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Development and assessment of fire-related risk unavailability matrices to support the application of the maintenance rule in a PWR nuclear power plant

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Abstract

Two methods are presented which serve to incorporate the fire-related risk into the current practices in nuclear power plants with respect to the assessment of configurations. The development of these methods is restricted to the compulsory use of Fire Probabilistic Safety Assessment (PSA) models. The first method is a Fire Protection Systems and Key Safety Functions Unavailability Matrix which is developed to identify Structures, systems, and components significant for fire-related risk. The second method is a Fire Zones and Key Safety Functions (KSFs) Fire Risk Matrix which is useful to identify fire zones which are candidates for risk management actions. Specific selection and quantification methodologies have been developed to obtain the matrices. The Monte Carlo method has been used to assess the uncertainty of the unavailability matrix. The analysis shows that the uncertainty is sufficiently bounded. The significant fire-related

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risk is localized in six KSF representative components and one fire protection system which should be included in the Maintenance Rule. The unavailability of fire protection systems does not significantly affect the risk. The Fire Risk Matrix identifies the fire zones that contribute the most to the fire-related risk. These zones belong to the control building and electric penetrations building.

Key Words: Fire safety analysis; PSA; PWR type reactor; reliability; fire protection systems; key safety functions; maintenance rule; core damage frequency; Monte Carlo method; risk management action.

1. Introduction

The Nuclear Engineering Research Group (NERG) from the Technical University of Catalonia (UPC) has a collaboration agreement with a Spanish, Pressurized Water Reactor (PWR) Nuclear Power Plant (NPP). The main objective of the collaboration is to study and apply the Probabilistic Safety Assessment (PSA) methodology for risk-informed decision making processes. One of the research activities within the frame of the collaboration is devoted to the Fire PSA. The goal of the Fire PSA related research activity is to develop support tools for risk-informed decision making.

The assessment of plant configurations in accordance with Section (a) (4) of 10 CFR 50.65 (the Maintenance Rule (MR)) [1] and high-level guidance in Nuclear Management and Resources Council (NUMARC) [2] is of current practice nowadays in nuclear power plants. However, methods to incorporate fire-related risk into these current practices are still under development and assessment.

The objective of this paper is to present innovative methods to incorporate fire-related risk into the current assessment of plant configurations. A method to identify Structures, Systems and Components (SSCs) significant for fire-related risk is presented. A method to identify Fire Zones[c] (FZ) which are candidate for potential risk management actions is also presented. The development of these methods was restricted to the compulsory use of the Fire PSA of the NPP. The products of these methods are matrix structures assessed by means of risk criteria. The NPP PSA team has provided technical guidance throughout the development of the methods. The methodology followed to

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[c] A fire zone is not necessarily bounded by fire barriers. Zones are often delimited taking into account the FPSs present in each area.

delineate the matrices is described in section 2. The quantification of the matrices is presented in section 3. Section 4 presents the risk criteria used to evaluate the results, and sections 5, 6 and 7 contain the assessment of the results.

2. Matrices delineation. Selection of representative basic events

2.1 Matrices definition

The Fire Protection Systems (FPS) and Key Safety Functions (KSF) Unavailability Matrix (UM) is developed to identify significant SSCs for fire-related risk. The UM contains the Core Damage Frequency (CDF) given by the Spanish NPP Fire PSA model when combining the unavailability of FPSs and KSFs. Matrix results are analyzed by means of risk assessment criteria provided by the NPP.

The method developed to identify fire zones which are candidate for potential risk management actions involves a fire zones and key safety functions Fire Risk Matrix (FRM). The FRM contains the contribution of each FZ (i.e. dCDF) to the NPP's fire CDF when SSCs representative of KSFs are considered to be unavailable.

2.2 Matrices delineation

The rows of the UM matrix host all the fire protection systems within the scope of the Fire PSA. Likewise, the rows of the FRM contain all the fire zones analyzed in the Fire PSA detailed analysis. Columns host key safety functions' representative basic events for both UM and FRM. A screening analysis has been carried out for the purpose of selecting basic events which are significant to and exclusively represent one of the KSFs. **Figure 1** shows the methodology followed to select the elements to be introduced in the UM.

< Figure 1 >

2.3 Introduction of FPS in the UM

The Fire PSA detailed analysis only includes four generic types of fire protection systems: Prompt suppression (PS), automatic detection (PDA), automatic suppression (PEA), and fire brigade (PFB) [3]. Each generic type of FPS is linked to several specific fire protection systems of the plant [4][5]. It is assumed that the FPSs of a fire zone are independent from those of the other zones [6], thus the unavailability or failure of an FPS of a zone will not cause the unavailability or failure of a FPS in a different zone. The unavailability matrix contains 167 FPSs [3].

2.4 Screening analysis for KSFs' representative basic events

The fundamental safety functions of defense in depth are: Reactivity control, removal of heat from the core, and confinement of radioactive materials [7]. The accomplishment of these functions in all of the operations modes avoids the initiation and/or progression of accidental sequences. In this paper, the fundamental safety functions have been divided into a more detailed set of six Key Safety Functions to better describe and analyze plant safety. The Key Safety Functions analyzed in both matrices are: Subcriticality (S), Core cooling (C), Heat Sink availability (H), Reactor Coolant System (RCS) integrity (P), RCS inventory (I), Electricity supply (E). The Subcriticality KSF is equal to the reactivity control fundamental safety function. The Core cooling, Heat Sink availability, and RCS inventory KSFs have to be maintained in order to ensure the removal of heat from the core fundamental safety function. The RCS integrity KSF is associated with the confinement of radioactive materials fundamental function. Containment integrity is not included as a key safety function because the Fire PSA used in the analysis is level 1. Electricity supply has been included in the key safety functions list because the failure to accomplish this function could jeopardize all three fundamental safety functions, either together or separately.

The screening analysis for selecting KSFs' representative basic events is based on a risk importance analysis. The importance analysis has been applied to the Boolean equations of unavailability of the internal events' mitigation headers. All those basic events whose Risk Achievement Worth (RAW) [8] importance measure is greater than a specific value are selected for further analysis. The screening RAW value is set to ten. The screening value is more restrictive than that for other applications where the plant's CDF is evaluated because the quantity of basic events evaluated in a header is much smaller than the quantity of basic events evaluated in the Boolean equation for the plant's CDF. The Nuclear Power Plant support team agreed with the screening value. The basic events selected from all the headers analysis are merged in a new list which includes all the basic events selected by means of the importance analysis. This is referred to as Representative events (list 1) in figure 1.

A list of qualitatively chosen basic events is added to the importance analysis list. This is referred to as Representative events (list 2) in figure 1.The SSCs represented by these qualitatively chosen basic events are considered to be important regarding the accomplishment of a KSF. The procedure used to choose those basic events in list 2 is the so called Performance analysis in figure 1. The performance was carried out by the Nuclear Power Plant support team.

An exclusivity analysis is applied to the final list of basic events in order to screen out: All the repeated basic events (leaving one representative in the list); basic events representing more than one KSF.

Besides, a single representative basic event is chosen from all those basic events related to components whose unavailability has exactly the same risk impact on the performance of an SSC (for instance, components in series in the same Train or symmetric components).

The final matrices include 29 KSF representative basic events. Both matrices have a column to represent the scenario in which all the KSF representatives are in normal state. The dimension of the UM is 168x30, whereas the dimension of the FRM is 43x30 (i.e. the Fire PSA assesses 41 zones [3]).The FRM includes a row to present the exposure time to reach an accumulated increment of Core Damage Probability (ΔCDP) of 1.0E-06. **Figure 2** shows the definitive layout of both matrices.

< Figure 2 >

3. Matrices quantification

The Fire PSA RiskSpectrum® model of the Spanish NPP provides the core damage Boolean equation for each fire case, and each fire zone included in the analysis. However, it does not provide the whole plant's core damage Boolean equation. The CDF of the whole plant is the risk measure used in the UM. Therefore, the CDF of the plant is quantified by means different to RiskSpectrum®. Equation 1 is used to calculate the plant's CDF associated with each element of the unavailability matrix.

$$CDF_{z_i,s,k} = \sum_{z}\left(dCDF_{z,OK,k}\right) - dCDF_{z_i,OK,k} + dCDF_{z_i,s,k} \tag{1}$$

Equation 1 has three degrees of freedom: the zone (z), the FPS (s), and the KSF (k). The acronym dCDF refers to the core damage frequency related to a fire zone. So to say, a dCDF is a single and specific value of core damage frequency, independent from other dCDFs, which is solely associated with fires postulated in a specific fire zone**.** Each dCDF is considered as the contribution of a fire zone to the CDF of the plant. In average conditions[d], the overall CDF of the plant is in fact the result of the summation of all the dCDFs. In consequence, the first term of equation 1, which is the summation of the dCDFs of all the fire zones in the PSA, is equal to the CDF of the plant as long as no FPS is set unavailable. In a case where one FPS is unavailable, the contribution of the fire zone affected by the unavailability of the FPS has to be subtracted from the first term. The dCDF of the affected fire zone, computed with the unavailable FPS set to TRUE, is added as the third term of the Equation 1. All the Equation 1 terms have to be assessed with the specific KSF representative basic event in TRUE state when assessing the unavailability of a KSF. The outcome of Equation 1 is the CDF of the plant restricted to the unavailability of an FPS and/or the unavailability of a KSF representative basic event.

The risk measure assessed in the FRM is the contribution of each fire zone (i.e. dCDF) to the NPP's fire CDF when SSCs representative of KSFs are unavailable. These dCDFs are used in the terms of Equation 1 (i.e. dCDFz, OK, k). Both matrices are then calculated using the same methodology.

3.1 Quantification in RiskSpectrum®

The objective of the quantification in RiskSpectrum® is to obtain all the fire zones' contributions to plant's fire CDF (dCDFs in Equation 1). The procedure shown in **Figure 3** is followed. It is a pivoting quantification process whose pivots are the four generic types of fire protection systems. 260 RiskSpectrum® runs have been carried out to obtain all those dCDFs.

< Figure 3 >

3.2 Matrices calculation and completion

The calculation of the UM elements has been completed using two Python^{TM}

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[d] No fire protection system is considered as unavailable.

scripts. The first script translates RiskSpectrum® results' files into proper text files adapted for the second script. The second script performs two tasks. The first task is to generate an ancillary matrix called dCDF matrix which contains all the dCDFs computed with RiskSpectrum®. The layout of the dCDF matrix is similar to that of the UM. The second task is to calculate the UM elements by means of Equation 1 and the data stored in the dCDF matrix. Both are provided in text files and are translated to an Excel® worksheet to facilitate the treatment of data.

The FRM elements are extracted from the dCDF matrix. The FRM is made up of all those dCDF matrix elements associated with the unavailability of a KSF representative and the NORMAL state of all the FPSs (Rows called OK). The FRM is built in Excel® using the formulation of the software.

4. Risk assessment criteria applied to evaluate the unavailability matrix

The risk assessment criteria (see **Table 1**) applied to evaluate the UM have been provided by the Spanish NPP. These criteria are based on the concepts of exposure time (TE) and accumulated increment of core damage probability (ΔCDP) of the situation assessed (see Equation 2). The risk assessment criteria are similar to what is proposed by the Spanish regulatory body for the assessment of findings [9].

$$\Delta CDF \cdot \left(\frac{T_E}{365}\right) = \Delta CDP \qquad (2)$$

ΔCDF is the difference between the CDF of each matrix element (CDF_a, i.e. the CDF of the plant restricted to the unavailability of an FPS and/or the unavailability of a KSF representative basic event) and the plant's reference fire CDF. The ΔCDP threshold to differentiate between not significant and significant risk is set to 1.0E-06, in compliance with other risk criteria that make use of this figure [5][9]. The metric used to evaluate the risk is the TE needed to reach the ΔCDP threshold. Table 1 shows both the qualitative levels of risk criteria, and the risk assessment quantitative criteria. The quantitative risk criteria presented in column three of table 1 are the result of isolating CDFa from the criteria in column 2. The plant's reference fire CDF is used for that purpose. The value of the plant's reference fire CDF is roughly 9.83E-06 (1/r*y).

< Table 1 >

The risk criteria are divided in four qualitative levels: very low (green), low or moderate (yellow), high (orange), and very high risk (red). The fire-related risk is significant for the yellow level and above. For the very low region of risk, the ΔCDP threshold of 1.0E-06 is not reached after 7 days of operation under the situation assessed (see column two of table 1). No corrective actions are needed to fix the situation assessed. If the situation is the consequence of maintenance, the maintenance can last as much time as needed. For the low or moderate region of risk, the ΔCDP threshold of 1.0E-06 is reached after 3 days, and before 7 days, of operation under the situation assessed. Corrective actions should be taken to fix the situation assessed before 7 days have passed. If the situation is the consequence of maintenance, the maintenance can last as many as 7 days. For the high region of risk, the ΔCDP threshold of 1.0E-06 is reached before 3 days of operation under the situation assessed. Corrective actions should be taken to fix the situation assessed at most before 3 days have passed. If the situation is the consequence of maintenance, the maintenance could last 3 days at most. To enter the very high region of risk, the CDF of the situation assessed has to be higher than 1.0E-03. This is an unacceptable situation. Corrective actions should be taken immediately after the situation triggers and the plant may have to be shutdown. The situation cannot be consequence of an online maintenance. An online maintenance associated with such a high value of CDF cannot and will not be allowed.

5. The unavailability matrix

The majority of the UM matrix elements (see figure 2), namely, a 79% of elements, belong to the very low risk region (green). The situations described by the elements in the green region are not a safety concern and do not require corrective actions as long as the plant takes a suitable time to return to normal operation. The fire-related risk significant matrix elements (yellow or above, see **Table 2**) are mainly localized in six columns (KSF representatives) and one row (FPS). The matrix elements of these six columns and one row are all belonging to a significant level of fire-related risk. Besides, there is a small quantity of isolated combinations of unavailability whose fire-related risk is significant. These isolated combinations are the only noticeable impact of the unavailability of FPS aside from the yellow row. The unavailability of FPSs, apart from the yellow row and those isolated combinations, does not significantly affect the matrix results and, so, the fire-related risk. The fire-related risk significant combinations of unavailability are mostly influenced by the unavailability of KSF representatives.

< Table 2 >

The FPSs associated with isolated combinations of unavailability whose fire-related risk is significant belong to the auxiliary, control, and auxiliary feedwater buildings. New statements and/or restrictions taking into account those SSCs and FPSs related to the significant isolated combinations of unavailability and the SSCs and FPSs in Table 2 should be included in the maintenance rule.

6. Uncertainty analysis for the unavailability matrix

6.1 Introduction to the uncertainty analysis

The purpose of this analysis is to evaluate the uncertainty associated with the development and quantification of the UM. The goal is to conclude whether the tool is robust and the results provided are trustworthy enough. The target of the analysis is to estimate the mean and the 95 percentile of the UM matrix elements so as to compare them with the point estimate values provided by the methodology presented in section 3.

The only uncertainty-related data available for the development of the uncertainty analysis are the cumulative distribution functions and the probability density functions of the dCDFs used to compute the UM matrix elements (see section 3). RiskSpectrum® provides both functions in a discrete manner, their analytical expressions are unknown.

6.2 Methodology for the uncertainty analysis

The Monte Carlo method is used to carry out the uncertainty analysis because it suits the available data. The Monte Carlo method is sequentially applied to each matrix element. The flow chart from **Figure 4** shows the Monte Carlo methodology used to apply the uncertainty analysis. The discrete cumulative distribution functions of the dCDFs are adjusted to segmented linear regressions. Random seeds between 0 and 1 are used to obtain random point estimate values of the dCDFs for each simulation. A simulation corresponds to the execution of Equation 1 for one UM matrix element. The mean and the 95 percentile of a matrix element are computed after running the desired number of simulations.

< Figure 4 >

The Monte Carlo methodology presented in Figure 4 is executed using a Matlab®

script. The script provides the uncertainty parameters (i.e. mean and 95 percentile) for all the matrix elements in a matrix layout equal to that of the UM.

The Matlab® script has been satisfactorily validated by comparison of results with RiskSpectrum®'s uncertainty analysis algorithm for a specific made-up case. RiskSpectrum®'s uncertainty analysis is also based upon the Monte Carlo method [10]. A sensitivity analysis has been performed to decide that 10000 is the optimal number of simulations to be carried out per matrix element, executing the Matlab® script.

6.3 Results and conclusions of the uncertainty analysis

The 95 percentile of the NPP's Fire CDF is the representative figure of the uncertainty associated with the development and quantification of the unavailability matrix. However, the Monte Carlo method slightly overestimates the Fire CDF. The comparison between mean values and point estimates values yields that the former are greater than the latter. Therefore, part of the difference between the 95 percentile values and the point estimate values belongs to overestimation, not to uncertainty.

427 elements of the Unavailability Matrix ascend to the directly superior risk category when evaluating the 95 percentile results instead of the point estimate values. 427 elements constitute the 8.5 % of the whole matrix. No matrix element ascends to a two times superior risk category. 304 of these 427 elements belong to two columns whose point estimate values are near the threshold between two risk categories. The point estimate values of the rest of ascending elements, which belong to different columns, are also near the threshold between two risk categories. The difference between the 95 percentile value and the point estimate value is roughly one to two orders of magnitude lower than the point estimate values for the majority of matrix elements.

The conclusions regarding the risk category of matrix elements when assessing the 95 percentile instead of point-estimate values are virtually the same. From the 8.5% of the matrix elements which ascend to the directly superior risk category, a 74% (314) are already considered as risk significant. Besides, the small difference between the 95 percentile value and the point estimate value, and the overestimation fact, show that the uncertainty associated to the matrix analysis is low. The uncertainty analysis demonstrates that the UM is a robust tool. The results obtained are trustworthy enough as to be used in risk-informed decision making processes. Further research will be devoted to the use of sensitivity analyses in the assessment of model and assumption uncertainties for the risk significant cases.

7. The fire zones and key safety functions fire risk matrix

The fire zones and key safety functions matrix (see figure 2) presents the contribution of each fire zone (i.e. dCDF, rows) to the plant's fire CDF (first row of the matrix) conditioned to the unavailability of KSF representative SSCs (columns). The fire protection systems are always in NORMAL state. The purpose of this matrix is to highlight those fire zones that can be the object of risk management actions when a KSF representative is unavailable.

Matrix elements highlighted within a column are the dCDFs which contribute the most to the plant's fire CDF associated with that column. Columns are independent from each other (i.e. they represent different situations). Only those highlighted dCDFs which belong to a plant's fire CDF whose associated risk is low / moderate or above (risk criteria in section 4) are actually significant from the point of view of risk. The zones related to those latter highlighted dCDFs are considered to be the main contributors to fire-related risk when the associated KSF representative (column) is unavailable, and are candidates to be the target of risk management actions.

The fire zones that contribute the most to the fire-related risk when the DC bar is unavailable (very high risk situation, see Table 2) are: the transfer panel and no train electrical equipment zone from the control building, the A train voltage measurement stations from the control building, and the east-south aisle zone from the electrical penetrations building. These zones are strong candidates to be the target of risk management actions when the DC bar is unavailable. For instance, brigade walkdowns could be introduced in these zones.

8. Conclusions

The Unavailability Matrix and the Fire Risk Matrix are methods to incorporate the fire-related risk into the assessment of plant configurations in accordance with the Maintenance Rule [1] and high-level guidance in Nuclear Management and Resources

Council [2]. The UM contains the Core Damage Frequency given by the Spanish NPP Fire PSA model when combining the unavailability of fire protection systems and key safety functions. The FRM contains the contribution of each fire zone (i.e. dCDF) to the NPP's fire CDF when SSCs representative of KSFs are considered to be unavailable.

The risk assessment criteria applied to the unavailability matrix have been provided by the Spanish nuclear power plant. The majority of unavailability matrix elements belong to the very low risk region (green). The fire-related risk significant combinations of unavailability are mostly influenced by the unavailability of KSF representatives. The risk significant matrix elements are localized in six columns (KSF representatives) and one row (FPS, the control room fire suppression system). There is a small quantity of isolated combinations whose risk is significant. These combinations are the only noticeable impact of the unavailability of FPSs aside from the control room fire suppression system row. New statements and restrictions should be included in the maintenance rule to take into account the fire-related risk significant SSCs: a motor pump from the Auxiliary feedwater system, vital electric bars A and B, a DC bar, a pneumatic valve from the safeguards service water system, and a retention valve in the high pressure safety injection system. The uncertainty associated with the unavailability matrix analysis has been assessed by means of a Monte Carlo method. The uncertainty analysis demonstrates that the UM is a robust tool. The results obtained are trustworthy enough as to be used in risk-informed decision making processes. Further research will be devoted to the use of sensitivity analyses in the assessment of model and assumption uncertainties for the risk significant cases.

The FRM is used to identify those fire zones that are candidates for risk management actions due to its risk significance. The fire zones that contribute the most to the fire-related risk when the DC bar is unavailable (very high risk situation) are: the transfer panel and no train electrical equipment zone from the control building, the A train voltage measurement stations from the control building, and the east-south aisle zone from the electrical penetrations building. These zones are strong candidates to be the object of risk management actions when the DC bar is unavailable. For instance, brigade walkdowns could be introduced in these zones.

Nomenclature:

AFW: Auxilliary FeedWater system.

dCDF: Contribution of a fire zone to the plant's fire CDF.

ΔCDF: Increase of the core damage frequency due to the variation of the state of a component.

ΔCDP: accumulated increment of core damage probability

CDF: Core Damage Frequency

CDFa: Fire Core Damage Frequency of an altered state. The altered state corresponds to the unavailability of a FPS and/or a KSF representative.

FPS: Fire Protection System.

FRM: Fire Risk Matrix.

FZ: Fire Zone.

HPSI: High Pressure Safety Injection.

KSF: Key Safety Function.

NPP: Nuclear Power Plant.

NUMARC: Nuclear Management and Resources Council

MR: Maintenance Rule.

PDA: Automatic Detection.

PEA: Automatic suppression.

PFB: Fire Brigade.

PS: Prompt Suppression.

PSA: Probabilistic Safety Assessment.

PWR: Pressurized Water Reactor.

RAW: Risk Achievement Worth.

RCS: Reactor Coolant System

SSCs: Structures, Systems, and Components.

SSWS: Safeguards Service Water System.

T_E (h): Exposure time.

UM: Unavailability Matrix.

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Figure captions

Figure 1. Methodology followed to delineate the unavailability matrix.

Figure 2. Unavailability Matrix and Fire Risk Matrix definitive layouts.

Figure 3. Quantification procedure in RiskSpectrum®.

Figure 4. Monte Carlo methodology.

Table 1. Risk assessment qualitative and quantitative criteria and color code

Color	**Qualitative criteria**	**Quantitative criteria**	**CDF_a (1/r*y) criteria**
Green	Very low	$\Delta CDF*(7/365) < 1.0E-06$	$CDF_a <$ **6.20E-05**
Yellow	Low / moderate	$\Delta CDF*(7/365) > 1.0E-06$	**6.20E-05** $< CDF_a <$ **1.31E-04**
Orange	High	$\Delta CDF*(3/365) > 1.0E-06$	**1.31E-04** $< CDF_a <$ **1.0E-03**
Red	Very high	$CDF_a > 1.0E-03$	$CDF_a >$ **1.0E-03**

Table 2. Risk significant fire protection systems and key safety functions representatives

Description	**Risk**	**System**	**KSF**
Motor pump	Yellow	AFW	Heat Sink
Vital electric bar A	Yellow	Electricity supply	Electricity supply
Pneumatic valve	Yellow	SSWS	Heat Sink
Control Room suppression	Yellow	FPS	
Retention valve	Orange	HPSI	RCS inventory
Vital electric bar B	Orange	Electricity supply	Electricity supply
DC bar	Red	Electricity supply	Electricity supply