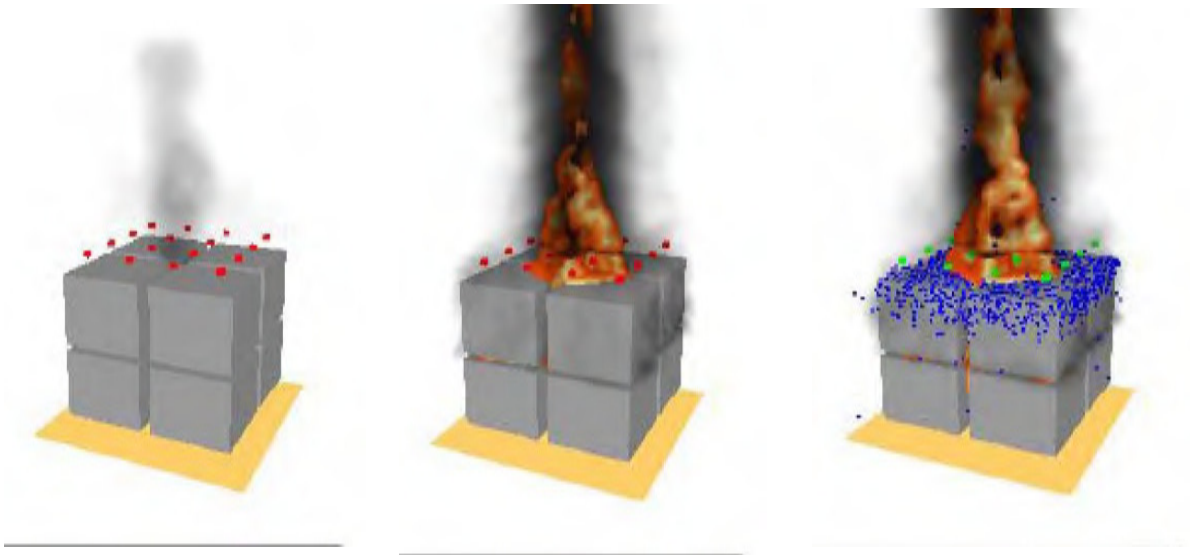
Rational Analysis Methods

- Algebraic equations
  - ASMET or ASETC
- Scale modeling
- Node and network modeling
  - CONTAM
- Zone Models
  - CFAST
- CFD Models
  - FDS



Why FDS?

- Program specifically designed for unsteady fire simulation.
- Program designed for fast execution.



How did they do it?

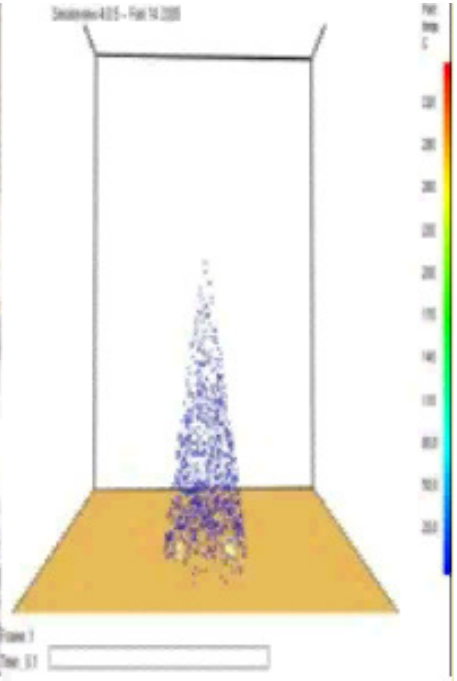
- Recognize the complexity of the problem,
- Simplify physical processes, and
- Focus on very fast numerical solvers.

Recognize complexity of problem

- Bluff body aerodynamics,
- Multi-phase flow, (liquid or solid fuels, gaseous products)
- Turbulent mixing and combustion,
  - Ignition,
  - Pyrolysis,
  - Homogeneous and heterogeneous combustion possibilities,
- Radiative heat transfer, and
- Conjugate heat transfer (conduction & convection together).

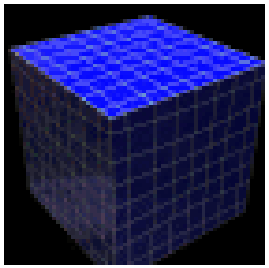
Simplify physical processes

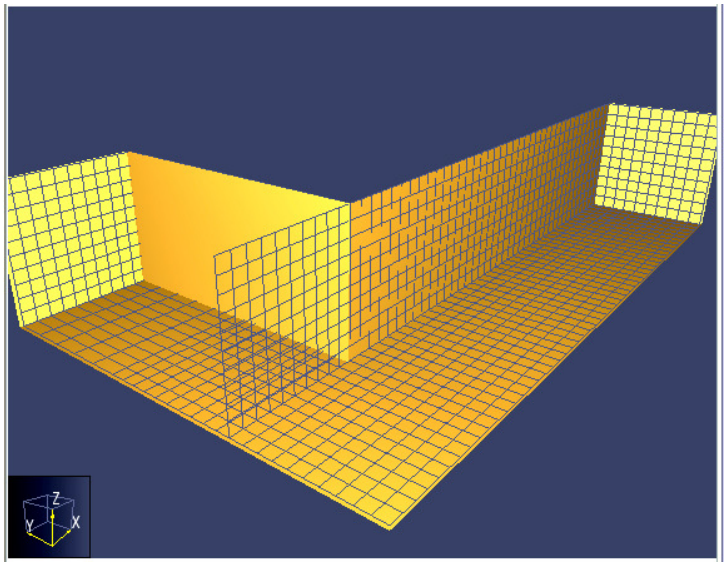
- Use LES (Large Eddy Simulation) approximation for turbulence,
- Use “low-Mach number” combustion equations,
- Divide continuum of physical space where fire flow occurs into a finite number of rectangular cells, inside of which all flow properties are uniform and change only with time, and
- Approximate complicated processes with “adequate” algorithms.



Focus on very fast numerical solvers

- Use a one step non-iterative method to invert Poisson equation associated with fluid pressures, which requires that one
- Limit grids to rectangular cells and rectangular grids.





CFAST vs FDS Comparison

- NUREG-1824 (2006), Vol. 1, 4, & 6
- Criterion 1 – Are the physics of the model appropriate for the calculation being made?
- Criterion 2 – Are there calculated relative differences outside the experimental uncertainty?
- Color Code for Criteria

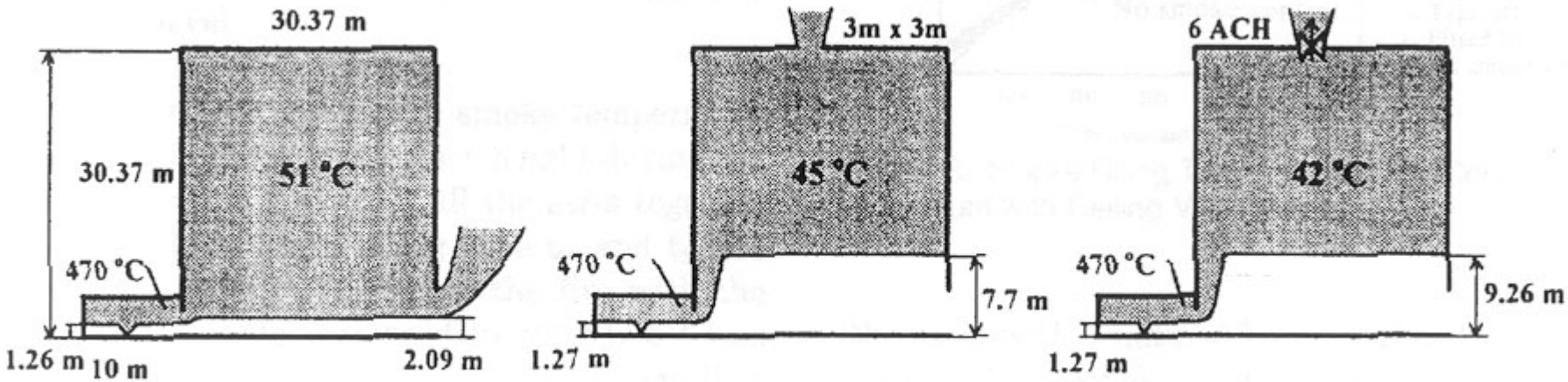
Green	: Both criteria are satisfied, model can be used with confidence
Yellow	: 1st criterion is satisfied, but differences are outside experimental uncertainty with no pattern of over- or under-prediction.
Red	: 1st criterion is not satisfied.

Parameter		Fire Model	
		CFAST	FDS
Hot gas layer temperature ("Upper Layer Temperature")	Room of origin	Green	Green
	Adjacent room	Yellow ±30%	Green
Hot gas layer height ("Layer interface height")		Green	Green
Ceiling jet temperature ("Target/Gas temperature')		Yellow -16 to +100%	Yellow ±20%
Plume temperature		Not calculated	Green
Flame Height		Green	Yellow [1]
Oxygen concentration		Yellow ±20%	Yellow ±20%
Smoke Concentration		Yellow-35 to +450%	Yellow -33to +400%
Room pressure		Green	Green
Target temperature		Yellow ±50%	Yellow ±30%
Radiant heat flux		Yellow-50 to +150%	Yellow ±50%
Total heat flux		Yellow -90 to +70%	Yellow ±30%
Wall temperature		Yellow ±60%	Yellow ±50%
Total heat flux to walls		Yellow -70 to +90%	Yellow ±30%

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



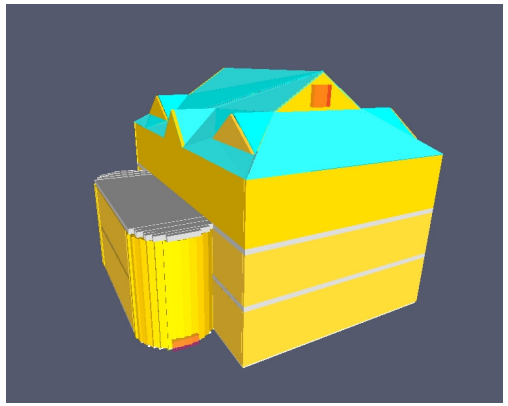
No Smoke Control
Smoke Filling

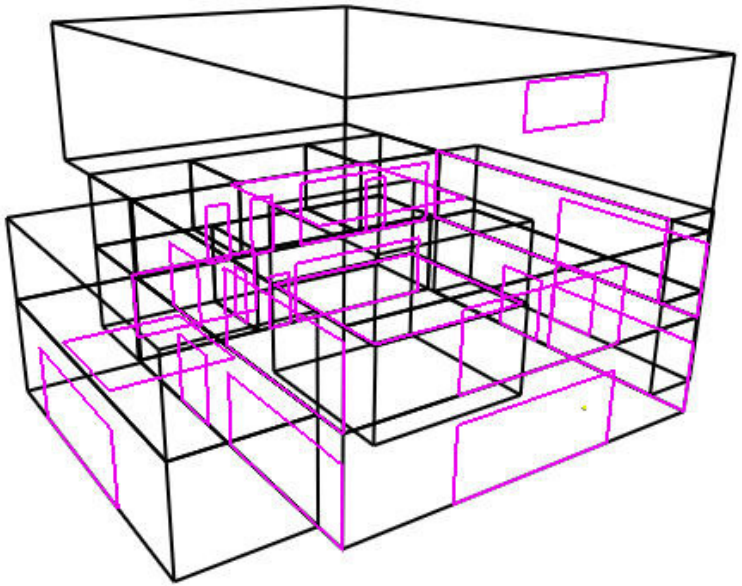
Natural Venting =
Gravity Venting

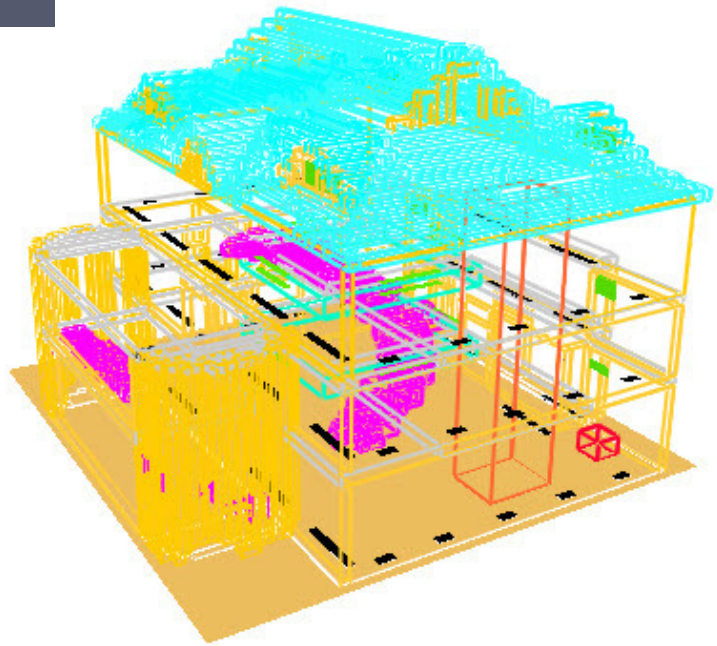
Forced Venting =
Smoke Exhaust

CFD & CFAST Simulation of a Three Story Building

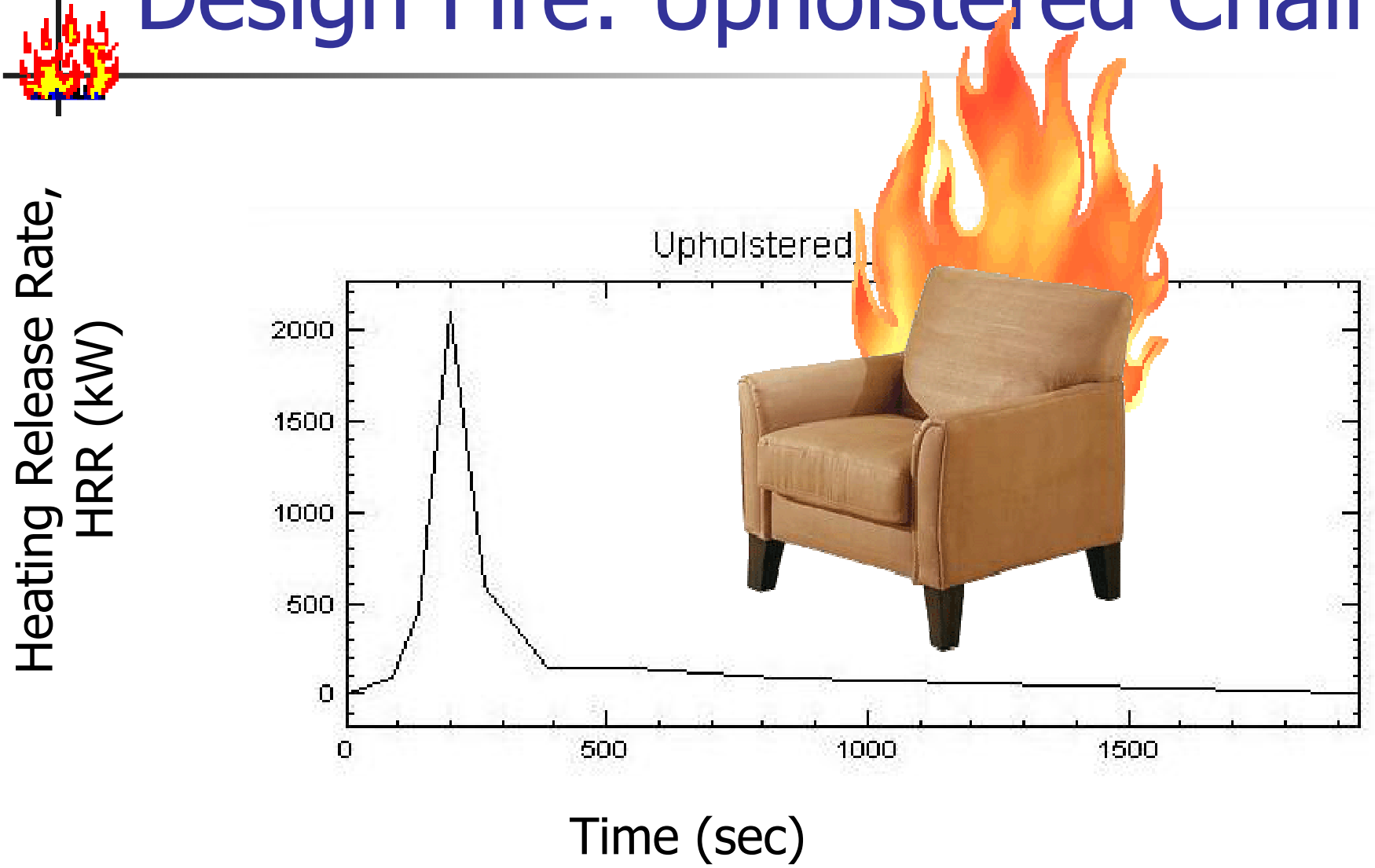
Test Building Configuration





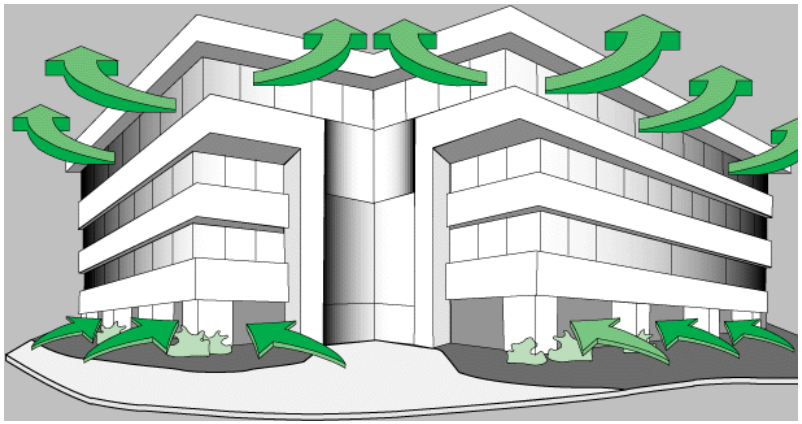


Design Fire: Upholstered Chair



Including Wind Field Results in CFAST

- User specifies wind speed and direction for CFAST at openings to calculate exterior pressures.
- These are used with empirical pressure coefficients to adjust inflow and exhaust rates through windows, doors, and vents.



C_D = opening discharge coefficient

C_V = Wind pressure and direction correction

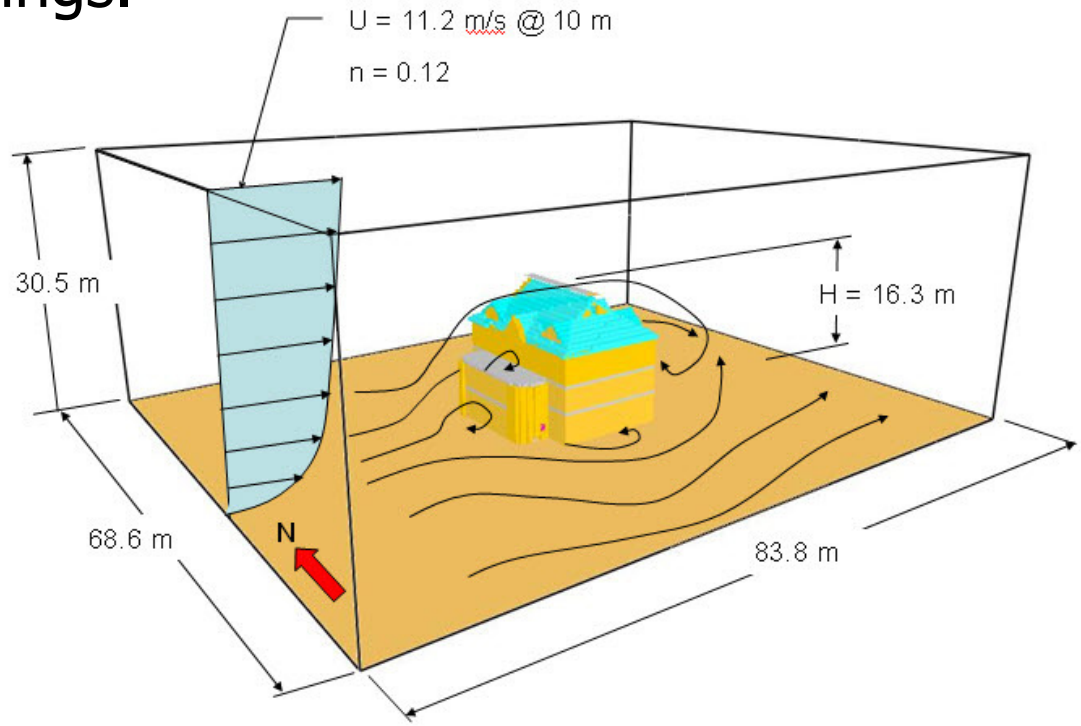
= 0.5 - 0.6 for perpendicular winds, and

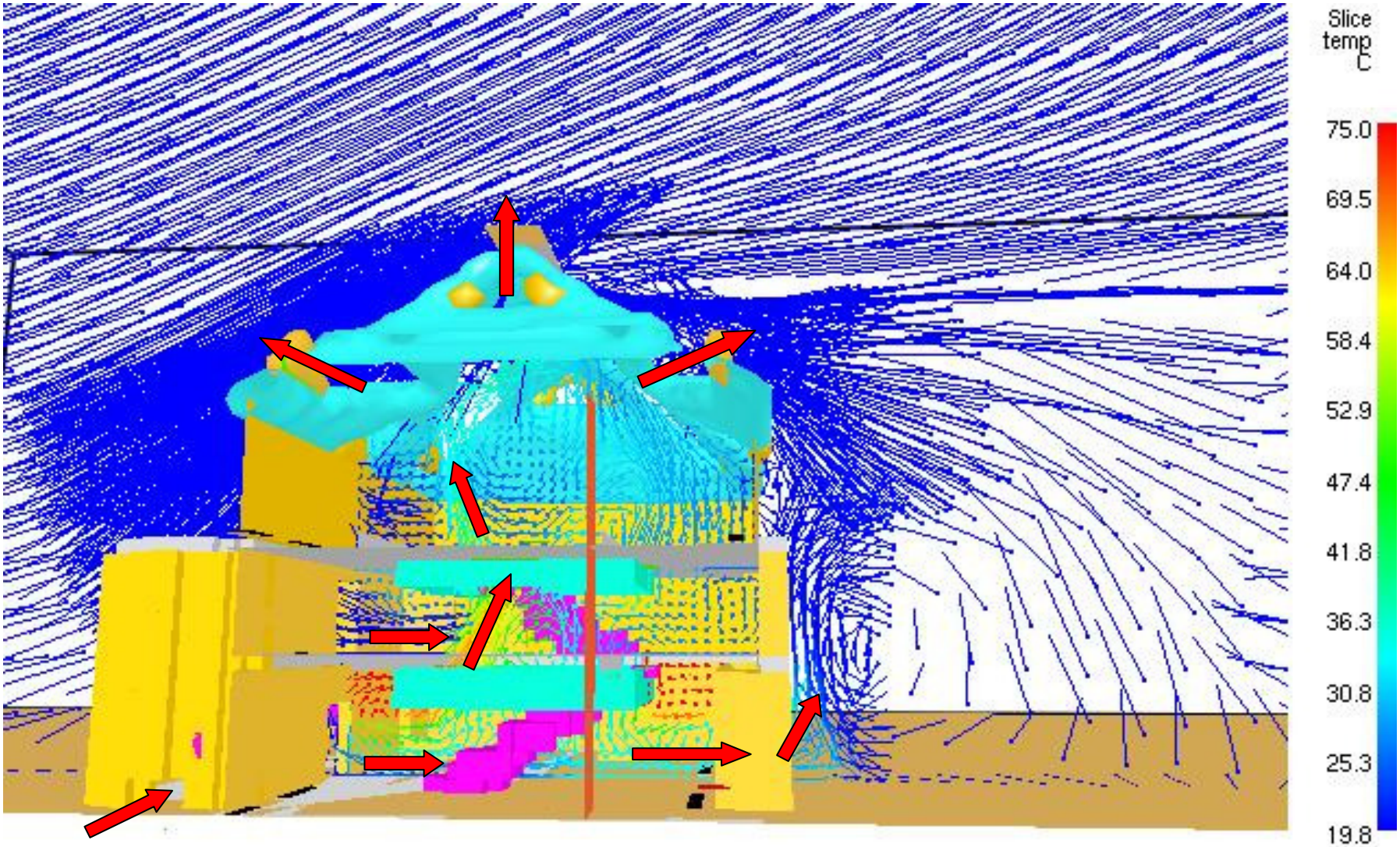
0.25 - 0.35 for oblique winds

$$Q = C_V C_D A \sqrt{\frac{\Delta p}{2\rho}}$$

Including Wind Field Results in FDS

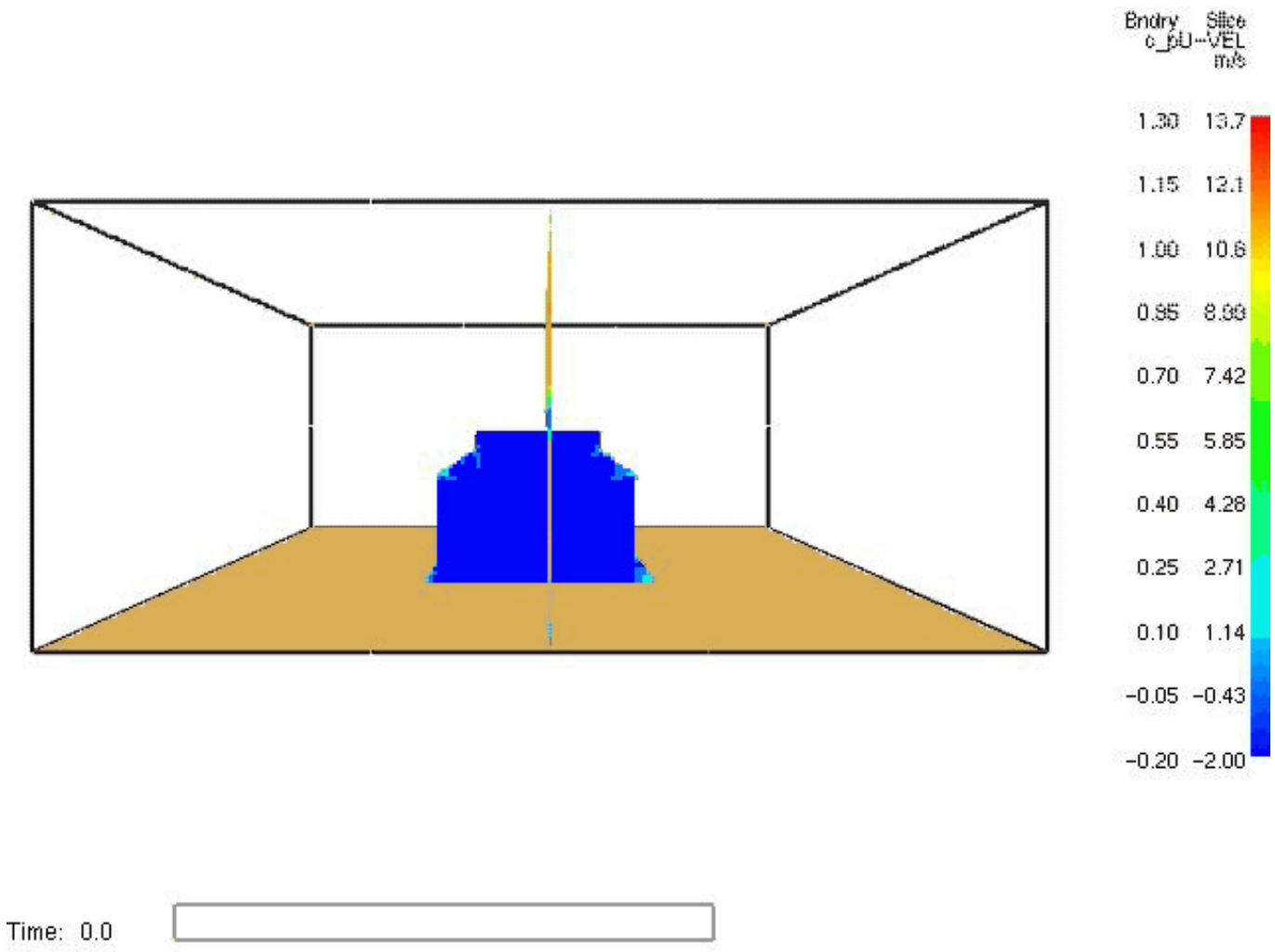
- FDS calculates explicitly the exterior flow fields, associated secondary flows and pressure fields.
- Interior flows are directly coupled to exterior through openings.



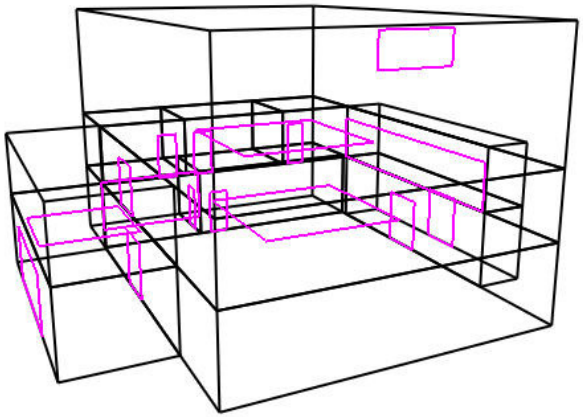


Time: 242.5

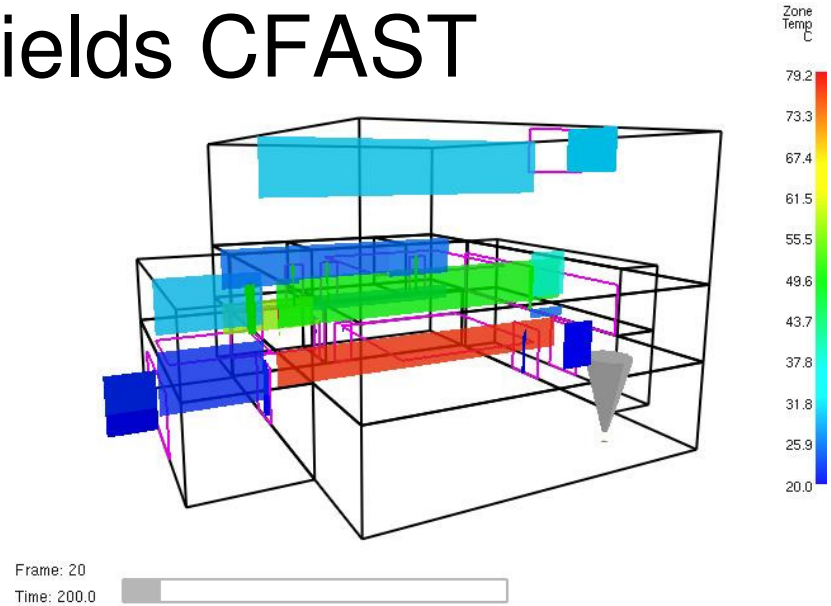
FDS Calculated Pressure Fields



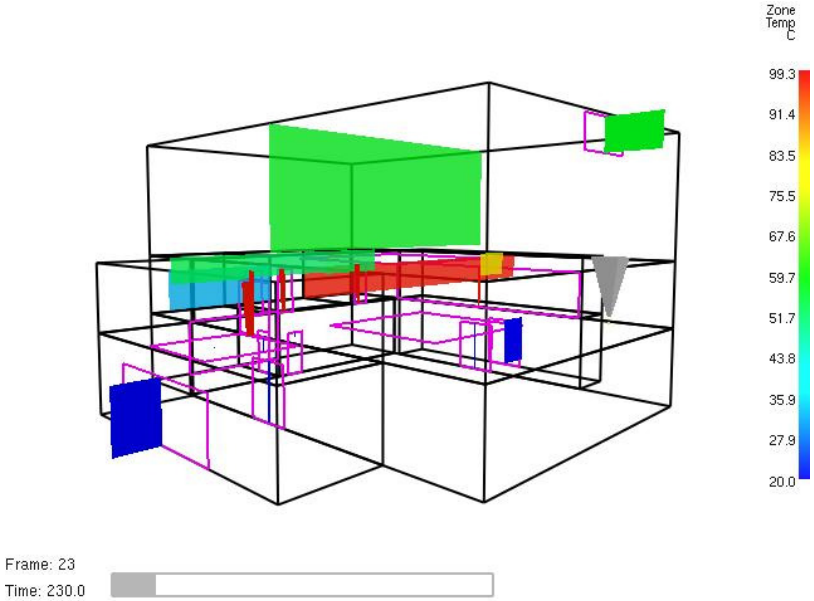
Temperature Fields CFAST



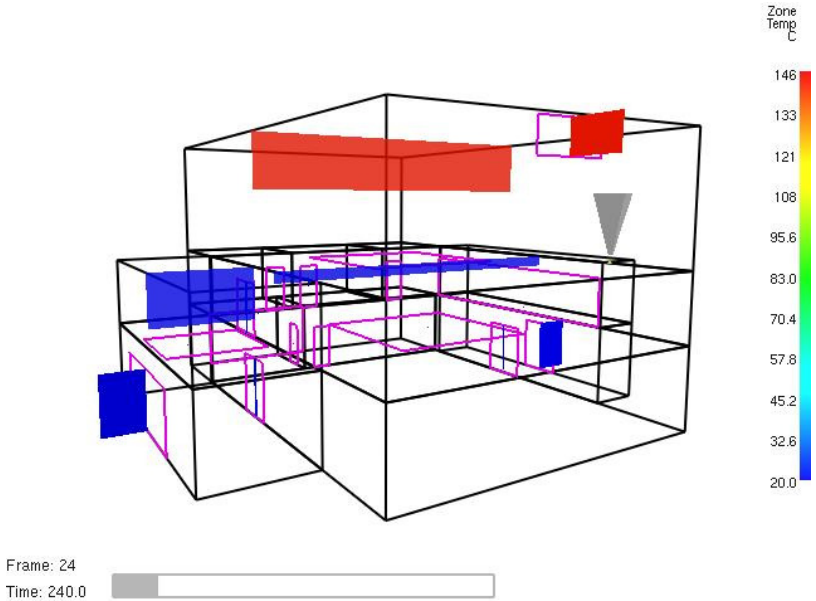
No Fire



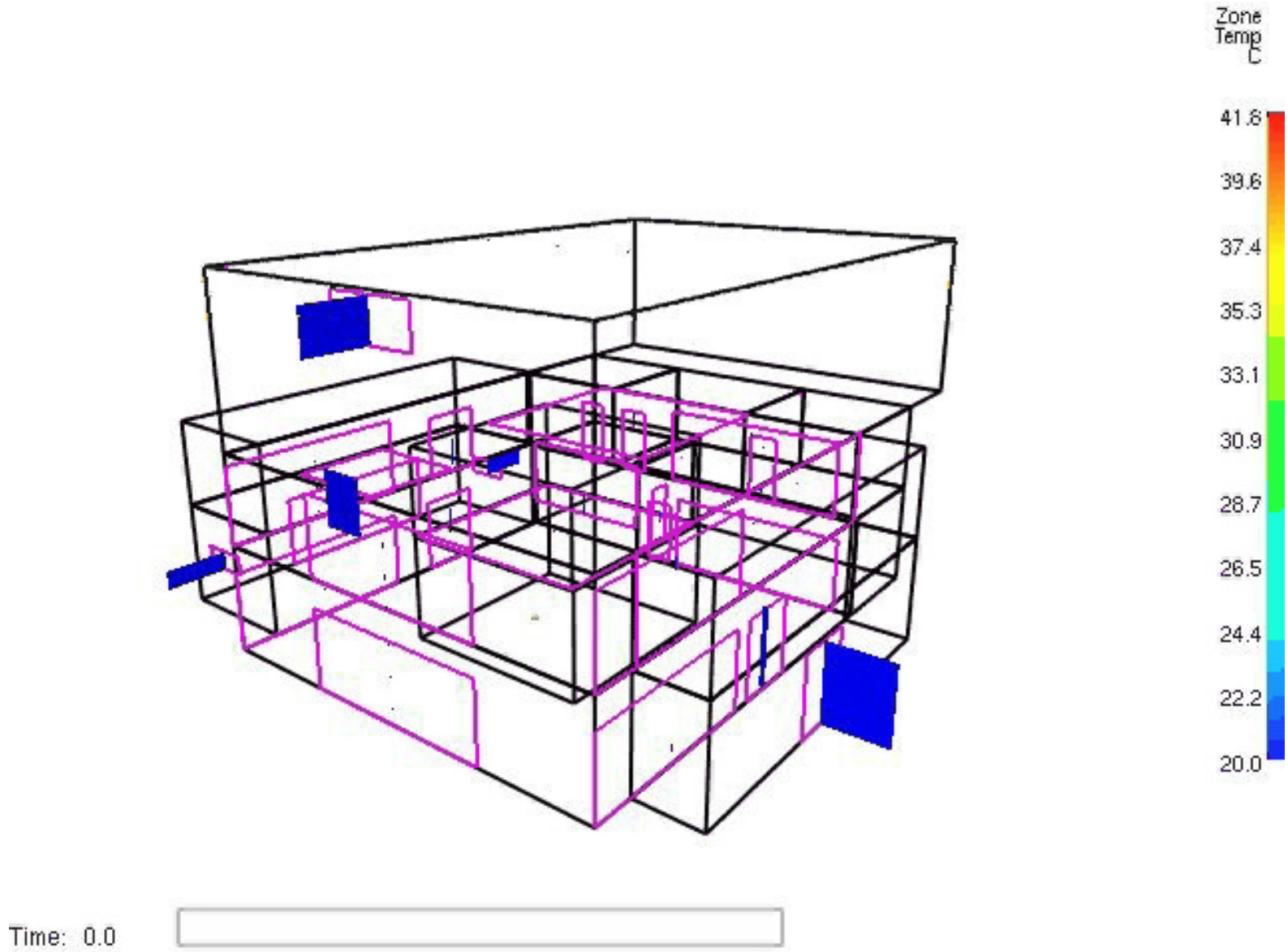
Fire Main Level

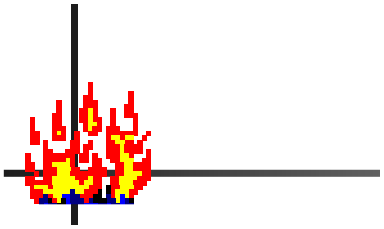


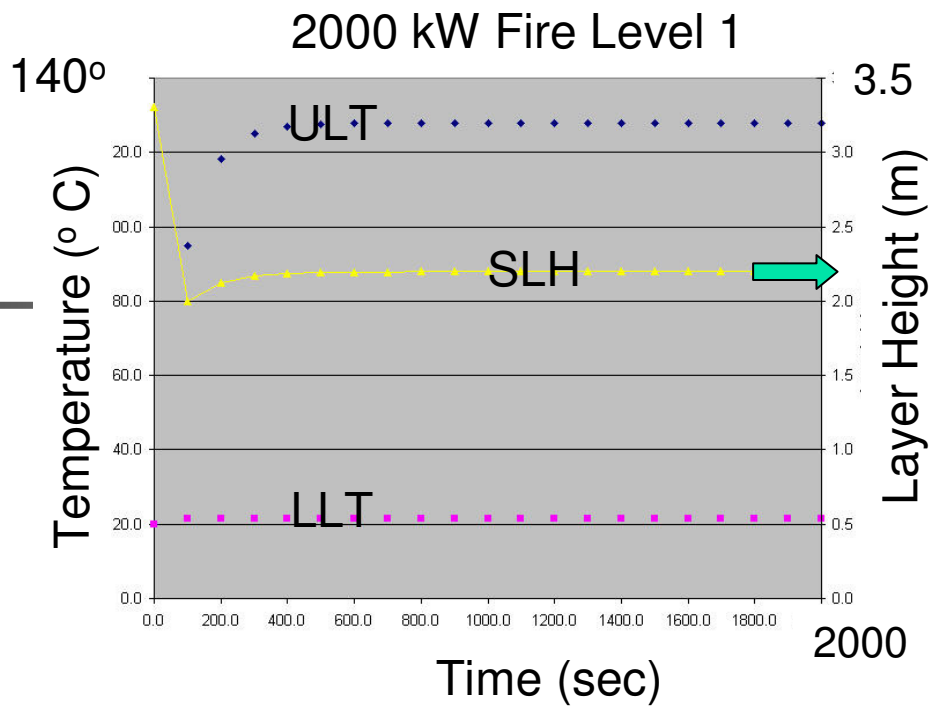
Fire 2nd Level

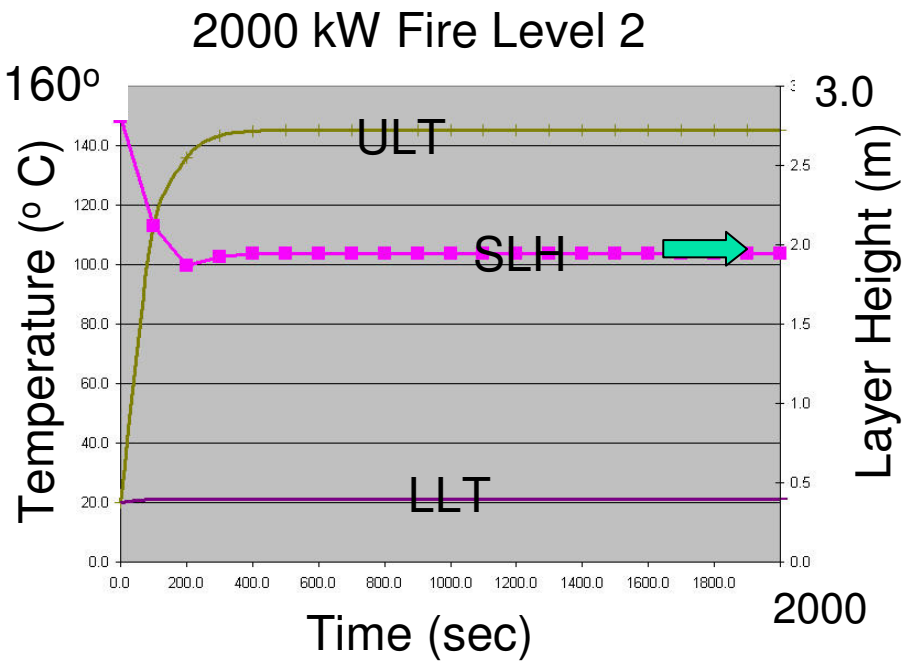


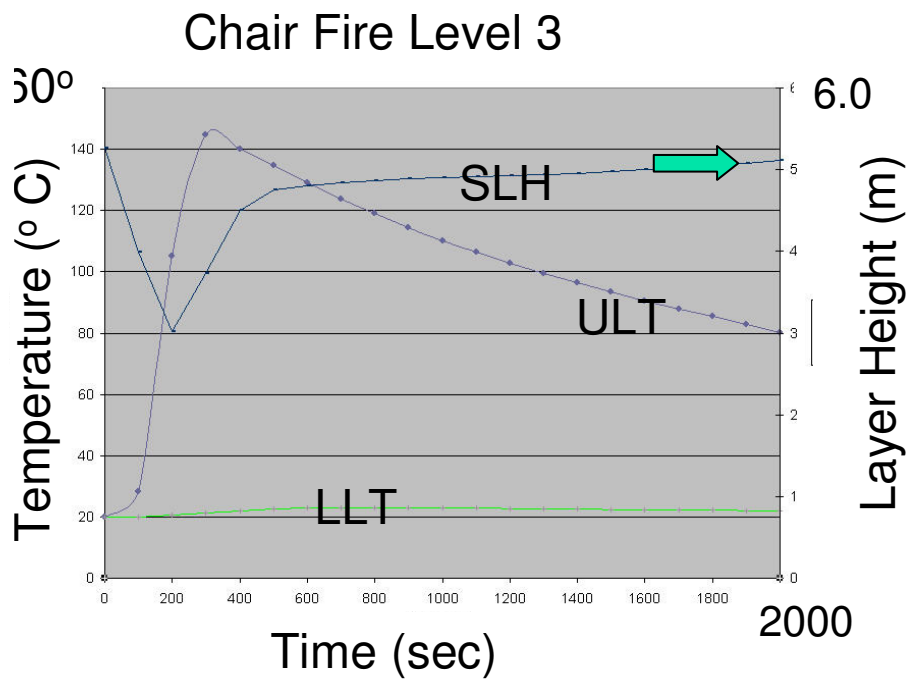
Fire 3rd Level


Zone
Temp
C
41.8
39.6
37.4
35.3
33.1
30.9
28.7
26.5
24.4
22.2
20.0
Time: 0.0

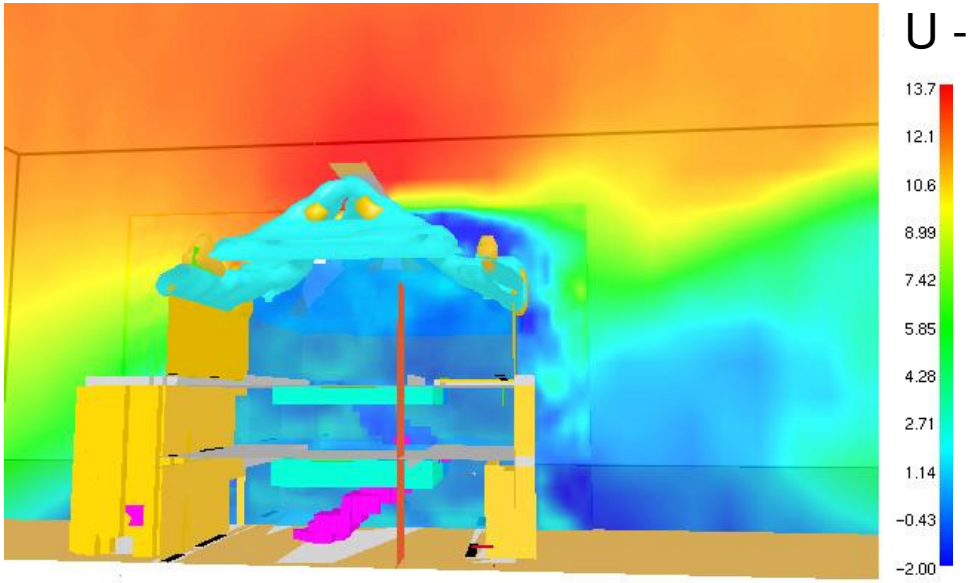



2000 kW Fire Level 1
140°
3.5
ULT
SLH
LLT
Temperature (° C)
Layer Height (m)
Time (sec)
2000

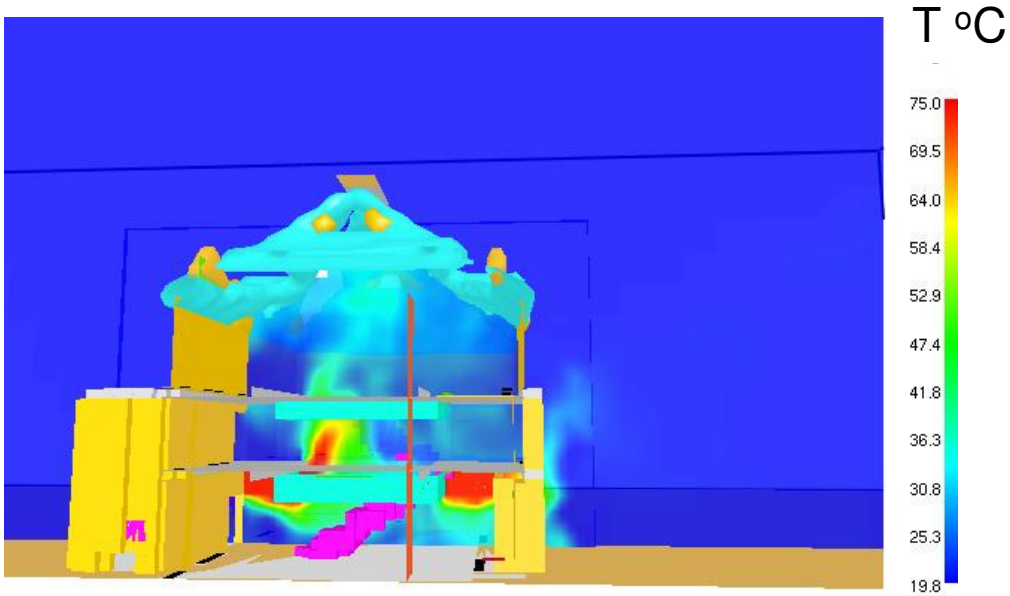

2000 kW Fire Level 2
160°
3.0
ULT
SLH
LLT
Temperature (° C)
Layer Height (m)
Time (sec)
2000


Chair Fire Level 3
6.0
SLH
ULT
LLT
Temperature (° C)
Layer Height (m)
Time (sec)
2000

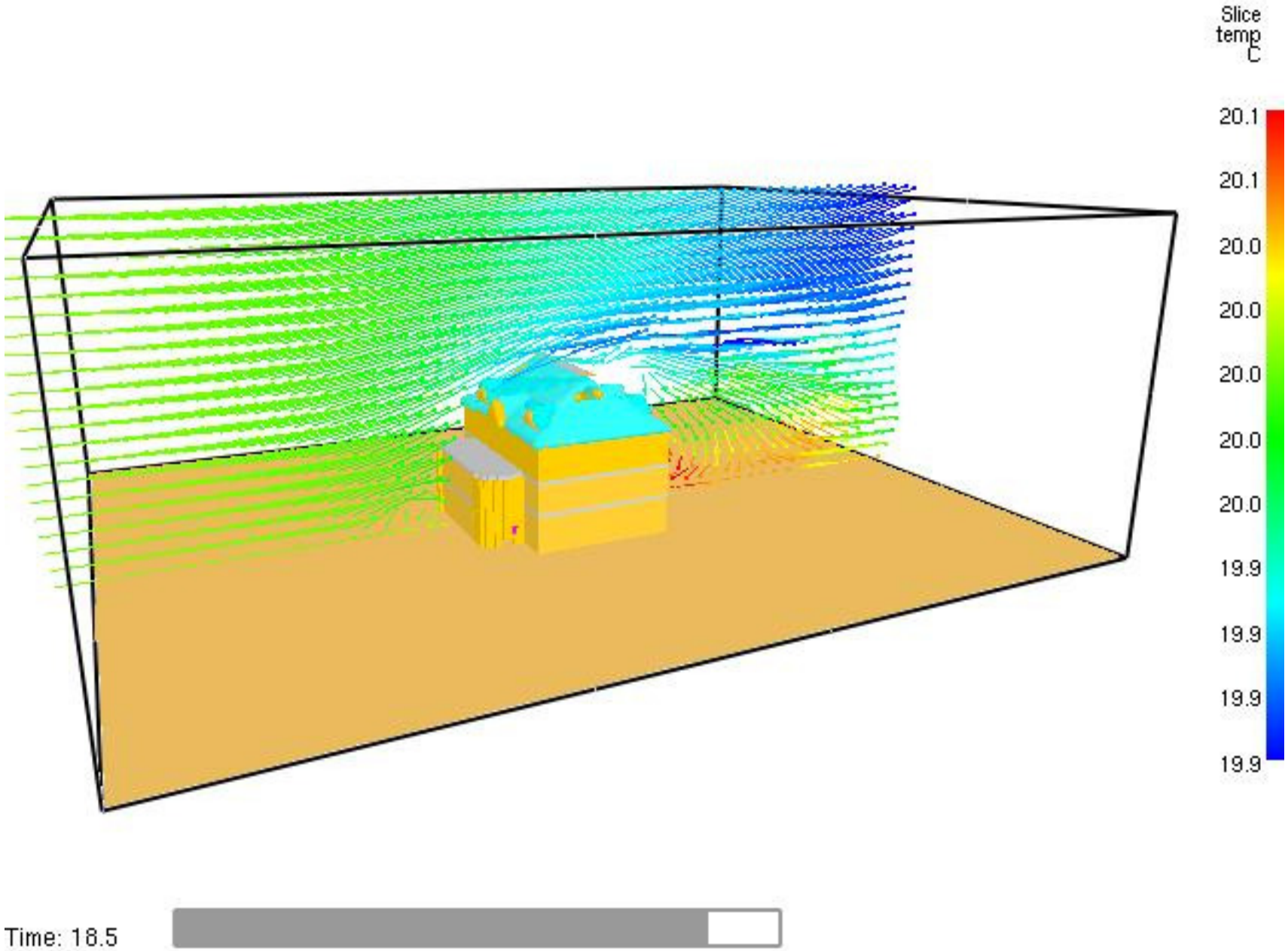
Velocity & Temperature Fields FDS



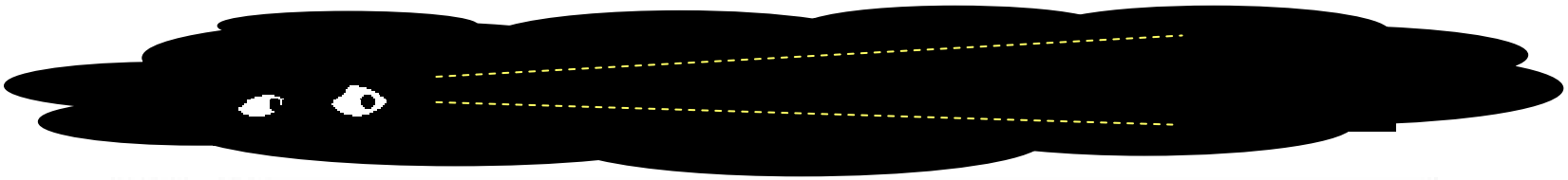
Time: 224.5

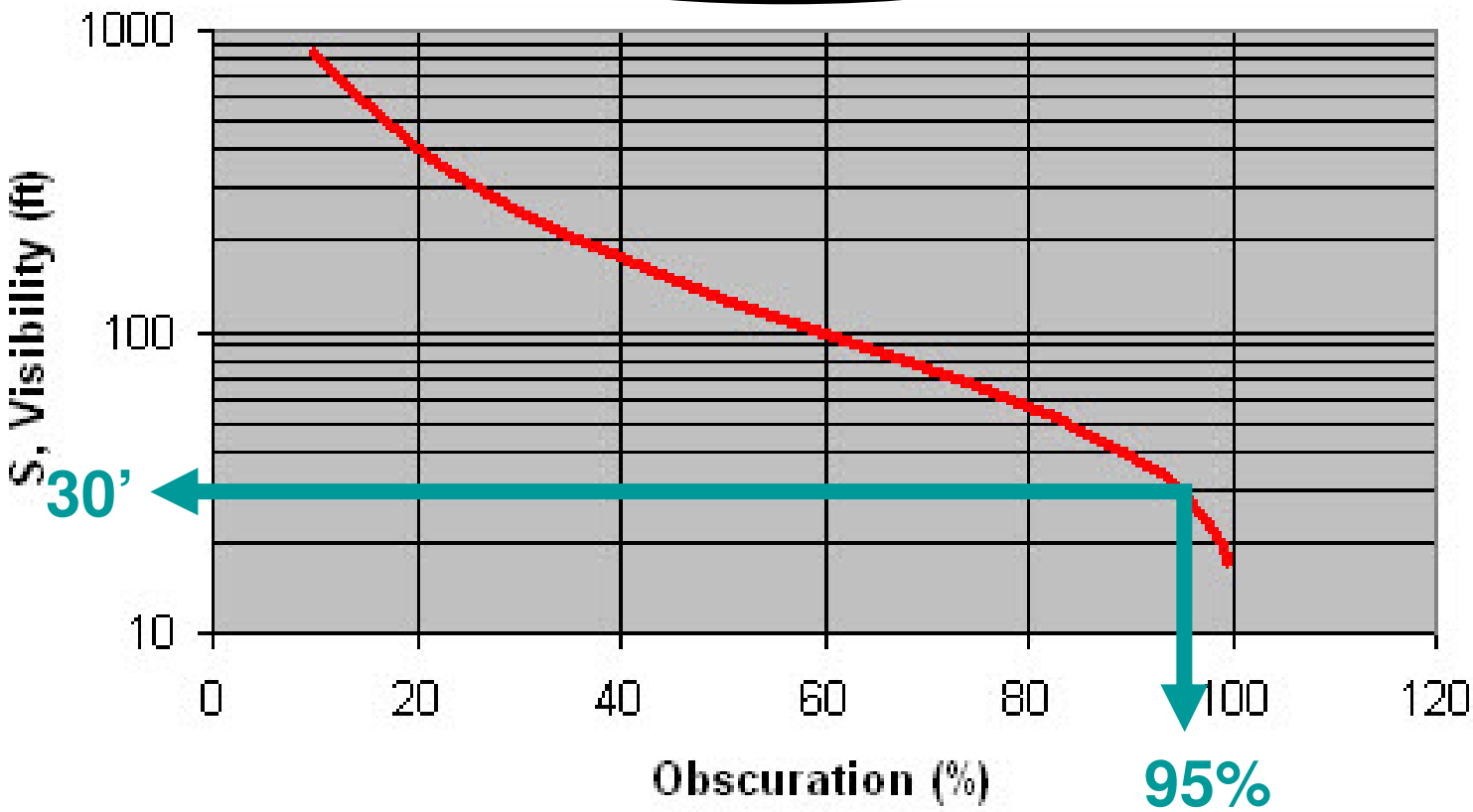


Time: 231.5


Slice
temp
C
20.1
20.1
20.0
20.0
20.0
20.0
20.0
19.9
19.9
19.9
19.9
Time: 18.5

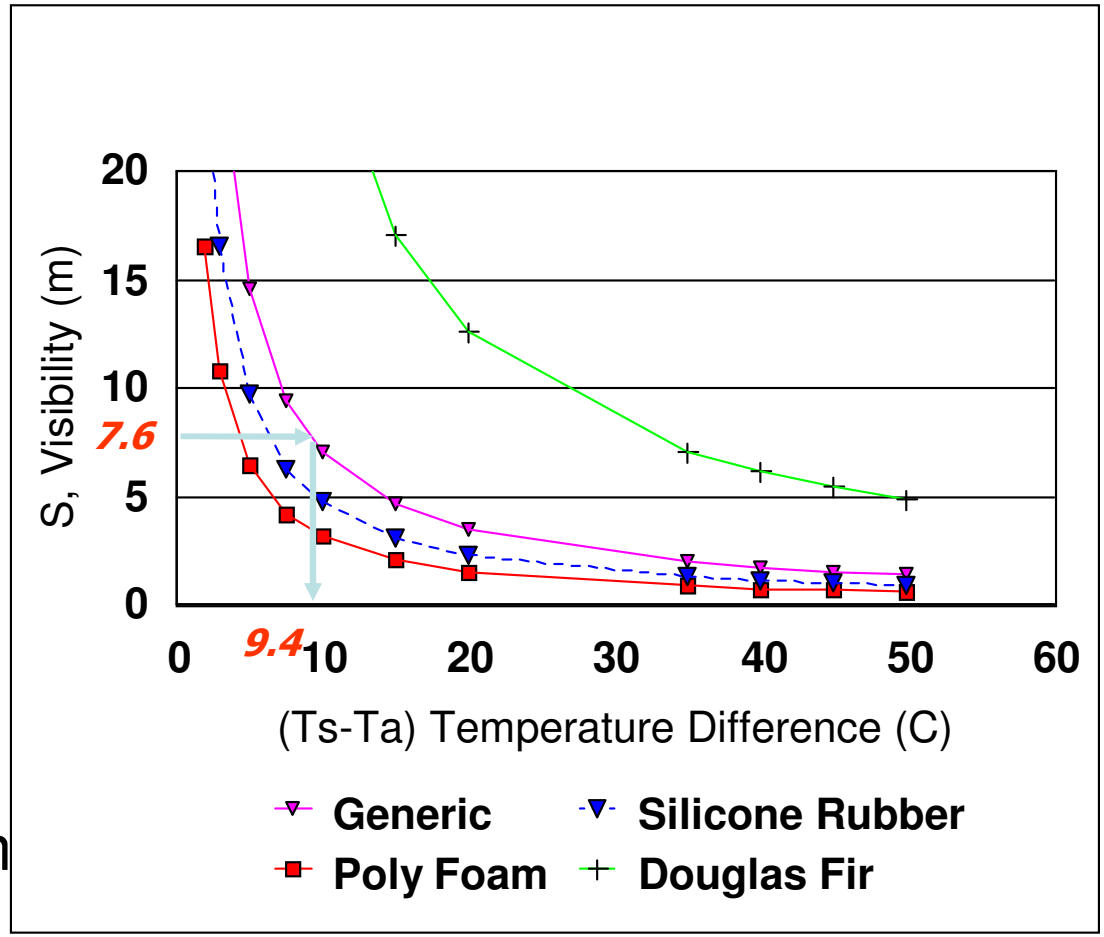
Obscuration vs Visibility



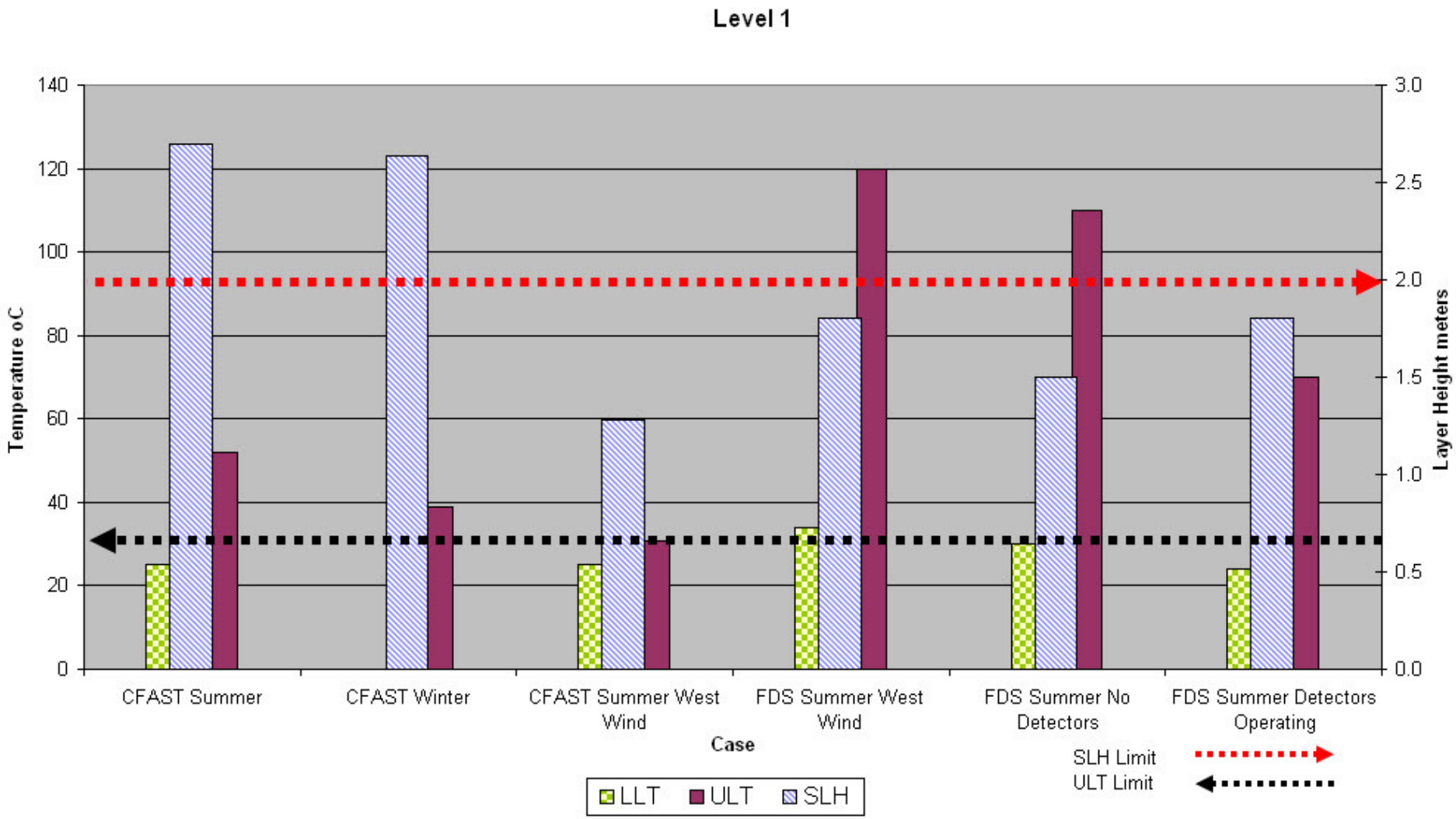


Visibility (S vs T_{smoke})

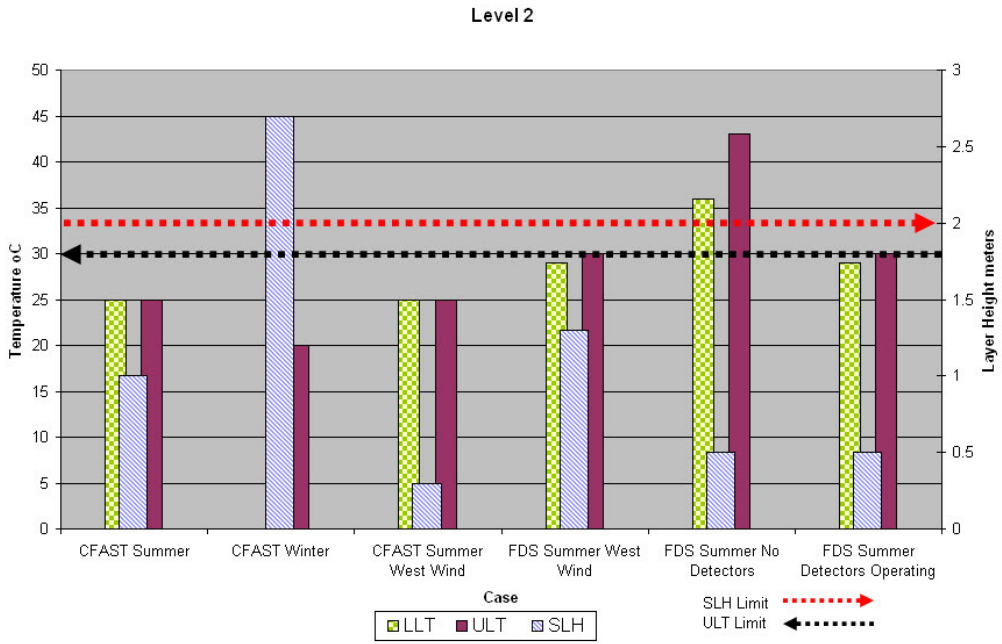
- Visibility is a function of smoke particle loading
- Particle density can be related to mass and type of fuel, HRR
- Typical criteria is visibility S > 25 ft (7.6 m) the min distance to see a reflective unlit sign

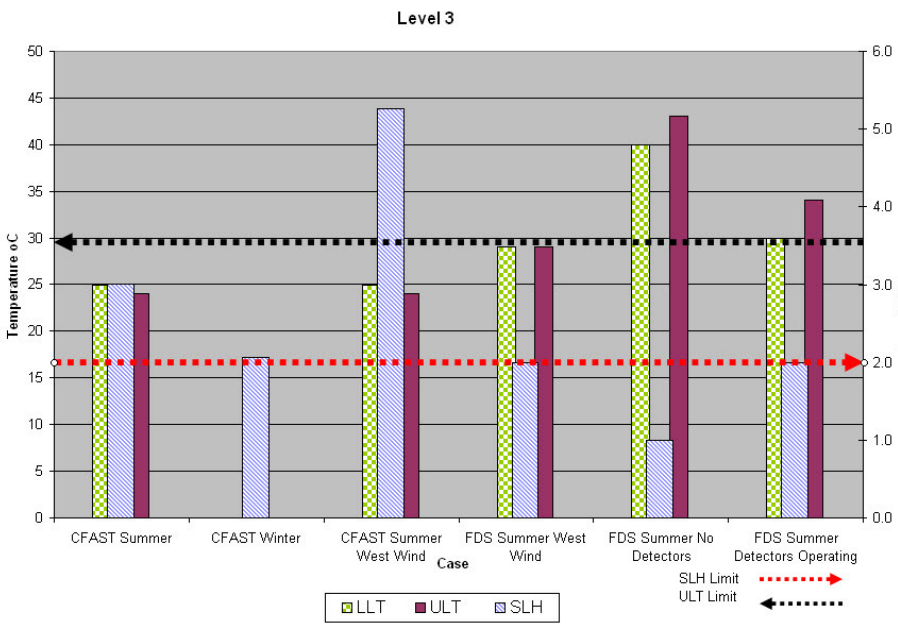


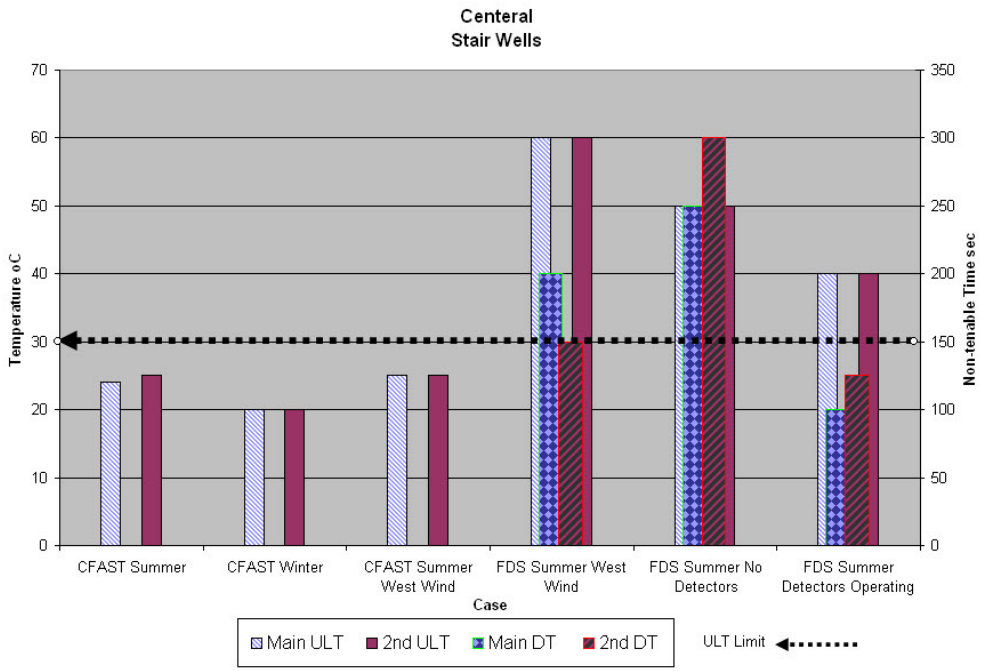
ULT, LLT & SLH on 1st floor



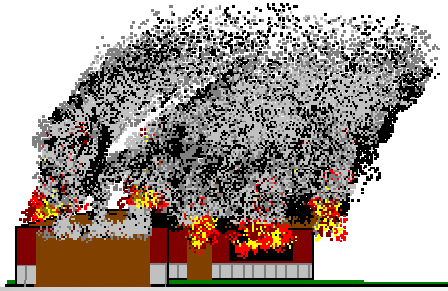
ULT, LLT, & SLH on 2nd, 3rd floor and stairs







Summary



- CFAST provides a fast screening model.
  - Flexibility and speed permits many alternative scenarios to be examined quickly.
- FDS produces detailed spatial information, but at a cost in time and computer resources.
  - Simulations follow fire development realistically and permit great visualization.

The End: Thank you for your attention

Il Fuoco: Fire

- Giuseppe Arcimboldo (1527-1593)
- Court painter to Hapsburg Emperor Rudolph II
- One of most bizarre and distinctive painters of art history producing composite heads of variety of objects, natural and man-made

Limitations of CFAST

- Requires an a priori specification of the temporal behavior of a fire;
- Limited by assumptions in the zone model formulation of the conservation equations;
- Limited to low-Mach number situations (ie. no acoustic waves, detonations, explosions, etc.)
- Momentum is not explicitly considered in the conservation equations;
- Does not model all mitigative systems;
- It has limited chemical source term generation and transport capabilities;
- Does not output all important variables; and,
- Limited access to modeled variables.

Size Limitations CFAST

- Maximum simulation time (sec or hr) 86,400 or 24
- Maximum number of compartments 30
- Maximum number of fires in a single test case 31
- Maximum HRR (MW/m^3) 1
- Maximum number of thermal property definitions 125
- Maximum number of slabs in a wall 3
- Total number of ducts 60
- Total number of connections between rooms 62
- Ratio of area vents/room volume < (m^{-1}) 2
- Maximum number of mechanical driven vents 15
- Maximum number of targets 90
- Maximum number of data points in spread sheet 900

Limitations of FDS

- Low-speed flow assumption –
  - No sonic effects, no choking due to speed of sound limitations, no explosions, detonations, i.e.
  - Mach < 0.3.
- Rectilinear Geometry –
  - Fast, direct solver for pressure field REQUIRES rectilinear mesh,
  - NO exceptions.
- Fire Growth and Spread –
  - Model works best when HRR is specified and heat and exhaust products are calculated, T and V are then accurate to 10-20%.
  - If HRR is predicted then uncertainty in flow and transport is larger; because, a) properties of fuels are uncertain, and b) numerical methods are more sensitive to physical conditions.

Limitations of FDS (concld.)

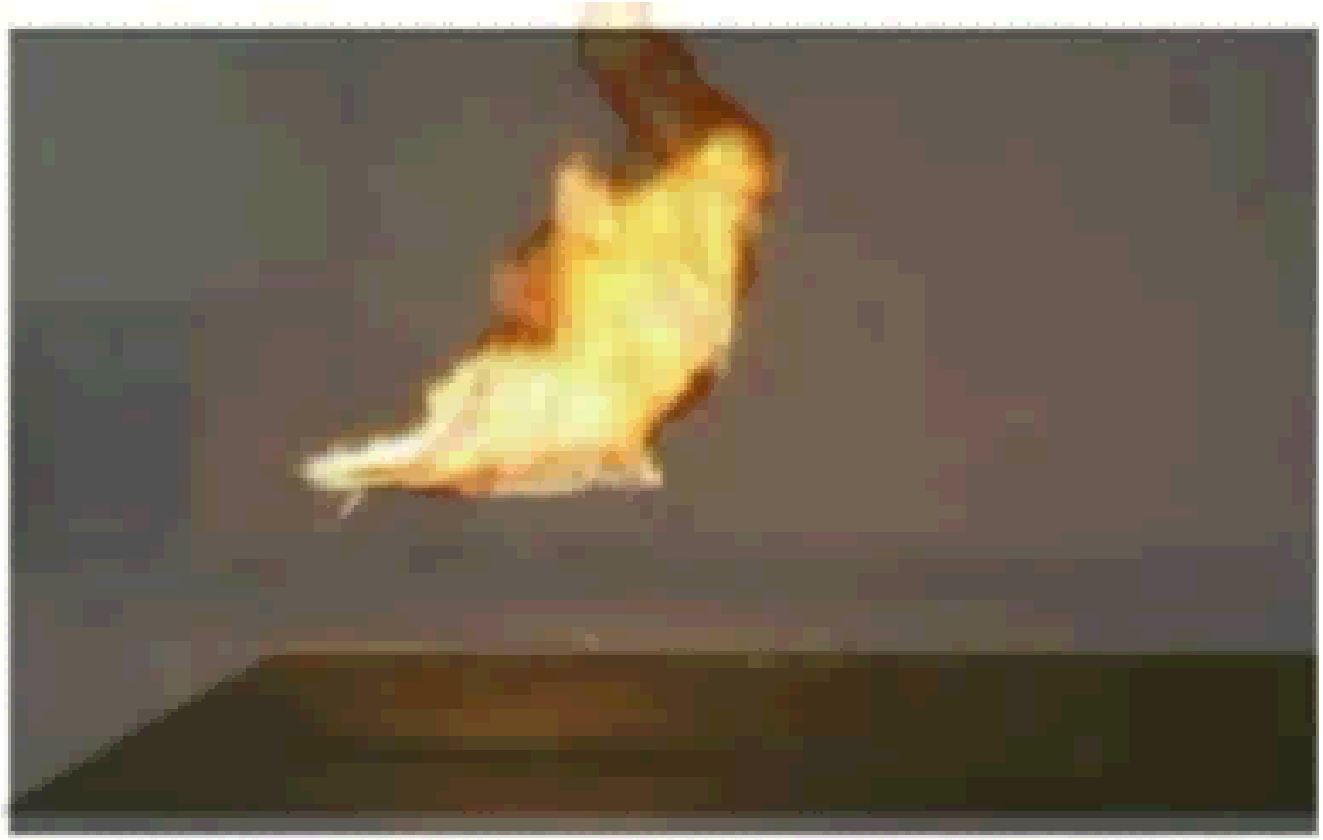
- Combustion –
  - Mixture-fraction-based model assumes combustion is mixture controlled, and infinitely fast regardless of temperature. For well-ventilated fires this is a good assumption.
  - If fire is under-ventilated, CO_2 is introduced, or fuel and oxygen do not burn, then program uses empirical criteria to approximate suppressing effects which introduces greater uncertainty.
- Radiation –
  - Gray gas model does not allow for actual very complex interaction of radiation with composition and temperature.
  - Typically, only a finite number of angles are considered, which introduces errors for targets at large distances.

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. … 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.

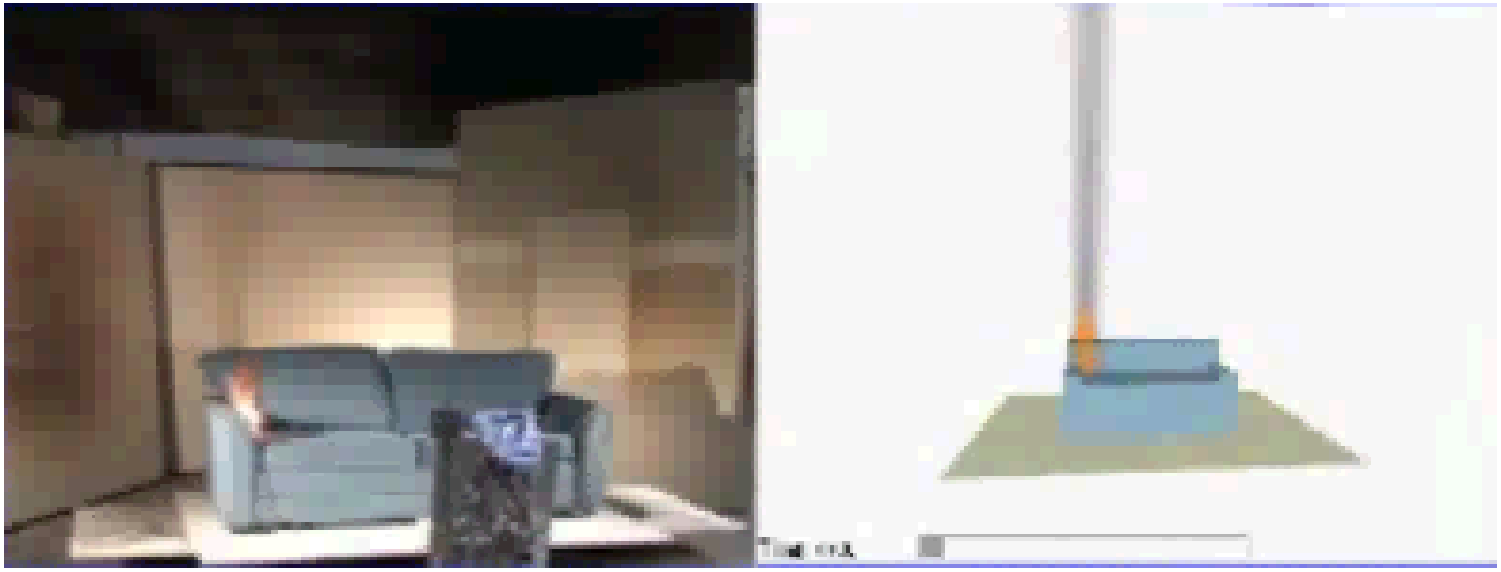
Spray Burner Simulation

Experimenters: Doug Walton & Jason Floyd
Simulation: Kevin McGrattan



Sofa Burn

Video: Steve Kerber



Tree Fire

Video: William “Ruddy” Mell