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INCORPORATION OF PASSIVE SYSTEMS WITHIN A PRA FRAMEWORK

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PRESENTATION OUTLINE

- **Introduction**
  - **Passive Systems Reliability**
  - **PRA**
- **Natural Circulation Systems**
  - **Isolation Condenser**
- **Event Tree and Fault Tree Model**
  - **Passive System Unavailability**
- **Illustrative example**
- **Results**
- **Conclusions and step forward**

INTRODUCTION

- **Innovative reactors largely implement passive systems**
  - **no external input to operate**
  - **reliance upon « natural physical principles (natural convection, conduction, gravity, etc.) » under extreme boundary conditions**
  - **thermal-hydraulic (t-h) passive systems (natural circulation)**

- **Applications of passive systems for innovative reactors demand high availability and reliability**
- **PSA analysis**
- **Accident sequence definition and assessment**
  - **Event Tree and Fault Tree model**

- **Introduction of a passive system in an accident scenario in the fashion of a front-line system**

INTRODUCTION cont'd

- **Occurrence of physical phenomena leading to pertinent failure modes, rather than classical component mechanical and electrical faults**
- **Different system model adopted in fault tree approach**
- **Natural circulation: small engaged driving forces and thermal-hydraulic factors affecting the passive system performance**
- **Physical principle deterioration dependency on the boundary conditions and mechanisms needed for start-up and maintain the intrinsic principle**

OBJECTIVE

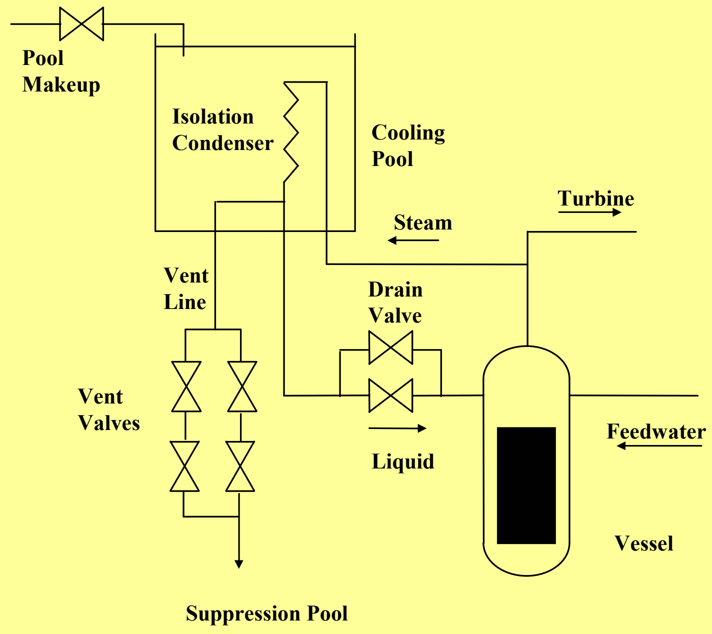
- **Objective: approach for introducing passive system unreliability in an accident sequence, with reference to t-h natural circulation cooling systems performance (type B passive systems, cfr.IAEA)**

- **Passive Systems for decay heat removal implementing in-pool heat exchangers and foreseeing the free convection (e.g. PRHR for AP 600 and AP1000, Isolation Condenser for SBWR and ESBWR)**

- **Accident sequences defined by Event Tree (ET) technique**
  - **initiating event**
  - **safety or front-line systems success or failure**
  - **safety systems unavailability matching the ET headings (simplest and commonly adopted way)**
  - **safety system unavailability assessed by Fault Tree (FT) technique (system analysis)**
  - **passive systems to be evaluated as safety systems**

ISOLATION CONDENSER

- **Core decay heat removal from the reactor, by natural circulation following an isolation transient**
- **Limit the overpressure in the reactor system at a value below the set-point of the safety relief valves, preventing unnecessary reactor depressurization**
- **Actuation on main steam isolation valve position, high reactor pressure and low reactor level**

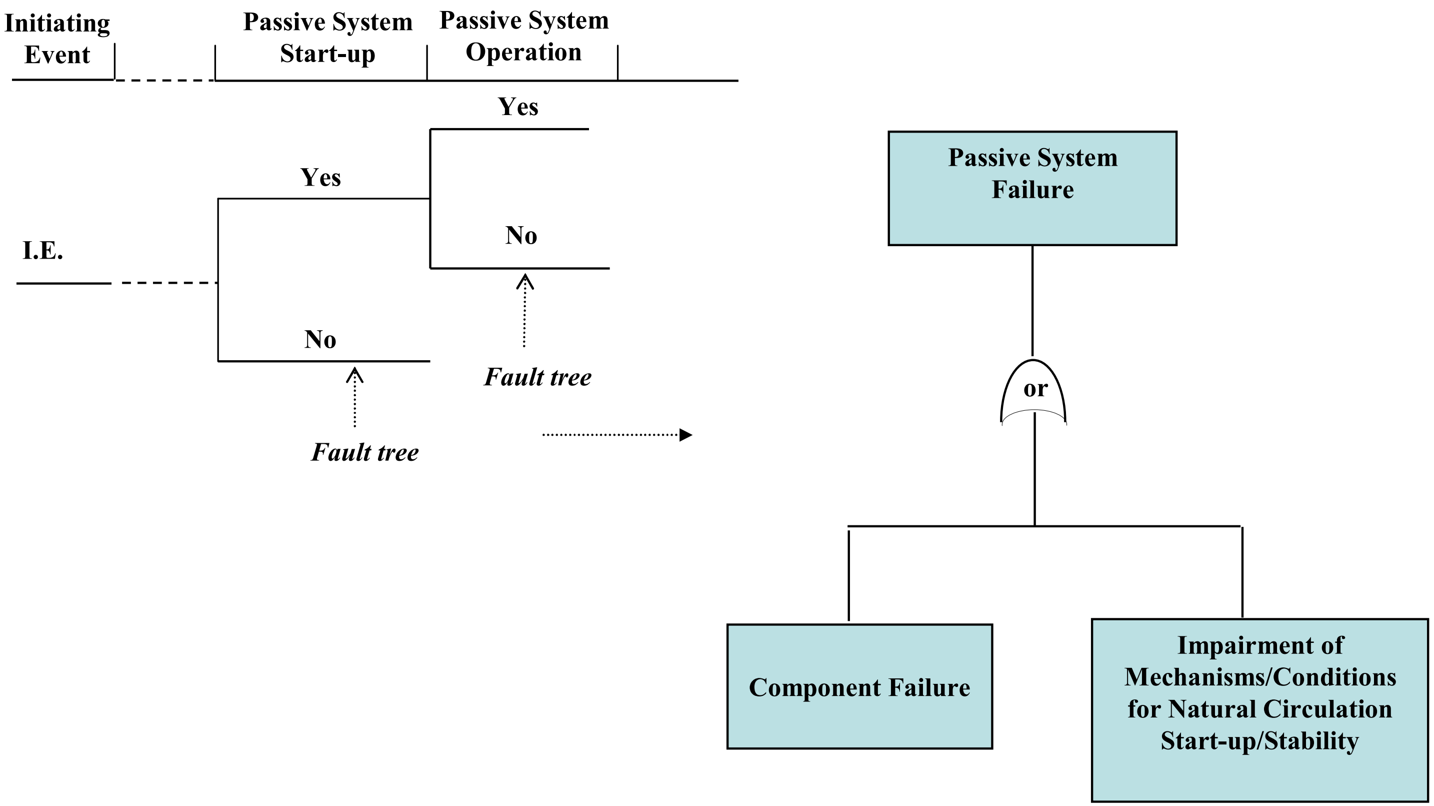


Scheme of the Isolation Condenser

EVENT TREE DEVELOPMENT

- **Two kinds of system malfunction, to be considered as ET headings:**
  - **failure to start-up (e.g. drain valve failure to open)**
    - **Specific fault tree**
      - **mechanical components (prevailing)**
      - **boundary conditions**
  - **failure to continue operating (i.e. natural circulation stability impairment)**
    - **Specific fault tree**
      - **mechanical components**
      - **boundary conditions (prevailing)**

EVENT TREE DEVELOPMENT cont'd



PASSIVE SYSTEM UNAVAILABILITY

- **System/component reliability (piping, valves, etc.)**
  - **mechanical component reliability**
- **Physical phenomena "stability" (natural circulation)**
  - **performance/stability of the physical principles (heat exchange and density difference) upon which passive system is relying, in terms of characteristic parameters as flow rate or exchanged heat**
  - **dependency on the surrounding conditions related to accident progress, affecting system behaviour**
  - **this could require not a unique unreliability figure, but the reevaluation for each sequence following an accident initiator**
  - **thermal-hydraulic analysis is helpful to evaluate parameter evolution**
- **Identification of the failure modes**
- **Unavailability quantification, i.e. assessment in probabilistic terms of the failures**

IDENTIFICATION OF THE FAILURE MODES

- **Component and functional Failure Mode and Effect Analysis (FMEA) methodology**
  - **evaluation of natural circulation in terms of potential "phenomenological" factors, whose consequences can degrade or stop the function**

- **Several factors leading to disturbances in an Isolation Condenser System**
  - **unexpected mechanical and thermal loads, challenging primary boundary integrity**
  - **mechanical component malfunction, i.e. drain valve**
  - **HX tube plugging**
  - **non-condensable gas build-up**
  - **heat exchange process reduction: surface oxidation, thermal stratification, etc.**

FMEA RESULTS

- **List of critical parameters direct indicators of the physical failures**
  - **Non-condensable gas fraction**
  - **Undetected leakage (crack size or leak rate)**
  - **Partially Opened Valve in the drain line**
  - **Heat loss**
  - **HX plugged pipes**
  - **Piping layout**
- **Probabilistic characterization of the critical parameters**

UNAVAILABILITY ASSESSMENT

- **Failure modes to be assessed through the FT development in the form of critical parameter elementary basic events, linked by Boolean (AND et OR) algebra rules**
- **Adoption of non conventional failure model (i.e. exponential, $e^{-\lambda t}$, λ failure rate, t mission time)**
- **Basic Event model requires:**
  - **the assignement of both the probability distribution and range of the parameter**
  - **associated failure criterion, e.g. non-condensable fraction > x%, leak rate > x (gr/sec) or crack size > x (cm^2)**

UNAVAILABILITY ASSESSMENT cont'd

- **Lack of consistent experimental and operating data base**
  - **expert/engineering judgement**
  - **plausible considerations, e.g. range to exclude unrealistic values or representing a limit zone for the system operation**
- **Uncertainties of epistemic character, i.e. related to the lack of knowledge**
- **Subjective probability distributions**

UNAVAILABILITY ASSESSMENT cont'd

- **Simplification of the issue**
  - passive function failure probability evaluation "classicaly", as unavailability of components designed to assure the conditions for passive function performance and stability (e.g. vent valves for non-condensables removal or HX for heat transfer)
  - fault tree developed at component level
  - limitation: range of failure modes to which the system may be potentially subject is not fully covered
- **Alternative: thermal-hydraulic assessment by code simulation**
  - set of cases defined by design and critical parameters randomly selected from the relative probability distribution (Monte Carlo simulation)
  - failure criterion (e.g. peak clad temperature)
  - probability of failure: $P_f = N_f/N$
  - large number of simulations for a relevant accuracy ($\sim 1/P_f$)

UNAVAILABILITY ASSESSMENT cont'd

- **Probability of failure of the passive system:**

$$P_t = 1-(1-P_1)*(1-P_2)*\ldots*(1-P_n)$$

P_t	*overall failure probability*
P_1 through P_n	*individual probabilities of failures pertaining to each failure mode, assuming mutually non-exclusive independent events*

- **Failure model relative to each single event:**

$$P_i = \int_{x \geq x_o} p(x)\, dx$$

x_o = threshold value (failure criterion)

$p(x)$ = pdf of the parameter

UNAVAILABILITY ASSESSMENT cont'd

- **Statistical independence between parameters (zero covariance)**
- **In case of statistical dependence, parameters can not be combined freely and independently**
- **Joint pdfs**, e.g. multivariate distributions
- **Conditional subjective probability** distributions
- **Covariance matrix**
- **Functional relationships** between the parameters

ILLUSTRATIVE EXAMPLE

- **Four parameters under consideration**
  - Partially opened valve (fraction)
  - HX plugged pipes (fraction)
  - Heat loss (Kw)
  - Non-condensable gas fraction (fraction)
- **Uniform, Triangular and Doubly-truncated Normal distributions**

Parameter range and failure threshold

Parameter	Range	Failure Threshold	Nominal
Valve closure coefficient	0-0,5	0,3	0
HX plugging (%)	0-15	10	0
Heat loss (Kw)	5-100	60	5
Non-condensable fraction	0-0,8	0,5	0

ILLUSTRATIVE EXAMPLE cont'd

- Uniform distribution as "default"
  – expert's degree of knowledge about the parameter range

Parameter	Range	p(x)	Characteristics
Partially closed valve	0-0,5	2	$\mu = 0,25$ $\sigma = 0,02$
HX plugged pipes	0-0,15	6,66	$\mu = 0,075$ $\sigma = 0,0018$
Heat loss (Kw)	5-100	0,01	$\mu = 52,5$ $\sigma = 752,8$
Non-condensable gas	0-0,8	1,25	$\mu = 0,4$ $\sigma = 0,05$

ILLUSTRATIVE EXAMPLE cont'd

- **Triangular distribution**
  - expert's estimate of the most likely value
  - mode as the expected value in nominal conditions

Parameter	Range	Mode	p(x)	Characteristics
Partially closed valve	0-0,5	0	4-8x	$\mu = 0{,}16$ $\sigma = 0{,}013$
HX plugged pipes	0-0,15	0	13,3-88,8x	$\mu = 0{,}05$ $\sigma = 0{,}0012$
Heat loss (Kw)	5-100	5	0,022-0,00022x	$\mu = 36{,}6$ $\sigma = 501{,}3$
Non-condensable gas	0-0,8	0	2,5-3,12x	$\mu = 0{,}27$ $\sigma = 0{,}035$

ILLUSTRATIVE EXAMPLE cont'd

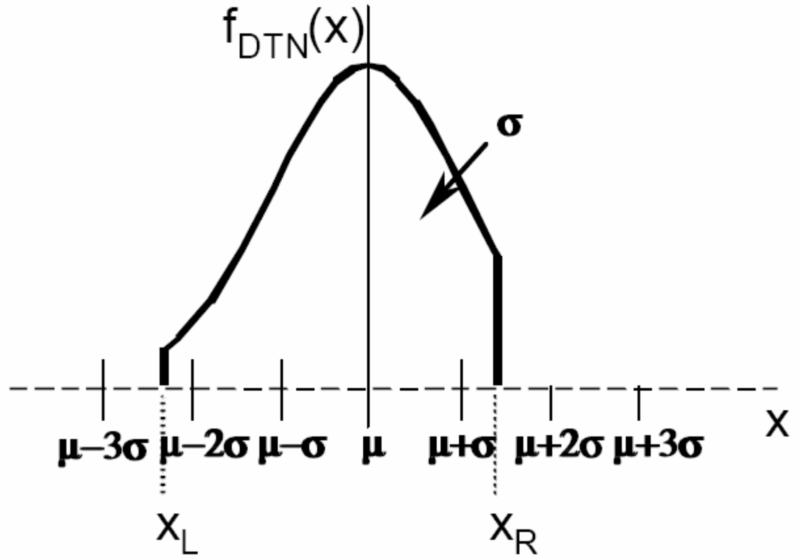
- **Truncated normal distribution over the estimated range**
  - **mean as the nominal value**
  - **standard deviation as ½ of the range (~ one sided 95% confidence interval)**

Parameter	Range	Characteristics	Left and Right Limits (standard form)
Partially closed valve	0-0,5	$\mu = 0$ $\sigma = 0{,}25$	$k_L = 0$ $k_R = 2$
HX plugged pipes	0-0,15	$\mu = 0$ $\sigma = 0{,}075$	$k_L = 0$ $k_R = 2$
Heat loss (Kw)	5-100	$\mu = 5$ $\sigma = 47{,}5$	$k_L = 0$ $k_R = 2$
Non-condensable gas	0-0,8	$\mu = 0$ $\sigma = 0{,}4$	$k_L = 0$ $k_R = 2$

ILLUSTRATIVE EXAMPLE cont'd

$$f_{DTN}(x) = \begin{cases} 0, & -\infty \le x \le x_L \\ f(x)/[F(x_R) - F(x_L)], & x_L \le x \le x_R \\ 0, & x_R \le x \le +\infty \end{cases}$$

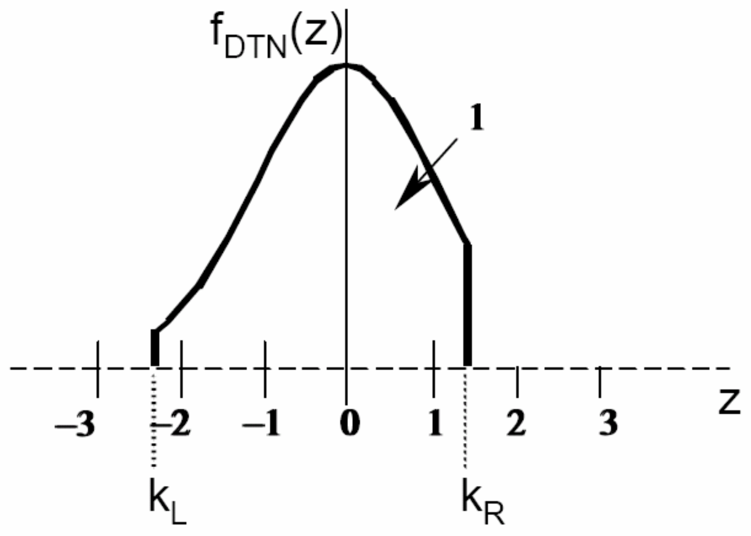
$$f(x) = (1/\sigma \sqrt{2\pi}) \exp -((x-\mu)^2/2\sigma^2)$$



ILLUSTRATIVE EXAMPLE cont'd

$$F_{DTN}(z) = \begin{cases} 0, & -\infty \leq z \leq k_L \\ [F(z)-F(k_L)]/[F(k_R)-F(k_L)], & k_L \leq z \leq k_R \\ 1, & k_R \leq z \leq +\infty \end{cases}$$

$z = (x- \mu)/\sigma$



EXAMPLE Results

- **Failure probabilities for different probability distributions for each failure mode**

$$P_i(x_o) = \int p(x)\,dx$$

$$x \geq x_o$$

Parameter	Pdf	Unavailability
Partially closed valve	Uniform	0,4
	Triangular	0,16
	Truncated Normal	0,19
HX plugged pipes	Uniform	0,33
	Triangular	0,11
	Truncated Normal	0,14
Heat loss	Uniform	0,4
	Triangular	0,18
	Truncated Normal	0,20
Non-condensable gas	Uniform	0,37
	Triangular	0,14
	Truncated Normal	0,17

EXAMPLE Results

- **Failure probabilities among the different distributions are of the same order of magnitude and lie around 1.0E-1value**
- **Triangular and truncated normal distributions are comparable**
  - **Degree of approximation of normal pdf with triangular pdf**
- **Slightly higher values for the uniform distribution**
- **Results conditional upon the assumptions taken in the model**
  - **critical parameters range and distributions through subjective/engineering assessment**
- **Final reliability figure P_f will depend upon the occurrence and combination of the natural circulation failure modes and parameter evolution during the accident/transient**

CONCLUSIONS and STEP FORWARD

- **Integration of passive system unavailability within a PRA framework**
- **Probabilistic estimation of the failure modes**
  - **fault tree incorporating failure model suitable for describing the thermal-hydraulic phenomena**
- **Dynamic event tree to consider the process parameter evolution during the accident in order to evaluate the interaction with the passive system performance**
- **T-h analysis**
- **Monte Carlo simulation technique**
- **Uncertainty in the final results**