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

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ABSTRACT

This paper proposes a methodology for a thorough specification of sprinkler systems following the performance-based method, by providing a theoretical approach into meeting the scenario's phenomenological fire behavior with the system's design features seeking to obtain personnel protection and fire suppression as design objectives. Specific design criteria are developed for the most important characteristics of a sprinkler system such as activation time, discharge coefficient k and spray density based on simulations and experimental correlations found in literature. Several experimental fire cases are studied to validate models, correlations and applying methods.

Key Words: Sprinkler system, Performance-based design, Fire phenomenon

INTRODUCTION

Performance-based design has been the method recently developed to study fire behavior in a specific scenario to defeat uncertainty regarding design failures in sprinkler systems which can lead to higher property damage; nowadays, many countries such as the USA, Australia, New Zealand, Canada, Japan and some North-European countries like the UK and Sweden have already started changing their fire safety codes from a prescriptive approach to a performance-based one, attempting to provide a clearer guidance concerning effectiveness in meeting protection objectives. [1]

Five primers have been developed by the NFPA Performance-Based Support Team [2], created in 1995 to assist in the transition in order to establish a procedure that assures goals are met, yet no current legislation has replaced or modified the prescriptive design.

These five primers are the next:

1. Goals, objectives and criteria
2. Characteristics and assumptions
3. Fire scenarios
4. Verification methods
5. Reliability

This paper follows these primers into proposing a new method that allows analyzing the case and systematically adjusting the most important fire sprinkler system's characteristics to a protection objective set by a specific criterion (the Critical Time), which takes personnel safety, fire escalation and structural damage into account, indicating the moment in which human presence is impossible due to high temperatures and the presence of smoke covering the upper part of the enclosure down to less than 2m (~10ft) high; therefore setting the adequate sprinkler activation time.

Thereafter, each design specification for the fire sprinkler system is used as a design criterion and related to a fire phenomenon according to the way it's affected by the water spray. Each relation is described by experimental correlations developed in several research institutes as they're shown in Table1 and are thoroughly explained in this paper:

Table 1. Main correlations found as design criteria.

Design Criteria	System Characteristics	Fire Phenomena
Activation time	Sprinkler glass bulb	Critical time
Discharge coefficient K	Drop diameter	Heat absorption
Spray density	Flow duration	Extinction time

Finally, this paper proposes a methodology for a thorough specification of sprinkler systems following the performance-based method, by providing a theoretical approach into meeting the scenario's phenomenological fire behavior with the system's design features seeking to obtain personnel protection and fire suppression as design objectives. Specific design criteria are developed for the most important characteristics of a sprinkler system such as activation time, discharge coefficient K and spray density based on simulations and experimental correlations found in literature. Several experimental fire cases are studied to validate models, correlations and applying methods.

OBJECTIVES

General Objective: This study seeks to propose a series of criteria for characteristic specification in fire sprinkler systems design following the performance-based design method focusing to ensure <u>personnel safety and fire extinction as design objectives</u>.

Specific Objectives:

1. To obtain a fire model allowing to perform a fire behavior simulation which results can be compared with experimental results.
2. To perform a bibliographical research for existing experimental correlations describing the effects of sprinkler systems design features over fire behavior.
3. To develop an algorithm for creating a method allowing to relate fire behavior and design features, searching for an effective system functioning able to comply with the design objectives.

METHODOLOGY

This project starts with a thorough research on fire modelling, theoretical and experimental approaches, searching to develop a design criterion relating sprinkler system feature selection and fire behavior to reach the design objective.

The main strategy for developing a system following the Performance-Based design method is to relate variables affecting fire with the sprinkler characteristics in the system.

First of all a reliable fire simulation must be performed, allowing to effectively predict fire behavior. The next step is to relate sprinkler features and its effect on the fire, this way the correct features and the system specifications are adjusted to ensure an efficient protection design, avoiding water waste for unnecessary activation and preventing property damage.

Figure 1. Performance-based design flow.

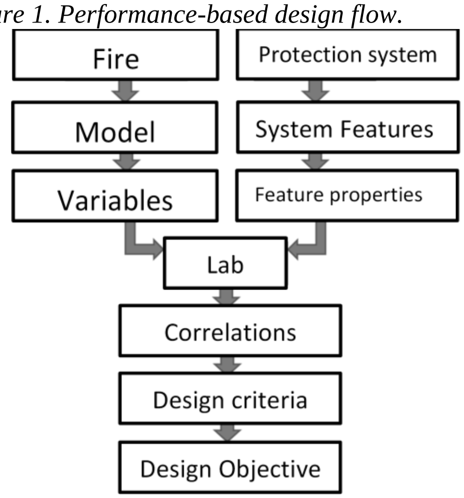


Figure 1 shows how to follow the performance-based design method in which variables regarding fire behavior and sprinkler system features, are related through experiments performed in controlled environments where correlations are developed and validated, allowing us to adjust the system design to a certain design criterion in order to meet the design objective.

Table 2: Main variables and correlations taken into account to solve the problem.

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	

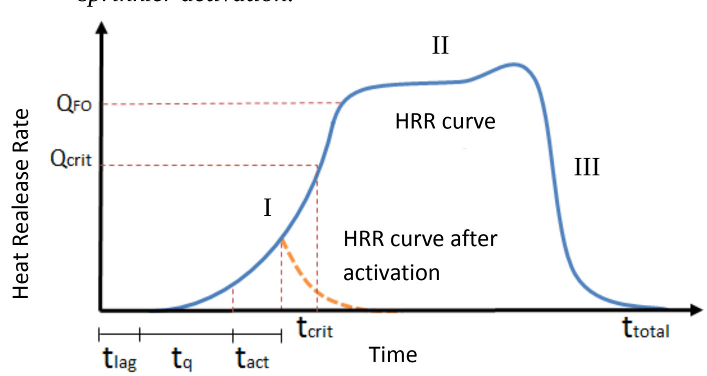
Thereafter, an algorithm (Fig. 2, page 3) is proposed stating the relations between the variables in Table 2 to define the design criterion that is going to comply with the design objective; personnel safety and fire extinction represented by the Critical Time.

The design criterion is marked in a square indicating that the system design must be adjusted to set the sprinkler nominal activation time($\mathbf{t_q}$) plus its lag time ($\mathbf{t_{act}}$) prior to the critical time of the system($\mathbf{t_{crit}}$).

Equation 1. $$t_{act} + t_q < t_{crit}$$

At the left-hand side in Figure 2 we can see the fuel and enclosure properties, related to several variables that are going to interact through correlations, which will lead to a certain system requirement, such as sprinkler head type, pump power, total flow, or to a fire phenomenon such as the heat release rate or the critical time. To the other side of the figure we can find the hydraulic requirements that will support the whole system and assure its correct functioning.

Figure 3. Heat release rate curve with and without sprinkler activation.



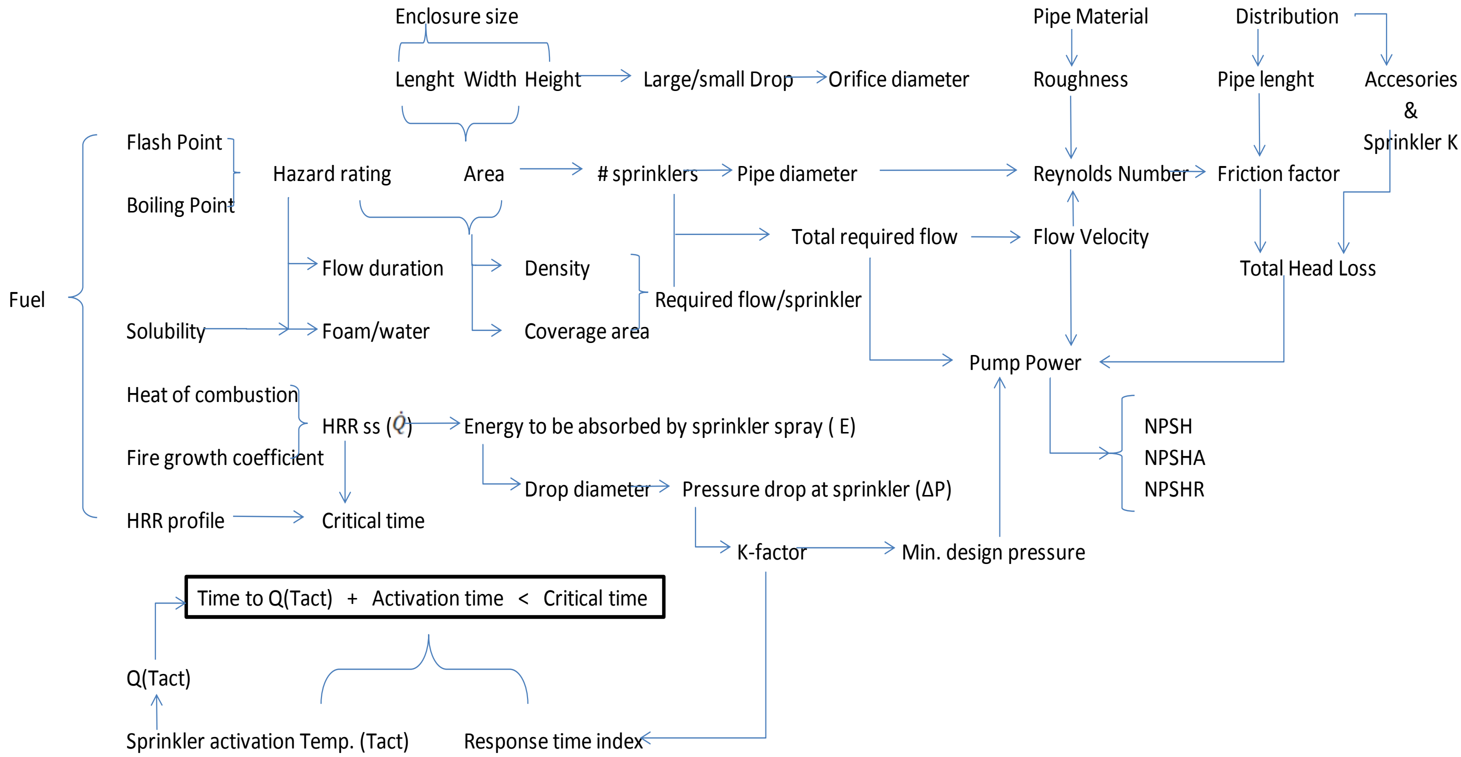


Figure 2. Performance-based design Algorithm

Figure 3 explains the design criterion (Eq. 1), showing the effect of the sprinkler system activation on the Heat release rate profile of the fire over time.
It also allows us to understand fire behavior in order to determine key moments in which the sprinkler system should be activated to comply with the design objective.

In Fig. 3 we can observe the three stages in a fire; the first stage (I) in which the fire starts and has a certain lag time until enough material is burnt for the fire to start growing exponentially until most of the material in the compartment is burnt and so a flashover can occur, moment in which temperature has risen considerably and leading to structural damage. The second stage (II) describes the moment when most of the enclosure is filled with smoke and there's not enough air for the fire to continue growing, instead its heat release stabilizes. Finally in the third stage (III) the fire has consumed all combustible material and starts to die off until it's completely extinguished. [3]

The critical time it's the most important factor to be considered for the sprinkler system design since it will determine the limit in which the system should be activated. This critical time is related to a specific HRR (Q_{crit}) which should be located during the first stage while the fire still controllable and doesn't represent a life danger, that's necessarily before reaching the heat for a Flash over (Q_{FO}).

The final factors presented in Fig. 3 are related to the sprinkler system, its features are going to able to be adjusted so that the design meets the expectations set. The system should be activated before the fire's HRR reaches the Critical time so the fire can be controlled before higher damages take place. The Activation time is related to a Nominal activation time (t_q) which represents the moment at which the sprinkler should be activated according to its model specifications, but there's also latency in sprinkler activation associated to its Response time index (RTI), which includes factors such as water discharge; the time it takes for the fire to be affected by the spray, reaching it from the ceiling (t_{act}).

FIRE MODELS & VALIDATIONS

Fire is a phenomenon very difficult to describe since it is affected simultaneously by multiple different variables, themselves, impossible to predict as their behavior seems completely random; variables such as fuel spill size and shape, ventilation, fire plume movement, wind shifts, etc.

This is the reason why several fire models have been developed in order to have an idea on how the fire is going to affect the system and to design the appropriate strategy to fight it. These models are mostly correlations originated in controlled experimental environments, with a high cost implication as well as important limitations; e.g. most of them are only able to describe the first fire stage under specific condition ranges.

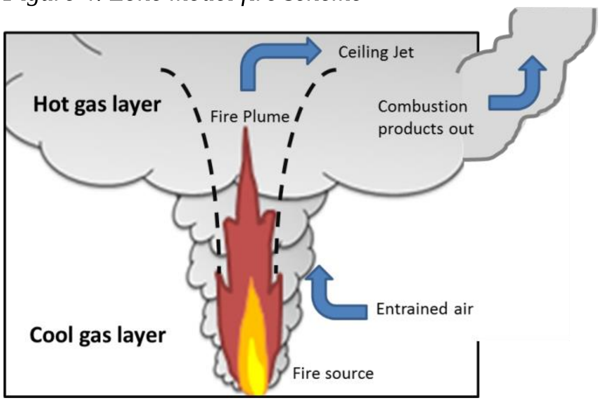
In this paper we analyze some of these models and compare them to experimental results found in literature in order to validate their results and to demonstrate the need for a further scientific cooperation into developing better models that allow us to predict the fire phenomenon more accurately.

Scenario Description: A fire scenario has different characteristics which are going to affect the fire behavior and thus giving us the parameters to develop a performance-based design.

In this project enclosure size, ventilation openings, surface materials, environmental conditions, fuel type and quantity are defining the fire scenario and, through models and simulations we are able to obtain the most important variables involved in the phenomenon such as the Heat release rate profile, Hot gas layer height and temperature and the Ceiling jet.

Fig. 4 shows a simplified zone model fire scheme in which variable behavior and relations between mass and energy balances in the system are evident.

Figure 4. Zone model fire scheme



Heat Release Rate (HRR): Fire development is normally described by its heat release rate, calculated from the fuel's energy potential related in its combustion heat and its mass loss rate following the stated in Eq. 2. [4]

Equation 2. $\dot{Q}_{Total} = \Delta H_{comb} * \dot{m}$

Three models are analyzed to describe fire behavior in the case that experimental or simulation data are not available. It is also important to notice that for this project only the first fire stage needs to be described, since during this stage the fire develops rapidly and so it must be controlled by the sprinkler system activation, before a flashover occurs and a greater risk appears.

Standard t^2 Model: This model is only able to describe the first fire stage and shows fire growth proportional to the square of time, depending on the HRR rating ($\boldsymbol{\alpha}$) in which four categories are defined as Slow, Medium, High and Ultra High ***[5]*** related in the following equation:

Equation 3. $\dot{Q} = \alpha\, t^2$

This model was developed to specify fire detector's response, for which it is possible to use, although it's very limited and is shown efficient for fires less than 500KW.

McCaffey, Quintiere & Harkeroad Model: Takes into account the effect of variables such as ventilation, fuel quantity, heat loss through walls based on mass and energy balances. Considers heat penetration in surrounding materials and the moment when a flashover may occur [6]. Eqs. 4 to 6 show how these variables are related:

Equation 4.

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

Equation 5. $\Delta T_g = 6.85 \left(\frac{\dot{Q}_{Total}{}^2}{h_k\, A_T\, A_o \sqrt{H_0}}\right)^{1/3}$

Where ΔT_g is the hot gas temperature rise compared to room temperature.

Equation 6. $h_k = \left(\frac{k\, \rho_{wall}\, c}{t}\right)^{1/2}$

The term h_k takes into account heat loss in wall transfer, valid for the first fire stage for all moments before thermic penetration time associated to flashover.

Simplified HRR model: This model was developed by observing HRR profiles found in literature, where most fires reach the maximum heat released at the 80% of the total fire duration, and flashover time is reached at the 10% [7]. This way an approximated HRR profile can be stated, although this model has great disadvantages and must be taken as a very general approach.

This model needs the total fire time calculation related to the fuel load (W) [8], mass loss coefficient and enclosure area as follows:

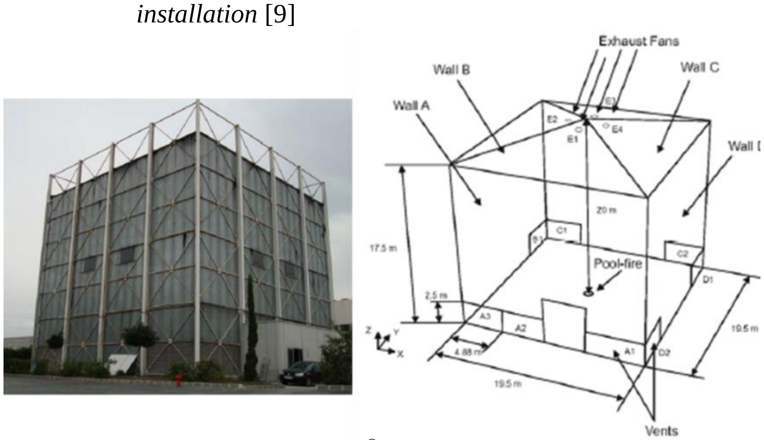
Equation 7. $t_{total} = \frac{W\, A}{\dot{m}}$

The McCaffey et al. model is the most widely accepted and used in most fire simulators as it is based in mass and energy balances, taking into account much more scenario variables than other models allowing to model higher scale scenarios such as warehouses and process facilities to which this project is focused.

HRR Model Validation: A high rise atrium is used as scenario in order to validate HRR profile model results by comparing them with the experimental results and a simulation performed by the Fire dynamics simulator (FDS) Pyrosim®.

This experiment was developed by Gutierrez-Montes et al. [9] at the Metal Technological Center in Murcia, Spain, where a steel structure (19.5m x 19.5m) with 20m high and a ventilation opening (4m x 2m) was exposed to 44Lt heptane fire located in the middle of the room in an open recipient, as shown in Fig. 5.

Figure 5. Spatial distribution for the experimental installation [9]



Through the Pyrosim® interface the fire scenario can be simulated to obtain heat flow and temperature profiles, reflected on the enclosure surfaces. The ceiling is the most important surface, since it shows the Ceiling jet formation as well as the place where the sprinklers will be located. Results are shown in Fig. 6.

Models, experimental and simulation results were put in parallel in Fig. 7, and a precision analysis was performed by comparing each model result with the real data obtained experimentally, shown in Table 3.

Figure 7. Parallel comparison between HRR results.

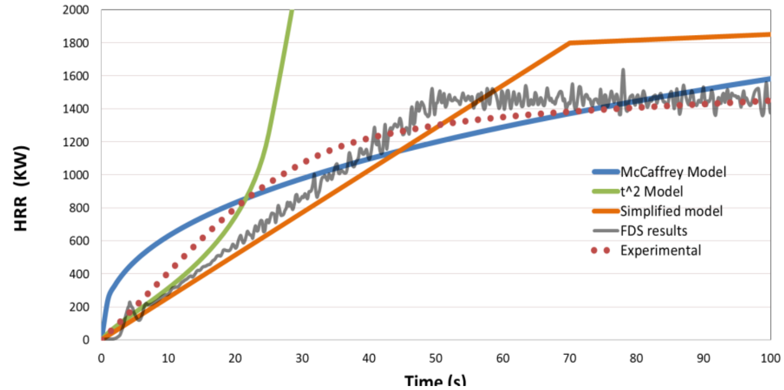


Table 3. Relative error comparing models and experimental results.

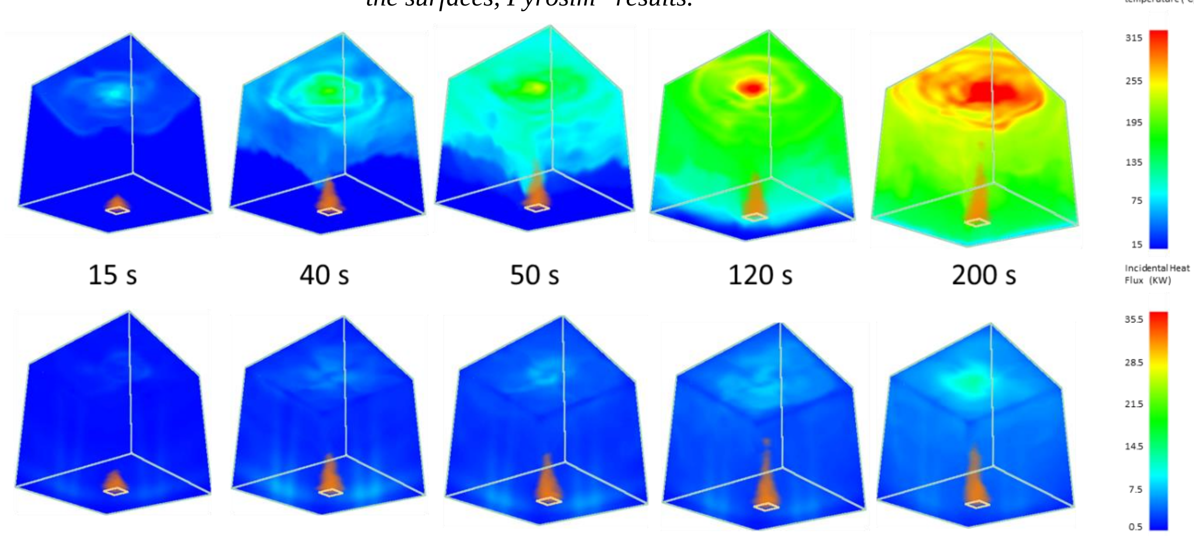
Model	Relative Error
McCaffrey et al.	10.5%
t^2	24.1%
Simplified	23.8%
FDS (PyroSim)	8.2%

As can be seen in Fig. 7, most models adjust to the experimental results regarding the first fire stage, the FDS results have the least relative error and show a similar profile, linear growth, to the one obtained by the simplified model.

The McCaffrey model shows a very similar behavior to the experimental results, the inflection reflects an accurate prediction with a 10.5% relative error and its theoretical basis, this model can be used in a mayor variety of scenarios.

The t^2 model shows a significant offset when approaching the second stage, due to its limitations to modelling small scale fires.

Figure 6. Temperature and incidental heat flow into the surfaces, Pyrosim® results.



Fire Characterization: In order to fully assess the fire scenario and to entirely understand the risk affecting personnel and property damage, other fire properties must be considered, such as the Ceiling jet, Hot gas layer and Flashover heat.

Ceiling Jet: Is composed by the resulting combustion products projected into the ceiling surface, reflecting on an incidental temperature and the fire plume velocity, which shows how fast these products are reaching the ceiling.

These factors will determine the moment the sprinklers would be activated and to obtain them the Alpert correlations [10] were used as follows:

Ceiling Jet Temperature

Equation 8.

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

Equation 9.

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

Ceiling Jet Fire Plume Velocity

Equation 10. For r/H < 0.15: $$U = 0.96\left(\frac{Q}{H}\right)^{\frac{1}{3}}$$

Equation 11. For r/H > 0.15: $$U = 0.195\,\frac{Q^{1/3}\,H^{1/2}}{r^{5/6}}$$

Hot Gas Layer (HGL): In the zone model it's the control volume where the mayor concentration of combustion products gases can be found, it also represents the layer with the higher temperature and toxicity by the presence of carbon monoxide and nitrates representing a health and structural risk.

Hot Gas Layer Temperature: Can be obtained by solving Eq. 5 for the hot gas layer temperature in McCaffrey model.

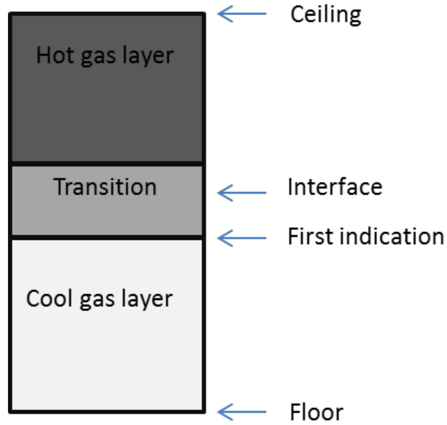
Hot Gas Layer Height: It's an important factor to take into account to comply with the design objective as it indicates the maximal personnel permanence time in the enclosure in case of fire, since when the HGL height reaches 2m(~10ft) there's an imminent human risk.

Equation 12.

$$\frac{z}{H} = C_{10} - 0.28\,\ln\left(\frac{t\,Q^{\frac{1}{3}}\,H^{-\frac{4}{3}}}{\frac{A_s}{H^2}}\right)\ ;\ C_{10} = 1.11$$

This factor is calculated as stated by the NFPA 92B [11], in an experimental correlation developed for smoke treatment in large scale enclosures with a steady HRR. It refers to the first smoke indication of the HGL instead of its interface, taking the compartment floor as reference. This is important to consider since in real fires a transition zone exists in which the layer isn't completely formed as shown in Fig. 8.

Figure 8. Layer separation in an enclosure.



Flashover (FO): Represents the moment when the enclosure temperature gets high enough to consume most of the combustible materials present and the HGL and flames cover most of the volume, making it inaccurate to predict temperatures as they're distributed unevenly, this means models until now used become invalid. Also at this point the fire has grown to be uncontrollable and impossible to be overcome by any automated or manual system apart from firefighter action.

The most commonly used correlation to calculate Flashover heat was developed by Thomas et al. [6], taking into account HGL mass balance and ventilation heat loss as follows:

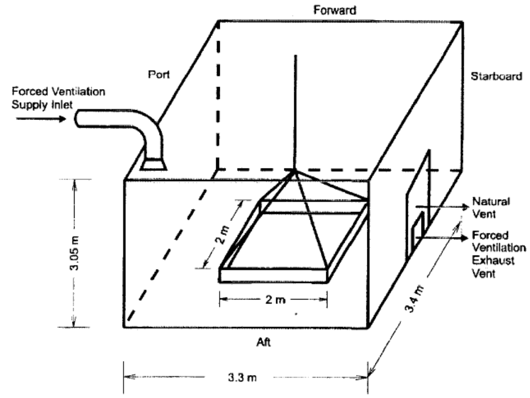
Equation 13. $$\dot{Q}_{FO} = 7.8\,A_T + 378\,(A_O\sqrt{H_O})$$

Eq. 13 was based on experimental results in which FO occurred at 600°C and surface heat loss was averaged by the term $7.8A_{Total}$, for which the result is a lower FO occurrence limit in which it is certain to apply the fire growth models and a maximum indication to when the sprinkler system should be activated. It is also possible that small scale fires die out by themselves and don't get to the FO heat.

Fire Characteristic Validation: As for the HRR profile, the lately explained fire characteristics were validated by comparing them to experimental results.

In this case, the experiment was carried out by the NIST to compare with CFAST predictions for real scale fires [12], results obtained determined that free combustion models tend to overrate fire variables since other factors are underestimated, such as surface heat loss. This test represents a diesel spill, in a bucket 84cm wide in the middle of a 3.4m x 3.3m enclose 3.05m high, with a 2m x 2m ventilation opening, 1.6cm thick steel walls, as shown in Fig. 9.

Figure 9. Spatial distribution for the experimental installation [12]



Models and experimental results were related and put in parallel as shown in Fig. 10. In this case the relative error is used to compare the models' accuracy (Table 4).

Table 4. Relative error comparing Fire Characteristics and experimental results.

Variable	Relative Error
HRR	14.3%
Ceiling Jet	16.6%
HGL Temperature	13.3%
HGL Height	12.5%

The dotted line indicates when the FO should take place and the second fire stage starts, all comparisons were made until this point.

These correlations may have an acceptable error rank; in this case what matters for meeting the design objectives is to have an overall idea of the fire behavior, it is ever suggested to overestimate fire outcomes to prevent malfunctioning and ensure effective security measures. Therefore, these fire models can certainly be used as well as the McCaffrey model, once again compared to evince its accuracy.

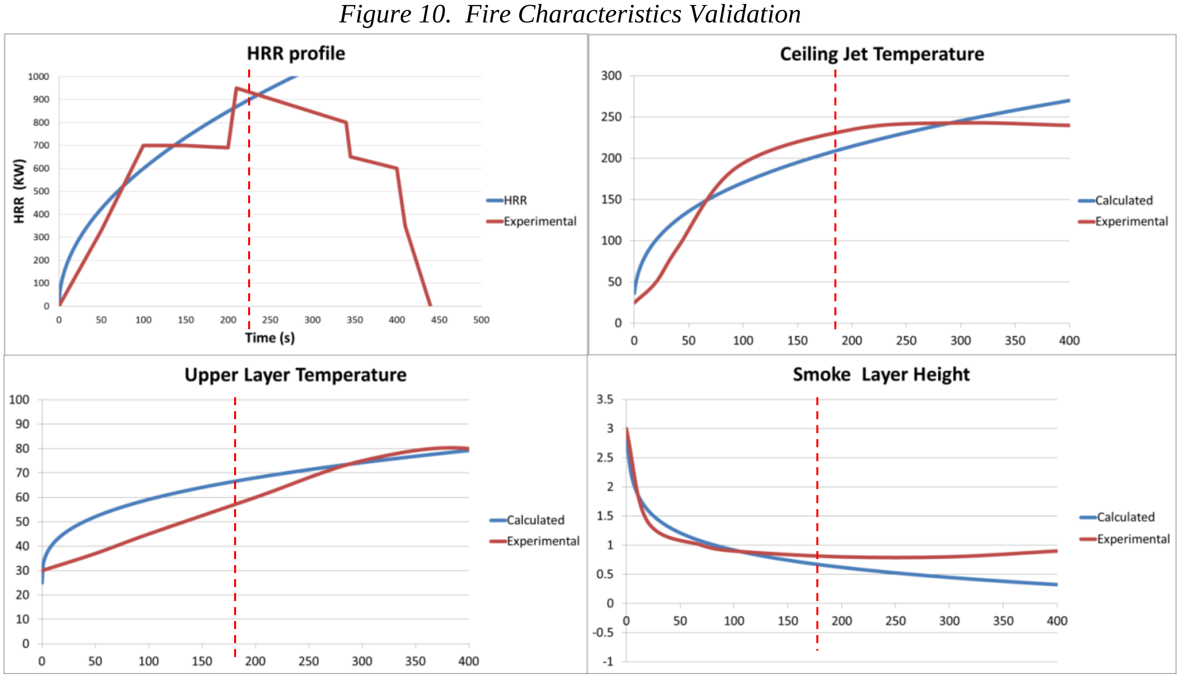
DESIGN CRITERIA

Searching to comply with the Design objectives, the sprinkler system must be designed to be activated at a precise moment, in which personnel safety is assured and material damage is prevented whether by fire or water damage, in the case of early or unnecessary activation. Personnel safety is attained by assuring activation just before the Critical time and material damage is reduced by the system's design adaptability to be activated precisely at the Critical time.

Other design criteria are the Heat reduction and Extinction time, which are going to define certain of the sprinkler system features, such as the Drop diameter related to the sprinkler head K-factor and system pressure, as well as discharge duration determining the amount of water needed to extinguish the fire.

Heat reduction is also considered to show the fire exhaustion progress in graphical representations, but it doesn't define any system requirement.

Figure 10. Fire Characteristics Validation



Critical Time: This criterion is the most important regarding the system design, it comes from a correlation developed by Yashiro [13], who performed fire experiments taking into account fire and human behavior to set a critical time in which fire sets a considerable risk to personnel safety, also indicating the moment in which the fire becomes uncontrollable by personnel intervention, therefore the automatic sprinkler system should come to action.

Equation 14.

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

The sprinkler activation depends on two times, the Nominal activation time (t_q), according to the bulb Nominal activation temperature (T_{act}), and the Actual activation time (t_{act}) which is a delay associated to Fire plume velocity, the Response Time Index (RTI) and adequate discharge availability, indicating the moment the sprinkler system will actually be activated.

Equation 15. $\dot{Q}_{act} = 0.0144\,(T_{act} - T_\infty)^{\frac{3}{2}}\,H^{5/2}$

Eq. 15 is used to know the heat needed to brake the sprinkler bulb, therefore the time the fire HRR reaches this point will indicate the Nominal activation time (t_q). The Actual activation time is calculated using Eq. 16. [14]

Equation 16. $t_{act} = \frac{RTI}{\sqrt{U}}\ln\left(\frac{T_G - T_\infty}{T_G - T_{act}}\right)$

The Actual activation time must comply with the design objective as stated in Eq. 1.

Heat Absorption: States the amount of energy that can be absorbed by the sprinkler activation effect over the fire. This criterion defines the Drop diameter specification for sprinkler heads, to meet the heat absorption requirement. This can be done by using the correlations developed by Kung [15], which takes into account drop absorption through conduction and evaporation according to the amount of water sprayed.

Equation 17. $E = \frac{\dot{Q}_{conv}}{\dot{m}_w(H_{evap} + C_{pw}*(T_{evap} - T_\infty)}$

Where $\dot{Q}_{conv}$ indicates the convective heat portion, usually 70% of the total heat released. Drop diameter is related as follows:

Equation 18. $E = 0.11\,d_r^{-0.73}$

Finally, the Drop diameter found will allow us to determine the system required pressure drop, which will be reflected in a certain K-factor [5] that is going to indicate the right sprinkler head to choose between available standards.

Equation 19 . $d_r = \left(\frac{\Delta P}{\Delta P_0}\right)^{-1/3}\left(\frac{D}{D_0}\right)^{2/3}$ [15]

Equation 20. $K_{sp} = \frac{\dot{m}_w}{\sqrt{\Delta P}}$

Extinction Time: Determines the time it would take to extinguish the fire by taking into account the amount of water sprayed by unit area, drop diameter, HRR, mass loss rate and enclosure height. This correlation developed by Unoki can be used for large scale fires. [16]

Equation 21. $t_{ex} = 1.05\,A^{*2.3}\,\frac{\dot{m}^{3.5}\,M}{\dot{m}_w^{\,2}\,H^{2.5}}\left(\frac{\rho_{FP}}{d_r}\right)^{3.75}$

Equation 22. $A^* = \frac{\dot{Q}}{Cp\,\rho_\infty\,T_\infty\,\rho_w\sqrt{g}}$

In order to determine the amount of water that must be sprayed to extinguish the fire we also have to determine the discharge rate using the prescriptive criteria imposed by the NFPA 13. [17]

Table 5. Water supply requirements for sprinkler systems.

OCCUPANCY CLASSIFICATION[a]	SPRINKLER SYSTEM: DESIGN DENSITY L/min/m² (GPM/ft²)	SPRINKLER SYSTEM: DESIGN AREA m² (ft²)[b]	HOSE STREAM ALLOWANCE L/Min (GPM)	DURATION OF SUPPLY Minutes
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

The Extinction time is a criterion that indicates the minimum time the sprinkler system should function so that the fire is effectively extinguished, although it must be noticed that 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.

Heat Reduction: This correlation developed by Madrzykowski [18] sets an upper limit to indicate heat reduction by the sprinkler system activation effect over the flame. The empirical relation was obtained by experimental methods using wooden structures, so limited to low risk fires, but as it uses the material Activation heat ($\dot{Q}_{act}$) property, then it can be assumed as an approximation to fire reaction upon sprinkler activation. It applies to the fire growth stage while its behavior is predictable though the models previously explained, in which FO hasn't occurred.

Equation 23. $\dot{Q}_{red} = \dot{Q}_{act}\, e^{-0.0022\,(t-t_{act})}$

Result Validation

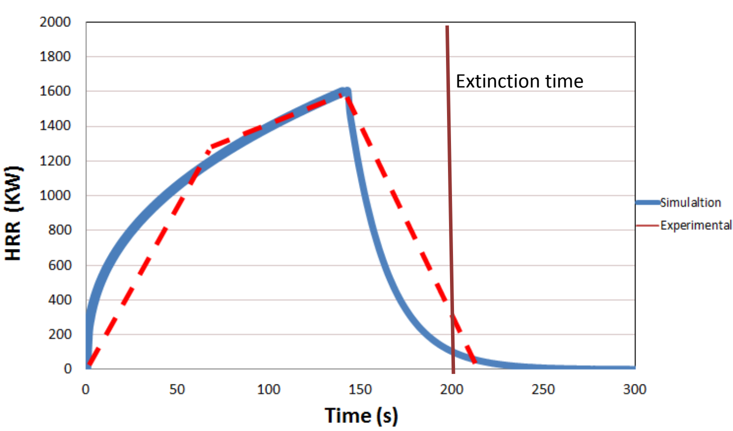
The previously explained Design criteria were tested to see their precision in describing the effect the sprinkler system has over the fire. In this case we used an experiment carried out by the Swedish National Testing and Research Institute [19] in which a diesel fire was controlled by the use of sprinklers.

The scenario had a surface area of 7.1m x 7.1m and 5m high, the fuel was placed in a 20cm diameter bin containing 500mL diesel. Nine sprinklers were installed in a wet pipe with a 7.5mm/min distribution density, 25.9(LPM/atm^1/2) discharge coefficient K, and 79°C activation temperature sprinklers, 1.5m from the ceiling.

Figure 11. Sprinkler activation during the experiment. [19]

The scenario simulation was performer for the HRR model, its results were compared to the measures obtained during the experiment and a relative error of 19.3% was found, a significant difference but something significant was found. As it can be seen in Fig. 12, 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.

Figure 12. Experimental and simulated results compared



HIDRAULIC REQUIREMENTS

The water supply network must ensure the system's correct functioning, by means of providing the minimal design pressure to the last sprinkler at the end of the grid, also the water availability should be guaranteed during the time the sprinklers are activated.

ALGORITHM PROGRAMMING "SPRINKFIT"

The last step to test the methodology and algorithm developed in this paper is to actually couple all the concepts and obtain a design suggestion for an efficient fire protection system. This was achieved by programming a Module in Excel® using its VisualBasic application which we called "Sprinkfit" seeking to develop a tool able to simulate the fire and adjust the system characteristics to meet the stablished criteria and comply with the design objectives.

The Module has a graphical interface where the scenario is set in place using enclosure measures and data bases for common fuels and surface lining materials. It also includes results panels showing graphs obtained in simulations, design criteria specifications to be met; such as the Critical time, Activation time and heat to Flashover. The last panel features system and hydraulic requirements such as the number of sprinklers needed, its flow and pump power, as well as a suggestion for sprinkler type and commercial known product references meeting these requirements.

The objective with this Module is to develop a tool with commercial potential to be used as a design support to obtain the system's requirements in an fast, efficient and easy to use manner. Therefore, special attention was given to its graphic design and user interface. Aiming this target, a logo was designed (Fig. 13) to identify the Module as a product inspired in the Los Andes university symbol.

Figure 13. "Sprinkfit" Module logo.

This Module, its components, functioning and results applied in two cases can be seen in the Annex section at the end of this document.

RECOMMENDATIONS

It's important to keep in mind that the effectiveness in the use of these design criteria in sprinkler system feature selection depends directly in the reliability of the input parameters and de capability to simulate the fire, for which model restrictions and limitations should be considered.

It is recommended to test and validate model results describing fire behaviors by using simulation tools such as FDS, with a most efficient and robust method in order to develop a more assertive criterion.

CONCLUSIONS

The Performance-based design method is a new concept in the fire protection field responding to the necessity to accomplish specific objectives, in this project we searched to assure personnel safety and human safety by preventing the fire to reach the Flashover point and achieving fire extinction.

Scenario simulations are the foundations of the Design criteria for they allow us to understand fire behavior and how to fight it, but existing models have serious limitations due to the high complexity of the phenomenon, some are simple approximations and haven't been thoroughly validated.

Cooperation between governments, the academy and the industry is essential to validate and reformulate methods in order to develop further knowledge and new strategies searching to provide safer environments.

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ANNEXES

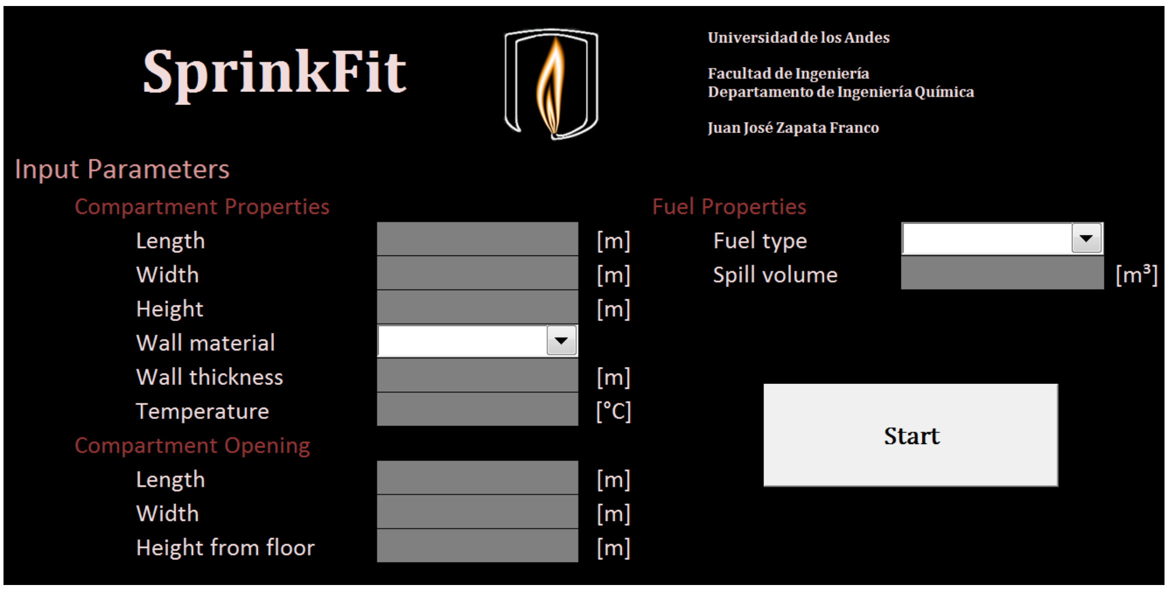
SPRINKFIT MODULE PROGRAMMING

GRAPHICAL INTERFACE

The first module spreadsheet was used to allow the user to insert scenario specification properties and dimensions of the compartment (Length, Width, Height, Ambient, material coating and wall thickness), the dimensions of the natural ventilation openings, the type of fuel that will start a fire and spill volume.

The coating material of the walls and the type of fuel can be selected from a drop-down list, or if not found, can be added to the spreadsheet database filling requirements properties of the material or substance to add.

From these data the simulation calculates and obtains design criteria for specifying the characteristics of the sprinkler system. The user interface module is shown below:



The "Start" button has an associated code that initializes the solvers that are required to perform the calculations (Selection of the activation temperature and friction factor), which is completed in the spreadsheet setting criteria, therefore this method is able to select the design specifications of the system characteristics and the results panel is initialized.

Calculations Sheet
In this spreadsheet all necessary calculations to meet the design criteria were performed, all equations are described in this document and graphics are made with profiles that describe fire behavior.

Database
In this spreadsheet, all tables that will be used for the selection of materials for coating the walls and fuel present in the compartment were located, has physical and chemical properties required to perform the calculations necessary to obtain the specifications of the system features from the design criteria.

The following table shows the materials and fuels available in the database of the module:

Fuels	Lining Materials
Methanol	Aluminum Alloy
Ethanol	Glass
Benzene	Glass Fiber, Coated
Hexane	Glass Fiber, Insulation
Heptane	Gypsum Board
Xylene	Hardboard, High Density (1/2 in)
Acetone	Hardboard, Siding
Dioxane	Brick
Diethyl ether	Calcium Silicate Board
Benzine	Celullose Insulation
Diesel	Cement Mortar
Gasoline	Concrete, Light Weight
Kerosene	Concrete, Normal Weight
Jet fuel -4	Concrete/gypsum composite
Jet fuel -5	Firebrick
Transformer oil	Iron
Fuel oil	Maranite Concrete Layered
Crude oil	Marmol
Propane	Mineral Fiber Insulation
	Particle Board, High Density
	Particle Board, Low Density
	Plate Glass
	Plywood
	Polyethylene
	Polystyrene
	PVC
	Steel, 304 Stainless (1/4 in)
	Steel, Plain Carbon
	Wood Board (1/2 in)
	Wood, Hardwoods
	Wood, Softwoods

It also has a table in which various types of commercially available sprinklers under the discharge coefficient, a factor that is defined by the specific geometry according to the manufacturer, were selected, includes reference to two major companies Tyco ® and Viking ® and Internet link associated with the specification sheet. From this table the sprinkler that meets the design criteria are selected.

Other tables include the nominal values which are to be found to approximate the values of calculations, in order to specify the design commercially available values. This is the case of the inside diameter of the pipe and the temperature of the glass bulb sprinkler.

Results panels

To submit a properly organized and the results obtained, the module is divided into three panels, each showing a parameter of the design criteria and finally specifying the main features of the sprinkler system. Results The three panels are arranged as follows:

1. The first panel shows the results of the simulation of the fire in the specified scene includes graphs of heat release profiles (HRR), the Ceiling Jet and the temperature and height of the hot gas layer. This module will have two buttons with the options of leaving the panel or move to the next panel.

2. Second panel shows the effect of the selected features from the design criteria on the heat release profile, allows observing the time at which the system operates; the activation times, the associated delay, critical time, the time when the fire is extinguished and heat reduction profile given by the activation of the system is given. The total duration of the fire and the heat required for the flashover in the compartment of is also specified.

3. The third panel shows the results of the specifications of the system characteristics, the discharge coefficient, nominal activation temperature, the color of the glass bulb, the orifice diameter, the response time index (RTI) and reference sprinkler along with a link that leads to the specification sheet and an image of the selected sprinkler. The hydraulic requirements of the system, number of sprinklers, each sprinkler flow, the total flow, the diameter of the pipe, the pressure drop in the sprinklers and the power of the pump are also shown.

APPLICATION OF THE ALGORITHM

This section will use all the concepts, equations and models described in this document, the input parameters required by the module specification stage study will be introduced and the algorithm uses the design criteria to determine the characteristics of the system.

Results

Initially, take into account that this case used for the validation of the correlation for heat reduction modeling was conducted by Arvidson et al. [19], in order to demonstrate the importance of selecting an appropriate activation temperature that meets the design criteria studied, especially critical time determining this system feature.

Subsequently the application of the algorithm is performed, the case studied was the one developed by Gutiérrez-Montes et al. [9] for system specifications, that is because this scenario has a surface area and the risk of a significantly large fire, which corresponds to the target scenarios which aims the project, e.g. storage compartments or where processes are performed hazardous chemicals.

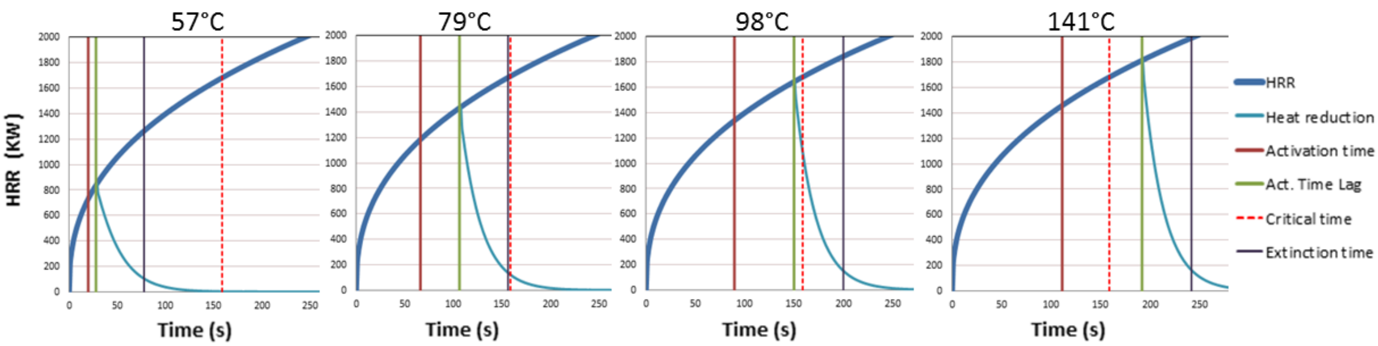
Case 1: Temperature Activation

This scenario was originally developed to study the effect of sprinkler system activation on the HRR from a fire and managed to check that correlations that are available describe a profile heat reduction which has a similar behavior to the real one and that, by simulating the system with the same activation temperature, the system is activated at the same time.

This scenario will be used to study the right moment in which the system should activate according to the activation temperature, determined by the respective glass bulb.

Entering the scenario in the SprinkFit module and run the program, it was found that the sprinkler activation temperature that meets the design criteria for this parameter is 93 ° C, while the temperature at which the tests were performed is 79 ° C.

In order to observe the effect of this parameter on the behavior of fire and the time of system activation, the scenario simulation was performed with different nominal activation temperatures commercially available. The graphics obtained are shown below:



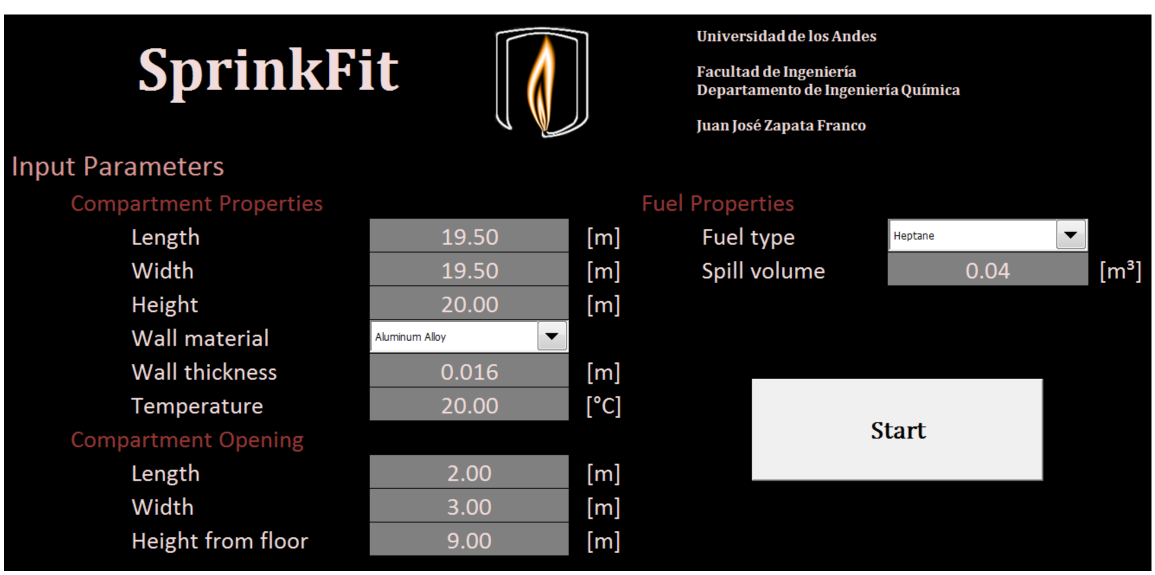
It can be seen that the difference of time of operation of the system is significant and is generally in the range of 50sec - 70sec making it relevant to select a proper activation temperature so the scenario can be protected as each one represents an increase in the release of heat of about 500KW between Tact = [57 ° C - 79 ° C] and about 200KW among other intervals, this difference may result in unnecessary or late sprinklers activation leading to significant losses.

The design criterion used in this case is the critical time as indicated by the dashed red line, as explained earlier, it takes into account a variety of factors, and indicates the time the sprinkler system activation is imperative, since the fire becomes impossible to fight manually.

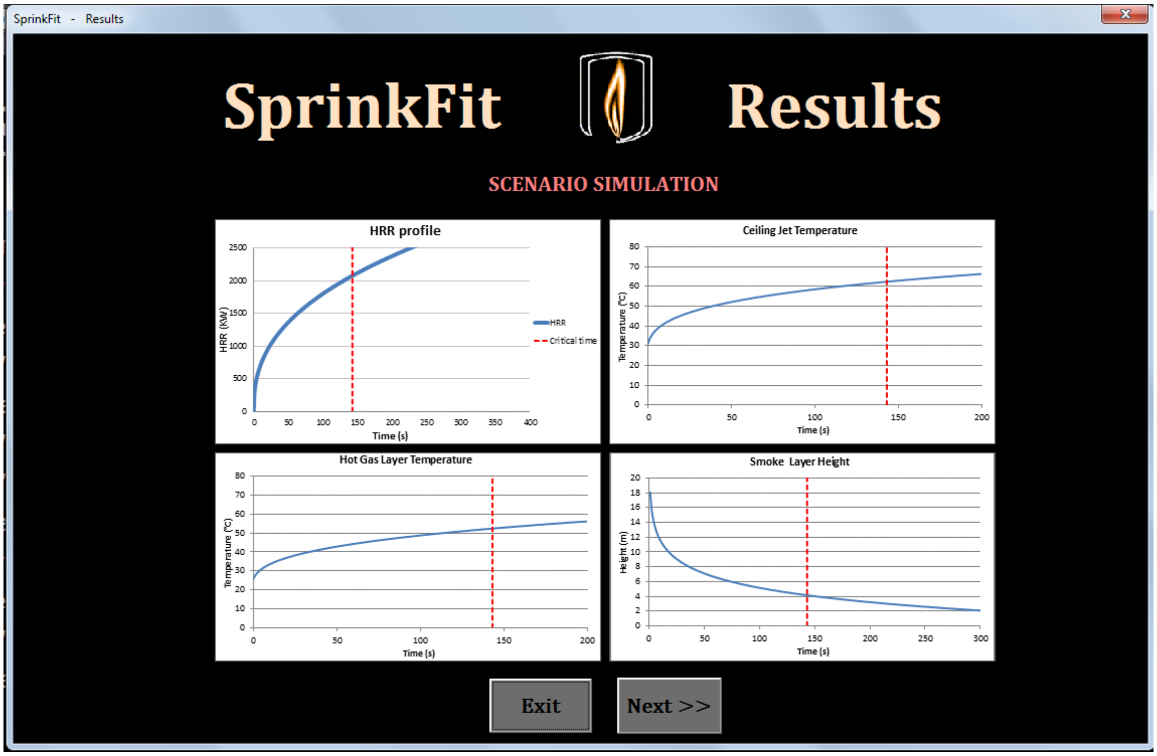
This criterion selects the temperature of 98 ° C which is close to the limit, thus ensuring system activation at the right time and taking into account that the heat reduction occurs almost immediately, it is certain that if the system is active at this time, the heat released by the fire will fail to exceed the critical limit.

Case 2: Sprinkler System Design

The case developed at the University of Murcia, Spain by Gutierrez-Montes et al. [9] was introduced into the SprinkFit module interface, with the following parameters:



The program was executed, the fire properties were calculated using the criteria developed; design specification features for the sprinkler system were obtained that fit the protection scenario. The following graphs show the panels of the results produced by the module:



This way the characteristics of the sprinkler system were completely specified for the protection of this scenario. The results are based on the algorithm developed throughout this document and supported by the theoretical basis describing the phenomenological processes carried out in the fire scenario and correlations that define the effect of each of the protection system features to lead to effective fire suppression.