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Considerations of uncertainties in evaluating dynamic reliability by GO-FLOW methodology – example study of reliability monitor for PWR safety system in the risk-monitor system

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The uncertainty analyses have been considered as a relevant topic since WASH-1400 and analysis was performed for identifying the risk measure, e.g. plant- and core-damage frequency or the frequency of a large early release of radioactivity in the probabilistic safety assessment (PSA) or probabilistic risk assessment. There are two main sources of uncertainty such as aleatory uncertainty and epistemic uncertainty (parameter uncertainty, model uncertainty and completeness uncertainty) for risk analysis in PSA or risk-monitor system. A sensitivity analysis is related field to uncertainty, which can provide information of the most effective on those inputs of PSA, which are mostly contributed to the uncertainty.

In this paper, uncertainty analysis (epistemic) has been conducted in the evaluation of dynamic reliability of safety-related subsystem for risk analysis. GO-FLOW methodology has been employed for the procedure of uncertainty analysis alternatively to Fault Tree Analysis and Even Tree because it is success-oriented system-analysis technique and comparatively easy to conduct the reliability analysis of the complex system. The method used sample data from Monte Carlo simulation to quantify uncertainty in terms of appropriate estimates for analysis results. Pressurized water reactor containment spray system has been taken as an example of safety-related subsystem. The results of this paper show that the uncertainty analysis is an important part for the practical evaluation of the system dynamic reliability and makes the reliability prediction more accurate compared with the result without the uncertainty analysis. The GO-FLOW methodology can be employed easily for uncertainty analysis with its advance functions.

Keywords: *dynamic reliability; uncertainty analysis; sensitivity analysis; risk-monitor system; reliability monitor; GO-FLOW methodology; containment spray system; PWR; Monte Carlo simulations*

1. Introduction

The uncertainty ranges of system failure probabilities are important information in probabilistic safety assessments (PSA) for the evaluation of the results of system-reliability analyses [1]. Uncertainties and the uncertainty analyses have been considered as a relevant topic since WASH-1400 (1975) [2]. Uncertainty analysis was performed for identifying the risk measure, e.g. plant- and core-damage frequency (PDF and CDF) or the frequency of a large early release of radioactivity in the PSA [3,4]. The method used sample data from Monte Carlo (MC) simulation to quantify uncertainty in terms of appropriate estimates for the mean and variance plus some informative quantiles. According to

treatment of uncertainty analysis for PSA used in Risk-Informed Regulation, described in NRC report [5], the factors which bring uncertainty to PSA are “experienced failure data, analyses modeling and completeness of the model” [3].

PSA uncertainties have an important role in reliability analysis and risk management for decisions making. We speak of risk management in the broad sense of making decision based on the results of reliability analysis and risk analysis [6] in the risk-monitor system [7]. Uncertainties for risk analysis in the risk-monitor system or PSA are divided into two broad categories (i) aleatory uncertainty and (ii) epistemic uncertainty [8,9]. The aleatory uncertainty is the inherent variation in the

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physical system. Epistemic uncertainty is due to limited data and knowledge of the quantities identified with the system under consideration. The epistemic uncertainty consists of parameter uncertainty, model uncertainty and completeness uncertainty [10]. The sensitivity is the related field to uncertainty analysis [11] and can provide information of the most effective on those inputs of a PSA which are mostly contributed to the uncertainty of output frequencies like the CDF, PDF and system reliability and can indicate for which input uncertainties it would be most effective to improve the state of knowledge in order to reduce the uncertainty.

In this study, uncertainty analysis (epistemic uncertainty) with sensitivity analysis is considered in the evaluation of dynamic reliability of the pressurized water reactor (PWR) containment spray system (CSS) by GO-FLOW methodology for risk analysis. The purpose of this study is to conduct the practical and more accurate evaluation of dynamic reliability of safety system, and also to obtain the useful information from computer code runs through the intelligent use of sensitivity-analysis techniques which are important in order to develop the reliability monitor for PWR safety system in the new concept of risk-monitor system. Reliability results without considering the uncertainty analysis are presented in the author's previously presented papers [12,13] which does not give the sufficient information due to scarce knowledge of the input parameters for the GO-FLOW model. Therefore, previous numerical results of analysis can hardly be accepted as an absolute value for an overall availability of the safety system. In respect of input data, sensitivity analysis can give an insight into credibility of the result obtained and indicate the weak points which should be corrected. Traditionally, risk monitors are based on the combination of Fault Tree Analysis (FTA) [14] and Event Tree (ET) [15], and these methods have difficulty to evaluate the reliability of the machine systems which will change the operation mode with time (phased mission problem). Also, it is very time consuming to conduct FTA and ET for reliability analysis of the large complex system. GO-FLOW is a success-oriented reliability analysis technique and can be employed alternatively to FTA and ET. It is comparatively easy to conduct reliability analysis by GO-FLOW.

The analysis result consists of "cumulative probability distribution, probability density distributions, mean, standard deviation and variance" and some informative quantiles (e.g. the 5%, 50% and 95% quantiles) are derived and used as uncertainty quantification. It shows that the uncertainty analysis is an important part of practical evaluation of the system dynamic reliability and the fertile reliability prediction compared with the result without the uncertainty analysis. The results provide the valuable risk information to the operators for decision making to ensure the safe operation of nuclear power plant (NPP). This information might be useful for development of reliability monitor to evaluate the risk in

NPP. GO-FLOW methodology can be employed for uncertainty analysis with its advance functions.

2. Overview of uncertainty analysis of evaluating dynamic reliability by GO-FLOW methodology

NRC Report [5] and ASME/ANS, 2009 [16] recognized the importance of the identification and understanding of uncertainties that are part of PRA. Regulatory Guide 1.200 [17] states that full understanding of the uncertainties and their impact is needed and notice the following, "In understanding the base PRA result, an important aspect is to know the sources of uncertainty, assumptions and understanding of their potential impact. Uncertainties can be parameter, model or assumptions. The assumptions can be related either to PRA scope and level of detail or to model uncertainties. The impact of parameter uncertainties is gained through the actual quantification process. The PRA scope assumption and level of detail is inherent in the structure of the PRA model and requirement of the applications will determine whether they are acceptable or not. The impact of model uncertainties and related assumptions can be evaluated qualitatively or quantitatively. The sources of model uncertainty and related assumptions are characterized in terms of how they affect the base PRA model."

The GO-FLOW handles the parameter value uncertainty. The distribution of a system-failure probability is calculated by combining values selected by sampling from the probability for all the basic events. The analysis procedure consists of two steps. First, the minimal cut sets (MCS) are obtained for specific signal lines. The GO-FLOW is a success-oriented system-analysis technique. System states expressed in success probability are converted into the expression for the failure probability, and the MCSs are obtained. Next, the distributions of failure probabilities are assigned for the basic events in the MCSs and the distribution of a system-failure probability is obtained with the MC simulation. One of the following distributions can be assigned to the basic events, normal distributions, log-normal distribution, homogeneous, log-homogeneous, Gamma, binomial, Weibull, beta and histogram distributions.

As the analysis results, the followings are obtained; the values of median, mean, error factor, 5% and 90% ranges of uncertainty, cumulative probability distribution and probability density distributions. The time variation of uncertainty distribution is easily obtained [18]. The uncertainty analysis is made by Elevator Safety Analysis Tool (ELSAT) framework and detail explanations of all analysis steps are described in reference 18.

3. Risk-monitor system

3.1. Definition of risk monitor

The word "risk monitor" traditionally used in nuclear application has been a specific application of a

Living PSA [19] as a real-time analysis tool used to estimate the point-in-time “risk of core melts accident”. Wherein, the real-time analysis is based on the actual plant configuration defined in terms of power operation or one of the shutdown modes, the components that have been removed from service, the choice of running and standby trains for normally operating systems and setting the environmental factors.

The term risk monitor has been defined by International Atomic Energy Agency [20] as “a plant specific real-time analysis tool used to determine the instantaneous risk based on the actual status of the systems and components”. At any given time, the risk monitor reflects the current plant configuration in terms of the known status of the various systems and/or components. The Risk-Monitor model is based on, and is consistent with, the Living PSA. It is updated with the same frequency as the Living PSA. The risk monitor is used by the plant staff in support of operational decisions. The authors’ proposed concept of the new risk-monitor system [7], which is basically the same as the above definition of risk monitor, but the distinction lies in the definition of “risk”. The range of risk is not limited in core-damage accident but includes all kinds of dangerous states brought by severe accident. Accordingly, the configuration of the authors’ risk monitor system should be different from the traditional living PSA tools as to the way of how to organize the risk monitor and how to display the risk on the human interface. The risk-monitor system was discussed from four aspects: (i) design principle of nuclear safety to realize defense-in-depth concept, (ii) definition of risk and risk to be monitored, (iii) severe accident phenomena and (iv) scheme of risk ranking. The basic features of the authors’ risk-monitor systems which are described in the reference 7 are (i) definition of risk and risk ranking, (ii) anatomy of fault event occurrence, (iii) risk monitor by semiotic modeling, (iv) plant DiD risk monitor and reliability monitor, and (v) visualization as the dynamic risk monitor.

3.2. Definition of reliability monitor [21]

Reliability Monitor is assumed to provide an overview on the system’s stability and the related information in detail when any initiating event happens in the plant that may impact the stability of a system’s operation. The Reliability Monitor will calculate certain kind of “Stability Index” which shows the System Stability Measure (i.e. Reliability) over the assumed run time of the system. An important role of the Reliability Monitor of nuclear power plant is monitoring the operating performance of individual subsystems comprising the whole system and evaluates the “Reliability” of the subsystems. By monitoring the “Reliability” of individual subsystems, operator can gain insight on potential performance bottlenecks and establish baseline performance values. These baseline values can be used to assess the effectiveness of performance tuning and hard-

ware upgrades. Monitoring reliability helps us to find the problems before they cause loss of service. The reliability monitor in the risk-monitor system gives the qualitative evaluation by the way similar to Failure Mode and Effect Analysis [22] together with the quantitative reliability evaluation by the GO-FLOW method. The conditions setting to reliability monitors are (i) target subsystem, (ii) plant operation conditions and mode, (iii) types of accident initiators, (iv) common cause factors, (v) failure mechanism to be considered, (vi) failure data, etc [7]

4. Descriptions of PWR containment spray system

4.1. Function of PWR containment spray system

The configuration of the PWR containment spray system (CSS) employed is illustrated in **Figure 1**. CSS has the function to decrease the containment pressure during the loss of coolant accidents (LOCA) to attain the design pressure of the containment vessel (atmospheric pressure). The pressure transient during LOCA is analyzed for the maximum blow down energy of the reactor coolant system at the same time. CSS traps radioactive inorganic iodine to wash down into the containment sump by spraying the borated cooling water. Sodium hydroxide (NaOH) solution of about 30% concentration is added from spray additive tank (SAT). The CSS is designed to have redundancy according to single failure criteria. During the LOCA, if there is no offsite power, then the necessary electric power is supplied by diesel generators, and it can perform the specified safety function. In the CSS; there is a test line which is designed to allow periodical tests and inspections to verify the operability and integrity depending on the importance of safety [23].

As shown in Figure 1, CSS consist of containment spray pump (CSP), containment heat exchangers (CSHEX), refueling water storage tank (RWST), SAT, containment recirculation sump (CRS), etc. CSHEXs are cooled by component of cooling water system (CCWS). RWST is designed to provide the borated water which is pressurized with nitrogen. The redundant spray Pumps and Heat Exchangers of 100% capacity are installed. The NaOH solution makes water slightly alkali to enhance absorption of radioactive iodine and to prevent corrosion of the vessel during long-term cooling after the accident. It can minimize the transpiration of radioactive iodine from the recirculation sump water. When the containment pressure is increased during the LOCA then containment high-pressure signal is actuated and transmitted to CSS, CSHEXs outlet valve is opened, CSP is started, SAT injection valve is opened and the borated cooling water in RWST is sprayed into the containment vessel through the Spray nozzles attached on the spray headers (injection mode; phase 1).

When the water level in RWST becomes low until a certain value, then the water source is switched to the CRS, and after cooling the recirculation water by

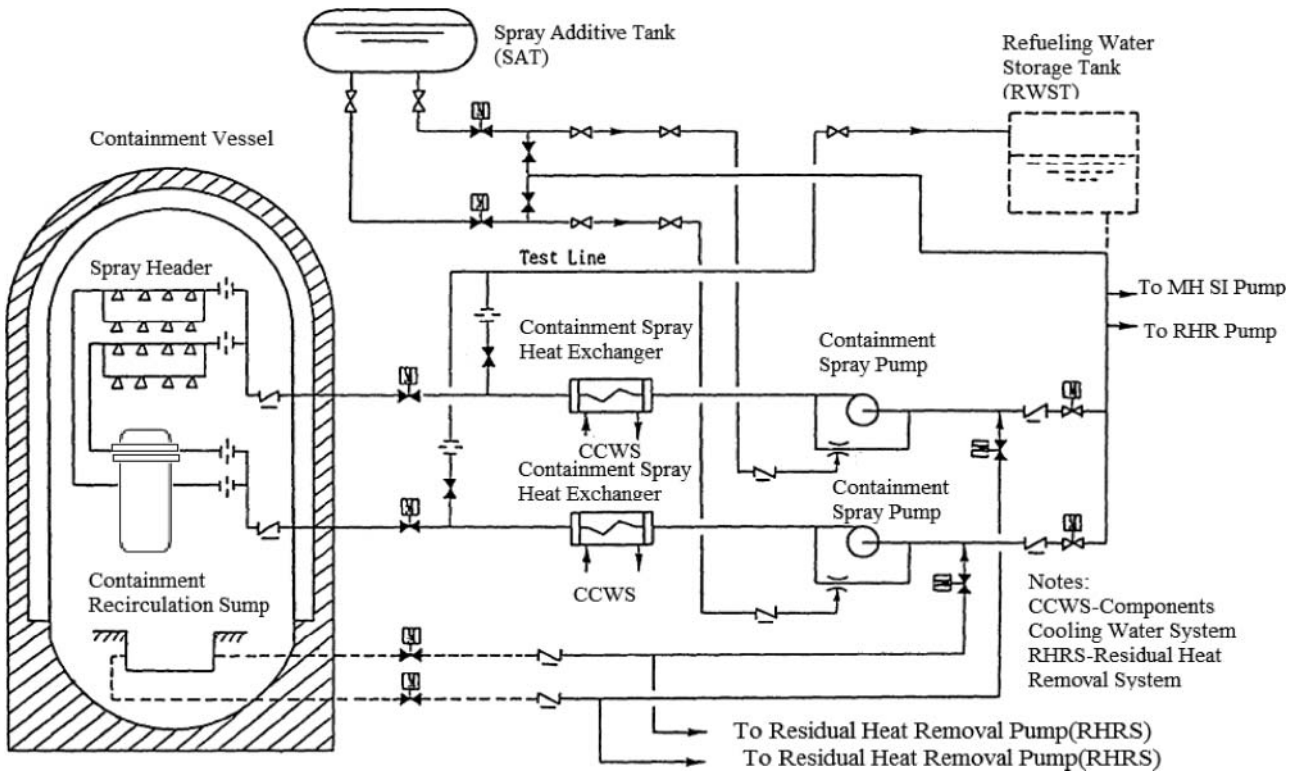


Figure 1. CSS of PWR plant [23].

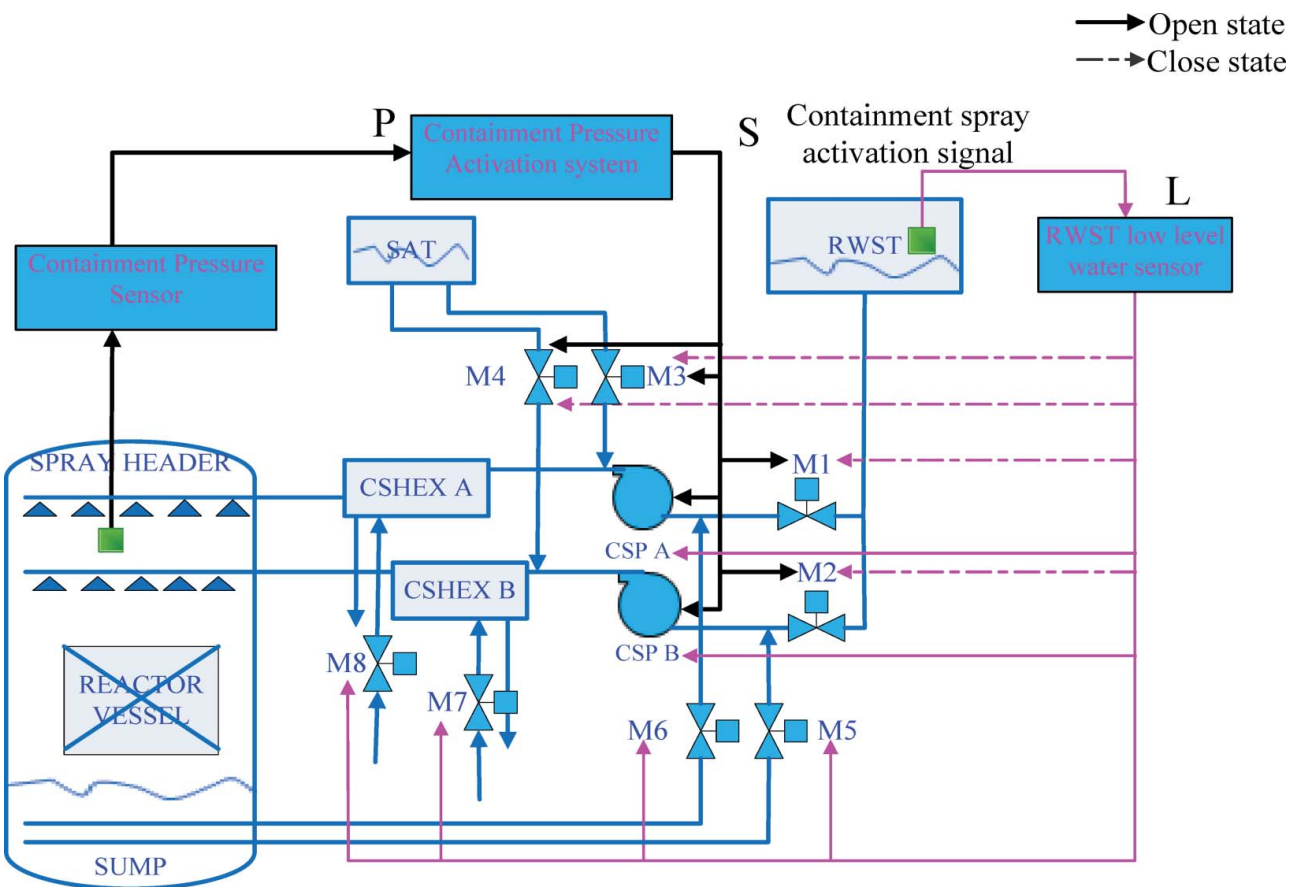


Figure 2. CSS in case of two lines running simultaneously.

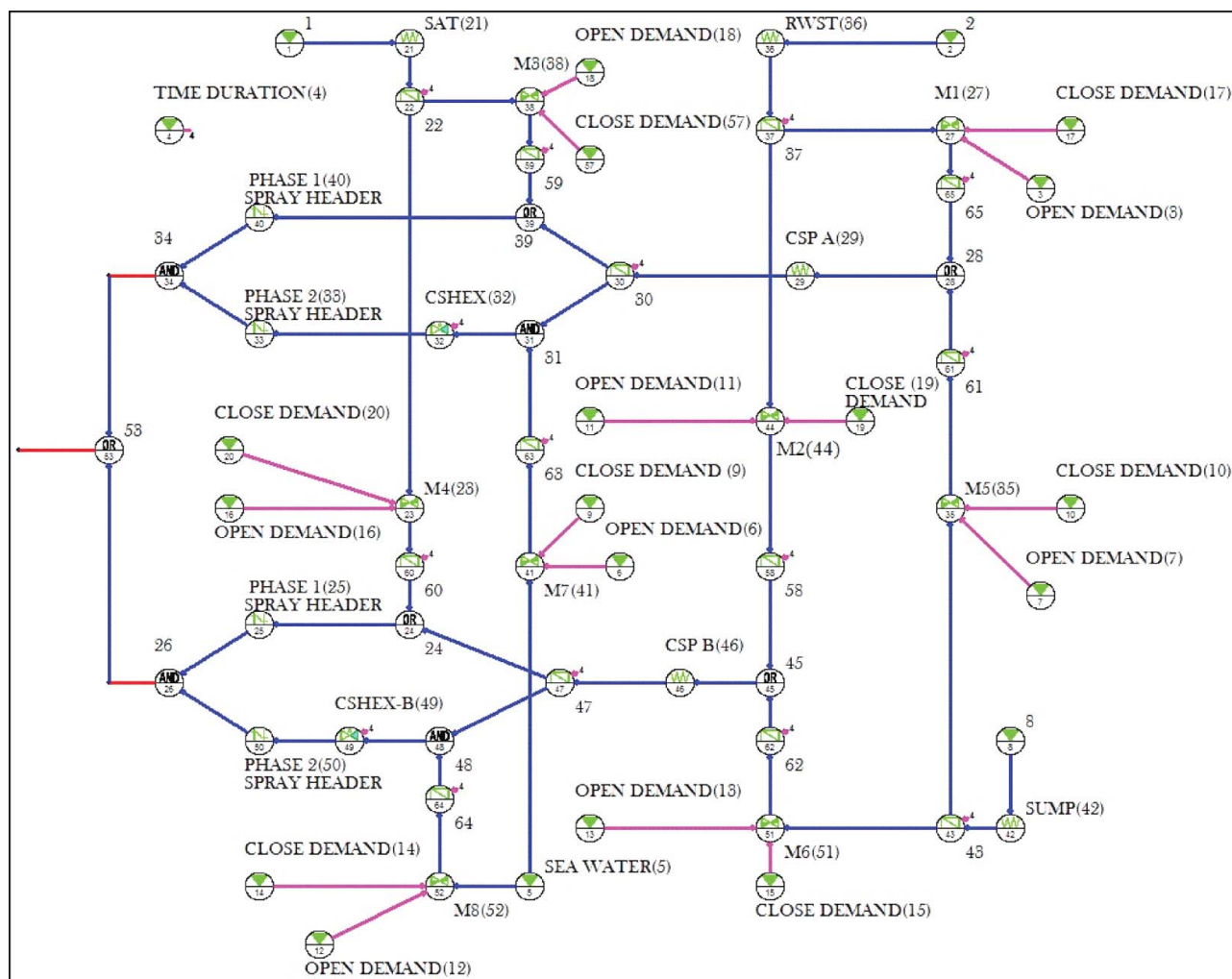


Figure 3. GO-FLOW chart in case of two lines running simultaneously.

CSHEXs, the water will be sprayed into the containment vessel (recirculation mode; phase 2) [23].

In the case of LOCA, time span of first phase is 0–1800 seconds and that for second phase is 1800–3600 seconds for GO-FLOW analysis. The value of time is taken on assumption base and it may be vary for different PWR plants. For Conventional four loop PWR, the time point 1800 second for shifting from phase 1 to 2 is taken by an engineering judgment that water's storage should be large enough to cover the needed time for continuous injection of water by both emergency core cooling system and containment spray for the large-break LOCA in the cold leg.

4.2. GO-FLOW modeling for the case of two parallel lines

In the real configuration of CSS, two parallel injection lines are assumed to run simultaneously as shown in Figure 1 and these two lines are expressed in a GO-FLOW model in Figure 2. In the GO-FLOW model

of CSS, test line is neglected because the test line can be used for periodical test and inspection to verify the operability and integrity of NPP during normal operation of Plant. CSHEXs secondary side is cooled by CCWS, but it is also neglected. The redundancy system of two lines enhances the reliability and can wash the radioactive material in containment more quickly as compared to single line and also reduced the containment pressure to atmospheric pressure. In the two lines containment spray model for GO-FLOW analysis, the following safety components have been considered such as, two CSP pumps and two heat exchangers and eight motor-operated valves, each valve corresponding to each line. The abbreviations used in the GO-FLOW model of the CSS are as follows, RWST stands for refueling water storage tank, SAT; CSHEX containment sprays heat exchanger, CRS and M1–M8 are motor-operated valves. RWST, SAT, CSHEX and CRS are passive components, which have no need of any power source for actuation.

CSP is active one, which needs a source for actuation, and it should be operated in both phases. However, the motor-operated valves from M1 to M8 are active ones, which have open and close state. In the control system of CSS, P is containment pressure activation system, S is containment spray activation signal and L is a low-level water signal of RWST. During the LOCA, M1–M4 are opened and CSP A and B are operated on the receipt of high-containment pressure signal (injection phase) and M5–M8 are opened and CSP A and B are operated on the receipt of low-level water signal of RWST (re-circulation phase). In the control system, solid and dotted arrows represent the open and close state of components, respectively, in respective phase.

4.3. GO-FLOW calculation for containment spray system

The GO-FLOW chart of two parallel lines is shown in **Figure 3** and reliability data assigned in the GO-FLOW analysis is given in **Table 1**.

In GO-FLOW chart, the final signals are 26, 34 and 53 are output signals, and these output signals give the output that is failure probability of the required system mission.

In Table 1,

- Pg = Probability for successful operation
- Pp = Probability for premature operation
- Po = Probability for valve successfully open
- Pc = Probability for valve successfully close
- λ_o = Failure rate for open state
- λ_c = Failure rate for close state

In the GO-FLOW chart, there are two phases (injection phase and recirculation phase).

For phase 1, RWST, SAT, CSP A and B, and M1–M4 are needed and for phase two, RCS, CSHEX A and B, CSP A and B and four motor operated valves from M5 to M8 are needed. The operation of these components

used in the case of two parallel lines redundancy system is also given in Table 1.

The analysis results are shown in the **Figure 4**, where failure probability curve versus real time is drawn. The failure probability of CSS is very small in phase 1 and it step wisely increases at the beginning of phase 2 because of the failure of some safety components. This dynamical reliability of CSS is not final evaluation; therefore, further study has been conducted by considering the uncertainty analysis with sensitivity analysis to get the most reliable and realistic result. In Section 5, authors have discussed the uncertainty analysis with sensitivity analysis by GO-FLOW to evaluate the dynamical reliability.

5. Uncertainty analysis of PWR containment spray system by GO-FLOW

5.1. Sensitivity calculation to prioritize several important parameters to the dynamic reliability

The sensitivity analysis is a technique used to determine the appropriate values assign to the numerical item in the model and how these values of an independent variable will impact a particular dependent variable in a given set of assumptions. It is applied in reliability evaluation study how sensitive the reliability is with respect to changes in input parameters or model assumption of the system model. If the portion change in the model output (result) is large compared to the change in input, we say that the system is sensitive to the input element that was changed. A sensitivity studies identify the important epistemic uncertainties, and quantification of the latter. In a risk-informed environment, the proper role of sensitivity studies is “to identify what is important to the results, not to replace uncertainty analyses” [17].

In this study, sensitivity analysis has been made by GO-FLOW methodology for the calculation to prioritize the several important parameters to the dynamic

Table 1. Failure rate used in the present analysis [23,24].

Components	Kind	Success probability or failure rate	Phase 1	Phase 2
RWST	Passive	$P_g = 0.999999, \lambda_o = 1 \times 10^{-5}/\text{second}$	On	Off
SAT	Passive	$P_g = 0.99, \lambda_o = 1 \times 10^{-5}/\text{second}$	On	Off
CRS	Passive	$P_g = 0.999999, \lambda_o = 1 \times 10^{-5}/\text{second}$	Off	On
CSHEX	Passive	$\lambda_o = 1 \times 10^{-8}/\text{second}$	Off	On
CSP	Active	$P_g = 0.99, \lambda_o = 1 \times 10^{-5}/\text{second}$	On	On
M1, M2, M3, M4	Active (open and close action)	$P_o = 0.96/\text{demand}, P_c = 1.0/\text{demand}, P_p = 0.96, \lambda_o = 1 \times 10^{-8}/\text{second}, \lambda_c = 1 \times 10^{-8}/\text{second}$	Open	Closed
M5, M6, M7, M8	Active (open and close action)	$P_o = 0.96/\text{demand}, P_c = 0.96/\text{demand}, P_p = 0.0, \lambda_o = 1 \times 10^{-8}/\text{second}, \lambda_c = 1 \times 10^{-8}/\text{second}$	Closed	Open

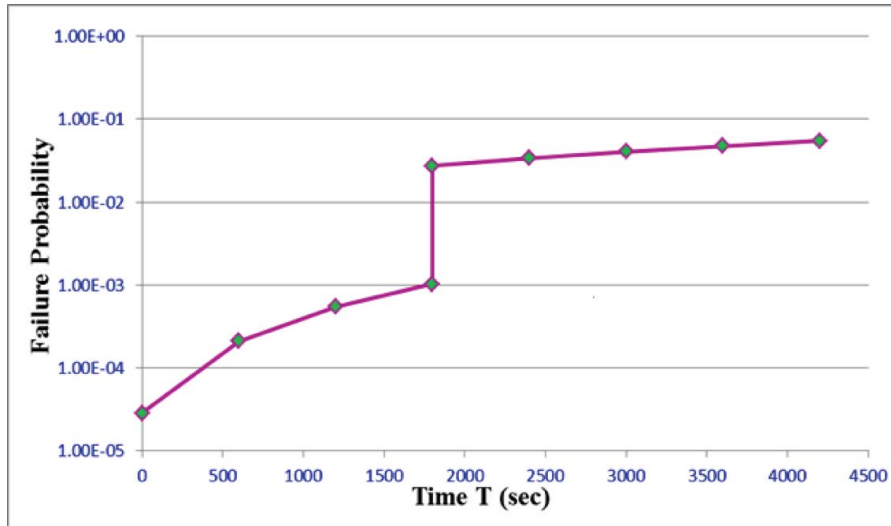


Figure 4. Failure probability of CSS (point-estimated values).

reliability of the CSS. In GO-FLOW analysis, 10 time points are defined and signal 53 represents the success probability of system mission as shown in Figure 4. For sensitivity analysis, the results have been considered at time point 5 and 10 as the representative cases for phases 1 and 2, respectively.

The most significance terms at time point 5 (phase 1) and 10 (phase 2) are given in the following first and second lists respectively in which they are expressed in failure probabilities.

The first list means, for example, the term is the products of signals of 86 and 90, and failure probability 0.00049346 contributes to the total system mission failure probability at time point 5.

According to the first list, the largest contributions to system failure probability are produced by 86, 90, 108, 91, 104 and 87 signals. These signals are internally

For phase 1 (time point 5):
First list.

86	90		0.00049346
86	108	91	0.00002857
104	90	87	0.00004430
104	90	88	0.00001107

For phase 2 (time point 10):
Second list.

81		0.04113118
99	82	0.00160184
99	92	0.00160346
109	92	0.00160507
109	82	0.00160346

generated numbers and can be identified by output list of GO-FLOW analysis program. It is also possible to

Table 2. Main contribution for phase 1.

Important contribution (operator number)	Upstream (operator number)	Largest failures (operator number and failure probability)	Main contribution (operator number)
37	36	37 = 0.018	37
22	21	21 = 0.01, 22 = 0.018	21, 22
59	38, 22, 21	38 = 0.04, 22 = 0.018	22, 38
60	23, 22, 21	23 = 0.04, 22 = 0.018	22, 23
65	27, 37, 36	27 = 0.04, 37 = 0.018	27, 37
58	44, 37, 36	44 = 0.04, 37 = 0.018	44, 37

Table 3. Main contribution for phase 2.

Important contribution (operator number)	Upstream (operator number)	Largest failures (operator number and failure probability)	Main contribution (operator number)
43	42	43 = 0.036	43
33	32, 63, 41, 30, 29	30 = 0.036, 41 = 0.04	30, 41
50	49, 64, 52, 47, 46,	47 = 0.036, 52 = 0.04	47, 52
61	35, 43, 42	35 = 0.04, 43 = 0.036	35, 43
62	51, 43, 42	51 = 0.04, 43 = 0.036	51, 43

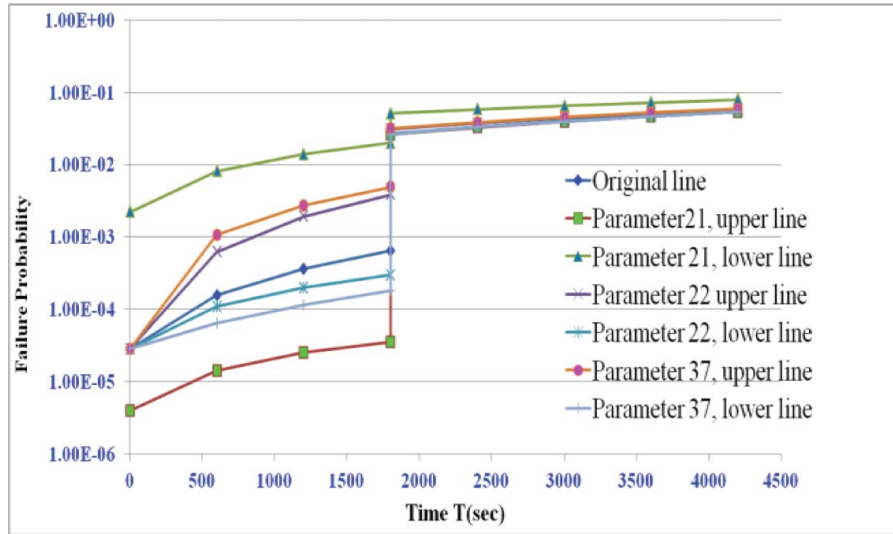


Figure 5. Most sensitive parameter in phase 1.

identify that signal 108 is successively produced from operators 103, 39 and 59 from the GO-FLOW chart structure and output list. The following correspondences are found out.

86	<—	37
90	<—	22
108	<—	59
91	<—	60
104	<—	65
87	<—	58

Thus, the important contribution to the failure for phase 1 is produced by operators 22, 37, 58, 59,

60 and 65. Then, it also necessary to pick up main contributors among the upstream operators connected each important contributor. The results for phase 1 are given in **Table 2**.

But the operators 23, 27, 38 and 44 are all type 39 operators and have the successful close probability $P_c = 1.0/\text{demand}$ at time point 6 (100% success for close demand), therefore, they can be omitted in sensitivity analysis. Similar results can be obtained for phase 2 as shown in **Table 3**.

The all main contributions (operators) have been considered for sensitivity analysis because they all have a great impact on the results of failure probability.

Hence, input with high sensitivity should be further investigated with uncertainty analysis. Parameters with

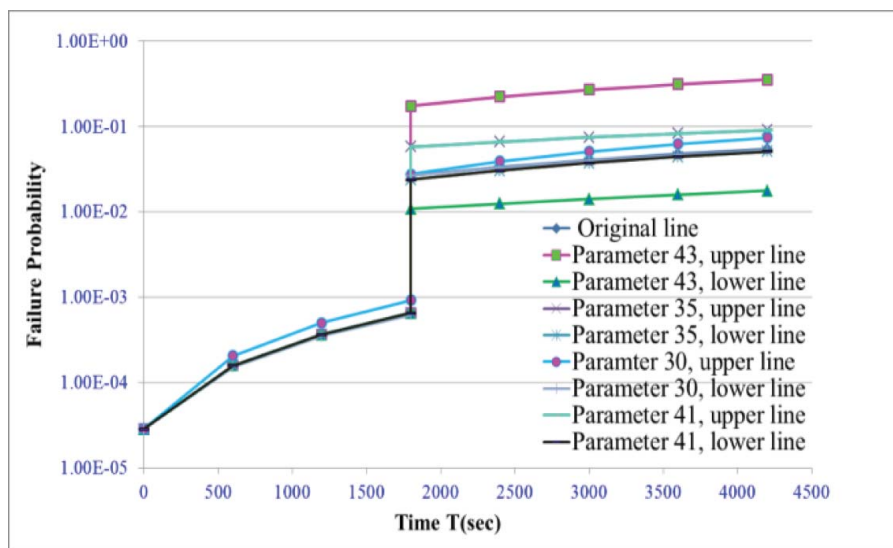


Figure 6. Most sensitive parameter in phase 2.

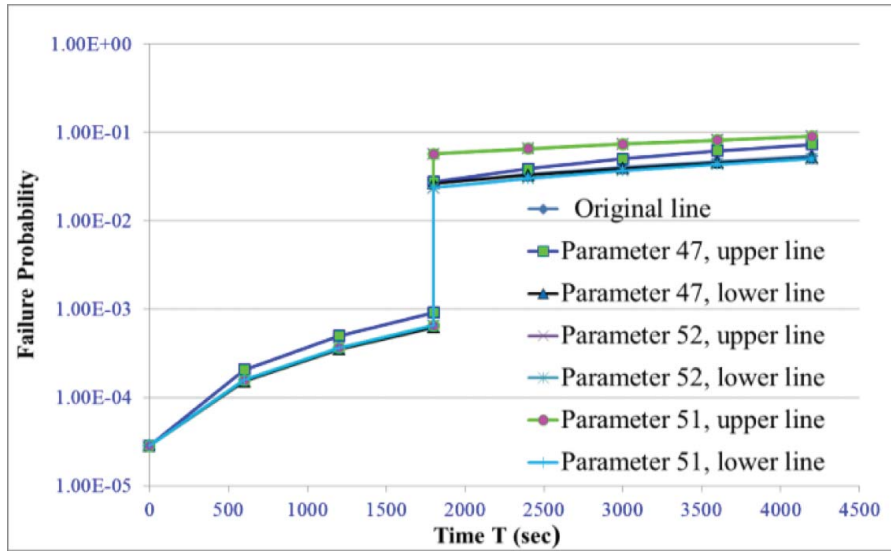


Figure 7. Most sensitive parameter in phase 2.

low sensitivity, on the other hand, should not be dedicated resources for further analysis since their impacts on the results are not of a significant order.

From above description of sensitivity analysis, the important operators in phases 1 and 2 which have a great impact on the results are 21, 22, 30, 35, 37, 41, 47, 51 and 52. For checking their impact on failure-probability results, analysis has been made by GO-FLOW methodology by changing the failure values 10 times larger and 1/10 smaller than the original one. The impact of parameter value change for operators 21, 22 and 37 on system-failure probability in phase 1 is shown in **Figure 5**. Operator 21 is two states operator with successful probability $P_g = 0.99$ which represent the SAT.

So if we increase successful probability P_g , 10 times large then results of system-failure probability will decrease and will increase by decreasing the successful probability 1/10 times smaller than original one. Therefore, its upper and lower lines are different from the other operators. But have large impact on the system-failure-probability results.

Similarly, the impact of parameter value change for operators 30, 35, 41, 43, 47, 51 and 52 on system-failure probability in phase 2 is shown in **Figures 6 and 7**.

From the results of sensitivity analysis as shown in Figures 5–7, there are two lines for each parameter, the upper line drawn by the failure value 10 times larger than original one and lower line drawn by the failure value

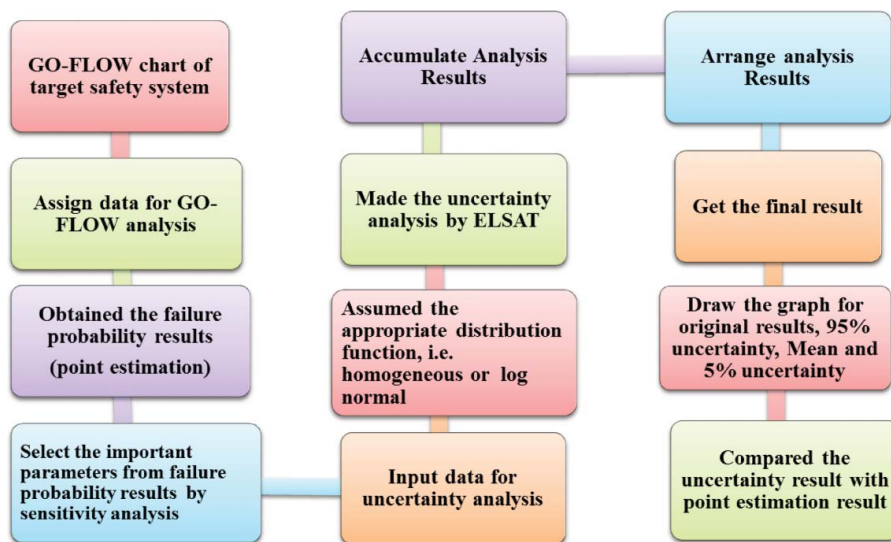


Figure 8. Block diagram of uncertainty analysis procedure by GO-FLOW methodology.

オペレータタイプ	信号線番号	V1	V2	V3	分布型	分布パラメータ 1	分布パラメータ 2	分布パラメータ 3	ヒストグラム ファイル
21	16	0.99	0	0	一様分布	0.93	0.997		
21	28	0.99	0	0	一様分布	0.93	0.997		
21	53	0.99	0	0	一様分布	0.93	0.997		
21	23	0.999999	0	0	点推定				
21	39	0.999999	0	0	点推定				
26	35	0	0.96	0	一様分布	0.93	0.99		
26	37	0	0.96	0	一様分布	0.93	0.99		
26	48	0	0.96	0	一様分布	0.93	0.99		
26	50	0	0.96	0	一様分布	0.93	0.99		
27	18	0.04	1	0.96	点推定				
27	25	0.04	1	0.96	点推定				
27	55	0.04	1	0.96	点推定				
27	57	0.04	1	0.96	点推定				
35	19	1E-08	0	0	点推定				
35	26	1E-08	0	0	点推定				
35	36	1E-08	0	0	点推定				
35	38	1E-08	0	0	点推定				

(a)

オペレータタイプ	信号線番号	V1	V2	V3	分布型	分布パラメータ 1	分布パラメータ 2	分布パラメータ 3	ヒストグラム ファイル
35	19	1E-08	0	0	点推定				
35	26	1E-08	0	0	点推定				
35	36	1E-08	0	0	点推定				
35	38	1E-08	0	0	点推定				
35	49	1E-08	0	0	点推定				
35	51	1E-08	0	0	点推定				
35	56	1E-08	0	0	点推定				
35	58	1E-08	0	0	点推定				
35	17	1E-05	0	0	対数正規分布	0.00001	10		
35	24	1E-05	0	0	対数正規分布	0.00001	10		
35	29	1E-05	0	0	対数正規分布	0.00001	10		
35	40	1E-05	0	0	対数正規分布	0.00001	10		
35	43	1E-05	0	0	対数正規分布	0.00001	10		
37	31	1E-08	0	0	点推定				
37	45	1E-08	0	0	点推定				
40	21	2	5	0	点推定				
40	41	2	5	0	点推定				

(b)

Figure 9. (a) Uncertainty analysis results for CSS (homogeneous and range). (b) Uncertainty analysis results for CSS (log-normal distribution, median and error factor).

1/10 times smaller than original one. From Figure 5, we can figure out which of the parameters affect the system-failure probability more than the other one. So the more accurate estimates can be obtained for the most impor-

tant one. In the case of phase 1, the parameter 21, is most sensitive. Similarly, from Figures 6 and 7 the parameter 43 is most sensitive in phase 2 than the others. Thus, the sensitivity analyses can, therefore, be used as a tool for

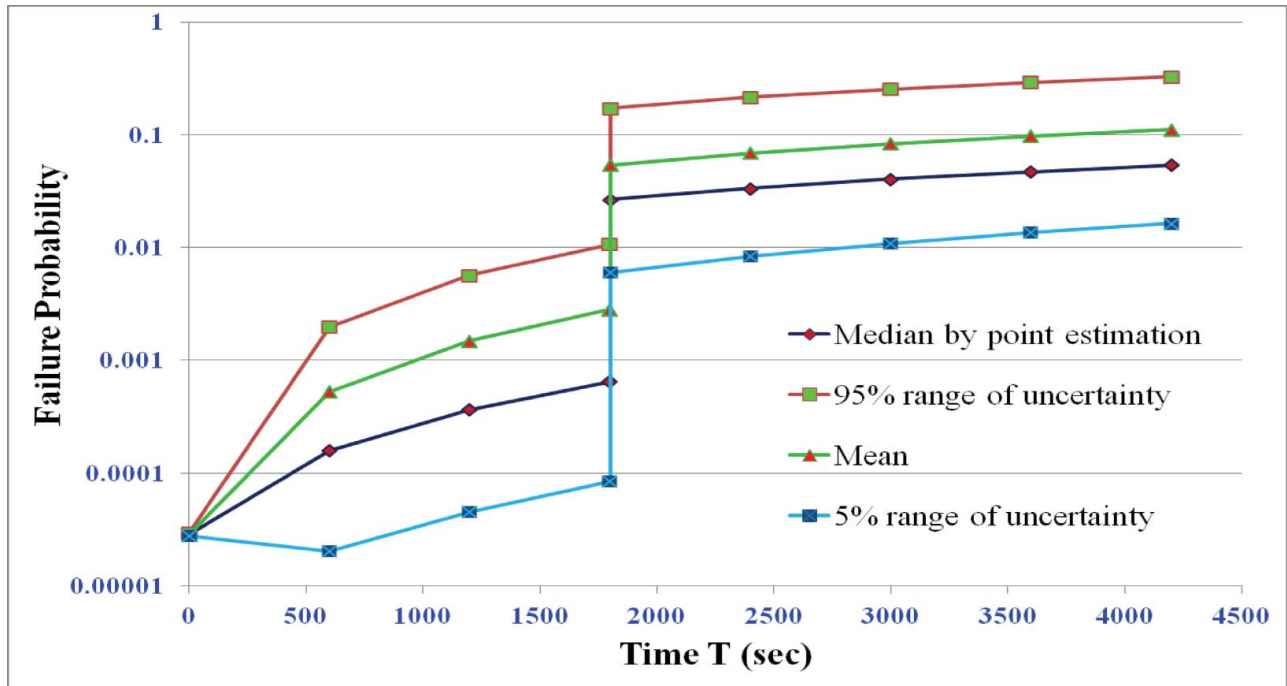


Figure 10. Uncertainty analysis results.

identification of important parameters, which are more effective on the calculation of a reliability assessment. A sensitivity analysis can also be performed for measuring the effects of completeness uncertainty by including or excluding possible relevant elements like failure modes and then evaluate if they are significant for the results or not.

5.2. Uncertainty analysis for the selected important parameters for dynamical reliability

A task of uncertainty analysis is to determine the uncertainty features of the system outputs as a function of uncertainties in the system model itself, and the stochastic variables involved [25]. The uncertainty analysis investigates the uncertainty of vari-

ables that are used in decision-making problems. It makes a technical contribution to decision-making through the quantification of uncertainties in the relevant variables [26]. The procedure for the treating the uncertainty analysis by GO-FLOW methodology are given by following steps [1] and block diagram is shown in **Figure 8**. MC method is applied to the uncertainty analysis. MC method is a useful tool for evaluating the effect of different design on system performance [26]:

- (1) Construct the GO-FLOW chart according to the structure and function of the target safety system.
- (2) Assign failure rates or probabilities to the all components according to their function and failure mechanism.

Table 4. Results of uncertainty analysis of PWR CSS.

Time	Median by point estimated	95th percentile	Mean	5th percentile	Standard deviation
0	0	0	0	0	0
0.1	2.8498E-05	0.0000294	0.000028	0.0000277	5.22E-7
600	0.000158	0.00197	0.000526	2.03E-05	0.00128
1200	0.000365	0.00564	0.00148	4.54E-05	0.00408
1800	0.000648	0.0107	0.00282	8.46E-05	0.00784
1800.1	0.026659	0.172	0.054	0.00601	0.073
2400	0.033484	0.215	0.069	0.00836	0.0887
3000	0.04031	0.255	0.0835	0.0109	0.101
3600	0.047139	0.292	0.0974	0.0136	1.15E-01
4200	0.05397	0.327	0.111	0.0164	1.26E-01

	A	B	C	D	E	F	G	H	I	J	K	L	M
1192													
1193	SIGNAL NUMBER= 54, TIME POINT= 5												
1194													
1195													
1196	LOG SCALE : PROBABILITY DENSITY.												
1197	% -----												
1198	1.00E-05	0.0											
1199	1.43E-05	0.0											
1200	2.03E-05	0.0											
1201	2.89E-05	0.0											
1202	4.12E-05	0.0											
1203	5.88E-05	0.4	***										
1204	8.38E-05	1.2	*****										
1205	1.19E-04	2.8	*****										
1206	1.70E-04	5.5	*****										
1207	2.42E-04	7.4	*****										
1208	3.46E-04	8.4	*****										
1209	4.92E-04	10.5	*****										
1210	7.02E-04	11.2	*****										
1211	1.00E-03	D 10.2	*****										
1212	1.43E-03	9.3	*****										
1213	2.03E-03	8.4	*****										
1214	2.89E-03	E 7.5	*****										
1215	4.12E-03	5.4	*****										
1216	5.88E-03	3.7	*****										
1217	8.38E-03	3.0	*****										
1218	1.19E-02	* 2.1	*****										
1219	1.70E-02	1.0	*****										
1220	2.42E-02	0.7	*****										
1221	3.46E-02	0.6	*****										
1222	4.92E-02	0.2	**										
1223	7.02E-02	0.2	*										
1224	1.00E-01	0.2	*										

Figure 11. Result of uncertainty analysis (probability density distribution).

- (3) Obtain the system unavailability which takes into account only Median by Point estimation.
- (4) Select the important parameters by sensitivity analysis from the GO-FLOW chart structure and unavailability analysis result.
- (5) Assume the appropriate distribution functions to select the important parameters by selecting one of these distributions such as, the normal, log-normal, homogeneous, log homogeneous, gamma, binomial, Weibull, beta and histogram distributions.
- (6) Made the uncertainty analysis by ELSAT.
- (7) Arrange the analysis results.

ELSAT is an integrated and convenient analysis framework in which figures of analysis results are automatically obtained if the analysis conditions are given in advance as input data [18]. In the uncertainty analysis of the PWR CSS, the twelve operators 21, 29, 46, 35, 41, 51, 52, 22, 37, 30, 43, and 47 are selected from the GO-FLOW chart because these operators have relatively large failure rate or failure probability. They are main contribution operators identified in Section 5.1 and additional two operators 29 and 46.

Input data consist of types of failure distribution and values of distribution parameters for uncertainty analysis. The uncertainty analyses with data for PWR CSS are given in **Figure 9(a)** and (b), where homogeneous

distribution and ranges of uncertainty are presented in **Figure 9(a)** and log-normal distribution, median and error factors in **Figure 9(b)**. The homogeneous distribution was assigned both for the failure of SAT, CSPs; A and B and four motor operated valves M5–M8 failure in open and close action. Log normal distribution was selected for others components 22, 37, 30, 43 and 47. The range of uncertainty of operators 21, 29 and 46 (0.93–0.997) is different from range of uncertainty of operator 35, 41, 51 and 52 (0.93–0.99) because these operators have different probability for successful operation P_g such as the value of $P_g = 0.99$ for 21, 29 and 46 whereas for operators 35, 41, 51 and 52 is 0.96 [1,24,25].

Simulation generates random numbers from probability distributions. It is, therefore, important to run the model a sufficient number of times for achieving convergence and thus stable results. The method used sample data from MC simulation to quantify uncertainty in terms of appropriate estimates for the mean and standard deviation plus some informative quantiles (5%, 50% and 95%). The 3000 numbers of iterations have been set in the analysis.

5.3. Discussion on the uncertainty analysis result

The uncertainty analysis results consist of “cumulative probability distribution, probability density distributions, mean, standard deviation and variance” and some informative quantiles (e.g. the 5%, 50% and 95%

quantiles) are derived and they are used as uncertainty quantification.

The uncertainty results for PWR containment spray given **Table 4** are described by “Median by point estimated (results of the standard cases), mean, standard deviation, 95th percentile and 5th percentile range of the uncertainties (informative quantiles)” and these results are presented in **Figure 10**.

The most complete and ideal description of uncertainty is the probability density distribution of the quantity subject to uncertainty, which is shown in **Figure 11**. By comparing the results of uncertainty analysis with point estimate results by GO-FLOW, it shows that the uncertainty analysis is an important part of practical evaluation of the system dynamic reliability where the results of system reliability are presented in the form of mean and informative quantiles (5%, 50% and 95%). This analysis makes the reliability prediction more practical compared with the result without the uncertainty analysis. The results provide the valuable risk information to the operators for decision making to ensure the safe operation of nuclear power plant. This information might be useful for the reliability monitor to evaluate the risk in NPP. GO-FLOW methodology can be employed for uncertainty analysis with its advance functions.

A measure of individual uncertainty is illustrated by the difference between the median and 5th percentile or 95th percentile estimates. Lack of data cause statistical uncertainties in the estimated parameters and reliability model often use assumptions to overcome data shortcomings. Differences in plant specific conditions like operational environment, maintenance procedures, collection methods and rapidly changing technology may result in a data material which will not be relevant for the specific system under evaluation. Therefore, competence is thus needed in order to reduce data uncertainty by ensuring good collection methods and selection of relevant data for the assessment. Model uncertainty reflects the inability of a model or design technique to represent precisely the system’s true physical behavior. Therefore, the level of detail or suitability of a model also restricted by the time, approximation formulas and software solutions available.

The uncertainty related to analysis conditions may be due to omission of factor, like failure modes, failure mechanisms or lack of knowledge, like the exclusion of unknown failure modes. Unknown uncertainties are hard to reduce because they are not visible for the analyst. Further, improvement in the analysis results can be achieved through research, data collection and careful manufacturing.

6. Concluding remarks

In this paper, uncertainty analysis with sensitivity analysis has been conducted in evaluating the reliability of safety-related subsystem by GO-FLOW alternatively to FTA and ET because GO-FLOW is success-

oriented analysis technique and comparatively easy to conduct reliability analysis. Reliability monitor of the PWR CSS has been taken as an example of the safety-related sub-system for analysis in the risk monitor system.

Sensitivity analyses can provide useful information on those input uncertainties of a PSA which mostly contribute to the uncertainty of output reliability. Thus, they can indicate for which input uncertainties it would be most effective to improve the state of knowledge in order to reduce the uncertainty of the reliability. The sensitivity analysis presented in this paper has been made by GO-FLOW method and method used sample data from MC simulation to quantify uncertainty in terms of appropriate estimates for analysis results. The present paper shows the uncertainty analysis conducted for PWR safety system and the results of uncertainty analysis show that uncertainty analysis is an important part for the practical and more accurate evaluation of the system dynamic reliability where the results of system reliability (points estimation) are presented in the form of mean, and informative quantiles (5%, 50% and 95%). This analysis makes the reliability prediction more practical compared with the result without the uncertainty analysis and are valuable to develop the reliability monitor for CSS in the new concept of risk-monitor system. This can be able to measure the value of risk in NPP at accident. These results provide the risk information to the operators for decision making to ensure the safe operation of nuclear power plant. The improvement in reliability results can be achieved through research, collection and classification of failure data and careful manufacturing for further study.

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