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# A case study of time-dependent risk informed integrated safety assessment under complex accident sequences



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#### ARTICLE INFO

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### ABSTRACT

A time-dependent risk informed integrated safety assessment methodology is suggested to evaluate the response of nuclear power plants under complex accident sequences caused by failures of multiple safety features. Event propagation is modeled based on the combination of deterministic and probabilistic safety assessment methods, with results representing changes in plant risk over time. Operators can utilize the time-dependent risk information as a quantitative basis, and results can determine the degree of safety enhancement by the improvement of emergency operator action procedures or by strengthening the design of safety features. The concepts of consequential failure probability and point-estimate failure time are introduced. The consequential failure probability, calculated from central limit theorem, identifies the key safety system and provides a precise risk calculation. The point-estimate failure time, using non-parametric order statistics, justifies the crediting of emergency operator actions. As a case study, risk of large early radioactive release due to pressure-induced multiple steam generator tube rupture following main steam line break accident in Advanced Power Reactor 1400 is considered. Results are used to discuss the credibility of operator mitigation actions, and a remedy to enhance plant safety to satisfy safety goals is suggested.

# 1. Introduction

## 1.1. Research background

Traditionally, the design basis states of nuclear power plants (NPPs) are classified into operational states (i.e., normal operation, anticipated operational occurrences) and design basis accidents (DBAs). Design basis accidents are composed of a set of accidents categorized by expected occurrence frequency and consequences. The purpose of DBA analysis is to ensure the safety of NPPs by assessing the performance of the safety systems, the applicability of design and operating parameters, and the validity of technical specifications.

In a historical view, there have been three occurrences of beyond design basis accidents (BDBAs): Three Mile Island in 1979, Chernobyl in 1986, and Fukushima in 2011. The term BDBAs is used for accidents that are not included in DBAs and not fully considered in design and operation; their occurrence is judged to be highly improbable. However, following the Fukushima Daiichi accident, global safety analysis methods have been evolving to cope with BDBAs. As part of this effort, the International Atomic Energy Agency (IAEA) has

established a new NPP state called design extension conditions (DEC) (IAEA, No. SSR-2/1, 2012).

The main purpose of the introduction of DEC was to further improve the safety of NPPs by actively including BDBAs in design basis states and operation. The goals of safety analysis under DEC are to identify additional threats that may potentially lead to severe conditions, to prevent the occurrence of these threats, and to mitigate the consequences. Compared to safety assessment for DBAs though, which assume a single initiating event with a single failure of safety features, challenges arise for DEC on account of their complex sequences.

#### 1.2. Objective and scope

The main objective of this research is to suggest a time-dependent risk informed integrated safety assessment methodology (TRISAM) for performing systematic and comprehensive safety assessment of NPPs to support a determination of safety enhancement measures under complex accident sequences (CAS). These accident sequences involve failures of multiple engineered safety features (ESF), which cause the loss of single or multiple safety functions. As a type of DEC, significant fuel

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Abbreviations

APR1400	Advanced Power Reactor 1400	T&M	]
AFW	Auxiliary Feedwater	Unc.	ι
BDBA	Beyond Design Basis Accident	VOPT	I
BEPU	Best Estimate plus Uncertainty		
CAS	Complex Accident Sequences	Symbols	
CFP	Consequential Failure Probability		
CDF	Core Damage Frequency	Ν	N
CLT	Central Limit Theorem	$T^{\gamma}$	γ
DEC	Design Extension Conditions	$\widehat{T}^{\gamma}$	F
DBA	Design Basis Accident	$\widehat{T}_i^{\gamma}$	F
DSA	Deterministic Safety Assessment	To	0
DTET	Discrete Time-dependent Event Tree	γ	Ι
ET	Event Tree	δ	Ι
ESF	Engineered Safety Features	Р	Г
EOP	Emergency Operation Procedure	$\widehat{P}$	N
EUR	European Utility Requirement	$\hat{P}^{\frac{\alpha}{2}}$	Г
FT	Fault Tree		(
IAEA	International Atomic Energy Agency	$\hat{p}^{\frac{\alpha}{2}}$	í
I&C	Instrumentation and Control	$\frac{1}{i}$	г Г
IE	Initiating Event	$\frac{L_{\alpha}}{2}$	
IRWST	In-containment Refueling Water Storage Tank	$E_n$	1
KSS	Key Safety System	$E_{n-1}$ $E^{i}$	1. r
LER	Large Early Release	$P(F^{i} \cdot t)$	F
LWR	Light Water Reactor	$P(E_n^{OP})$	I
MSLB	Main Steam Line Break	$P_{ir}$	ī
MSI	Main Steam Isolation	F(t)	s
NPP	Nuclear Power Plant	$C_{\cdot}$	0
PZR	Pressurizer	X.	F
PDF	Probabilistic Density Function	$\frac{1}{R}(t)$	Ť
PFT	Point-estimate Failure Time	R <sub>T</sub>	ſ
PSA	Probabilistic Safety Assessment	R.	A
RCS	Reactor Coolant System	Cn	(
RRW	Risk Reduction Worth	сp	ć
RAW	Risk Achievement Worth	C.	6
SRS	Simple Random Sampling	U <sub>A</sub>	ć
SGTR	Steam Generator Tube Rupture	ΔP:	F
SG	Steam Generator	ΔP <sub>n</sub>	N
SI	Safety Injection	$\Delta P_2$	Ţ
SCN	Scenario	—- a	ć
TRISAM	Time-dependent Risk informed Integrated Safety		-

T&MTest and MaintenanceUnc.UncertaintyVOPTVariable Over Power TripSymbolsNMinimum required number for SRS calculation $T^{\gamma}$ $\gamma^*100$ th percentile of a true failure time $\hat{T}^{\gamma}$ Point estimator of $T^{\gamma}$ of scenario iToOperator action initiating time $\gamma$ Degree of percentile for PFT $\delta$ Degree of confidence level for PFT $P$ True value of consequential failure probability $\hat{p}$ Maximum Likelihood Estimator of P $\hat{p}^{\frac{\alpha}{2}}$ The upper limit of estimation interval of P at two sided $(1 - \alpha) * 100$ confidence interval $\hat{p}_1^{\frac{\alpha}{2}}$ $\hat{p}_1^{\frac{\alpha}{2}}$ $\hat{p}_2^{\frac{\alpha}{2}}$ of scenario i $Z_{\frac{\alpha}{2}}$ The point at which $P(Z > Z_{\alpha/2}) = \alpha/2$ , $Z \sim N(0,1)$ $E_n$ nth event $E_{n-1}$ n-1th event $E_n^{i}$ nth event of scenario i $P(E_i^{iOP})$ Unreliability of operator action $P_{E_i}^{OP}$ Unreliability of scenario i at time $t_n$ $P(E_i^{OP})$ Unreliability of scenario i at time $t_n$ $R_i(t)$ Time-dependent Risk of scenario i at time t $X_j$ Random variable of bernoulli trial $R_i(t)$ Time-dependent Risk of scenario i at time t $R_T$ Total potential risk $R_c$ Acceptable target risk criterion $C_p$ Conditional probability for one or more tube ruptures during transient $\Delta P_n$ Peak differential pressure across tubes during transient $\Delta P_n$ Normal operating pressure	TRI	Time-dependent Risk Information
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$\begin{array}{lll} \gamma & \mbox{Degree of percentile for PFT} \\ \delta & \mbox{Degree of confidence level for PFT} \\ P & \mbox{True value of consequential failure probability} \\ \hat{P} & \mbox{Maximum Likelihood Estimator of P} \\ \hat{P}^{\frac{\alpha}{2}} & \mbox{The upper limit of estimation interval of P at two sided} \\ & (1-\alpha)*100 \mbox{ confidence interval} \\ \hat{P}^{\frac{\alpha}{2}} & \mbox{P}^{\frac{\alpha}{2}} & \mbox{of scenario i} \\ Z_{\frac{\alpha}{2}} & \mbox{The point at which } P(Z > Z_{\alpha/2}) = \alpha/2, Z \sim N(0,1) \\ E_n & \mbox{nth event} \\ E_{n-1} & \mbox{n-th event} \\ E_n^{-1} & \mbox{n-th event of scenario i} \\ P(E_n^{i}, t_n) & \mbox{Probability of Occurrence of nth event at time t_n } \\ P(E_i^{OP}) & \mbox{Unreliability of operator action} \\ P_{\text{IE}} & \mbox{Initiating Event Frequency} \\ F_i(t_n) & \mbox{System unreliability of scenario i at time t_n } \\ C_i & \mbox{Consequence of scenario i} \\ X_j & \mbox{Random variable of bernoulli trial} \\ R_i(t) & \mbox{Time-dependent Risk of scenario i at time t} \\ R_T & \mbox{Total potential risk} \\ R_c & \mbox{Acceptable target risk criterion} \\ C_p & \mbox{Conditional probability for one or more tube ruptures} \\ during transient \\ C_A & \mbox{Conditional probability for one or more tube ruptures scharing transient} \\ \Delta P_n & \mbox{Normal operating pressure across tubes during MSLB accident} \\ \Delta P_a & \mbox{Peak differential pressure across tubes during MSLB accident} \\ \end{array} \right$	To	Operator action initiating time
$ \begin{split} \delta & \mbox{Degree of confidence level for PFT} \\ P & \mbox{True value of consequential failure probability} \\ \widehat{P} & \mbox{Maximum Likelihood Estimator of P} \\ \widehat{P}^{\frac{\alpha}{2}} & \mbox{The upper limit of estimation interval of P at two sided} \\ & (1-\alpha)*100 \ confidence interval \\ \widehat{P}^{\frac{\alpha}{2}} & \widehat{P}^{\frac{\alpha}{2}} \ of \ scenario i \\ Z_{\frac{\alpha}{2}} & \mbox{The point at which } P(Z > Z_{\alpha/2}) = \alpha/2, \ Z \sim N(0,1) \\ E_n & \ nth \ event \\ E_{n-1} & \ n-1 \ th \ event \\ E_n & \ nth \ event \ of \ scenario i \\ P(E_i^{1}; t_n) & \ Probability \ of \ occurrence \ of \ nth \ event \ at \ time \ t_n \\ P(E_i^{OP}) & \ Unreliability \ of \ operator \ action \\ P_{IE} & \ Initiating \ Event \ Frequency \\ F_i(t_n) & \ System \ unreliability \ of \ scenario \ i \\ X_j & \ Random \ variable \ of \ bernoulli \ trial \\ R_i(t) & \ Time-dependent \ Risk \ of \ scenario \ i \ at \ time \ t \\ R_T & \ Total \ potential \ risk \ criterion \\ C_n & \ Conditional \ probability \ for \ one \ or \ more \ tube \ ruptures \ during \ transient \\ C_A & \ Conditional \ probability \ for \ one \ or \ more \ tube \ ruptures \ during \ transient \\ \Delta P_n & \ Normal \ operating \ pressure \ differential \ across \ tubes \ during \ MSLB \ accident \\ \Delta P_a & \ Peak \ differential \ pressure \ across \ tubes \ during \ MSLB \ accident \\ \end{array}$	γ	Degree of percentile for PFT
$ \begin{array}{lll} P & \mbox{True value of consequential failure probability} \\ \widehat{P} & \mbox{Maximum Likelihood Estimator of P} \\ \widehat{P}^{\frac{\alpha}{2}} & \mbox{True value of consequential failure probability} \\ \widehat{P}^{\frac{\alpha}{2}} & \mbox{True value of consequence interval} \\ \widehat{P}^{\frac{\alpha}{2}} & \widehat{P}^{\frac{\alpha}{2}} & \mbox{of scenario i} \\ Z_{\frac{\alpha}{2}} & \mbox{The point at which } P(Z > Z_{\alpha/2}) = \alpha/2, Z \sim N(0,1) \\ E_n & \mbox{nth event} \\ E_{n-1} & \mbox{n-th event} \\ E_n & \mbox{nth event of scenario i} \\ P(E_n^{i}; t_n) & \mbox{Probability of Occurrence of nth event at time t_n} \\ P(E_i^{OP}) & \mbox{Unreliability of operator action} \\ P_{\text{IE}} & \mbox{Initiating Event Frequency} \\ F_i(t_n) & \mbox{System unreliability of scenario i at time t_n} \\ C_i & \mbox{Consequence of scenario i} \\ X_j & \mbox{Random variable of bernoulli trial} \\ R_i(t) & \mbox{Time-dependent Risk of scenario i at time t} \\ R_T & \mbox{Total potential risk} \\ R_c & \mbox{Acceptable target risk criterion} \\ C_p & \mbox{Conditional probability for one or more tube ruptures} \\ \mbox{during transient} \\ C_A & \mbox{Conditional probability for one or more tube ruptures} \\ \mbox{during MSLB accident} \\ \Delta P_n & \mbox{Normal operating pressure differential across tubes during MSLB accident} \\ \end{array}$	δ	Degree of confidence level for PFT
$ \begin{array}{lll} \widehat{P} & \mbox{Maximum Likelihood Estimator of P} \\ & & \widehat{P}^{\frac{\alpha}{2}} & \mbox{The upper limit of estimation interval of P at two sided} \\ & & (1-\alpha)*100 \mbox{ confidence interval} \\ & & & \widehat{P}^{\frac{\alpha}{2}} & \mbox{$\widehat{P}}^{\frac{\alpha}{2}} & \mbox{of scenario i} \\ & & & & & \\ & & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \\ & $	Р	True value of consequential failure probability
$ \begin{array}{ll} \widehat{P}^{\frac{1}{2}} & \text{The upper limit of estimation interval of P at two sided} \\ & (1-\alpha)*100 \text{ confidence interval} \\ \widehat{P}_{i}^{\frac{\alpha}{2}} & \widehat{P}^{\frac{\alpha}{2}} & \text{of scenario i} \\ \hline{Z}_{\frac{\alpha}{2}}^{\frac{\alpha}{2}} & \text{The point at which } P(Z > Z_{\alpha/2}) = \alpha/2, Z \sim N(0,1) \\ E_n & \text{nth event} \\ E_{n-1} & n-1 \text{th event} \\ E_n & n \text{th event of scenario i} \\ P(E_n^{i}; t_n) & \text{Probability of Occurrence of nth event at time } t_n \\ P(E_i^{OP}) & \text{Unreliability of operator action} \\ P_{\text{IE}} & \text{Initiating Event Frequency} \\ F_i(t_n) & \text{System unreliability of scenario i at time } t_n \\ C_i & \text{Consequence of scenario i} \\ X_j & \text{Random variable of bernoulli trial} \\ R_i(t) & \text{Time-dependent Risk of scenario i at time t} \\ R_T & \text{Total potential risk} \\ R_c & \text{Acceptable target risk criterion} \\ C_P & \text{Conditional probability for one or more tube ruptures} \\ during transient \\ C_A & \text{Conditional probability for one or more tube ruptures} \\ during MSLB accident \\ \Delta P_n & \text{Normal operating pressure across tubes during MSLB accident} \\ \Delta P_a & \text{Peak differential pressure across tubes during MSLB accident} \\ \end{array}$	Ω P	Maximum Likelihood Estimator of P
$ \begin{array}{cccc} (1-\alpha)^* 100 \ confidence \ interval \\ \widehat{P}_i^{\frac{\alpha}{2}} & \widehat{P}^{\frac{\alpha}{2}} \ of \ scenario \ i \\ Z_{\alpha}^{\frac{\alpha}{2}} & The \ point \ at \ which \ P(Z>Z_{\alpha/2})=\alpha/2, \ Z\sim N(0,1) \\ E_n & nth \ event \\ E_{n-1} & n-1 \ th \ event \\ E_n^{-1} & n+1 \ th \ event \ of \ scenario \ i \\ P(E_n^{i}: \ t_n) & Probability \ of \ occurrence \ of \ nth \ event \ at \ time \ t_n \\ P(E_i^{OP}) & Unreliability \ of \ operator \ action \\ P_{IE} & Initiating \ Event \ Frequency \\ F_i(t_n) & System \ unreliability \ of \ scenario \ i \ at \ time \ t_n \\ C_i & Consequence \ of \ scenario \ i \\ X_j & Random \ variable \ of \ bernoulli \ trial \\ R_i(t) & Time-dependent \ Risk \ of \ scenario \ i \ at \ time \ t \\ R_T & Total \ potential \ risk \\ R_c & Acceptable \ target \ risk \ criterion \\ C_P & Conditional \ probability \ for \ one \ or \ more \ tube \ ruptures \ during \ transient \\ C_A & Conditional \ probability \ for \ one \ or \ more \ tube \ ruptures \ during \ MSLB \ accident \\ \Delta P_n & Normal \ operating \ pressure \ differential \ across \ tubes \ during \ MSLB \ accident \\ \Delta P_a & Peak \ differential \ pressure \ across \ tubes \ during \ MSLB \ accident \\ \end{array}$	$\hat{P}^{\frac{\alpha}{2}}$	The upper limit of estimation interval of P at two sided
$ \begin{array}{lll} \hat{P}_{i}^{\frac{\alpha}{2}} & \hat{P}^{\frac{\alpha}{2}} & \text{of scenario i} \\ \mathbb{Z}_{\underline{\alpha}}^{2} & \text{The point at which } \mathbb{P}(\mathbb{Z} > \mathbb{Z}_{\alpha/2}) = \alpha/2, \mathbb{Z} \sim \mathbb{N}(0,1) \\ \mathbb{E}_{n} & \text{nth event} \\ \mathbb{E}_{n-1} & \text{n-1th event} \\ \mathbb{E}_{n}^{i} & \text{nth event of scenario i} \\ \mathbb{P}(E_{n}^{i}, \mathbf{t}_{n}) & \text{Probability of Occurrence of nth event at time } \mathbf{t}_{n} \\ \mathbb{P}(E_{i}^{OP}) & \text{Unreliability of operator action} \\ \mathbb{P}_{\text{IE}} & \text{Initiating Event Frequency} \\ \mathbb{F}_{i}(\mathbf{t}_{n}) & \text{System unreliability of scenario i at time } \mathbf{t}_{n} \\ \mathbb{C}_{i} & \text{Consequence of scenario i} \\ \mathbb{X}_{j} & \text{Random variable of bernoulli trial} \\ \mathbb{R}_{i}(t) & \text{Time-dependent Risk of scenario i at time t} \\ \mathbb{R}_{T} & \text{Total potential risk} \\ \mathbb{R}_{c} & \text{Acceptable target risk criterion} \\ \mathbb{C}_{p} & \text{Conditional probability for one or more tube ruptures} \\ & \text{during transient} \\ \mathbb{C}_{A} & \text{Conditional probability for one or more tube ruptures} \\ & \text{during MSLB accident} \\ \Delta \mathbb{P}_{n} & \text{Normal operating pressure across tubes during MSLB accident} \\ \Delta \mathbb{P}_{a} & \text{Peak differential pressure across tubes during MSLB accident} \\ \end{array} $		$(1 - \alpha) * 100$ confidence interval
$Z_{\underline{\alpha}}$ The point at which $P(Z > Z_{\alpha/2}) = \alpha/2$ , $Z \sim N(0,1)$ $Z_{\underline{\alpha}}$ The point at which $P(Z > Z_{\alpha/2}) = \alpha/2$ , $Z \sim N(0,1)$ $E_n$ nth event $E_{n-1}$ n-1th event $E_n^i$ nth event of scenario i $P(E_i^{l}: t_n)$ Probability of Occurrence of nth event at time $t_n$ $P(E_i^{OP})$ Unreliability of operator action $P_{IE}$ Initiating Event Frequency $F_i(t_n)$ System unreliability of scenario i at time $t_n$ $C_i$ Consequence of scenario i $X_j$ Random variable of bernoulli trial $R_i(t)$ Time-dependent Risk of scenario i at time t $R_T$ Total potential risk $R_c$ Acceptable target risk criterion $C_P$ Conditional probability for one or more tube ruptures during transient $C_A$ Conditional probability for one or more tube ruptures during MSLB accident $\Delta P_n$ Normal operating pressure differential across tubes $\Delta P_a$ Peak differential pressure across tubes during MSLB accident	$\widehat{P}^{\frac{\alpha}{2}}$	$\hat{P}^{\frac{\alpha}{2}}$ of scenario i
$ \begin{array}{cccc} & & & & & & & & & & & & & & & & & $	$Z_{\alpha}$	The point at which $P(Z > Z_{\alpha/2}) = \alpha/2$ , $Z \sim N(0.1)$
$ \begin{array}{lll} & n-1 \mbox{the event} \\ E_{n-1} & n-1 \mbox{the event} \\ E_{n}^{i} & n \mbox{the event} \mbox{of scenario} & i \\ P(E_{i}^{i}:t_{n}) & \mbox{Probability of Occurrence of nth event at time } t_{n} \\ P(E_{i}^{OP}) & \mbox{Unreliability of operator action} \\ P_{IE} & \mbox{Initiating Event Frequency} \\ F_{i}(t_{n}) & \mbox{System unreliability of scenario} & i \mbox{at time } t_{n} \\ C_{i} & \mbox{Consequence of scenario} & i \\ X_{j} & \mbox{Random variable of bernoulli trial} \\ R_{i}(t) & \mbox{Time-dependent Risk of scenario} & i \mbox{at time } t \\ R_{T} & \mbox{Total potential risk} \\ R_{c} & \mbox{Acceptable target risk criterion} \\ C_{P} & \mbox{Conditional probability for one or more tube ruptures} \\ \mbox{during transient} \\ C_{A} & \mbox{Conditional probability for one or more tube ruptures} \\ \mbox{during MSLB accident} \\ \Delta P_{n} & \mbox{Normal operating pressure across tubes during MSLB accident} \\ \Delta P_{a} & \mbox{Peak differential pressure across tubes during MSLB accident} \\ \end{array}$	$E_n^2$	nth event
	$E_{n-1}$	n-1th event
$ \begin{array}{lll} P(E_{a}^{i};t_{n}) & \mbox{Probability of Occurrence of nth event at time }t_{n} \\ P(E_{a}^{OP}) & \mbox{Unreliability of operator action} \\ P_{IE} & \mbox{Initiating Event Frequency} \\ F_{i}(t_{n}) & \mbox{System unreliability of scenario i at time }t_{n} \\ C_{i} & \mbox{Consequence of scenario i} \\ X_{j} & \mbox{Random variable of bernoulli trial} \\ R_{i}(t) & \mbox{Time-dependent Risk of scenario i at time t} \\ R_{T} & \mbox{Total potential risk} \\ R_{c} & \mbox{Acceptable target risk criterion} \\ C_{P} & \mbox{Conditional probability for one or more tube ruptures} \\ & \mbox{during transient} \\ C_{A} & \mbox{Conditional probability for one or more tube ruptures } \\ & \mbox{during MSLB accident} \\ \Delta P_{n} & \mbox{Normal operating pressure differential across tubes} \\ \Delta P_{a} & \mbox{Peak differential pressure across tubes during MSLB accident} \\ \end{array} $	$E_n^i$	nth event of scenario i
$\begin{array}{lll} {\rm P}(E_i^{OP}) & {\rm Unreliability\ of\ operator\ action} \\ {\rm P}_{\rm IE} & {\rm Initiating\ Event\ Frequency} \\ {\rm F}_i({\rm t}_n) & {\rm System\ unreliability\ of\ scenario\ i\ at\ time\ {\rm t}_n} \\ {\rm C}_i & {\rm Consequence\ of\ scenario\ i} \\ {\rm X}_j & {\rm Random\ variable\ of\ bernoulli\ trial} \\ {\rm R}_i({\rm t}) & {\rm Time-dependent\ Risk\ of\ scenario\ i\ at\ time\ t} \\ {\rm R}_T & {\rm Total\ potential\ risk} \\ {\rm R}_c & {\rm Acceptable\ target\ risk\ criterion} \\ {\rm C}_P & {\rm Conditional\ probability\ for\ one\ or\ more\ tube\ ruptures\ during\ transient} \\ {\rm C}_A & {\rm Conditional\ probability\ for\ one\ or\ more\ tube\ ruptures\ during\ MSLB\ accident} \\ {\rm \Delta}P_i & {\rm Peak\ differential\ pressure\ across\ tubes\ during\ MSLB\ accident} \\ {\rm \Delta}P_a & {\rm Peak\ differential\ pressure\ across\ tubes\ during\ MSLB\ accident\ during\ MSLB\ accident} \\ \end{array}$	$P(E_n^i: t_n)$	Probability of Occurrence of nth event at time t <sub>n</sub>
$\begin{array}{lll} P_{IE} & Initiating Event Frequency \\ F_{i}(t_{n}) & System unreliability of scenario i at time t_{n} \\ C_{i} & Consequence of scenario i \\ X_{j} & Random variable of bernoulli trial \\ R_{i}(t) & Time-dependent Risk of scenario i at time t \\ R_{T} & Total potential risk \\ R_{c} & Acceptable target risk criterion \\ C_{p} & Conditional probability for one or more tube ruptures during transient \\ C_{A} & Conditional probability for one or more tube ruptures during MSLB accident \\ \Delta P_{i} & Peak differential pressure across tubes during MSLB accident \\ \Delta P_{a} & Peak differential pressure across tubes during MSLB accident \\ \end{array}$	$P(E_i^{OP})$	Unreliability of operator action
$\begin{array}{lll} F_i(t_n) & \text{System unreliability of scenario i at time } t_n \\ C_i & \text{Consequence of scenario i} \\ X_j & \text{Random variable of bernoulli trial} \\ R_i(t) & \text{Time-dependent Risk of scenario i at time t} \\ R_T & \text{Total potential risk} \\ R_c & \text{Acceptable target risk criterion} \\ C_P & \text{Conditional probability for one or more tube ruptures} \\ during transient \\ C_A & \text{Conditional probability for one or more tube ruptures} \\ during MSLB accident \\ \Delta P_i & \text{Peak differential pressure across tubes during transient} \\ \Delta P_a & \text{Peak differential pressure across tubes during MSLB accident} \\ \end{array}$	$\mathbf{P}_{\mathrm{IE}}$	Initiating Event Frequency
$\begin{array}{lll} C_i & & Consequence of scenario i \\ X_j & & Random variable of bernoulli trial \\ R_i(t) & & Time-dependent Risk of scenario i at time t \\ R_T & & Total potential risk \\ R_c & & Acceptable target risk criterion \\ C_P & & Conditional probability for one or more tube ruptures \\ & & during transient \\ C_A & & Conditional probability for one or more tube ruptures \\ & & during MSLB accident \\ \Delta P_i & Peak differential pressure across tubes during transient \\ \Delta P_n & Normal operating pressure differential across tubes \\ \Delta P_a & Peak differential pressure across tubes during MSLB accident \\ \end{array}$	F <sub>i</sub> (t <sub>n</sub> )	System unreliability of scenario i at time t <sub>n</sub>
$\begin{array}{llllllllllllllllllllllllllllllllllll$	Ci	Consequence of scenario i
$\begin{array}{lll} R_i(t) & \mbox{Time-dependent Risk of scenario i at time t} \\ R_T & \mbox{Total potential risk} \\ R_c & \mbox{Acceptable target risk criterion} \\ C_P & \mbox{Conditional probability for one or more tube ruptures} \\ during transient \\ C_A & \mbox{Conditional probability for one or more tube ruptures} \\ during MSLB accident \\ \Delta P_i & \mbox{Peak differential pressure across tubes during transient} \\ \Delta P_n & \mbox{Normal operating pressure differential across tubes} \\ \Delta P_a & \mbox{Peak differential pressure across tubes during MSLB accident} \\ \end{array}$	Xj	Random variable of bernoulli trial
$\begin{array}{llllllllllllllllllllllllllllllllllll$	R <sub>i</sub> (t)	Time-dependent Risk of scenario i at time t
R <sub>c</sub> Acceptable target risk criterion   C <sub>P</sub> Conditional probability for one or more tube ruptures during transient   C <sub>A</sub> Conditional probability for one or more tube ruptures during MSLB accident   ΔP <sub>i</sub> Peak differential pressure across tubes during transient   ΔP <sub>n</sub> Normal operating pressure differential across tubes   ΔP <sub>a</sub> Peak differential pressure across tubes during MSLB accident	R <sub>T</sub>	Total potential risk
$ \begin{array}{llllllllllllllllllllllllllllllllllll$	R <sub>c</sub>	Acceptable target risk criterion
$\begin{array}{llllllllllllllllllllllllllllllllllll$	C <sub>P</sub>	Conditional probability for one or more tube ruptures
$ \begin{array}{llllllllllllllllllllllllllllllllllll$		during transient
$\begin{array}{ll} during \mbox{ MSLB accident} \\ \Delta P_i & \mbox{Peak differential pressure across tubes during transient} \\ \Delta P_n & \mbox{ Normal operating pressure differential across tubes} \\ \Delta P_a & \mbox{Peak differential pressure across tubes during MSLB accident} \\ \end{array}$	CA	Conditional probability for one or more tube ruptures
$\begin{array}{llllllllllllllllllllllllllllllllllll$		during MSLB accident
$\begin{array}{llllllllllllllllllllllllllllllllllll$	$\Delta P_i$	Peak differential pressure across tubes during transient
$\Delta P_a$ Peak differential pressure across tubes during MSLB accident	$\Delta P_n$	Normal operating pressure differential across tubes
dent	$\Delta P_a$	Peak differential pressure across tubes during MSLB acci-
		dent

Assessment Methodology

degradation must be prevented under CAS (IAEA, No. SSR-2/1, 2016; EUR for LWR NPPs, 2012).

This research includes an overview, research survey, procedure, and case study. In the overview, a general description of TRISAM is given by comparing the existing safety assessment methodologies. Relevant research is then introduced, followed by the procedure section where a detailed description is given for all steps of TRISAM: scenario identification using time-dependent event trees, accident consequence analysis, system reliability analysis, and time-dependent risk information (TRI) generation. In the case study, availability and applicability are shown by applying the TRISAM to a containment bypass accident analysis. As this research aims at preventing severe core damage occurrence under CAS, it is considered out of present scope to address phenomenological aspects after the core damage condition is reached.

#### 2. Overview of TRISAM

At present, there are two main safety analysis methodologies: deterministic safety assessment (DSA) and probabilistic safety assessment (PSA). The former has served a vital role in DBA analysis under the defense in depth philosophy. The deterministic approach has strengths regarding familiarity to utility and regulatory bodies, completeness of its application, clarity in predicting the sequence of an accident in a pre-determined scenario, and a straightforward interpretation of results where, based on a margin calculation, status is regarded as safe or unsafe depending on the margin for the acceptance criteria.

Since the deterministic approach assumes that system and operator behaviors can be captured and modeled with a fixed frame, it has limitations in handling unknown threats such as: the possibility of multiple ESF failures, internal hazards, external hazards, digital system failures, and operator error. In this perspective, the DSA is regarded as an incomplete methodology for BDBA analysis.

To overcome the limitations of the deterministic approach, PSA was introduced in 1975 to identify unknown threats in NPPs (U.S. NRC, NUREG-75/014, 1975). The probabilistic approach identifies possible scenarios not considered in the deterministic approach, and calculates the frequency of scenario occurrence that can potentially lead to core damage. The biggest advantage of the probabilistic approach is that it can provide insights for decision-making in the process of design and operation.

While the deterministic approach aims to evaluate safety in a dichotomous way, the probabilistic approach perceives safety as a Download English Version:

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