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# INTEGRAL METHODOLOGY FOR FIRE SPRINKLER SYSTEM DESIGN FOLLOWING THE PERFORMANCE-BASED DESIGN CRITERIA

Universidad de los Andes

# PBD five primers

## PBD vs. Prescriptive

| System type | Agent didn't reach the fire | Usufficient amount of agent released | Inappropiate system for fire type | Manual intervention defeated system | System component failure | Maintenance failure | Total fires a year |
|---|---|---|---|---|---|---|---|
| **Wet pipe** | 47% | 25% | 15% | 6% | 3% | 3% | 303 |
| **Dry pipe** | 16% | 60% | 3% | 3% | 3% | 14% | 45 |
| **Dry chemical** | 57% | 34% | 2% | 2% | 0% | 3% | 291 |
| **CO2** | 49% | 51% | 0% | 0% | 0% | 0% | 17 |

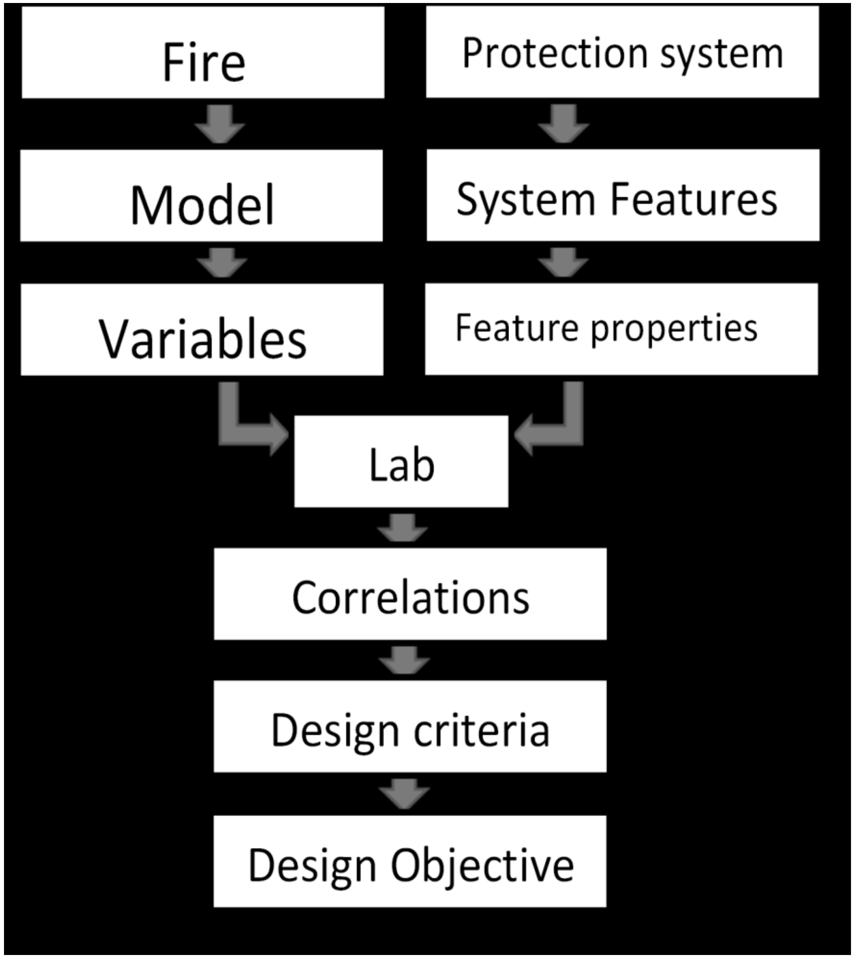
- Goals, objectives and criteria
- Characteristics and assumptions
- Fire scenarios
- Verification methods
- Reliability

# Goals, objectives and criteria

Personnel Safety And Fire Extinction

- Fire behavior simulation to compare with experimental results.
- Bibliographical research for correlations to describe sprinkler system's effects over fire behavior.
- Develop an algorithm to design an effective protection system able to comply with the design objectives.

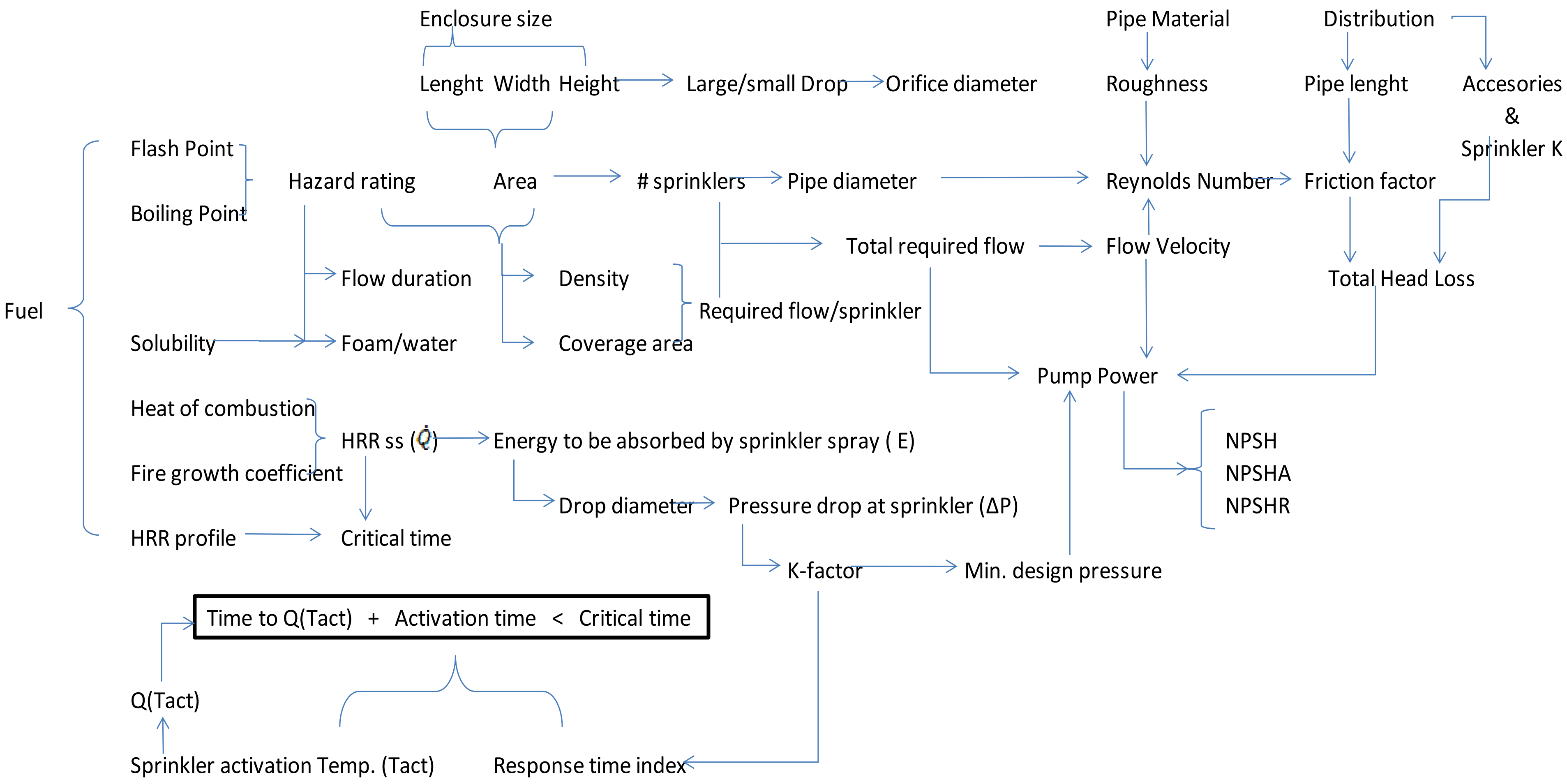
# Design Concept



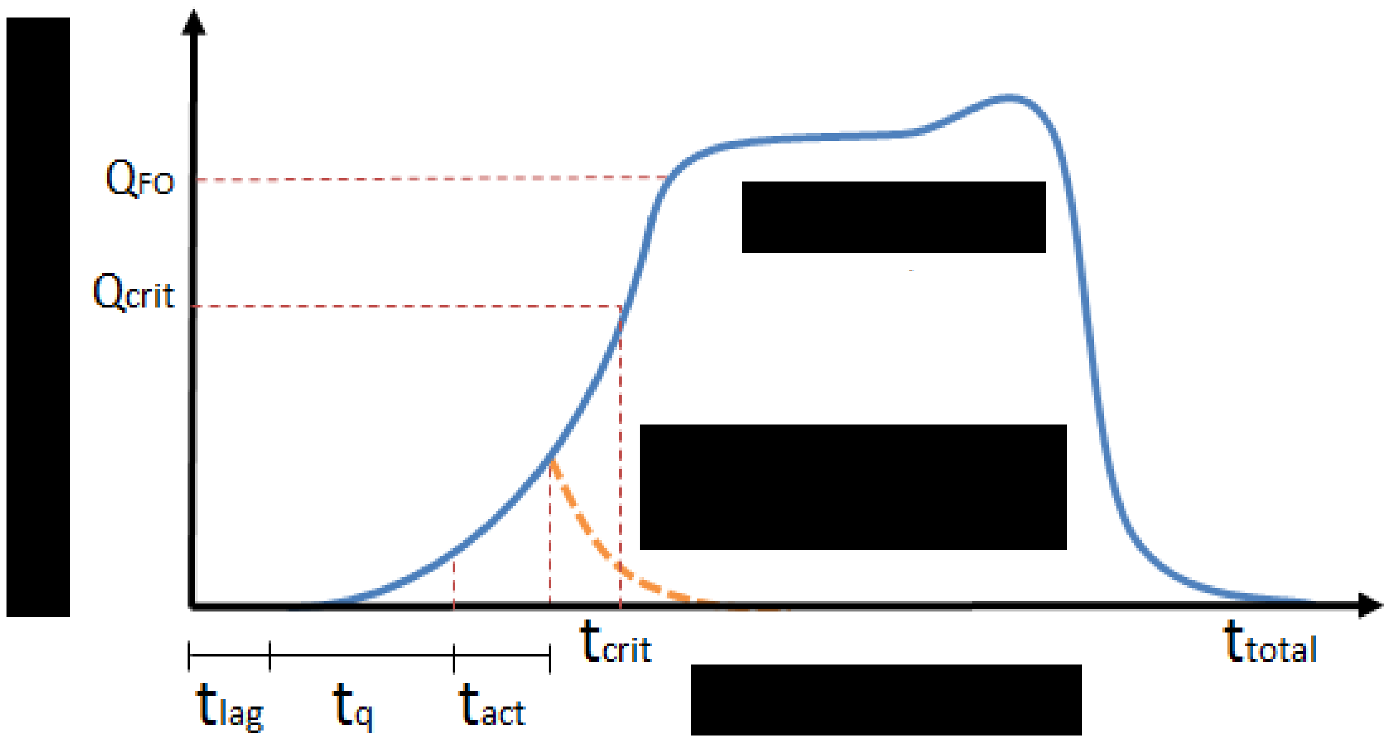
# Variables and Correlations

| Fire Phenomenon | System Properties | Correlations |
|---|---|---|
| Heat Release Rate (HRR) | • Activation time | |
| Hazard rating | • Activation temperature | |
| Fuel properties | • Flow duration | • Energy absorbed |
| Enclosure properties | • Flow per unit area | • Heat reduction |
| Fire load | • Drop diameter | • Extinction time |
| Critical time | • Pressure drop | |
| Total time | • Discharge coefficient K | |

# Design Flow


Enclosure size
Lenght Width Height
Large/small Drop
Orifice diameter
Pipe Material
Roughness
Distribution
Pipe lenght
Accesories
&
Sprinkler K
Flash Point
Boiling Point
Hazard rating
Area
# sprinklers
Pipe diameter
Reynolds Number
Friction factor
Total required flow
Flow Velocity
Total Head Loss
Fuel
Flow duration
Density
Required flow/sprinkler
Solubility
Foam/water
Coverage area
Pump Power
Heat of combustion
HRR ss ($\dot{Q}$)
Energy to be absorbed by sprinkler spray ( E)
NPSH
NPSHA
NPSHR
Fire growth coefficient
Drop diameter
Pressure drop at sprinkler (ΔP)
HRR profile
Critical time
K-factor
Min. design pressure
Time to Q(Tact) + Activation time < Critical time
Q(Tact)
Sprinkler activation Temp. (Tact)
Response time index

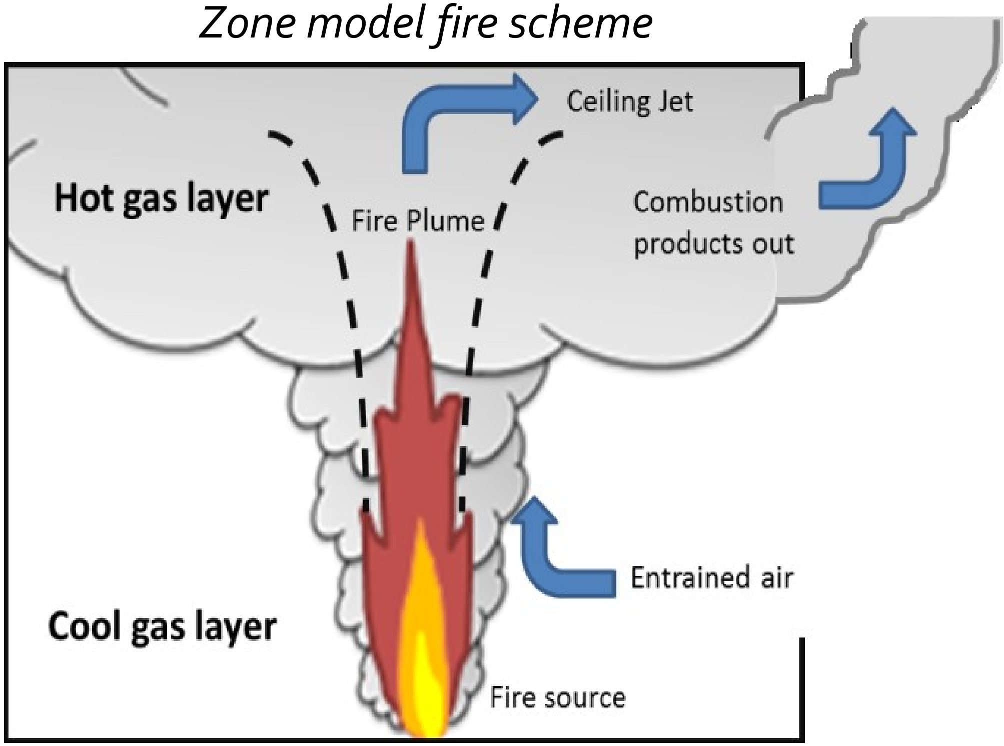
# Heat Profile

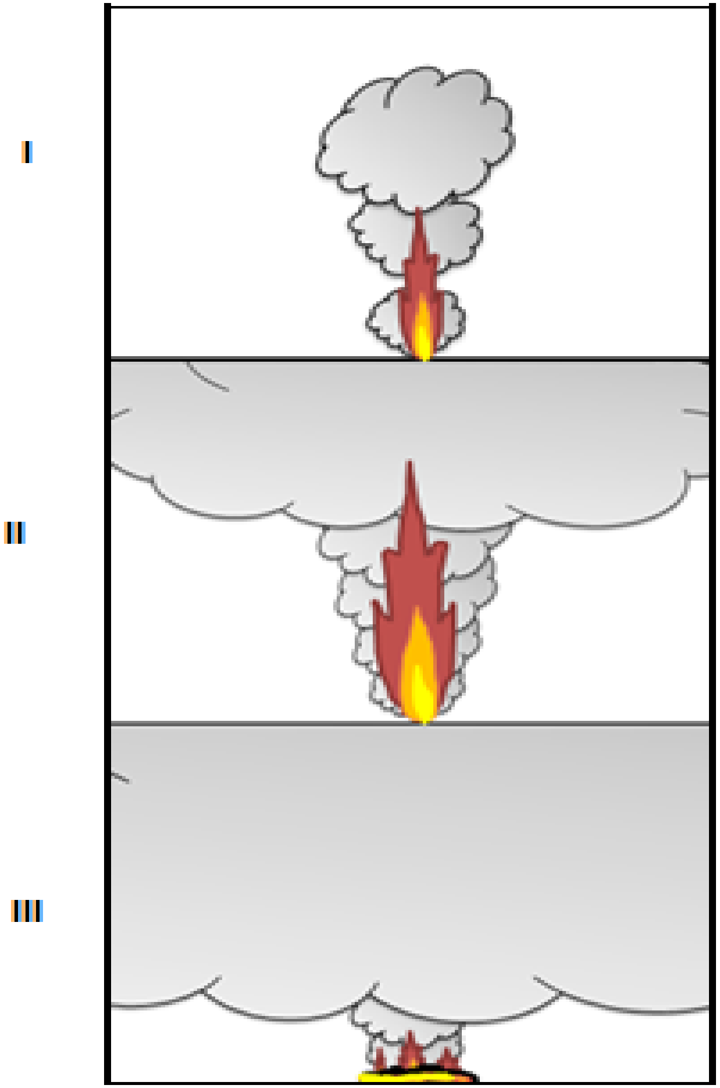



$$t_{act} + t_q < t_{crit}$$

# Characteristics and assumptions

*Zone model fire scheme*



# Fire Models

- ***Standard t² Model***

$$\dot{Q} = \alpha t^2$$

- ***Simplified HRR model***

maximum heat released 80% of the total fire duration, and flashover time reached at the 10%

$$t_{total} = \frac{W A}{\dot{m}}$$

# Fire Models

- ***McCaffey, Quintiere & Harkeroad Model***

$$\dot{Q} = [\sqrt{g}\, Cp\, \rho_\infty\, T_\infty{}^2 \left(\frac{\Delta T_g}{480}\right)^3 ]^{1/2} (h_k\, A_{total}\, A_o \sqrt{H_0})$$

$$\Delta T_g = 6.85 \left(\frac{\dot{Q}_{Total}{}^2}{h_k\, A_T\, A_o \sqrt{H_0}}\right)^{1/3}$$

$\Delta T_g$ is the hot gas temperature rise compared to room temperature.

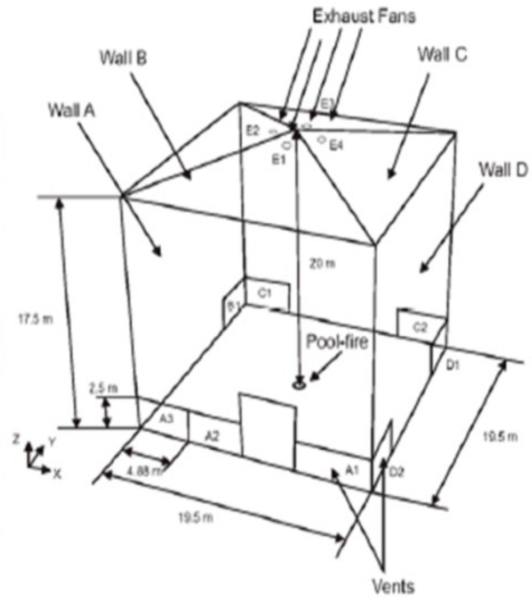
$$h_k = \left(\frac{k\, \rho_{wall}\, c}{t}\right)^{1/2}$$

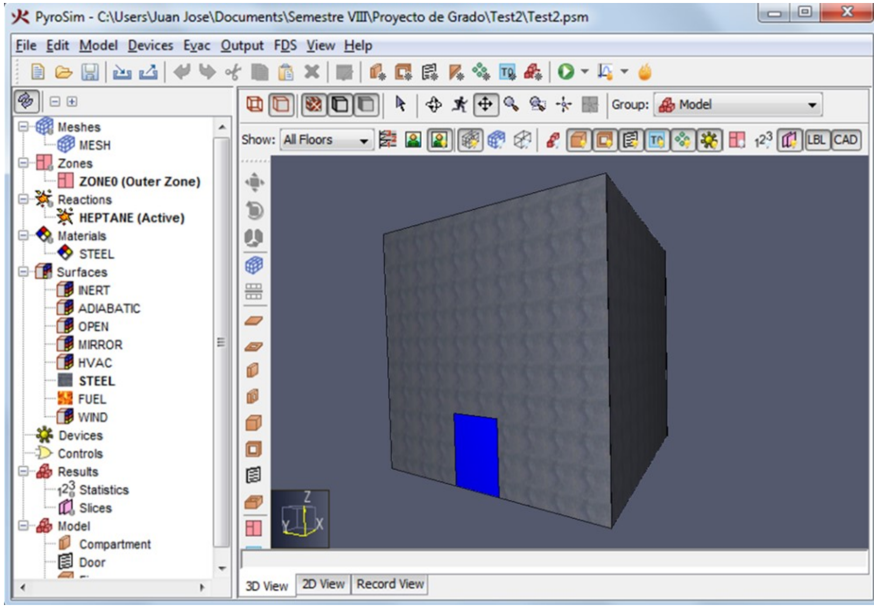
$h_k$ takes into account heat loss in wall transfer

# Fire scenario

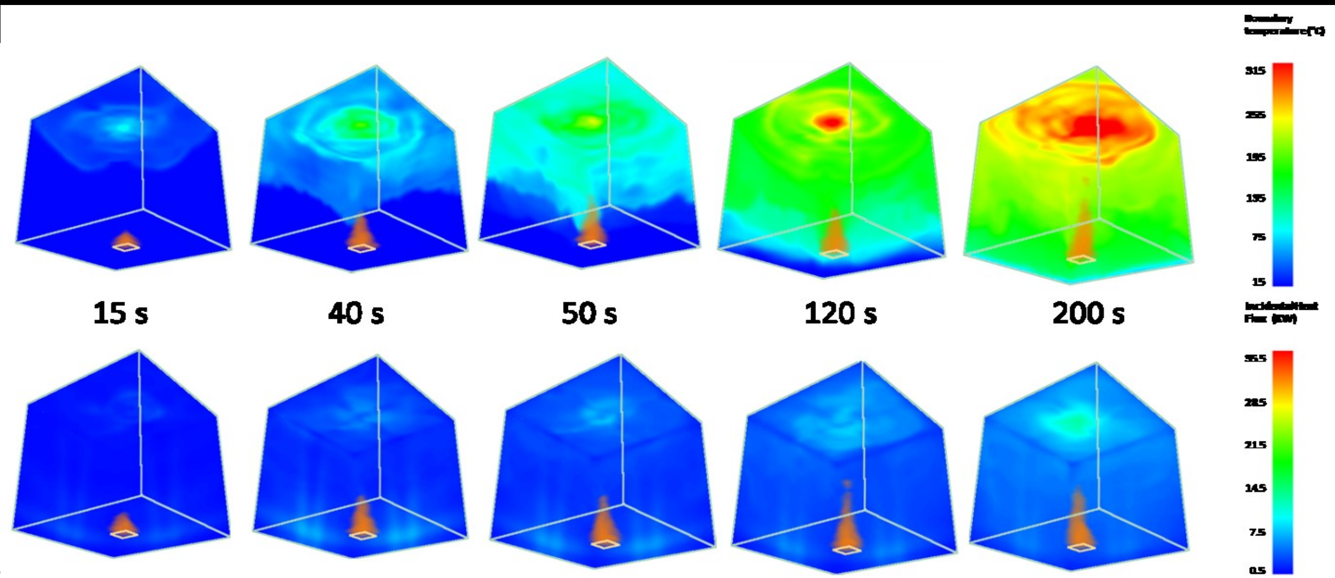
**Metal Technological Center in Murcia, Spain**

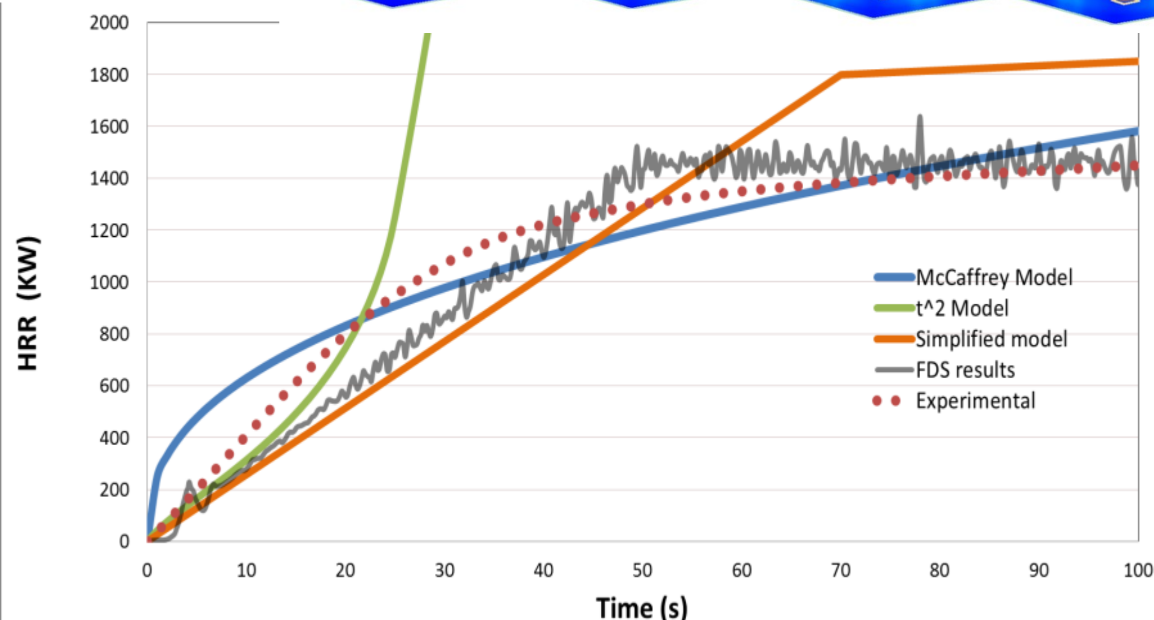
Steel structure (19.5m x 19.5m) with 20m high and a ventilation opening (4m x 2m)
Exposed to 44Lt heptane fire



# Verification methods




| Model | Relative Error |
|---|---|
| McCaffrey et al. | 10.5% |
| t^2 | 24.1% |
| Simplified | 23.8% |
| FDS (PyroSim) | 8.2% |

# Fire Characteristics

***Alpert's Correlations***

- *Ceiling Jet Temperature*

For r/H < 0.18: $$T_{CJ} - T_{amb} = 16.9\ \frac{Q_{conv}^{\frac{2}{3}}}{H^{5/3}}$$

For r/H > 0.18: $$T_{CJ} - T_{amb} = 5.38\ \frac{(Q_{conv}/r)^{\frac{2}{3}}}{H}$$

- *Ceiling Jet Fire Plume Velocity*

For r/H < 0.15: $$U = 0.96\ \left(\frac{Q}{H}\right)^{\frac{1}{3}}$$

For r/H > 0.15: $$U = 0.195\,\frac{Q^{1/3}\ H^{1/2}}{r^{5/6}}$$

# Fire Characteristics

***Hot Gas Layer*** **--** NFPA 92B

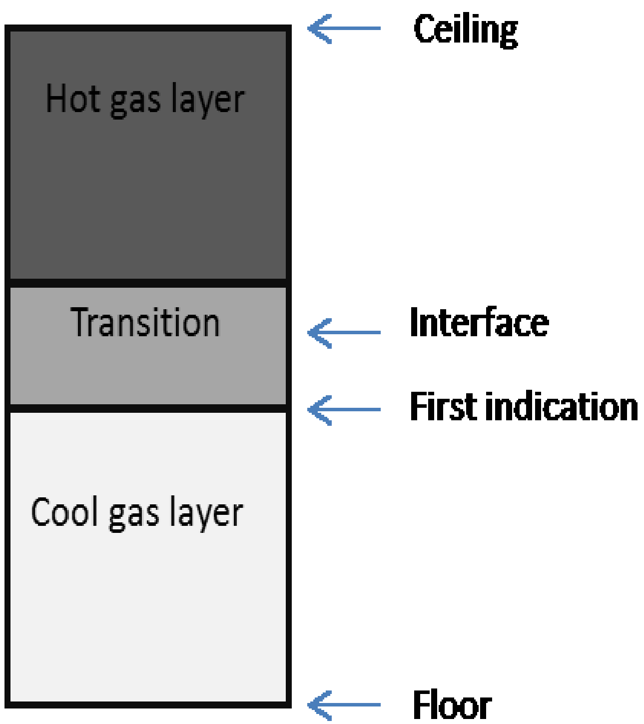
- *Hot Gas Layer Temperature*: solving for the hot gas layer temperature in McCaffrey model.

$$\Delta T_g = 6.85 \left( \frac{\dot{Q}_{Total}^{\ 2}}{h_k \, A_T \, A_o \sqrt{H_0}} \right)^{1/3}$$

- *Hot Gas Layer Height*

$$\frac{z}{H} = C_{10} - 0.28 \ln \left( \frac{t \ Q^{\frac{1}{3}} \ H^{-\frac{4}{3}}}{\frac{A_s}{H^2}} \right) ;$$

$$C_{10} = 1.11$$



# Fire Characteristics

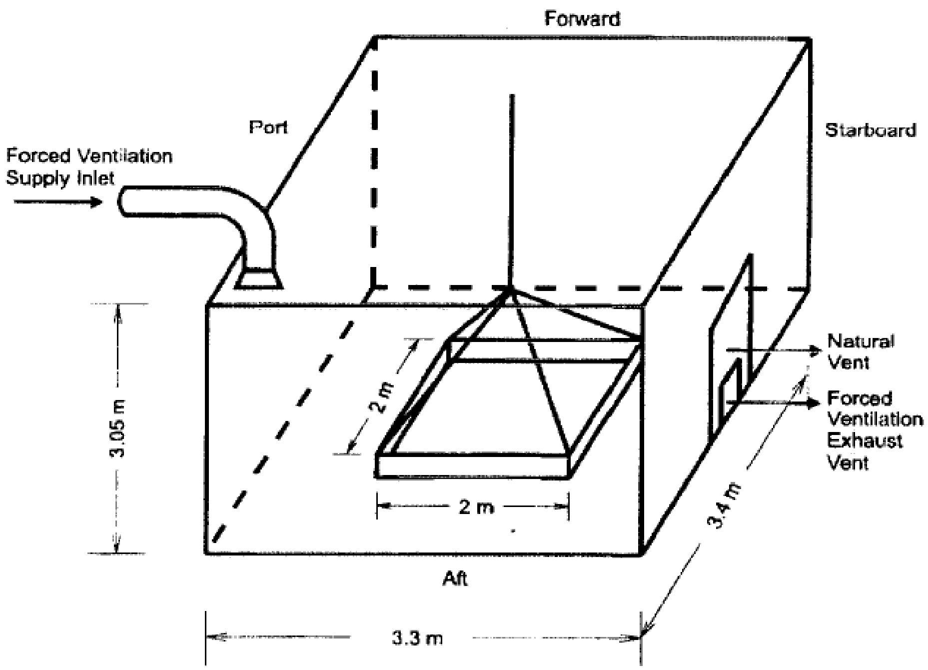
***Flashover* -- *Thomas***

$$\dot{Q}_{FO} = 7.8\, A_T + 378\, (A_O \sqrt{H_O})$$

Based on experimental results in which FO occurred at 600°C and surface heat loss was averaged by the term $7.8A_{Total}$

# Fire Scenario

Carried out by the NIST to compare with CFAST predictions for real scale fires




Diesel spill

Bucket 84cm wide

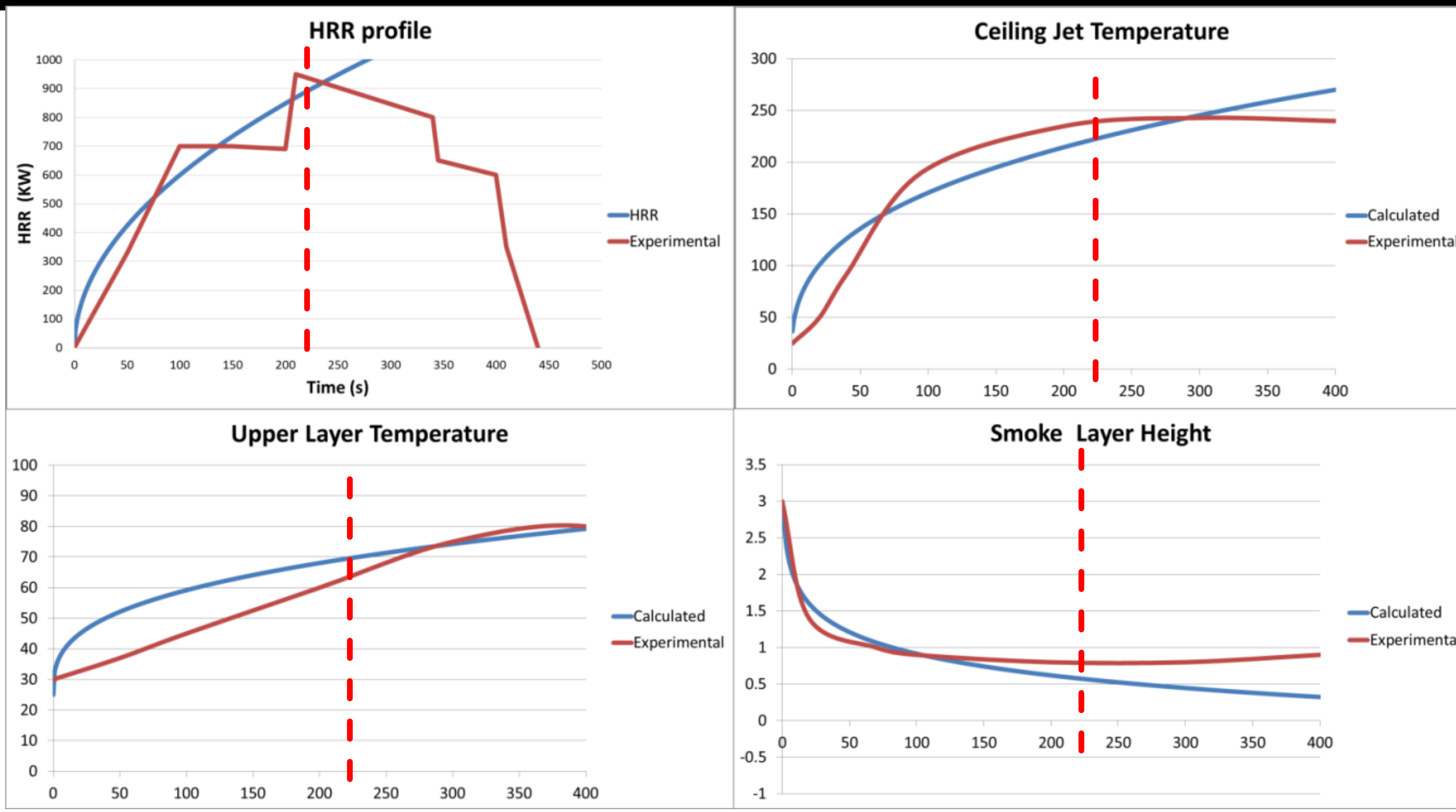
3.4m x 3.3m enclosure

3.05m high

2m x 2m ventilation opening

1.6cm thick steel walls

# Verification Method




| Variable | Relative Error |
|---|---|
| HRR | 14.3% |
| Ceiling Jet | 16.6% |
| [redacted] | 13.3% |
| [redacted] | 12.5% |

# Design Criteria

- ***Critical Time*** **--** *Yashiro*

*Related to personnel safety , evacuation models and fire growth considering the HGL*

$$t_{crit} = \frac{5}{2} \frac{\rho_\infty}{k} \frac{A_S}{\dot{m}^{\ 1/3}} \left[\frac{1}{(1.6 + 0.1H)^{2/3}} - \frac{1}{H^{2/3}}\right]^{3/5}$$

$\dot{Q}_{act}$ (Nominal activation heat)Indicates the heat nessesary to break the bulb:

$$\dot{Q}_{act} = 0.0144\ (T_{act} - T_\infty)^{\frac{3}{2}}\ H^{5/2}$$

$t_{act}$ (Actual activation time) Delay related to fire plume velocity, Response Time Index (RTI) and adequate discharge availability -- **M. D. MARZO**

$$t_{act} = \frac{RTI}{\sqrt{U}} \ln\left(\frac{T_G - T_\infty}{T_G - T_{act}}\right)$$

Equations must comply with:

$$t_{act} + t_q < t_{crit}$$

# Design Criteria

- ***Heat Absorption*** **--** *Kung*

States the amount of energy that can be absorbed by the sprinkler spray activation effect over the fire

$$E = \frac{\dot{Q}_{conv}}{\dot{m}_w(H_{evap} + C_{pw} * (T_{evap} - T_\infty))}$$

Where $\dot{Q}_{conv}$ indicates the convective heat portion, usually 70% of the total heat released

**Correlation between drop diameter and heat absorption**

$$\mathbf{E = 0.11\, d_r^{-0.73}}$$

Drop diameter is related to the pressure drop at the sprinker head

$$d_r = \left(\frac{\Delta P}{\Delta P_0}\right)^{-1/3} \left(\frac{D}{D_0}\right)^{2/3}$$

Sprinkler head Specification

$$K_{sp} = \frac{\dot{m}_w}{\sqrt{\Delta P}}$$

# Design Criteria

- ***Extinction Time -- Unoki***

Minimum time the sprinkler system should function so that the fire is effectively extinguished, determines the amount of water that must be sprayed

Regulations require sprinkler systems to be shut off manually form an isolated valve, so this calculation applies only as a rough indication on the amount of water to be used.

$$t_{ex} = 1.05\, A^{*\,2.3} \frac{\dot{m}^{3.5}\, M}{\dot{m}_w^{\;2}\, H^{2.5}} \left(\frac{\rho_{FP}}{d_r}\right)^{3.75}$$

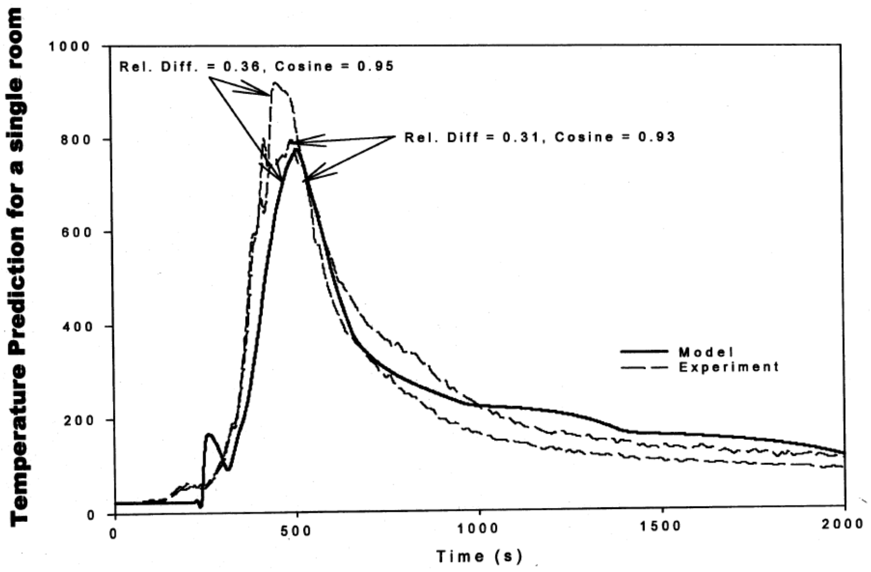
$$A^* = \frac{\dot{Q}}{Cp\, \rho_\infty\, T_\infty\, \rho_w \sqrt{g}}$$

Discharge rate according to the prescriptive criteria by the NFPA 13

| OCCUPANCY CLASSIFICATION[a] | SPRINKLER SYSTEM | | HOSE STREAM ALLOWANCE L/Min (GPM) | DURATION OF SUPPLY Minutes |
|---|---|---|---|---|
| | DESIGN DENSITY L/min/m² (GPM/ft²) | DESIGN AREA m² (ft²)[b] | | |
| Light Hazard | 4.1 (0.10) | 280 (3000) | 950 (250) | 60 |
| Ordinary Hazard Group 1 | 6.1 (0.15) | 280 (3000) | 1900 (500) | 60 |
| Ordinary Hazard Group 2 | 8.2 (0.20) | 280 (3000) | 1900 (500) | 90 |
| Extra Hazard Group 1 | 12.2 (0.30) | 280 (3000) | 2840 (750) | 120 |
| Extra Hazard Group 2 | 16.3 (0.40) | 280 (3000) | 2840 (750) | 120 |

# Design Criteria

- ***Heat Reduction*** -- *Madrzykowski*




upper limit to indicate heat reduction by the sprinkler system activation effect over the flame

$$\dot{Q}_{red} = \dot{Q}_{act}\, e^{-0.0022\,(t-t_{act})}$$

# Design Criteria

| CORRELATION | VARIABLE | FEATURE |
|---|---|---|
| Critical Time | Sprinkler Activation time | Sprinkler Bulb |
| Heat Absorption | Drop Diameter | Sprinkler Head |
| Extinction Time | Spray Density | Water Discharge |

# Fire Scenario

**Swedish National Testing and Research Institute**


Surface area of 7.1m x 7.1m and 5m high

fuel placed in a 20cm diameter bin

500mL diesel

9 sprinklers installed in a wet pipe

7.5mm/min distribution density

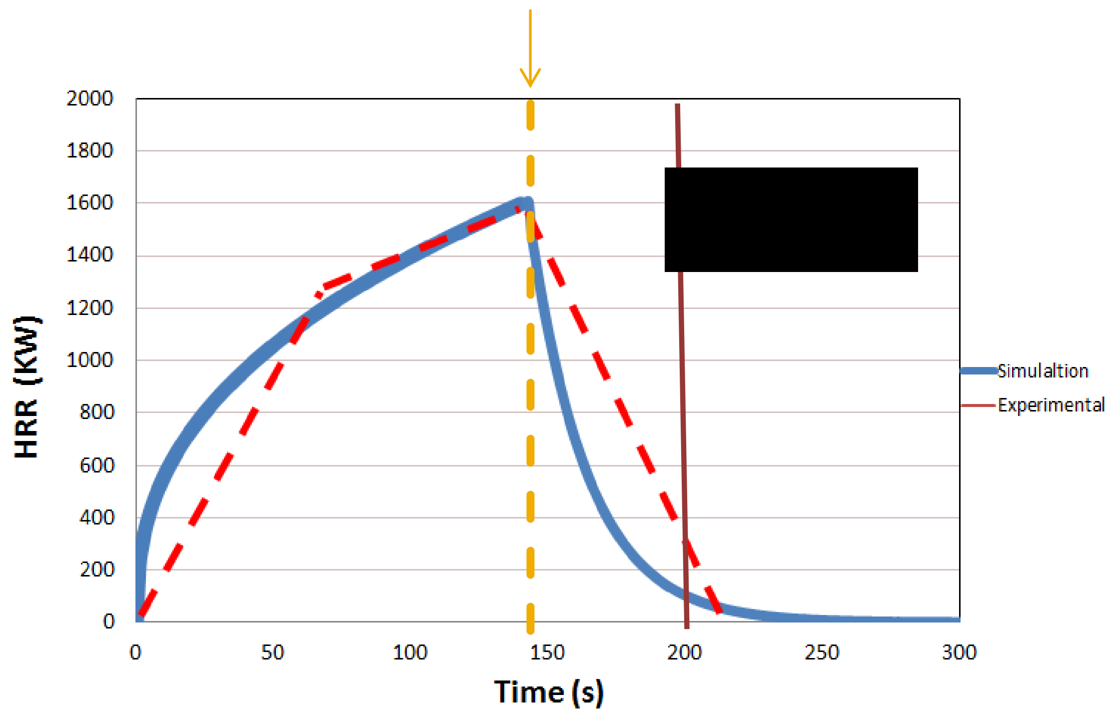
25.9(LPM/atm^1/2) discharge coefficient K

79°C activation temperature sprinklers

1.5m from the ceiling.

# Verification Method

Activation time

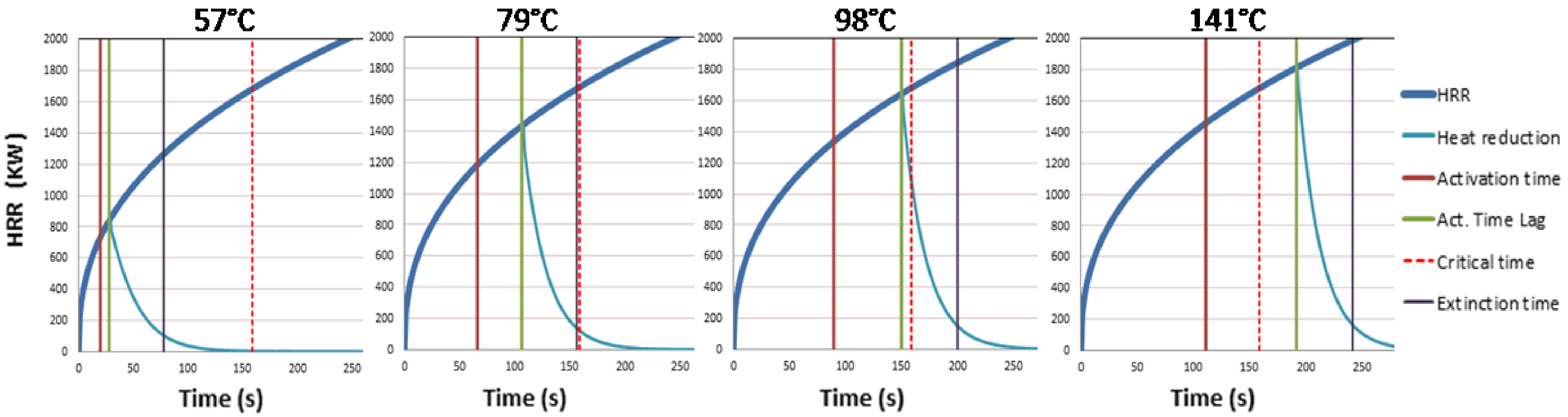



Relative error: 19.3%

Both curves are comparable as they match in their overall behavior regarding fire growth and its reduction following sprinkler activation.

They also coincide in the sprinkler activation time confirming the correlation's accuracy in predicting this moment; as well as for the extinction time.

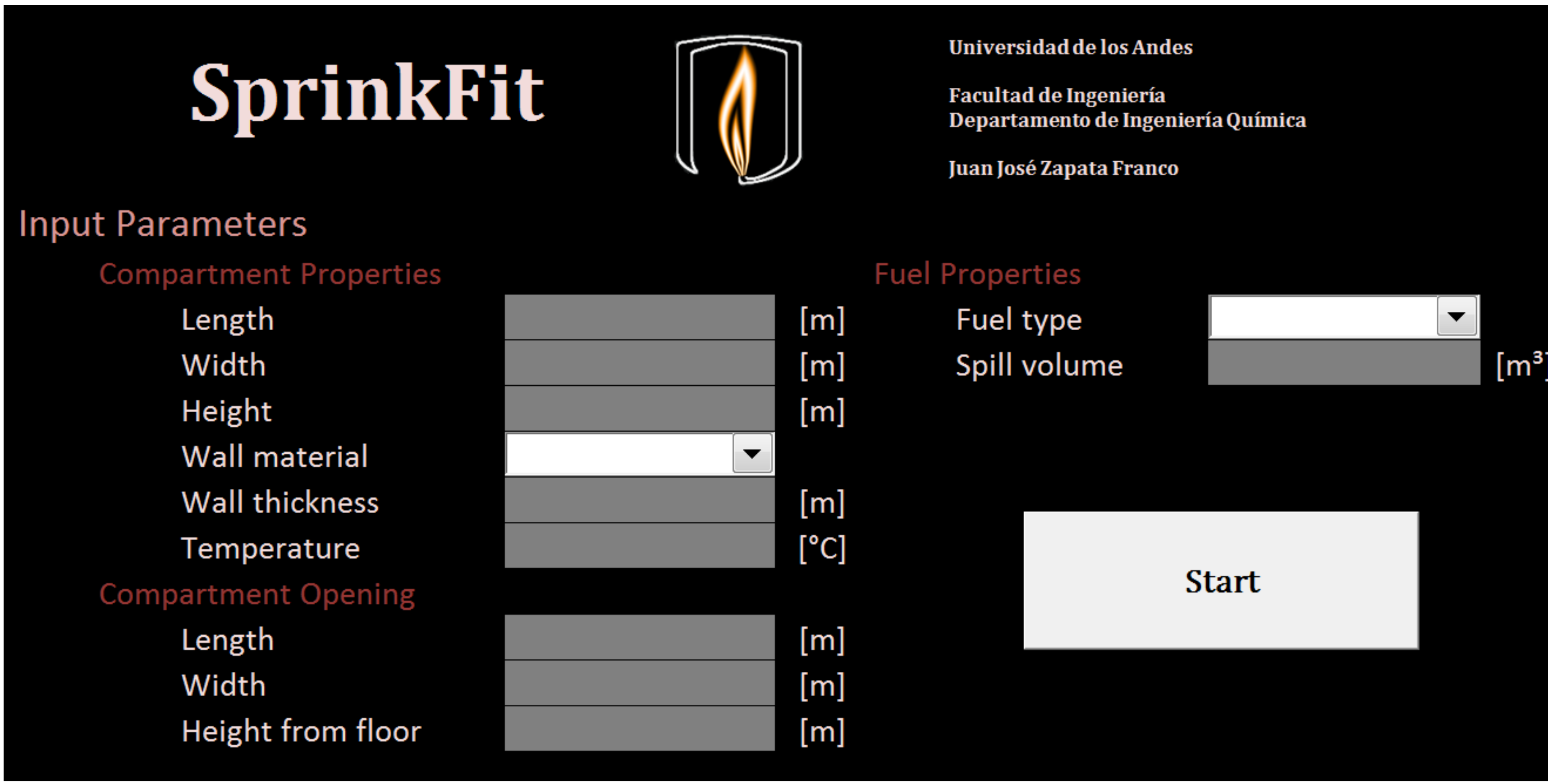
# Verification Method



# Hidraulic Requirements

- Minimal design pressure to the last sprinkler at the end of the grid
- Water availability should be guaranteed during the time the sprinklers are activated
- Discharge until appropiate action is assured

# Algorithm Programming



# Algorithm Programming

# SprinkFit

Universidad de los Andes

Facultad de Ingeniería
Departamento de Ingeniería Química

Juan José Zapata Franco

## Input Parameters

### Compartment Properties

| | | |
|---|---|---|
| Length | 19.50 | [m] |
| Width | 19.50 | [m] |
| Height | 20.00 | [m] |
| Wall material | Aluminum Alloy | |
| Wall thickness | 0.016 | [m] |
| Temperature | 20.00 | [°C] |

### Compartment Opening

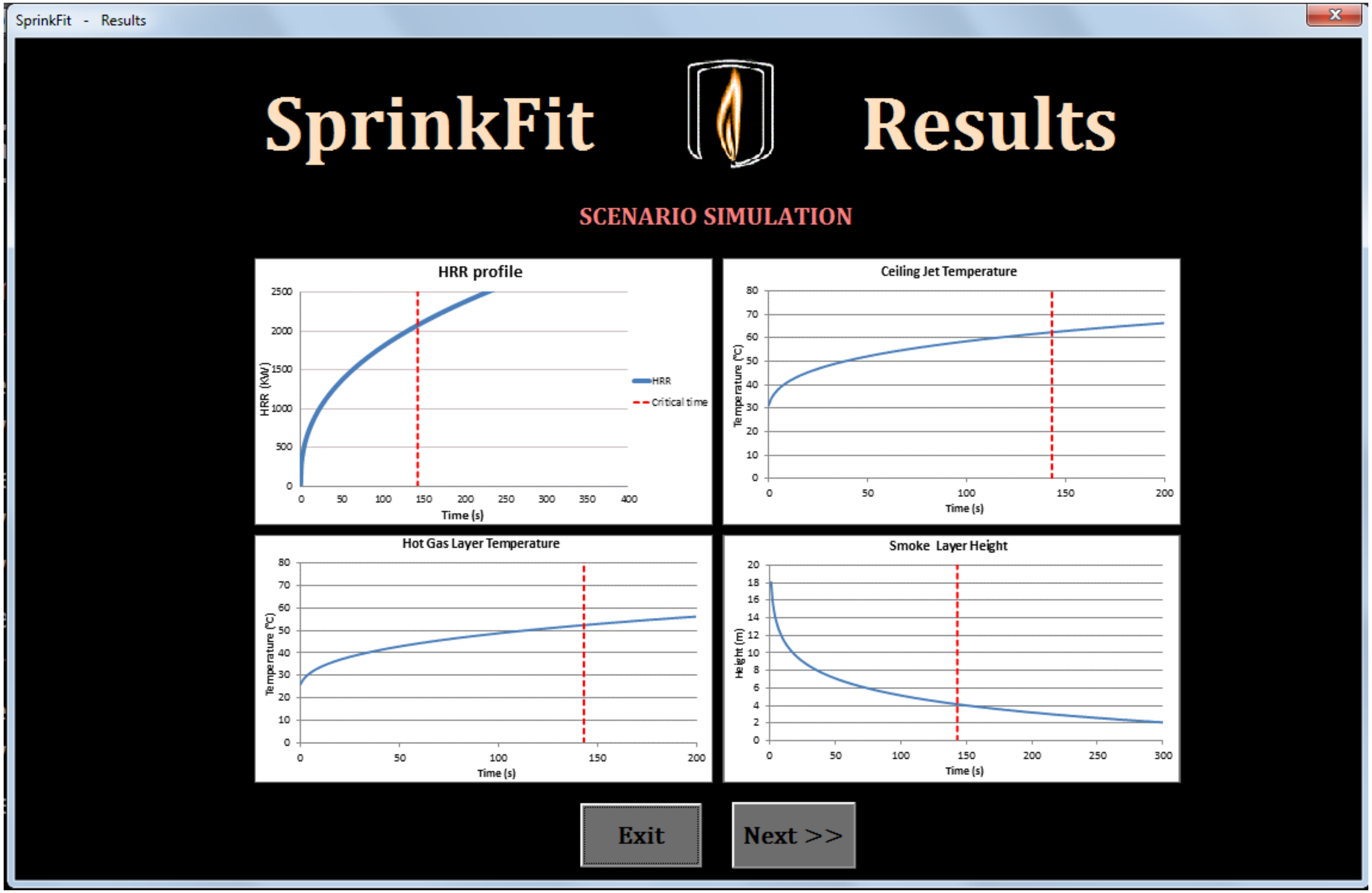
| | | |
|---|---|---|
| Length | 2.00 | [m] |
| Width | 3.00 | [m] |
| Height from floor | 9.00 | [m] |

### Fuel Properties

| | | |
|---|---|---|
| Fuel type | Heptane | |
| Spill volume | 0.04 | [m³] |

Start

# Algorithm Programming



# Algorithm Programming

## SprinkFit Results

### DESIGN CRITERIA


| | | |
|---|---|---|
| Critical Time | 143.11 | [s] |
| Activation Time | 111.4 | [s] |
| Activation Lag Time | 51.71 | [s] |
| Total Fire Time | 607.59 | [s] |
| Heat To Flashover | 1816.7 | [KW] |

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# Algorithm Programming

# Reliability

- Reliability is related to experimentation and is subject to modelling and simulation restrictions and limitations
- Validation and Verification is needed

# Conclusions

- Performance-based design method is a concept responding to the necessity to accomplish protection objectives
- Scenario simulations are the foundations of the Design criteria.
- Cooperation is needed
- Great opportunities for improvement

# Recommendations

- Continue with experimental research to improve reliability
- Research method could be applied in different areas of engineering (construction, process design, etc.)
- Potential to develop as a commercial design tool
- New technology to design products

# THANK YOU!

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