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DYNAMIC PSA STUDIES FOR ADVANCED REACTOR USING RAVEN

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ABSTRACT

Probabilistic Safety Assessment (PSA) is used extensively to evaluate the risks associated with complex engineering systems like Nuclear Power Plants (NPPs). Current PSA models are based on the Event-Tree/Fault-Tree (ET/FT) methodology. ET and FT models are static and are based on Boolean logic approaches. In the past, concerns have been raised in the literature regarding the capability of the traditional static modelling approaches to adequately account for the impact of process, hardware, software, firmware and human interactions on the stochastic system behaviour. To overcome the limitations of the traditional approach to PSA, several dynamic PSA methodologies have been proposed. One of the dynamic PSA methodologies used for dynamic evaluations is Dynamic Event Tree (DET) framework which can be used to assess the impact of the parameter variability and scenario dynamics on the PSA model for the initiating event. The DET framework couples the stochastic model (number of component/trains that start on demand, operator action timing, etc.) with a Thermal-Hydraulic (TH) model of the plant.

This paper explores the use of DET along with a case study on advanced reactor. The initiating event selected for the study was Class IV power supply failure event. The TH analysis considering uncertainty in various parameters was performed using RELAP5 and **R**eactor **A**nalysis and **V**irtual control **EN**vironment (RAVEN) tool. Based on the uncertainty analysis, it is concluded that the peak clad temperatures (PCT) are within the limits in all the code runs implying a high-degree of safety margin. However, variation in time to reach the PCT was observed among the code runs and the mean time to reach the PCT was found to be around 8590sec (approximately 2.4 hours). Hence, sufficient time margin is available for human intervention and the operator might have a relatively stress-free state during such an accident scenario. Due to the static nature of the traditional PSA models, the safety margin available was lesser, whereas, with the help of dynamic PSA models, one can demonstrate that the actual available safety margin is more in the present case study and is valuable input from the design point of view

Keywords: Probabilistic Safety Assessment, Advanced Reactor, Dynamic Event Tree, Thermal Hydraulic Analysis, RAVEN.

I INTRODUCTION

Probabilistic Safety Assessment (PSA) is an analytical technique for assessing the risk by integrating diverse aspects of design and operation of complex engineering systems like Nuclear Power Plants (NPP), chemical and process plants, etc. Risk can be defined as the product of the likelihood of occurrence of an undesirable event and the consequences from that event. In the context of a NPP, core damage of the reactor represents an undesirable event and release of radioactivity in the public domain and its effects on them will be the consequence. The classical combination of Event-Tree/Fault-Tree (ET/FT) analysis is used to develop risk models in PSA. ET and FT analysis are static and are based on Boolean logic approaches. Many static PSA tools are available commercially, such as Risk Spectrum, Isograph, IRRAS, SAPHIRE, etc. In general, the present static PSA models do not adequately account for dynamic effects such as impact of process, hardware, software, firmware and human interactions on the stochastic system behaviour. In view of this the present study focuses on implementation of dynamic effects in static PSA models by using dynamic PSA methodologies.

Dynamic methodologies for PSA are defined as a time dependent phenomenological model of system evolution together with its stochastic behaviour to consider all possible dependencies between failure events. The term Dynamic PSA reflects the incorporation of dynamic effects in the PSA models. In this context, the dynamic effects refer to the consideration of effect of time (time dependency) in the input parameters of PSA model. One needs to consider the following points while implementing the dynamic effects in the PSA model such as:

i What are the various dynamic effects that need to be considered in estimating the risk and how do they affect the risk?

ii Do the current PSA models consider the dynamic effects?

iii Can the dynamic effects be implemented in the existing PSA methodologies? If yes, how to implement it and what are the changes required to be carried out?

As described in K.-S. Hsueh and A. Mosleh [1] the dynamic effects can be divided into short time and long time effects as shown in Fig. 1. **Short time effects** occur in a short period of time and in general these effects come into effect once the initiating event starts. Whereas, the **long time effects** occur in a long period of time and they can be effective at any point of time of plant operation.

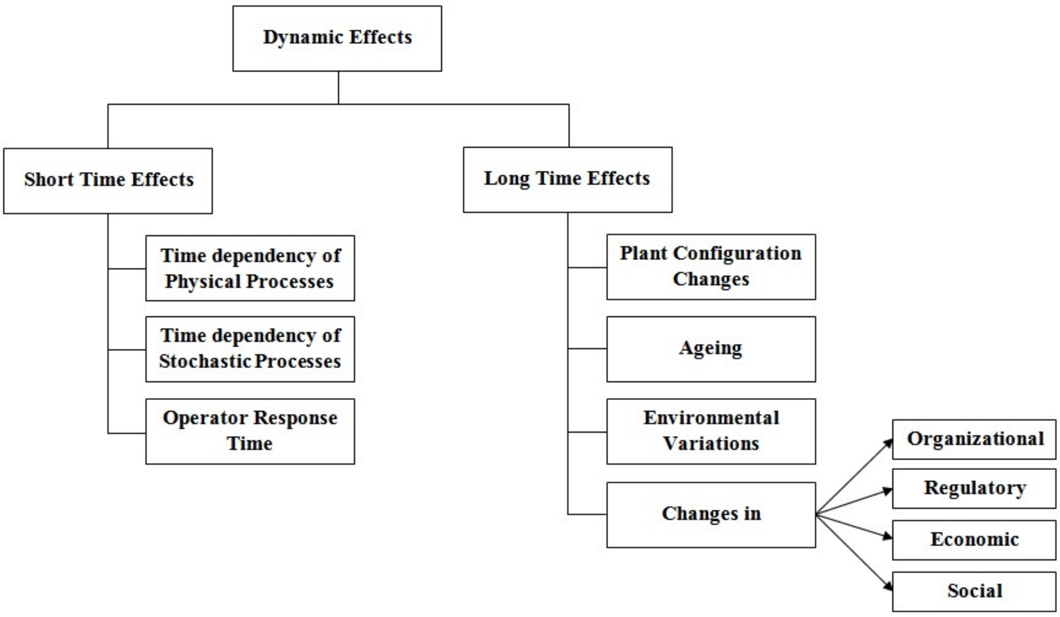

Figure 1. Different types of dynamic effects [1]

1.1 Concerns with Existing PSA Models

Current PSA models are based on the Event-Tree/Fault-Tree (ET/FT) methodology. In the past, numerous concerns have been raised in the literature [2-5] regarding the capability of the traditional static modelling approaches such as the ET/FT methodology to adequately account for the impact of process, hardware, software, firmware and human interactions on the stochastic system behaviour. From a historical perspective, the first challenge identified with the ET/FT methodology was modelling of logic loops. Some other concerns raised in the literature regarding static methodologies include:

- Dealing with the uncertainties resulting from arbitrary discretization of the state space in modeling the process.
- Assumption of a specific type of relation between process variables due to control action, such as proportional change.
- Handling of non-coherence
- Modeling of human behavior

If one carefully examines the existing PSA models the dynamic effects related to long time effects can be incorporated in the existing PSA models. The long time dynamic effects can be accommodated by modifying the estimates of the probabilities of the basic events to reflect the ageing of the components, development of logic models for different plant configurations, and periodic updating of the PSA models. In particular, methods for more explicit representation of component aging effects and the influence of organizational factors are in very early stages of development. In contrast, only a limited, implicit treatment of short time dynamic effects is possible with conventional PSA methodologies. In general, conventional PSAs are limited in representing the interactive nature of the roles of the systems, plant physical processes and operators in forming the accident scenarios.

1.2 Need for Dynamic PSA Tools

Incorporating dynamic (time dependent) interactions into the PSA models is difficult. Such challenges can arise due to human interactions, digital control systems and passive components etc. To overcome the limitations of the traditional approach to PSA, several dynamic PSA methodologies are proposed. However, they are highly computation intensive and can produce very large amounts of data that are difficult to analyze without the use of post processing tools. It should be emphasized that dynamic PSA methodologies should not be regarded as alternative to the traditional PSA but rather complementary for the improved modelling of the systems with significant process, hardware, software, firmware and human interactions.

2 AN OVERVIEW OF DYNAMIC PSA METHODOLOGIES

To predict the response of a system due to the disturbances, one needs to consider the uncertainties arising from the stochastic nature of events (aleatory uncertainties) as well as those arising from lack of knowledge about the processes relevant to the system (Epistemic uncertainties). Usually, it is difficult to distinguish between epistemic and aleatory uncertainties. Dynamic PSA methodologies provide a unified framework to account for the combined effects of both types of uncertainties simultaneously in predicting the distribution of the system response. As per NUREG/CR-6901 [2] dynamic PSA methodologies can be divided into following three categories:

(i) Continuous-time methods
   a. Continuous Event Tree (CET) approach
   b. Continuous Cell to Cell Mapping (CCCM)

(ii) Discrete-time methods
   a. Dynamical logical Methodology (DYLAM)
      - Dynamic Event Tree Analysis Method (DETAM)
      - Dynamic Discrete Event Tree (DDET)

- Accident Dynamic Simulator (ADS)

b. Monte-Carlo (MC) Simulation Approach

c. DDET/MC Hybrid Simulation

d. Cell-to-Cell Mapping Technique (CCMT)

(iii) Methods with visual interfaces

a. Petri Nets

b. Dynamic Flowgraphs

c. Dynamic Fault Trees

d. Event Sequence Diagram Approach

e. GO-FLOW Methodology

Each method has its own advantages and disadvantages. However, in the present study for dynamic evaluations Dynamic Event Tree (DET) framework has been utilised to assess the impact of the variability and scenario dynamics on success criteria and its impact on PSA model for the initiating event. The DET framework couples the stochastic model (number of component/trains that start on demand, operator action timing etc.) with a Thermal-Hydraulic (T-H) model of the plant. For this T-H code simulations need to be carried out for different combinations of scenarios.

3 CASE STUDY ON ADVANCED REACTOR

Accidents in nuclear power plants involves complex interactions among safety system, process system and operator actions. In static PSA, calculations with pre-determined state of equipment and operator times, there is simplification of the complex interactions. For example, the total time of operator action time (diagnosis and execution) can be dynamic. The dynamics of the process may force the operator to go through different sets of procedure steps depending on the state of safety system and plant parameters to variation in operator response time. Since dynamic reliability of a full scope PSA is a challenging task and not conceivable at present, the methodology is explained by considering one initiating event and its corresponding event progression for a typical advanced reactor. The advanced reactor considered in this study is a 300 MWe vertical, pressure tube type, boiling light water cooled natural circulation reactor [6][7]. The reactor core is housed in a calandria that contains low pressure heavy water, which acts as moderator as well as reflector. The reactor consists of several passive features such as Emergency core cooling system (ECCS), Passive Poison Injection System (PPIS), Isolation Condensers (ICs), Passive Containment Isolation System (PCIS) etc. A large source of heat sink is located close to top of the containment called gravity driven water pool (GDWP) system serves as a heat sink for several passive systems.

3.1 Static Event Tree

In this case study, Class IV power supply failure has been considered as an initiating event. The various systems which needed to be operated on demand are Reactor Protection System (RPS), PPIS, ICs, Emergency Power Supply System (EPSS) and Shutdown Cooling System (SDCS). In this transient, when there is a Class IV power supply failure, reactor will trip on “main heat transport system high pressure”. Reactor protection system has two independent, diverse and automatic shutdown systems each capable of independently shutting down the reactor and maintaining the reactor in shutdown state. If reactor fails to trip due to wired system failure, Passive Poison Injection System will be actuated. Isolation Condensers (IC) are used to remove the decay heat from the core, during shut down condition for 3 days without operator intervention. When reactor is tripped, the ICs will be ‘valved in’. The ICs will cool the core from 285^{o}C to 150^{o}C. For cooling below 150^{o}C and holding it cold enough for carrying out maintenance work, Shutdown cooling system (SDCS) is provided for long term decay heat removal. In case of unavailability of both main condenser and isolation condenser, the shutdown cooling can be valved in at hot shutdown conditions. Class III power supply is required for operating the shutdown cooling system pumps. The static event tree for Class IV power supply failure is shown in Fig. 2 (without dotted lines).

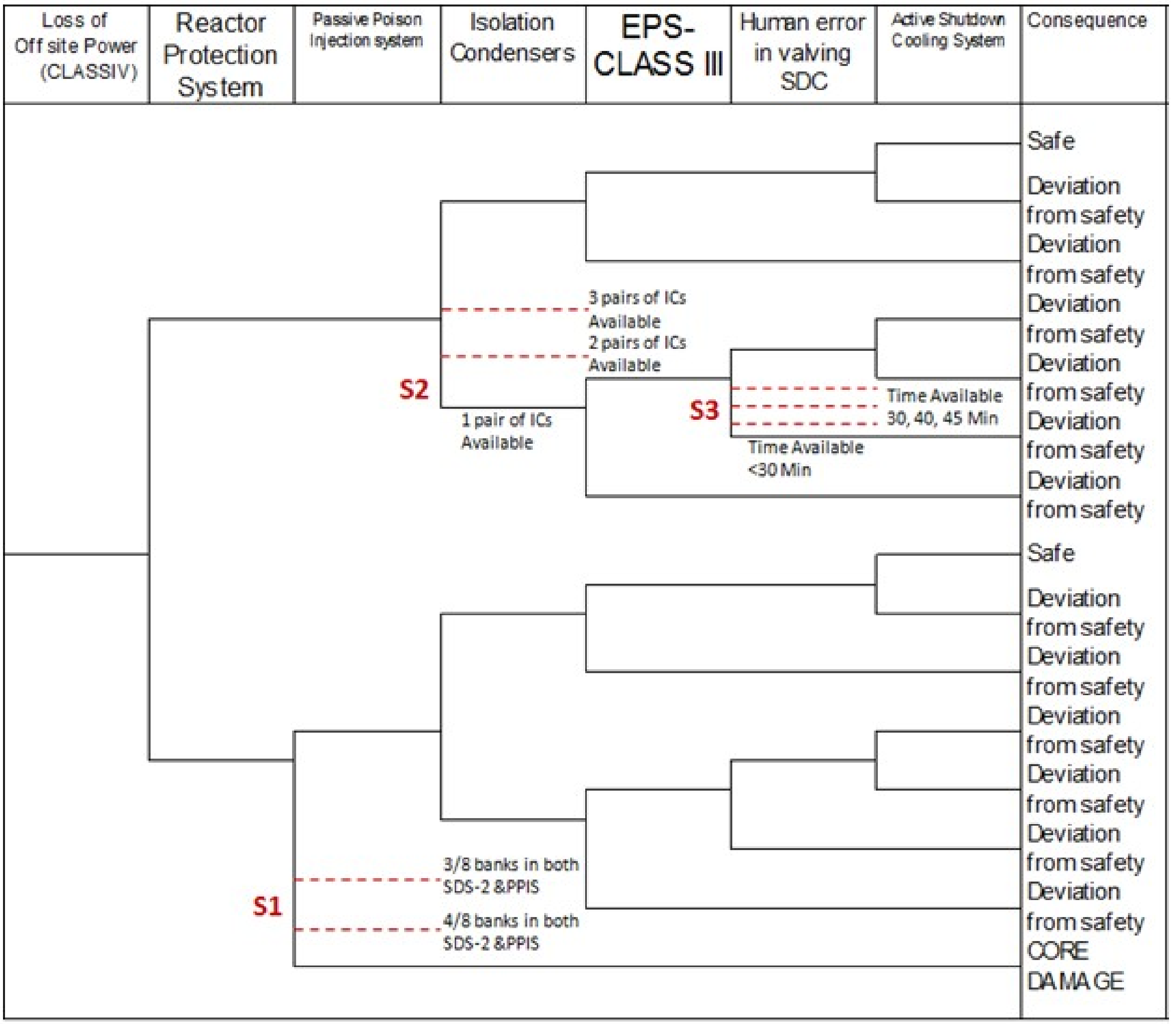

Figure 2. Static and Dynamic Event tree for Class IV Power supply failure in Advanced Reactor

3.2 Dynamic Aspects in Class IV Failure Event

The possibilities of dynamic situations in the above explained accident scenario is listed below:

i Partial SDS-2 injection with partial PPIS injection. SDS-2 and PPIS is assumed to be failed, if two or more poison tanks fail to inject within designed time. Core damage is assumed even if 6 banks are injected from both the systems.

ii What is the impact of variation in IC success criteria (with 4 or less loops) on decay heat removal? How long it will take to remove decay heat with various IC success criteria options? This will impact the role of Class III availability.

iii Operator action time for hot valving in of SDCS, with IC failure postulated in 5 or more loops.

iv SDCS valving in time variation due to operator action uncertainties, in case of success of IC.

The present static event tree is developed on the conservative basis which does not consider partial functioning of the safety systems, stochastic failure of components/systems and variation in the operator action time. When such dynamic conditions are incorporated (dotted lines in Fig. 2) the possible accident sequences for dynamic event tree will increase many folds. As one can see from Fig. 2, the number of accident sequences in dynamic event tree is more than the static event tree. One needs to carryout deterministic TH analysis for all the scenarios to find out the realistic consequence from Class IV power supply failure and is highly computationally intensive [8] [9]. In the present study three scenarios were identified such as failure of safety systems in the shutdown phase, failure of safety systems in the decay heat removal phase and human intervention during the decay heat removal phase as mentioned below:

- Scenario 1 (S1): Partial SDS-2 injection with partial PPIS injection.
- Scenario 2 (S2): Failure of both Class IV & Class III power supply failure (Station Black Out, SBO, event) along with Availability of ICs with various success criteria (1 pair out of 4 pairs of ICs available)
- Scenario 3 (S3): Operator action time for hot valving in of SDCS, with IC failure postulated in 5 or more loops.

4 EVALUATION OF DYNAMIC SCENARIOS

In this section the methods adopted for handling dynamic actions in the analysis are explained. As described in the previous section there are three dynamic scenarios identified in the present study. However, for demonstration purpose scenario 2 has been considered. These scenarios were analysed in the DET frame work using RELAP5 and RAVEN tools.

4.1 Modelling of Accident Scenario using RELAP5

Reactor Excursion and Leak Analysis Program (RELAP5) [10] is a light water reactor transient analysis code developed for simulation of a wide variety of hydraulic and thermal transients in both nuclear and nonnuclear systems. RELAP5 can be used for reactor safety analysis, reactor design, simulator training of operators, and as an educational tool by universities. In the present case study RELAP5 code has been used for TH analysis. A RELAP5 specific plant model has been developed for the transient analysis with the thermal-hydraulic component and a point kinetic model with reactivity feedback from coolant void, coolant temperature and with fuel temperature. Fig. 3 shows RELAP5 nodalization of the system under study.

The TH analysis was performed with variations in the number of isolation condenser available for the safety function and was performed using RELAP5. The analysis showed that the availability of more than one isolation condenser is sufficient to keep the clad temperature within limits under Class IV and Class III failure. Hence, further uncertainty analysis was carried out with one pair out of 4 pairs of isolation condensers available. The base case scenario was simulated and the results have been obtained for peak clad temperature (PCT) as shown in the Fig. 4. In the present analysis following failure criteria (exceedance of PCT over a prescribed threshold value) has been adopted [8]:

i. Safe: PCT < 400^0C
ii. Deviation from Safety: 400^0C < PCT < 800^0C
iii. Core Damage: PCT > 1200^0C

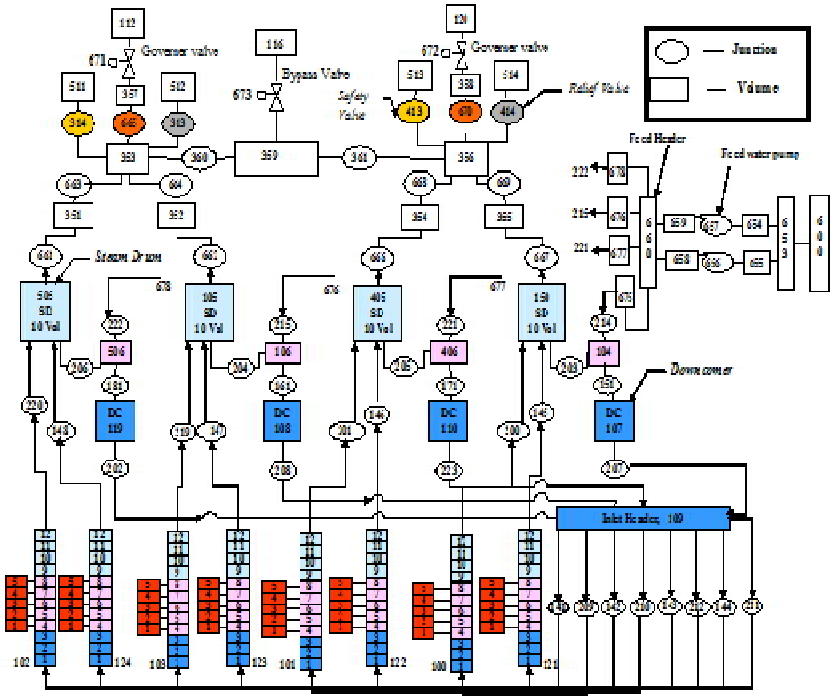

Figure 3. RELAP5 Specific Model for Accident Scenario

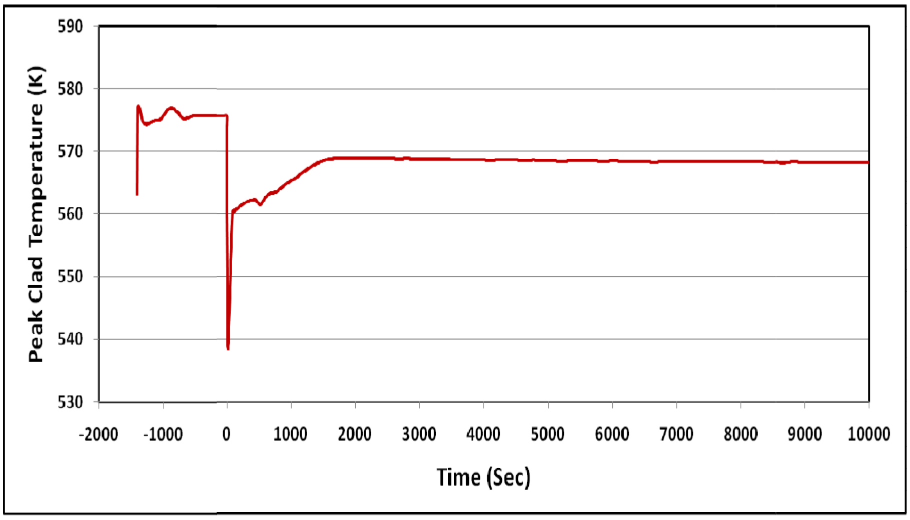

Figure 4. Peak Clad Temperature in Base Run

4.2 Uncertainty Analysis using RAVEN

As the dynamic PSA analysis involves lot of computations it needs software tools to incorporate stochastic behaviour. One such software tool available is **R**eactor **A**nalysis and **V**irtual control **EN**vironment (RAVEN) [11]. RAVEN is a software framework developed by Idaho National Laboratory (INL), to perform parametric and stochastic analysis based on the response of complex system codes. In the present analysis RAVEN has been used for carrying out the uncertainty analysis.

Sensitivity studies have been carried out to identify the parameters which have more effect on Peak Clad Temperature (PCT). Based on the sensitivity studies, the following parameters have been chosen for uncertainty analysis Heat Transfer Coefficient (HTC), Non Condensable (NC) gas flow rate, Power Level and Pressure Loss coefficient. The various uncertain parameters used in the analysis along with their distributions are given in Table I. To perform the sampling of the input Space Monte Carlo sampling approach of forward sampler category has been used. The samples so created are shown in Fig. 5 for the case of HTC. TH analysis has been carried out by using RELAP5 for various samples generated. Based on the analysis, the variation in the peak clad temperature as a function of time for different scenarios is evaluated and is shown in Fig. 6. Further, comparison of available safety margin and variation of time to reach PCT among various cases are also analysed and are shown in Fig. 7 and Fig. 8 respectively.

From the view point of uncertainty analysis, there is not much variation in Peak Clad temperature, in all simulations. Even though, static PSA has considered the Class IV failure along with failure of IC as 'Deviation from safety', it has been observed that sufficient margin exists and Peak clad temperature is well below 400^{o}C in all the simulations. Similarly, the mean time to reach PCT is found to be around 8590 sec (approximately 2.4 hours). Hence, sufficient time margin is available for human intervention and also for further mitigation of accident scenario. This brings clarity of stress level of operator and complexity of scenario for human reliability analysis as well.

Table I: Various uncertain parameters used in the TH Analysis

Parameters	Range			Distribution
	Upper Limit	Nominal	Lower Limit	
Heat Transfer Coefficient (W/m^2-K)	22095	18413	14730	Uniform
Non Condensable Gas (%)	6.6	5.5	4.4	Uniform
Decay Heat (MWTh)	1012	920	828	Uniform
Pressure Loss coefficient	1.2	1	0.8	Uniform

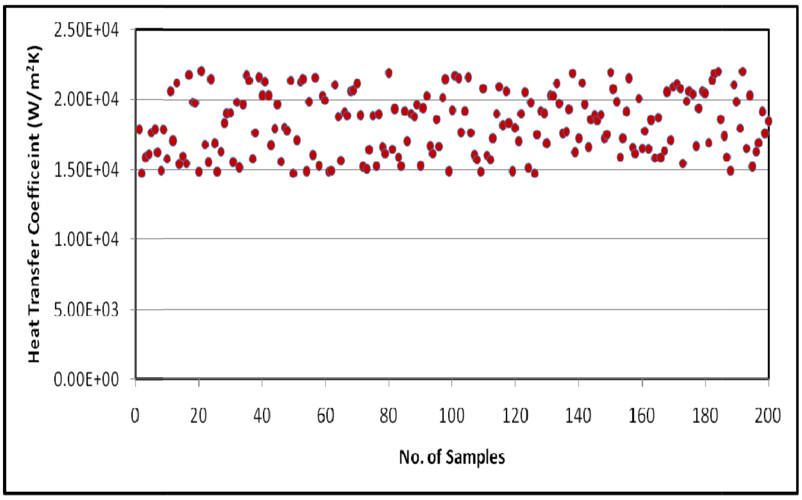

Figure 5. Input sample space of Heat Transfer Coefficient

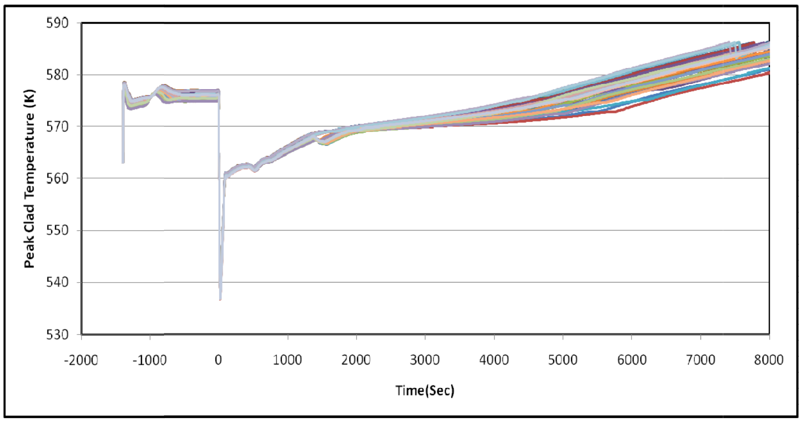

Figure 6. Peak Clad Temperature for various cases using RAVEN

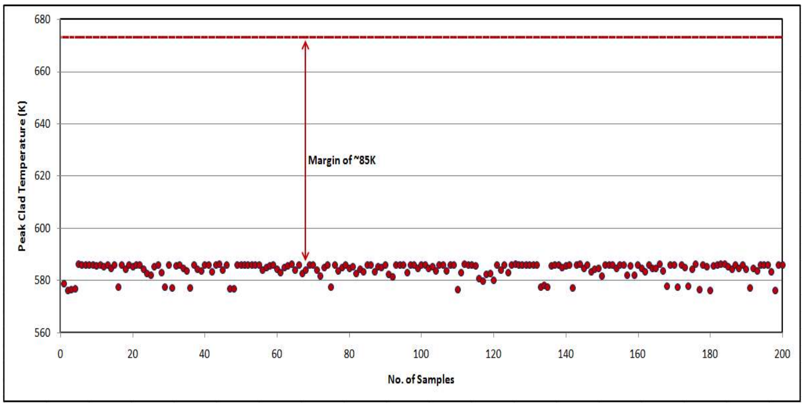

Figure 7. Comparison of Safety Margin among various cases

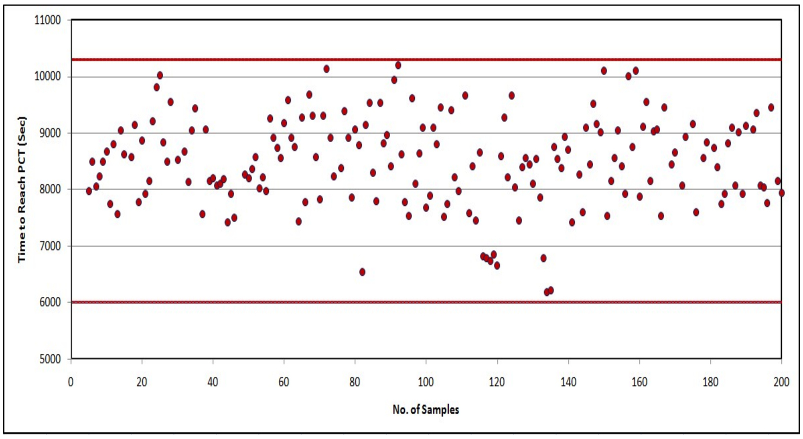

Figure 8. Variation of time to reach PCT among various cases

5 CONCLUSIONS

The present paper explains the various dynamic PSA methodologies used for dynamic evaluations and the use of DET frame work has been highlighted with a case study on advanced reactor. The initiating event considered for the study is Class IV power supply failure event. The dynamic aspect of analysis is considered as availability of ICs with various success criteria. The TH analysis was performed with variations in the number of isolation condenser available for the safety function and was performed using

RELAP5. Uncertainty analysis was carried out by considering the uncertainty in Heat Transfer Coefficient, Non Condensable gas flow rate, Power, and Pressure Loss coefficient. All the code runs predict that the peak clad temperatures are within the limits implying a high-degree of safety margin. The time to reach the peak clad temperature is varying depending on the code runs but the variation is not very high. The mean time to reach PCT is found to be around 8590sec. Hence, sufficient time margin is available for human intervention and the operator might have a relatively stress-free state during such an accident scenario as more margin is available from safety point of view. Due to the static and conservative nature of the traditional PSA models, the safety margin available was lesser, whereas, with the help of dynamic PSA models, one can demonstrate that the actual available safety margin (PCT margin is around 85 K) is more in the present case study and is a good input from the design point of view.

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