# PRELIMINARY PHASE OF A MCDET ANALYSIS OF A HIGH PRESSURE SCENARIO WITH POTENTIAL STEAM GENERATOR TUBE RUPTURE

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***Abstract:*** *The tool MCDET for Integrated Deterministic Probabilistic Safety Analyses (IDPSA) allows for performing MC simulation, DET simulation or a combination of both to account for any kind of uncertainty in the behavior of a complex dynamic system. The efficient link of deterministic and probabilistic models which can be realized by MCDET essentially facilitates a more realistic analysis and improved safety assessment of the system. An extra Crew Module permits to calculate time-dependent human action sequences interacting with the simulated system behavior and with any other influencing factor. The MCDET capabilities have already been demonstrated by several applications. A new application currently prepared aims to assess the potential of a thermally induced steam generator tube rupture during a high pressure scenario in a pressurized water reactor. This paper gives an overview on the new application case. The MCDET methods selected to be applied as well as the high pressure scenario and the uncertainties taken into account are described. Special emphasis is given to probability models used for uncertainty quantification. Furthermore, the computer code to be applied in combination with MCDET is outlined.*

## I. INTRODUCTION

IDPSA methods consistently integrate deterministic and probabilistic models and are recommended to be applied in a complementary analysis to the classical deterministic (DSA) and probabilistic (PSA ) safety analysis to better cope with the influence of uncertainties on the behavior of a complex dynamic system [1, 2]. They make extensive use of a simulation code from DSA and apply advanced modelling techniques to simulate system dynamics affected by uncertainties and to provide well-founded probabilistic safety assessments.

The tool MCDET (Monte Carlo Dynamic Event Tree) allows for applying Monte Carlo (MC) simulation, Dynamic Event Tree (DET) simulation or a combination of both to perform an IDPSA [3]. The efficient and consistent link of powerful deterministic and probabilistic models which can be realized by MCDET essentially facilitates the simulation of the inherent interactions of a complex dynamic system whilst both aleatory (due to random events) and epistemic (due to lack of knowledge) uncertainties can be taken into account in a rather comprehensive manner. MCDET can be coupled with any computer code for system dynamics simulation. What makes MCDET particularly useful for safety analyses of complex systems where human actions play an essential role is its Crew Module. This Module allows for considering human actions as a time-dependent sequence which is able to interact with the simulated system dynamics and with any other potential influencing factor.

The capability of MCDET has already been demonstrated by several applications [4]. A new application currently prepared aims to probabilistically assess the potential of a thermally induced steam generator (SG) tube rupture during a high pressure accident scenario in a pressurized water reactor (PWR). Most of the aleatory uncertainties selected to be considered relate to the performance of technical components and human actions when they are demanded to fulfill safety relevant tasks. An important aspect in this context is the timing such as the times of component failures during mission time or the time periods for executing human actions. Besides aleatory uncertainties, epistemic uncertainties are considered as well. They refer, on the one side, to model formulations and parameters of the applied simulation code and, on the other side, to parameters of the probability models used to quantify the aleatory uncertainties.

In Section II, the MCDET methods to be applied and their usage for handling aleatory and epistemic uncertainties are addressed. Section III gives an overview on the application case. The high pressure scenario and the uncertainties selected to be considered are outlined. Special emphasis is given to two probability models describing aleatory uncertainty. One model refers to the performance of the pressurizer valves when they are cyclically demanded for primary side pressure limitation;

the other refers to the degree of degradation of the SG tubes when the accident is initiated. Section III also addresses the computer code selected to be applied for accident simulation and the upgrades performed to efficiently run the computer code in combination with MCDET. The conclusions are presented in Section IV.

## II. MCDET METHODS

MCDET can be coupled with any computer code used for accident simulation. It implements MC simulation, DET simulation and a combination of both to consider the influence of epistemic and aleatory uncertainties. The method recommended to be applied for epistemic uncertainties is MC simulation. In this case, possible values of the epistemic variables (= variables subject to epistemic uncertainty) are sampled and then successively transferred as part of the input to corresponding simulation runs. Further input to and the configuration of these simulation runs are determined by the method applied to investigate the influence of aleatory uncertainties. In principle, the possible values of the epistemic variables are considered in the outer loop whereas those of the aleatory variables (= variables subject to aleatory uncertainty) are considered in the inner loop of the simulation runs. For the analysis of the influence of aleatory uncertainties, either MC simulation, DET simulation, or the combination of both can be applied. To better cope with failures of components on demand which only occur with rather low probabilities and, additionally, with failures of components to run until the end of mission time, the combination of MC and DET simulation is proposed and, therefore, selected to be applied for the analysis described in this paper.

For the combination of MC and DET simulation, both sampling and transition related information must be specified as input of MCDET. After the simulation of the root sequence was started, MCDET evaluates the system state at each point in time of the simulation run to find out whether a condition either for sampling the values of aleatory variables (sampling condition) or for generating a random transition of the system state (transition condition) is fulfilled.

When MCDET detects that the time and/or system state of a simulation run fulfill a sampling condition (e.g., initial system state, demand of a safety system), it evaluates the information associated with the sampling condition and correspondingly samples a value from the respective distribution of each involved aleatory variable.

When the time and/or system state of a simulation run satisfy a transition condition (e.g., initial system state, demand of a safety system, time corresponds to failure time of a safety system), MCDET immediately initiates the transition according to the information associated with this condition. The information includes the possible values (transition outcome alternatives) to be assigned to a system state variable and the corresponding transition probabilities. If there are at least two system state values to be considered as transition outcome (e.g., success and failure on demand), MCDET automatically generates a branching point at the time when the corresponding transition condition is fulfilled. All system states which are likely to occur at the branching point - even those of low transition probabilities - are considered in separate simulation branches. For instance, at the point in time, when a safety system is demanded, both successful and failed operation of the safety system are considered. From the simulation run currently evaluated and scheduled for running the successful operation of the safety system, a new simulation branch is cloned and appropriately modified so that the failed operation of the safety system is considered. Subsequently, the new simulation branch is automatically launched in a separate process running in parallel with the simulation processes already created. Each time when MCDET detects that the time and/or system state of a simulation run fulfill another transition condition requiring at least two system state alternatives to be considered, another branching point is generated and the corresponding new simulation branches are automatically started. Since the system state of each new simulation branch is evaluated as well by MCDET, this branch may, in turn, be the parent of other new simulation branches.

When a transition condition is fulfilled, the corresponding transition outcome alternatives must not be fixed values. An aleatory or epistemic variable can be assigned to a system state variable as well. In this case, MCDET automatically assigns an appropriate value previously sampled for the involved aleatory or epistemic variable to the corresponding system state variable. This allows for adequately considering transition outcome alternatives referring to continuous system state variables such as the opening diameter of a valve or the injection capacity of a pump. For instance, at the point in time, when a valve is demanded to open for pressure release, two alternatives can be considered, namely the valve opens successfully or it opens with a reduced diameter. In the latter case, the value of the reduced opening diameter can be sampled from an appropriate distribution and assigned to the corresponding system state variable. MCDET can sample the value before the simulation is actually started (e.g., initial system state) or at the point in time when the value is needed (e.g., demand of the valve). The latter alternative allows for considering the impact of the system state on the aleatory uncertainty referring, for instance, to the valve opening diameter. So, a distribution with a higher probability for a lower valve opening diameter may be considered, if high temperature and pressure seriously aggravate the ambient condition of the corresponding valve.

A transition which can be handled by MCDET must not occur at a deterministic point in time, for instance, at the time when a safety system is demanded, but can also occur at a random point in time. For this purpose, the transition condition must require that the time of a simulation run has to correspond to an appropriate time variable for which a possible value was previously sampled. Such a time variable is, for instance, the failure time of a technical component during operation. The value to be considered for this failure time can be sampled, for instance, at the point in time when the component is demanded.

MCDET automatically assigns a conditional probability to each simulation branch. Multiplication of the conditional probabilities of all branches which make up a whole sequence finally gives the sequence probability. The results provided by the combination of MC and DET simulation can be considered as a sample of individual DETs. Each DET is constructed on condition of values each randomly sampled for a selected – mostly continuous - aleatory variable. Due to the effects of the different values sampled for the aleatory variables, timing and order of events may differ from DET to DET. As analysis results, MCDET provides the conditional DET-specific distributions of a system state and the corresponding unconditional (scenario-specific) distribution at each point in time. The latter is estimated as the mean distribution over the sample of corresponding DET-specific distributions. From these results, (conditional) probabilities of damage states can be easily derived. Additionally, a statistical confidence interval [e.g., [5]) around any probability of the scenario-specific distribution can be provided. Each interval may be used to represent the uncertainty of the corresponding (mean) probability due to the limited number of DETs (i.e. number of values sampled per continuous aleatory variable) considered in the analysis.

More information on the MCDET methods can be found in [3, 4].

## III. APPLICATION CASE

This section outlines the accident scenario, followed by a description of the aleatory and epistemic uncertainties selected to be considered and by an overview on the computer code to be applied in combination with MCDET.

### III.A. Accident Scenario

To assess the potential of a steam generator tube rupture (SGTR) in a high pressure situation, a station black-out (SBO) scenario is considered. The scenario is assumed to occur in a PWR at nominal power. Initiating event is a total SBO characterized by the total loss of power from offsite, redundant emergency diesel generators and other sources. Batteries are assumed to guarantee DC power supply to all battery supported functions over the time period of 20000 s selected as the maximum problem time of the application. Power is assumed not to be recovered within the considered time period. Due to the loss of power, the main coolant pumps and all operational systems fail. Failure of the main coolant pumps causes automatic scram and turbine trip. In the following, heat removal from the reactor core to the steam generators (SG) is reached through natural circulation.

Failure of the main heat sink leads to pressure increase in the SG until the secondary side pressure relief valves are supposed to open for pressure release of the SG to a corresponding pressure level. Besides the relief valve, also a safety valve is available per SG for pressure release. The pressure level is supposed to be kept until the feed water level of the SG decreases under a corresponding level. In this case, the emergency operating procedure (EOP) 'Secondary side bleed and feed' is supposed to be initiated. The procedure includes the further depressurization of the SG so that feed water from different sources can be injected into the SG.

On the primary side, the pressure decreases after the pressure release of the SG and then increases again. Due to the volume expansion of the coolant on the primary side, the pressurizer level increases and the pressurizer relief valve (PRV) is supposed to open for automatic pressure limitation on the primary side. If the pressure decreases far enough, the PRV is supposed to close. Besides the PRV, two safety valves (SV1, SV2) can also operate for pressure limitation. There is a cyclic opening and closing of the pressurizer valves during automatic pressure limitation.

When the corresponding signal indicates that the criterion is fulfilled to manually open all pressurizer valves for primary side pressure release (EOP 'Primary side bleed and feed), the corresponding human actions are assumed not to be performed. This has the consequence that the system pressure remains on a high level. Only pressurizer valves which stuck open during automatic pressure limitation could lead to a pressure relief on the primary side. If in this case, the pressure on the primary side has decreased far enough, the accumulators can inject their coolant inventory, provided the associated source and additional isolation valves open on demand.

Due to the scenario and the uncertainties taken into account, the core may experience gradual damage. High core melt temperatures in combination with high system pressure may lead to the failures of the main coolant piping in the hot leg and the pressurizer surge line. Elevated primary-to-secondary system differential pressure may cause the thermally induced SGTR.

**III.B. Aleatory Uncertainties**

With regard to the secondary side, the performance of the corresponding pressure relief valves and safety valves when they are demanded to open for pressure release of the SG to a plant-specific level have been originally considered as aleatory uncertainties. However, it can be assumed that already the opening of one valve out of 8 is able to release the pressure in all four SG so that the stuck close failure of one or more valves would just extend the time until a thermally induced SGTR may occur. Furthermore, it can be assumed, that the very unlikely failure of all valves does not lead to the elevated primary-to-secondary system differential pressure considered to pose the greatest threat for a thermally induced SGTR. For these reasons, it was decided not to consider the aforementioned aleatory uncertainties.

Since SG depressurization increases the primary-to-secondary system differential pressure whereas the subsequent feed water injection into the SG in turn reduces the differential pressure, only the first main human task of the EOP 'Secondary side bleed and feed', namely the bleeding, was selected to be considered. Using the Crew Module of MCDET, the corresponding human actions can be modeled as a time-dependent sequence where both the timing and outcome (success or error of omission) of an action can be considered as aleatory uncertainty. Furthermore, the timing and outcome can be influenced by an external factor such as the actual process state calculated by the computer code coupled to MCDET. Running the Crew Module with simultaneous consideration of aleatory uncertainties provides probability distributions for the time periods needed to accomplish relevant EOP tasks. These tasks include the deactivation of the automatic functions of the reactor protection system, the preparation of the electricity supply of the bleed bus bar and the opening of the relief valves for SG depressurization. The latter task can only be started, if intermediate results of the applied computer code say that the corresponding process criterion is fulfilled. Each probability distribution provided by the Crew Module can be considered as non-parametric discrete distribution, or it can be approximated by an adequate parametric distribution. In any case, MCDET is able to perform MC simulation based on the given distributions in order to appropriately consider the variation of the timing of relevant EOP tasks.

With regard to the primary side, the aleatory uncertainties selected to be considered concern the performance of the PRV and the two safety valves SV1 and SV2 during the repeated demand cycles of the automatic pressure limitation. It was decided to consider the individual failure behaviors of the valves when they are cyclically demanded to open or to close. The data to assess the behavior of the valves are obtained from operational experience and include the probabilities for independent and common cause failures (CCF) for the failure modes 'failure to open' and 'failure to close', respectively. The probability model applied to consider the aleatory uncertainty on the behavior of the valves is described in more detail in paragraph III.B.1.

As already mentioned in paragraph III.A, the primary side pressure release is assumed not to be performed. That means a condition of the analysis is the failure of the crew to open the operating pressurizer valves. Only pressurizer valves which stuck open during automatic pressure limitation could lead to a pressure relief on the primary side.

If the pressure on the primary side can be released to a level below 2.5 MPa, the accumulators can inject their coolant inventory. The successful injection from the accumulators requires that the source isolation valve and the additional isolation valves of the accumulators open on demand. The performance of each valve when it is demanded to open is considered as aleatory uncertainty. The corresponding probability for a failure on demand is derived from data from operational experience.

Other aleatory uncertainties selected to be considered refer to the degree of degradation of the SG tubes. An important uncertainty in this context is the time period between the last test of the SG tubes and the initiating event of the accident scenario. The longer this time period the longer the tubes are exposed to stress which might increase the degradation of the tubes. The probability model applied to consider the uncertainty on the degree of degradation of the SG tubes is described in more detail in paragraph III.B.2.

*III.B.1. Behavior of the Pressurizer Valves*

The pressurizer valves PRV, SV1, and SV1 are used for automatic pressure limitation of the primary side. They are demanded to open and to close in repeated cycles. The corresponding independent failure-on-demand probabilities derived from operational experience are constant over the number of demand cycles, i.e. no degradation of the valves in the course of repeated demands is assumed. However, the failure probabilities of the PRV on the one side and the two safety valves on the other side differ from each other.

As mentioned in Section II, the combination of MC and DET simulation shall be applied to analyze the influence of aleatory uncertainties. This combination essentially facilitates the treatment of the aleatory uncertainties with respect to the behavior of the pressurizer valves. The uncertainties selected to be considered are the number of the demand cycle (failure cycle) at which a valve may fail during the repeated demand cycles and the failure mode of a valve. Each valve may fail in a 'stuck close' or in a 'stuck open' failure mode. Whereas the failure mode of a valve shall be directly considered by two different branches in a DET, the possible values of the failure cycle of a valve shall be at first sampled from the corresponding probability distribution and then separately considered as branching points of a DET.

The probability distribution of the failure cycle of a valve can be deduced from following considerations.

If $p_{sc}$ and $p_{so}$ denote the constant failure probabilities given for a 'stuck close' and a 'stuck open' failure on demand, the probability for a 'stuck close' failure at the first demand cycle is equal to $p_{sc}$ (Eq. (1)).

$$P(\text{stuck close failure at } 1^{st} \text{ cycle}) = p_{sc} \tag{1}$$

The failure of a valve to close at its first demand cycle is only possible on condition that it successfully opened before. Therefore, the probability that the valve fails to close at its 1st demand can be calculated according to Eq. (2).

$$\begin{aligned} &P(\text{stuck open failure at } 1^{st} \text{ cycle}) \\ &\quad = P(\text{stuck open failure} \mid \text{open at } 1^{st} \text{ cycle}) \cdot P(\text{open at } 1^{st} \text{ cycle}) \\ &\quad = p_{so}(1 - p_{sc}) \end{aligned} \tag{2}$$

The probability that a valve fails (either to open or to close) at its 1st demand cycle (Eq. (3)) is the sum of the probabilities given in Eqs. (1) and (2).

$$P(\text{failure at } 1^{st} \text{ demand cycle}) = p_{sc} + p_{so}(1 - p_{sc}) \tag{3}$$

The failure of the valve to open at its 2nd demand cycle is only possible on condition that the valve survived its 1st demand cycle. Hence, the probability that the valve fails to open at its 2nd demand cycle is calculated as indicated in Eq. (4).

$$\begin{aligned} &P(\text{stuck close failure at } 2^{nd} \text{ cycle}) \\ &\quad = P(\text{stuck close failure} \mid \text{survive } 1^{st} \text{ cycle}) \cdot P(\text{survive } 1^{st} \text{ cycle}) \\ &\quad = p_{sc}(1 - p_{sc})(1 - p_{so}) \end{aligned} \tag{4}$$

The failure of the valve to close at its 2nd demand cycle can only occur on condition that the valve survived the 1st demand cycle and opened successfully at its 2nd demand. The corresponding failure probability is given in Eq. (5).

$$\begin{aligned} &P(\text{stuck open failure at } 2^{nd} \text{ cycle}) \\ &\quad = P(\text{stuck open failure} \mid \text{survive } 1^{st} \text{ \& open at } 2^{nd} \text{ cycle}) \\ &\qquad \cdot P(\text{survive } 1^{st} \text{ \& open at } 2^{nd} \text{ cycle}) \\ &\quad = p_{so} \cdot (1 - p_{sc})(1 - p_{sc})(1 - p_{so}) \end{aligned} \tag{5}$$

Thus, the probability that a valve fails at its 2nd demand cycle (Eq. (6)) is the sum of the probabilities in Eqs. (4) and (5).

$$P(\text{failure at } 2^{nd} \text{ cycle}) = [p_{sc} + p_{so}(1 - p_{sc})]\,[(1 - p_{sc})(1 - p_{so})] \tag{6}$$

Analogue reasoning and calculation for failure probabilities at demand cycles > 2 provides the formula for the Geometric probability distribution with parameter $p = p_{sc} + p_{so}(1 - p_{sc})$ and $n = 1,2,\ldots$ as indicated in Eq. (7).

$$P(\text{failure at } n^{th} \text{ cycle}) = [p_{sc} + p_{so}(1 - p_{sc})] \cdot [(1 - p_{sc})(1 - p_{so})]^{n-1} \tag{7}$$

For $p_{sc}$ = 5.83E-3 and $p_{so}$ = 3.50E-3, the density and the cumulative distribution function of the Geometric distribution are shown in Fig.1.

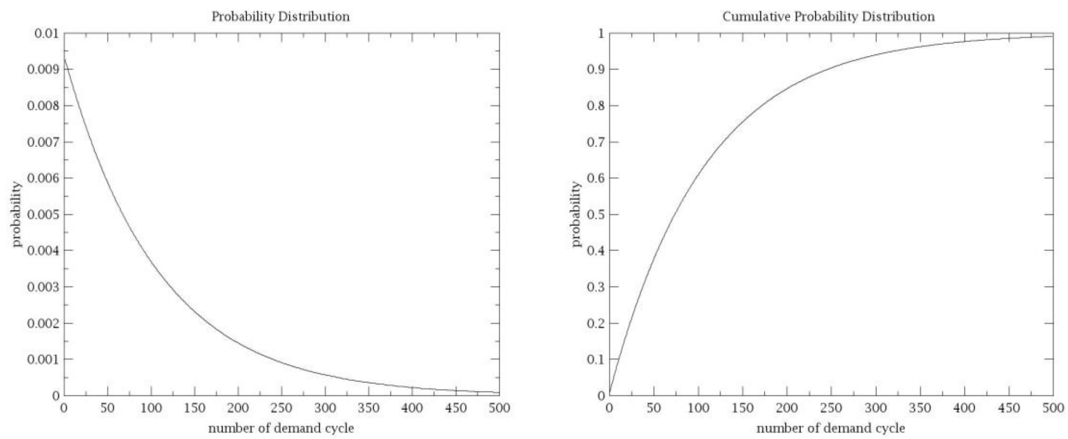


Fig. 1. Density and the cumulative distribution function of the Geometric distribution.

To account for the influence of different failure cycles in more detail, it was decided to simultaneously consider three different intervals for the failure cycles. For that purpose, the range of possible values of the failure cycle is divided into values between 1 and 20 (early failure time), between 21 and 60 (medium failure time) and values exceeding 60 (late failure time). To sample failure cycles from each of these intervals, the Geometric distribution (Fig. 1) over each interval has to be normalized. The normalization also has to account for the condition that a stuck open failure does not happen until demand cycle 60. This condition is assumed in order to keep the pressure on the primary side at a high level for a longer time period.

Each set of values for early, medium and late failure cycles available after application of the sampling procedure shall be treated in a corresponding DET as branching points of two branches (branch 1: valve operates successful, branch 2: valve fails). The conditional probabilities assigned to the failure branches are given by (where *FC* = failure cycle):

- $p_1$ = P(1 ≤ stuck close *FC* ≤ 20) / P(stuck open *FC* > 60) for a branching at early failure time
- $p_2$ = P(21 ≤ stuck close *FC* ≤ 60) / P(*FC* > 20 ∧ stuck open *FC* > 60) for a branching at medium failure time

It should be pointed out that a branching at late failure time is generated only, if the corresponding - randomly selected - failure cycle falls within the problem time of the application. If this is the case, it must be taken into account, that the failure times of a stuck close and a stuck open failure are different, although the same failure cycle is considered for both failure modes. So, if a branching at late failure time has to be considered, the conditional probabilities assigned to the failure branches are given by

- $psc_3$ = P(stuck close *FC* > 60) / P(*FC* > 60) for the stuck close failure
- $pso_3$ = 1 for the stuck open failure, i.e. it is absolutely sure that a valve fails in stuck open mode at a demand cycle > 60, if it does not fail in stuck close mode and already survived the first 60 demand cycles

Fig. 2 shows the sequences to be considered in a DET with regard to the behavior of the pressurizer valves.

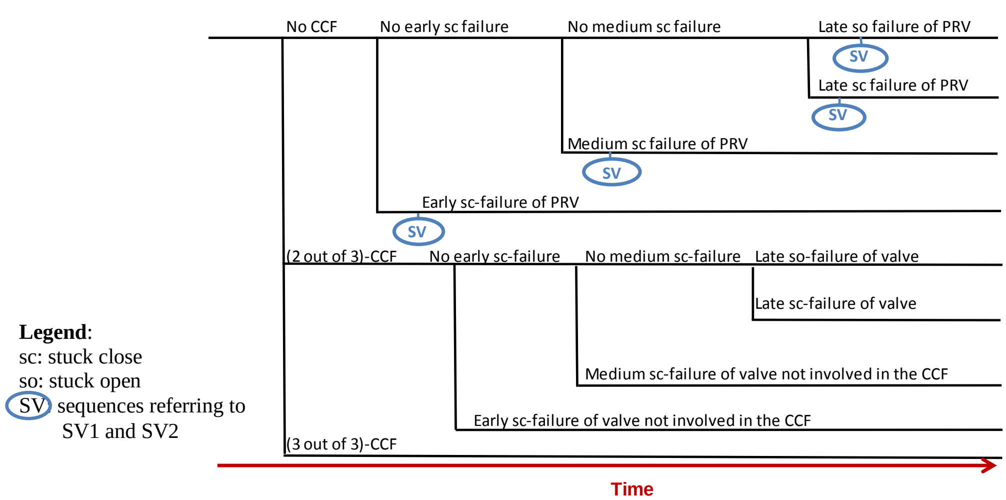


Fig. 2. DET Sequences addressing the behavior of the pressurizer valves.

Besides the independent failures on demand of the pressurizer valves, different CCF combinations are considered as well. Since the PRV and the two safety valves are judged as functionally similar, they are treated as one component group. For the same reason as mentioned above, namely to keep the pressure on the primary side at a high level, only the stuck close CCF are taken into account. The corresponding (3 out of 3) and (2 out of 3) CCF shall be considered in separate DET branches automatically created, when the valve involved in the CCF-combination is demanded for the first time. The combination considered for the (2 out of 3) CCF shall be randomly selected from the total of 3 combinations which are possible in this context. The conditional probabilities assigned to the CCF branches are given by:

- $p_{sc33}$ = P((3 out of 3) stuck close CCF)/P(no stuck open CCF)
- $p_{sc23}$ = P((2 out of 3) stuck close CCF)/ P(no stuck open CCF)

$p_{sc23}$ is the sum of the probabilities of 3 possible (2 out of 3) stuck close CCF. The probability (1 - $p_{sc33}$- $p_{sc23}$) is assigned to the branch considering no CCF.

*III.B.2. Degree of SG Tube Degradation*

Due to lack of data, the modelling of the aleatory uncertainty of the degree of SG tube degradation is based on several assumptions largely derived from German KTA 1403 [6]:

i) During operation, a tube is supposed to experience a progression of degradation due to temperature and pressure stresses. The degradation appears as a reduction of wall thickness.
ii) The resilience of a tube towards stress decreases as the state of degradation increases. That is, the higher the degree of degradation the less the tube is able to resist stresses and, therefore, the degradation proceeds at a higher rate.
iii) Degradations ≥ 20% are assumed to be definitely detected in a test.
iv) The test interval of SG tubes is 5 years. During each test, 20% of the tubes are tested. Hence, a maximum time of about 25 years might exist between two tests of the same tube.

For the analysis, the potentially weakest tube of the whole bundle of SG tubes is considered and assumed to be exposed to the highest stresses. Based on the aforementioned assumptions, a Markov chain model is proposed to get the probability distribution of the degree of degradation of the weakest tube. The Markov chain accounts for 5 degradation classes, namely < 20 %, 20-40 %, 40-60 %, 60-80 % and 80-100 %. Within one year of operation, the degradation is supposed to remain in its state or to proceed from one class into the next higher class. According to assumption (ii), the probability of the degradation to proceed to the next higher class depends on the origin degradation class. For example, the probability of the degradation to proceed from class 1 (degradation < 20%) into class 2 (degradation 20-40%) is smaller than the probability of the degradation to proceed from class 2 to class 3 (degradation 40-60%) within one year of operation. At the time when the initiating event of the accident occurs, the degradation of the weakest tube can range from class 1 to class 5.

The transition matrix P of the Markov chain for one year of operation with regard to the weakest tube is given in Eq. (8).

$$\mathbf{P} = \begin{pmatrix} p_{1,1} & p_{1,2} & 0 & 0 & 0 \\ 0 & p_{2,2} & p_{2,3} & 0 & 0 \\ 0 & 0 & p_{3,3} & p_{3,4} & 0 \\ 0 & 0 & 0 & p_{4,4} & p_{4,5} \\ 0 & 0 & 0 & 0 & p_{5,5} \end{pmatrix} \tag{8}$$

$p_{i,j}$ denotes the probability of the tube degradation to remain in class $i$ $(i = j)$ or to proceed from class $i$ to class $j$ $(i < j)$ within one year of operation for $i$, $j = 1,.., 5$. These transition probabilities are considered as uncertain due to lack of knowledge (epistemic uncertainty).

Assuming that the weakest tube is in degradation class 1 (< 20%) at the last test, the degradation of the tube can proceed to any class $i$, $i = 1,\ldots,5$, depending on the corresponding transition probabilities as well as on the time period ($t_{init} - t_1$) between the last test at time $t_1$ and the initiating event at time $t_{init}$. The probability that the weakest tube is in degradation class $i$ after $N$ years of operation is denoted as $\pi(N) = (\pi_1(N), \pi_2(N), \ldots, \pi_5(N))$. At $N = 0$, i.e. at the last test at time $t_1$, the state probability is given by $\pi(0) = (1, 0, 0, 0, 0)$. That is, the tube is in degradation class 1 (degradation < 20%) with probability 1. Using the transition matrix $P$ (Eq. (8)) and the state vector $\pi(0)$, the probabilities that the degradation of the weakest tube is in the classes 1,..., 5 after $N$ years of operation can be calculated according to Eq. (9).

$$\pi(N) = \pi(0) \cdot P^N \tag{9}$$

The number $N$ of years from the last test at time $t_1$ to the point in time $t_{init}$, when the initiating event occurs, is considered as aleatory uncertainty and supposed to be distributed according to the discrete uniform distribution between 1 and 25 (assumption iv)). Considering the influence of $N$ by applying MC simulation to the formula in Eq. (9) provides a sample of probability vectors $\pi(N)$. Each $\pi(N)$ of the sample defines a possible probability distribution of the tube degradation class at time $t_{init}$.

As mentioned in Section II, the combination of MC and DET simulation shall be applied to analyze the influence of aleatory uncertainties. Therefore, alternative ways can be applied to consider the degree of tube degradation. For instance, the value of the degree of tube degradation can be sampled from the Histogram distribution defined by π(N) and then considered in the corresponding DET simulation runs. Alternatively, two or more degradation classes can be assigned to corresponding branches within a DET and the degradation value explicitly considered in these branches can be sampled from the normalized Histogram distribution of the respective degradation class. For example, if the two degradation classes ≤ 60 % and > 60 % are considered, the probabilities of the branches are given by $\pi_1(N) + \pi_2(N) + \pi_3(N)$ (degradation ≤ 60%) and $\pi_4(N) + \pi_5(N)$ (degradation > 60%), respectively (Eq. (9)). The degradation value explicitly taken into account in a branch has to be sampled from the normalized Histogram distribution over the range ≤ 60 % and > 60 %, respectively. The latter alternative is computationally more intensive, but it is especially useful for a more detailed analysis of the influence of the degree of tube degradation.

### III.C. Epistemic Uncertainties

Most of the epistemic uncertainties selected to be considered refer to the reliability parameters of the components assumed to fail in the course of the accident scenario and to the human error probabilities with respect to the secondary side depressurization.

The reliability parameters with respect to the failure behavior of the pressurizer valves (PRV, SV1 and SV2) during automatic pressure limitation refer to independent failures on demand as well as to CCF for the failure modes ‘failure to open’ and ‘failure to close’, respectively. To quantify the epistemic uncertainties of the failure-on-demand probabilities, respective Beta distributions were derived from data from operational experience and the application of a Bayesian estimation method with non-informative prior [7]. Beta distributions are also used to quantify the epistemic uncertainties of the CCF probabilities. They were obtained by approximation to the corresponding 5%, 50% and 95% quantiles given for the CCF probabilities. With regard to the secondary side depressurization, the epistemic uncertainties refer to the human error probabilities used to assess the performance of corresponding human actions. Again, Beta distributions were selected to quantify the epistemic uncertainties on the probabilities.

Besides the aforementioned failure and human error probabilities, the transition probabilities used to derive the distribution of the degree of tube degradation (paragraph III.2.2) are considered as uncertain due to lack of knowledge. Since corresponding data are not available, Uniform distributions are used for epistemic uncertainty quantification.

Other epistemic uncertainties selected to be considered refer to models and parameters of the computer code applied for accident simulation (paragraph III.D). The relevant parameters subjected to epistemic uncertainty are

- the parameter indicating different model alternatives for the zirconium oxidation (Discrete distribution)
- the relocation velocity of metallic melt (Triangular distribution)
- the oxide (ceramic) melt temperature of $UO_2$ (relocation) (Uniform distribution)
- the oxide thickness (Triangular distribution)
- the correction factor for the ambient temperature used as input to the Larson-Miller model for predicting creep and rupture (Uniform distribution)

### III.D. Computer Code for Accident Simulation

The code ATHLET-CD (Analysis of THermal-hydraulics of LEaks and Transients - Core Degradation, [8]) was selected to be applied for accident simulation. ATHLET-CD has been developed and validated for accidents resulting in major core damage. For a comprehensive simulation of the thermal-fluid dynamics in the nuclear steam supply system, the thermal-hydraulic system code ATHLET (Analysis of THermal-hydraulics of LEaks and Transients, [9]) has been fully integrated.

ATHLET-CD and ATHLET fulfill the requirements to run in combination with MCDET:

- Tick-based simulation: Simulation must be performed in time-discrete, synchronized computation steps.
- Data access: It must be possible to read and modify the state data of the simulation.
- Restart-capability: Code must be able to hold and save the system state of a simulation run in order to restore it later and to continue.
- Status indication: Code must provide the status of the simulation process (busy or idle).
- Early termination: Code should allow stopping the simulation prematurely.

To enable code variables to be immediately accessed at each computed time step, ATHLET-CD and ATHLET were modified in a way that relevant variables were defined as global variables of a shared library (data map). Furthermore, an

ATHLET-CD specific interface to MCDET was developed. This interface controls and synchronizes the simulation runs and retrieves requested code variables by accessing the data maps of ATHLET-CD and ATHLET. The aforementioned additional effort makes the GRS codes ATHLET and ATHLET-CD to rather comfortable simulation codes for running in combination with MCDET and performing IDPSA analyses.

An important extension of ATHLET-CD for the application case was the implementation of the Larson-Miller Model. This model can determine the SGTR and the breaks of the pressurizer surge line and the main coolant piping in the hot leg in dependence of the ambient temperature and pressure provided by ATHLET-CD.

## IV. CONCLUSIONS

The application presented in this paper aims to probabilistically assess the potential of a thermally induced SGTR during a high pressure accident scenario in a reference PWR. Since the classical DSA and PSA are not able to sufficiently account for the wide range of accident sequences which may evolve in this context and to provide an adequate probabilistic assessment, it was decided to apply the tool MCDET in order to benefit from the implemented IDPSA methods. These methods are able to better cope with uncertain influencing factors and their interaction with the dynamics of a complex system.

The aleatory uncertainties of the application mainly relate to the performance of technical components and human actions. An important influencing factor in this context is the timing of events. For instance, the time when a pressurizer valve fails at one of the repeated demand cycles during automatic pressure limitation may essentially affect the accident evolution. To consider the failure time (failure cycle) of a pressurizer valve, a Geometric distribution was derived from corresponding data available from operational experience. From this distribution, values of the failure demand cycle can be sampled and appropriately considered in the MCDET analysis. Other time factors refer to the time periods needed to accomplish human tasks required by the EOP ‘Secondary side bleed and feed’. The probability distributions needed in this context are obtained by running the Crew-module of MCDET. Besides the performance of technical components and human actions, the degree of degradation of the SG tubes is considered as aleatory uncertainty. Again, an important factor in this context is the timing, namely the time period between the last test of the SG tubes and the initiating event of the accident scenario. This time period and a Markov chain model were used to obtain the distribution of the degree of tube degradation.

Most of the epistemic uncertainties of the application refer to probabilities, namely to failure probabilities of components, human error probabilities and the transition probabilities with respect to the degradation classes considered for the SG tubes. Other epistemic uncertainties refer to models and parameters of the computer code ATHLET-CD selected to be applied for accident simulation. ATHLET-CD is a rather comfortable simulation code for running in combination with MCDET.

The next steps to be performed are the execution of simulation runs and the evaluation of the corresponding results in order to assess the potential of a thermally induced SGTR.

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## REFERENCES

1. Y. ADOLFSSON et al. (eds.), “IDPSA - Integrated Deterministic-Probabilistic Safety Assessment - 2nd workshop,” KTH, Stockholm, Sweden (2012).
2. T. ALDEMIR, “A Survey of Dynamic Methodologies for Probabilistic Safety Assessment of Nuclear Power Plants,” *Annals of Nuclear Energy*, **52**, pp. 113–124, (2013).
3. M. KLOOS and J. PESCHKE, “MCDET - a Probabilistic Dynamics Method Combining Monte Carlo Simulation with the Discrete Dynamic Event Tree Approach,” *Nuclear Science and Engineering*, **153**, pp. 137-156, (2004).
4. M. KLOOS et al. “MCDET: A Tool for Integrated Deterministic Probabilistic Safety Analyses,” *Advanced Concepts in Nuclear Energy Risk Assessment and Management.* (To appear at)*:* World Scientific Publishing Company (2016).
5. S. KOTZ and N. L. JOHNSON (eds.). *Encyclopedia of Statistical Sciences*, Volumes 1-9, John Wiley & Sons (1982).
6. KTA 1403, „Alterungsmanagement in Kernkraftwerken“, *Kerntechnischer Ausschuss Regelentwurf,* Fassung vom 20.06.2010.
7. G. E. P. BOX and E. G. TIAO, “Bayesian Inference in Statistical Analysis” Adison Wesley (1973).
8. H. AUSTREGESILO et al. “ATHLET-CD, Mod 3.0 Cycle A” *User’s Manual*, GRS–P–4, Vol. 1, Garching (2013)
9. GRS, “ATHLET, Mod 3.1 Cycle A, Program Overview,” Garching (2016)