Fire Modelling

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December 11th /2014

Agenda:

Introduction

Types of Models

Applicability

Case Study 1

Case Study 2

Case Study 3

CFAST vs. Hand Calculations

CFAST vs. Hand Calculations Vs NUREG 1805

CFAST Exercise

Introduction

Fire Development in Compartment Fires

- Ignition
  - Period during which fire begins / Pilot ignition / Auto ignition
- Growth
  - Initially fire grows without any compartment effects
  - Fire can be described in terms of HRR and product generation
  - With sufficient oxygen and fuel fire will continue to grow causing increase of compartment temperature

Introduction

Flashover

- Flashover is defined as the event at which all combustible items in a room ignite due to high heat fluxes from the flames and the hot layer.
- Experimentally flashover occurs when the upper layer temperature reaches 500-600 ºC.
- Another criterion used for flashover is the time at which the radiant heat flux to the center of the floor reaches 20 kW/m2 (reached when to hot layer temperature is 600 ºC)
- This value is sufficient to ignite common light combustible materials in a short time.
- Transition from growing fire to a fully developed fire.

Introduction

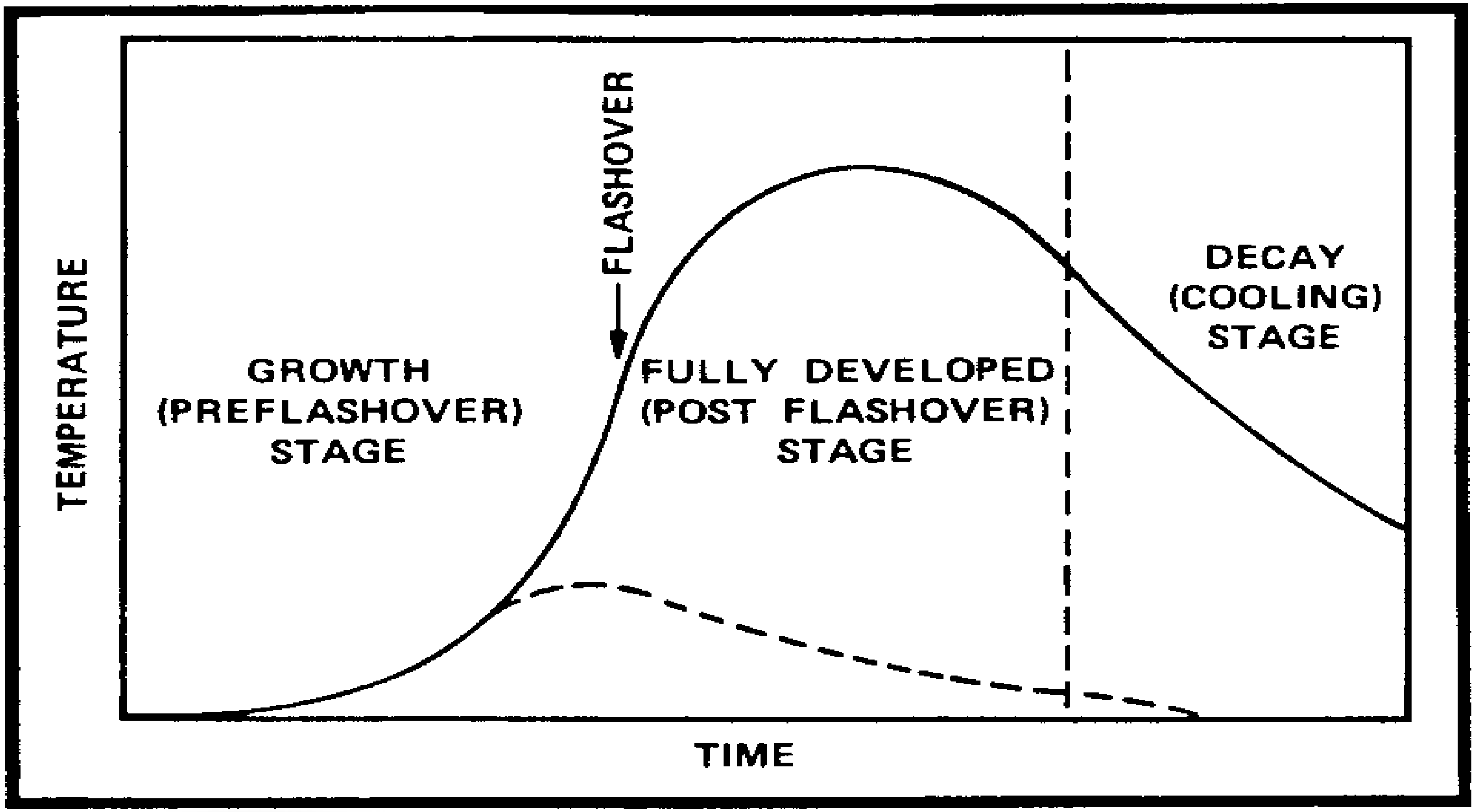
Fully Developed Fire

- HRR is the greatest during this stage
- Fire becomes ventilation controlled
- Flames issue from compartment openings (unburned fuel)

Decay

- Decay occurs as fuels become consumed by the fire and HRR declines
- Fire changes from ventilation control to fuel control

Introduction



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Introduction

The Pre-flashover Fire:

Introduction

Flashover:

Introduction

Fire Spread

- Fire may spread from the room of origin to adjacent rooms or adjacent buildings.
- Spread of fire is due to following:
  - Direct flame contact to combustibles in adjacent rooms
  - Radiation heat transfer
  - Conduction heat transfer through walls, doors
  - Flaming brands

Introduction

Heat Transfer

•Conduction

❖ Through building elements

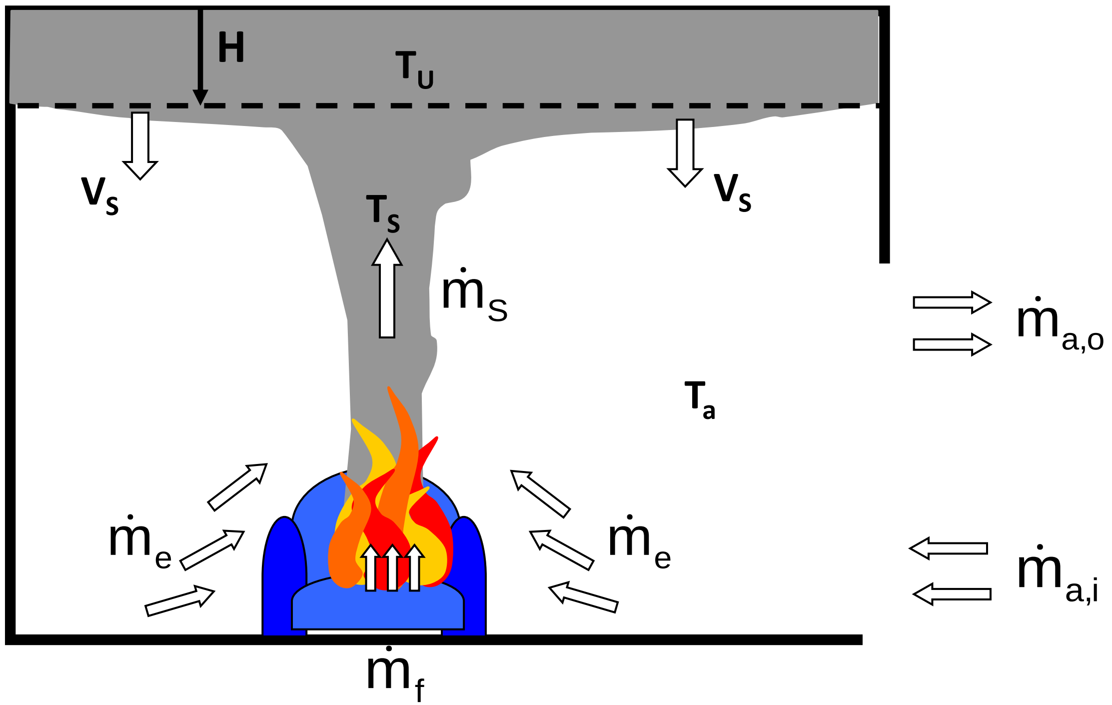
• Convection

❖ From hot layer to walls and ceiling

•Radiation

❖ From flames and hot layer to room boundaries

Introduction



Upper Layer – The parameters that need to be evaluated are:

- -The temperature of the upper layer: $\mathbf{T_u}$
- -The velocity at which the Upper Layer descends:

$$V_S = \frac{dH}{dt}$$

Introduction

These parameters can be obtained from, the ideal gas law and conservation of mass and energy in the Upper Layer

$$P = \rho R T_u$$

$$\frac{\partial}{\partial t}\left(A\rho(T_u)H(t)\right) = \dot{m}_S$$

$$\frac{\partial}{\partial t}\left(A\rho(T_u)H(t)C_p T_u\right) = \dot{m}_S C_p T_S$$

Introduction

$$\frac{\partial}{\partial t}\left(A\rho(T_u)H(t)C_pT_u\right) = \dot{m}_S C_p T_S$$

$$\dot{m}_S = \dot{m}_f + \dot{m}_e$$

$$Q_P = \dot{m}_S C_p (T_S - T_a)$$

- Unknowns: $\begin{cases} Q_P \\ \dot{m}_f \\ \dot{m}_e \end{cases}$

Introduction

The "Energy Release Rate"

$$Q = \Delta H_C \dot{m}_f$$

Mass of air entrained

$$\dot{m}_e = 0.20\left(\frac{\rho_a^2 g}{C_P T_a}\right)^{1/3} Q^{1/3}(H_0 - H(t))^{5/3}$$

Mass Burning Rate: Generally obtained from empirical correlations

$$\dot{m}_f = f(D,Q,Fuel)$$

Introduction

- Total Energy: $$Q = Q_P + Q_F + Q_r$$
- Feedback is generally assumed to be small $$Q_F \approx 0$$
- Radiation is assumed to be a fraction of the total energy released $$Q_r \approx \chi Q$$ $$\chi \approx 0.3$$

$$Q_P \approx (1-\chi)Q \approx 0.7Q$$

Introduction

- Under these assumptions we can correlate everything with "Q"
- There is no need to "calculate" Q_P directly
- How do we calculate "Q"?

$$Q = \Delta H_C \dot{m}_f$$

$$\dot{m}_e = 0.20\left(\frac{\rho_a^2 g}{C_P T_a}\right)^{1/3} Q^{1/3}(H_0 - H(t))^{5/3}$$

$$\dot{m}_f = f(D, Q, Fuel)$$

Introduction

Simple representation of the HRR

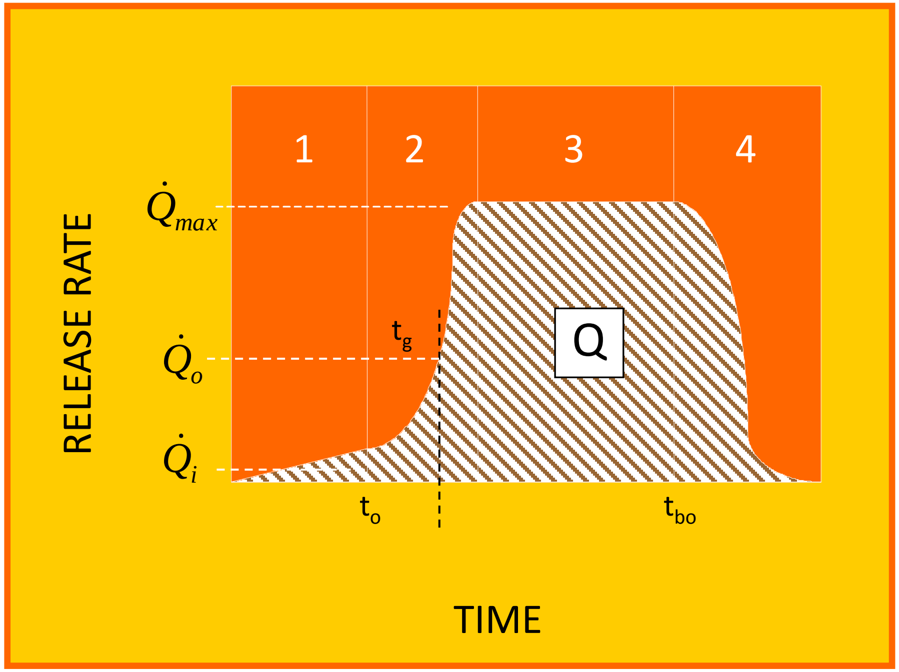
$$\dot{Q} = \Delta H_C \dot{m}_f = \Delta H_C A_B \dot{m}_f''$$

$$A_B = \pi r^2 = \pi (V_f t)^2 = (\pi V_f^2) t^2$$

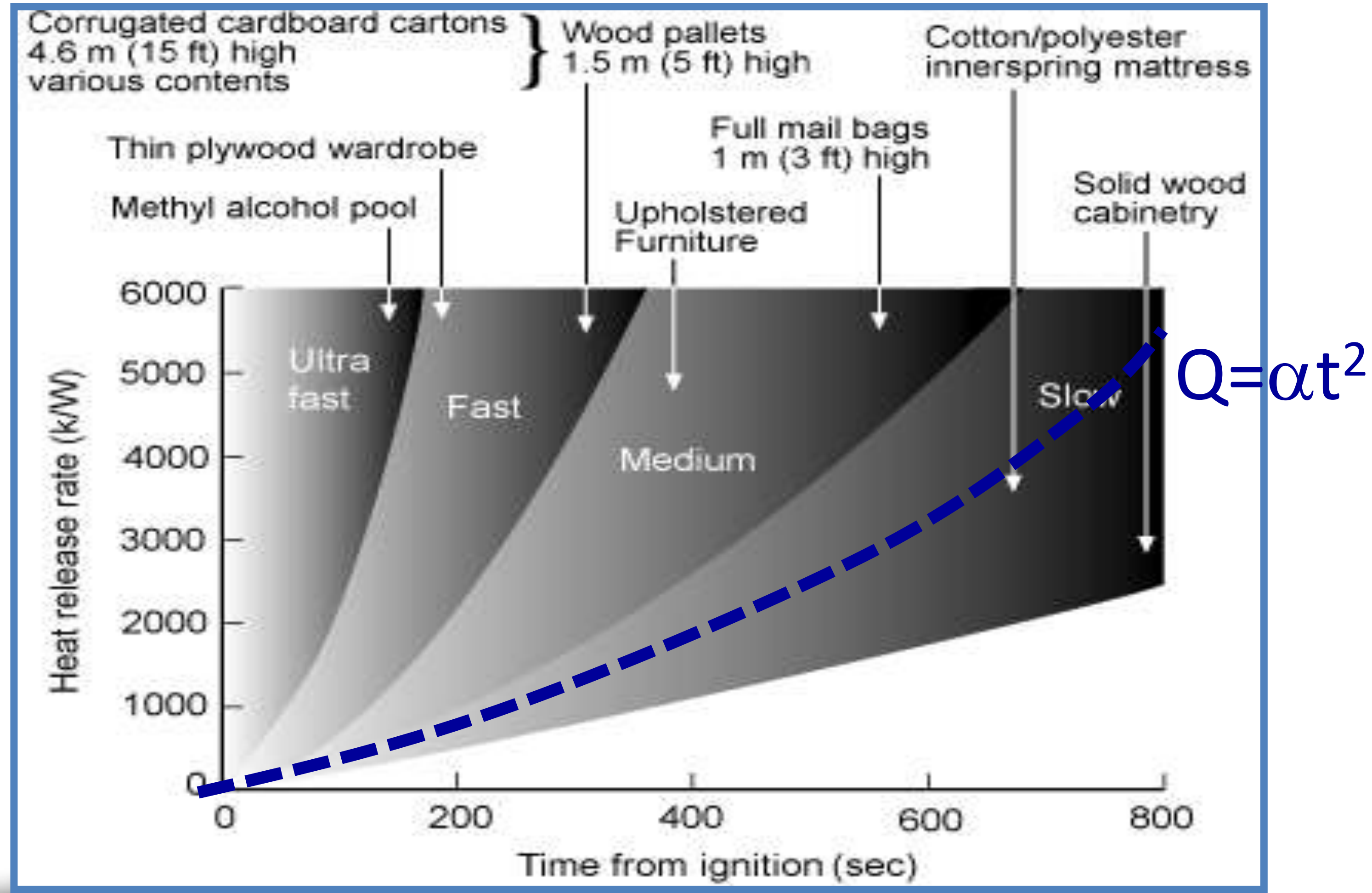
$$\dot{Q} = \Delta H_C A_B \dot{m}_f'' = \left[\Delta H_C (\pi V_f^2) \dot{m}_f''\right] t^2 = \alpha t^2$$

Introduction

- Incipient heat release rate (Q^*_i)
- Incipient period (t_o)
- Growth time (t_g)
- Growth HRR(Q^*_o)
- Peak HRR (Q^*_{max})
- Total HR (Q)
- Burnout time (t_{bo})



Introduction



Introduction

Ignition Properties

$$\frac{1}{\sqrt{t_{ig}}} = \frac{2}{\sqrt{\pi}} \frac{1}{\sqrt{k\rho c}} \frac{\dot{q}''_e}{(T_{ig} - T_\infty)}$$

Material	T_{ig} [ºC]	kρC [s.kW²/m⁴K²]	Critical Heat Flux [kW/m²]
Douglas Fir	382	0.94	16
Cedar	402	1.22	18
Iroko	410	1.30	17
Polyisocianurate	445	0.02	21
Polyurethane	390	0.30	16
PMMA	378	1.02	15
Acrilic	300	0.42	10

AN OPERATIVE MODEL

Equations

$$\frac{dm_i}{dt} = \dot{m}_i$$

mass equation

$$\frac{dP}{dt} = \frac{\gamma - 1}{V}\left(\dot{h}_L + \dot{h}_U\right)$$

pressure equation

$$\frac{dE_i}{dt} = \frac{1}{\gamma}(\dot{h}_i + V_i \frac{dP}{dT})$$

energy equation

$$\frac{dV_i}{dt} = \frac{1}{\gamma P}((\gamma - 1)\dot{h}_i - V_i \frac{dP}{dT})$$

volume equation

$$\frac{d\rho_i}{dt} = -\frac{1}{c_p T_i V_i}((\dot{h}_i - c_p \dot{m}_i T_i) - \frac{V_i}{\gamma - 1}\frac{dP}{dT})$$

density equation

$$\frac{dT_i}{dt} = \frac{1}{c_p \rho_i V_i}((\dot{h}_i - c_p \dot{m}_i T_i) + V_i \frac{dP}{dT})$$

temperature equation

Introduction

Fire Modelling is the evaluation of fire scenarios to answer questions about heat, smoke, and toxic gas production.

- Fire Modelling is used to:
  - → Develop accident scenarios from fire hazards and determine the consequences of a particular fire, example: radioactive release
  - → To evaluate performance or objective based design alternatives
  - → Provide guidance when prescriptive codes and standards do not address or conform to specific situations

Introduction

- Fire modelling is used to determine:
  - →Heat release rate of a fire
  - →Height and size of a flame
  - →Flow of hot gases in a room
  - →Radioactive release
  - →Temperatures in the hot gas layer and in the room
  - →Heat fluxes to objects in the room
  - →Temperatures on adjacent items
  - →Detector Activation
  - →Occupant Response to the fire

Agenda:

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CFAST vs. Hand Calculations

CFAST vs. Hand Calculations Vs NUREG 1805

CFAST Exercise

Types of Models

Hand Calculations:

- Hand calculations are correlations or simplifications to real world physics.
  - → They are often developed from numerous experimental trials and have limited scope of applicability.

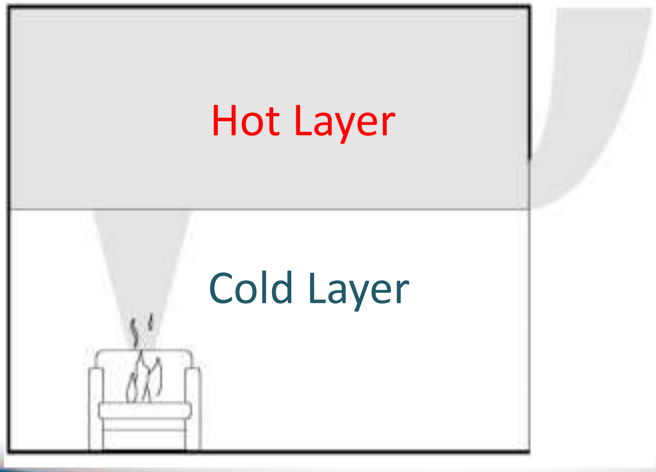
- Calculation methods have been developed for a wide variety of topics in fire safety including:
  - → Heat release rate from a fire $\dot{Q} = \alpha t^2$
  - → Flame height $l = 0.235\dot{Q}^{2/5} - 1.02D$
  - → Radiation from a fire $\dot{q}'' = \varepsilon\sigma T^4$
  - → Detector Activation $T_d(t) - T_d(0) = \frac{\Delta T}{\Delta T^*}\Delta T^*\left[1 - \frac{(1 - e^{-Y})}{Y}\right]$
  - → Occupant Evacuation time $t_{evac} = t_{travel} + t_{pre-evac}$

Types of Models

Two Zone Models:

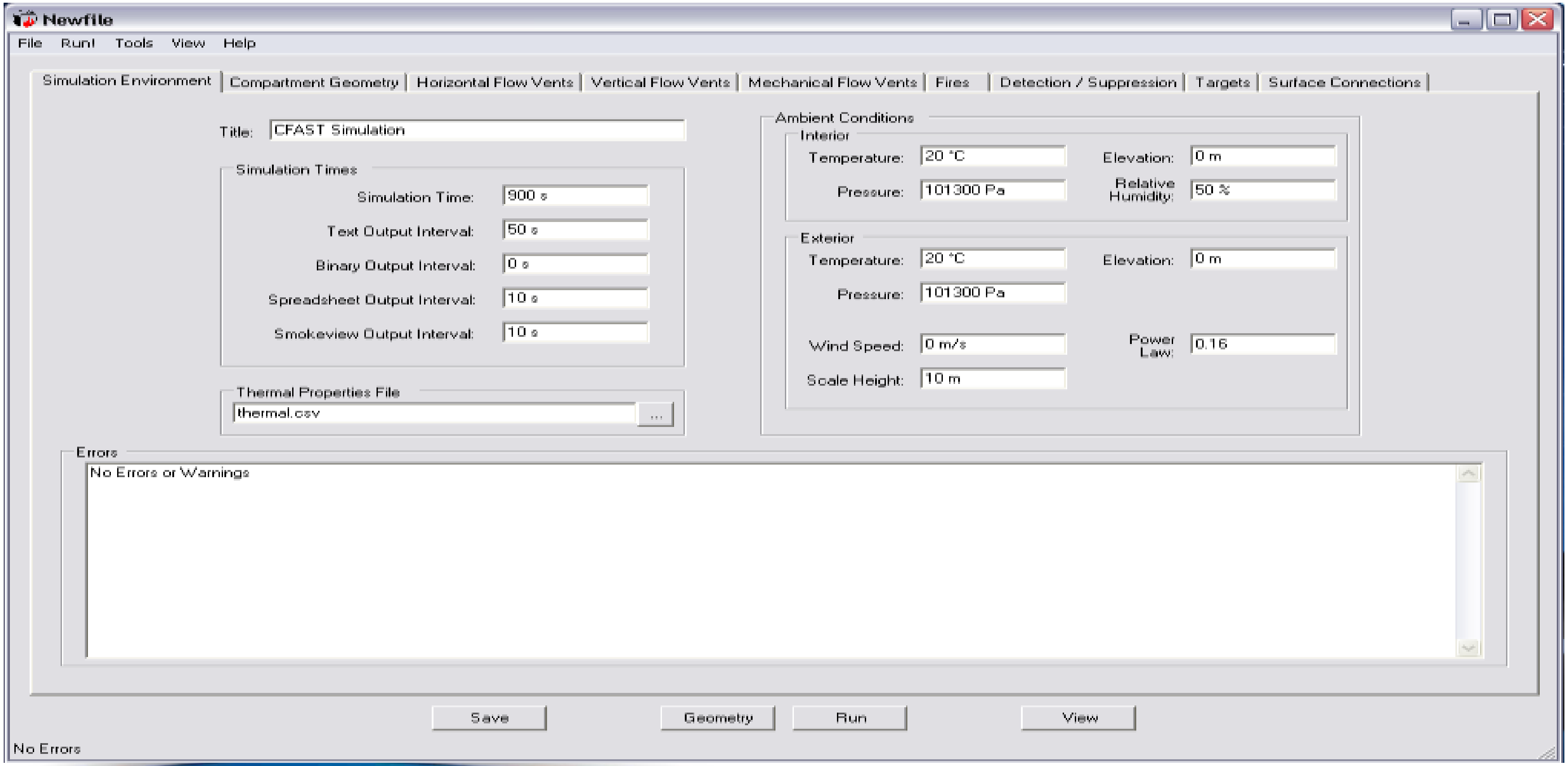
Two zone models rely on fundamental theories in physics but use basic knowledge of fire scenarios to simplify and approximate the equations.

- →As a room fills with smoke, it is approximated as having two distinct layers: a hot upper layer and cooler lower layer.
- →Fire compartments can be connected to adjacent compartments to form entire buildings.



Types of Models

Two Zone Models – CFAST Input Screen:



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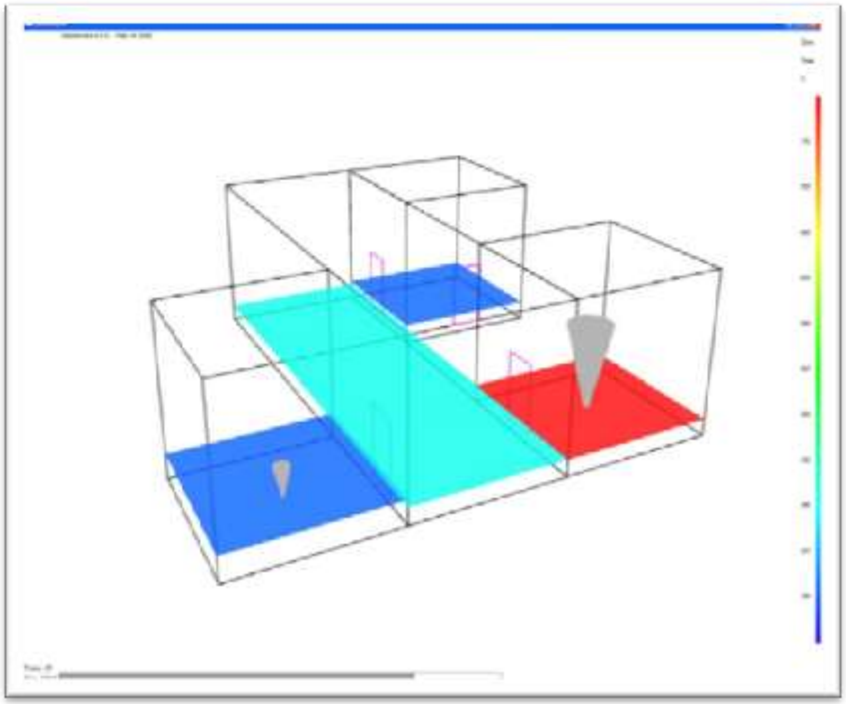
Types of Models

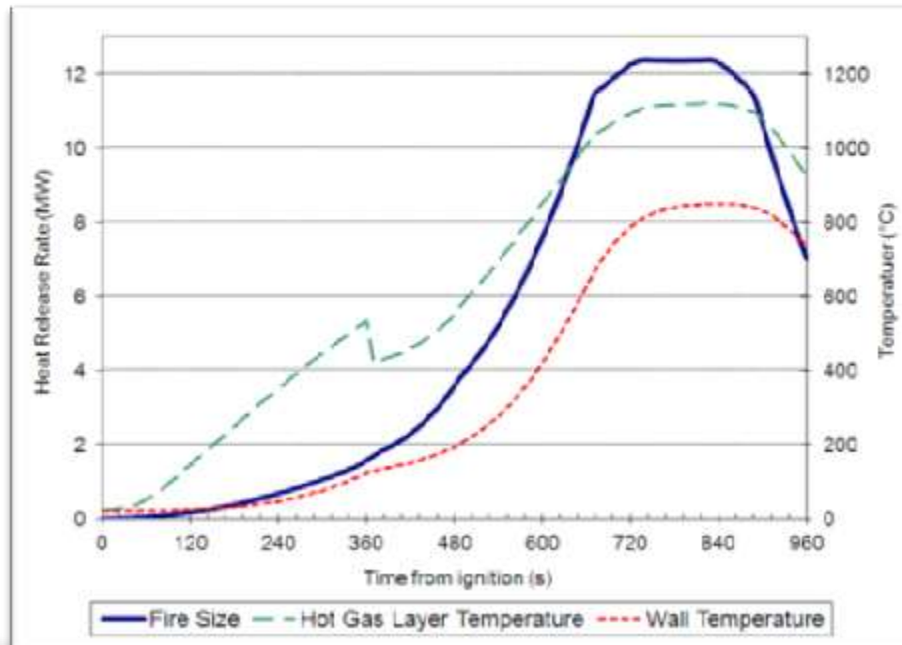
Two Zone Models – CFAST Input Screen:

```
VERSN,6,CFAST Simulation
!!
!!Environmental Keywords
!!
TIMES,450,-30,0,10,10
EAMB,293.15,101300,0
TAMB,293.15,101300,0,50
CJET,WALLS
CHEMI,10,393.15
WIND,0,10,0.16
!!
!!Compartment keywords
!!
COMPA,Container,2.34,5.88,2.39,0,0,0,STEEL1/8,OFF,STEEL1/8
!!
!!vent keywords
!!
HVENT,1,2,1,2.31,2.29,0,1,0.01,0,1,0.25
EVENT,H,1,2,1,180,1,1
!!
!!fire keywords
!!
OBJECT,10 pallets,1,0.6,0.6,1,1,3,12500,0,0,1
OBJECT,10 pallets,1,0.6,1.8,1,1,1,0,0,0,1
OBJECT,10 pallets,1,0.6,3,1,1,3,12500,0,0,1
OBJECT,10 pallets,1,0.6,4.2,1,1,3,12500,0,0,1
OBJECT,10 pallets,1,0.6,5.4,1,1,3,12500,0,0,1
OBJECT,10 pallets,1,1.8,0.6,1,1,3,12500,0,0,1
OBJECT,10 pallets,1,1.8,1.8,1,1,3,12500,0,0,1
OBJECT,10 pallets,1,1.8,3,1,1,3,12500,0,0,1
OBJECT,10 pallets,1,1.8,4.2,1,1,3,12500,0,0,1
OBJECT,10 pallets,1,1.8,5.4,1,1,3,12500,0,0,1
```

Types of Models

Two Zone Models – CFAST Outputs:

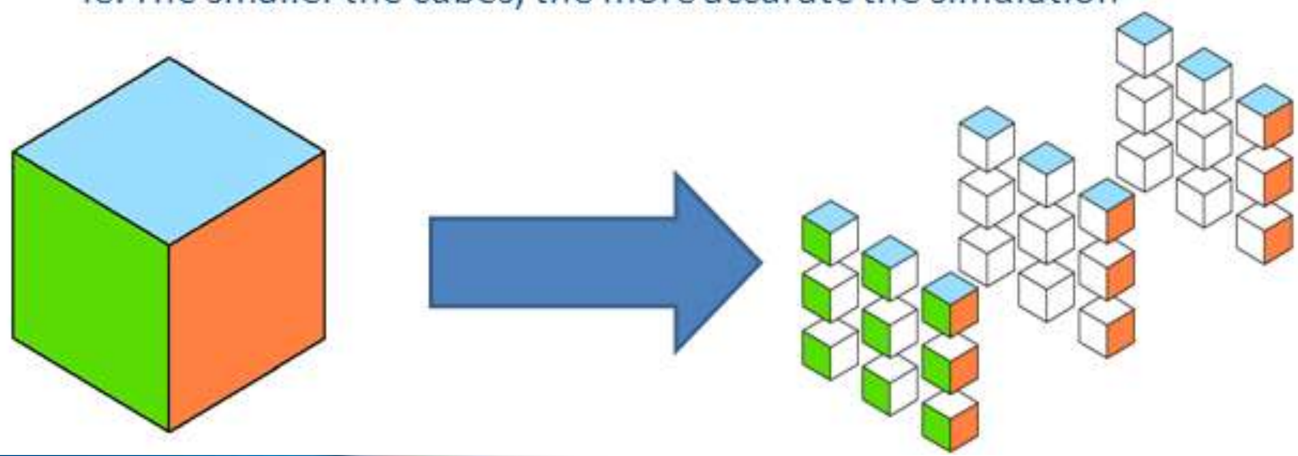




Types of Models

FDS Fire Simulations

- FDS (Fire Dynamic Simulator) models approximate fundamental physics equations for conservation of mass, energy, momentum, and species for small volumes.
  - → Three-dimensional volumes are broken up into a small cubes.
  - → Results can be grid dependant
    ie. The smaller the cubes, the more accurate the simulation

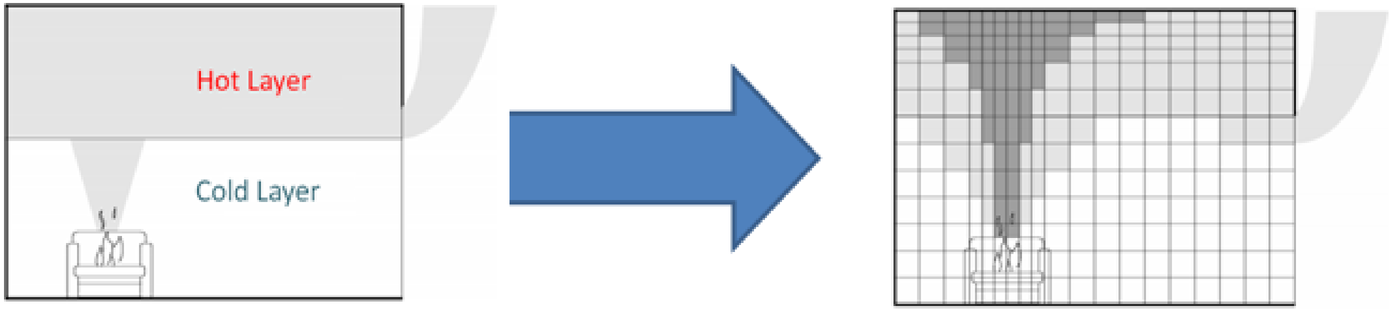


Types of Models

FDS Fire Simulations

- FDS is on example of CFD (computational fluid dynamics) models that approximate fundamental physics equations for conservation of mass, energy, momentum, and species for small volumes.
  - → Three-dimensional volumes are broken up into a small cubes.
  - → Results can be grid dependant

    ie. The smaller the cubes, the more accurate the simulation



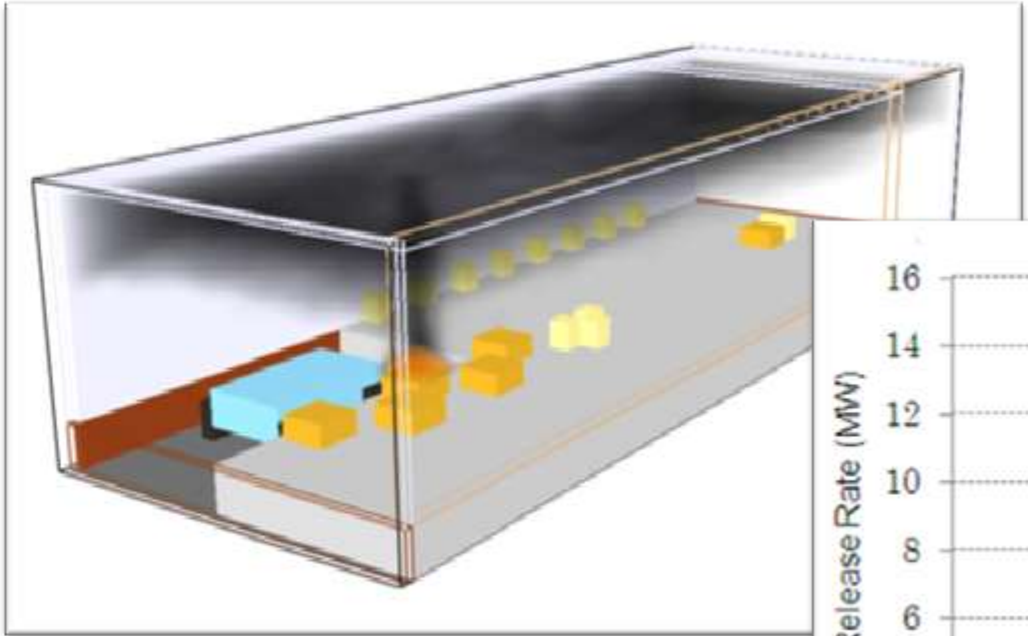
Types of Models

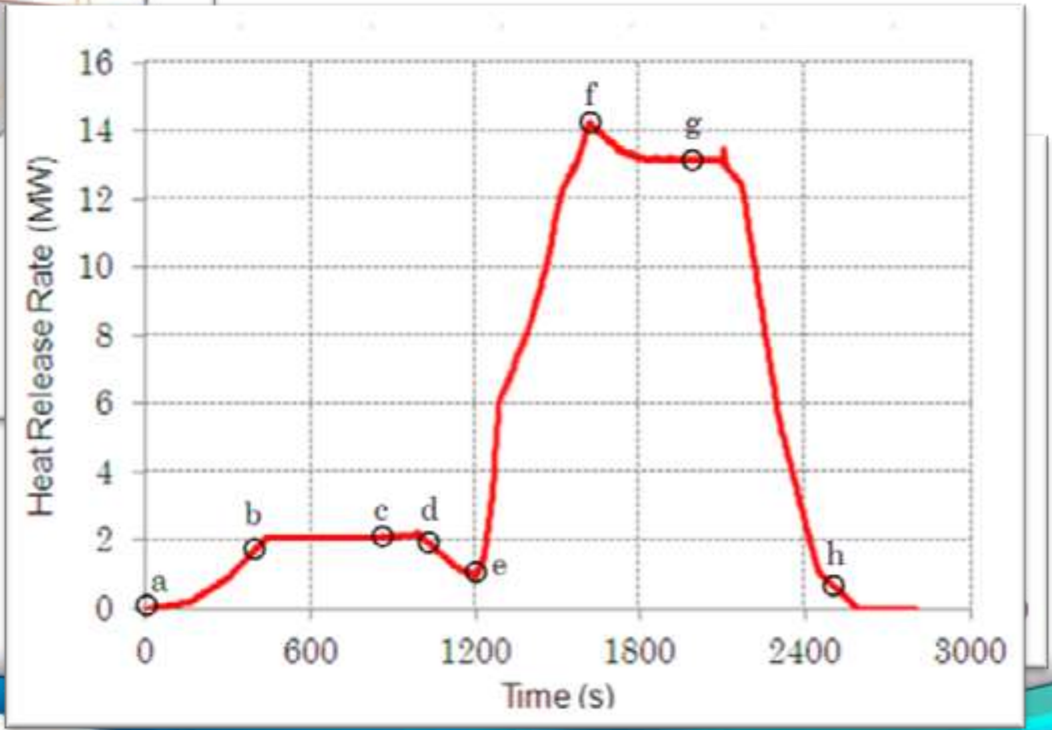
CFD Fire Simulations – FDS Inputs

```
%%-----------------------------
%%           SURFACES
%%-----------------------------
&SURF ID            = 'Lumber'
      MATL_ID       = 'PineWood'
      BACKING       = 'EXPOSED'
      BURN_AWAY     = .TRUE.
      HRRPUA        = 750
      THICKNESS     = 0.02
      SPREAD_RATE   = 0.0046
      XYZ           = 0.0, 0.4, 0.40 /

&SURF ID            = 'Ceiling Tile'
      MATL_ID       = 'PineWood'
      BACKING       = 'EXPOSED'
      RGB           = 234,234,234
      TRANSPARENCY  = 0.8
      THICKNESS     = 0.02 /

&SURF ID            = 'Ceiling Tile2'
      MATL_ID       = 'PineWood'
      BACKING       = 'EXPOSED'
      RGB           = 234,234,234
      TRANSPARENCY  = 0.0
      THICKNESS     = 0.02 /

%%-----------------------------
%%        FIRES AND FUELS
%%-----------------------------
&OBST XB = -5.40, 5.40, -0.20, 1.00, 0.00, 0.20, COLOR='SILVER' /
&OBST XB = -0.40, 0.40, 0.00, 0.80, 0.20, 0.40, SURF_IDS='Lumber','INERT','INERT', COLOR = 'GOLDENROD', BNDF_FACE(+3) = .TRUE. /
&HOLE XB = -0.40, -0.20, 0.00, 0.20, 0.20, 0.40 /
&HOLE XB = 0.20, 0.40, 0.00, 0.20, 0.20, 0.40 /
&HOLE XB = -0.40, -0.20, 0.60, 0.80, 0.20, 0.40 /
&HOLE XB = 0.20, 0.40, 0.60, 0.80, 0.20, 0.40 /

%%-----------------------------
%%        Ceiling Tiles
%%-----------------------------
&OBST XB = 0.20, 0.80, -0.20, 1.00, 2.40, 2.40, SURF_ID = 'Ceiling Tile'/
```

Types of Models

CFD Fire Simulations – FDS Outputs





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CFAST Exercise

Applicability

Attribute	Model		
	Hand Calculations	CFAST	FDS
Plume Temperature	Yes	Yes	Yes
Ceiling Jet Temperature	Yes	Yes	Yes
Hot Gas Layer Temperature	Yes	Yes	Yes
Flame Height	Yes	Yes	Yes
Sprinkler or detector activation	Yes	Yes	Yes
Radiation to Targets in room	Yes	Yes	Yes
Total Heat Transfer to Targets		Yes	Yes
Wall Temperature		Yes	Yes
Target Temperature		Yes	Yes
Smoke Concentration		Yes	Yes
Oxygen Concentration		Yes	Yes
Room Pressure		Yes	Yes
Combustion Reactions			Yes
Obstacles in the room			Yes
Complex room geometry			Yes
Toxic gas production			Yes
Sprinkler sprays			Yes
Evacuation studies			Yes

Applicability

Applicability of Models – Summary:

- Hand Calculations
  - → They are simple to use with relatively fast results.
  - → Limited to fires involving one or two combustibles and objects in the fire plume. Correlations must be used within specified ranges.
- CFAST
  - → Can be used for multiple burning items and objects in multiple rooms.
  - → Limited to geometry without any obstructions.
  - → More suitable for pre-flashover situations where the two-zone assumption holds true.
- FDS
  - → Performs detailed simulation of fire scenarios for complex geometry
  - → Provides good visual outputs of fire phenomena
  - → Time intensive

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CFAST Exercise

Case Study 1

BACKGROUND

- Building 1 and Building 2 contain low-level radiological waste in the form of soil and building materials stored in metal drums and metal boxes.
- Building 1 does not have adequate spatial separation required by the NBCC and FHA in regards to exposure protection. The building to which Building 1 may pose as an exposure hazard is Building 2 to the south. The spatial separation and exposure protection are based on minimizing radiant heat flux on adjacent buildings in order to prevent their ignition. To address that deficiency, the Building 1 FHA recommendation number 5 suggests upgrading "....*the west exterior wall assembly of* Building 1 *that directly exposes* Building 2 *to provide a 1 hour fire resistance rating*."

Case Study 1

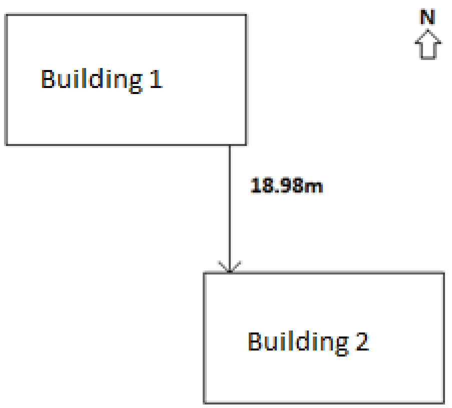
EVALUATION

The spatial separation between the exposed building (Building 2) and the fire source (Building 1) is 18.98m (see Figure 1 next slide). For the purposes of ensuring ultra-conservative measures the area of Building 1 is assumed to be one compartment.

A worse case fire scenario will be assessed to calculate the radiant heat flux (in kW/m^2) emitted from Building 1 . This calculation is based on the total fire load available in the building, to determine if it is of sufficient value to ignite combustibles in adjacent buildings (Building 2); i.e. to determine if Building 1 poses as an exposure hazard. This radiant heat calculation was not calculated in the FHA .

Case Study 1

Adjacent Building(s)



Case Study 1

Building 1 **BREAKDOWN OF COMBUSTIBLES**

Combustible Type and Amount Contribution (Kg)

❖Wooden Shelving Units (2 small)
2 x 30 Kg = 60 kg
❖Wooden Pallets
90 x 20 kg = 180 kg

❖Total Combustibles = 240 kg

Case Study 1

Fire Scenario:

All 90 wooden pallets and 2 small shelving units are burning simultaneously Location of these pallets is on the south end of Building 1 facing the north side of Building 2 for the least possible distance.

3 pallets on top of each other = 30 stacks (each stack of 3 pallets)

Critical Conditions for Building 2 to ignite:

The critical value for ignition of the adjacent unprotected wooden building is 12.5kW/m^2. This radiant heat has to travel a distance that exceeds 18.98m. The equation below is specifically designed for standards pallets. Therefore the length, height and width are included within the formula.

Case Study 1

H_c = 25cm = 0.25m

<u>Pallet Dimensions:</u>

Height = 10-1/4” = 25 cm (3 wooden pallets stacked on top of each other)

Width = 49” = 122 cm

Length = 49” = 122 cm

$$\dot{Q} = 1,000\,(1 + 2.14\,h_c)(1 - 0.027\,M)$$

$\dot{Q}$ = heat release rate (kW)

h_c = stack height (m)

M = moisture content

@ T = 20C & RH = 35% M = 0.09

Total Q =1531 kW x 30 stacks = 45930 kW

Case Study 1

Mass of wooden shelving units $M = 60$ kg

Calorific value $\Delta Hc = 16$ MJ/kg

Energy content of fuel:

$E = M\Delta Hc = 60$ kg x 16 = 960 MJ

Surface burning rate $q = 0.009$ kg/s/m^2 (soft board wood)

Wood crane floor area $Af = 28.908m \, x$ 12.171m = 351.839 m^2

Specific heat release rate

$Qs = q\Delta Hc = 0.009 \times 16 = 0.144$ MW/m2 = 144 kW/m2

Total heat release rate

$Q = Qs$ Af = 144 x 351.839 = 50664.816 kW

Total Q = Qpallets + Qshelving = 45930 kW + 50664.816 kW = 96594.816 kW

Case Study 1

$$\dot{q}'' = \dot{Q}_{rad} \frac{\cos\theta}{4\pi r^2}$$

Therefore, $Q_{rad} = Q_{total}$ x 0.3 = 96594.816 kW x 0.3 = 28978.4448 kW is radiant heat flux

Q_{total} is total heat release

Q_{rad} is radiant heat

Where $\theta = 0$ and $\cos\theta = 1$.

$$12.5\ kW/m^2 = \frac{28978.44\ kW}{4\pi r^2}$$

r = 13.58 m

Therefore, 13.58 m < 18.98 m.

With the present combustible load the critical radiant heat travels 13.58 m. This distance is less than the actual distance (18.98 m) between Building 1 and Building 2. Therefore, it does not meet the ignition condition.

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CFAST Exercise

Case Study 2

Life Safety & Flashover for Building 1 (Room 001) :

The design basis fire conditions are simulated using a computer based fire model and representative outputs are shown below in Building 1 in Room 001. The model used for the analysis of fires in the units is CFAST, Version 6.0.10.

Case Study 2

<u>The 2 zone model is designed with the following conservative assumptions:</u>

•Assume that all wall and partitions are plywood with no fire retardant painting.

•Assume 2 fires at the same time and in the same place (kerosene and 2 panel work station).

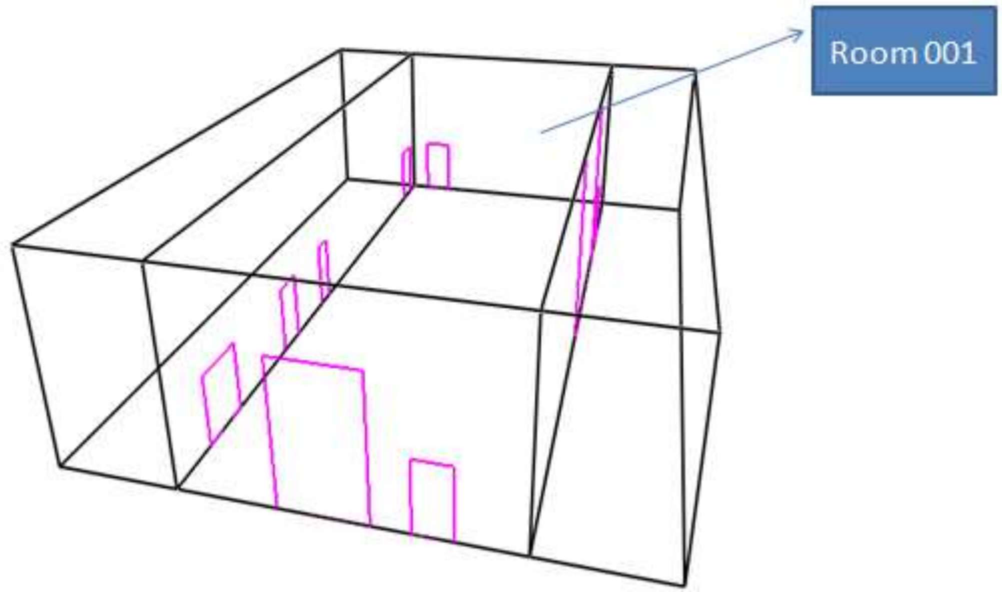
•Assume that all doors were closed at all time and that there were no windows for life safety calculations.

•Assume door are open and there is 2 windows for flashover calculations.

➢ The output of the CFAST model is summarized in figures 1- 4 below. The output confirmed that there are no life safety issues; no flashover and no fire spread concerns in Room 001.

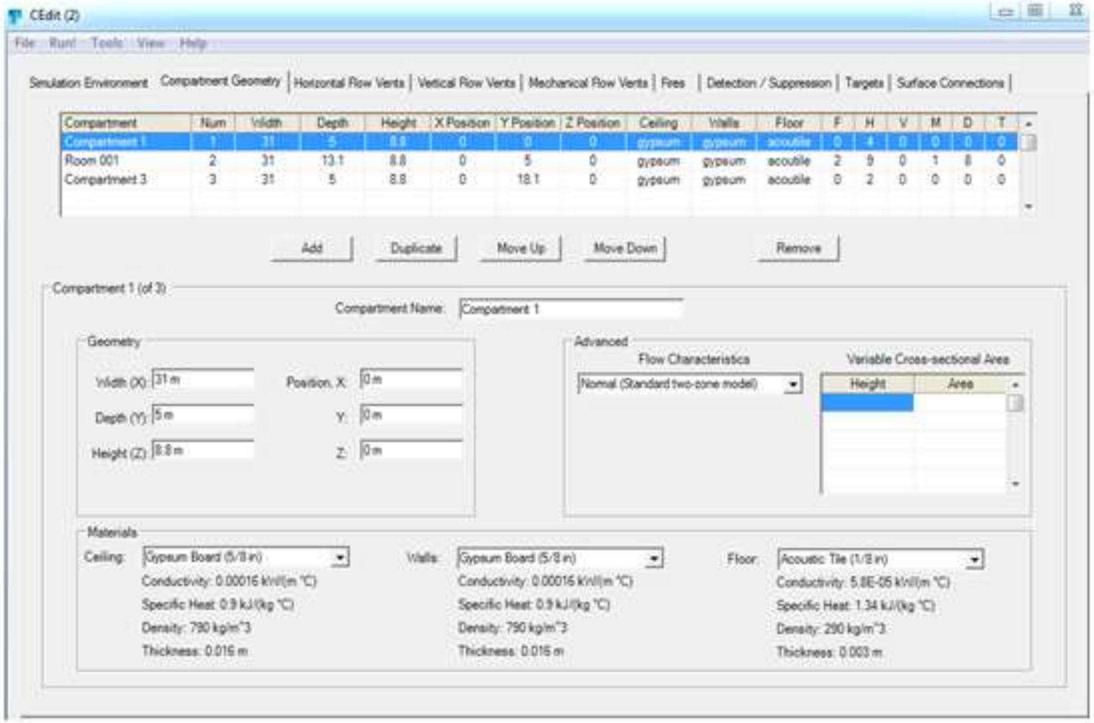
Case Study 2

CFAST input



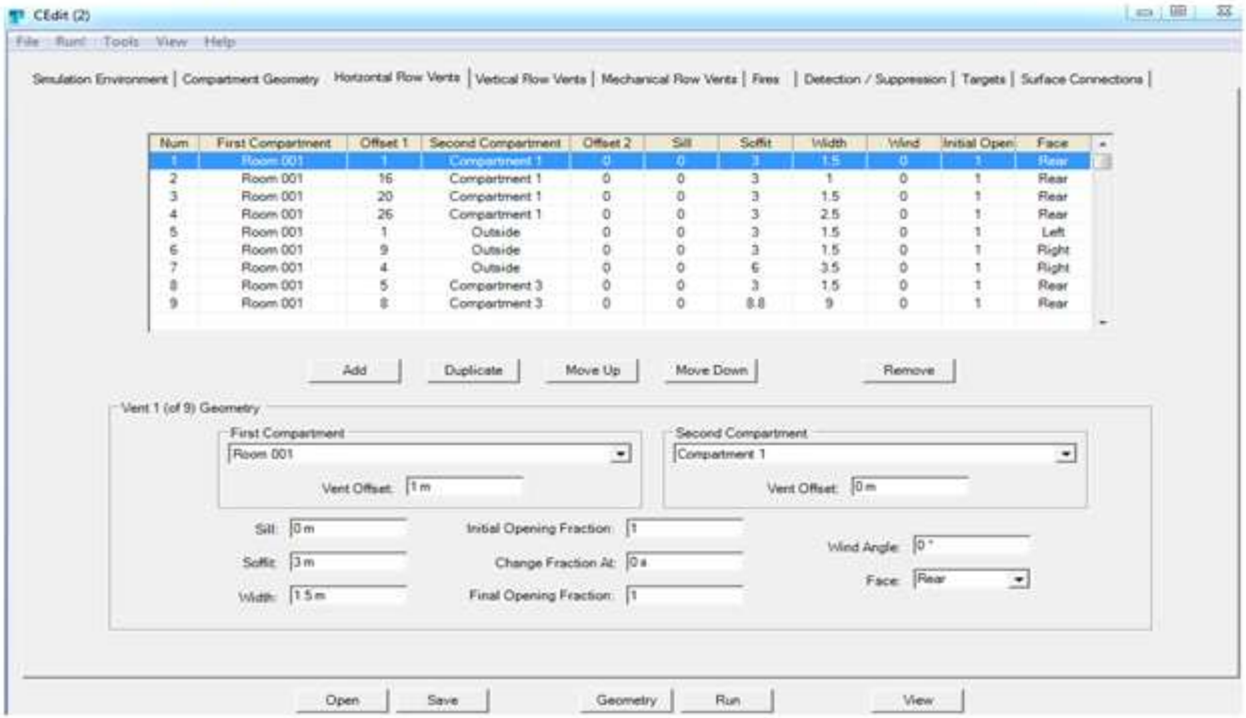
Case Study 2

CFAST input



Case Study 2

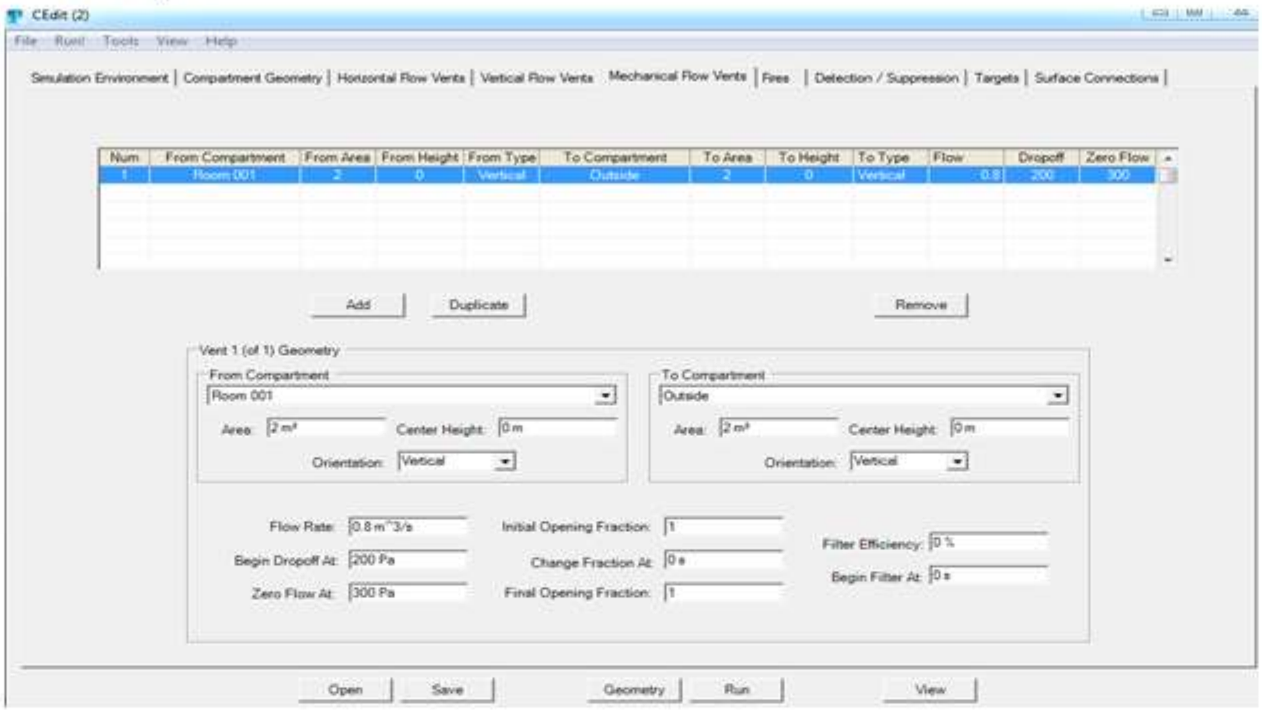
CFAST input



Num	First Compartment	Offset 1	Second Compartment	Offset 2	Sill	Soffit	Width	Wind	Initial Open	Face
1	Room 001	1	Compartment 1	0	0	3	1.5	0	1	Rear
2	Room 001	16	Compartment 1	0	0	3	1	0	1	Rear
3	Room 001	20	Compartment 1	0	0	3	1.5	0	1	Rear
4	Room 001	26	Compartment 1	0	0	3	2.5	0	1	Rear
5	Room 001	1	Outside	0	0	3	1.5	0	1	Left
6	Room 001	9	Outside	0	0	3	1.5	0	1	Right
7	Room 001	4	Outside	0	0	6	3.5	0	1	Right
8	Room 001	5	Compartment 3	0	0	3	1.5	0	1	Rear
9	Room 001	8	Compartment 3	0	0	8.8	9	0	1	Rear

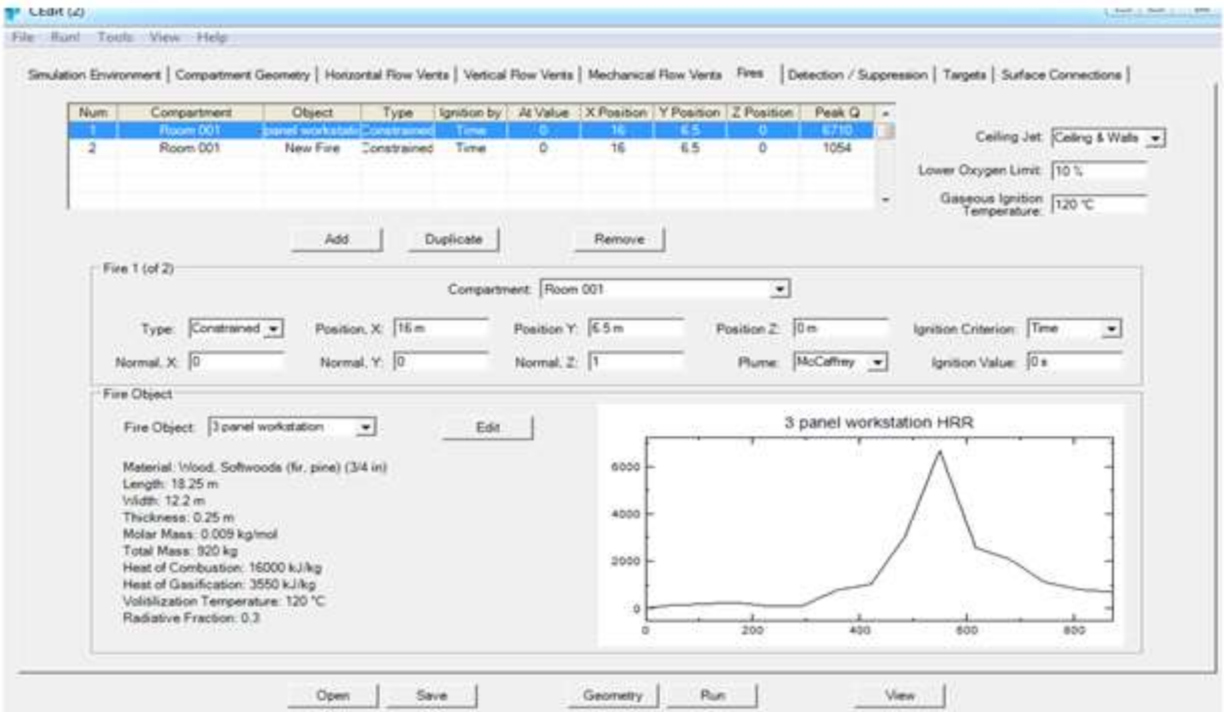
Case Study 2

CFAST input



Case Study 2

CFAST input



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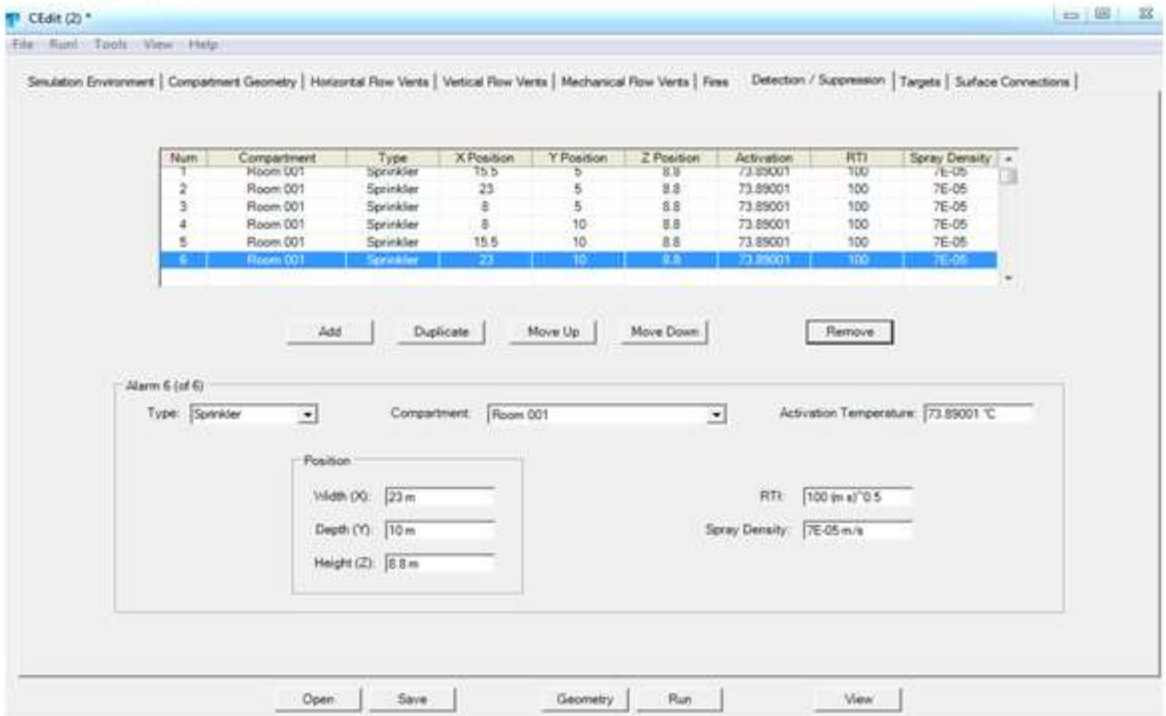
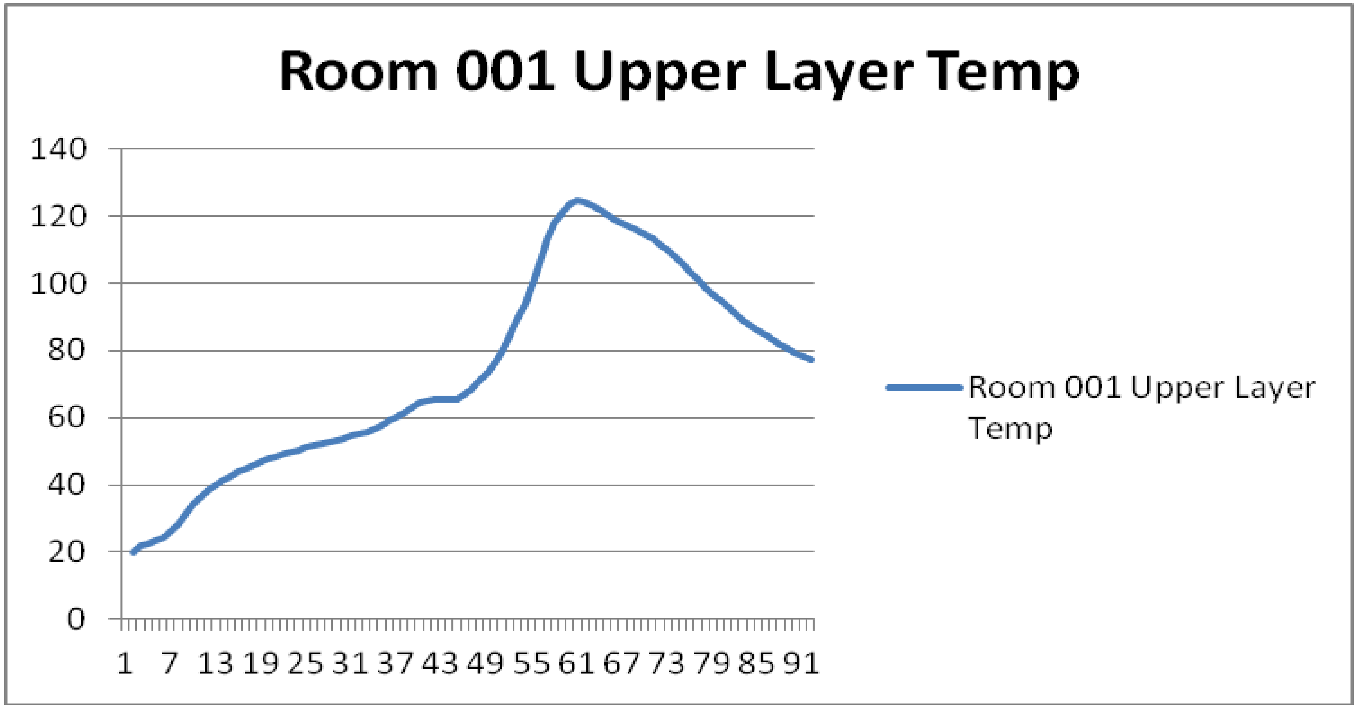
Case Study 2

CFAST input



Case Study 2

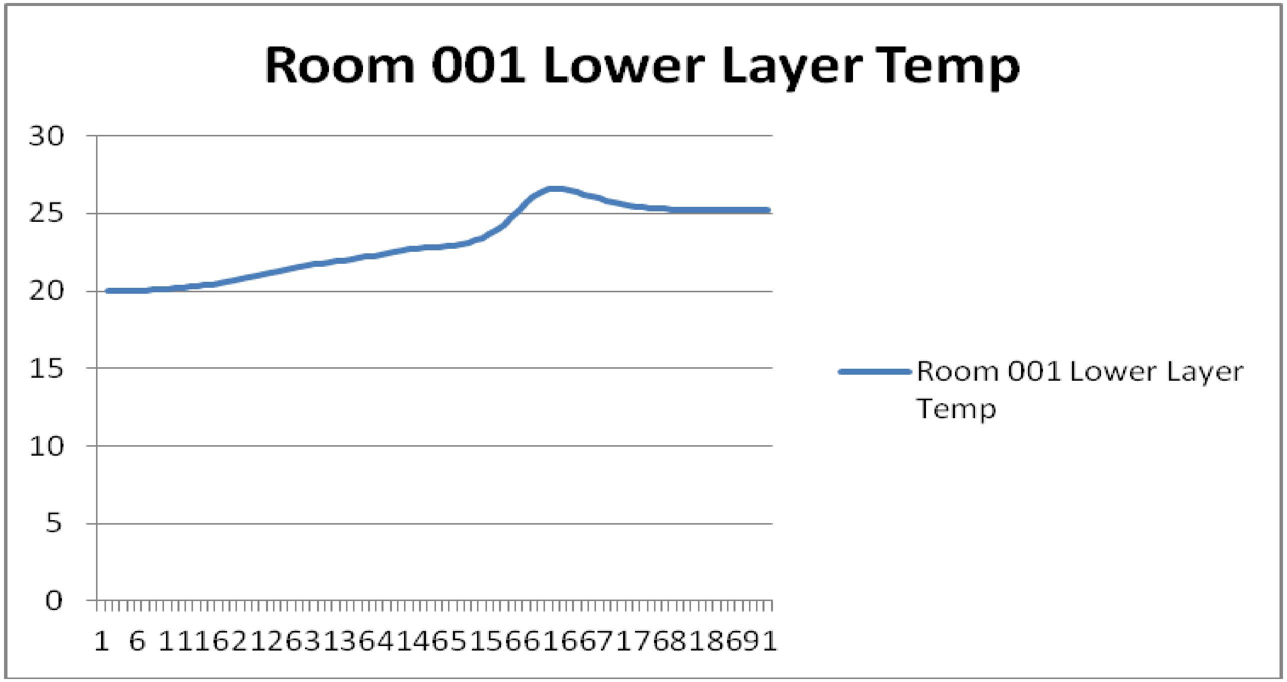
CFAST output:



Conclusion: Maximum upper layer temperature was 124 C which is much lower than the flashover temperature between (500 – 600 C). Note that as this is upper layer temperature the sprinkler system will activate by 80 C.

Case Study 2

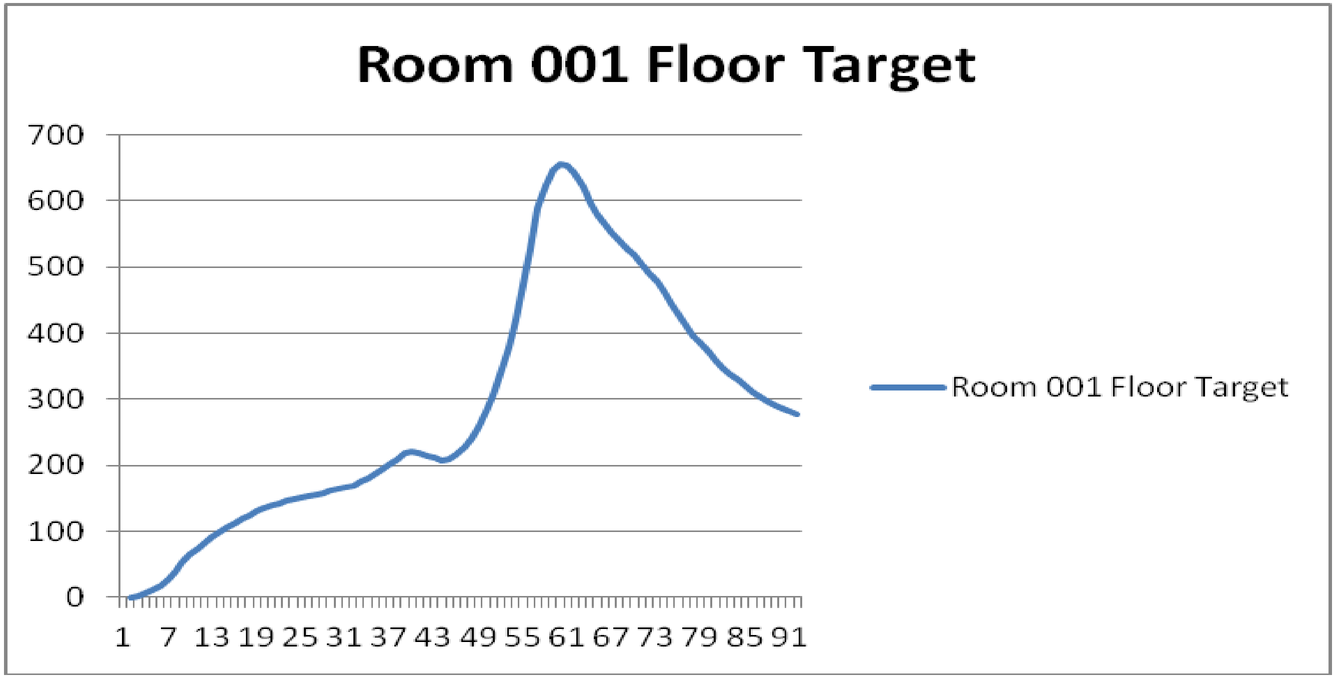
CFAST output:



Result: There is no human skin threat as the maximum temperature of 27 C didn’t exceed the safety limit of 120 C at 1.5 meter.

Case Study 2

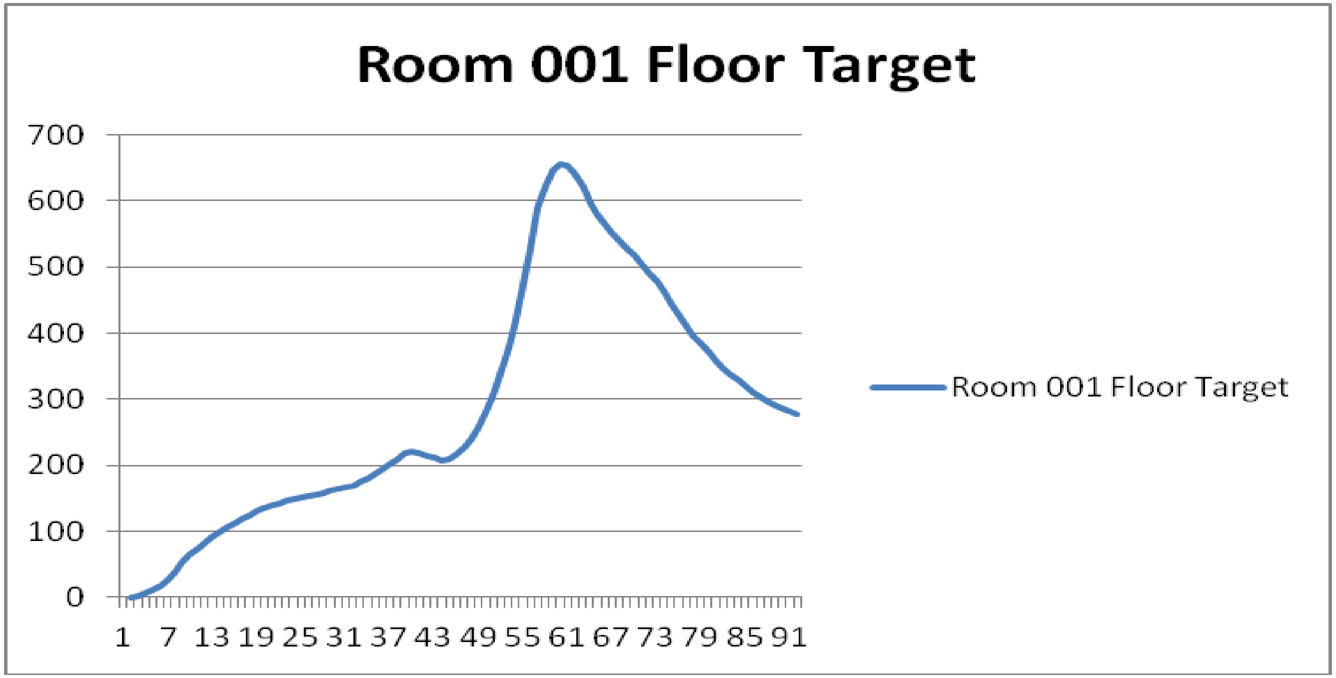
CFAST output:



Conclusion: There will be no flashover as the maximum radiant heat flux was 0.65 KW/m2 and the flashover radiant heat flux is over 20 KW/m2.

Case Study 2

CFAST output:



Conclusion: There will be no human skin threat as the maximum radiant heat flux was 0.65 KW/m2 and didn't exceed the skin safety limit of 2.5 KW/m2.

Case Study 2

Conclusion

- The output of the fire model (CFAST) confirmed that there are neither life safety concerns nor flashover in Room 001 in Scenario 2 in Building 1 FHA

Recommendation

- Sealing all penetrations/holes through partitions or ceiling structures and painting the plywood/masonite walls/ceilings/doors/mezzanines with fire retardant paint. (ULC listed fire stop).

Agenda:

Introduction

Types of Models

Applicability

Case Study 1

Case Study 2

Case Study 3

CFAST vs. Hand Calculations

CFAST vs. Hand Calculations Vs NUREG 1805

CFAST Exercise

Case Study 3

Recommendation 5 from the Building 1 FHA states that:

- "Upgrade the structure to provide 45 min fire-resistance rating for the combustible load bearing walls, columns and arches supporting the floor assemblies. Also floor assemblies and combustible mezzanines to be upgraded to provide fire resistance rating of at least 45 minutes. Please note that existing elements may already have the required fire-resistance rating, however this could not be ascertain as based on the available documents. Due to the fact that the building is existing, and this issue has no nuclear safety impact, and the fact that this undertaking may be impractical and cost prohibitive, alternate approaches, such as additional sprinkler mitigation, or other measures may be considered subject to AHJ approval. A further review indicating proposed mitigating measures is recommended. The Building Condition Assessment Report has additional details of the required measures to achieve 45 minutes fire resistance ratings."

Case Study 3

- In room 304, the total combustible loads were decreased form 1.40E+04 kg & 5.33E+08 kJ on May 19/2010 to 1935.64 kg &5.04E+07 kJ on March 17/2014.
- In area 130, the total combustible loads were decreased form 7520 kg & 1.54E+08 kJ on May 19/2010 to 2101.69 kg & 7.82E+07 kJ on March 17/2014.

➢ The main objective of this model was to evaluate the maximum temperature in area 130 & room 304, determine if radiation emitted from the fire scenario 1 & 3 is enough to ignite adjacent objects and the if there is possibility for fire flashover?

Case Study 3

•The design basis fire conditions were simulated using a computer based fire model. The model used for the analysis of fires in the units was FDS.

•FDS is a multi- zone model. These models are based on fundamental laws of physics rather than empirical correlation. For this reason, CFD models offer the most adaptable approach for solving problems. Though, due to their difficult nature, they need expert knowledge from the user.

Case Study 3

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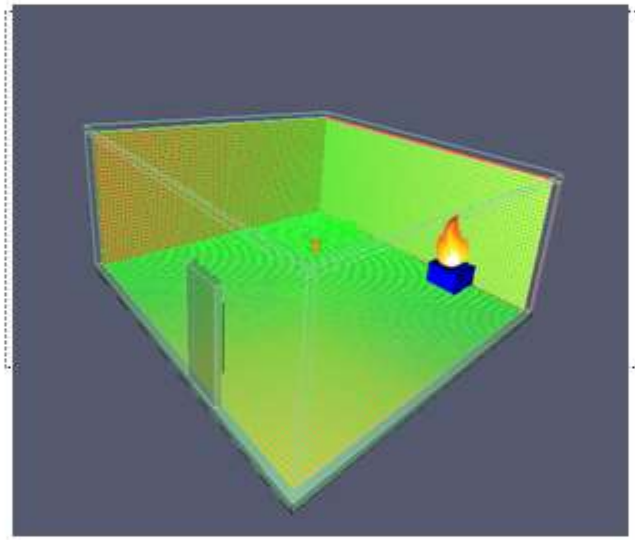
Case Study 3

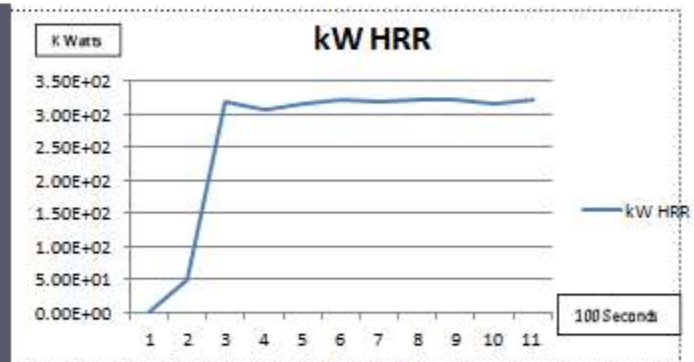
For Room 304

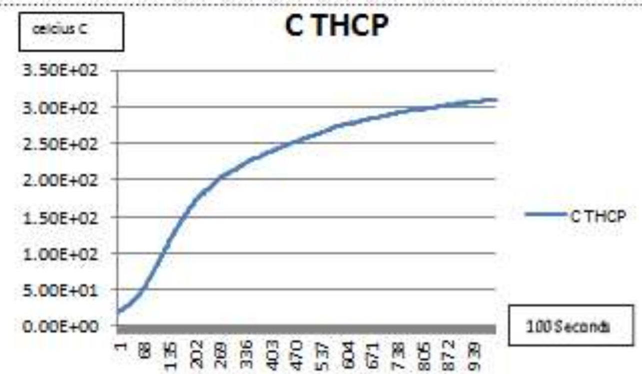
- A mesh size of 80 cm x 80 cm x 30 cm was used in the FDS model. The fire was modeled using Q = 1000kw/m2. This methodology assumes a t^2fire is growth. The materials that were used in the model for the floor, walls and ceiling were plywood and tiles.
- There was a Thermocouple THCP added inside the room with coordinates (4m, 4m, and 1m) for the purpose of keeping a registry of the temperature at this specific location.

Case Study 3

FDS Output:







Case Study 3

- The maximum HRR is 322 KW and 310 C; therefore there were will be no fire flashover in this scenario
- **Employ the simple model:** The flame is characterised as a point source at mid-height along the centre line of the vertical axis of the flame. The heat flux at some distance r from this point source is:

$$\dot{q}'' = \dot{Q}_{rad} \frac{\cos\theta}{4\pi r^2}$$

Therefore, $Q_{rad} = Q_{total}$ x 0.3 = 322 KW x 0.3 = 96.6 KW

$\dot{q}''$ is radiant heat flux

Q_{total} is total heat release

Q_{rad} is radiant heat

Where θ = 0 and cos θ = 1.

Case Study 3

12.5 kW m^{-2} is the critical radiant flux for the ignition of wood

$\dot{q}''_{net}$ = net heat transfer leaving surface 12.5 (kW m^{-2})

$$12.5\ kW/m^2 = \frac{xkW}{4\pi r^2}$$

$$12.5\ kW/m^2 = \frac{96.6\ kW}{4\pi r^2}$$

r = 0.78 m

- The maximum calculated radiant heat emissive distance is 0.78 m and will not ignite any objects beyond 0.78 m.

Case Study 3

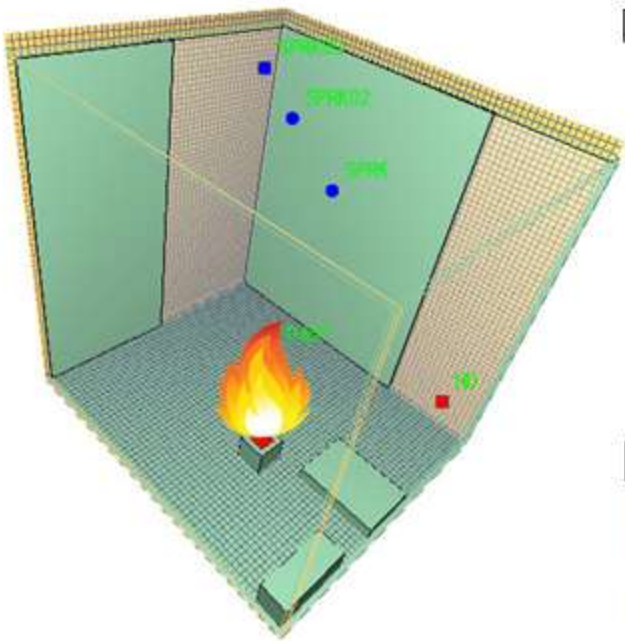
For Area 130

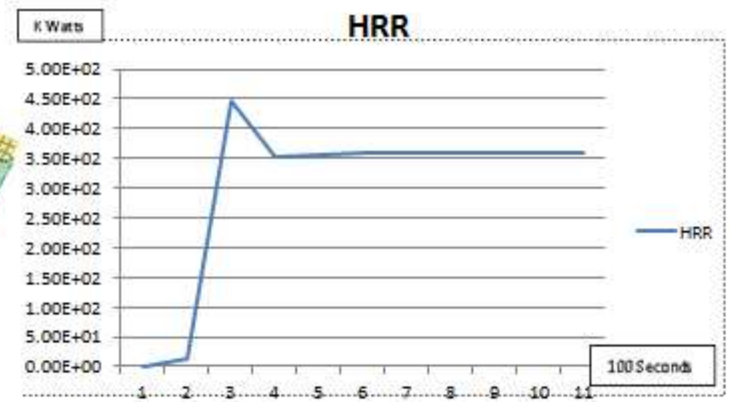
•A mesh size of 105 cm x 125 cm x 125 cm was used in the FDS model. The fire was modeled using Q = 1000kw/m2. This methodology assumes a t^2fire is growth. The materials that were used in the model for the floor, walls and ceiling were Plywood, Yellow pine and tiles.

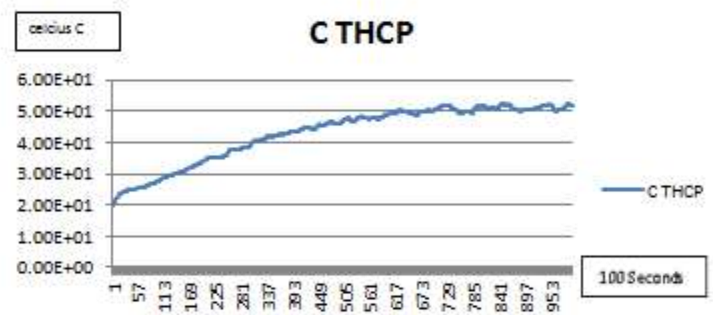
•The sprinkle system will activate at 78 C and was placed on the ceiling of the room 130 at 12.2 m height. There was a Thermocouple THCP added inside the room with coordinates (6m, 5m, and 3m) for the purpose of keeping a registry of the temperature at this specific location.

Case Study 3

FDS Output:







Case Study 3

- Since the maximum HRR is 360 KW and 310 C, therefore there were will be no fire flashover in this scenario. As the sprinkle system will activate at 78 C. Even though the sprinkle system is located at the ceiling which is 12.2 m high, it will fully contain and suppress the fire.
- **Employ the simple model:** The flame is characterised as a point source at mid-height along the centre line of the vertical axis of the flame. The heat flux at some distance r from this point source is:

$$\dot{q}'' = \dot{Q}_{rad} \frac{\cos\theta}{4\pi r^2}$$

Therefore, $Q_{rad} = Q_{total}$ x 0.3 = 360 KW x 0.3 = 120 KW

$\dot{q}''$ is radiant heat flux

Q_{total} is total heat release

Q_{rad} is radiant heat

Where $\theta = 0$ and $\cos\theta = 1$.

Case Study 3

New Recommendations for Building 1 based on Additional Fire Hazards

Deficiency	Additional Recommendations	Priority	Status
Reduce & monitor the amount of combustible materials in Building 1	Obtain photographs of Building 1 rooms identifying the current configuration and provide to Fire Protection Program. Photographs to be maintained by Chief Fire Prevention Officer as a reference point to ensure that there are no additional combustibles accumulating over the years and to assure that these conditions are maintained between the monthly inspections.	Medium	
Absence of non-combustible storage cabinets in room 304	Provide non-combustible storage cabinets for room 304.	Medium	

Agenda:

Introduction

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Case Study 2

Case Study 3

CFAST vs. Hand Calculations

CFAST vs. Hand Calculations Vs NUREG 1805

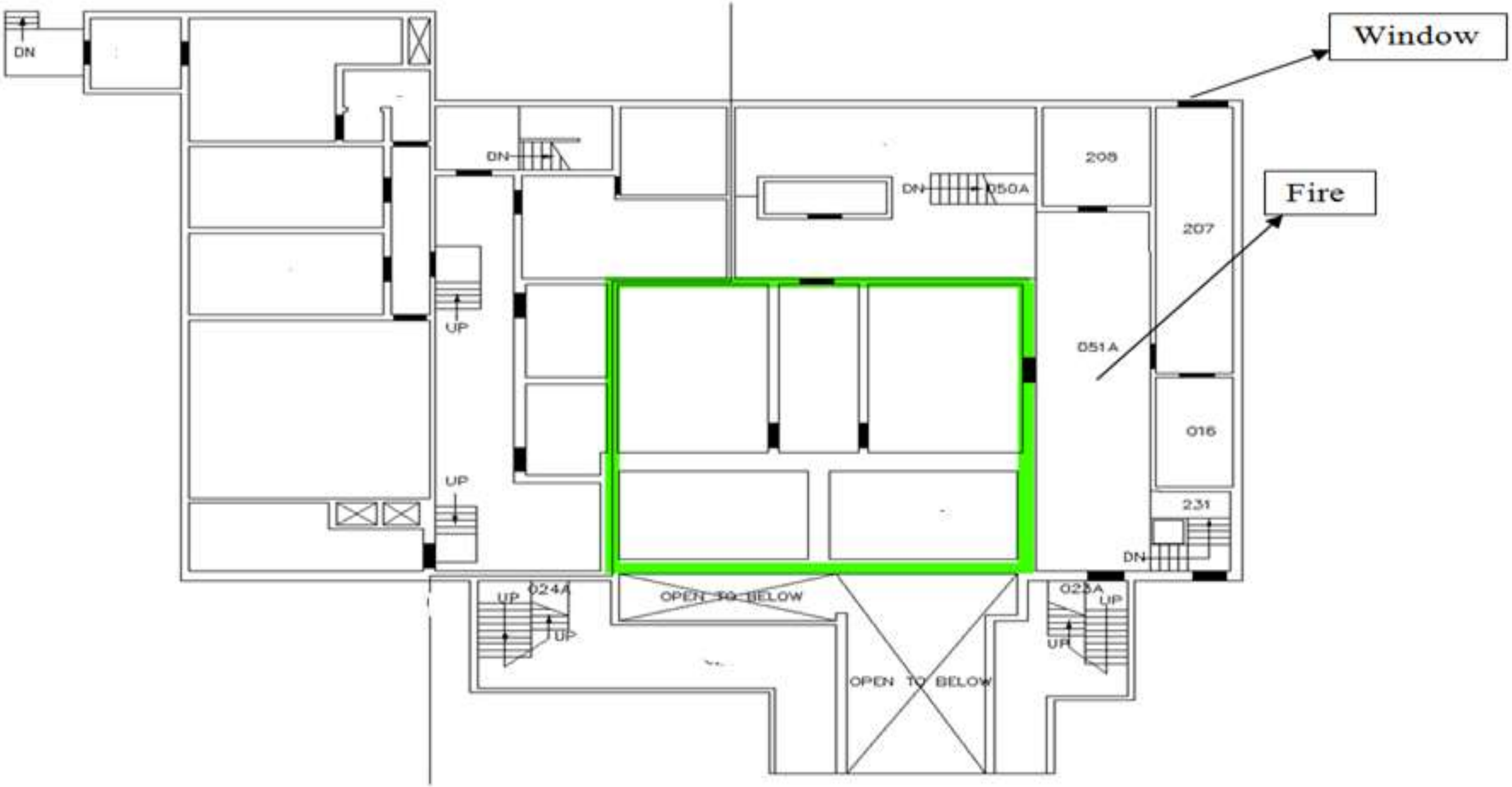
CFAST Exercise

CFAST vs. Hand Calculations

- The design basis fire conditions were simulated using a computer based fire model. The model used for the analysis of fires in the units was CFAST, Version 6.0.10. This program is supported by appropriate technical documentation and is widely accepted. The program was verified as being appropriate for the applications used in this building.

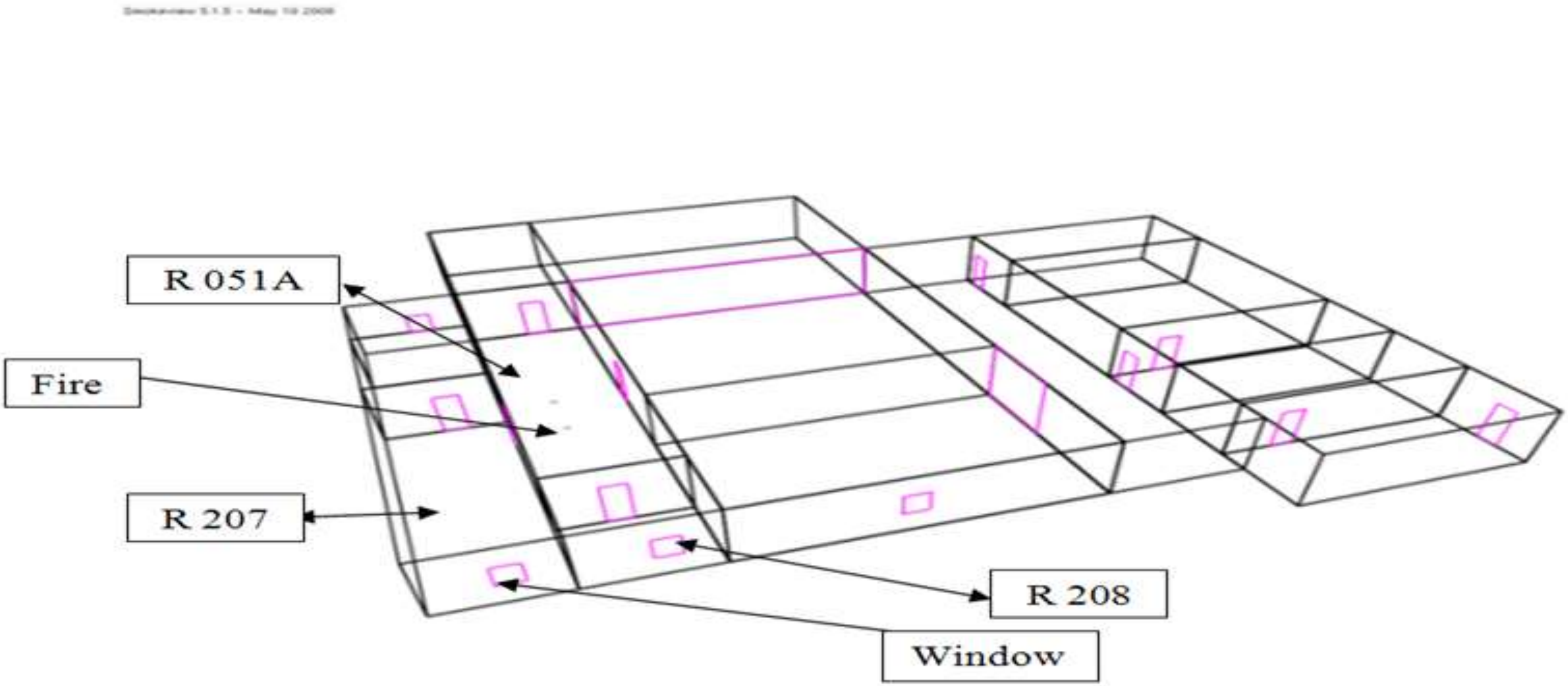
- The 2 zone model fire scenario was designed assuming an ultra fast fire growth rate t^2 and the material is 1 m^3 of methane with heat of combustion of 50,000 kJ/kg in room 051 in B200.

CFAST vs. Hand Calculations



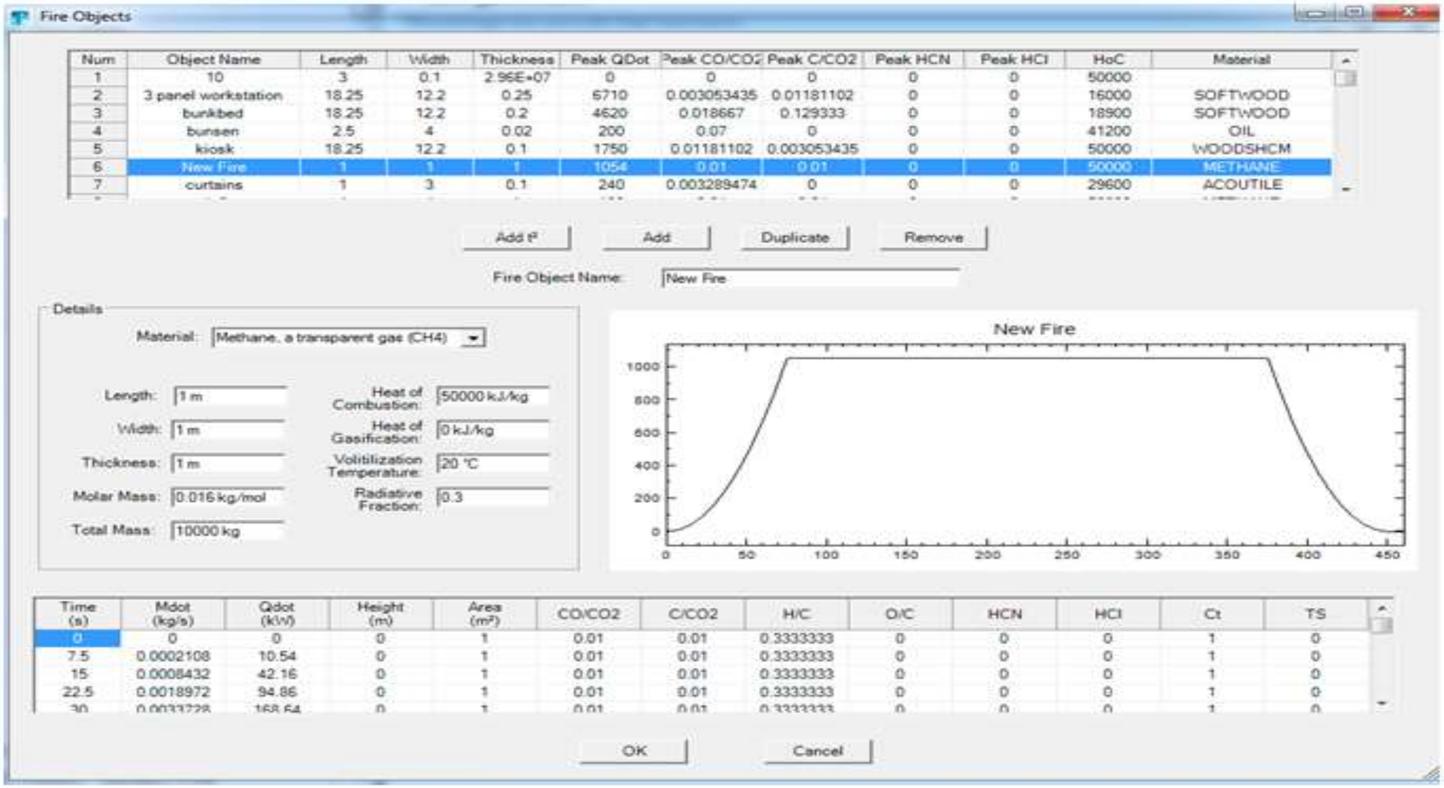
CFAST vs. Hand Calculations

CFAST input



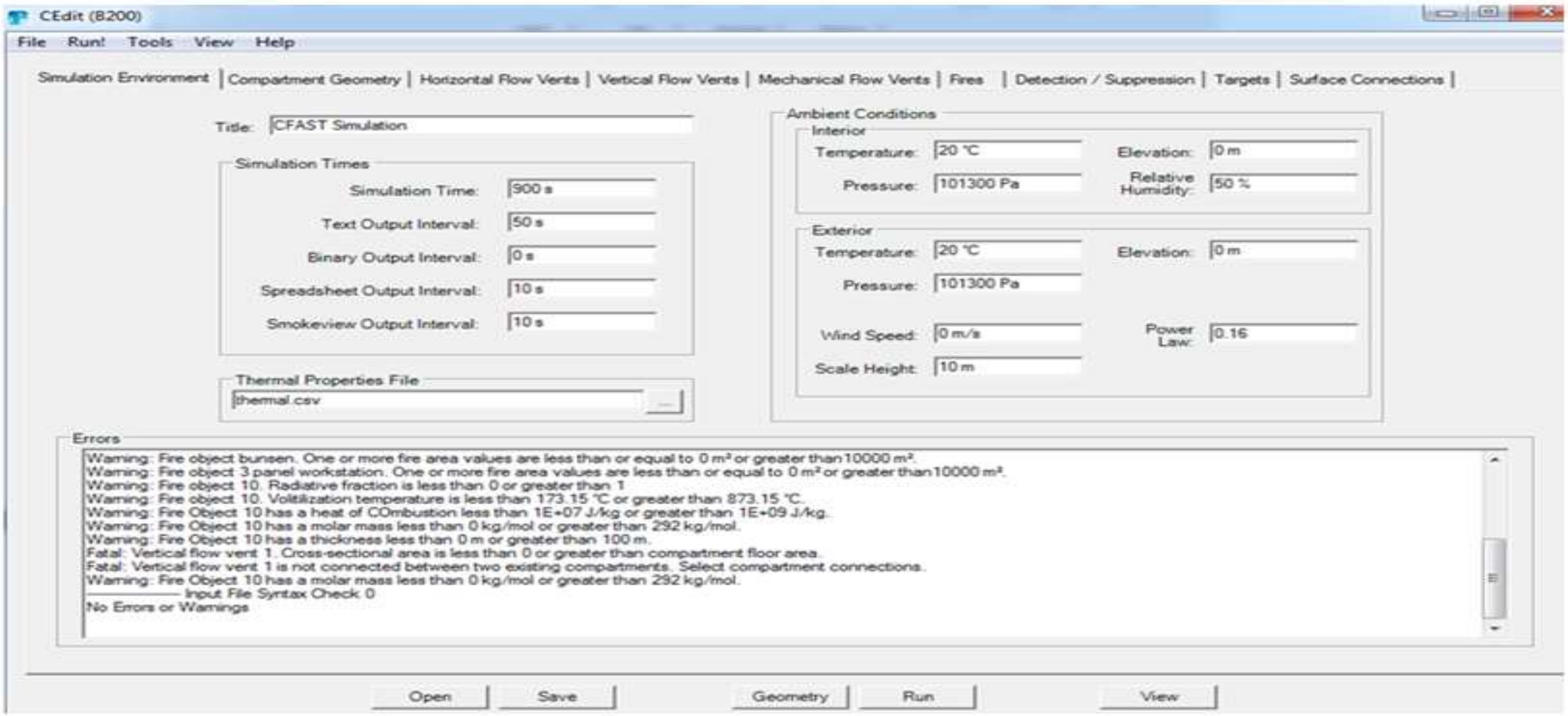
CFAST vs. Hand Calculations

CFAST Fire input in Room 051:



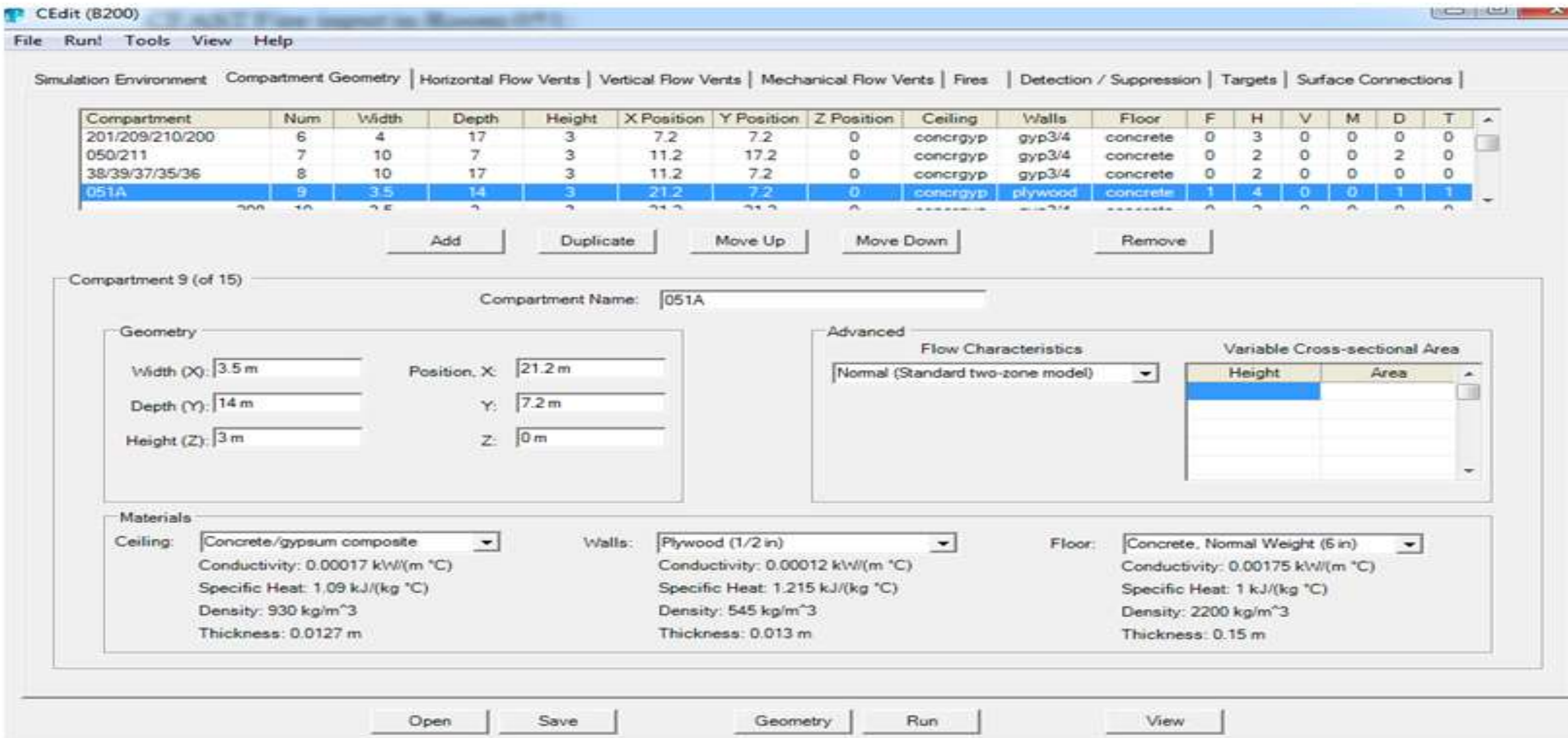
CFAST vs. Hand Calculations

CFAST simulation input:



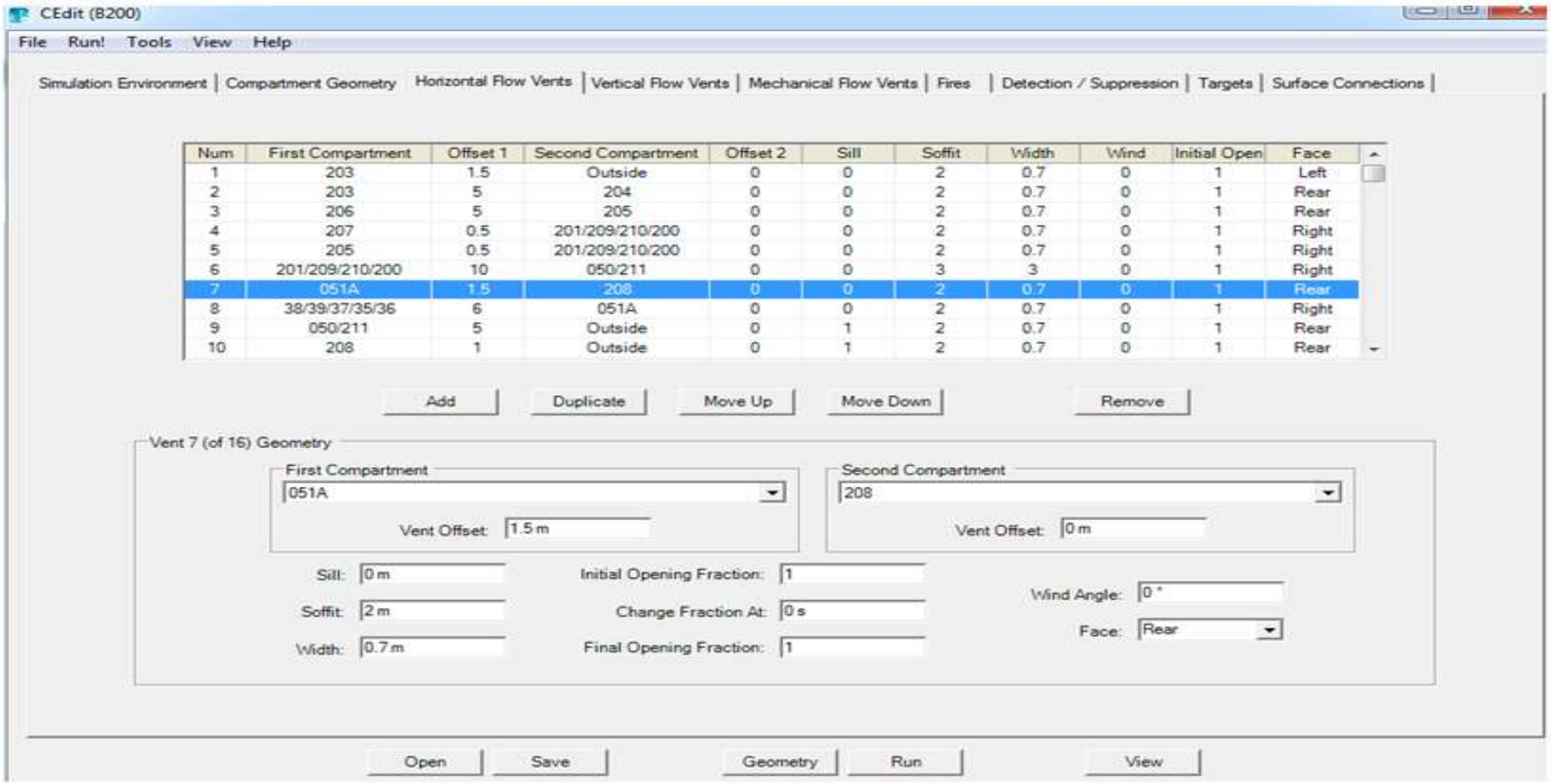
CFAST vs. Hand Calculations

CFAST Room 051:



CFAST vs. Hand Calculations

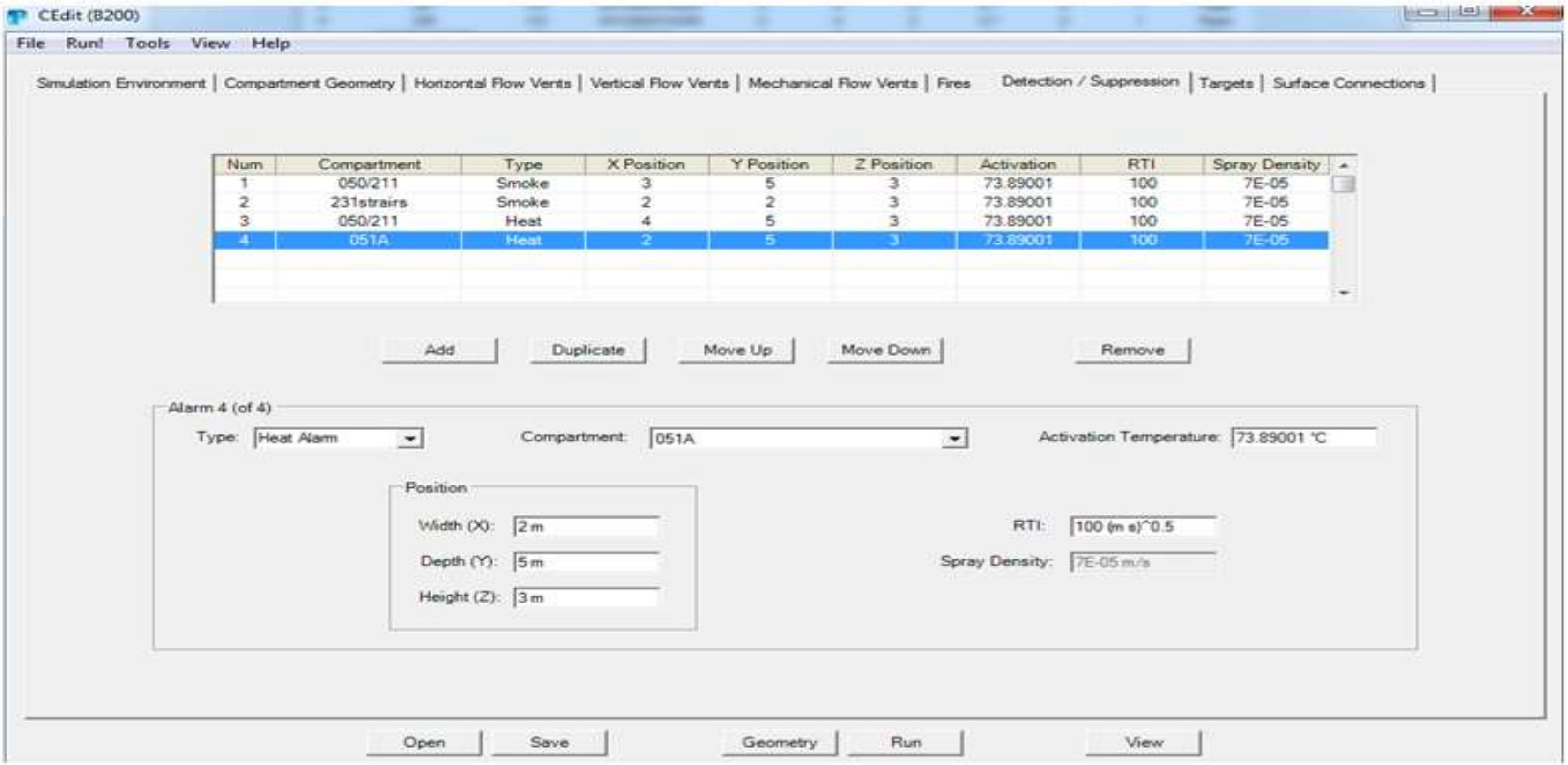
CFAST Room 051 door:



Num	First Compartment	Offset 1	Second Compartment	Offset 2	Sill	Soffit	Width	Wind	Initial Open	Face
1	203	1.5	Outside	0	0	2	0.7	0	1	Left
2	203	5	204	0	0	2	0.7	0	1	Rear
3	206	5	205	0	0	2	0.7	0	1	Rear
4	207	0.5	201/209/210/200	0	0	2	0.7	0	1	Right
5	205	0.5	201/209/210/200	0	0	2	0.7	0	1	Right
6	201/209/210/200	10	050/211	0	0	3	3	0	1	Right
7	051A	1.5	208	0	0	2	0.7	0	1	Rear
8	38/39/37/35/36	6	051A	0	0	2	0.7	0	1	Right
9	050/211	5	Outside	0	1	2	0.7	0	1	Rear
10	208	1	Outside	0	1	2	0.7	0	1	Rear

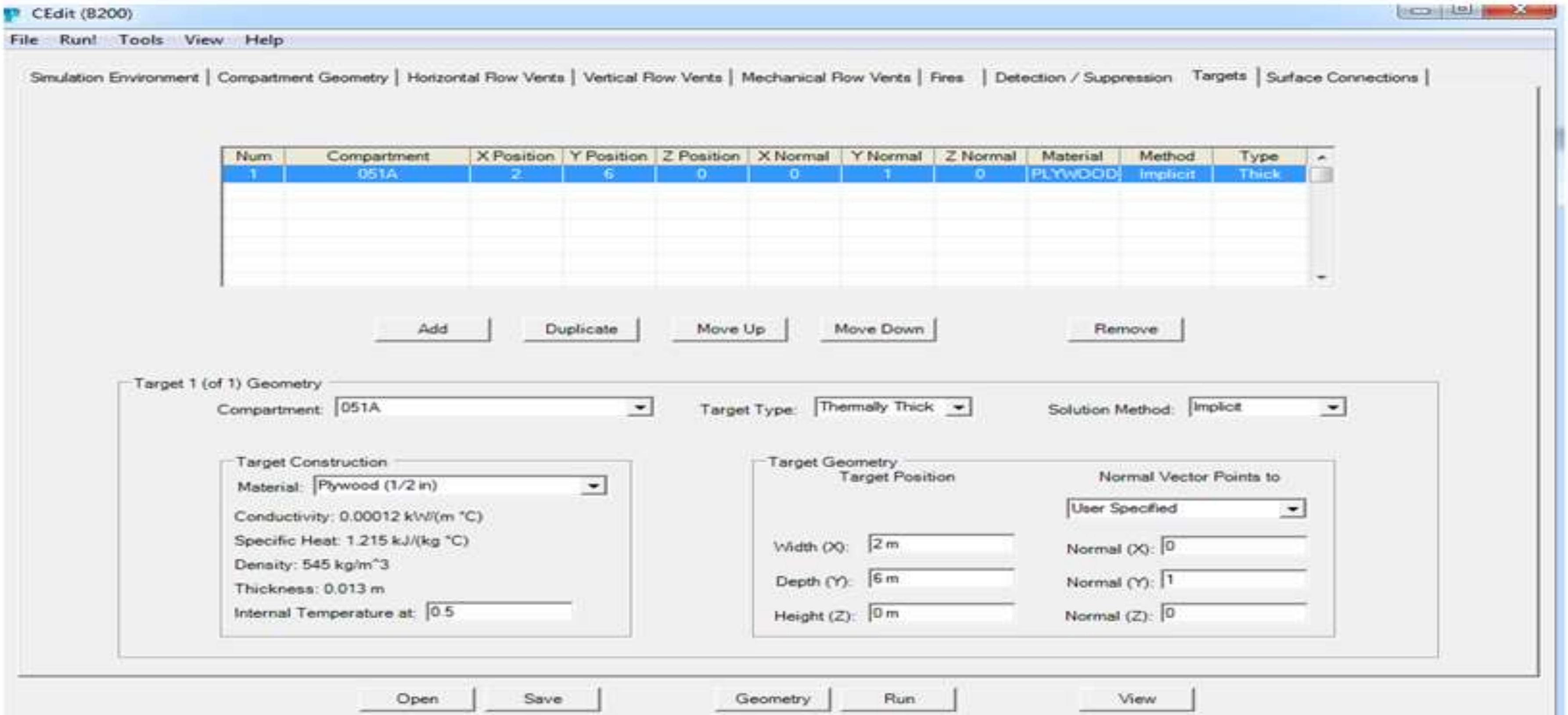
CFAST vs. Hand Calculations

CFAST Room 051 heat detection:



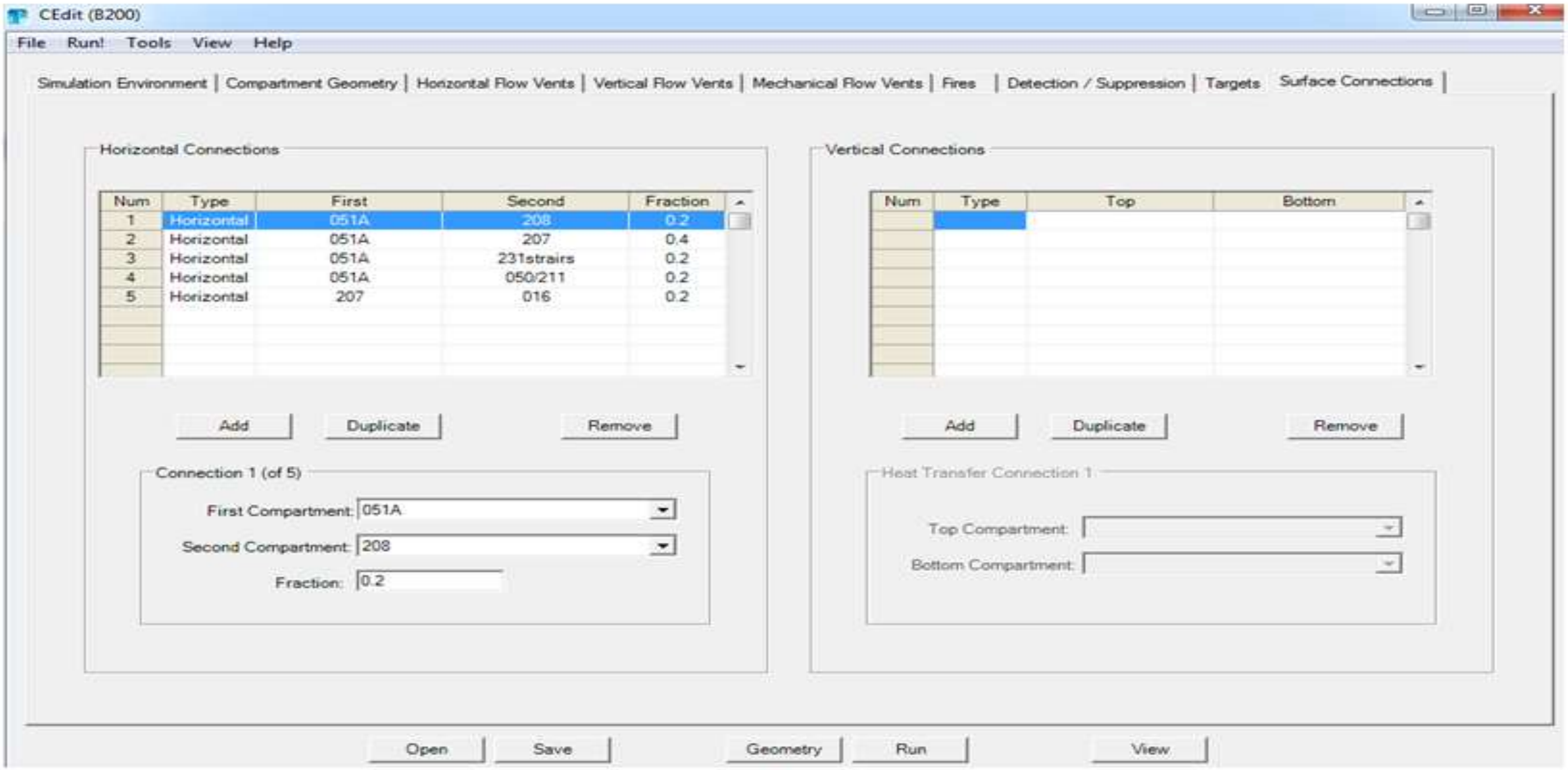
CFAST vs. Hand Calculations

CFAST Room 051target:



CFAST vs. Hand Calculations

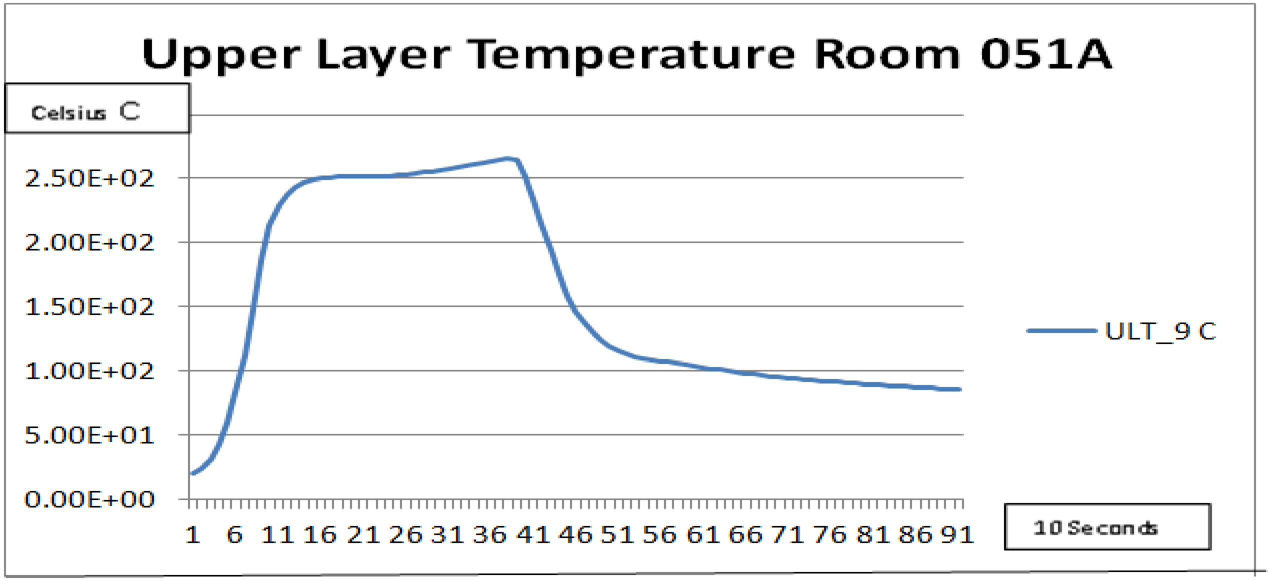
CFAST Room 051 connections:



CFAST vs. Hand Calculations

CFAST output:

Upper Temperature Distribution in room 051 A
Temperature °C vs. Time 10 sec

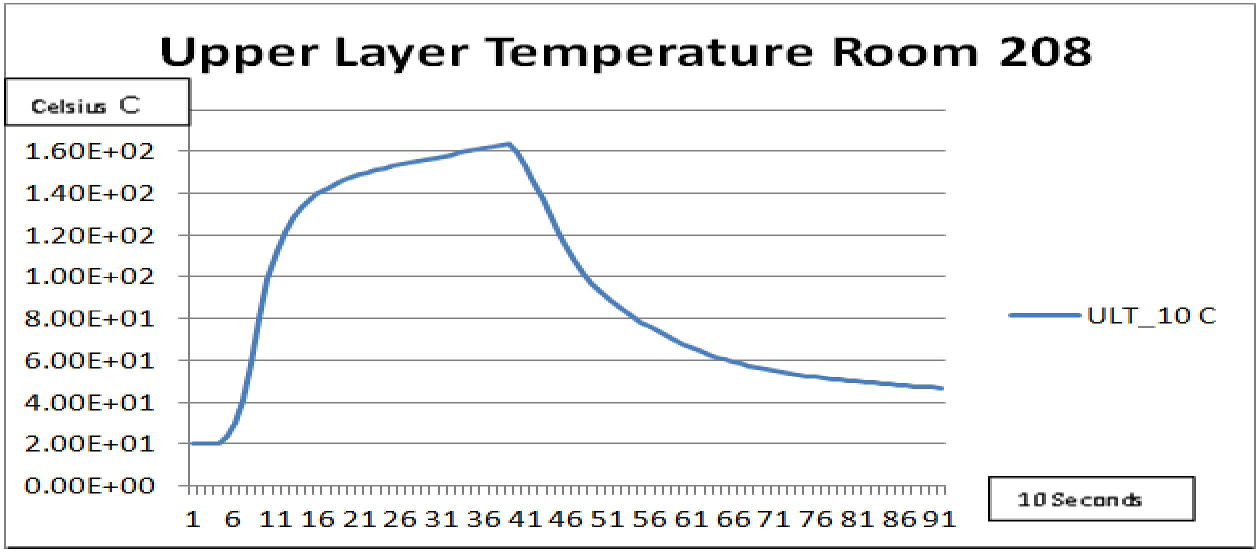


There will be no flashover as the maximum temperature was 257 C and the flashover temperature is (Between 500 – 600 C). No wood will ignite as well (Ignition for wood at 350°C).

CFAST vs. Hand Calculations

CFAST output:

Upper Temperature Distribution in room 208
Temperature °C vs. Time 10 sec

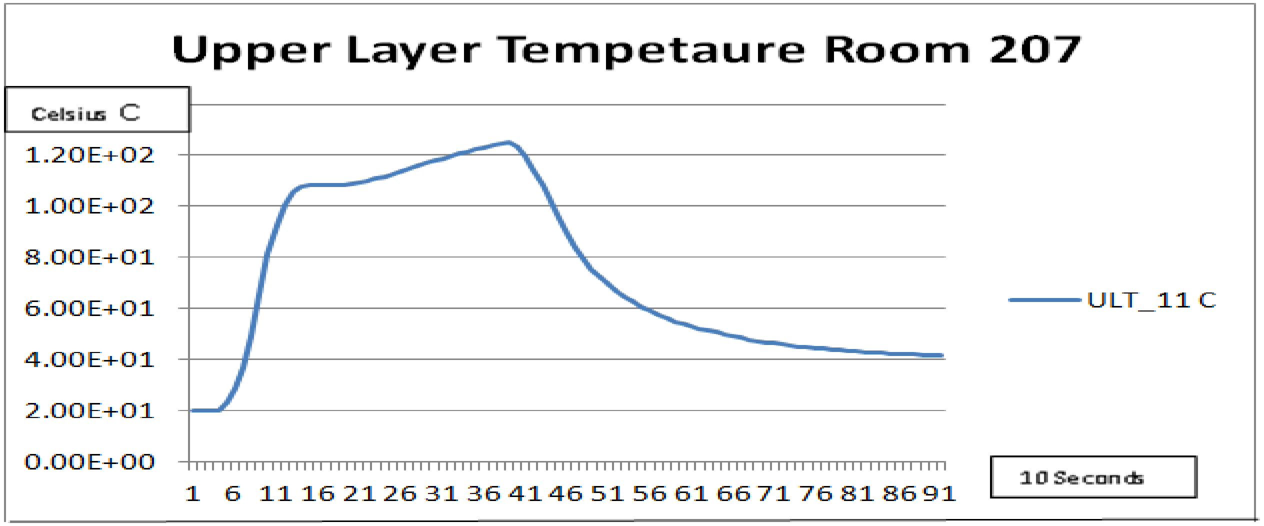


There will be no flashover as the maximum temperature was 161 C and the flashover temperature is (Between 500 – 600 C). No wood will ignite as well (Ignition for wood at 350°C).

CFAST vs. Hand Calculations

CFAST output:

Upper Temperature Distribution in room 207
Temperature °C vs. Time 10 sec

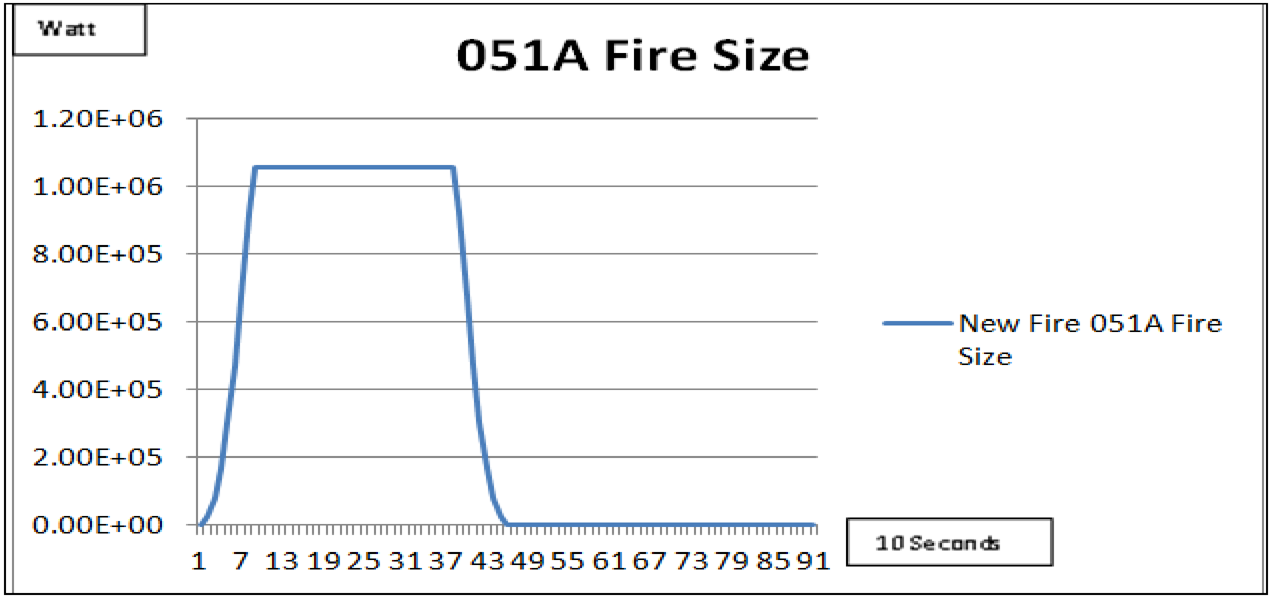


There will be no flashover as the maximum temperature was 123 C and the flashover temperature is (Between 500 – 600 C). No wood will ignite as well (Ignition for wood at 350°C).

CFAST vs. Hand Calculations

CFAST output:

Heat Release Rate Distribution in room 051
Watt vs. Time 10 sec

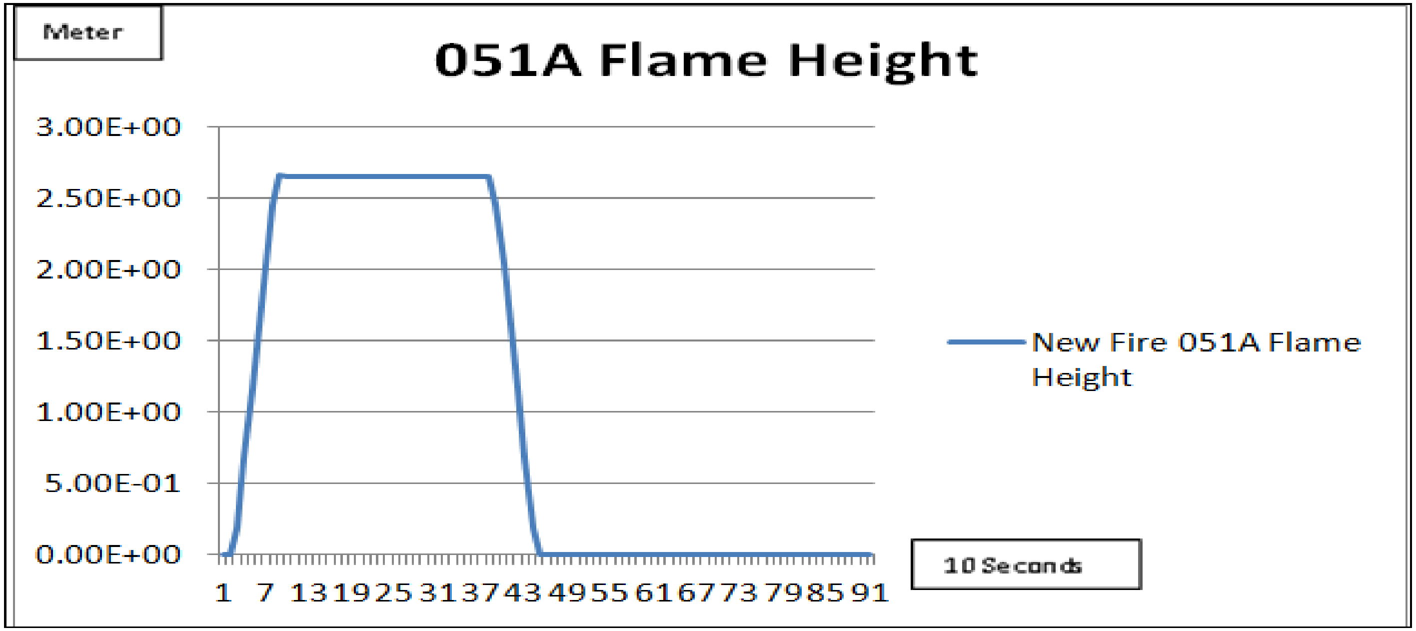


The maximum HRR is 1054kW.

CFAST vs. Hand Calculations

CFAST output:

Flame Distribution in room 051
Watt vs. Time 10 sec

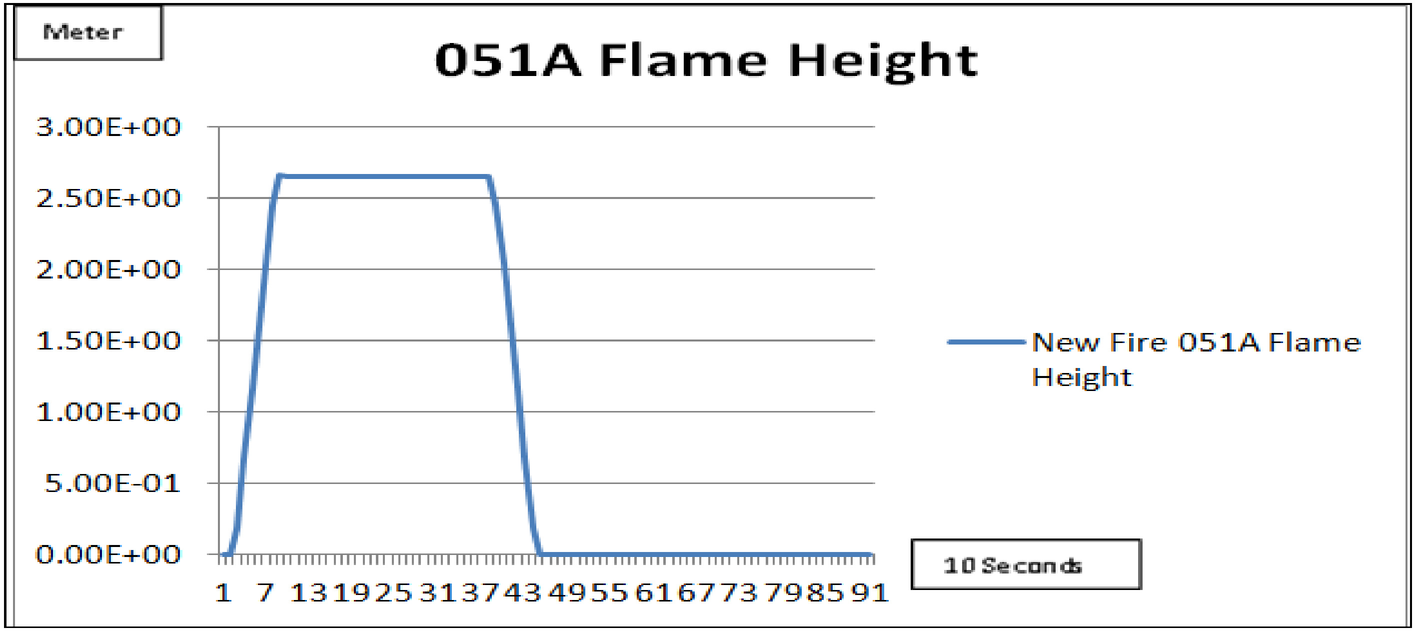


The maximum flame height is 2.6 m.

CFAST vs. Hand Calculations

CFAST output:

Flame Distribution in room 051
Watt vs. Time 10 sec

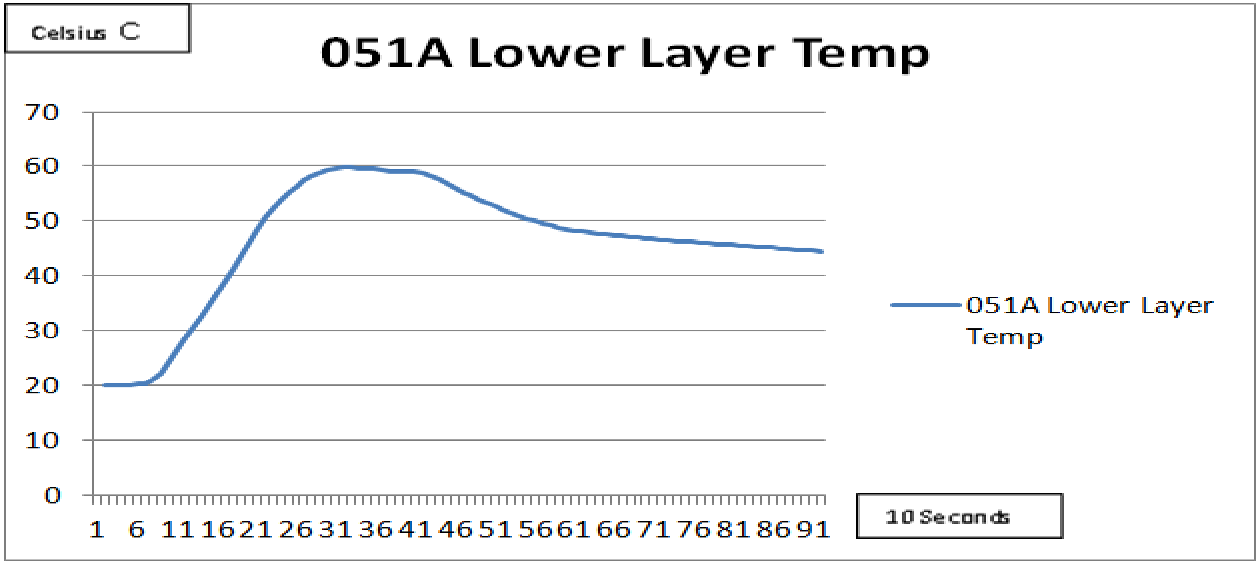


The maximum flame height is 2.6 m.

CFAST vs. Hand Calculations

CFAST output:

Lower Temperature Distribution in room 051 A
Temperature °C vs. Time 10 sec

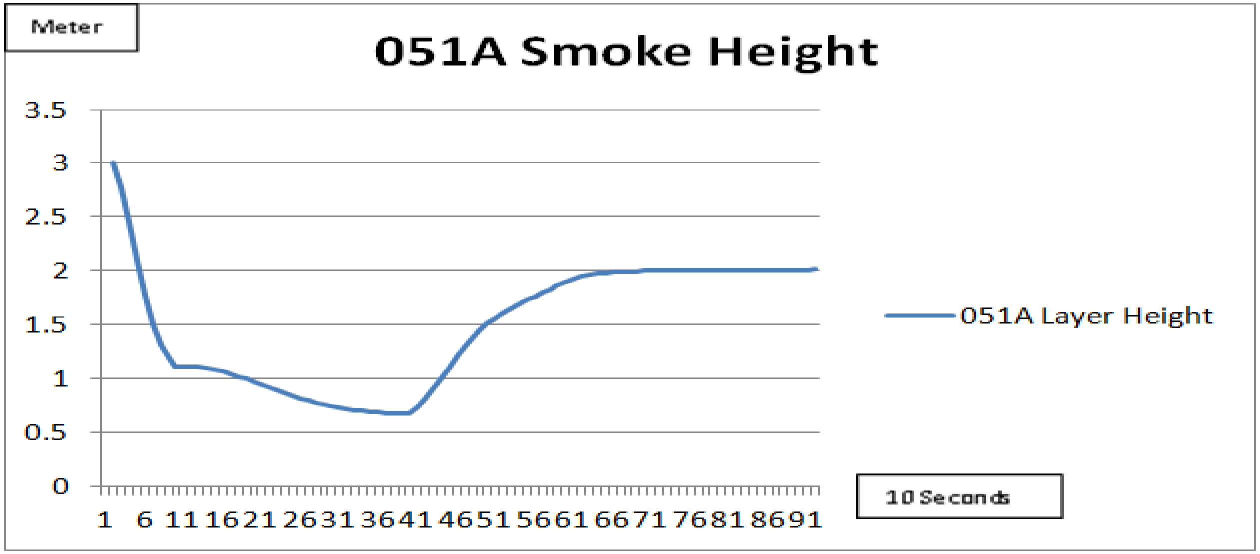


There is no human skin threat as the maximum temperature didn't exceed 120 C.

CFAST vs. Hand Calculations

CFAST output:

Smoke Height Distribution in room 051 A
Meters vs. Time 10 sec

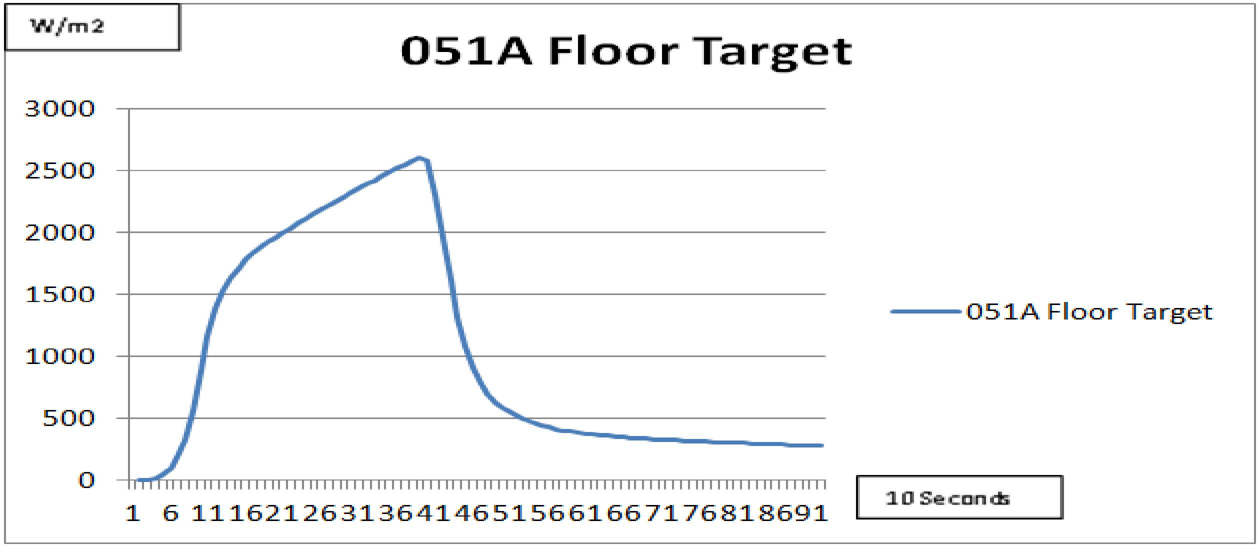


The smoke height will be steady at 2 m after the first 600 seconds of fire.

CFAST vs. Hand Calculations

CFAST output:

Floor Radiant Heat in room 051
Watt vs. Time 10 sec

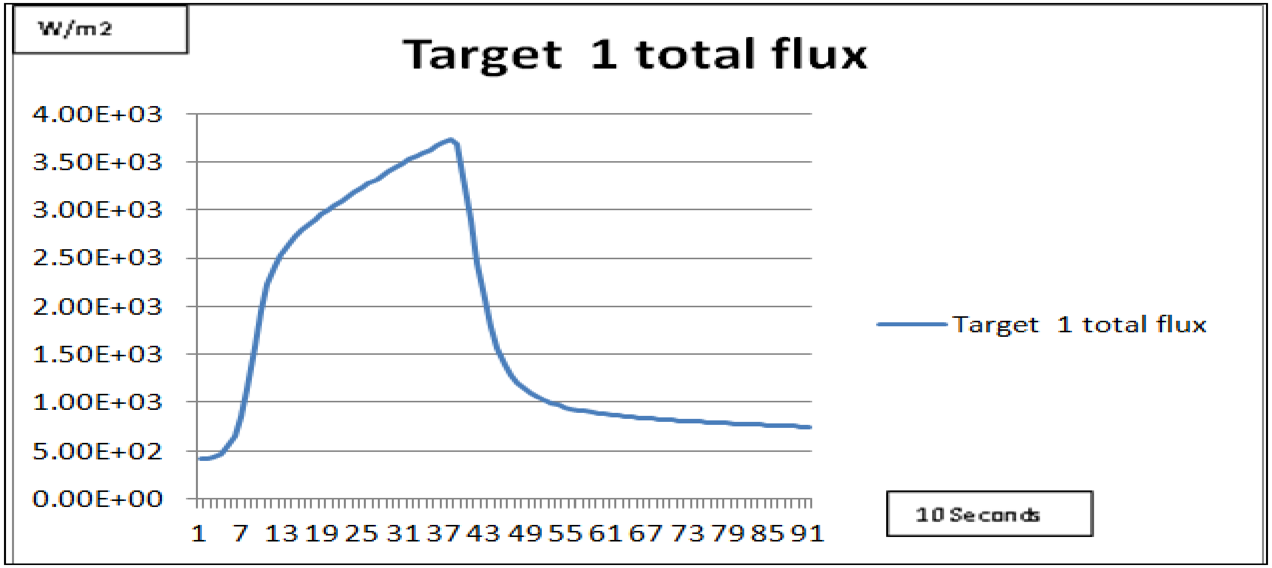


There will be human skin threat as the maximum radiant heat flux was 2.6 KW/m2 as it exceeds the limit of 2.5 KW/m2.

CFAST vs. Hand Calculations

CFAST output:

Target Total Heat Flux in room 051 A

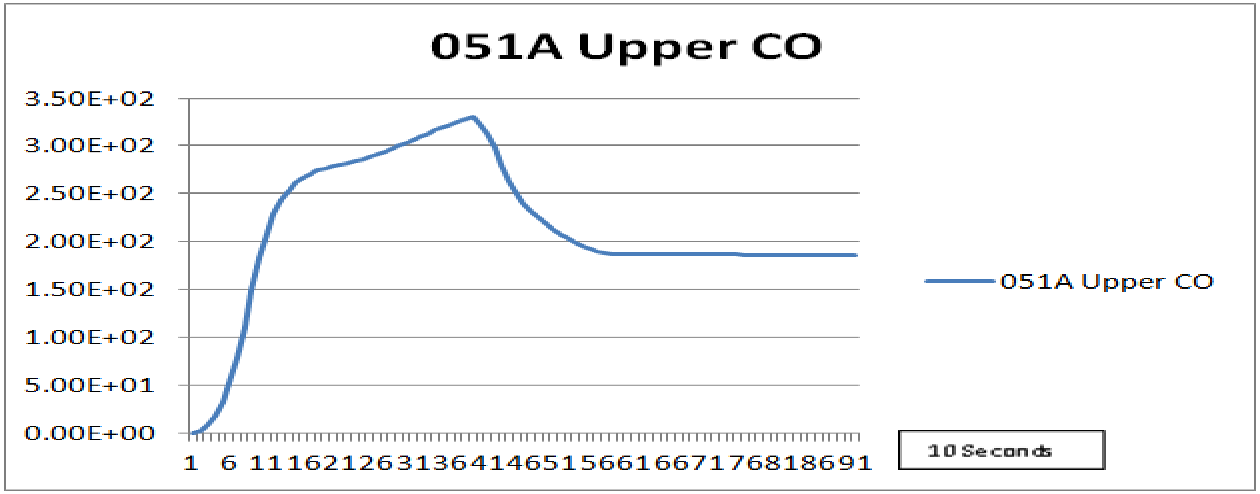


Maximum radiant heat flux at the target 2 meter away from the fire is 3.75 kW/m2.

CFAST vs. Hand Calculations

CFAST output:

Carbon Monoxide Distribution in room 051 A
vs. Time 10 sec



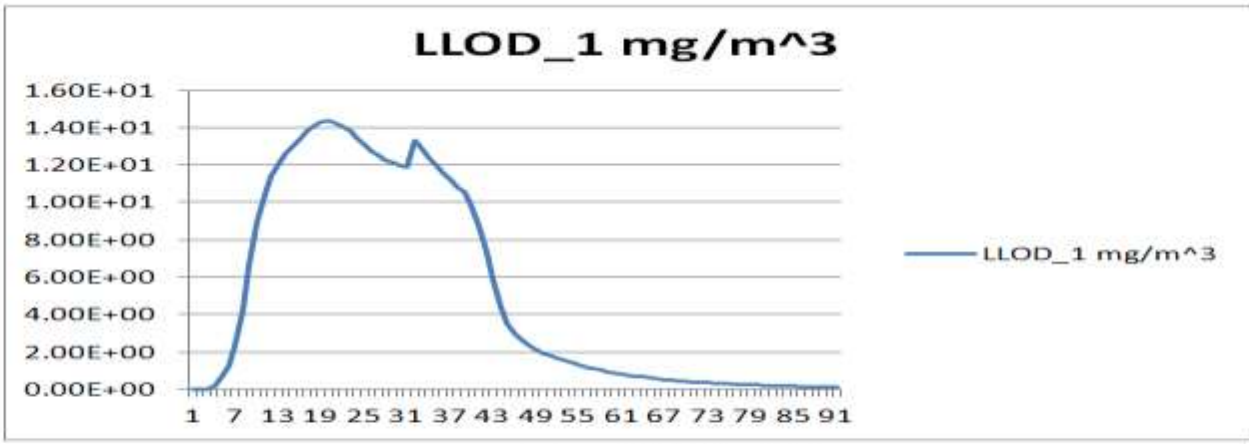
$$FED(t) = \frac{\int_0^t V_{CO}(t')\,dt'}{35{,}000\ \text{ppm} \cdot \text{min}}$$

The maximum CO concentration is 203 ppm at 190 seconds (3.16 minutes) (highest CO ppm)
Therefore FED = (203 x 3.16) / 35,000 = 0.018 < 1.
At the end of the 900 seconds = 190 ppm x 900 seconds (15 minutes) (Longest time)
Therefore FED = (190 x 15) / 35,000 = 0.08 < 1.

CFAST vs. Hand Calculations

CFAST output:

Optical Density Distribution in room 051 A
vs. Time 10 sec



S = visibility (m)

For light-emitting signs: KS = 8
For light-reflecting signs: KS = 3 $K = K_m C_s$

For flaming combustion of wood & plastics
$K_m \sim 7.6\ m^2 / g$

Maximum C_S = 14.2 mg/m³ = 1.42 g/m², Therefore K = 1.42 g/m² x 7.6 m²/g = 10.79
Therefore in this case light-emitting sign = 8, S = 8/10.79 = 0.74 m

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CFAST vs. Hand Calculations

Hand Calculations:

Radiant heat:

$\dot{Q}_{rad} = Q_{total} \times 0.3 = 1054\ kW \times 0.3 = 316\ kW$ (Compared to 330 kW from CFAST)

Target Calculation:

Employ the simple model: The flame is characterised as a point source at mid-height along the centre line of the vertical axis of the flame

$$\dot{q}'' = \dot{Q}_{rad} \frac{\cos\theta}{4\pi r^2}$$

$\dot{q}''$ is radiant heat flux

Q_{total} is total heat release

$\dot{Q}_{rad}$ is radiant heat

Where $\theta = 45$ and $\cos\theta = 0.717$

r = distance (meters)

$\dot{q}'' = 316\ kW \times (0.717 / 4 \times \pi \times (2m)^2) = 4.5\ kW/m2$.(Compared to 3.75 kW/m2 from CFAST)

CFAST vs. Hand Calculations

Hand Calculations:

Flame height (Correlation - Heskestad 1983)

$$L = 0.235\, Q^{2/5} - 1.02\, D$$
$$= 0.235\,(1054)^{2/5} - 1.02\,(D)$$

$$\text{Area} = 1\text{m} \times 1\text{m} = \pi (D/2)^2$$

$$D = 1.27\text{ m}$$

$$L = 0.235\,(1054)^{2/5} - 1.02\,(1.27\text{ m})$$

$= 2.53$ m. (Compared to 2.6 m from CFAST)

CFAST vs. Hand Calculations

Hand Calculations:

Maximum Temperature:

$\dot{q}" = \varepsilon\sigma\varphi(T_E{}^4)$

$T_E{}^4 = \dot{q}"/\ \varepsilon\sigma\varphi$

ε is the emissivity ~ 0.9

σ is the Stephen-Boltzman constant (5.67×10^{-8} W/m^2K^4)

T_E is the temperature from the exposing source (K), and

$\dot{q}"net$ = net heat transfer

φ = Configuration factor ~ 0.5

$T_E{}^4 = 3{,}750\ W\ m^{-2} / (0.818 \times 5.67 \times 10^{-8}\ W/m^2\ K^4 \times 0.3)$

T_E = 638 K ~ 365 °C. (Compared to 257 C from CFAST)

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CFAST vs. Hand Calculations vs. NUREG 1805

CFAST Exercise

CFAST vs. Hand Calculations vs. NUREG 1805

➢Assume a pool fire that contains 1000 litres of lube oil. Calculate the HRR?

Hand Calculations:

Assume one drum of Lube oil leaked:
Therefore,

$$\dot{m}'' = \dot{m}''_{\infty}\left(1 - e^{-k\beta D}\right)$$

$\dot{m}''$ = rate of mass loss / area ($g\ m^{-2}\ s^{-1}$)

D = pool diameter (m)

$\dot{m}''_{\infty} = \lim_{D\to\infty} \dot{m}''$

k = flame extinction coefficient (m^{-1})

β = mean beam length corrector

CFAST vs. Hand Calculations Vs NUREG 1805

$$\dot{Q} = H_{ch} \, A_F \, \dot{m}''$$

$\dot{Q}$ = rate of heat release (kW)

H_{ch} = actual heat of combustion (kJ g^{-1})

A_F = surface area of fuel (m^2)

Calculate radiative flux at target as

$$\dot{q}'' = \dot{Q}_{RAD} \cos\theta / (4 \pi r^2)$$

$$\dot{Q} = \dot{m}''_{\infty} (1 - e^{-k\beta D}) H_{ch} \frac{\pi}{4} D^2$$

For Lube oil:

Mass Burning rate = 0.039 kg/m^{2}s
Heat of combustion = 46,000 kj/kg
Empirical Constant = 0.7 m^{-1}

CFAST vs. Hand Calculations Vs NUREG 1805

$$\dot{Q} = H_{ch} A_F \dot{m}''$$

$\dot{Q}$ = rate of heat release (kW)

H_{ch} = actual heat of combustion ($kJ\ g^{-1}$)

A_F = surface area of fuel (m^2)

Calculate radiative flux at target as

$$\dot{q}'' = \dot{Q}_{RAD} \cos\theta / (4 \pi r^2)$$

$$\dot{Q} = \dot{m}''_{\infty} (1 - e^{-k\beta D}) H_{ch} \frac{\pi}{4} D^2$$

For Lube oil:

Mass Burning rate = 0.039 kg/m^2s
Heat of combustion = 46,000 kj/kg
Empirical Constant = 0.7 m^{-1}

CFAST vs. Hand Calculations Vs NUREG 1805

For Lube oil:

Mass Burning rate = 0.039 kg/m^2s
Heat of combustion = 46,000 kj/kg
Empirical Constant = 0.7 m^{-1}

The drum of Lube oil contains 1000 Litres = 1 m^3
If spilled with height 1 m

Area = 1.0 m^3 / 1 m = 1 m^2

Area = $\pi r2$ = 1 m^2

Therefore r = 0.55 m
And Diameter D = 1.1 m

Therefore $Q = 0.039\ kg\ m^{-2}\ s^{-1} \times (1 - e^{-0.7 \times 1.1}) \times 46{,}000\ kj/kg \times \pi/4 \times (1.1)^2$
Q = 1003.8 kW

CFAST vs. Hand Calculations Vs NUREG 1805

NUREG 1805:

CHAPTER 3. ESTIMATING BURNING CHARACTERISTICS OF LIQUID POOL FIRE,
HEAT RELEASE RATE, BURNING DURATION, AND FLAME HEIGHT
Version 1805.0

The following calculations estimate the heat release rate, burning duration, and flame height for liquid pool fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Select
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

Fuel Spill Volume (V)	275.00	gallons	1.0410 m^3
Fuel Spill Area or Dike Area (A_{dike})	11.00	ft^2	1.022 m^2
Mass Burning Rate of Fuel (m")	0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg	
Fuel Density (ρ)	760	kg/m^3	
Empirical Constant (kβ)	0.7	m^{-1}	
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Gravitational Acceleration (g)	9.81	m/sec^2	
Ambient Air Density (ρ_a)	1.18	kg/m^3	

Calculate

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

CFAST vs. Hand Calculations Vs NUREG 1805

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m'' (kg/m²-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Density ρ (kg/m³)	Empirical Constant $k\beta$ (m⁻¹)
Methanol	0.017	20,000	796	100
Ethanol	0.015	26,800	794	100
Butane	0.078	45,700	573	2.7
Benzene	0.085	40,100	874	2.7
Hexane	0.074	44,700	650	1.9
Heptane	0.101	44,600	675	1.1
Xylene	0.09	40,800	870	1.4
Acetone	0.041	25,800	791	1.9
Dioxane	0.018	26,200	1035	5.4
Diethy Ether	0.085	34,200	714	0.7
Benzine	0.048	44,700	740	3.6
Gasoline	0.055	43,700	740	2.1
Kerosine	0.039	43,200	820	3.5
Diesel	0.045	44,400	918	2.1
JP-4	0.051	43,500	760	3.6
JP-5	0.054	43,000	810	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	760	0.7
561 Silicon Transformer Fluid	0.005	28,100	960	100
Fuel Oil, Heavy	0.035	39,700	970	1.7
Crude Oil	0.0335	42,600	855	2.8
Lube Oil	0.039	46,000	760	0.7
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Select Fuel Type: Lube Oil

Scroll to desired fuel type

Click on selection

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page [illegible]

ESTIMATING POOL FIRE HEAT RELEASE RATE

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page [illegible]

$Q = m'' \Delta H_{c,eff} (1 - e^{-k\beta D}) A_{dike}$

Where
- Q = pool fire heat release rate (kW)
- m'' = mass burning rate of fuel per unit surface area (kg/m²-sec)
- $\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)
- $A_f = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m²)
- $k\beta$ = empirical constant (m⁻¹)
- D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

Where
- A_{dike} = surface area of pool fire (m²)
- D = pool fire diamter (m)

$D = \sqrt{(4A_{dike}/\pi)}$

$D =$ **1.141** m

Heat Release Rate Calculation

(Liquids with relatively high flash point, like transformer oil, require localized heating to achieve ignition)

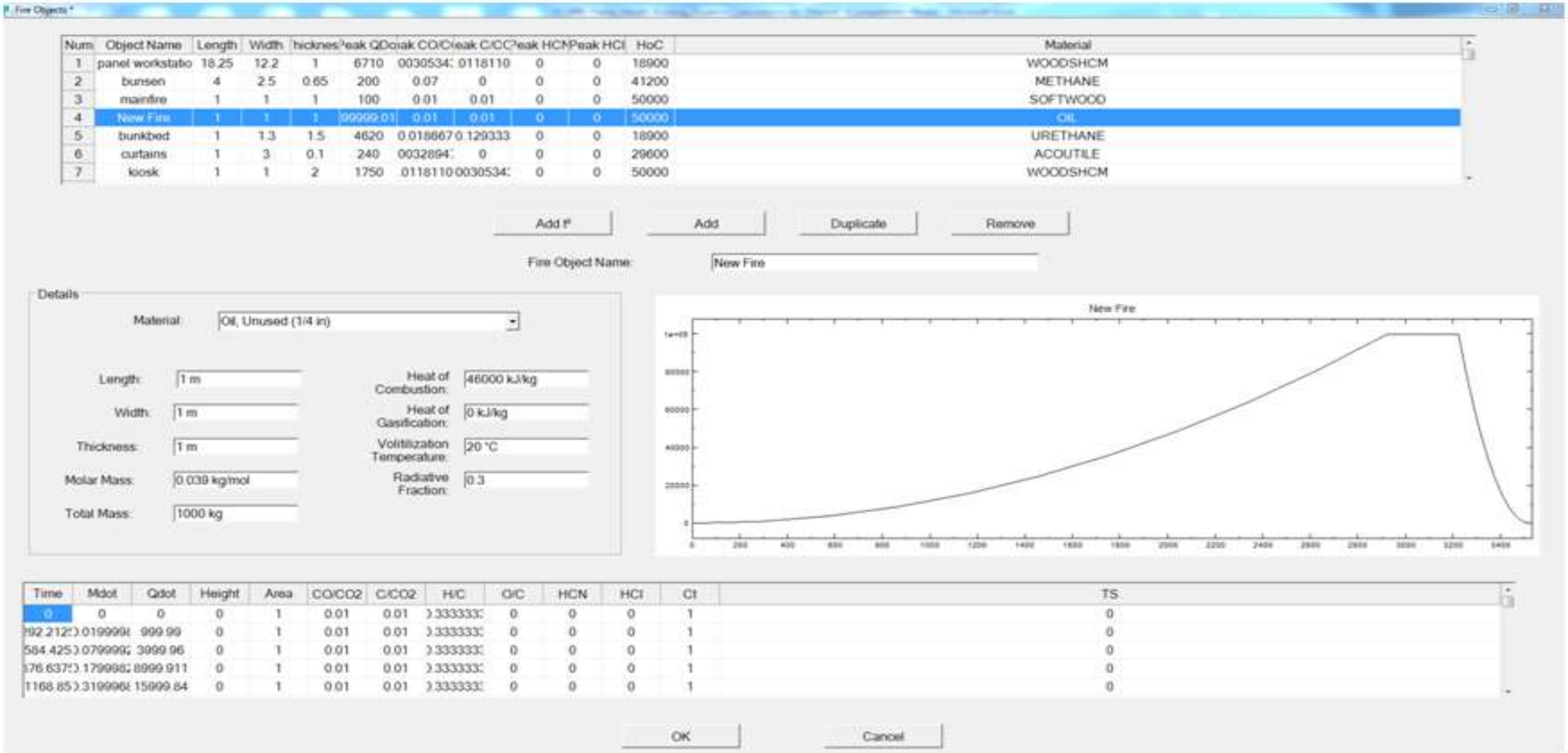
$Q = m'' \Delta H_{c,eff} (1 - e^{-k\beta D}) A_{dike}$

Q = 1008.32 kW 955.71 Btu/sec Answer

Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

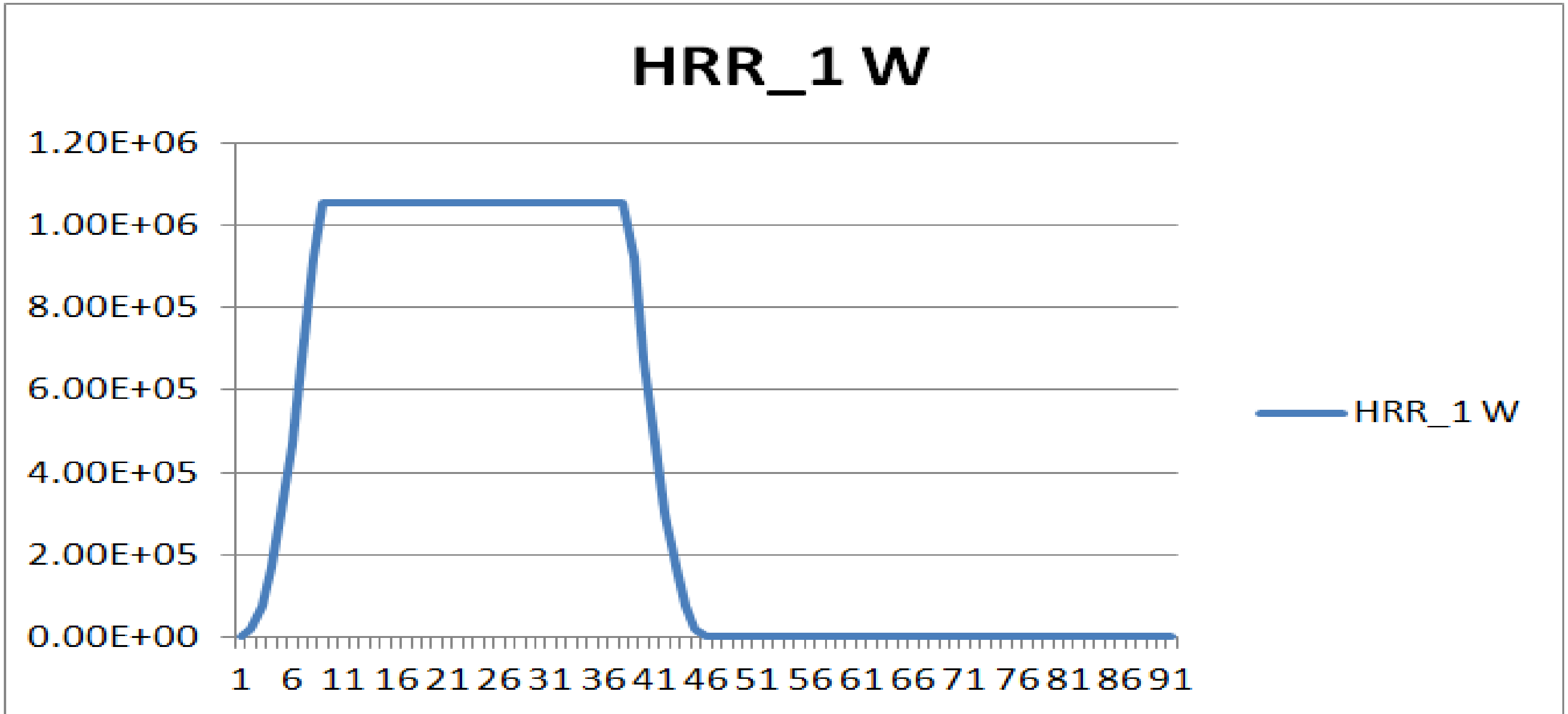
CFAST vs. Hand Calculations Vs NUREG 1805

CFAST:



CFAST vs. Hand Calculations Vs NUREG 1805

Output:



Q = 1050 kW

Agenda:

Introduction

Types of Models

Applicability

Case Study 1

Case Study 2

Case Study 3

CFAST vs. Hand Calculations

CFAST vs. Hand Calculations vs. NUREG 1805

CFAST Exercise

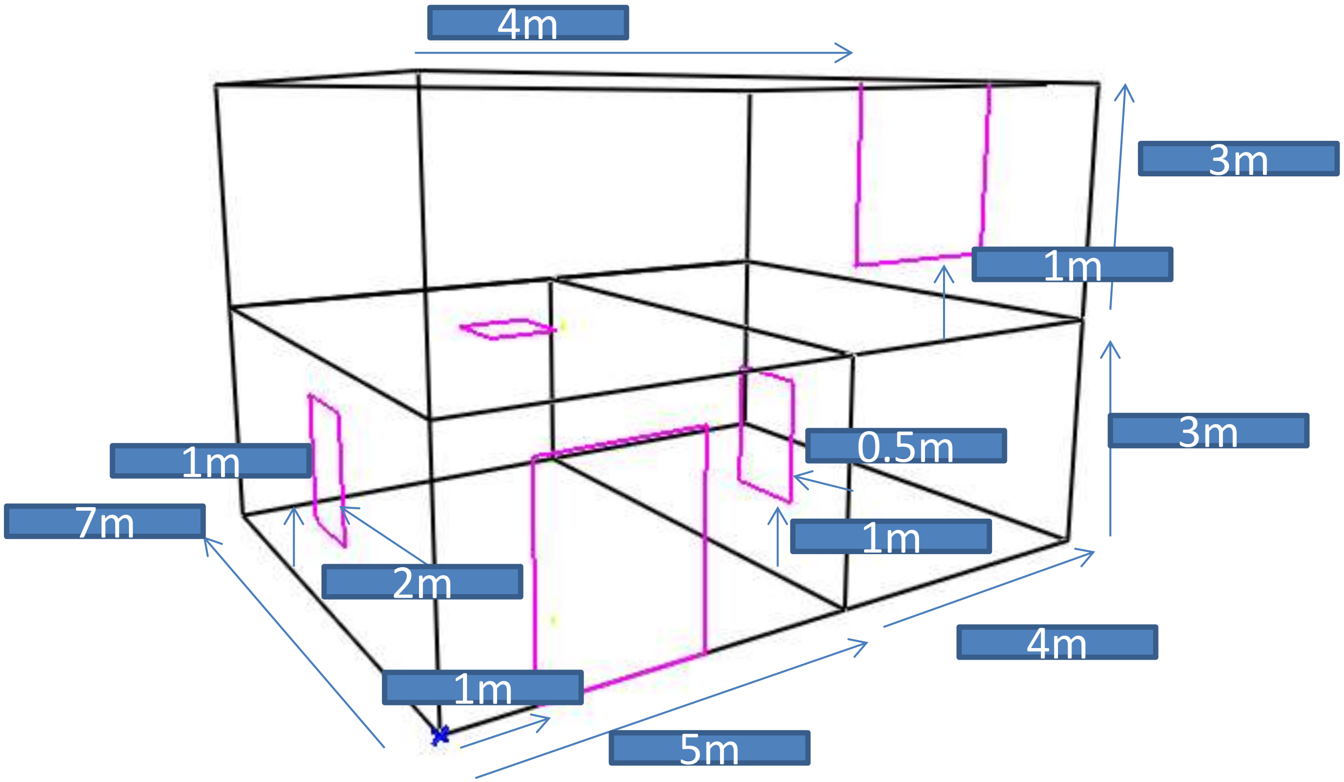
CFAST Exercise 1

Room 4m x 3m x 3m with one door in the front at distance 1m. The door is 0.7m X 2m. The fire is 3 panel work station in the middle of the room. All walls and celing are 5/8 gypsum board and floor is light concrete.

Using CFAST (Simulation time: 6 minutes), Calculate:

- ➢HRR?
- ➢Maximum Heat flux?
- ➢Flame height?
- ➢Highest temperature?
- ➢Life safety? (CO & Optical distance)

CFAST Exercise 2



CFAST Exercise 2

All walls and ceiling are 5/8 gypsum board and floor is light concrete. In room 1, the door dimension is 2m width x 2.5m height. The windows dimension in the room 1 are 1m width x 1.5m height. In room 3, the window dimension is 2m width x 2m height. In room 1, there is a round opening to room 3 with area of 0.8m2.

Fire 1 in room 1 of a box spring and mattress in the middle of the room.

Fire 2 in room 2 of bunkbed in the middle of the room.

Fire 3 in room 3 of a kiosk in the middle of the room.

Using CFAST, Calculate:

- HRR in room 3?
- Maximum floor Heat flux in room 2?
- Human heat flux in room 3?
- Smoke height in room 1?
- Highest temperature in room 1?

References

[1] Different engineering correlations are proposed in the literature

- SFPE Handbook of Fire Protection Engineering
- NFPA-The Fire Protection Handbook
- Karlsson and Quintiere, “Enclosure Fire Dynamics,” CRC Press, 2000.
- Drysdale, “An Introduction to Fire Dynamics,” John Wiley and Sons, 1999
- Cox, “Combustion Fundamentals of Fire,” Academic Press, 1995

[2] ISO/DTS 13571, “Life threat from fires - guidance on the estimation of the time available for escape using fire data”

[3] National Research Council of Canada (2010). *National Building Code of Canada 2010.* Canadian Commission on Building and Fire Codes: Ottawa, On.

[4] D. Drysdale, An Introduction to Fire Dynamics,Wiley, 1999, Chap 1

[5] National Fire Protection Association, NFPA 801, *Standard for Facilities CarryingRadioactive Material*, 2003 Edition

[6] C.L. Tien, K.Y. Lee and A.J. Stretton, “Radiation Heat Transfer”Section 1 / Chapter 4, SFPE Handbook, 2nd Ed. (1995)

[7] ISO/DTS 13571, “Life threat from fires - guidance on the estimation of the time available for escape using fire data”.

[8] http://www.msc.ec.gc.ca/windchill

[9] Timber Design Manual

[10] J.P. Holman, Heat Transfer

[11] J.G. Quintiere, “Surface Flame Spread”SFPE Handbook, 2nd Ed. (1995)

[12] V. Babrauskas, “The Cone Calorimeter”SFPE Handbook, 2nd Ed. (1995)

[13] E. Mikkola, “Ignitability of Solid Materials”, in Heat Release in Fires, Elsevier Applied Science, 1992.

[14] A. Tewardson, ”Generation of Heat and Chemical Compounds in Fires" Section 3 / Chapter 4, SFPE Handbook, 2nd Ed. (1995)

[15] T.Z. Harmathy, A New Look at Compartment Fires, Parts I and II

[16] B***-*****-FHA-001 Rev. 1; *Building *** Fire Hazard Analysis*

[17] National Building Code of Canada, 2010 Edition

[18] National Fire Code of Canada, 2010 Edition

*[19] B*** ---- Memo B***-*****-****-0001*.

[20] National Fire Protection Association (NFPA) 801, *Fire Protection for Facilities Handling Radioactive Materials,* 2008 Edition

[21] A. Tewardson, ”*Generation of Heat and Chemical Compounds in Fires" Section 3 / Chapter 4, SFPE Handbook, 2nd Ed. (1995)*