Application of Fire PSA in Defining System Reliability Criteria: Detection and Suppression Systems in I&C Electrical Panel Room

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Abstract:
Probabilistic Safety Assessment (PSA) is a key part of a Nuclear Power Plant (NPP) licensing process. It considers the elaboration and updating of probabilistic models that estimate the risk associated to operation, allowing the risk monitoring from the design to the plant decommissioning, for both operational as regulatory matters. Despite its maturity, there is doubt about whether PSA as presented today can be considered as a design tool. Therefore, the presentation of cases in which PSA was used in the design phase represents an important contribution to such discussion. In this context, this paper presents a case study in which PSA is applied to the definition of design requirements. Thus, given a predefined risk acceptance criteria, the reliability characteristics for the fire detection and suppression systems in two instrumentation and control (I&C) electrical panel rooms were established. In order to do so, based on the method for the detailed fire modeling presented by U. S. Nuclear Regulatory Commission (USNRC) in NUREG/CR-6850, a probabilistic model was developed and fed with data from simulations performed in a Computational Fluid Dynamics (CFD) model, and from the Conditional Core Damage Probabilities (CCDP) obtained from the Plant Response Model (PRM) of the Fire PSA for the plant.

Keywords: Fire PSA, Design of Nuclear Power Plants, Reliability of Fire Protection Systems, Computational Fluid Dynamics.

1. INTRODUCTION

PSA is a key part of a NPP licensing process [1]. It considers the elaboration and updating of probabilistic models that estimate the risk associated to the operation, allowing the risk monitoring from the design to the plant decommissioning, for both operational as regulatory matters. The PSA of industrial installations is a subject that has evolved with the complexity of the systems [2][3], and presents specific methodologies for some hazard groups – e.g., flood, fire and seismic events. Nowadays, it is considered a logical, comprehensive and structured methodology, focused on identifying and evaluating risks of complex technological systems, with the final purpose of improving their safety and performance characteristics while maintaining an acceptable cost-benefit ratio [4]. However, despite the recognized benefits of its application in the early stages of design [5] – e.g., given an overall safety requirement, the probabilistic models obtained through the PSA can help in the specification of a safety system to be installed –, there is controversy over defining PSA as a design tool [2][6]. In addition, there is resistance to its quantitative results [7], since its substantial demand for data (not always available) can lead to non-trivial assumptions to make analyze feasible [8]. In spite of the difficulty of handling uncertainties during complex systems design, the risk associated with critical systems operation should be limited [9] – in general, in compliance with a design criterion, such as the threshold for the reactor core damage frequency (CDF) in nuclear power plants; to be presented in the Final Safety Analysis Report (FSAR) [1]. To quantify this risk, in addition to the information on the operational environment – e.g., natural phenomena statistics –, PSA is based on combining equipment and operator reliability data.

The use of PSA results for design alternatives comparison is not a new concept [10][11], and has been

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applied or identified as important in a variety of areas [3]. The study of PSAs performed in various industries helps to understand the consensus about this concept, and highlights these analyses potential contribution in developing new systems [3]. Exploring this potential depends on elaborating simple, quantitative, realistic, and prospective processes and models that should be able to feed analyses at the design stage, and able to bring results that can be interpreted by professionals involved in the design decision making process. In addition, the presentation of cases in which PSA was used in the design phase represents an important contribution to the discussion on its needs and limitations. In this context, this text presents a case study in which PSA is applied in a safety system specification. Thus, the following sections present the application of the Fire PSA methodology proposed by the USNRC [12] on the development of a probabilistic model wish can be used to determine the required reliability of the detection and suppression systems in an I&C electrical panel room of the plant. In principle, however, a brief description of the plant is made – focusing on its PSA –, followed by a presentation of the employed Fire PSA methodology. After the mentioned discussion, the conclusions are presented.

2. PLANT DESCRIPTION

The nuclear plant considered is a 48MWth two-loop pressurized water reactor (PWR) in the design phase. In this plant, the pressure vessel, steam generators, the primary pumps, and the pressurizer are enclosed in a steel containment, which is surrounded by a water pool used as shielding and ultimate heat sink. A confinement building houses the steel containment and a secondary system with two turbo-generators. The PSA level 1 of the reactor was developed as part of the plant licensing process, i.e., to meet the regulatory requirements of the Comissao Nacional de Energia Nuclear (CNEN) – which regulates the Brazilian nuclear sector and adopted the NUREG-0800 [1] as a pattern to evaluate the FSAR of the plant. In its initial version, the PSA level 1 presented the results in Table 1. This table shows the groups of initiating events which, in principle, were considered relevant for the calculation of the plant's CDF. Subsequent evaluations, however, have shown that some of these events contribute little (in relation to the others) to the CDF – these events can be identified by "*" in the "CDF" column of Table 1. Thus, for example, the frequency of the event "Aircraft Crash" does not result in a relevant contribution to the CDF – this frequency was calculated at 1.25E-08/yr and thus, considering that any aircraft crash results in damage to the reactor core, its contribution to the total CDF would be less than 0.01%.

Table 1: CDF in the PSA Level 1

Operational Mode	Initiating Event		CDF (/yr)	Percentage of Total CDF
Full Power	**Internal Events**	Transients	3.99E-06	1.80%
		Loss of Coolant Accident (LOCA)	3.30E-06	1.49%
		Anticipated Transient Without SCRAM (ATWS)	3.26E-07	0.15%
		Interfacing Systems Loss of Coolant Accident (ISLOCA)	*	0.00%
	External Events	Seismic Events	*	0.00%
		Internal Fire	1.66E-04	74.75%
		Internal Flood	3.25E-06	1.46%
		Tornado	*	0.00%
		External Flood	*	0.00%
		Aircraft Crash	*	0.00%
Low Power and Shutdown	**Internal Events**	Shutdown	4.52E-05	20.35%
Total CDF			**2.22E-04**	**100%**

The PSA level 1 is currently under revision – to consider the project progress. This will allow for a less conservative modeling of plant response (through the potential initiating events). Therefore, it is expected that the estimated total CDF of 2.22E-04/yr (see Table 1) will fall considerably after this revision (and before the plant commissioning), and more realistically discriminate the risk condition of the plant. As an example of conservative assumption cause in the PSA level 1, one can cite the incomplete information on cable routing, on the I&C electrical panel rooms layout, and on the fire detection and suppression systems – which added excess of conservatism to the internal fire analysis.

Table 1 shows that internal fires occurring in full power were associated with a CDF of 1.66E-04/yr – 74.75% of the total CDF. A list of the physical analysis units (PAUs) [12] that most contributes to this CDF is presented in Table 2 – the PAUs not presented contribute significantly less than the listed ones.

Table 2: Contribution to the CDF of Internal Fires

PAU	CDF (/yr)	Percentage of CDF for internal fires occurring in full power.
Internal Fire	**1.66E-4**	**100%**
I&C Electrical Panel Room A	8.00E-5	48.11%
I&C Electrical Panel Rooms B	8.00E-5	48.11%
Area Around Steel Containment	3.80E-6	2.29%

As the plant project advanced, more information on the I&C electrical panel rooms became available, allowing the updating of the Fire PSA. Thus, one of the analysis conservatism reduction activities addressed the refinement of the Fire PSA with respect to PAUs for these rooms. On this occasion, however, since the reliability data of the fire detection and suppression systems to be installed in these compartments were not yet available, it was decided to use the PSA detailed analysis modeling to assist in these systems specification. The following sections present a summary of the methodology proposed by the USNRC [12] and its application on the fire detailed analysis of the I&C electrical panel rooms.

3. FIRE PSA METHODOLOGY

The Fire PSA was performed according to the methodology proposed by the USNRC in [12]. This methodology divides the analysis into two parts. In the first part, the analysis is organized around compartments (the PAUs), assuming that a fire would have widespread impact within the compartment – in the PSA revision, this part of the analysis was not changed. In the second part, the focus is shifted towards specific fire scenarios within the compartment, and the objective is to estimate their frequencies of occurrence [12] – considering the physical fire behavior (i.e., fire growth and propagation analysis), equipment damage, fire detection, and fire suppression. Thus, for those compartments found to be potentially risk-significant (i.e., unscreened compartments) in the first part of the analysis, the second part provides a detailed analysis. For a general single compartment, the procedures applicable to the fire scenarios frequency calculation are summarized in Table 3 [12].

Moreover, for the plant under study, a detailed analysis of the area around the steel containment was performed as part of the initial PSA (the CDF presented in Table 2 already considers this). Next section presents the detailed fire analysis performed for the I&C electrical panel rooms – it is presented according to the steps equivalent to those described in Table 3.

4. DEVELOPMENT OF THE PROBABILISTIC MODEL

The next topics present the obtention of the probabilistic model developed in the detailed analysis of the I&C Electrical Panels Rooms A and B of the plant. Thus, except for steps 9 and 10, the steps in Table 3 were followed – in item 4.9, steps 9 and 10 were adapted to calculate the probability of suppression in the interest intervals and, considering the group of panels damaged before fire suppression, allow the calculation of the scenarios frequency contributing to the CDF.

4.1. Relevant Features of the Compartment

The compartments to be analyzed were defined in the initial PSA – during the Fire PRA Plant Partitioning [12] –, being identified as I&C Electrical Panel Rooms A and B. These rooms are redundant, with identical functions (control of security systems) and characteristics (with small differences between them). In this analysis step, these compartments were characterized with respect to: a) height, width and length; b) type of wall construction and thickness; c) ventilation; d) drainage;

e) obstacles in the ceiling, and; f) fire detection and suppression systems. The relevant information for the understanding of this paper will be presented along the next steps.

Table 3: Summary description of the detailed analysis steps [12]

Step 1: Characterize relevant features of the compartment	**Step 2: Identify and characterize fire detection and suppression features**	**Step 3: Identify and characterize fire ignition sources**	**Step 4: Identify and characterize secondary combustibles**	**Step 5: Identify and characterize target sets**
Identify the fire compartment and characterize compartment features relevant to fire propagation, target damage and operator actions; define general compartment characteristics of importance.	Identify fire detection and suppression features such as smoke and heat detectors, continuous fire watch, automatic and manual fixed suppression systems and fire brigade capabilities; characterize the operation the fire detection and suppression features in the compartment.	Identify and characterize fire ignition sources to be analyzed in terms of location within the compartment, type, size, initial intensity, growth behavior, severity/likelihood relationship, etc.; estimate frequency of ignition for the ignition source.	Identify and characterize secondary combustibles nearby fixed equipment such as cables that may be damaged by a fire in the selected ignition source.	Identify the target set relevant to each fire ignition source considered in the fire growth and damage analysis. The locations of a target set in relation to the fire ignition source, target types, failure modes, failure criteria, and other relevant information are collected.
Step 6: Define fire scenarios	**Step 7: Conduct fire growth and spread analysis**	**Step 8: Conduct fire detection and suppression analysis**	**Step 9: Calculate non-suppression probability and the severity factor**	**Step 10: Calculate scenario frequency**
Once the ignition source, secondary combustibles and targets have been identified and characterized, fire scenarios in the room can be defined, including transient and fixed ignition sources.	Select the appropriate fire modeling tool(s); analyze growth behavior of the initial fire source; analyze fire spread to secondary combustibles; analyze growth of fire in secondary combustibles; estimate the resulting adverse environmental conditions relevant to the assessment of target set damage; estimate time to target set damage.	Assess fire detection timing; assess timing, reliability, and effectiveness of fixed fire suppression systems; assess manual fire brigade response; estimate probability of fire suppression as a function of time; calculate conditional non-suppression probability for each ignition source/target set combination.	Based on the results of fire growth and spread analysis, and stochastic distributions of various input parameters of the models, the conditional probability of the fire being of the postulated severity level is established; based on the operation of the detection and suppression fire protection systems in the room, and the calculated time(s) to target damage, non-suppression probability is calculated.	Using the fire ignition frequency, non-suppression probability, and severity factor of the scenario, the overall scenario occurrence frequency can be established.

4.2. Fire Detection and Suppression Features in the Compartment

The fire fighting strategy for the I&C Electrical Panel Rooms A and B includes: 1) a fixed fire detection system; 2) a fixed gaseous fire suppression system; and 3) combat by fire brigade. Table 4 presents a summary of these systems characteristics.

4.3. Fire Ignition Sources

In this step, the ignition sources considered for the I&C Electrical Panel Rooms A and B were grouped between fixed and transient sources, and its intensities and frequencies were characterized. The ignition source which is permanently kept in the compartment under analysis is classified as fixed [12]. The selection of the ignition events in fixed sources to compose the fire analysis scenarios in the I&C Electrical Panel Rooms A and B, reflected the following observations and considerations: a) The fixed sources of ignition that can be considered are I&C electrical panels, cables and junction boxes; b) Among the equipment, components or materials presented in item 4.1, no fixed sources of ignition were found to be relevant; c) It is observed a high density of cables in the ceiling, distributed throughout the room; d) It is observed that about 30 I&C panels (of each PAU) are distributed throughout the room; e) It is considered that the ignition of the panels occurs in its upper part, in a ventilation vent near the top – region nearest to the cable tray on the ceiling of the room; f) The contribution of the electric panels to the ignition frequency is two orders of magnitude higher than the frequency of the other sources – see the last paragraph of this item (4.3); g) *Ignition mechanism*: no fixed components have been found that could suffer catastrophic failure (e.g., high-energy electrical components, flammable fuels) and start a fire that becomes fully developed instantly. The assumed ignition mechanism for fixed sources involved fires that start relatively small and grow over a period of time – as in [12] for panels similar to those installed in the plant.

On the basis of these observations, the ignition on the panels is considered to be a conservative representation of the ignitions in nearby cables and junction boxes – this is because the panels are closer to sensitive equipment in neighboring panels and, moreover, as will be seen in item 4.4, the cables have resistance to flame propagation and will be covered by thermal blanket (the ignition frequency of the panels has been adjusted to take into account the frequencies assigned to the cables and junction boxes – see the last paragraph of this item). Thus, for the composition of the fire scenarios, the individual ignitions of each I&C panel present in I&C Electrical Panel Rooms A and B will be considered.

Table 4: Summary description of firefighting resources considered

Fixed fire detection and alarm system	Fixed gaseous fire suppression system	Fire brigade
• The detection and alarm system consists of photoelectric smoke detectors, manual triggers, locking switches and audio/visual indicators. • Each room has 4 detectors. • The alarm and fault information of the field elements will be sent to the central detection and alarm panel. • The central panel has an emergency power supply to maintain operation in the event of an external power failure. • The time for all control devices to be checked is less than 2 seconds and the activation time of the control modules is a maximum of 3 seconds – so the transmission time does not exceed 5 seconds (t_{sinal}). • The obscuration time required for the activation of the detector is a function of the HRR (depends on the fire evolution).	• Fixed suppression system employs the agent FK-5-1-12 – clean agent listed in NFPA 2001 [13]. • One 420-lb FK-5-1-12 cylinder will be installed for each room, plus a 250 lb cylinder for the under-floor area – being sufficient for multiple discharges. • The concentration of FK-5-1-12 used is 4.5% volumetric. • Discharge will occur after a programmable delay of up to 30 seconds (t_{delay}). • The discharge time required to achieve 95% of the minimum design concentration of the flame extinguishing agent does not exceed 10 seconds [13] ($t_{discharge}$).	• Given the success of the detection system in issuing the alarm, operators communicate the event to the brigade for manual fire fighting. • The fire brigade has its base at 1560 meters from the plant. • Operators keep brigade access clear. • The passage through the access areas and the permanence in the plant, in the event of a fire in the I&C rooms, do not cause exposure to radiation or other adverse environmental conditions besides those resulting from the burning of the materials present in the rooms. • As the plant is not in operation, for the preliminary evaluation of brigade behavior, the data of the Fire Department of the State of Sao Paulo [14] and USNRC [12][15] will be considered. Thus, the following times for the brigade response are considered: a) the communication time: 60s [14] ($t_{communication}$); b) preparation time: 90s [14] ($t_{reaction}$); c) the travel time: 140s [14] (t_{travel}), d) fire brigade effectiveness: function of the time available for combat (depends on the evolution of the fire), can be calculated by [12]: $P(success\ of\ the\ brigade) = 1 - e^{-\lambda*(time\ to\ suppress)}]$ (1) Where the suppression rate considered (λ) is given in [15] for "electrical fires", i.e., 9.80E-02 – since the equipment present in these rooms are basically cables and panels.

Unlike fixed fuels, transient fuels are materials that remain temporarily in the compartment [12], and the ignition of transient fuels was considered in this work – see [12]. In order to reflect the close positioning of sensitive targets, the ignition of transient materials positioned next to the panels associated to the highest CCDP in each PAU were considered (see item 4.5). Thus, a solvent spillage was considered – it was considered the spill of 0.747 kg of acetone (0.95 l), with a spread rate of 0.060 m/s [16] (commonly used to clean components). It was considered a poll formation, with height of 1.7 mm and diameter of 0.84 m.

Concerning the intensity of the fire, the heat release rate (HRR) for a given fire is a difficult variable to predict [12]. Thus, in general, a profile is adopted for the evolution of the HRR. Based on [12], the profile for the electrical panels is as follows: a) growth phase: 11.4 minutes until the peak HRR value; b) stationary phase: 7.1 minutes at steady state; and c) decay phase: 19 minutes decay until flame extinction (HRR = 0). And based on the acetone firing characteristics, the HRR profile for transient fuels is as follows: a) growth phase: 0 seconds until peak HRR; b) stationary phase: 8.11 minutes at steady state – calculated as the mean of the time of burning of several transient fuels mentioned in [12]; and c) decay phase: 0 seconds until the flame extinction (HRR = 0).

Given an initial source of fire, the peak HRR value (for burning a given type of fuel at a nuclear plant) is presented in a probability density function – see appendix G of [12]. Thus, for each ignition source, different HRR values can be attributed, with different severity factors – essentially, the severity factor represents the probability associated with specific fire intensity [17] –, characterizing different scenarios. Table 5 presents a discrete form for the HRR probability density distribution of the panels of I&C Electrical Panel Rooms A and B, and for the transient fuels. In this table, seven peak values are presented for ignition source, associated to the respective probability of occurrence. It is emphasized that the discrete presentation of the distribution for the HRR was conservatively obtained – e.g., HRR values less than 87 kW and greater than 34 kW are represented by 87 kW in the model (higher intensity, therefore). Although it adds conservatism to the analysis, this form of presentation for the HRR is convenient because it allows the analysis of a limited number of fire scenarios.

Table 5: Peak values of HRR and their respective probabilities

Electrical panels			Transient fuels		
Peak HRR (kW)	**Probability (%)**	**Cumulative probability (%)**	**Peak HRR (kW)**	**Probability (%)**	**Cumulative probability (%)**
34	28.30	28.30	47	25.11	25.11
87	21.38	49.69	85	24.93	50.03
211	25.77	75.45	142	25.61	75.64
702	22.60	98.05	317	22.44	98.08
979	1.45	99.50	404	1.42	99.50
1790	0.49	99.99	650	0.49	99.99
> 1790	0.01	100.00	> 650	0.01	100.00

The panel ignition frequency calculations of the I&C Electrical Panel Room A is identical to those of the Panel Room B. The ignition frequencies were calculated based on the data presented in the initial version of the PSA level 1. The ignition frequency per panel was obtained by dividing the total ignition frequency of the room (obtained from the PSA of the plant) by the number of panels. The results are shown in Table 6. Otherwise, the calculation of the ignition frequency of transient fuels was performed considering the frequency assigned in the initial version of the PSA level 1 for: a) Fire by welding cable: 3.41E-05/yr; b) Transient fire by welding (auxiliary building): 7.34E-06/yr, and; c) Transients (auxiliary building): 1.79E-05/yr. Thus, the frequency of ignition of transients was calculated as 5.93E-05/yr.

Table 6: Ignition frequency per panel, in year^{-1}

Description	Ignition frequency	Panels per room	Ignition frequency per panel
Self-ignited cable fires (plant wide)	3.87E-05	29	6.16E-05
Electrical panels(plant wide)	1.72E-03		
Junction Boxes(plant wide)	3.25E-05		
Ignition frequency per room	*1.79E-03*		

4.4. Secondary Combustibles

The possible secondary fuels found in the I&C Electrical Panel Rooms A and B are internal equipment to the electrical panels, cables and junction boxes. Among the equipment, components and materials presented in 4.1 (e.g., wall cladding, ducts), no relevant secondary fuels were found. As the panels used in these rooms are IP 55 [18] (protection against dust and water jets) and have a content, structure and compartmentation that allows the propagation to the panel internal components – the internal cables are considered to be fire-resistant [19] and therefore maintain combustion only when immersed in the flame –, it is considered that the equipment internal to the panel will only combust when the fire starts inside the panel itself – non-propagation to the internal components of a panel does not imply that its failure is disregarded in this analysis (see item 4.5). Similarly, the cables outside the panels are fire resistant [19] (maintain combustion only when immersed in the flame). In addition, these cables are protected by a ceramic fiber blanket [20], constituting passive protection, i.e., preventing contact of the cable with the flame from the burning of the electric panels and transient fuels. Thus, in general, the probability of propagation of the fire for cables and junction boxes is considered negligible. Conservatively, however, in the case of a very high HRR (associated to the ignition source), the propagation for all fuels in the room is considered, as will be discussed in item 4.6.

4.5. Target Sets

The PRM used to represent the behavior of the plant in the event of a fire was proposed as part of the initial Fire PSA and was not changed – the PRM is a fault tree composed specifically for the fire events (i.e., failure of equipment in a fire), having been elaborated based on the fault tree modeled for the Internal Events PSA to calculate the CCDP associated to the damage of the target sets in each fire scenario (see item 4.8). The target sets have been identified and characterized by considering the components, cables and equipment in the I&C Electrical Panel Rooms A and B which are part of the PRM and which may fail due to the spread of the fire from the ignition sources, according to following tasks: a) Survey and identification of the components and cables inside the compartments; b) Location of components and cables inside the compartments – i.e., in which of the cabinets (in each room) the components and cables are allocated; c) Location of the components and cables inside the cabinets – i.e., in which of the panels in each room the components and cables are housed, and; (d) Examination of failure criteria for components and cables: it was considered that the failure mode of a component (e.g., spurious performance of a controller) occurs if the temperature in the surface of the panel is 65°C – as calculated in the simulations presented in item 4.7.

4.6. Fire Scenarios

In the scope of this work, a fire scenario is defined as a sequence of events, from the beginning of the fire to the reactor core damage. Once the firefighting equipment (item 4.2), the ignition sources (item 4.3), the secondary fuels (item 4.4), and affected target sets (items 4.5 and 4.7) has been identified and characterized, it was possible to postulate the fire scenarios that refer to the I&C Electrical Panel Rooms A and B. The equipment affected in each scenario was defined as a function of the fire simulations presented in item 4.7 (they were performed to estimate the elapsed time between the ignition and the temperature increase of the target sets, up to 65°C) – since they are affected one by one as the fire progresses. In the composition of the scenarios, it was considered that the equipment associated with the initial fire source (in case of panel) is failed, independently of the reaction of the firefighting systems, at the instant of ignition. In addition, it was considered that the fixed gaseous suppression system, once acting, interrupts the process of fire evolution, being sufficient to reach the effective fire control. Thus, each postulated fire scenario is characterized by the position and type of the ignition source (panel or transient), by the fire intensity (defined by the HRR profile), by the group of affected equipment, and by the interval at which suppression occurs (or does not occur). For scenarios with instabilities in the simulation (associated with the low concentration of oxygen in the compartment), only the simulated interval before the instabilities was considered – it was considered that if suppression occurs after the instability, all equipment in the room will be damaged (see simulation results presented in Table 7, in the column "Truncation").

Thus, for example, for the case of ignition in panel P27 (located in I&C Electric Panel Rooms A) with peak HRR equal to 87 kW (see simulation results presented in Table 7), it was possible to establish scenarios in which occur: a) the damage of the contents of cabinet "27-32" (which contains panel P27), when suppression occurs in the interval between the instant of ignition and 1019s – this because the damage to P27 occurs at time 0s and, up to 1019s, the damage is restricted to the cabinet "27-32"; b) the damage to the contents of cabinets "27-32" and "46-50" (in this order), when suppression occurs in the interval between 1019s and 1285s of ignition, and; c) damage to the contents of cabinets "27-32", "46-50" and "41" (in this order), if the suppression occurs after 1285s of the ignition or not occurring.

4.7. Fire Growth and Propagation Analysis

The analysis of fire growth and propagation in the I&C Electrical Panel Rooms A and B were performed with help of a CFD software: the version 5.5.3a of the Fire Dynamics Simulator (FDS) [21] – a freeware distributed under a GNU license. The FDS is a FORTRAN software that solves a form of the Navier-Stokes equation appropriated for low-speed, thermally-driven flow with emphasis on smoke and heat transfer. It approximates the conservation equations (mass, momentum and energy) by finite differences numerical method, updating the solution in time in a rectilinear grid. For the thermal radiation, a finite volume method is used, while for the particles (smoke and sprinkler particles movement), the Lagrangian particles method is adopted [22]. This kind of assumptions causes FDS to be very restricted to the use that has been developed for, but it is enough to solve the most part of non-complex fire cases, making this tool a powerful software credited by the National Institute of Standards and Technology (NIST) and NRC – which developed a report for the use of FDS for nuclear plants safety analysis purposes [23].

For this work, the geometry parameters were extracted from [21], and adapted for the FDS rectilinear grid when required. The size of grid was selected according to a non-dimensional expression suggested in [21] – according to [23], reasonable results were obtained for values ranged from 4 to 16 for that expression. Thus, for the peak HRR values of 979 kW, 702 kW and 211 kW, the grid size was 10 cm, for the peak HRR values of 87 kW and 34 kW, the mesh was refined to elements of 5 cm, and for the peak HRR of 1790 kW, a value of 20 cm for the grid size was defined.

Thus, simulations were performed for each ignition source, considering the different fire intensities indicated in item 4.3, recording the time elapsed between the ignition and the time at which the target sets reach the 65°C (as a failure criteria). Figure 1 illustrates the HRR profile considered for panel P27 ignition (located in I&C Electrical Panel Room A, as indicated in Figure 2), considering the peak HRR of 34 kW. This figure also shows the evolution of the oxygen concentration in the room. Figure 2 illustrates the evolution of the surface temperature of the equipment present in the room, given the ignition in panel P27 considering the profile shown in Figure 1, and after 1065s. For this same case, Table 7 shows the time at which each target set presented in the room reaches the temperature of 65°C.

Figure 1: P27 HRR profile and oxygen concentration in the room

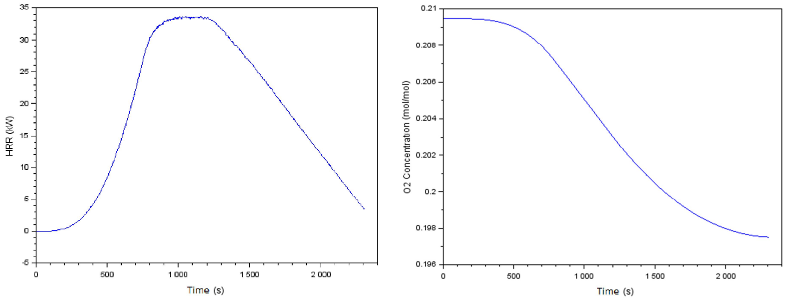
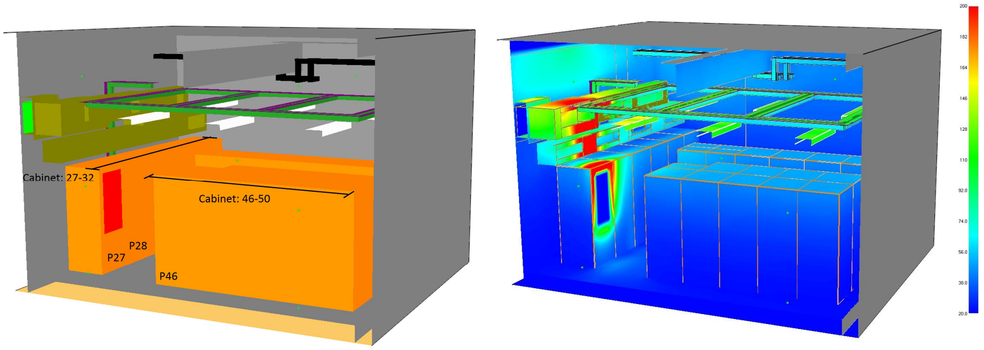


Figure 2: I&C Electrical Panel Rooms A – P27 ignition (after 1065s)



4.8. Fire Detection and Suppression Analysis

In the analysis of the detection and suppression systems, the characteristics mentioned in item 4.2 – which also presented the characteristics of the fire brigade – were considered. Based on this information and on the HRR profiles for each scenario and on the obscuration times of the detectors, the time to start the suppression (t_{total}), and the time for the fire brigade response beginning ($t_{brigade}$) were calculated, and presented respectively in Table 8 and Table 9 (as the sum of the times presented in the precedent lines of the table). The Alpert, Milke and Mowrer ratios described in [16] were used to calculate the detection time ($t_{detection}$) presented in Table 8. For the calculation of the time for the alarm (t_{alarm}) presented in Table 9, the times $t_{detection}$ and t_{sinal} (presented in Table 8) were summed. The other times indicated in these tables were obtained from Table 4.

Considering the proposed fire fighting strategy (item 4.2), four possibilities of response of the fire fighting systems were enrolled, given the ignition: 1) Automatic detection and automatic injection occur; 2) Automatic detection and fire brigade response occur (automatic injection failure); 3) Automatic detection occurs and both automatic injection and brigade fail, and; 4) Automatic detection does not occur. Figure 3 presents an event tree illustrating these possibilities.

Table 7: P27 ignition – time for target sets damage

Ignition Source	Peak HRR	Time to damage (equipment reaches 65°C) [s]														Truncation*
	Cabinet	27-32			33	34	35-38	39	40	41	42-45	46-50		51	52-55	
	Panel	27	28	Other panels	33	34	Any panel	39	40	41	Any panel	46	Other panels	51	Any panel	
27	34	0	1234	-	-	-	-	-	-	-	-	-	-	-	-	-
	87	0	778	-	-	-	-	-	-	1285	-	1019	-	-	-	-
	211	0	582	-	-	-	-	-	-	751	-	670	-	-	-	-
	702	0	473	-	-	-	-	-	-	549	-	501	-	-	-	860
	979	0	458	-	-	-	-	-	-	534	-	487	-	-	-	810
	1790	0	412	-	-	-	-	-	-	458	-	440	-	-	-	690

()*This column discriminates the instant the simulation presented instability. In this work the data were used only until this time.

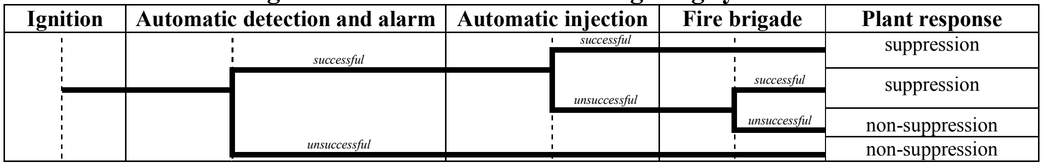
Table 8: Elapsed time for the suppression system performs the discharge

Fuel	Fixed						Transient					
Peak HRR [kW]	34	87	211	702	979	1790	47	85	142	317	404	650
$t_{detection}$ [s]	631	463	346	233	209	171	35	13	19	5	4	2
t_{sinal} [s]	5						5					
t_{delay} [s]	30						30					
$t_{discharge}$ [s]	10						10					
t_{total} [s]	676	508	391	278	254	216	80	58	64	50	49	47

Table 9: Elapsed time for the fire brigade response

Fuel	Fixed						Transient					
Peak HRR [kW]	34	87	211	702	979	1790	47	85	142	317	404	650
t_{alarm} [s]	636	468	351	238	214	176	40	18	24	10	9	7
$t_{communication}$ [s]	60						60					
$t_{raction}$ [s]	90						90					
t_{travel} [s]	140						140					
$t_{brigade}$ [s]	926	758	641	528	504	466	330	308	314	300	299	297

Figure 3: Event tree for the firefighting systems



4.9. Suppression Probability and Scenario Frequency

In this work, the evaluation of the severity factor and the probability of suppression were performed simultaneously. In this step, the objective was to calculate the CDF associated with the fire scenarios (that result in damage to the reactor core). Thus, considering the ignition frequency for each source (see item 4.3), the probability associated with each peak HRR for this source (see item 4.3), and the probability of suppression in the interval when the damage is restricted to the sets (considering the times discussed in item 4.6 – see the example in Table 7), it was possible to calculate the frequency of damage to the equipment of the sets (associated to each scenario). From this information and using the PRM to calculate the CCDP, it was possible to calculate the CDF associated to the scenario. The results obtained for the ignition in panel P27 were reproduced in Table 10 for the peak HRR of 34kW and 87kW.

In Table 10, the damage frequency of the affected equipment was obtained by multiplying the ignition frequency, the peak HRR probability and the probability of suppression in the interval. The probability of suppression in the interval was calculated considering the event tree shown in Figure 3 for each scenario. For example, for the first line of Table 10, for the peak HRR of 34 kW, regardless of when the suppression occurs (even when it does not occur), the damage will be restricted to the equipment in the cabinet "27-32". In the case of the peak HRR of 87 kW, it was necessary to calculate the probability associated with each interval – [0s, 1019s[, [1019s, 1285s[and [1285s, ∞[. Thus, considering that suppression, if successful, occurs at 508s of the ignition (see Table 8 and Table 10), and that the brigade initiates combat at 758s after ignition (see Table 9 and Table 10) – with the probability of success calculated by Eq. (1), see Table 4 –, the probability of the suppression occurring in each interval has been calculated according to Table 11 – the probability of success of the detection and suppression systems being initially considered to be 95%.

Table 10: CDF for the scenarios with ignition in Panel P27

Ignition Source	***Ignition Frequency (see Table 6)***	***Peak HRR [kW]***	***Peak HRR probability (see Table 5)***	***Affected equipment***	***Interval at which suppression occurs [s] (see Table 7)***		***Time for automatic combat, in [s] (see Table 8)***	***Time for the fire brigade response beginning, in [s] (see Table 9)***	***Probability of suppression in the interval***	***Frequency of damage to affected equipment***	***CCDP***	***CDF per scenario***
					begin	***end***						
27	6.16E-05	34	2.83E-01	27-32	0	N/A	676	926	1.00E+00	1.74E-05	7.33E-04	1.28E-08
27	6.16E-05	87	2.14E-01	27-32	0	1019	508	758	9.19E-01	1.21E-05	7.33E-04	8.87E-09
27	6.16E-05	87	2.14E-01	27-32 e 46-50	1019	1285	508	758	1.09E-02	1.44E-07	1.26E-03	1.81E-10
27	6.16E-05	87	2.14E-01	27-32, 46-50 e 41	>1285		508	758	7.01E-02	9.23E-07	1.71E-03	1.58E-09

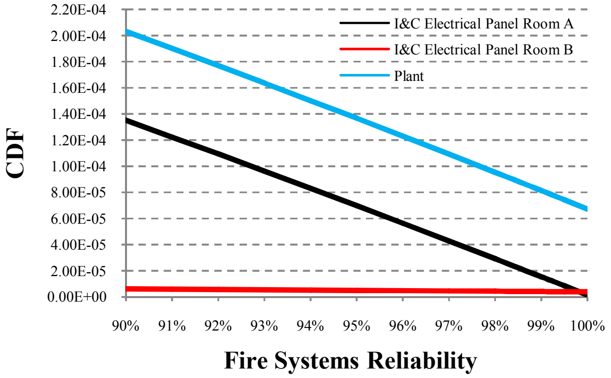
Table 11: Probability of the suppression for panel P27 (Peak HRR: 87 kW)

Interval	**Possible mutually exclusive events in the interval**	**P(*suppression in the interval*)**	
$[0s, 1019s[$	a) The success of detection (95%) and automatic injection (95%) occur, or; b) The success of detection (95%), failure of injection (5%), and success of the brigade (with time available for combat equal to 1019s minus 758s) occurs;	$95\%*95\% + 95\%*5\%*[1-e^{-0.098*(1019-758)}]$	= 9.19E-01
$[1019s, 1285s[$	c) Detection success (95%), injection failure (5%), and success of the brigade occurs between 1019s and 1295s;	$95\%*5\%*\{[1-e^{-0.098*(1285-758)}]-[1-e^{-0.098*(1019-758)}]\}$	= 1.09E-02
$[1285s, \infty[$	d) Detection failure (5%), or; e) Successful detection (95%), injection failure (5%), and brigade success occurs after 1295s.	$5\% + 95\%*5\%*\{1-[1-e^{-0.098*(1285-758)}]\}$	= 7.01E-02

5. FIRE SYSTEMS RELIABILITY SPECIFICATION

The probabilistic model presented in section 4 represents the refinement of the Fire PSA, and allows the updating of the CDF associated to the I&C Electrical Panel Rooms A and B (by the sum of the CDFs associated with each scenario: e.g., see column "CDF scenario" in Table 10). This calculation can be done for different reliability values for the modeled fire systems (in the example presented in item 4.9, the reliability of 95% for firefighting systems was considered). In this way, Figure 4 presents the results of the CDF for each analyzed compartment, considering the same reliability value for the detection and alarm systems, and for the injection system.

Figure 4: CDF, given the fire systems reliability



Using the calculated values for the CDFs of the analyzed compartments to update the data presented in Tables 1 and 2, the Total CDF for the plant was obtained as a function of the fire systems reliability – the result was plotted in Figure 4. Figure 4 shows that reliabilities greater than 98% for fire detection and suppression systems lead the plant's CDF to acceptable values, assuming a maximum CDF of 1.00E-04 as a risk acceptance criterion [1]. In this case, fire fighting systems must be specified to have reliability greater than 98%, given a fire – considering the same reliability value for detection and alarm, and for injection systems in both I&C electrical panel rooms.

6. CONCLUSIONS

Considering that a PSA already presents a study for a plant as a whole and that the detailed analysis for the PAUs for the I&C rooms was not carried out, and considering that the fire fighting systems for these rooms had not been designed, it is possible to develop a probabilistic model to assist in the specification of these systems. Thus, once developed, this probabilistic model can be used both to compose the Fire PSA of the plant and to define the reliability characteristics of the detection and injection systems to be installed. Based on these ideas, given a predefined risk acceptance criterion – based on the overall acceptable CDF and on partial results for different plant operational modes (e.g., at power, shutdown) and different hazard types (e.g., internal events, internal fires, flood) defined in preliminary analyses –, the reliability characteristics for the fire detection and suppression systems in two I&C panel room were established. In order to do so, based on the method for the detailed fire modeling presented by USNRC in NUREG/CR-6850 [12], a probabilistic model was developed and fed with data from simulations performed in a CFD model, and the CCDP obtained from the PRM of the Fire PSA for the plant.

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