COMPUTING SOURCE TERMS WITH DYNAMIC CONTAINMENT EVENT TREES

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In this paper, integrated dynamic and probabilistic safety analysis (IDPSA) modelling is demonstrated using a steam explosion case and the new FinPSA 2.0 tool for PRA level 2 analysis. In the case study, a simplified level 2 model containing steam explosions was constructed for a boiling water reactor nuclear power plant. Supporting analyses were performed using deterministic computer code MELCOR to gather knowledge on timings of events and initial conditions for the fuel-coolant interaction phenomena. The results of deterministic analyses were incorporated into a probabilistic containment event tree (CET) model. The level 2 method implemented in FinPSA is based on dynamic CETs and CETL programming language. The CETL is used to define functions to calculate conditional probabilities of CET branches, timings of the accident progression and amounts of releases.

I. INTRODUCTION

Integrated deterministic and probabilistic safety assessment (IDPSA) combines two methodologies to support risk-informed decision making. IDPSA takes both stochastic disturbances and deterministic response of a nuclear power plant, and especially their mutual interactions, into account in safety justifications. The methodology can also reveal new plant weaknesses and reduce conservatism in the analysis.

This paper concerns the application of IDPSA to the analysis of severe nuclear power plant accidents and level 2 probabilistic risk assessment (PRA). Level 2 PRA analyses how large and probable are radioactive releases after core damage (Ref. 1). Severe accidents involve complex physical phenomena of which information can be best gathered by performing deterministic analyses.

The paper presents a case study where a simplified level 2 containment event tree model was constructed for a boiling water reactor (BWR) nuclear power plant (Ref. 2). The study focused on ex-vessel steam explosion modelling. Supporting analyses were performed using deterministic computer code MELCOR (Ref. 3) to gather knowledge on timings of events and initial conditions for the fuel-coolant interaction phenomena. Especially, the effects of different emergency core cooling system recovery times and depressurization times were examined. The results of deterministic analyses were incorporated into a probabilistic containment event tree model. The level 2 model was developed using the new FinPSA 2.0 tool (Ref. 4). The model presented in Ref. 2 has been developed further, and a newer version of the model is presented in this paper.

II. DYNAMIC CONTAINMENT EVENT TREE ANALYSIS

Software tool FinPSA (Ref. 4) offers dynamic containment event tree (CET) approach that supports IDPSA. Dynamic CETs combine event trees with programmable parametric modelling. In dynamic CETs, the user defines functions to calculate conditional probabilities of CET branches, timings of the accident progression and amounts of releases using CETL programming language. A CETL function is defined for each branch of a dynamic CET. The model also contains an initial routine that defines the plant damage state and initialises the analysis, and a finish routine that is used for source term calculation. Modelling with CETL programming is very flexible. At any branch, new value can be calculated for any variable that has been defined in an earlier section, and that way accident progression can be modelled and dynamic dependencies can be taken into account. For example, a time variable can be updated in each section and it can have different values in different branches and accident sequences. In the initial conditions, binning rules can be defined to classify the end states of the CET into release categories.

To account for uncertainties related to variable values, it is possible to define uncertainty distributions and perform Monte Carlo simulations. At each simulation run, a value is sampled from each defined distribution, and based on that, conditional probabilities are calculated for all the CET branches, and values are calculated for all variables at each end state of the CET. Based on simulation results, statistical analyses are performed to calculate frequency and variable value distributions for each end state and release category among other statistical results and correlation analyses. It is also possible to calculate with point values based on the mean values of distributions.

III. EX-VESSEL STEAM EXPLOSIONS

A severe nuclear accident that leads to a core meltdown can escalate (among other undesired events) into a steam explosion which can take place if molten fuel gets in contact with water and vaporizes it rapidly. More generally such processes are called fuel-coolant interactions (FCI). Steam explosions are considered plausible both in the reactor pressure vessel (RPV) and underneath it in the lower drywell (LDW) of containment. An in-vessel steam explosion can lead to a so called alpha-mode containment failure, but the probability of such event is at present considered almost negligible. Ex-vessel explosions are regarded more hazardous if vessel melt-through occurs and melt is ejected into flooded LDW. This paper concentrates more on ex-vessel explosions.

There are certain events and phenomena that need to precede a steam explosion. A core meltdown can basically be due to overpower or undercooling conditions, which typically relate to reactivity transients or loss of coolant accidents, respectively. After the core is uncovered, the fuel temperature increases, and several oxidation processes begin to produce more heat and hydrogen. Meltdown itself starts when heat production rate in the core exceeds heat removal rate. When temperature raises high enough, core relocation processes begin, starting from the relocation of molten fuel cladding materials. Eventually, the core collapses, and when the core support plates fail, the molten corium slumps into the lower plenum of the RPV. The molten corium can be cooled from inside with water injections to keep the melt in the vessel. But the RPV lower head may fail despite cooling efforts, although probably later than without in-vessel water injection. In that case, if there is enough water in the cavity below the vessel, an ex-vessel steam explosion may occur when the molten corium jet reaches the water.

III.A. Deterministic Analyses

Ex-vessel steam explosions were studied based on Olkiluoto 1&2 units, which are BWR type of reactors (Ref. 2). Information on accident progression was gathered in deterministic simulations using MELCOR software (Ref. 3). This information included timings of events and initial conditions for the fuel coolant interaction phenomena.

The accident scenario begins with loss of all AC power and the reactor is scrammed. In the beginning of accident progression, the reactor pressure is kept at 70 bars by safety relief valves. Then, the reactor can be depressurised by discharging steam into the wetwell by use of automatic depressurisation system (ADS) and its relief valves. This action is initiated by very low water level in the reactor. Depressurisation allows the use of low-pressure core spray to provide core cooling to avoid core uncovery that could eventually lead to a vessel melt-through. Also, a high-pressure melt ejection is even more undesired event than a low-pressure melt ejection because it is less predictable. After 30 minutes, the LDW is flooded from the wetwell to cool the ejected melt in case of a vessel breach to protect LDW penetrations for e.g. piping and to delay radioactive release. Flooding is initiated manually by operators who follow severe accident management guides, but in the MELCOR model the flooding time is fixed at 30 minutes. The emergency core cooling system (ECCS), i.e. core spray and high-pressure injection, is also implemented in the model so that the significance of the recovery of AC power can be examined. ECCS is dependent on AC power whereas relief valves operate with batteries.

Six different cases were selected to find out how the availability of ADS and the recovery time of ECCS affect accident sequence progression. The analysis was mostly performed in a bounding sense, i.e. for example ADS either functioned or not, and for instance, the sensitivity of results to ADS valve capacity was not investigated. Delay in ECCS actuation was the main parameter varied – for both high and low RPV pressure scenarios. After evaluating this kind of extreme situations, expert judgment can be used to interpolate to less drastic scenarios and avoid performing too many simulations.

III.B. Containment Failure Probabilities

The weakest point in the LDW is typically the LDW door and the LDW strength refers to the strength of the door structure. In this study, a lognormal distribution with mean value of 50 kPa·s and error factor of 2.0 was used. For explosion impulses, lognormal distributions were also used, and they primarily depended on three things:

- LDW flooding
- Containment debris fraction
- Reactor coolant system (RCS) pressure

It is assumed that LDW flooding has to be halfway through at the time of vessel failure (melt ejection) so that a containment threatening pressure impulse could be considered plausible.

Containment debris fraction is assumed equal to core meltdown fraction if vessel breach occurs. If containment debris fraction exceeds 50%, melt amount engaged in fuel-coolant interaction is considered large; otherwise the interpretation is that there is only a little melt involved. The melt amount is assumed to have influence on both the mean value and the shape of the impulse distribution. High melt amount both shifts the distribution to the right and lengthens its tail, reflecting the possibility of really massive explosion impulses. The pressure impulse distributions are of the same magnitudes as the impulses found in literature (Ref. 5).

Fig. 1 illustrates the load distributions and also shows the distribution used for LDW strength. In the case names, “HP” refers to high pressure, “LP” refers to low pressure, “1” means that much melt is ejected, and “2” means that little melt is ejected. The most severe explosion is the one with low pressure and much melt.

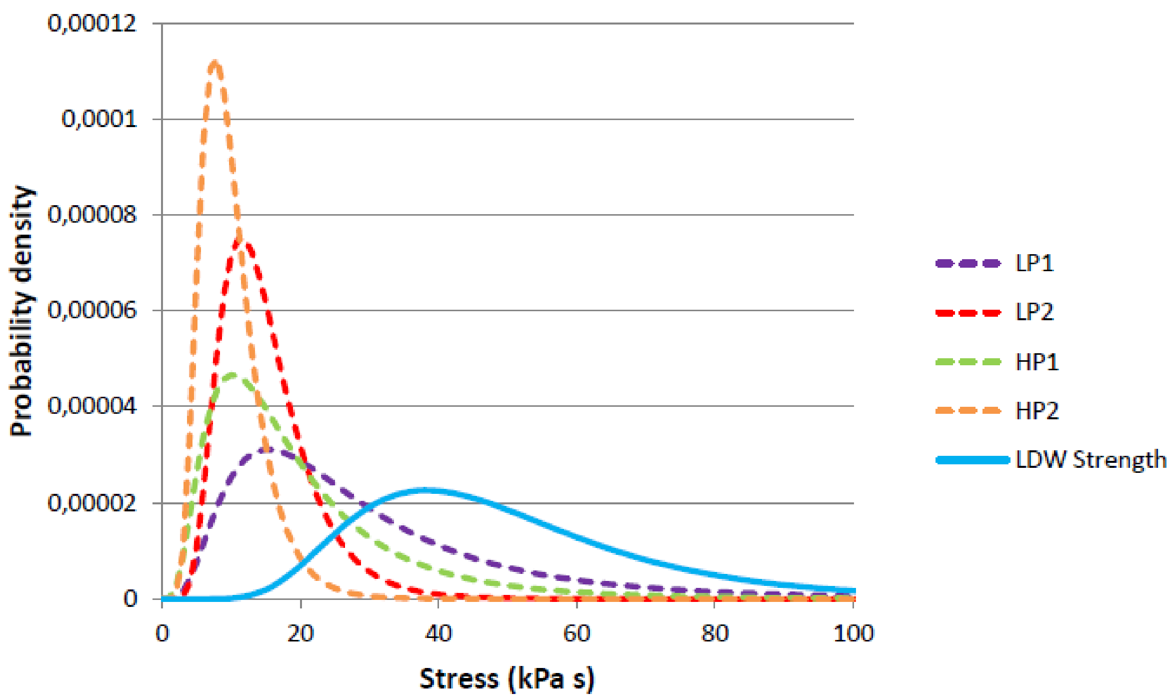

Fig. 1. Distributions used to determine whether LDW fails due to pressure impulse caused by ex-vessel steam explosion.

TABLE I presents the conditional probabilities of impulse load exceeding LDW strength given vessel failure, explosion trigger and enough water in LDW. Being conditional probabilities, the values in TABLE I do not take into account that for high-pressure cases the explosion is triggered more likely. Thus, the difference between high and low pressure cases is really not as big as it appears at first sight. Melt amount engaged in fuel-coolant interactions phenomena plays a more significant role.

TABLE I. Conditional probability of explosion impulse exceeding strength of LDW walls

	Much melt ejected (case 1, late or no ECCS recovery)	Little melt ejected (case 2, early ECCS recovery)
RCS depressurised (case LP)	0.207	0.021
RCS not depressurised (case HP)	0.091	0.003

RCS depressurisation is modelled to have an effect on the triggering of an explosion, and also on its magnitude. If primary circuit is pressurised when the vessel breaches, the triggering of an explosion is assumed to take place with probability 0.99, whereas low-pressure melt ejection triggers explosive fuel-coolant interaction phenomenon with probability 0.5. In the CET model, log-normal uncertainty distributions are set for these probabilities. While explosions associated with high pressure melt ejection are triggered more likely, they are also estimated milder than explosions that occur after low-pressure melt ejection.

IV. LEVEL 2 PRA MODEL

IV.A. Containment Event Tree Model

A containment event tree (CET) model for a boiling water reactor plant was developed in Ref. 2, and this paper presents a newer version of the CET. This CET represents a station blackout scenario, and the plant damage state covers both low and high pressure transients. The upper part of the CET is presented in Fig. 2. In the lower part of the CET, the structure is exactly similar for the non-depressurised scenarios as for the depressurised scenarios. The failure of containment isolation leads directly to radioactive releases. Containment failure modes are presented in TABLE II.

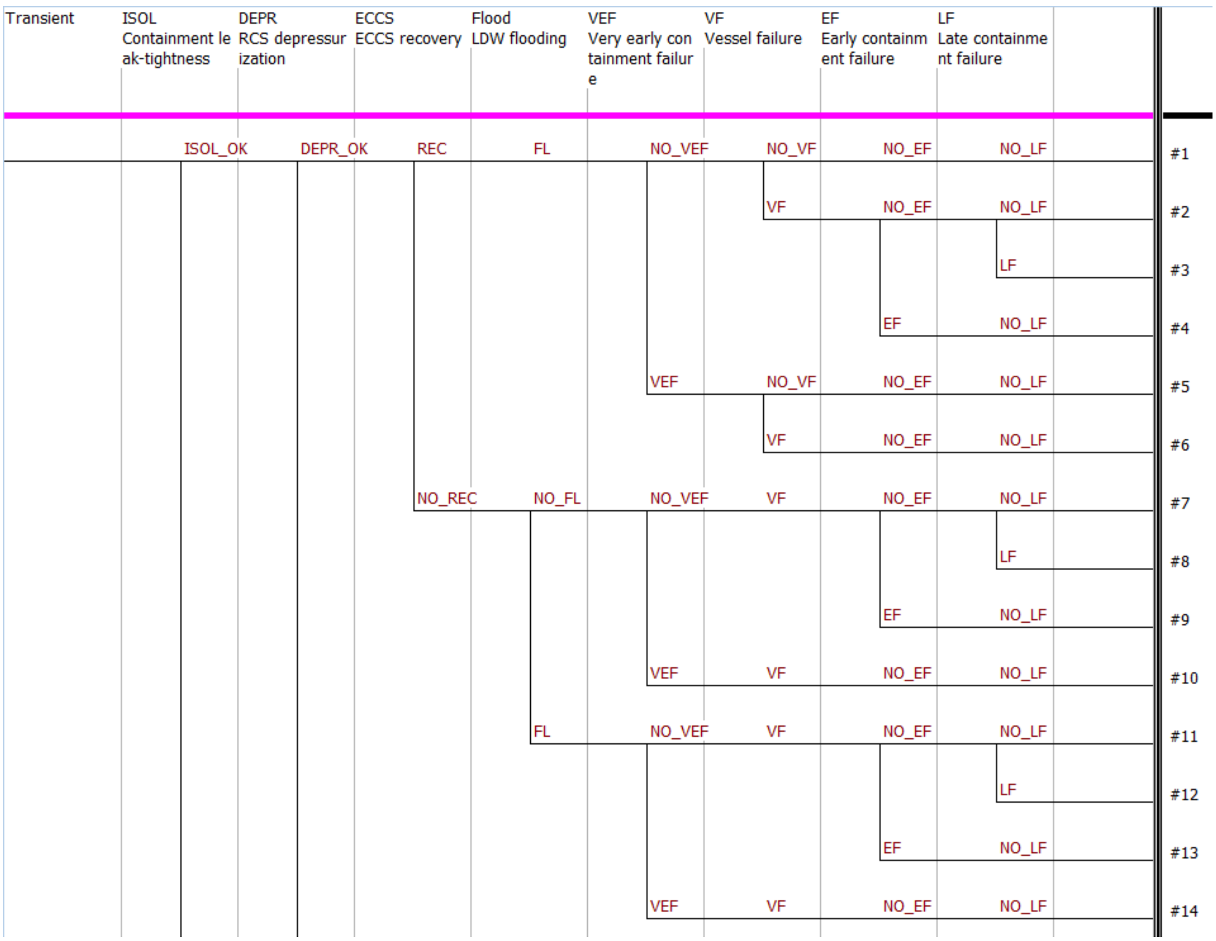

Fig. 2. The CET model.

TABLE II. Containment failure categories and the corresponding failure modes used in the CET model

Release category	Containment failure/vent mode
No containment failure or filtered venting (OK)	-
Isolation failure (ISOL)	1. Containment not leak-tight (ISOL)
Very early containment failure (VEF)	1. Containment over-pressurisation (COP) 2. Hydrogen deflagration/detonation (H2) 3. Alpha-mode failure (ALPHA)
Early containment failure (EF)	1. Ex-vessel steam explosion (STEAM) 2. Failure of containment penetrations (PENE)
Late containment failure (LF)	1. Non-coolable ex-vessel debris causes basemat melt-through (BASE)
Filtered venting (FV)	1. Very early venting (VEFV) 2. Early venting (EFV) 3. Late venting (LFV)

IV.B. CET Sections

The conditional probabilities of the CET branches are calculated in the CETL functions. All probability parameters are associated with uncertainty distributions. Some branch probabilities come directly from single distributions, while others are calculated based on multiple parameters and conditions. In addition, CETL functions calculate other variable values such as timings of different events and different release fractions. These parameters do not affect the probabilities, but they are used in the source term computation.

IV.B.1. ISOL, DEPR, ECCS and Flood

Containment isolation failure, depressurisation failure, emergency core cooling system recovery failure and LDW flooding failure are modelled with single failure probabilities. Though, ECCS recovery failure probability comes from different distribution in depressurised and pressurised case. The ECCS recovery fails more likely in depressurised case. ECCS and containment spray recovery time is also drawn from a distribution as well as flooding start and end times.

IV.B.2. VEF

In VEF section, meltdown timings are determined. Containment over-pressurisation failure probability is the product of recriticality probability and the probability that containment fails due to recriticality. Hydrogen explosion failure probability is the product of the probability that the containment is not inert and the probability that hydrogen explosion breaks the containment if it is not inert. A single probability is given for the containment failure due to an in-vessel steam explosion. The very early containment failure probability is the sum of these probabilities. Only one failure mode is realised in one simulation cycle. The failure mode is drawn based on the fractions of the failure mode probabilities. Containment failure time is also determined in the VEF section and it depends on the failure mode.

If very early containment failure does not occur, very early filtered venting can occur if the core is recritical. The venting probability is higher if the depressurisation has failed. Venting time is also set.

IV.B.3. VF

Vessel failure is modelled with a single probability. In VF section, the core meltdown fraction is updated depending on whether the vessel fails or not. The meltdown fraction must be large if the vessel fails and small if the vessel does not fail. Debris fraction is equal to the core meltdown fraction if the vessel fails. Vessel failure time is also determined. If LDW flooding has failed, the debris coolability fraction is set to zero.

IV.B.4. EF

The probability of early containment failure is the sum of ex-vessel steam explosion failure probability and containment penetrations failure probability. Both probabilities depend on the depressurisation and ECCS recovery. The steam explosion related probabilities were given in the previous section. In addition, the amount of melt ejected to the LDW has its own probability distribution. The probability of the containment penetrations failure comes from single distribution that differs depending on depressurisation and LDW flooding. The probability is high if LDW flooding has failed. If depressurisation and LDW flooding have worked, the probability is 0. Again, only one failure mode is realised in one simulation cycle, and the failure mode is drawn based on the fractions of the failure mode probabilities.

In the case of ex-vessel steam explosion, core meltdown fraction and debris fraction are updated, because higher fractions are more likely if an explosion occurs. Containment failure time is assumed to be the vessel failure time. In the case of the failure of containment penetrations, LDW dryout delay time is small if LDW flooding has been successful.

If early containment failure does not occur, early filtered venting can occur. The probability is calculated based on recriticality probability and a probability parameter that depends on ECCS recovery and depressurisation. Venting time is also set.

IV.B.5. LF

The basemat melt-through probability depends on ECCS recovery and flooding. The probability is the product of the probability that debris exists, the probability that the debris is not coolable and the probability that the basemat melt-through occurs if the debris is not coolable. If basemat melt-through occurs, small values are given for debris coolability fraction and LDW dryout delay time. Containment failure time is also set.

If late containment failure does not occur, late filtered venting can occur. The venting probability is higher if the depressurisation has failed. Venting time is set.

IV.C. Source Term Computation

The source term model is based on the model described in Ref. 6, which in turn has been influenced by the so called XSOR method (Ref. 7). The model here concerns only three radionuclide groups: noble gases (source variable S_Xe), cesium (S_Cs) and rutherium (S_Ru). The three groups were chosen so that the behaviour of radionuclides belonging to different groups deviates significantly from each another. Iodine releases are also often considered in release models but not here. Anyway, the behaviour of iodine releases would be closer to the behaviour of Cs than the behaviour of Xe. Source term modelling contains considerable uncertainties, especially with regard to fission product transport. Therefore, the model aims to give order of magnitude estimates instead of trying to predict accurate values.

Fission product model applies for atmospheric, i.e. gaseous releases. All releases, except noble gases, are assumed to be in aerosol form, which means that they follow the same diffusion, deposition and decontamination mechanisms and rules throughout the simulations. For noble gases, there is no such release decreasing phenomenon, and all noble gases released from the core are released from the containment as well. The basic idea of the source term model is presented in Fig. 3. The meanings of parameter/variable names can be checked from TABLE III. Almost all parameters used in the source term model are treated probabilistically as distributions because of the uncertainties involved. The starting point for the calculation of releases is the core release. After the core release, there are three different release mechanisms: early and late release from the reactor coolant system (RCS), and ex-vessel debris release.

Core release corresponds to severe core degradation and it is sampled for each radionuclide group from a distribution assigned to it. The actual release mechanisms are dependent on the core release fraction.

Early RCS release refers to fission products that are first released from the core and then penetrate the RCS. Release fraction from the primary circuit is sampled from a distribution which depends on whether RCS is pressurized or not. The expected value for early RCS releases is higher for low-pressure case because the residence time of fission products in the RCS is longer. The time interval for early releases is from the start of core melting to the end of melting. The melting can end due to the recovery of ECCS or core being fully molten.

Late RCS release is formed from the fission products that do not penetrate the RCS but are deposited on the RCS structures. Late in-vessel release occurs when these deposits are revaporised. The revaporisation fraction for each radionuclide group also comes from a distribution. If the ECCS is recovered in time, the revaporisation fraction is set to zero. The length of the release interval for late revaporisation release is assumed to be normally distributed between 1 and 9 hours, and the release starts when the RPV breaches.

Ex-vessel debris release consists of core contents that are not involved in releases from the RCS, and it can occur only if the vessel fails. Source term variable specific debris release fraction is sampled from a distribution assigned to it, and only the non-coolable part of debris is assumed to contribute to the release. A debris coolability fraction is used, and it has a non-zero value if there is water in the LDW. The length of ex-vessel debris release time interval is assumed normally distributed between 1 and 5 hours (truncated distribution). The release begins when the vessel breaches. If the flooded LDW dries out because of a containment failure, a dryout delay is taken into account in the start time.

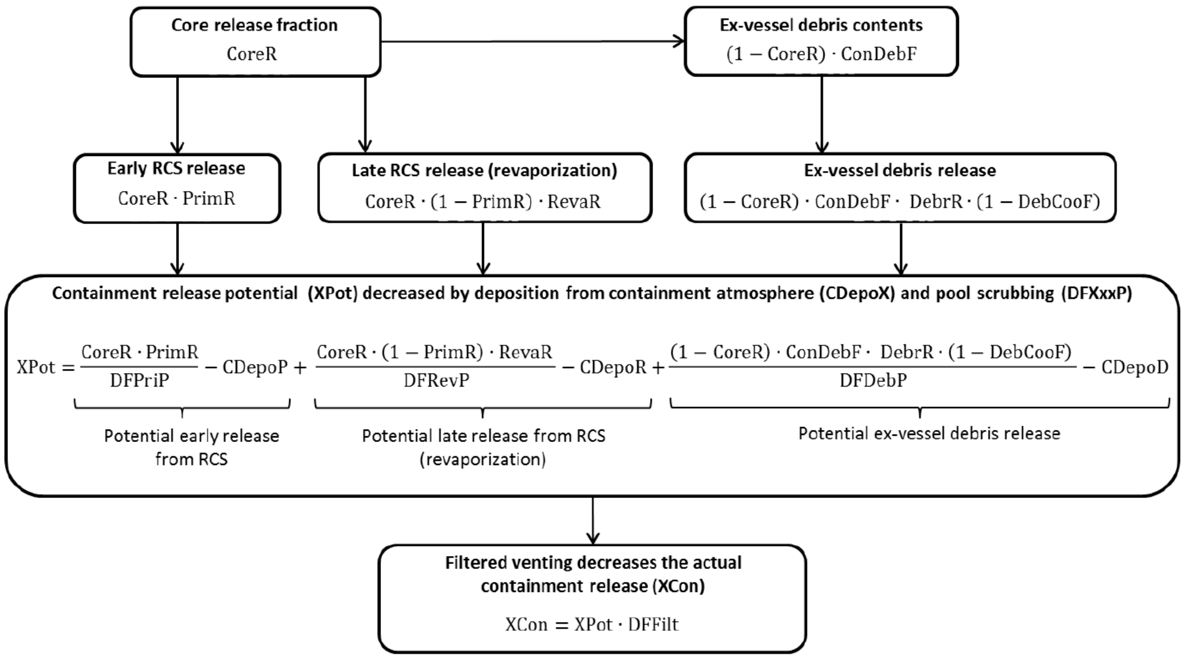

Fig. 3. Source term model that calculates releases out of the containment.

TABLE III. The meanings of the model's variables

Variable	Meaning
CoreR	Core release fraction
ConDebF	Fraction of potential ex-vessel debris actually formed
PrimR	Primary release fraction (Fission products from core penetrating RCS)
RevaR	Release fraction due to revaporisation
DebrR	Debris release fraction
DebCooF	Debris coolability fraction
XPot	Potential release from the containment
DFPriP	Pool decontamination factor for primary release
CDepoP	Deposition from containment atmosphere for primary releases
DFRevP	Pool decontamination factor for revaporisation release
CDepoR	Deposition from containment atmosphere for revaporisation releases
DFDebP	Pool decontamination factor for debris release
CDepoD	Deposition from containment atmosphere for debris releases
XCon	Actual release from the containment
DFFilt	Decontamination factor for filters

Fig. 4 summarises release intervals for all release mechanisms and places them along major events that occur during the accident progression.

Pool scrubbing occurs when fission product releases are driven through a water pool, and then, the release is decontaminated before it enters the containment atmosphere. The effect of pool scrubbing is implemented by using decontamination factors, which are defined as the ratio of radionuclide flow into pool and radionuclide penetration through the pool. Each release mechanism and radionuclide group pair has its own decontamination factor. For late RCS revaporisation release, the factors are only nominal and do not have big effect, because any release is assumed to flow out of the RCS directly into the containment atmosphere practically without pool decontamination. For debris release, pool scrubbing occurs only if the LDW is flooded and does not dry out completely when the vessel breaches. A decontamination factor can then be decreased by a gradual LDW dryout. For noble gases, there is no pool scrubbing related decontamination at all.

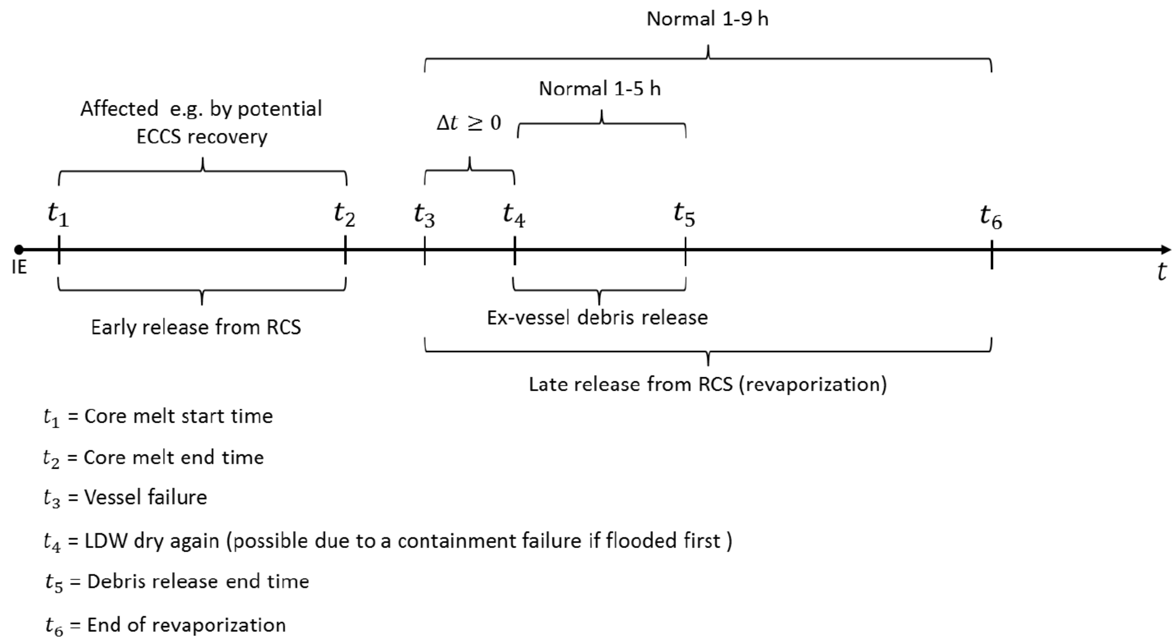

Fig. 4. The timings of the different release mechanisms.

When the fission products are in the containment atmosphere, they can get gradually deposited on containment structures and in water pools. The approach taken to model **containment deposition** is based on defining a deposition rate for the fission products. The deposition rate is affected by the containment area available for deposition which in turn depends on LDW flooding. Also, the free gaseous volume in the containment influences the process. From the release rate, the actual amount of deposited fission products is derived using release time intervals defined for each release mechanism. The effect of containment spray is included in the containment deposition consideration, and the value assigned to the spray impact is also treated probabilistically. The spray is assumed to operate if the ECCS recovery is successful. Containment deposition is calculated similarly using the same parameter values for all releases, but some parameters can have different values because release timings are not the same.

Release from the containment is calculated as a sum of releases associated with all different release mechanisms, as suggested by Fig. 3, taking into account containment deposition and pool scrubbing decontamination. The sum represents the containment release potential. The actual release is calculated by applying decontamination factors related to filtered containment venting, which can occur if there is no major containment failure. Filters do not have any effect on noble gases.

Source term calculations are performed at each end state of the CET at the end of the analysis on each simulation run. The release time interval for each release mechanism is divided into ten, and a discrete point release is calculated at the centre of each tenth and added to total release. The accuracy can be increased by dividing the release interval into larger number of subintervals, but ten is considered sufficient.

After all the simulations (10 000 runs) have been performed, the results are binned into release categories. The categorization can be seen in TABLE II with the exception that early containment failure modes have separate release categories. Forming a specific release category for ex-vessel steam explosions alone is generally not reasonable or recommended, but in this study, steam explosions needed to be separated to facilitate the analysis of results.

IV.D. Results

TABLE IV presents the results including the conditional probabilities and release fractions for all release categories. The four values in the cells of the table are mean, 5th percentile, median and 95th percentile. Filtered venting (FV) and OK bins are dominant with a combined share of 75% of the probability. Very early failure (VEF) is also quite probable with a share of 20%. Early containment failure caused by a steam explosion (EF_STEAM) occurs with mean probability 0.027. Hence, the contribution of steam explosions to early containment failure is significant.

TABLE IV. The summary of results

Bin	Prob.	S_Xe	S_Cs	S_Ru
OK	2.21E-01	7.67E-11	0.00E+00	0.00E+00
	1.38E-02	1.84E-11	0.00E+00	0.00E+00
	3.22E-01	9.94E-11	0.00E+00	0.00E+00
	4.16E-01	1.00E-10	0.00E+00	0.00E+00
ISOL	9.91E-03	8.42E-01	2.57E-01	8.94E-03
	4.55E-03	4.41E-01	6.83E-02	0.00E+00
	9.11E-03	9.96E-01	2.42E-01	3.46E-03
	1.79E-02	1.00E+00	4.74E-01	3.41E-02
VEF	1.95E-01	7.60E-01	1.15E-01	3.91E-03
	9.66E-02	1.74E-01	8.88E-03	2.29E-06
	1.79E-01	9.94E-01	8.80E-02	7.68E-04
	3.48E-01	1.00E+00	3.24E-01	1.87E-02
EF_PENE	1.74E-03	8.34E-01	2.41E-01	8.26E-03
	4.67E-06	4.13E-01	6.15E-02	8.94E-08
	1.28E-03	9.97E-01	2.25E-01	3.05E-03
	4.81E-03	1.00E+00	4.62E-01	3.22E-02
EF_STEAM	2.72E-02	7.76E-01	1.54E-01	5.31E-03
	3.84E-03	2.01E-01	1.42E-02	7.16E-07
	2.07E-02	9.95E-01	1.35E-01	1.33E-03
	7.18E-02	1.00E+00	3.74E-01	2.32E-02
LF	1.24E-02	7.93E-01	1.74E-01	5.36E-03
	1.02E-03	2.82E-01	3.18E-02	0.00E+00
	8.88E-03	9.95E-01	1.55E-01	1.52E-03
	3.58E-02	1.00E+00	3.86E-01	2.21E-02
FV	5.33E-01	7.41E-01	7.67E-04	2.50E-05
	7.94E-04	1.38E-01	1.12E-06	0.00E+00
	7.10E-01	9.60E-01	5.09E-05	1.82E-07
	8.44E-01	1.00E+00	2.72E-03	4.69E-05
Weighted	1.00E+00	5.92E-01	3.21E-02	1.09E-03
Total	1.00E+00	8.94E-02	4.44E-03	6.01E-07
	1.00E+00	5.83E-01	2.37E-02	3.00E-04
	1.00E+00	1.00E+00	8.78E-02	4.85E-03

Source term for noble gases (S_Xe) is generally very high because there is neither decontamination nor deposition considered for them and release fraction parameters for noble gases used in calculations are the highest for every release mechanism. Even for OK bin there is a minor leakage of noble gases. Cesium release (S_Cs) is also quite high for all release categories where containment fails whereas filtered releases are more moderate. Rutherium (S_Ru) release behaves similar to cesium release but the release is a couple of orders of magnitude smaller.

V. CONCLUSIONS

Steam explosions were modelled in a level 2 PRA model utilising IDPSA methodology. MELCOR simulations were performed to obtain knowledge on physical parameters affecting steam explosions. The analysis showed clear differences between high and low pressure cases with regard to important steam explosion parameters such as ambient pressure and LDW water pool subcooling. Particularly, useful knowledge was acquired about the timing of events and about the time available for ECCS recovery. Containment failure probabilities were calculated using load vs. strength approach. Depending on accident progression, four different pressure load impulse distributions were used for sampling in CET simulations, and whenever load exceeded LDW strength, a containment failure was induced.

Even if simplifications and compromises were made in modelling work, the study demonstrated successfully how to use IDPSA methodology in level 2 PRA and in FinPSA 2.0 tool. General knowledge on selected severe accident phenomenon and modelling capabilities were also obtained. The focus was on steam explosions, but similar approach can be applied to other accident phenomena too.

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