Results of an IDPSA Aimed to Assess the Potential of a Thermally Induced Steam Generator Tube Rupture

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Abstract: The tool MCDET (Monte Carlo Dynamic Event Tree) was used to perform an IDPSA (Integrated Deterministic Probabilistic Safety Analysis) aimed to investigate the potential of a thermally induced steam generator (SG) tube rupture during a high pressure accident in a pressurized water reactor (PWR). The aleatory uncertainties of the analysis refer to the degree of SG tube degradation when the accident occurs as well as to the performances of the technical components and human actions demanded during the accident to accomplish safety related tasks. Special focus was given to the failure times of components and to the timing of human actions. Epistemic uncertainties were considered for the failure probabilities of components, human error probabilities and the transition probabilities needed to model the degree of SG tube degradation. Further epistemic uncertainties were regarded for models and parameters of the computer code ATHLET-CD coupled with MCDET to simulate the accident sequences. The method applied to consider the aleatory and epistemic uncertainties was a combination of Monte Carlo (MC) and Dynamic Event Tree (DET) simulation. The paper presents first results derived from the outcome of the MCDET/ATHLET-CD analysis.

Keywords: IDPSA, Dynamic PSA, MCDET, Uncertainty.

1. INTRODUCTION

IDPSA (Integrated Deterministic Probabilistic Safety Analysis) is a complementary analysis to the classical deterministic (DSA) and probabilistic (PSA) safety analysis and helps to thoroughly investigate the influence of aleatory and epistemic uncertainties on the behavior of a complex dynamic system [1]. It may improve the understanding of the mutual dependences between the system dynamics and potential influencing factors and provide probabilistic assessments of the performances of involved subsystems, components and human actions which are difficult to evaluate otherwise.

An appropriate tool for IDPSA is MCDET which allows for performing Monte Carlo (MC) simulation, Dynamic Event Tree (DET) simulation or a combination of both [2, 3]. The efficient link between a computer code for system dynamics simulation and of advanced modelling and simulation techniques which can be realized by MCDET essentially facilitates the simulation of the inherent interactions of a complex dynamic system in the presence of uncertainties. Both aleatory (due to random events) and epistemic (due to lack of knowledge) uncertainties can be taken into account in a rather comprehensive manner. What makes MCDET particularly useful for safety analyses of complex systems where human actions play an essential role is its Crew Module [4]. This module allows for considering human actions as a time-dependent sequence which may be affected in the course of time by perturbing and severe process states, system and component failures, human errors, internal and external hazards, and so-called performance shaping factors such as ergonomics or stress.

In the analysis described in this paper, MCDET was applied in combination with its Crew Module and the computer code ATHLET-CD (Analysis of THermal-hydraulics of LEaks and Transients - Core Degradation, [5]) to simulate and probabilistically assess the accident sequences which may evolve in a pressurized water reactor (PWR) during a high pressure scenario. Based on the simulation results and the associated probabilistic assessments, the potentials for a thermally induced steam generator (SG) tube rupture (SGTR) and of breaks of the main coolant pipe in the hot leg and of the pressurizer surge line were investigated.

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The code ATHLET-CD applied together with MCDET has been developed and validated for the simulation of 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) has been fully integrated [6].

Most of the aleatory uncertainties considered in the analysis refer to the performances of technical components and human actions when they are demanded during the accident to fulfil safety related tasks. Significant factors in this context are the times when components fail and the time periods needed to accomplish human tasks. Another important aleatory uncertainty refers to the degree of degradation of SG tubes at the time when the initiating event of the accident occurs. Some of the epistemic uncertainties refer to failure probabilities of components and human error probabilities. Others relate to models and parameters of the code ATHLET-CD.

The high pressure scenario and the uncertainties considered in the analysis are outlined in Section 2. An overview on the analysis steps and on the methods used to handle the uncertainties is given in Section 3. The analysis results obtained so far are described in Section 4. The conclusions are presented in Section 5.

2. HIGH PRESSURE SCENARIO AND UNCERTAINTIES

2.1. Scenario and Aleatory Uncertainties

The high pressure scenario was supposed to occur in a PWR at nominal power. Initiating event is a total station black-out (SBO) characterized by the total loss of power from offsite, redundant emergency diesel generators and other sources. Batteries were assumed to guarantee DC power supply to all battery supported functions over the whole considered time period of maximally 20000 s. Power was assumed not to be recovered within this time period.

The loss of power causes the main coolant pumps to trip which subsequently results in an automatic scram and turbine trip. In the following, heat removal from the reactor core to the steam generators (SGs) is reached through natural circulation. Failure of the main heat sink leads to pressure increase on the secondary side. When a pressure of 8.6 MPa is reached, the main steam relief valves of the SGs are demanded to open in order to reduce the pressure to the level of 7.5 MPa. This step of partial SG depressurization is assumed not to be performed completely. As a consequence, the SG pressure remains on a high level of about 8.3 MPa.

Since on-site power plus the emergency diesel generators are not available, the crew is demanded to carry out the emergency operating procedure (EOP) ‘Secondary side bleeding and feeding’. The procedure includes the further depressurization of the SGs (‘bleeding’) so that feed water from different sources can be injected into the SGs (‘feeding’). To induce a situation with high primary-to-secondary side pressure difference at elevated SG tube temperature, it was assumed that only the ‘bleeding’ is performed whereas the ‘feeding’ is omitted with the consequence that the SGs are getting dry in the course of the accident. The time periods needed to accomplish the tasks for the ‘bleeding’ were considered as uncertain. The probability distributions representing the aleatory uncertainties of these time periods were derived from the simulation results provided by the combination of MCDET and its Crew Module [7].

The model of human actions for the ‘bleeding’ was constructed based on corresponding documents of the reference PWR and provided as input to the Crew Module. Uncertain parameters and the corresponding probability distributions were entered as input to MCDET. If feasible, the probabilities of human errors were derived from the method ASEP (Accident Sequence Evaluation Program, [8]) recommended by the technical document on PSA methods [9] supplementing the German PSA Guide. Based on the input data, the combination of MCDET and its Crew Module calculated a huge amount of potential sequences of human actions. The subsequent evaluation of the corresponding output data finally provided the probability distributions of the time periods needed to perform the human tasks for the secondary side bleeding.

On the primary side, the pressure at first decreases after the pressure release of the SGs and then increases again. Due to the volume expansion of the coolant, the pressurizer level goes up, so that the pressurizer relief valve (PRV) is demanded to open for pressure release. When the pressure has dropped far enough, the PRV is demanded to close again. This process is repeated in the following to keep the primary side pressure within specific limits around 16.5 MPa. If the PRV should fail to open at one of its demand cycles or its capacity should not be sufficient, two safety valves (SV1, SV2) are additionally available to carry out the pressure limitation of the primary side.

The performances of the pressurizer valves when demanded to open and to close for pressure limitation were considered as uncertain. The probabilistic modelling of the corresponding aleatory uncertainties was based on operational experience which had shown that independent as well as common cause failures (CCFs) of the pressurizer valves may occur for the two failure modes ‘failure to open (stuck close)’ and ‘failure to close (stuck open)’. To account for the influence of independent failures, it was decided to explicitly consider three different failure times (failure cycles) for each valve. Each failure cycle was randomly sampled from one of the following three intervals: cycle nos. 1 – 20 (early failure time), cycle nos. 21 – 60 (medium failure time), and cycle nos. > 60 (late failure time). The underlying probability distributions were evaluated as Geometric distributions appropriately normalized over the corresponding intervals [10]. Different from the original plan of considering stuck open failures only for late failure cycles, both stuck close and stuck open failures were considered for all three failure cycles. CCFs were also considered for both failure modes. The combination of valves considered for the (2 out of 3) CCF was randomly sampled from the corresponding total of 3 combinations. Failures of the valves due to the heavy temperature loads during the accident progression were not considered.

Due to continued boil-off of water and venting through the pressurizer valves, the core is gradually uncovered. The EOP ‘Primary side bleeding and feeding’ where the crew shall manually open all pressurizer valves so that coolant from different sources can be injected into the primary side was assumed not to be performed. So, the primary side pressure remains on a high level and only pressurizer valves which may randomly fail in stuck open mode during the ongoing process of pressure limitation could lead to a substantial pressure relief. If the pressure can be released far enough, the accumulators can inject their coolant inventory provided the source isolation valve and the additional isolation valves of the accumulators do open. These valves were assumed to operate successfully. It should be kept in mind that coolant from the high- and low-pressure emergency core cooling systems (ECCS) cannot be injected, since these systems cannot be activated without power.

An important aleatory uncertainty refers to the degree of degradation of the SG tubes at the time when they are exposed to the high pressure conditions. In the analysis, the weakest tube of the whole bundle of SG tubes was considered. Like all other tubes, it is supposed to be made of Inconel. To probabilistically assess the degree of degradation of the weakest tube, a Markov chain model was proposed [7, 10]. The model provides a conditional probability distribution over the 5 degradation classes < 20 %, 20-40 %, 40-60 %, 60-80 %, and 80-100 %. The probability distribution depends on the time period between the last test of the weakest tube and the initiating event of the high pressure scenario. The longer the time period the longer the tube is exposed to stress which in turn increases its degradation. The degradation was realized as a reduction of the wall thickness of the SG tube. In the analysis, the maximum degree of degradation was restricted to 70 %, because test runs have shown that the SG tube fails instantly for degradations > 70 %. Furthermore, only the two degradation classes < 20 % and ≥ 20 % (i.e. 20-70 %) were considered.

High primary-to-secondary system differential pressure during the accident progression in combination with a substantially elevated SG tube temperature (due to absence of feed water) may cause a sooner or later SGTR depending on the degree of SG tube degradation. Furthermore, since the core may experience gradual damage during the accident, high core melt temperatures may lead to the failures of the main coolant piping in the hot leg and of the pressurizer surge line.

2.1. Epistemic Uncertainties

The epistemic uncertainties considered in the analysis refer to the probabilities used to quantify the aforementioned aleatory uncertainties and to parameters of the computer code ATHLET-CD applied for system dynamics simulation. Table 1 gives an overview on these probabilities and parameters together with the corresponding distributions used to quantify the epistemic uncertainties.

Table 1: Epistemic variables and corresponding probability distributions

Epistemic variables	**Distributions (parameters)**
Failure probabilities of the pressurizer valves:	
probability of independent PRV stuck close failure	Beta (0.5, 161.5)
probability of independent PRV stuck open failure	Beta (0.5, 161.5)
probability of independent SV1 (SV2) stuck close failure	Beta (2.5, 426.5)
probability of independent SV1 (SV2) stuck open failure	Beta (1.5, 427.5)
probability of 2v3 stuck close CCF of PRV (SV1, SV2)	Beta (0.43, 3094)
probability of 3v3 stuck close CCF of PRV (SV1, SV2)	Beta (0.31, 4838)
probability of 2v3 stuck open CCF of PRV (SV1, SV2)	Beta (0.39, 277967)
probability of 3v3 stuck open CCF of PRV (SV1, SV2)	Beta (0.24, 450846)
Transition probabilities of the Markov model applied to assess SG tube degradation:	
probability of degradation proceeding from class 1 to class 2	Uniform (0.001, 0.01)
probability of degradation proceeding from class 2 to class 3	Uniform (0.01, 0.07)
probability of degradation proceeding from class 3 to class 4	Uniform (0.07, 0.15)
probability of degradation proceeding from class 4 to class 5	Uniform (0.15, 0.3)
Computer code parameters:	
time delay of scram signal (s)	Uniform (0.4, 1.2)
correction factor for decay heat	Uniform (0.9, 1.1)
maximum steam pressure (Pa)	Polygonal Line (value – density height) 8630000 – 0 / 8730000 - 3.3e-06 / 8930000 - 3.3e-6 / 9030000 - 0
additional change of set value of maximum steam pressure (Pa)	Uniform (-150000, +150000)
contraction value of steam discharge	Polygonal Line (value - density height) 0.6 – 0 / 0.7 – 3.33 / 0.9 – 3.33 / 1.0 – 0
pressure loss in nozzle (Darcy-Weisbach friction factor)	Polygonal Line (value - density height) 0.05 – 0 / 0.10 – 2.1 / 0.50 – 2.1 / 0.60 – 0
correction factor for opening cross section of PRV	Uniform (0.9, 1.1)
correction factor for opening cross section of PRV	Uniform (0.9, 1.1)
correction factor for opening cross section of main steam safety valves	Uniform (0.9, 1.1)
correction factor for heat conductivity of UO_2	Uniform (0.88, 1.12)
correction factor for heat conductivity of ZR	Uniform (0.9, 1.1)
correction factor for heat conductivity of ZRO_2	Uniform (0.9, 1.1)
correction factor for heat capacity of UO_2	Uniform (0.88, 1.12)
correction factor for heat capacity of ZR	Uniform (0.88, 1.12)
total mass threshold to relocation (kg)	Uniform (55000, 75000)
ceramic mass threshold to relocation (kg)	Uniform (8000, 12000)
model selection for the failure of the lower plenum of the reactor pressure vessel (RPV)	Discrete (model - probability): ASTOR approximation – 0.334 Larson-Miller approach – 0.333 Temperature Criterion (1600 °C) – 0.333
correction factor for relocation velocity of metallic melt	Uniform (0.9, 1.1)
correction factor for relocation velocity of ceramic melt	Uniform (0.9, 1.1)
model selection of zirconium oxidation	Discrete (model - probability): Cathcart/Prater/Courtright – 0.333 Cathcart/Urbanic/Heidrick – 0.334 Leistikow/Prater/Courtright – 0.333
correction factor for melt temperature of UO_2	Uniform (0.9, 1.1)
correction factor for melt temperature of metallic zircaloy	Uniform (0.9, 1.1)

3. ANALYSIS

3.1 Analysis steps

The first stage of the analysis dealt with the preparation of the input data of the computer code ATHLET-CD used for system dynamics simulation and of the tool MCDET. It included, on the one side, the modelling of the plant behavior during the high pressure accident conditions and, on the other side, the probabilistic modelling of the uncertainties mentioned in Section 2. Furthermore, ATHLET-CD was extended by the Larson-Miller model. This model was applied in the second stage of the analysis to determine whether the temperature and pressure challenges of the accident may lead to a rupture of an SG tube or to breaks of the pressurizer surge line or of the main coolant piping in the hot leg.

With the input data prepared in the first analysis stage, the tandem of MCDET and ATHLET-CD was run on a cluster of 6 Windows PCs each with up to 8 CPUs. The calculations of ATHLET-CD and those of the Probabilistic Module of MCDET were supervised by the new MCDET Scheduler which allows for performing parallel and distributed simulations on multicore workstations and cluster environments [3]. The sequences were calculated up to maximally 20000 s (~5.6 h). When either a break of the main coolant pipe in the hot leg or a break of the pressurizer surge line occurred in a sequence, the calculation was automatically terminated at the corresponding point in time. 4216 different sequences were calculated in total to consider the influence of the uncertainties described in Section 2. They were constructed by the special simulation technique of MCDET which combines MC and DET simulation.

The influence of the epistemic uncertainties was considered by MC simulation. 50 different sets of values were randomly sampled for the corresponding parameters (epistemic variables). Each set was used as input to the construction of a pair of DETs each of which completely handled the aleatory uncertainties of component states (e.g. success/failure of a pressurizer valve to open or to close at a demand cycle). Each DET of the pair was additionally constructed on condition of a different set of values randomly sampled for all those aleatory variables selected to be handled by MC simulation. For instance, the (early, medium, and late) failure cycles randomly sampled for a pressurizer valve were used to determine the points in time when to generate new branchings with respect to the state of the valve. When the actual demand cycle of the valve reached a sampled failure cycle and the valve was demanded to open, besides the current branch where the valve opened as demanded, a new branch was generated with the valve remaining stuck closed. When the actual demand cycle reached the failure cycle and the valve was demanded to close, another new branch was created with the valve remaining stuck open.

In total, a sample of 100 DETs was generated. Eq. (1) summarizes the relationship between the generated DETs and the contributions of the aleatory and epistemic variables.

$$DET_{ij} = DET(\, al^*;\, ep_i;\, al_j(\, ep_i\,)\,),\ i=1,\ldots 50,\ j=1,2 \tag{1}$$

where al^* = aleatory variables completely handled in a DET, ep_i = set i of values randomly sampled for the epistemic variables and $al_j(ep_i)$ = set j of values randomly sampled for the aleatory variables handled by MC simulation on condition of the set i of values randomly sampled for the epistemic variables.

3.2 Analysis Results

The simulation results provided by the tandem of MCDET and ATHLET-CD have been analyzed by the post-processing modules of MCDET.

To get information on the potential of a thermally induced SGTR, appropriate conditional probabilities were calculated. The diagram in Fig. 1 represents the epistemic uncertainties of conditional SGTR probabilities. In particular, Fig. 1 shows the distribution of the conditional SGTR probability obtained from 50 epistemic runs (black curve) and compares the respective distributions referring to tube degradations of < 20 % (low degradation, blue curve) and 20-70 % (high degradation, red curve). The subjective probability on the y-axis of the diagram corresponds to the relative frequency of the respective SGTR probabilities in 50 epistemic runs. It can be seen, that the SGTR probabilities are very high under the severe accident conditions assumed in the analysis (Section 2). They range between 0.883 and 1.0. Since the likelihood for a lowly degraded SG tube is very high compared to that for a highly degraded tube, the conditional SGTR probabilities over all degrees of degradation (black curve) and those referring to a low degree of degradation (blue curve) nearly do not differ. In comparison to the conditional SGTR probabilities of a lowly degraded tube, those of a highly degraded tube are in general larger (red curve). All probabilities relate to SGTRs occurring before a hot leg or surge line failure. Since the containment is bypassed in case of an SGTR, the results suggest a considerable likelihood for a direct and high release of fission products to the environment. If the main coolant pipe in the hot leg or the surge line fails additionally, releases to the environment may be reduced by a partially depressurized primary system with fission product deposition on the primary site (Figs. 3-4).

Figure 1: Epistemic Uncertainties of Conditional SGTR Probabilities

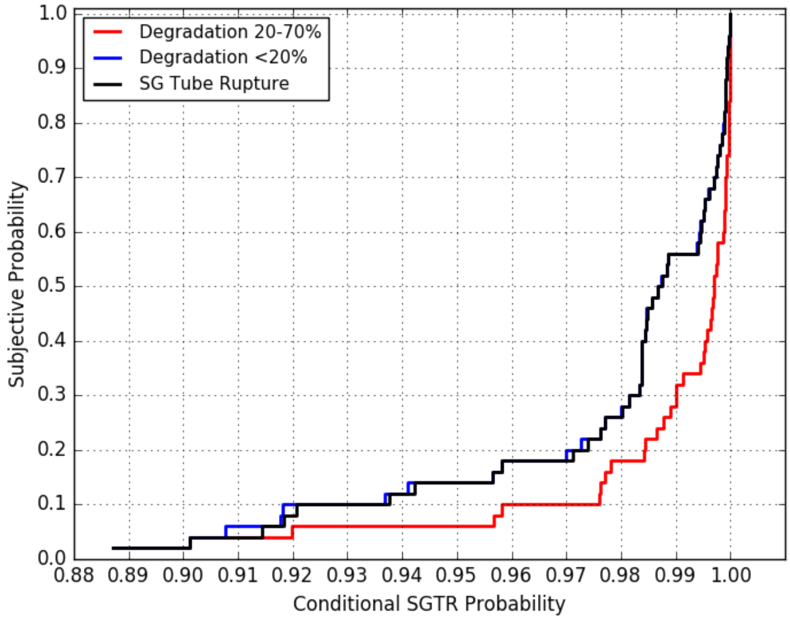


Fig. 2 shows the conditional probability distributions of the SGTR occurrence time with respect to all degrees of tube degradation (black curve), degradations < 20 % (low degradation, blue curve) and degradations between 20 % and 70 % (high degradation, red curve). Each distribution is the mean over all corresponding distributions derived from the 100 DETs of the analysis and reflects the common influence of the epistemic and aleatory uncertainties. The conditional distribution over all degrees of degradation (black curve) and that referring to a low degree of degradation (blue curve) nearly do not differ for the same reason as given for the corresponding relationship in Fig. 1. Fig. 2 suggests that the probability is about 0.95 that an SGTR may occur between 9200 s and 12000 s (black/blue curve). As expected, a tube with a higher degree of degradation fails earlier. The probability is about 0.60 that the failure time of a highly degraded tube is before 9000 s, and it is approx. 0.50 that the failure time is even before 5900 s (red curve).

Figure 2: Conditional Probability Distributions of SGTR Occurrence Times

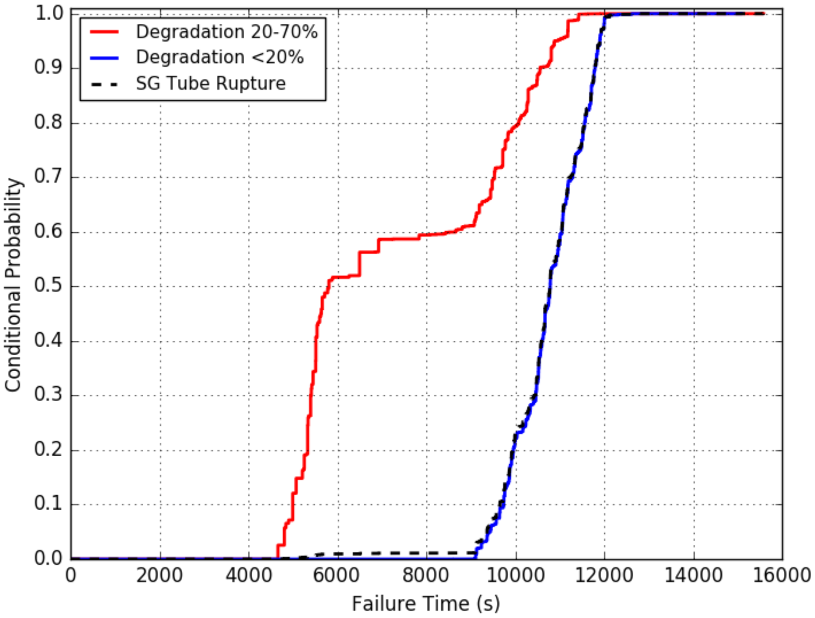


Figure 3: Epistemic Uncertainties of the Conditional Probabilities of Breaks of the Main Coolant Pipe and of the Pressurizer Surge Line

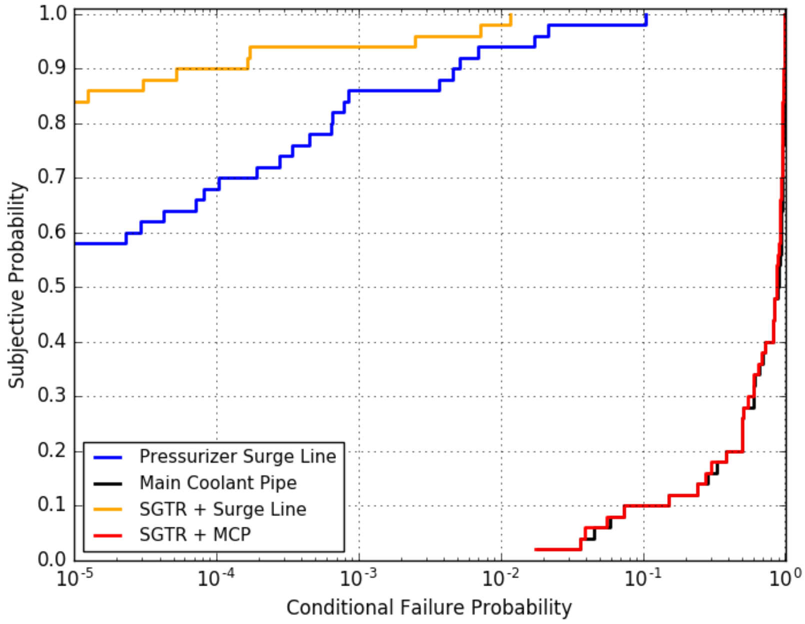
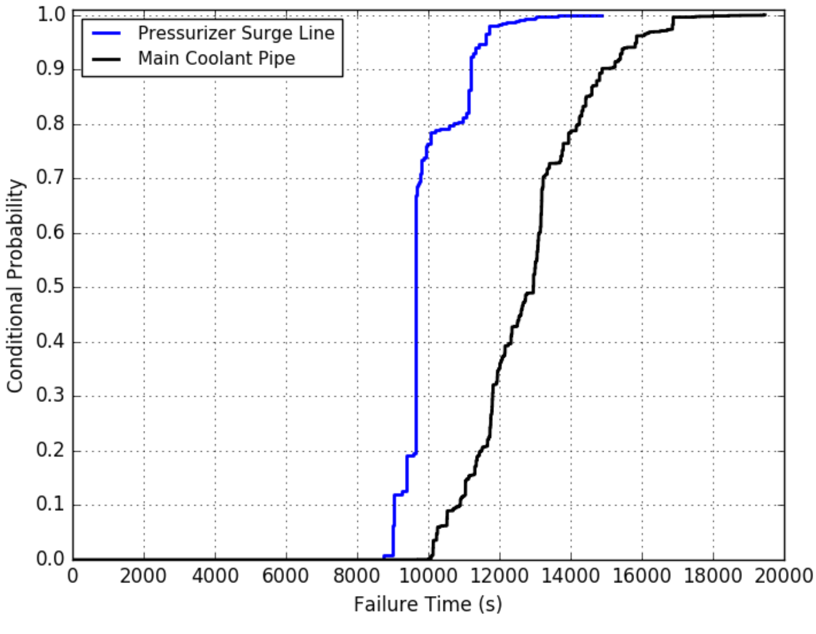


Fig. 3 reveals the epistemic uncertainties of the conditional probabilities for breaks of the main coolant pipe in the hot leg (black curve) and of the pressurizer surge line (red curve). In other words, Fig. 3 shows the distributions of the corresponding probabilities obtained from 50 epistemic runs. For the interpretation of the results, it should be remembered, that the calculation of an accident sequence was stopped, when either a break of the main coolant pipe or a break of the pressurizer surge line occurred. The figure shows much higher conditional probabilities of the main coolant pipe break compared to those of the surge line break. That means that the main coolant pipe fails more likely earlier than the surge line. While the conditional probabilities for a surge line break (before the main coolant pipe fails) do not exceed 0.1 and over 50 % of the probabilities are even smaller than 10^{-5}, 90 % of the probabilities of a main coolant pipe break exceed 0.1 and 50 % of the probabilities are even higher than 0.9. Since the joint probabilities of an SGTR and a subsequent break of the main coolant pipe (red curve) are nearly identical to the probabilities of a main coolant pipe break (black curve), it can be concluded that the main coolant pipe generally fails after an SGTR under the severe accident conditions supposed for the analysis (Section 2). The joint probabilities of an SGTR and a subsequent break of the pressurizer surge line (orange curve) significantly differ from the probabilities of a pressurizer surge line break. This indicates that different from the main coolant pipe which generally fails after an SGTR, the pressurizer surge line may also fail before an SGTR may occur.

Fig. 4 shows the conditional distributions of the failure times of the main coolant pipe (black curve) and the surge line (blue curve). The distributions represent the common influence of the epistemic and aleatory uncertainties of the analysis and were evaluated under the condition that the main coolant pipe or the surge line fails, respectively. The probability of a surge line break (before the main coolant pipe fails) is approx. 3.81E-3. The probability of a main coolant pipe break (before the surge line fails) is approx. 0.72. Fig. 4 indicates, that if the surge line fails, the respective failure times (blue curve) are generally earlier than those of the main coolant pipe (black curve). Noticeable is the high conditional probability of approx. 0.46 for a failure of the surge line at approx. 9650 s. This failure occurs in a single sequence assessed with this high conditional probability. The sequence is characterized by an SG depressurization at 5195 s, a successfully operating PRV, the additional opening of SV 1 at 7086 s, its subsequent closing and repeated opening and, finally, the stuck open failure of SV1 at 7388 s (2^{nd} demand cycle). An SGTR does not occur in this sequence. The degree of degradation considered for the lowly degraded tube in this sequence is 14 % (=1.03 mm wall thickness), that of the highly degraded tube is 37 % (=0.76 mm wall thickness).

Figure 4: Conditional Distributions of the Failure Times of the Main Coolant Pipe and of the Pressurizer Surge Line



Figs. 5 and 6 show the time histories of the pressure and temperature of the surge line for all sequences leading to a surge line failure. It can be seen that the failure of the surge line occurs under an extreme temperature load over 900°C combined with pressure levels below 12 MPa. These pressure levels are caused by pressurizer valves failed in stuck open mode. The stuck open valves lead to a fast core uncovery which in turn leads to a massive temperature increase in the hot leg and the surge line.

Figure 5: Surge Line Pressure in Sequences leading to a Surge Line Failure

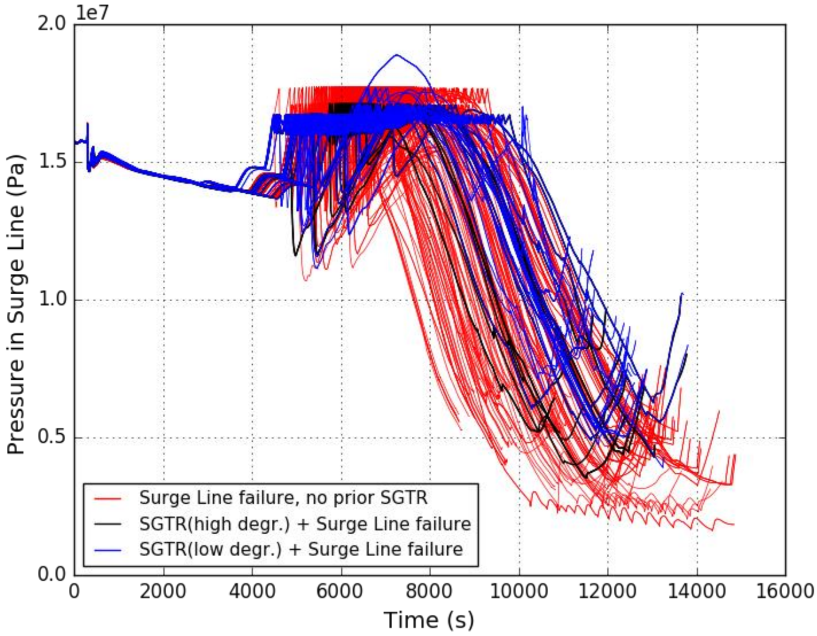


Figure 6: Surge Line Temperature in Sequences leading to a Surge Line Failure

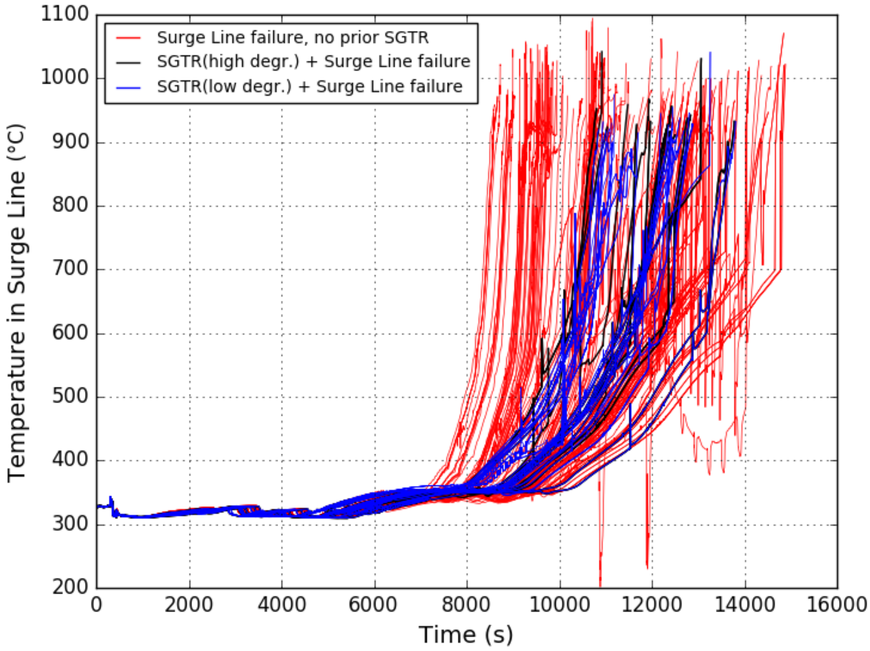


Fig. 7 compares the conditional distributions of the SG tube temperature at the SGTR occurrence time for tube degradations < 20 % (low degradation, blue curve) and 20-70 % (high degradation, red curve). Both distributions represent the common influence of the epistemic and aleatory uncertainties considered in the analysis. A scatter plot revealing the tube pressure associated with the tube temperature is given in Fig. 8. Fig. 7 indicates that the temperature load causing a rupture of a lowly degraded tube ranges approx. between 480 °C and 600 °C with a conditional probability of 0.95. The pressure at that temperature range is approx. between 12 MPa and 20 MPa as Fig. 8 shows. The temperature causing a rupture of a highly degraded tube ranges approx. between 315 °C and 500 °C with a conditional probability of 0.95. The pressure at that temperature range is approx. between 12 MPa and 19 MPa. The high conditional probability of nearly 0.5 for the rupture of a highly degraded tube at a temperature load of approx. 320 °C is remarkable. The pressure in the tube at this temperature level is between 13 MPa and 17.5 MPa. These temperature/pressure loads occur between

4900 s and 5900 s (Fig. 2). During that period, the pressure on the secondary side decreases and the SGs dry out due to the bleeding carried out before. The pressure on the primary side first decreases (after the bleeding of the secondary side) and then continuously increases until a level is reached at which the PRV or - if the PRV fails to open - one of the two safety valves is demanded for the first time to open and then to close in order to limit the pressure around 16.5 MPa. So, the pressure situations on the primary and secondary side shortly after the bleeding of the secondary side are one of the main reasons for the rupture of a highly degraded tube.

Figure 7: Conditional Distributions of the SG Tube Temperature at SGTR Occurrence Time

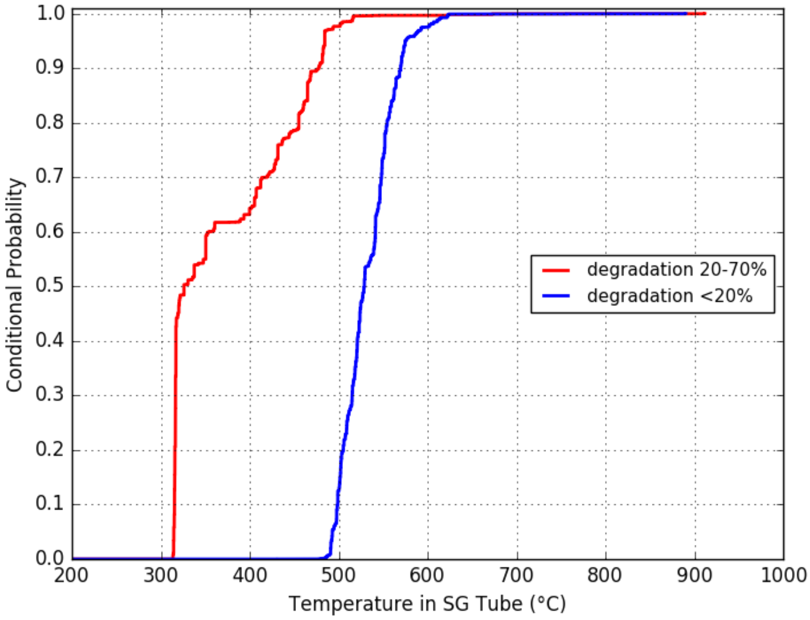


Figure 8: SG tube pressure and temperature at SGTR Occurrence Time

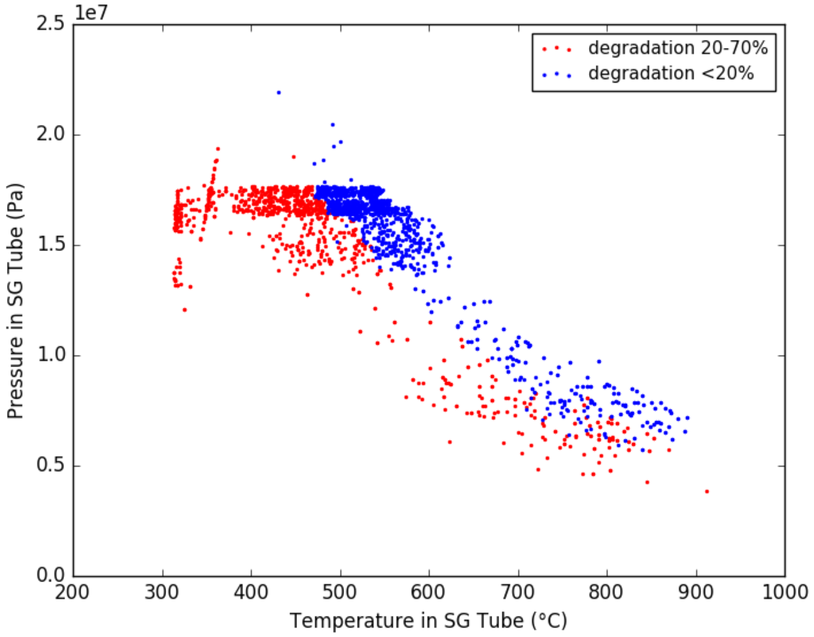
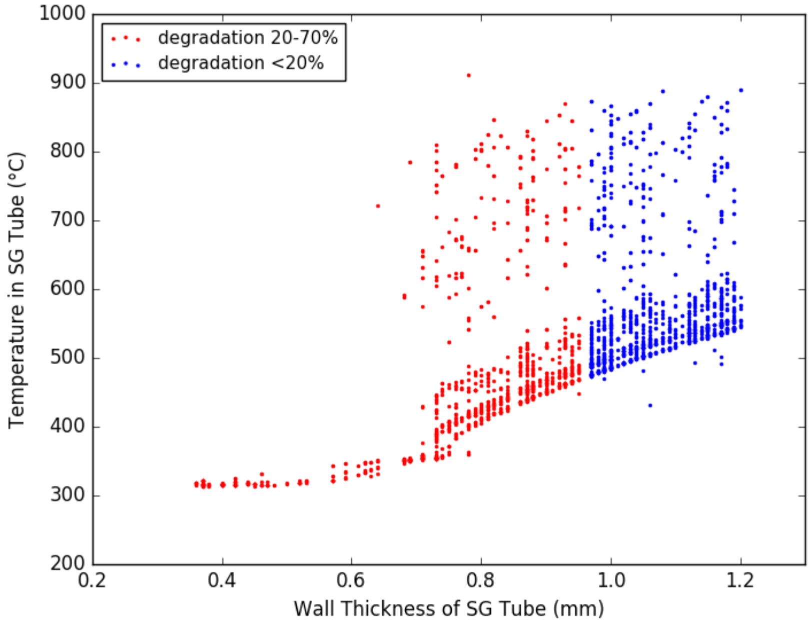


Fig. 9 shows the relationship between the tube degradation as realized by a reduced wall thickness and the temperature load at which the SGTR occurs (according to the Larson-Miller model). It can be seen that a tube with a wall thickness smaller than approx. 0.6 mm always fails at a temperature below 350 °C. The pressure in the tube at this temperature level ranges between 12 MPa and 17.5 MPa (Fig. 8). The corresponding primary-to-secondary side pressure difference is between 12°MPa and

16.8°MPa. From a comparison of the occurrence times of the SGTR and of the secondary side bleeding for more detailed tube degradation (wall thickness) classes, it can be concluded that the rupture of a highly degraded tube with a wall thickness below 0.6 mm is caused most likely by the primary-to-secondary side pressure difference occurring within 40 s – 240 s after the bleeding.

Figure 9: Temperature at SGTR and SG Tube Wall Thickness as Indicator of the Degradation



5. CONCLUSION

Aim of the IDPSA presented in this paper was to investigate the potential of a thermally induced SGTR during a high pressure accident in a PWR. Of special interest were the questions, whether and, if yes, how often an SGTR may occur, and how often it occurs before or after the main coolant pipe in the hot leg or the pressurizer surge line breaks. To simulate the accident progression under the influence of epistemic and aleatory uncertainties, the tool MCDET was run in tandem with the computer code ATHLET-CD. The method applied to consider the influence of the uncertainties was a combination of MC and DET simulation.

The first evaluation of the extensive outcome of the simulation runs focused on the likelihoods for a thermally induced SGTR as well as for breaks of the main coolant pipe in the hot leg and of the pressurizer surge line. Distributions representing the corresponding epistemic uncertainties were quantified. Furthermore, the conditional distributions of the occurrence times of the aforementioned failures were derived. An investigation of the evolution of process variables such as the pressure and temperature loads of the SG tubes or those of the main coolant pipe and the pressurizer surge line provided insights on the conditions leading to the damage states.

The results obtained so far may be useful for Level 2 PSAs aimed to derive the frequencies for different fission product releases to the environment. In case of an SGTR, the containment is bypassed and the fission products may be released directly to the environment either via stuck open or via cycling main steam relief and/or safety valves. If breaks of the main coolant pipe or the pressurizer surge line occur additionally, the releases to the environment are reduced due to fission product holdup and retention within the primary system. Breaks of the main coolant pipe or the pressurizer surge line may even prevent an SGTR and, thus, avert a direct release of fission products to the environment.

Future evaluation of the simulation results will address the individual effects of influencing factors on the accident progression. Such results may be useful for severe accident management, since they give hints, when countermeasures such as timely primary system depressurization and subsequent cooling options may be effective to prevent or mitigate fission product releases. To get information on the influence of epistemic uncertainties including the uncertainties referring to the applied computer code, a detailed epistemic uncertainty and sensitivity analysis will be performed.

Acknowledgements

The work presented in this paper was sponsored by the Ministry of Economics and Technology (BMWi) within the frame of the Research and Development Project RS1529.

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