

Effects of dependent critical parameters on reliability of natural circulation-based passive system

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Abstract: The adoption of passive safety systems in nuclear technological applications especially in advanced nuclear power reactors is on the increase purposely to improve on safety, simplicity and economics of operations. In order to guarantee the effectiveness of passive systems, the thermal-hydraulic and reliability analysis must be carefully carried out especially for the thermal-hydraulic passive systems which are characterized by several aleatory and epistemic uncertainties. It has been established that the critical parameters influencing the performance or failure behavior and consequently reliability of the thermal-hydraulic passive systems are interdependent in nature. As a result, it is important to critically consider the synergetic effects of the influencing parameters of reliability of such passive systems. Reliability methodologies are now being modified and improved upon by factoring the dependency nature of those influencing parameters into reliability analysis to obtain more realistic and accurate results. This paper thus focused on the effects of the dependent critical parameters on thermal-hydraulic (phenomenological) reliability using multivariate distribution analysis. A passively water cooled steam generator was used to demonstrate the interdependency effects of the key critical parameters. The results obtained justified the significance of considering the dependency effects of these parameters in thermal-hydraulic reliability analysis of the passive safety systems.

Keywords: critical parameters; reliability; natural circulation; passive safety system

1 Introduction

Efforts towards improving the level of safety of nuclear power reactors are on the increase. These efforts are evident in improving the design and operation of conventional reactors and developing innovative ones by fortifying them with robust passive safety systems (PSSs) which are inherently less prone to failure. In addition, the deployment of PSSs helps to maintain and foster a peaceful co-existence of the nuclear power plants (NPPs), man and the environment (living organisms and properties) as the inherent safety nature of the systems is transferred to the NPPs when adopted. Thus, operations of the NPPs will pose less or no havoc to lives and properties.

The PSSs are the front-line systems that do not require an external source of power, actuation or human intervention for them to mitigate the progression of incidents (undesired occurrences) in a plant or facility. These systems are now increasingly becoming very essential in advanced designs of nuclear power

reactors as the need to guarantee safety, reliable operation and process economics at the same time is on the rise. In addition, they are adopted to meet the high safety-licensing requirements^[1] and gain public acceptance.

To successfully incorporate these systems in the nuclear power plants, there is need to carry out detailed analysis of the passive components, systems and the associated phenomena to ensure their safety and reliability throughout the life cycle of the plants. One of the key challenges that must be surmounted to ensure safe, stable, dependable and effective operation of those reactors is quantification of the reliability of the adopted passive systems^[1].

Due to the nature of passive systems and their operations, new failure mechanisms that may be associated directly or indirectly and thus interfere with the fulfilment of their safety missions can be traced to the issues related to reliability^[2]. The issues highlighted in the literatures are the associated low-driving forces inherent in PSSs, uncertainties regarding the associated physical process phenomena

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/ mode of operations, inadequate real plant and related experimental data *etc.* All these issues make the thermal-hydraulic (t-h) and reliability analysis of the systems complicated thereby calling for measures and approaches to make the results of such analysis more realistic and of practical application.

Considering reliability analysis, aside the components and the phenomenal issues, one major issue is the environmental factors which is simply the interactive / interdependency effects of the critical parameters (CPs). The CPs are the precursors or signals to failure which in most cases are associated with phenomena such as non-condensable gas build-up, heat exchanger plugging *etc.* [2].

Dependency effects of the CPs can influence the behavior of the PSSs in several ways like alteration of the definition of failure criteria applicable when a set of CPs are independently considered and reduction of estimated reliability compared to that obtainable through independency consideration / series system configuration.

The phenomenological reliability which deals with the capability of a t-h phenomenon to satisfactorily carry out the expected safety mission within a given time frame under the prevailing conditions is important as failures of the t-h PSSs can be easily caused by a slight drift in operating or boundary conditions. Such deviation is more than enough to render the whole system ineffective. Therefore, in addition to PSS components reliability, phenomenological reliability should be given more attention.

In assessing the phenomenological reliability of PSSs, an important step is the identification of the associated failure mechanisms [3]. With the increasing coordinated research efforts on phenomenological reliability, several methods have been developed of which RMPS and APSRA are major and are being modified and improved upon [4]. Both methodologies required best estimate t-h codes for t-h performance evaluation of the systems. The methods define the t-h failure criteria and are based on probabilistic and deterministic tools to evaluate the overall reliability of the system under study. Through the methods, it

has been established that input parameters and boundary conditions are critical for the performance of the system. Thorough understanding of the parameters and boundary conditions in terms of variations between some limits and their effects on performance during normal operations and transients is important in evaluating the phenomenological reliability [5].

With emphasis on the phenomenological reliability, this paper focuses on the interactive effects of the CPs that are important in reliability analysis of a generic simple natural circulation (NC)-based system (passively water cooled steam generator).

2 Factors influencing the reliability of thermal-hydraulic passive systems

Passive system, described as either a system composed entirely of passive components and structures or a system which uses active components in a very minimal way to initiate subsequent passive operation or prevent the occurrence of undesirable initiating event(s)) are always influenced by various environmental factors which present themselves in different forms [6].

As the forces of nature which passive systems depend on rarely fail, it is reasonable to conclude that passive systems are theoretically likely to be much more reliable than the active ones as their operations do not based on any external forces that are prone to failure [7].

It is pertinent to note that these passive systems do fail in spite of their nature and operating mode and in most cases the failure analysis of the individual components of passive systems does not consider environmental interactions. Therefore, it is difficult to factor in the systems interactive effects on failure behaviors [8].

The physical phenomena (t-h) reliability accounts for the phenomena [9] that drive passive safety mission(s) and their interactions with the environment which influence their performance and stability.

2.1 Critical parameters of reliability of thermal-hydraulic passive systems

The CPs which are direct indicators of the passive system or component physical failure and malfunction^[10] signal the failure of a passive system in fulfilling its expected mission(s). They are a group of system parameters that characterize the passive system behaviors and are therefore adopted as indicators for the system failure causes or joint causes. Their identification requires in-depth study and thorough consideration of the mission(s) that the PSSs are meant to fulfill^[11]. The effects of the CPs are quantified using the influencing coefficients. Their effects can be positive or negative (increasing or decreasing the hazard rate) and discrete or continuous. In order to quantify their effects, the key indicating factors (CPs) must be adopted. While considering the CPs in reliability analysis, definition of the failure rates (for the failure modes that are considered major) which are functions of the adopted indicator values are required. The common CPs associated with the NC-based t-h PSSs are non-condensable fraction, heat exchanger plugging, valve closure coefficient and undetected leakage. In addition, some of the CPs are difficult to quantify and thus statistical approaches are adopted to estimate the relationships between failure rates and the influencing factors as there is virtually no or inadequate knowledge of the precise physical relationships in most cases^[12].

The CPs are treated effectively in two forms^[9]. The first is the simpler *independent parameters consideration* based on the premise of simplification and more conservative results are obtained by assuming no interaction between the influencing parameters. In this case, the failure of a single system can actually hinder the fulfillment of the mission(s) of the overall PSS. The second is the *dependent parameters consideration* based on interdependency nature and behavior of the influencing parameters. This approach seems more reliable and close to reality. In the latter, *evaluation of failure is more complicated as it assumes non-mutually exclusive phenomena behavior which is suitable for NC-based passive systems. The reason is due to synergy among the CPs that influences the overall system performance* (in terms of the likelihood of occurrence,

severity of the events / consequences)^[9].

2.2 Dependency consideration of critical parameters of t-h reliability

The computation of the overall failure probability (from which reliability can be obtained) by assuming independency of critical parameters has been proved to be over-conservative and thus less realistic. The conclusion of BURGAZZI, L.^[9] on the methodology for parameters independency adopted by ZIO, E., and PEDRONI, N.^[13] led to model development for *critical parameters dependency*. Provided that the dependencies among the relevant parameters are known to some extent or can be reasonably guessed to some level of certainty, conventional approaches that can account for interdependencies can be applied. The approaches are multivariate distributions (*e.g.* joint probability distribution or bivariate normal distributions), conditional subjective probability density functions, covariance matrices and functional relations among the key parameters.

2.2.1 Basic models and equations in dependency consideration of t-h passive reliability

The concept of stress-strength model of physics of failure has been established for defining the performance of t-h nuclear passive system (known as limit state function)^[14]. With R and S assigned as the “*functional requirement of a safety plant parameter*” (such as temperature and pressure) and “*system’s state*” (operating plant parameter) respectively. Both R and S are defined by probability density functions (pdfs) under the probabilistic model and they depend on many variables x which are characterized by various uncertainties. The pdfs are characterized by some elements such as mean, standard deviation and variance especially for the simple normal distribution.

$$G_I(x) = R(x) - S(x) \quad (1)$$

P_I , the overall failure probability, can be obtained from the overall system reliability, R_I as the two quantities add up to unity. P_I can be further evaluated over the failure region $G_I(\cdot) \leq 0$ and has been established as:

$$P_I = 1 - R_I = \int \dots \int_{G_I(x) \leq 0} f_x(x_1, x_2, \dots, x_n) dx_1 dx_2 \dots dx_n \quad (2)$$

Where $f_x(\cdot)$ is the joint pdf representing the

uncertainty in the parameters x ^[13]. The above case is for the maximum failure threshold ($G_1 < 0$, for failure of the system mission; and $G_1 > 0$, for safe function) and vice versa for the minimum failure threshold. $G_1 = 0$ being the limit state for both cases of thresholds.

Applying the concept above to the CP now it takes the form of x . As a result of the interactive effects of CPs which affect the occurrence, non-occurrence or severity of failures; the parameters have been observed with related contributions to the failure modes (FMs) and thus necessitate the application of dependency approach. To factor-in dependency effects, the earlier mentioned dependency approaches must be applied ^[15]. The truncated normal distribution, TND (s-normal pdf / central limit theorem) has been adopted as the best fit (a suitable approximation) for the selected failure modes in this work as it has been applied in previous research for similar systems ^[9, 16]. The reasons are because over the estimated range, the standard deviation is very small when compared to the mean value and in addition, the TND is simple and commonly applied practical engineering tool.

The TND has been established to be of the form:

$$f(x) = \left(\frac{1}{\sigma\sqrt{2\pi}} \right) * e^{-\left[\frac{(x-\mu)^2}{2\sigma^2} \right]} \tag{3}$$

where μ and σ^2 represent the mean and the variance respectively for parameters observed from a sample of x_i with sample size n .

Given the quantitative measures of two time-variant CPs as $X_1(t)$ and $X_2(t)$ at time, t . To simplify the analysis, time-invariant nature of the CPs is assumed and X_1 and X_2 obeys the s -dependent theorem (a simple form of the Bayes theorem) ^[17].

The reliability, R of the system under study can thus be estimated based on the approximated joint pdfs of the CPs influencing the system. To generalize the relation for reliability, taking time into consideration, $R(t)$ for n dependent CPs, as given by BURGAZZI, L ^{[18], [16]} is;

$$R(t) = \Pr\{X_1(t) \leq L_1, X_2(t) \leq L_2, \dots, X_n(t) \leq L_n\}$$

$$= \int_{L_{0,1}}^{L_1} \int_{L_{0,2}}^{L_2} \dots \int_{L_{0,n}}^{L_n} f\{x_1(t), x_2(t), \dots, x_n(t)\} dx_1 dx_2 \dots dx_n \tag{6}$$

where $f\{x_1(t), x_2(t), \dots, x_n(t)\}$ = the joint distribution function of $X_1(t), X_2(t), \dots, X_n(t)$ at time t , and also, L_i the failure limit (in this case, minimum failure threshold value).

The necessary condition for dependency of a pair of different CPs 1 and 2 for instance is,

$$S_{x_1, x_2} = Cov(X_1(t), X_2(t)) \neq 0 \tag{7}$$

Where in general,

$$S_{x_i, x_j} = Cov(x_i, x_j) = \frac{1}{n} \sum_{i=1}^n (x_i - \bar{x}_i)(x_j - \bar{x}_j)$$

Another important statistical variable is the Pearson's product moment correlation coefficient, r mathematically defined ^[17] as:

$$r_i = \frac{S_{xy}}{S_x S_y} = \frac{\sum (x_i - \bar{x})(y_j - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 (y_j - \bar{y})^2}} \tag{8}$$

While the generalized variance-covariance matrix ^[16, 19] for n set of CPs which can be used to test for dependency of the CPs is given as:

$$\begin{pmatrix} Var(X_1(t)) & Cov(X_1(t), X_2(t)) & \dots & Cov(X_1(t), X_n(t)) \\ Cov(X_2(t), X_1(t)) & Var(X_2(t)) & \dots & Cov(X_2(t), X_n(t)) \\ \vdots & \vdots & \ddots & \vdots \\ Cov(X_n(t), X_1(t)) & Cov(X_n(t), X_2(t)) & \dots & Var(X_n(t)) \end{pmatrix}$$

With $Var(X_n(t))$ denoting the variance of a sample of quantified CP n and $Cov(X_n(t), X_i(t))$, covariance of quantified CPs n and i . Each of the entry must satisfy Equation (7) for any of the CPs combinations to be dependent.

3 Case study: a generic NC-based system

The case study system is a simple NC loop in which the operation of most t-h PSSs is based. The system is a generic form of NC circuit commonly adopted by most advanced reactors specifically for removing the residual heat from the reactor core after a reactor emergency shutdown (scram). The PSSs in this category are passively cooled steam generator (water cooled) based on NC, passive residual heat removal heat exchangers (PRHR-HX) and passively cooled core isolation condensers ^[20].

3.1 Passively Water-Cooled Steam Generator

The operating principle of the NC-based passively cooled steam generator (SG) is very simple. The steam at the SG raised by the heat generated from the reactor vessel - at close to full system pressure and temperature - rises through the inlet of the PRHR system (riser) and is condensed in a heat exchanger (HX) submerged in a pool of water (condenser) (Fig. 1). The cold coolant returns to the SG through the outlet of PRHRS (downcomer) which is connected to the SG at a lower elevation compared to the riser^[20].

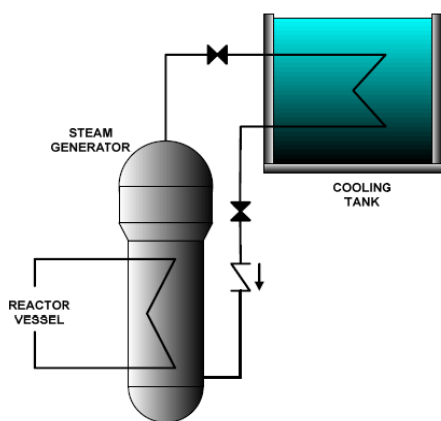


Fig. 1 Schematic diagram of the passively cooled steam generator.^[20]

The operation of this simplified system found specific application in the passively water-cooled SG adopted in the System-integrated Modular Advanced Reactor, SMART (Fig. 2).

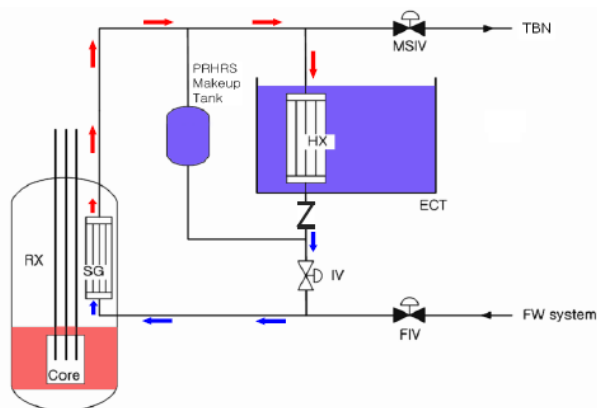


Fig. 2 Schematics of core decay heat removal by a passively water-cooled SG incorporated in SMART.^[20]

The passively water-cooled SG removes residual heat from the secondary side of SG through NC. The system is designed to cool the reactor coolant system (RCS) to a temperature of 200⁰C within 36 hours by removing decay heat of the core and the sensible heat

of reactor coolant once the reactor tripped from any power level. Some of the essential nominal parameters of SMART are presented (Table 1).

Table 1 Some nominal parameters of SMART^[20, 21]

Parameter	Value
Power (MWth)	330
Effective height-between SG and HX (m)	10
Operating Pressure (MPa)	15
SG inlet temperature (K)	596
SG outlet temperature (K)	568.7
Flow rate (Kg/s)	2090
Heat removed from the SG (MJ/s)	239.6
SG tube I.D./ O.D (mm)	12/17
Coolant	Light water

Table 2 shows the key CPs influencing the failure behavior of the NC loop. The four CPs are known to be the major CPs responsible for common failure modes which cause the overall system failure (Table 2). They are selected on the premise that they significantly influence the flow rate, pressure and water level of the SG which are key in the analysis of failure of such systems. The failure modes which are signaled by the CPs (Table 2) are located within the rectangular loop which comprises the steam generator (SG), hot leg, heat exchanger (HX), isolation / check valves and cold leg.

The failure mechanisms are pipe rupture / break (causing reduction in heat transfer rate or loss of coolant), blockage of HX pipes (which may be due to fouling, dirt *etc* causing reduction in flow rate), valves failure such as partial opening of valves in the discharge line (due to friction on the moving parts) and build-up of non-condensable gases (which causes reduction in heat transfer capability). The mechanisms are known to be interdependent in reality and characterized with different forms of uncertainties. The Table is a product of applying expert judgment and engineering assessment in characterizing the system and is due to inadequacy of experimental and operational data associated with the operations of the t-h PSSs^[22]. In addition, formulation of the pdfs essential in estimating the reliability of such systems was always done through expert judgment and experiences in previous related research. The nominal values depict the status of the system at steady state.

Using the co-variance approach, the analysis is started by computing the mean vector and the variance-covariance matrix (needed to test for

dependency) for the four CPs using four arbitrary sets of data as real data are scarce for these phenomena.

Table 2 Expert judgment characterization of key critical parameters associated with the case study [22]

S/N	Critical Parameter	Range of Indicator	Nominal / Average Operating Value	Failure Threshold	PDF
1	Non-condensable fraction	0.01- 0.8	0	0.5	D-TND
2	Heat exchanger plugging	0 - 0.15	0	0.10	D-TND
3	Valve closure coefficient	0 - 0.5	0	0.3	D-TND
4	Undetected leakage (cm ²)	0-10	0	1.0	D-TND

Legend to Table 2:

Non-condensable fraction: 0-absence of non-condensable, 0.8-presence of about 80% non-condensable as the presence of 100% non-condensable is not realistic.

HX plugged pipes: 0-total absence of plugged pipes, 0.15-unacceptable condition requiring replacement/fixing.

Valve closure coefficient: 0-valve completely open, 1-valve completely closed.

Undetected leakage: 0 cm²-no leakage, 10 cm² – maximum area of undetected leakage, failure threshold of 1.0 cm² (approximately 3/8 in.) is adopted as it is approximately the lower limit for Small Break Loss of Coolant Accident (LT-SBLOCA) in nuclear reactors.

D-TND: Doubly Truncated Normal Distribution

3.2 Multivariate analysis of CPs for the system

With,

$x_1 = NCF$ (non-condensable fraction)

$x_2 = HXP$ (heat exchanger plugging)

$x_3 = VCC$ (valve closure coefficient)

$x_4 = UL$ (undetected leakage)

being assigned to the four CPs and considering a set of four observations (similar values to the chosen ones have been used in literature based on expert judgment)^[19]. A matrix *A*, which is a vector of the randomly sampled values for the set of the selected

CPs within the success range (as defined in Table 2) for the NC-based system is:

$$A = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ 0.300 & 0.035 & 0.25 & 0.60 \\ 0.250 & 0.042 & 0.18 & 0.80 \\ 0.214 & 0.025 & 0.12 & 0.40 \\ 0.100 & 0.030 & 0.05 & 0.20 \end{bmatrix}$$

For each CP, the mean vector is the mean for the set of samples while the variance-covariance matrix is the variances of each variable along the leading diagonal and the covariance between each pair of variables in the other positions of the matrix as defined in section 2.2.1.

The mean vector:

$$\bar{\mu} = [0.216 \quad 0.033 \quad 0.150 \quad 0.500]$$

Using the Ms Excel statistical function tools (COVAR, PEARSON, etc.), all the possible combinations of the key CPs satisfied the dependency condition (Equation (7)) as shown by the covariance values (Table 3).

The values of *r* for the six possible combinations (⁴C₂) revealed that the CPs are correlated as the *r* values ranged between 0 and 1, with the least value being 0.453 which suggests that the combinations display a high positive correlation (Table 3).

Table 3 The correlation coefficients and covariance values for the possible combinations of the CPs

S/N	Critical Parameters Combination	Correlation Coefficient, <i>r</i>	Covariance Value (Cov)
1	$x_1 x_2$	0.453	0.00021
2	$x_1 x_3$	0.970	0.00527
3	$x_1 x_4$	0.814	0.00134
4	$x_2 x_3$	0.544	0.00253
5	$x_2 x_4$	0.818	0.00115
6	$x_3 x_4$	0.788	0.01300

Based on the results (Table 3), it is reasonable to take the CPs to be dependent. The variance-covariance matrix, *V* obtained using the earlier stated conditions is:

$$V = \begin{bmatrix} 0.007224 & 0.000210 & 0.005270 & 0.013400 \\ 0.000210 & 0.000053 & 0.000253 & 0.001150 \\ 0.005270 & 0.000253 & 0.007267 & 0.013000 \\ 0.013400 & 0.001150 & 0.013000 & 0.066667 \end{bmatrix}$$

The reliability can thus be evaluated using Equation (6) taking into consideration the mission fulfillment regions for each of the CPs *i.e.* ($x_1 < 0.5$, $x_2 < 0.10$, $x_3 < 0.3$ and $x_4 < 1.0$) using a suitable computational tool like MATLAB. This involves integrating the pdf (represented by the multivariate normal distribution) over the success limits earlier defined by applying a suitable integration method using Eq. (6)^[19], *i.e.*

$$R(t) = \Pr\{X_1(t) \leq L_1, X_2(t) \leq L_2, \dots, X_n(t) \leq L_n\}$$

$$= \int_{L_{0,1}}^{L_1} \int_{L_{0,2}}^{L_2} \dots \int_{L_{0,n}}^{L_n} f\{x_1(t), x_2(t), \dots, x_n(t)\} dx_{1t} dx_{2t} \dots dx_{nt}$$

With the TND as defined in Eq. (3), *i.e.*

$$f(x) = \left(\frac{1}{\sigma\sqrt{2\pi}} \right) * e^{-\left[\frac{(x-\mu)^2}{2\sigma^2} \right]}$$

Rewriting the TND describing the CPs, with variance taken to be variance-covariance matrix, V

$$f_x(x_1, \dots, x_n) = \left(\frac{1}{\sqrt{|V|} (n\sqrt{2\pi})} \right) * e^{-\left[\frac{(x-\mu)V^{-1}(x-\mu)^T}{2} \right]} \quad (9)$$

With n , the number of dependent CPs = 4, $|V|$ = the determinant of the variance-covariance matrix, V^{-1} is the inverse of the matrix V , x = vector of the x_i values, μ = the vector of the means of i distribution, T = symbol for the transpose of a matrix. The results obtained through the matrix V and the pdfs are presented in Table 4.

Table 4 Variance-covariance matrix and PDF related results

Variables	Values
Determinant of V	3.1184*10 ⁻¹¹
f(x ₁)	1.4850*10 ⁻⁵
f(x ₂)	3.0559*10 ⁻⁴
f(x ₃)	2.9088*10 ⁻⁴
f(x ₄)	0.0

The inverse of V obtained is,

$$10^{4*} \begin{bmatrix} 0.0334 & 0.0377 & -0.0190 & -0.0037 \\ 0.0377 & 3.0741 & -0.0399 & -0.0528 \\ -0.0190 & -0.0399 & 0.0320 & -0.0017 \\ -0.0037 & -0.0528 & -0.0017 & 0.0035 \end{bmatrix}$$

Applying the values obtained to Eq. (6), the final thermal-hydraulic reliability obtained is 0.21948.

3.3 Remarks on the approach and results

It is important to note that the use of engineering experience and expert judgment adopted in defining

the range of parameters and setting the failure limits for the CPs will definitely have some implications on the real nature and value of the estimated reliability. Also, in reality, the interdependency of CPs is a factor among several other environmental influences which can make the quantified reliability not to be very accurate but a bit representative. The time-invariant nature of the CPs assumed for simplification will also cause some discrepancies between the estimated reliability and the real value. This approach as presented seems more reasonable and close to reality compared to independent consideration of the CPs.

4 Conclusion

Through a critical consideration of the simple NC-based PSSs (passively cooled steam generator) adopted as case study, four key critical parameters that influence the thermal-hydraulic reliability of the system were selected. The critical parameters (CPs) were subjected to covariance method of multivariate analysis. The analysis justified the dependency consideration of the CPs as they were proved interdependent by showing non-zero co-variance values and highly positive correlation coefficients which depict strong relationships among the CPs. The influence of the CPs also reflected on the final value of the thermal-hydraulic reliability for the passive safety system studied.

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