FUNCTIONAL RELIABILITY QUANTIFICATION OF CAREM-LIKE PASSIVE ISOLATION CONDENSER WITH RMPS+

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This paper describes a performance assessment of the Isolation Condenser (IC) of a CAREM-like integral type reactor by means of its Functional Reliability (FR) quantification in order to avoid the RPV safety valves opening during Station Black-Out (SBO). FR is understood as the success probability of a Passive Safety Systems (PSS) to fulfill a specified design goal. Its achievement is evaluated by a Performance Indicator (PI), which is a measure of the "distance" to a limit established for that criterion. Then PI is quantified (by means of model runs) for each set of random values of operational, engineering and modeling relevant parameters, where uncertainties are assumed. FR for the PSS is quantified based on the number of cases whose PI exceeds the limit. Reliability Method for Passive Safety (RMPS) is used and improved to develop this task. The methodology also allow to rank relevant parameters according to its importance, and help to understand phenomena coupling, that could be masked when using classical conservative approach to design PSS.

CÁLCULO DE LA CONFIABILIDAD FUNCIONAL DE UN CONDENSADOR DE AISLAMIENTO PASIVO DE UN REACTOR SÍMIL-CAREM UTILIZANDO RMPS+

Este trabajo describe la evaluación de la performance de un condensador de aislación de un reactor de tipo integrado similar a CAREM, por medio del cálculo de la Confiabilidad Funcional (CF) de manera de evitar la apertura de válvulas de seguridad del recipiente de presión durante una pérdida completa de suministro eléctrico de potencia. La CF puede entenderse como una probabilidad de éxito de un Sistema Pasivo de Seguridad para cumplir un dado objetivo de diseño. Este es evaluado mediante un Indicador de Performance (IP), que es una medida de la "distancia" respecto el límite establecido para dicho objetivo. El IP es cuantificado (mediante ejecuciones del modelo) para cada conjunto de valores de parámetros relevantes de operación, ingeniería y modelado, en donde se asumen incertidumbres. La CF de un sistema pasivo se calcula a partir del número de casos cuyo IP excede el límite establecido. Se utiliza el "Método de evaluación de confiabilidad para sistemas pasivos" (RMPS, *Reliability Methods for Passive Systems*), el cual es mejorado, para llevar a cabo esta tarea. La metodología utilizada también permite una clasificación de los parámetros relevantes en cuanto a su impacto en la CF. Esto resulta útil para el entendimiento de fenómenos y sus acoples, los cuales podrían quedar enmascarados al utilizar aproximaciones clásicas que hacen uso de esquemas conservadores para el diseño de sistemas de seguridad.

INTRODUCTION

Strong reliance on passive safety design options has become a 'trademark' of many advanced reactor designs (IAEA, 2005), including several evolutionary designs and the majority of innovative small and medium sized reactor. Passive safety systems require verifications and testing to demonstrate and prove their reliable operation and, if necessary, adjust their design accordingly. While individual processes may be well understood, the combinations of these processes, which determine the actual performance of passive safety systems, may vary depending on changes in initial and boundary conditions and failure or malfunctioning of components. In this context, arises the need to develop methods for reliability assessment of passive safety system performance. Such methods would facilitate the application of risk-informed approaches in design optimization and safety assessment of advanced reactors, contributing to enhance safety and improve economics. Different methods have been developed; in particular it was of our interest the use RMPS methodology (Marquès et al., 2005) to evaluate the performance of CAREM-like reactor PSS. CAREM-like is an hypothetical reactor that approximates the design characteristics of CAREM prototype (geometric values, systems layout, etc.) and is used to setup a model to develop the present task. It is an accurate model for PSS evaluation purposes and for testing the methodology used.

A representative case is presented, where the role of IC to cope with a SBO is analyzed in terms of fulfilling a design goal RMPS is used, and the FR is quantified. The overall process methodology can be seen in Figure 1, where uncertainties are propagated trough a best-estimate (B-E) model to quantify the FR.

IC FUNCTIONAL RELIABILITY EVALUATION

FR is calculated from the number of cases where the PI exceeds the limit associated with the design goal and the required confidence level using the Wilks' formula (Wilks, 1941, Guba et al., 2003):

$$\beta \leq \sum_{j=0}^{s-1} \binom{N}{j} \gamma^{j} (1-\gamma)^{N-j} \qquad (1)$$

Where:

- β: confidence level
- N: number of samples
- s: position of the sample that represents the upper limit in the ordered data.
- γ: probability that samples do not exceed the upper limit. This figure represents the FR.

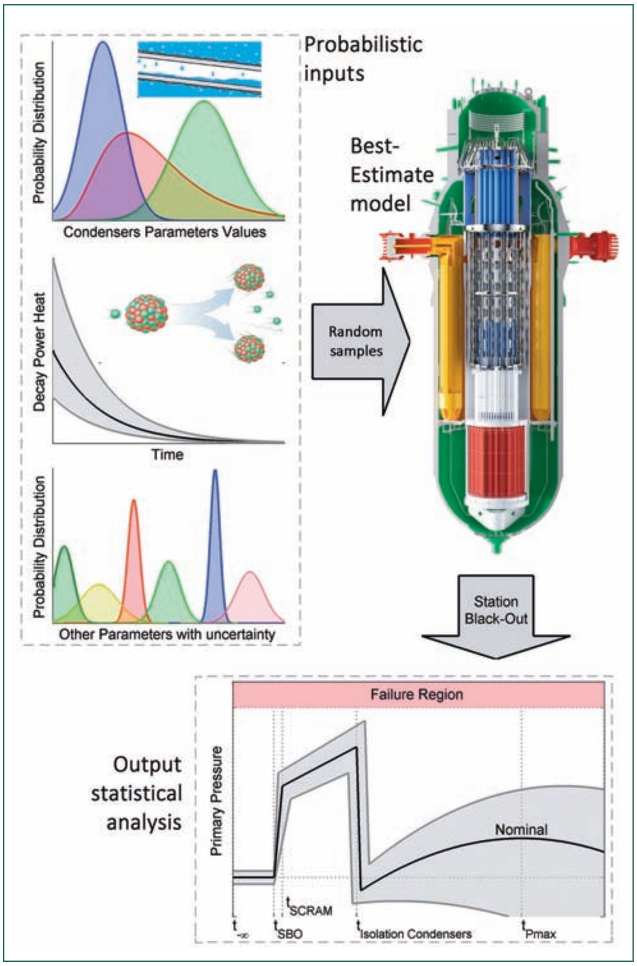

Figure 1. Methodology process for quantification of functional reliability.

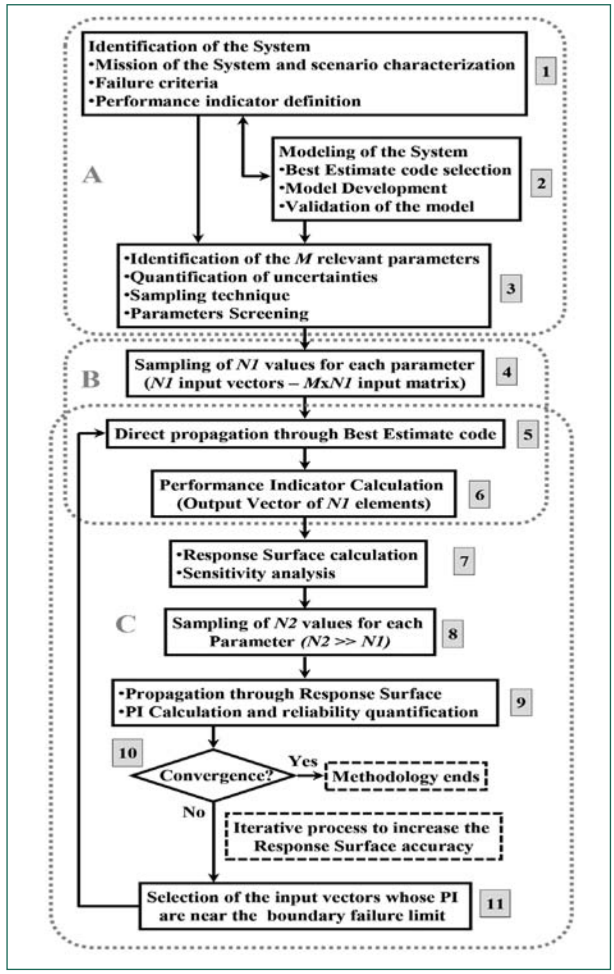

Figure 2. RMPS+ Methodology's Roadmap.

In case of large sample sizes and non-zero failure cases, equation (1) implementation become impractical due to computational effort; for this reason, there are some approximations which make it easier to compute and provide results barely conservative (Mezio, 2010). In case that none of the cases fail, then equation just becomes: $\beta \leq 1-\gamma^N$. To obtain FR, in order to address the objective of the present work, the RMPS methodology was used and slightly improved. The proposed roadmap is showed in Figure 2. This roadmap is based on RMPS one, which is briefly explained in Marquez et al, 2005. The proposed methodology basically is an improvement of RMPS's one, and is called RMPS+. It essentially consists of three blocks, which are briefly described below:

- **Block A:** includes steps to the development of the system's computational model that will be used to perform the assessment (steps 1, 2 and 3).
- **Block B:** Their objective is to obtain the FR of the passive system, as well as the sensitivity of this system against the relevant uncertain parameters. All these analysis are done based on the results obtained from the Best Estimate (B-E) simulation of a comprehensive plant model that includes passive safety systems (steps 4,5 and 6)
- **Block C:** The objective is to wisely increase the populationof cases evaluated near the failure domain, in order to improve the precision of the previous blocks results (steps 5, 6, 7, 8, 9, 10 and 11). Finally, PI is evaluated using an improved response surface as a surrogate model. The improvement consist in a re-evaluation of the response surface near the failure domain, which is the interest region. A more detailed RMPS+ description can be found in Mezio et al., 2010 and Mezio et al., 2014.

REACTOR DESCRIPTION

CAREM is an integral type light water reactor (Marcel, 2017). The primary system, core, steam generators (SG), pressurizer (steam Dome) and control rod mechanism, are contained inside a single pressure vessel. For low power modules (below 150 MWe), the core cooling is driven by natural circulation (Figure 3). Several safety improvements are implemented, as some initiating events preclusion by design, and incorporation of SBO event as a Design Basis Event; in this case, the reactor cooling Fundamental Safety Functions shall be fulfilled at least during the grace period (36hrs) without electrical power supply. Reactor sub criticality, also during cold shutdown, shall be assured by the First Shutdown System without boron addition to the coolant.

The Isolation Condenser (IC) has been designed to reduce the pressure on the primary system and to remove the decay heat in case of SBO. This PSS operates by condensing steam from the primary system within condenser tubes. A simplified picture is shown in Figure 3. The IC has four trains, each one with 50% capacity. Inlet valves in the steam line are always open, while outlet

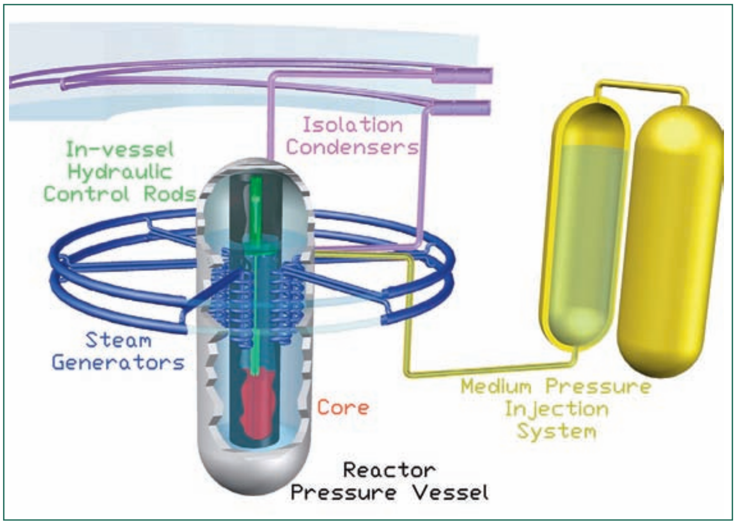

Figure 3. CAREM-like primary system, IC and Accumulator diagram.

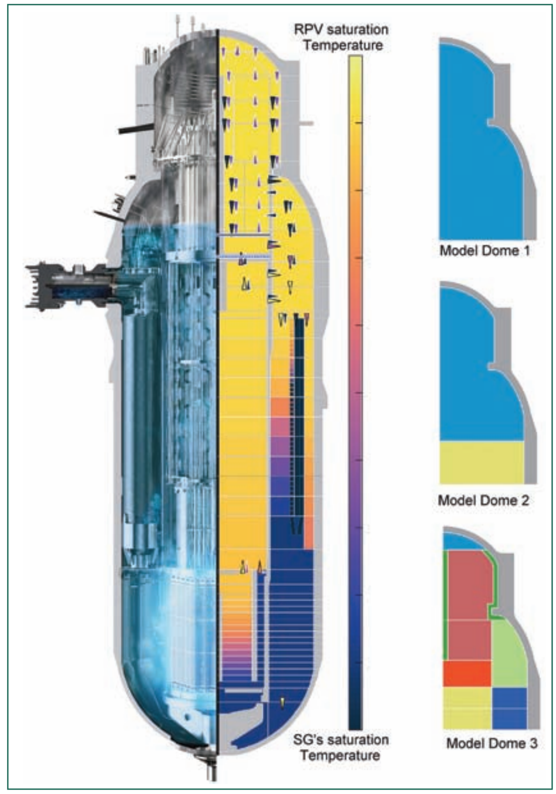

Figure 4. Primary system nodalization. Left: steady state temperature volumes and structures. Right: different dome models.

valves are normally closed. Therefore, in stand-by mode the tube bundles are filled with condensate. In case of primary system overpressure, the reactor protection system demands the opening of the outlet valves. Then the water drains from the tubes into the RPV and steam from the dome enters into the tube bundles, condensing on their cold surface. The condensate is returned to the reactor vessel, establishing a two-phase natural circulation circuit. During the condensation process, heat is transferred to a pool, located in the upper part of the containment.

IC FUNCTIONAL RELIABILITY

The present section describes the use of RMPS+ methodology in a SBO to verify by means of FR calculation, if IC heat removal capacity (design configuration: 2 out of 4 trains available) is enough to fulfill its design goal. Different models for RPV dome were developed in order to evaluate user effect on FR quantification.

Mission, scenario and PI description (Step 1)

The safety function to be performed by IC is to remove the decay heat (and the energy stored in the primary system) during a SBO event (system mission), thus reducing the pressure in the primary system. For this study case, only the short term is considered. During this stage, design goal is defined in order that, after IC demand, the primary system pressure shall be controlled and reduced in order to avoid the RPV safety valves opening. This inherently establishes as design goal limit the safety valves pressure set-point.

PI should characterize the PSS behavior regarding the failure criterion (i.e. safety valve opening). Considering this, it must reflect the "distance" between the primary system pressure and the safety valve opening set-point, after the IC demand. In this sense, PI is a measure of IC capability to perform its safety function. It is required that PI must also be a continuous function, among others mathematical goodness. For this case of study the following performance indicator (*PI*) is adopted:

$$PI = \frac{\eta_{\text{nominal}}}{\eta_{Fail}}$$

Where, η_{nominal}= actual power removed by IC (which actually is a factor that scales the functional dependence between the power removed by IC and the primary pressure) and η_{Fail}= minimum power removed by IC in order to avoid the safety valve opening. This factor, tells how much η_{nominal} has to be reduced in order to reach the failure limit (i.e. if $PI \geq 1$, then the design goal is fulfilled). The value of η_{Fail} was estimated through a simplified analytical model (lumped parameter) (Mezio 2010). One of the main advantages of this PI is that it varies linearly with the IC efficiency, which allows a reasonable linear extrapolation to the failure limit.

Models developed (Step 2)

Two reactor models were developed, one for RELAP5 3.3 code with a high degree of detail to perform the B-E simulations and a lumped-parameters model, as stated previously, in order to decrease calculation time when estimating the *PI*.

Reactor detailed model represents the primary system (Figure 4), IC and other PSS. Regarding primary system, dome modeling influences many of their parameters, like pressure (parameter of interest in this work) and void fraction in the riser, which in turns affects the reactor coolant mass flow rate. For this representation, the Dome was divided in order to allow macroscopic flow patterns (Dome 3) which is showed with different colors in Figure 4. In order to evaluate the user-effect (in developing a nodalization) on FR, two additional models where developed for the Dome, which are simpler than the previous one. It was observed that by using these simple models, enveloping results are obtained, from the steady state calculations point of view (Mezio, 2010). In model "Dome 1" the entire dome is modeled with a single RELAP volume. This option resulted in an over prediction of interfacial heat exchanges within the dome. The other one (Dome 2), all the Dome is mod-

Parameter	Truncated Distribution
Reactor power	Normal
Decay power factor (ANS79-3)	Lognormal
Reactor nominal pressure	Normal
RPV Dome water level	Normal
Primary circuit mass flow rate	Normal
RPV Dome (steam zone) heat losses	Normal
Feedback reactivity coefficients	Uniform
IC pressure set point	Normal
SCRAM signal delay	Lognormal
SCRAM safety rods total drop time	Lognormal
SCRAM pressure set point	Normal
Safety Valves Set-Point	Normal
IC pool temperature	Lognormal
IC tube thickness	Normal
IC fouling	Lognormal
IC pool's boiling heat transfer coefficient	Normal
IC tube's condensation heat transfer coefficient	Normal

Table 1. Selected parameters where uncertainties are postulated.

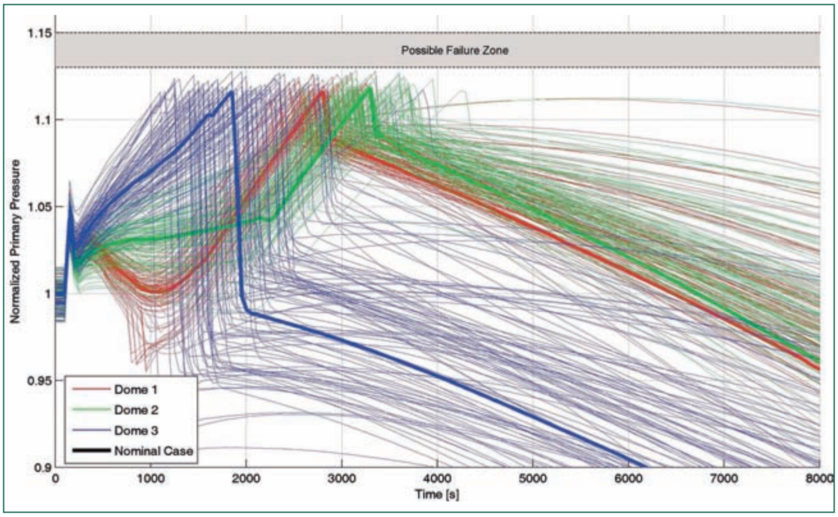

Figure 5. Short-term Pressure evolution for the 100 BE-runs for the three Dome models as well as their nominal case.

eled with only two vertical volumes: one for the lower region of the Dome (in which the primary flow turns from the riser towards the SG) and one for the upper zone (containing the inter-phase between liquid and steam, with a stratification regime). This option forces an artificial "uncoupling" within the Dome and the rest of the primary circuit which implies a large liquid sub-cooling in the hot leg.

Another aspect to remark is that RELAP source code was modified in order to model the uncertainties in the condensation and boiling heat transfer coefficients for the IC. This modified code version accepts the use of some constant coefficients, which internally act as factors that directly affects the desired heat transfer coefficients.

Direct propagation of uncertainties through B-E code (Steps 3 to 4)

Identification and quantification of uncertainties of relevant parameters were mainly carried out by means of expert judgment, see Table 1. Parameters probability distributions has been truncated, since sampling beyond the range limits could lead to unrealistic system configurations (overlapping of parameters ranges, non-realistic values for regulated variables, etc.). Sample size was 100, in order to satisfy 95%/99% criteria (reliability = 95%, confidence level= 99%) for one-sided tolerance interval, according to Wilks's formula.

Figure 5 shows the results obtained from Direct Monte Carlo simulations, for the three RPV Dome nodalizations. Each result corresponds to the pressure evolution calculated with the B-E code for the associated input vector (built for each parameter value). It can be observed, that none of the cases reaches the design failure criterion (i.e. none of the cases exceed the safety valve pressure set point, which is shown like a band because of the uncertainties assumed in their set point). As long as all simulated cases successfully accomplish the proposed design safety criteria, it can be assured that FR of IC is, at least, of 95%, with a 99% of confidence, according with the Wilks' formula of order N^{th}.

Functional Reliability quantification (steps 6 to 11)

The hyper-plane was selected as response surface (surrogate model), which means that a linear analysis was performed. Then, the assumption of linear relationship between the output observable ($Y = PI$) and the input parameters (X_i), is posed:

$$Y = \beta_0 + \sum_{i=1}^{N} \beta_i X_i$$

Where, N = number of relevant parameters; β_0 and β_i = regression coefficients; and X_i = values for the selected parameters.

In RMPS+ methodology, as it was mentioned, an iterative procedure was implemented in order to increase the accuracy of this surrogate model. It is important to remark that the hyper-plane coefficients are directly related with the sensitivity coefficients. Several mathematical checks were done for each obtained coefficient. It is interesting to remark that the values achieved for the "determination coefficients" were always higher than 0.9, which was used among other statistical test (Mezio, 2010) to validate the linear hypothesis. In Figure 6 can be observed the PI obtained for the original 100 set of values of the parameters. The additional 20 values (from 100 to 120), correspond to combination of parameters (within the population of 10^6 samples) that make the IC to be as near as possible to the failure zone boundary. It is important to remark that all the points were obtained based on calculation performed with the B-E code, and that the response surfaces was only used to assist the selection of the extra points. Moreover, these points were used to update the response surface. This procedure was repeated in several iterations.

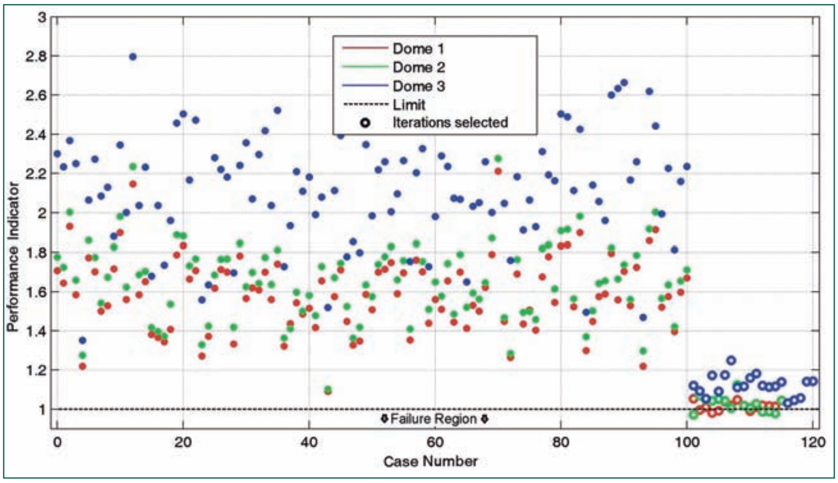

Figure 6. PI obtained for the 100 (plus cases nearest of the failure zone boundary) of BE-runs for the three Dome models.

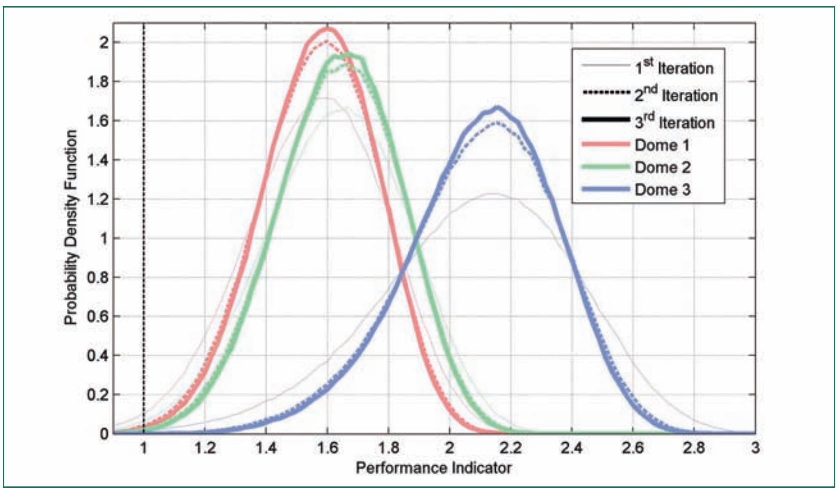

Figure 7. 10^6 cases distribution, for the three Dome model and the three respective iterations.

Number of feedback steps	Failure cases		
	Dome 1	Dome 2	Dome 3
1	8875	4965	1407
2	2193	1183	20
3	1416	784	3
Failure probability, 99% confidence level	1.5e-3	8.8e-4	1.0e-5

Table 2. Failure cases predicted by the surrogate model and failure probability with a 99% of confidence, for the 3rd feedback step.

Figure 7 shows the PI distributions of the 10^6 cases (or set of relevant parameters), using the response surfaces obtained after each iteration, and for the three Dome models. Convergence in the distributions for each Dome model can be observed, but not between them.

Table 2 shows the number of cases that are predicted to fail (i.e., those whose PI are equal or lower than one), according with the response surface calculation, and the number of feedback steps performed, for the three Dome models. It can be seen that the number of cases of IC failure, are highly reduced on the feedback process. Even more, it was checked that for the model Dome 3 (the most realistic approach of the three evaluated models), only 2 of the 3 failure cases truly fail according to the RELAP B-E model, between the million of cases. This shows the high precision reached with this method. The difference between the 3 cases predicted by the response surface, against the 2 ones obtained through the BE calculations, are just a resultant of the conservatism of the PI estimation, and goodness of the fit. Finally, it is shown the failure probability (one minus the FR) of IC for the last iteration feedback step and for the three RPV Dome models. These values have been obtained utilizing the Wilks' formula of N-M order, N the number of sampled values (in this case, equal to 10^6), M the number of failure cases. These results clearly show the influence of user-effect on PI. Dome 1 and Dome 2 models predict a lower FR of the IC. These models have difficulties due to poor modeling on predicting the flow and heat transfer regimes in the steam zone. The code predicts presence of a mixture of liquid and steam in IC inlet, producing partial flooding, with its respective performance degradation. Dome 3 shows a more realistic behavior in every analyzed aspect, mainly in predicting liquid stratification in large volumes with low flow velocities.

CONCLUSIONS

RMPS methodology has been applied to verify the capacity of IC under SBO in order to avoid safety valve opening, by using 2 out of 4 IC trains. System FR (detailed Dome nodalization) predicts that only 2 (two) over 1000000 cases reaches the safety valve set point. The very low figure achieved provides strong reliance of the IC basic engineering. It is important to remind that for this case, the FR is based in a design goal and it is not straightforwardly applicable to a Probabilistic Risk Assessment study in which acceptance conditions could be different depending on the analyzed event. User effect emerges as an important source of uncertainty, which cannot be intrinsically addressed by this methodology. In this work, and exercise was carried out, by applying RMPS+ using three different Dome models, obtaining different FR values for the IC; which remarks the need of user qualification and a comprehensive quality assurance program.

RMPS methodology was improved, tested and used to probabilistically quantify the performance of passive safety systems in order to verify the fulfillment of design goal. A crucial issue of this methodology is the right selection of the PI. Its adequacy sustains the results from direct Monte Carlo simulations and the calculations based on surrogate model; therefore, the PI must be strictly linked to the failure criteria and its definition have to assure that the correct system's phenomenology is encompassed. Then, PI definition is not a straightforward task, it is important to dedicate a considerably effort regarding its definition, implementation and results verification. Finally, it can be concluded that the improved methodology (RMPS+) provides very useful insights in engineering process at any design stage.

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