Standardized Probabilistic Safety Assessment Models: Applications of SPAR-CSN Project

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Abstract: The regulatory activity requires oversight of licensee performance to be made from an independent position. This position is better served when the regulatory body develops its own methodologies and tools. In particular, in the matter of probabilistic risk analysis, even if the licensees' analyses are subject to peer-review and/or are reviewed by the regulatory body, it is very difficult to manage the large number of hypotheses and assumptions behind the model. Thus, the development of a PRA model for regulatory use improves the knowledge of the NPP risks and can be seen as an enhancement of the regulatory practice.

In this regard, the Spanish Regulatory Body (CSN), in collaboration with the Universidad Politécnica de Madrid (UPM), has been assembling its own generic standardized model (SPAR-CSN) for 3-loop PWR-WEC designs. The present paper shows three examples of the application of the model to actual events occurred at different nuclear power plants.

Key Words: PSA, Standardized PSA models, Success Criteria, Fault Tree, Human Reliability, Validation and Verification of PSA models.

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1. INTRODUCTION

The regulatory activity requires oversight of licensee performance to be made from an independent position. This position is better served when the regulatory body develops its own methodologies and tools. In particular, in the matter of probabilistic risk analysis, even if the licensees' analyses are subject to peer-review and/or are reviewed by the regulatory body, it is very difficult to manage the large amount of hypotheses and assumptions behind the model. Thus, the development of a PRA model for regulatory use improves the knowledge of the NPP risks and can be seen as an enhancement of the regulatory practice.

In this regard, the Spanish Regulatory Body (CSN), in collaboration with the Universidad Politécnica de Madrid (UPM), has been assembling its own generic standardized model (SPAR-CSN) for 3-loop PWR-WEC designs. The purpose of the project considers the development of a standardized PSA model independent from the industry and providing a high-level view of risk to be used for regulatory purposes. The intended scope is to be comparable to USNRC SPAR models ([1], [2], [3]). To this end, the conclusions drawn from the comparison of the existing industry models are used to establish a common set of assumptions and standard modeling techniques for CSN models. The SPAR-CSN model aim to:

a) Better understand the main contributors to risk in Spanish NPPs.
b) Help define prioritization of areas of inspection and oversight tasks at Spanish NPPs through the analysis of systems and components' importance measures.
c) Assess inspection findings within the Spanish regulatory system, SISC.
d) Perform precursor analysis of operational incidents that occurred in Spanish NPPs in order to determine their closeness to a core damage scenario.
e) Identify and evaluate potential relevant differences between the Spanish NPPs PSA models.

The model development has been streamlined through the delineation and implementation of a suitable methodology that, based on a thorough comparison of different PSA models, prompts the following high-level steps [4]:

a) Comparison of the Event Trees (ET), success and failure sequences, and success criteria of each header from Spanish PSA, SPAR-NRC and other models.
b) Initial proposal of standardized ETs, headers, and their success criteria.
c) Comparison of the description and functional analysis of the Fault Trees (FT) models for each system considered in the event trees, and of the modeling hypotheses (this allows us to classify and analyze differences between the PSA models).
d) Comparison of Human actions (types 3/5) included in each ET of the analyzed PSA models, and identification of the EOPs used in each of the sequences.
e) Comparison of the reliability database used in the Spanish PSA models and NUREG/CR-6928.
f) Final proposal of ETs, headers, and their success criteria for the generic SPAR-CSN model.
g) Proposal for the standardization of FT models, including a standardized block diagram for each system, a common naming of system equipment and logic elements of the FTs, together with a first evaluation and proposal of hypotheses and modeling techniques.
h) Evaluation of the human actions and the applicable operating conditions, identification of data sources.
i) Final proposal of ET models including the identification of the EOPs involved and applicable human actions.
j) Final proposal of the reliability database to be considered in FTs.
k) Modeling of ET and FT models in the quantification code (RiskSpectrum).

All the identified and relevant differences, either regarding modeling decisions or adopted hypotheses, have been evaluated by CSN PSA experts, and a common practice established based on their experience.

The following sections summarize some of the preliminary results obtained within the project. The main premises, scope, and data sources of the generic SPAR-CSN model, with a brief description of some representative examples of ET and FT, are depicted in section 2. Section 3 summarizes the current results obtained with the generic model. Three applications are presented in section 4.

2. DESCRIPTION OF THE GENERIC SPAR-CSN MODEL

This section provides with a high-level description of the SPAR-CSN generic model, distributed as follows: subsections 2.1 and 2.2 depict the model scope of the Event Tree and Fault Tree tasks; subsection 2.3 summarizes the human reliability analysis task, focusing on the analysis methodology and its extent; finally, a list of the generic data sources from which the probabilities of equipment failures are taken is introduced in subsection 2.4.

It must be considered that, as mentioned in section 1, the SPAR-CSN generic model has been devised as a standard base from which to develop the specific SPAR-CSN models of 3-loop PWR-WEC Spanish NPPs. Hence, both the modeling assumptions and safety systems diagrams have been chosen to be representative of a generic plant, leaving the actual plant design details and operational characteristics for the specific SPAR-CSN models.

The methodology followed in the SPAR-CSN project to standardize the modelling criteria of the different PSA aspects can be found in [4].

2.1 Event Trees

This section summarizes the scope of the SPAR-CSN model regarding the Event Tree delineation. In its first version, 14 main ETs are included (Table I).

Table I. List of ETs of the SPAR-CSN generic model.

ID	Initiating event	ID	Initiating Event
LBLOCA	LOCA (>6 in.)	**MSLB-US**	Main Steam Line Break upstream of MSIV
MBLOCA	LOCA (2in. to 6 in.)	**MSLB-DS**	Main Steam Line Break downstream of MSIV
SBLOCA	LOCA (3/8 in. to 2 in.)	**SGTR**	Steam Generator Tube Rupture
GT	General Transient	**LCWA**	Loss of a CCWS train
ATWS	Anticipated transient without scram	**LNSW**	Loss of Non-essential Service Water System[1]
LC	Loss of Condenser	**LOOP/SBO**	Loss of Offsite Power/ Station Blackout
LDC-A	Loss of emergency DC-A bus	**LDC-B**	Loss of emergency DC-B bus

The general assumptions considered for the ET sequence delineation are:

- The mission time for the different accident mitigation strategies is 24 hours.
- After this time, sequences are classified either as core damage (*Consequence CD*) or as safe stable state (*Consequence S*).
- A safe stable state is defined as follows in NUREG-2122 [5]: “condition of the reactor in which the necessary safety functions are achieved”.

2.2 Fault Trees (FT)

This section summarizes the scope of the SPAR-CSN model regarding the FT task. In its first version, 18 safety systems are included (Table II), with 1695 logical gates and 1381 basic events.

Table II. List of system FTs of the SPAR-CSN model

ID	System	ID	System
AC	Emergency AC distribution system	**IA**	Instrumentation Air System
AF	Auxiliary Feedwater System	**LH**	Low Pressure Injection System
AI	Accumulators Injection System	**MS**	Main Steam System
CW	Component Cooling Water System	**NC**	Non-essential Component Cooling Water
DC	Emergency DC distribution system	**NS**	Non-essential Service Water System
DG-A/B	Emergency Diesel Generators	**PR**	RCS Pressure Relief System
DG-SBO	SBO Diesel Generator	**RP**	Reactor Protection System
ES/SQ	ESFAS/Sequencer	**SC**	RCS Seal Injection System
HH	High Pressure Injection System	**SW**	Essential Service Water System

The main assumptions considered for the FT construction are:

- All failures considered in the FTs occur during mission time. Situations, where a system or equipment was already failed before the initiating event due to any undetected latent failure (type 1 human errors) are not included in the model.
- A single unavailability basic event due to maintenance or testing is associated with each train of each safety system. These events include the contributions only from equipment that renders the train unavailable.

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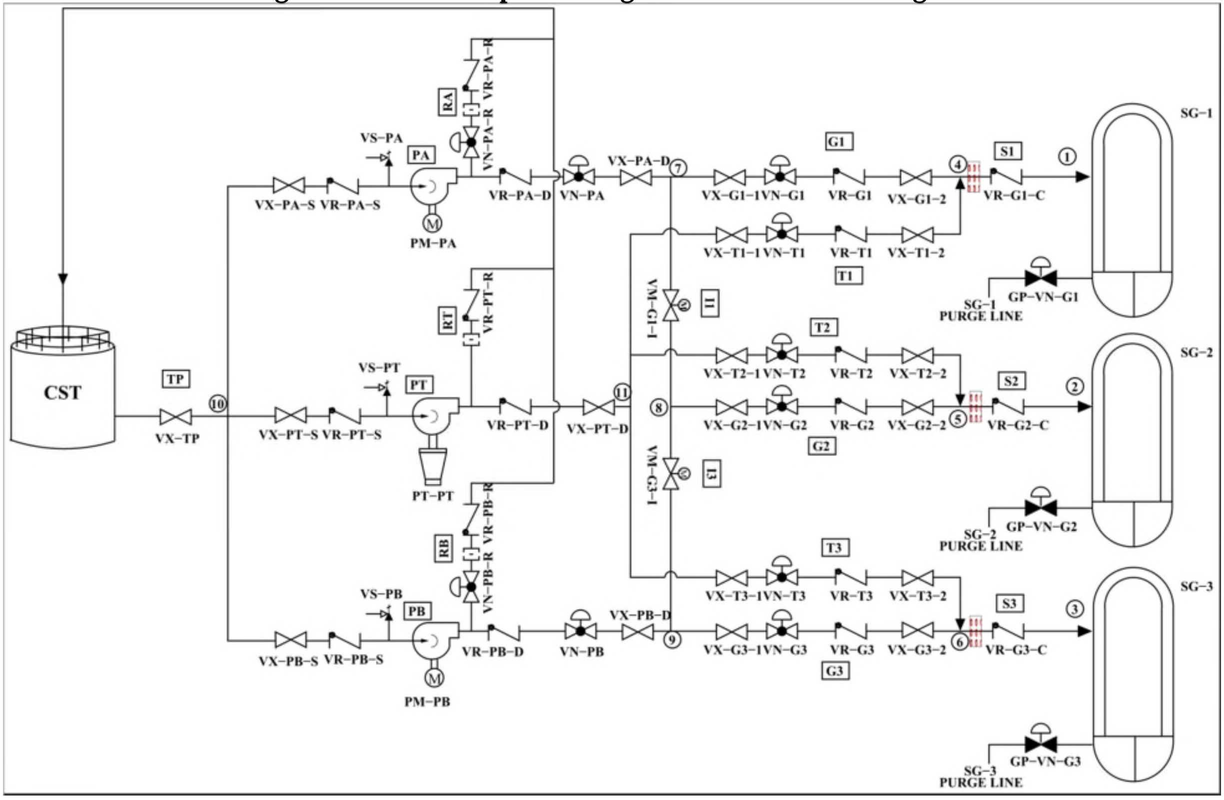
[1] The plant design chosen for the SPAR-CSN generic model includes two Service water systems: the Non-Essential Service Water System, which is normally operating, and the Essential Service Water System, which is normally in standby mode and starts when a Safety Injection or Loss of Offsite Power condition occurs, or whenever the Non- Essential Service water is lost.

- A high-level representation of the failure of the automatic startup signals is modeled, which includes the potential loss of the required AC/DC power supply and a single undeveloped basic event representing the signal generation failure, the probability of which has been computed from available sources.
- The failure events for manual actions do not include control room equipment failure, such as panels, levers, switches, etc.

As a representative example of a system diagram, the auxiliary feedwater system (AFWS) is depicted in Figure 1.

Figure 1. AFWS simplified diagram of the SPAR-CSN generic model



2.3 Human Reliability

Regarding the HRA task, the SPAR-CSN generic model uses the SPAR-H methodology [6] to quantify the error probability of type 3 human actions, similar to SPAR-NRC models. However, compared to SPAR- NRC models, a higher number of different human actions have been included, 38 in total, to better represent EOP following by the operating crew, and in line with plant-specific models for Spanish NPPs.

The available and the required times for each human action have been obtained from a complete review, comparison, and weighing of the Spanish NPPs PSA documentation. Human error probabilities range between 1E-05 and 1E-01 (before the dependency between human actions is considered).

A complete dependency analysis of type 3 human actions has been performed with the following process:

1. The probability value of each human error in the model is set to 1, to maximize the contribution of human actions.
2. The CD equation for each ET is calculated, identifying and choosing the combinations of human errors among the most important MCS.

3. The chosen combinations are studied following the SPAR-H dependency methodology to calculate the dependency level between the human actions involved.
4. Finally, a set of post-processing rules is created in the SPAR-CSN model, to change the probability value of the group of dependent human actions according to the dependency levels.

A set of 19 combinations of pairs of actions has been analyzed.

2.4 Reliability database

Two main public data sources have been used to assign reliability parameters to basic events related to equipment failures, system unavailability, and initiating events: NUREG/CR-6928 [7], NUREG/CR-5497 [8]. In addition, some other public references from SPAR-NRC models have been checked (e.g., [2], [6]).

3. GENERIC SPAR-CSN MODEL RESULTS

In this section, the main results related to the model overall CDF are presented and discussed. Table III shows the overall CDF obtained for the SPAR-CSN generic model and each ET contribution. The following remarks can be made:

- The CDF value is on the same order of magnitude of other SPAR models (e.g., the Plant-X SPAR model from [61] reports a CDF of 3,01E-05 for a 4-loop generic PWR plant, including human actions dependencies).
- The most important contribution to CDF comes from Generic Transients. This is a common result among other PSA models of PWR 3-loop NPPs. In particular, the highest MCS consists of the Generic Transient initiating event together with a human error to control Steam Generators level followed by a dependent human error in the Feed and Bleed operation.

Table III. CDF associated to every ET and overall CDF of the SPAR-CSN generic model

Initiator	Freq. (1/y)	CDF (1/y)	%CDF	Initiator	Freq. (1/y)	CDF (1/y)	%CDF
LBLOCA	5.91E-06	1.15E-08	0.09	**LCWA**	1.80E-03	7.08E-10	0.01
MBLOCA	1.50E-04	1.21E-07	0.94	**SGTR**	1.66E-03	3.46E-06	26.76
SBLOCA	4.01E-04	1.65E-07	1.28	**LNSW**	2.00E-04	2.19E-09	0.02
GT	6.76E-01	7.39E-06	57.19	**LDC-A**	5.00E-04	1.79E-08	0.14
LC	4.82E-02	5.14E-07	3.98	**LDC-B**	5.00E-04	1.50E-08	0.12
MSLB-DS	6.32E-03	7.54E-07	5.84	**LOOP**	3.11E-02	4.46E-07	3.45
MSLB-US	3.01E-04	4.15E-08	0.32	**Total CDF**	**1.29E-05**		

4. SPAR-CSN MODEL APPLICATIONS: ACCIDENT PRECURSOR ANALYSES.

This section shows the probabilistic analysis with SPAR-CSN models of two actual events, selected due to their interesting sequences of events. The first one was selected from the CSN Reported Events database and the second from the USNRC Accident Sequence Precursor Program. To expand the application of the model, additional situations of interest have been added or modified.

4.1. Application 1: Partial failure of Auxiliary Feedwater (AFW).

With the NPP operating at nominal power, a failure of an electronic card caused the reactor protection system to trip the reactor automatically, which caused the reactor to shut down. During this event, the auxiliary feedwater system was automatically started-up as expected, but the turbine-driven auxiliary feedwater pump (TDAFWP) stopped (failed) due to over speed.

SPAR-CSN model assumptions: TDAFWP Failed. Generic transient probability set to P=1; all other initiator probabilities set to P=0. Reactor SCRAM succeeds.

Table IV shows the minimal cutsets for this case. The dominant sequence (number 6, depicted in Figure 2), 69.29%, CCDP = 8.44E-06 is defined by:

- Initiator event: Generic Transient,
- Reactor SCRAM succeeds,
- Auxiliary feedwater (AF) fails,
- Feed & Bleed (HM+BM header) fails.

Figure 2: GT Event Tree SPAR-CSN Model. Dominant sequence in bold.

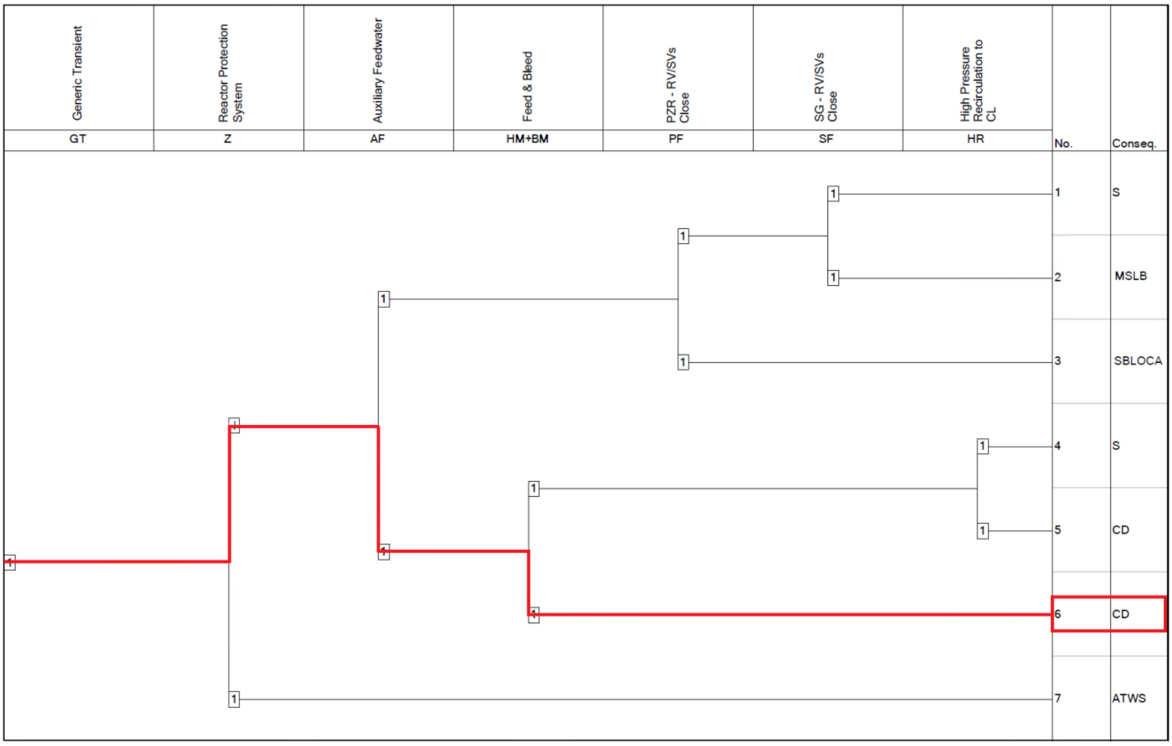


Table IV: Dominant MCS for GT.

No.	CCDP	%	Events
1	7.150E-06	58.7	Operator fails to control the SGs level; and operator fails to initiate Feed & Bleed
2	2.505E-06	20.6	Operator fails to control the SGs level; and operator fails to initiate high pressure CL recirculation
3	2.916E-07	2.4	Common cause failure of pump cooling units; and operator fails to initiate Feed & Bleed
4	2.210E-07	1.8	MS-PORV-G1 fails to close; operator fails to initiate high pressure CL recirculation; and operator fails to reduce safety injection flow
5	2.210E-07	1.8	MS-PORV-G3 fails to close, operator fails to initiate high pressure CL recirculation and operator fails to reduce safety injection flow
6	2.210E-07	1.8	MS-PORV-G2 fails to close, operator fails to initiate high pressure CL recirculation and operator fails to reduce safety injection flow
Total	1.219E-05		

Table V: Results comparison.

	SPAR-CSN	APP-1
CCDP GT	1.09E-05	1.22E-05

Table V shows the CCDP obtained for the Generic Transient, first with SPAR-CSN model and then applying the assumptions for the scenario of interest (APP-1: TDAFWP Failed).

4.2. Application 2: LOOP in a Twin-Unit NPP.

The site experienced a LOOP event. All EDGs and SBO-DG started automatically. The Unit 1 TDAFW pump was not immediately available due to surveillance testing when the reactor trip occurred; operators stopped the test, restarted, and aligned the TDAFWP flow to SG-A. Later in the sequence of events, the Unit 2 EDG tripped due to a coolant leak, so operators aligned the SBO-DG to Unit 2, making the SBO-DG unavailable for Unit 1. Three hours after the EDG trip, a Reserve Station Service Transformer (RSST) was returned to service and operators realigned offsite power to a Safety Bus in Unit 1. Nine hours after the initiating event, the offsite power was restored to all four safety buses.

SPAR-CSN model assumptions for Unit 1:

- The probability of LOOP was set to 1. All other initiators' probabilities were set to 0.
- EDG-SBO is not available.
- The Offsite Power Recovery Time include four cases:
    - Base case: T > 3 hrs. Event actual time.
    - Other cases: T > 1 hr. T > 1.5 hrs. T > 5.2 hrs. Included for sensitivity analysis.
- Automatic TDAFWP start failed because it was undergoing a surveillance test.
- Batteries depletion time in the SPAR-CSN model: 5.2 hrs.
- Two new basic events were added to quantify the fact that TDAFWP was undergoing surveillance testing and was not immediately available; and operators had to stop the test, restart and align TDAFWP flow to one SG:
    - Probability of TDAFWP undergoing surveillance test upon initiation of the LOOP, set to P=1.
    - Operator fails to reset and align TDP to SGs before SG Dry-out (Available time: 40 min, Time required: 20 min), P= 2.00E-02.
- The mission time in SPAR-CSN model it is 24 hrs. (1 hr. base case + 23 hrs.). A modified mission time of 9 hrs. (1 hr. base case + 8 hrs.) has been included to reflect the actual timing of the event.

For this scenario (Case 1) the SPAR-CSN model obtains a CCDP of 1.66E-04, a result very close to that obtained in the public documentation on the incident (2.00E-04). Table VI shows the minimal cutsets for Case 1. Table VII summarizes the CCDP for different scenarios with various combinations of equipment and plant events (sensitivity analysis). For Case 1 the dominant sequence is Nº 10 (90%, Figure 3): LOOP occurs; Reactor scram succeeds; Emergency power fails (EDGs); AFWS fails; Failure to recover Offsite Power.

Table VI: Dominant MCS for Case 1

Nº	CCDP	%	Event 1	Event 2	Event 3	Event 4
1	7.15E-06	4.32	Operator fails to control SGs level	Operator fails to perform Feed & Bleed action		
2	6.91E-06	4.17	TDAFWP operation failure (>1h)	CCF in operation of DG-A and DG-B		
3	6.65E-06	4.02	TDAFWP operation failure (>1h)	Unavailability for maintenance or testing of the DG-A generator	DG-B generator operation failure	
4	6.65E-06	4.02	TDAFWP operation failure (>1h)	DG-A generator operation failure	Unavailability for maintenance or testing of the DG-B generator	
5	6.16E-06	3.72	TDAFWP operation failure (>1h)	DG-A generator operation failure	DG-B generator operation failure	
6	4.87E-06	2.94	CCF at opening of circuit breakers	TDAFWP operation failure (>1h)		
7	4.21E-06	2.54	Unavailability for testing or maintenance TDAFWP during LOOP	CCF in operation of DG-A and DG-B	Operator fails in restarting and aligning TDAFWP with SGs	
8	4.06E-06	2.45	Unavailability for testing or maintenance TDAFWP during LOOP	DG-A generator operation failure	Unavailability for maintenance or testing of the DG-B generator	Operator fails in restarting and aligning TDAFWP with SGs
9	4.06E-06	2.45	Unavailability for testing or maintenance TDAFWP during LOOP	Unavailability for maintenance or testing of the DG-A generator	DG-B generator operation failure	Operator fails in restarting and aligning TDAFWP with SGs
10	3.76E-06	2.27	Unavailability for testing or maintenance TDAFWP during LOOP	DG-A generator operation failure	DG-B generator operation failure	Operator fails in restarting and aligning TDAFWP with SGs

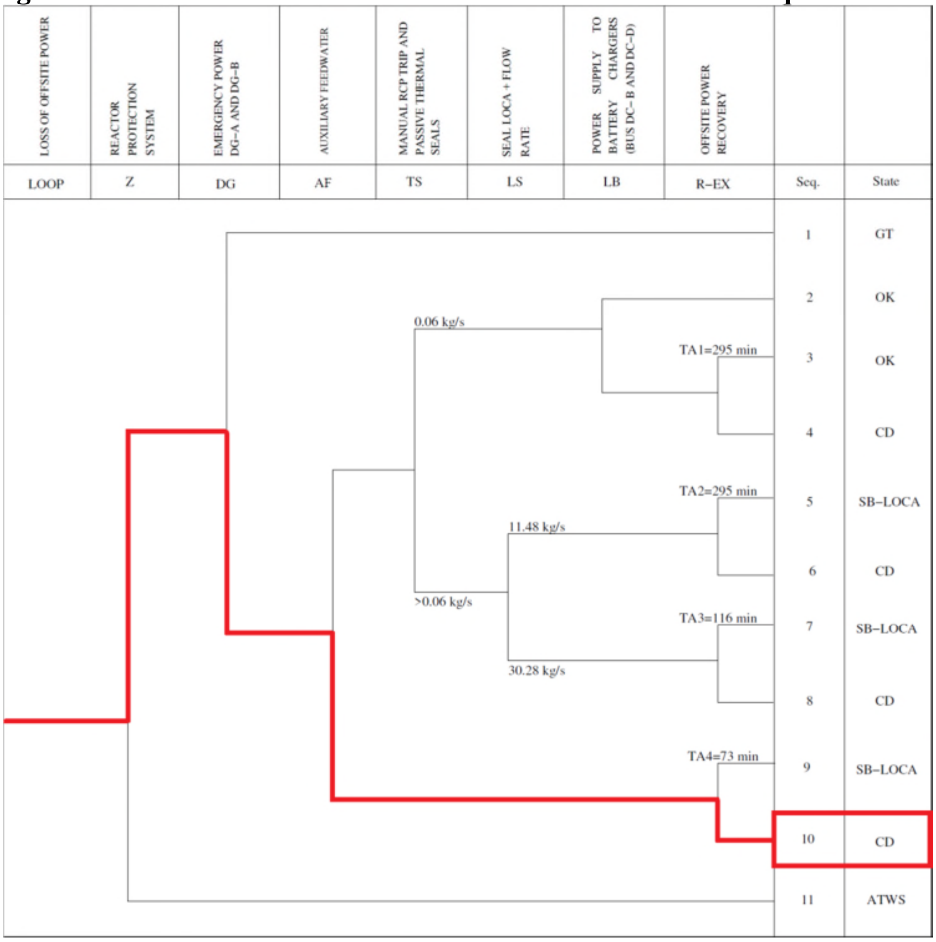
Table VII: CCDP obtained for different combinations of equipment and plant situations

LOOP	Unit 1	Rec AC [h]	Mission [h]	SBO-DG	Rec Ex Train B	Seals/TDP-AFW	CCDP
SPAR-CSN	**Case 0**	**> 0.0**	**24**	**Available**	**Available**	**Available**	**1.43E-05**
Base case RecAC > 1 h	**Case 0.1**	**> 1.0**	**24**	**NO**	**Available**	**Available**	**1.81E-05**
Base case RecAC > 1.5 h	**Case 0.2**	**> 1.5**	**24**	**NO**	**Available**	**Available**	**1.66E-04**
Base case	**Case 1**	**> 3.0**	**24**	**NO**	**Available**	**Available**	**1.66E-04**
Base case	**Case 2**	**> 3.0**	**24**	**NO**	**NO**	**Available**	**1.66E-04**
Base case RecAC > 5.2 h	**Case 3**	**> 5.2**	**24**	**NO**	**Available**	**Available**	**2.43E-03**
Case 1 - 2, T mission = 9 h	**Case 4**	**> 3.0**	**9**	**NO**	**Available**	**Available**	**1.14E-04**
	Case 5	**> 5.2**	**9**	**NO**	**Available**	**Available**	**2.43E-03**
Case 1 - 4, DG-SBO available	**Case 6**	**> 3.0**	**24**	**Available**	**Available**	**Available**	**1.63E-04**
	Case 7	**> 5.2**	**24**	**Available**	**Available**	**Available**	**6.35E-04**
	Case 8	**> 3.0**	**9**	**Available**	**Available**	**Available**	**1.11E-04**
	Case 9	**> 5.2**	**9**	**Available**	**Available**	**Available**	**5.88E-04**
Case 1 - 4, seal failure	**Case 10**	**> 3.0**	**24**	**NO**	**Available**	**NO**	**1.78E-04**
	Case 11	**> 5.2**	**24**	**NO**	**Available**	**NO**	**2.43E-03**
	Case 12	**> 3.0**	**9**	**NO**	**Available**	**NO**	**1.26E-04**
	Case 13	**> 5.2**	**9**	**NO**	**Available**	**NO**	**2.11E-03**

From the sensitivity analysis showed in Table VII, it can be seen that:

- By increasing the mission time, the CCDP increases slightly, because the increase in the operation times of the components implies an increase in their probability of failure.
- By increasing the time it takes to recover external AC, the CCDP increases by as much as an order of magnitude, as a larger number of sequences cannot be recovered.
- The influence of SBO-DG increases as the external AC recovery time increases and becomes significant for long external recovery times.
- The relative influence of seal failure is larger in incidents with shorter recovery times.

Figure 3: LOOP Event Tree SPAR-CSN Model. The dominant sequence in bold.



4.3 Application 3: Battery Life Extension

This application aims to model how the increase in battery life, due to load shedding, impacts the CCDP in the case of LOOP under normal conditions and with the same assumptions as application 2. Two new modifications are then proposed, namely the increase in battery life up to either 8 or 24 hours. These modifications have an impact on other system variables: the probability of non-recovery of external power must be recalculated, in addition to changing the related human actions, to obtain the event and fault trees suitable for the new scenarios. Figure 4 shows the modified event tree for battery life increased up to 24 hrs. The CCDP obtained for the SPAR-CSN model under nominal conditions are:

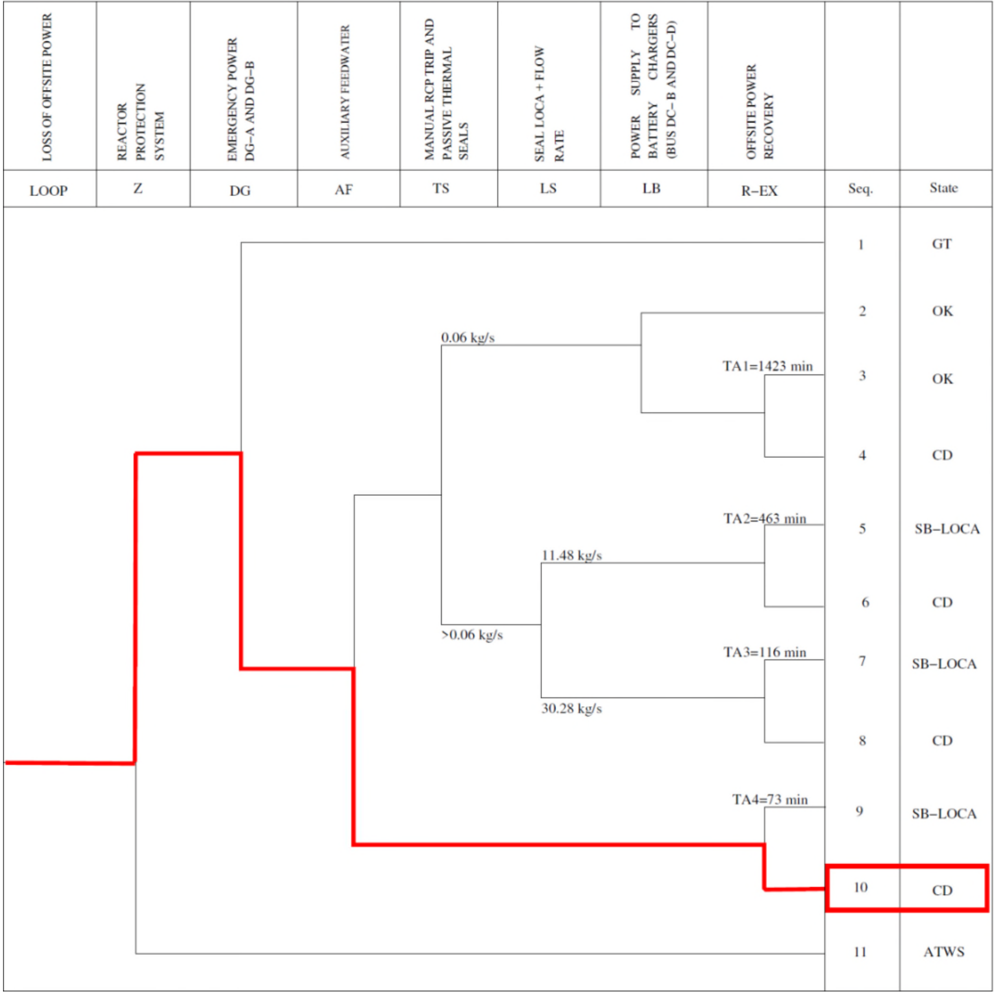
- LOOP-SPAR-CSN (DC=5.2 hrs.): 1.43E-05
- LOOP-SPAR-CSN (DC=8 hrs.): 1.41E-05
- LOOP-SPAR-CSN (DC=24 hrs.): 1.39E-05

As expected, it can be seen that the CCDP decreases if the battery life increases. Table VIII summarizes the CCDP for different scenarios with various combinations of equipment and battery life. Comparing case 17 (Table VIII) with case 3 (Table VII), it can be seen that even with longer external AC recovery times, having a longer battery life considerably decreases the CCDP.

Table VIII: CCDP obtained for different combinations of equipment and battery life.

LOOP	Unit 1	Rec AC [h]	Mission [h]	SBO-DG	Seals/TDP-AFW	Battery [h]	CCDP
SPAR-CSN	Case 0	> 0	24	Available	Available	5.2	1.43E-05
SPAR-CSN	Case 0.3	> 0	24	Available	Available	8	1.41E-05
SPAR-CSN	Case 0.4	> 0	24	Available	Available	24	1.39E-05
Base case battery 8 h	Case 14	> 3	24	NO	Available	8	1.64E-04
Base case RecAC > 8 h	Case 15	> 8	24	NO	Available	8	2.43E-03
Base case battery 24 h	Case 16	> 3	24	NO	Available	24	1.63E-04
Base case RecAC > 8 h	Case 17	> 8	24	NO	Available	24	1.86E-04

Figure 4: LOOP Event Tree SPAR-CSN Model. Batteries life up to 24 hrs.



5. CONCLUSIONS

The main conclusions drawn up to now can be summarized in the following points:

- The methodology delineated for the development of SPAR-CSN models has demonstrated the feasibility to standardize ETs, success criteria, FTs and human actions for the Spanish NPPs tackled in this project.
- Standardization features allow identifying and modeling the specific design differences between the plants and departures from the generic model; some effort is being invested for that purpose within the current project.
- The method has allowed to identify and assess relevant differences between the Spanish NPPs PSA models. These differences are seen in ETs (e.g., transfers between ETs, requirements for the containment safety systems, classification of LOCA break size categories), FTs (e.g., system operating modes and main failures distribution in the FT, transfer gates use, impossible failure combinations removal techniques, etc.) and modeling hypotheses, as well as Human reliability analysis results, and Data sources for equipment failure probability values.
- The SPAR-CSN model was applied to the analysis of two incidents with several sensitivity analyses cases. The results obtained are similar to those obtained in other SPAR models and show the importance of the Offsite Power recovery time and batteries depletion time.

The SPAR-CSN models are valuable tools to understand and evaluate the risk associated with the operation of Spanish NPPs. The standardized construction of these models in terms of modelling assumptions, level of detail, data, HRA methodology, etc., provides a consistent approach from which to evaluate individual plant risk impacts as well as industry-wide issues. The aim of CSN is that these SPAR-CSN models contribute to a better understanding of the main risk drivers in Spanish NPPs and be used as a tool for the different PSA applications currently used at CSN (e.g., precursor analyses, prioritizations in inspection and oversight tasks, assessment of inspection findings).

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