Dynamic Event Trees for Probabilistic Safety Analysis

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Abstract: In technical systems like nuclear power plants, an accident sequence starts with an initiating event and evolves over time through the interaction of dynamics and stochastics. This interaction is capable of producing infinitely many different sequences. Along the time line they define a continuous dynamic event tree with infinitely many branch points. At each point of time, the stochastic variability of the accident consequences is summarized by a multivariate probability distribution. A probabilistic safety analysis (PSA) requires an approximation to this distribution for selected consequence variables. It is felt that the conventional event tree analysis of Level 1 and of Level 2 PSA does often not permit a satisfactory probabilistic representation for PSA purposes. For this reason various methods of probabilistic dynamics have been suggested over the past decade. This paper presents a recent development that combines dynamic event tree analysis with Monte Carlo simulation. The advantages of this combination are explained and illustrated by a practical application involving MELCOR as the dynamics code.

1. INTRODUCTION

Event sequences evolve over time through the interaction of dynamics and stochastics in the system of man, machine, process and environment.

In the conventional event tree analysis of Level 1 PSA and in the accident sequence analysis of Level 2 PSA, the analysts prescribe the stochastic events together with the order in which they occur. While temporal information may be available for few selected sequences in Level 1 and on an event scale in Level 2, it is usually not given for the tree. These customary trees largely develop along a so-called effect line rather than a time line. Branch points of Level 1 event trees are prescribed by the order of safety system demands at set points. Usually, there are only two branches per point, namely "system starts" and "system fails to start". Due to limitations of the conventional event tree methodology no consideration can be given, for instance, to the consequences of failure to run for the intended time and/or with the required capacity.

Branchings in Level 2 accident sequence trees are frequently used to account for the stochastic variability of the consequence magnitudes from phenomena that do not permit mechanistic modeling. Presently, the multitude of possible accident sequences in Level 2 PSA is reduced to the degrees of freedom of a rather coarse grid in time (i.e. "early", "late" or "before", "after"), in space (i.e. "top", "bottom") and in magnitude (i.e. "small", "medium", "large"), etc. This does not permit to model the possible spectrum of interactions of dynamics, phenomena, component behaviour and human actions as close to reality as is desirable. Inherent to the coarse grid is the danger that

- important sequences, resulting from details in time, space, magnitude and order of events, remain unknown
- unrealistic sequences are generated, based on analyst specified conditions which otherwise would result from preceding events.

Probabilistic dynamics enable us to fully account for the temporal evolution of the interaction of dynamics and stochastics in the evaluation of accident consequences and their conditional (condition is the initiating event) probabilities. Probabilistic dynamics operate on the actual time/state space although discretizations have to be performed for the evaluations to be numerically manageable. The computational effort is considerably larger compared to a conventional event tree analysis. For this reason their application is still restricted to specific aspects of a PSA. The vision is, however, to be able to perform a dynamic PSA. Such an analysis would account for the interactions between the dynamics and set points in time/state space on one hand and the stochastics in initial and boundary conditions, in consequences of phenomena, in the failure behaviour of technical components and systems as well as in human actions on the other hand.

The most straightforward numerical procedure for such an analysis would be a Monte Carlo simulation. Its transition probabilities may depend on the state of the dynamic quantities, systems and components and even on residence times as well as on details of the sequence history. It suffices to prescribe rules for the evaluation of the probabilities of transitions to those states that are directly accessible from the present state. One Monte Carlo element generates only one sequence out of the population of infinitely many possible sequences and the Monte Carlo simulation produces a random sample of sequences. Low probability transitions will be adequately represented only if the sample is of sufficiently large size. The generation of each sequence requires a complete dynamics calculation starting from the initiating event and ending in one of the “absorbing” states. The latter include specified damage states, the state of no damage and controlled operation and possibly the arrival at the endpoint of the specified observation time.

The literature reports on a variety of methods from probabilistic dynamics [1 to 6] . They generally permit a considerable reduction of the computer time for the dynamics calculations through organization of the model runs such that duplication is avoided for sequence sections. Transitions of deterministic or random and discrete “when” and “where to” can be adequately treated by these methods. Transitions of many discrete “when” and/or “where to” generate many branches thereby blowing up the tree enormously. Transitions of random and continuous “when” and/or “where to” are not or not yet satisfactorily handled by these methods. The method described in the next paragraph closes this gap.

2. THE STOCHASTICS MODULE MCDET

A combination of Monte Carlo simulation and dynamic event tree analysis (the acronym is MCDET - <u>M</u>onte <u>C</u>arlo <u>D</u>ynamic <u>E</u>vent <u>T</u>ree) was developed and tested [7]. It permits an approximate treatment of continuous random transitions and also of those discrete random transitions with many transition alternatives. An estimate of the approximation error is provided by the method.

Each of the two characteristics of a transition, i.e. “when” it occurs and “where to” it goes, may be either deterministic, discrete and random, or continuous and random. MCDET considers all combinations of the “when” and “where to”. Discrete and random “when” and/or “where to” are generally taken into account by dynamic event tree analysis. Continuous and random “when” and/or “where to” are handled by Monte Carlo simulation. Transitions of deterministic “when” (set point transitions) are part of the general control module of the deterministic dynamics code. This module contains the points in time/state space where automatic reactions of the safety systems are initiated (set points).

MCDET can be identified as a special case from the class of so-called "variance reduction by conditioning" Monte Carlo simulation methods. Any scalar output quantity Y of a (dynamic) model h subject to aleatory uncertainties (stochastic events) can be represented as $Y=h(\mathbf{V})$ with $\mathbf{V}$ being the set of all stochastic variables involved. $\mathbf{V}$ is then divided into two subsets $\mathbf{V}_d$ and $\mathbf{V}_s$ with $\mathbf{V}_d$ = subset of selected discrete variables treated by event tree analysis and $\mathbf{V}_s = \mathbf{V} \backslash \mathbf{V}_d$ = subset of all remaining variables, i.e. all continuous and the remaining discrete variables. For instance, the variables in $\mathbf{V}_d$ may be regarded as representing the discrete system states into which the aleatory transitions may take place, the variables in $\mathbf{V}_s$ as representing the continuous aleatory times at which these transitions may occur.

The MCDET procedure may roughly be considered as consisting of two main computational parts:
(a) generate a value $\mathbf{v}_s$ of the variables from subset $\mathbf{V}_s$ by Monte Carlo simulation – this part will involve biasing techniques like sampling the 'failure to run' time of a system from the conditional distribution where the condition is the run time failure within the required operation time of the system and the failure branch probability is the condition probability,
(b) perform the computer model runs with the value $\mathbf{v}_s$ for the variables from subset $\mathbf{V}_s$ and with all possible combinations of all discrete values of the variables from the subset $\mathbf{V}_d$ (considered as paths of an event tree).
From this the respective discrete conditional distribution $F_{Y|Vs}(y|\mathbf{V}_s=\mathbf{v}_s)$ of the output Y given $\mathbf{V}_s=\mathbf{v}_s$ and its expectation $E[Y|\mathbf{V}_s=\mathbf{v}_s]$ can be computed analytically. Repeating these two steps n times independently, a sample of n conditional distributions/expectations is obtained from which many useful statements on the aleatory uncertainty in Y can be derived. In applications with computationally intensive models, a probabilistic "cut off" criterion must often be introduced to keep the computational effort practicable. It ignores all paths (=combinations of values of variables from $\mathbf{V}_d$) which have a conditional probability less than a user specified threshold value. Due to the well known relationships $E(E[Y|\mathbf{V}_s]) = EY$ and $var(E[Y|\mathbf{V}_s]) = var\ Y - E(var[Y|\mathbf{V}_s])$ it turns out that the estimate of any kind of expected values obtained from the MCDET procedure is more efficient, i.e. has smaller variance, than the corresponding estimate obtained from the crude Monte Carlo simulation with all aleatory variables, discrete as well as continuous, sampled with the same sample size n. Of course, the processing time for the dynamics calculations of a single MCDET run with all its paths may be much longer than the processing time for the dynamics calculations of a single sample element of the crude Monte Carlo simulation. For details see the efficiency considerations in chapter 2 of [7].

Dynamic event trees are continuous (with respect to continuous transitions) in time/state space. However, for practicality reasons they are discretized by the Monte Carlo simulation. A discrete dynamic event tree generated by MCDET, is an ensemble of paths randomly chosen from a population of possible ensembles. To obtain continuous dynamic event trees one would need to analytically solve the equations of probabilistic dynamics (for their formulation in a rather simplified situation see [8]). With the combination of discrete dynamic event tree analysis and Monte Carlo simulation, as in MCDET, an approximate solution of these equations in their most general formulation is obtained.

MCDET is implemented as a stochastics module that may be operated in tandem with any deterministic dynamics code, some basic input/output properties of the code assumed. For each element of the Monte Carlo sample, the tandem generates a discrete dynamic event tree and computes the time histories of all dynamics variables along each path together with the path probability. Each tree in the sample provides a conditional probability distribution (conditioned on the initiating event and on the values of the randomly sampled aleatory uncertainties) for each of the dynamics quantities and at all points of time. The mean distribution over all trees in the sample is the final result. From the random sample of discrete dynamic event trees, the probabilities of all dynamics and system states of interest may therefore be estimated. Together with these estimates confidence intervals are available that quantify the possible influence of the sampling error which is due to the limited sample size of the Monte Carlo simulation.

Modeling the stochastics requires the formulation of random laws and the specification of their parameter values. Laws and parameter values but also the relevance of phenomena, the formulation of the dynamics model, model parameter values, parameters of numerical solution procedures as well as input data of the dynamics code are subject to epistemic (i.e. state of knowledge) uncertainty. The combined influence of the epistemic uncertainties on the solution estimates provided by MCDET (or any other PSA method) needs to be quantified. To this end the state of knowledge to each of the epistemic quantities is expressed by a subjective probability distribution. The immediate way to estimate the combined influence of the epistemic uncertainties would again be by Monte Carlo simulation. This would lead to two nested Monte Carlo loops (also known as "double randomization" or "two-stage sampling") where the outer loop samples the epistemic quantities and the inner loop is the conditional MCDET for the continuous and some of the discrete aleatory (i.e. stochastic) quantities, given the values of the epistemic quantities from the outer loop. Frequently, the dynamics model is very processor time intensive and thus the obvious way of two nested Monte Carlo loops is often not practicable. An approximate epistemic uncertainty analysis was therefore suggested in [7,9]. It is based on the decomposition of the total variance into both, the contribution from the epistemic uncertainties and the contribution from the aleatory uncertainties treated by Monte Carlo simulation. The computational effort of this approximate method consists of only one repetition of MCDET thereby also sampling the epistemic quantities in the Monte Carlo simulation.

3. ILLUSTRATIVE APPLICATION OF MCDET WITH MELCOR

This paragraph describes an application of MCDET to a transient simulation with MELCOR which was chosen for demonstration purposes. First the transient is briefly discussed, followed by a short summary of main points of the plant representation in MELCOR and by a compilation of the aleatory uncertainties considered.

3.1 The transient

A total station black-out (SBO) in a 1300 MWe pressurized water reactor of Konvoi type at nominal power (end of cycle) was chosen to illustrate the applicability of MCDET in tandem with the dynamics code MELCOR [10]. The transient is characterized by the total loss of power (including emergency diesels and other sources). Furthermore, the analysis assumes that external power is restored not earlier than 5700 s and not later than 12000 s after the initial event. Due to the loss of power, the main coolant pumps and all operational systems fail. For some period of time, batteries guarantee DC power supply to all battery supported functions. Scram and turbine trip are performed automatically. Automatic pressure limitation via the pressurizer relief valve and the two safety valves is possible. After the corresponding signal indicates that a plant specific criterion is satisfied, primary side pressure relief (primary bleed as an accident management measure) is principally assumed.

Once 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. The high pressure and low pressure emergency coolant injection systems can be activated only once the power supply has been restored. After power restoration the four trains are reconnected to the grid one by one, each requiring some preparation time. In any case, some time is required after the bleed operation until coolant is injected into the primary side. Depending on how much time goes by, the core may experience gradual damage. The effects of this, particularly in connection with the finally occurring injection of coolant, depend on details of the timing of various events. The high core melt temperatures in combination with high system pressure (in the case of unsuccessful bleed operation) may lead to failure of main coolant piping in the hot leg or of the pressurizer surge line before the vessel integrity is lost.

Of particular interest are the time histories of dynamics quantities like pressure in the vessel as well as in the containment, core exit temperature and the degree of core degradation as expressed by the total melt mass and hydrogen mass generated. Also of interest is the conditional probability of primary side pressure relief with successful core cooling, etc..

3.2 Representation of the plant in MELCOR

MELCOR is a deterministic fully integrated, full plant severe accident simulation code for nuclear power plants. It was developed for applications in integrated severe accident analyses and probabilistic safety assessments (PSA) by Sandia National Laboratories. A detailed description of all its models may be found in [10]. The MELCOR code is used to model a wide range of phenomena including thermal hydraulics, core heat-up and degradation, core concrete interaction, radio-nuclide release and transport and melt ejection phenomena, etc.. Since 1998 GRS applies the extended version MELCOR 1.8.4. This version was used with MCDET for the illustrative application described here. With respect to the plant representation the following should be mentioned:

- The four main coolant loops are represented by two model loops. Each of these two loops is divided into five volumina and contains a model of the main coolant pump. The loop connected to the pressurizer, is one of the two loops. The remaining three loops are combined into the other model loop.

The pressurizer, its surge line to the hot leg and its relief tank are represented separately by altogether five volumina. The volumina are connected by flow paths which describe, as far as possible, the actual flow conditions. Pressurizer heating, relief valve and safety valves as well as rupture discs are modeled separately in agreement with the situation in the reference plant.

- Of the existing coolant injection systems the accumulators (their controls are modeled in detail, i.e. including their shut-off at the cold leg 500 s after the relevant emergency coolant injection signal) are represented together with their additional isolation valves. Especially for investigations of the reflooding phase after a total SBO, each of the four high pressure and low pressure injection systems is modeled together with its source isolation valve including the shut-off specifications of these three-way valves.

- The reactor core was modeled by five non-uniform radial rings and ten axial levels for the active core according to e.g. the axial and radial power profile.

For further details see [11]. Different to [11], a simplified model of the containment was used since the main interest focused on the processes within the reactor circuit.

3.3 Aleatory uncertainties

Whether the pressurizer relief valve and/or any of the two safety valves will fail during the many demand cycles of the automatic pressure limitation, is subject to aleatory uncertainty (stochastics). Their failure probability is assumed to increase with the number of demand cycles performed. Further aleatory uncertainties are the number of the failure cycle and whether the failure mode will be “fails to open” or “fails to close”. Gradual failures can be considered in MCDET but was not done so in this illustrative application.

After the corresponding signal indicates that the relevant criterion is satisfied, primary side pressure relief (primary bleed) is assumed to be initiated by the crew after some delay time. The length of this delay time as well as the opening of valves that have not yet failed during the pressure limitation (i.e. the total valve diameter available for the bleed operation), are subject to aleatory uncertainty.

The accumulators can inject their coolant inventory, provided the associated source and additional isolation valves open on demand, which is an aleatory uncertainty for each of the valves.

The high pressure and low pressure emergency coolant injection systems can be activated only once the power supply has been restored. The time of this event as well as the start on demand of each of the four high pressure and low pressure pumps, once reconnected, and the functioning of their source isolation valves are further aleatory uncertainties. The order of reconnection of the four emergency coolant trains depends on which source isolation valve was found not to open for accumulator injection. This train will be reconnected last.

4. RESULTS FROM THE ILLUSTRATIVE APPLICATION

A sample of 50 discrete dynamic event trees was generated by MCDET for the transient of paragraph 3. Section 4.1 presents the first paths (or event sequences) of two trees from the sample in the time/event plane and discusses some of the sequences. Section 4.2 shows the trees of section 4.1 for two dynamics quantities in the time/state plane and a conditional probability distribution is shown in section 4.3 for one of these trees. An example of the actual results obtained, namely the mean distribution over all discrete dynamic event trees in the Monte Carlo sample, is presented in section 4.4.

4.1 Selected trees in the time/event plane

Figs. 1 and 2 show the first fifty or so (out of over 200) paths of two discrete dynamic event trees (tree nos. 2 and 7) of the Monte Carlo sample in the time/event plane. The usual vertical lines at branch points are omitted for clarity of presentation. Instead, each branch is given an identifier consisting of the path number before the slash and the number of its origin (path where it branches off) after the slash. At the end of each path the path number is repeated together with the conditional path probability.

On the time line, at the bottom of each tree, the randomly chosen demand cycle (pressure limitation), with valve failure, is indicated for all three valves (denoted by AV, SV1, SV2). Furthermore the times of reconnection of the four emergency coolant trains, which are derived from the randomly chosen time of power restoration plus preparation time, are shown on the time line (denoted by S1, S2, S3 and S4).

Sequence no. 0 at the bottom of Fig. 1, is the base path. It is shown here from 4000 s onwards since none of the stochastic events considered can lead to a branching before this time. Along the base path no valve failure occurs during the demand cycles for pressure limitation. Pressure relief of the primary side (bleed) is performed after the randomly chosen delay time. All valves open as is indicated by the open square symbol between 6500 s and 7000 s. Once the pressure has decreased far enough, the accumulators inject coolant. As is indicated by the crossed square, the source isolation valves and the additional isolation valves for hot leg accumulator injection open on demand. The four diamonds following next on the base path indicate the times of the successful reconnection of each of the four high pressure and low pressure injection pumps and the opening of the corresponding source isolation valves both in the hot and cold legs as demanded.

Paths 1 and 2 branch off path 0 at the demand cycle of the pressurizer relief valve that was randomly chosen for this tree as failure cycle. In path 1 the relief valve fails to close (open triangle) and in path 2 it fails to open (closed triangle). Along paths 1 and 2 everything else is functioning as intended. Possible failure events lead to branch points on these paths. For instance, in path 3, which branches off path 2, the first safety valve fails to close in addition to the stuck closed pressurizer relief valve. The first diamond on path 2 indicates the bleed action with reduced total diameter (only the two safety valves open). For the meaning of further symbols see Table 3.10-1 in [7].

In paths 0 to 3 accumulator injection occurs before and in paths 4 to 6 after reconnection of the first emergency coolant train. This difference in the sequence of events is an immediate consequence of the interaction of stochastics and dynamics.

4.2 Selected trees in the time/state plane

Figs. 3 and 5 show the discrete dynamic event tree no. 2 of the sample in the time/state plane for the dynamics quantities (or state variables) total generated mass of UO_2 melt and of H_2. The corresponding information for tree no. 7 is shown in Figs. 4 and 6. The difference between tree nos. 2 and 7 is due to the randomly chosen

- demand cycles with valve failure (pressurizer relief valve and safety valves) during pressure limitation
- time between signal and actuation of depressurization of the primary side by the crew
- no. of the emergency coolant train with failure of the source isolation valve to open in the cold leg
- dito for hot leg
- no. of the emergency coolant train with failure of the additional isolation valve to open in the cold leg
- dito for hot leg
- time of recovery of external power supply.

4.3 Probability distributions for dynamics quantities

The PSA requires the conditional probability distribution of, for instance, the total generated H_2 mass at specific points of time. Fig. 7 shows this distribution at 12000 s as obtained from the discrete dynamic event tree no. 2 of the Monte Carlo sample.

The actual result of the probabilistic dynamics analysis with MCDET and MELCOR is, however, the mean distribution over all discrete dynamic event trees in the sample. This distribution at 12000 s is shown in Fig. 8.

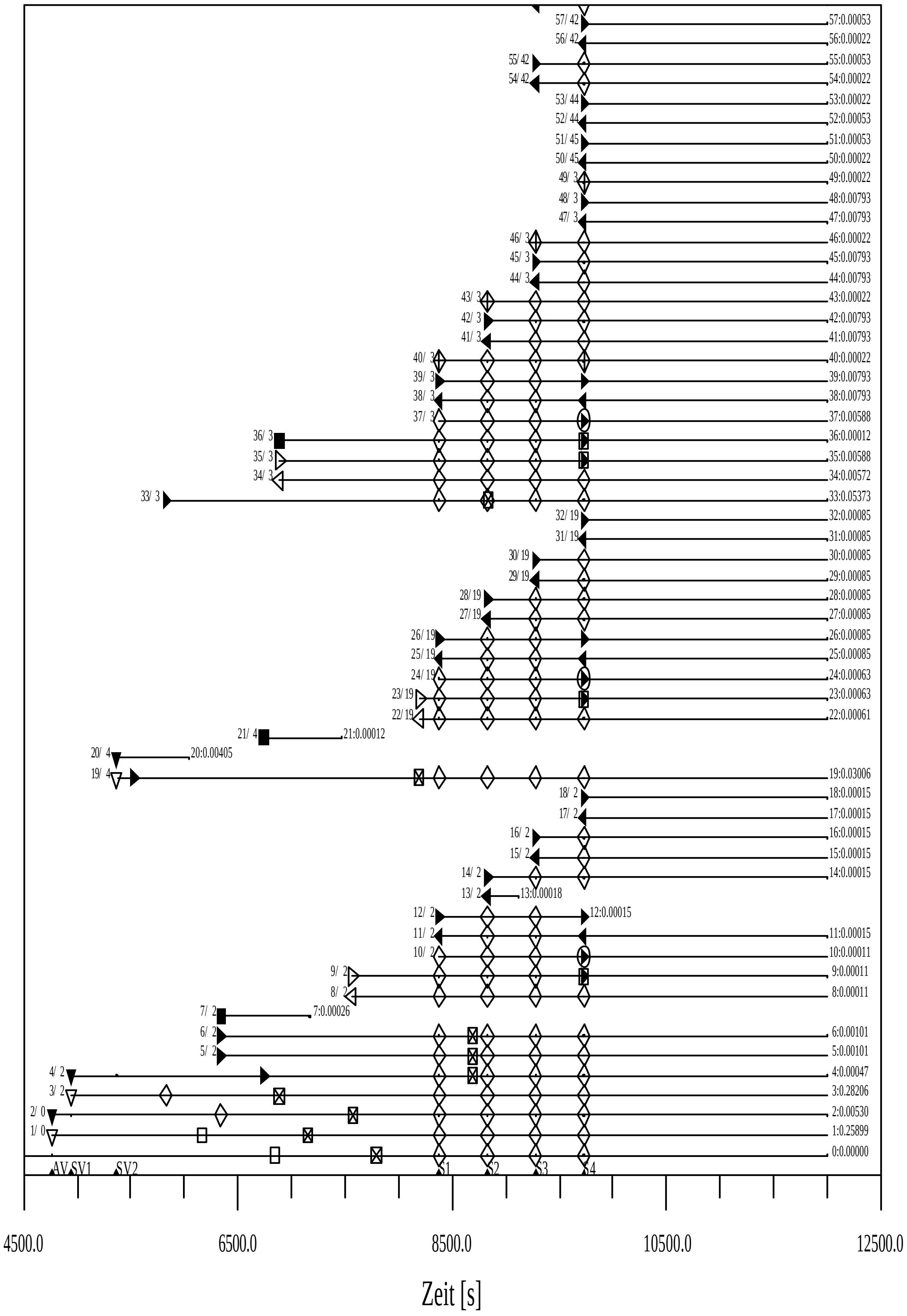

Fig 1: Path nos. 1 to 57 (of a total of 226) of the dynamic event tree no. 2 of the sample, presented in the time/event plane

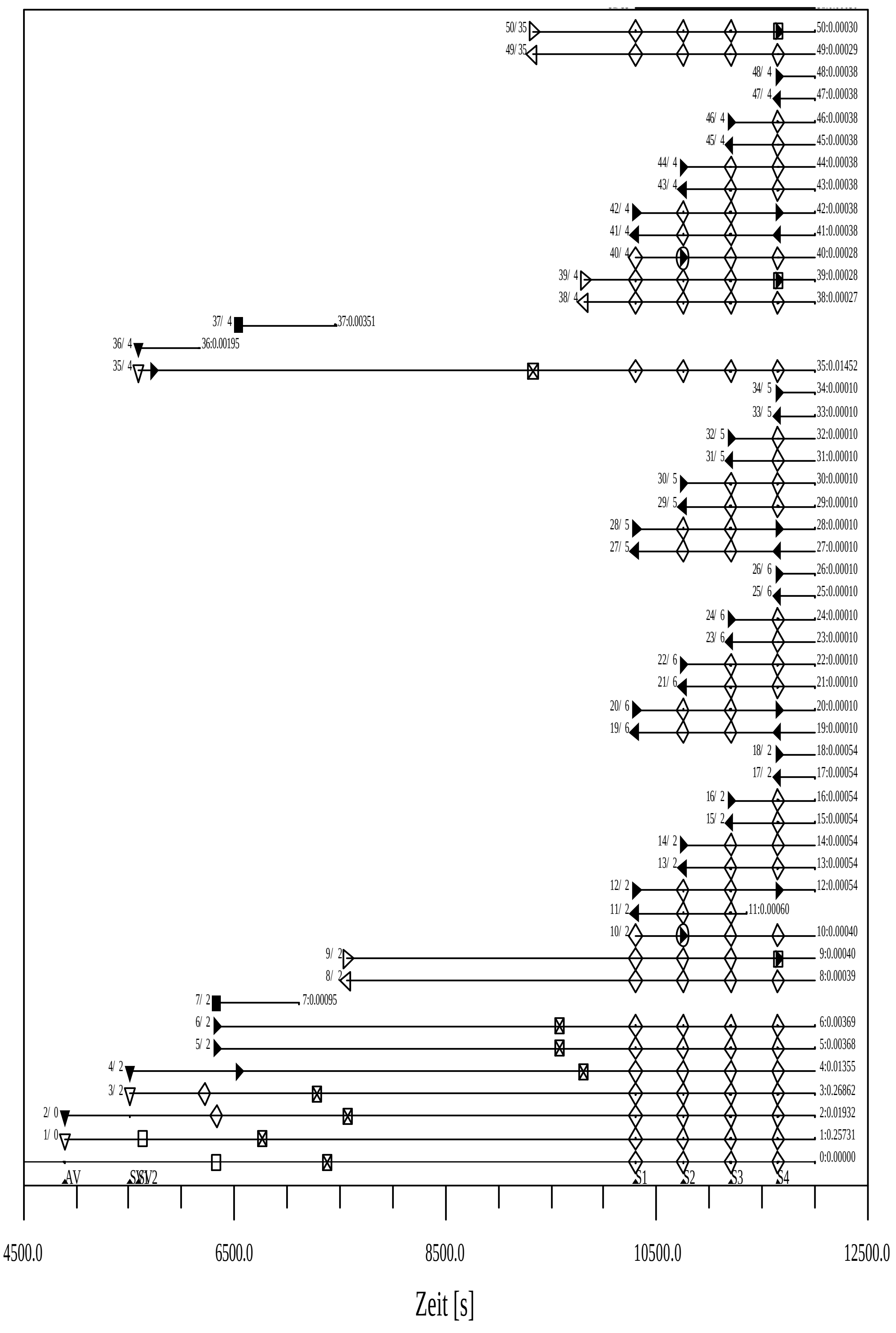

Fig. 2: Path nos. 1 to 50 (of a total of 251) of the dynamic event tree no. 7 of the sample, presented in the time/event plane

4.4 Final result of the probabilistic dynamics analysis

Fig. 8 shows the empirical conditional (condition is the considered SBO) probability distribution of the total generated H_2 mass at 12000 s. From this distribution one reads, for instance, that the H_2 mass does not exceed 320 kg with conditional probability 0.82, while it exceeds 200 kg with conditional probability 0.43. The corresponding information is available for all other dynamics quantities.

At any given value of the total H_2 mass generated up to 12000 s, the solution of the probabilistic dynamics equations is the mean value of the cumulative (or complementary cumulative) probabilities at this mass value from an infinitely large random sample of discrete dynamic event trees. The cumulative probability read from the mixture distribution in Fig. 8, at a given value of the H_2 mass, is´an estimate of this mean value, namely the arithmetic average of the cumulative probabilities at the same mass value from all trees in the Monte Carlo sample. Therefore confidence intervals and limits can be obtained for the solution mentioned above. They quantify the possible effect of the sampling error which is due to the limited sample size of the Monte Carlo simulation. Apart from the probability threshold for tree construction, this is the only error in the approximate solution of the probabilistic dynamics equations by the combination of dynamic event tree analysis and Monte Carlo simulation. The value of the cumulative probability in Fig. 8 remains below 1.0 because of the user selected probability threshold. Paths with conditional probability below this threshold are not generated in any tree of the sample. In Fig. 8, the difference to 1.0 is the arithmetic mean of the sums of the conditional probabilities of all such neglected paths from all trees in the Monte Carlo sample. The 50 dynamic event trees in the sample were generated on a system of 8 parallel compute nodes. One tree took between 2 and 3 days of processing time on a node. For reasons of storage requirements, the MELCOR output for further processing was limited to about 50 preselected variables.

Fig. 9 shows the probability distribution in Fig. 8 together with the band of local (at selected mass values) 90% confidence intervals. Of course, this band only quantifies the influence of the sampling error. The combined influence of the epistemic uncertainties on the cumulative probabilities would need to be obtained from an epistemic uncertainty analysis. An approximate approach to perform such an analysis is presented in [7,9].

5. CONCLUSIONS AND OUTLOOK

MCDET permits to adequately account for the temporal evolution of the interaction between stochastics and dynamics in the application of deterministic dynamics models for PSA Level 1 and 2. Gone is the necessity to restrict the analysis to few so-called enveloping sequences or scenarios selected by the analysts. With MCDET the event trees receive a time axis and thus become what they are in reality, namely dynamic event trees.

MCDET provides approximate solutions to the equations of probabilistic dynamics. Apart from the probability threshold for tree construction, the approximation error may be quantified by confidence intervals for cumulative probabilities of any dynamics quantity and at any point of time of interest. MCDET also permits to perform an approximate epistemic uncertainty and sensitivity analysis for the desired cumulative probabilities. None of the methods presented so far in the literature for probabilistic dynamics treats continuous random transitions and discrete random transitions with many alternatives in a comparably consistent manner. MCDET achieves this through the combination of dynamic event tree analysis with Monte Carlo simulation. The dynamics code runs along each path of the discrete dynamic event tree. This way it is possible to fully account for the interactions between stochastics and dynamics. The application of the dynamics code is controlled such that sequence sections shared by paths of the tree are computed only once. The tree construction as well as the Monte Carlo simulation can fully exploit the computational capacity of a system of parallel compute nodes.

The results of the illustrative application demonstrate for the first time the consequences of the full interaction between stochastics and dynamics as modeled in MCDET and MELCOR. Already the stochastics handled by the tree structure lead to a considerable spectrum of consequence magnitudes and associated probabilities. The stochastics additionally treated by Monte Carlo simulation lead to an

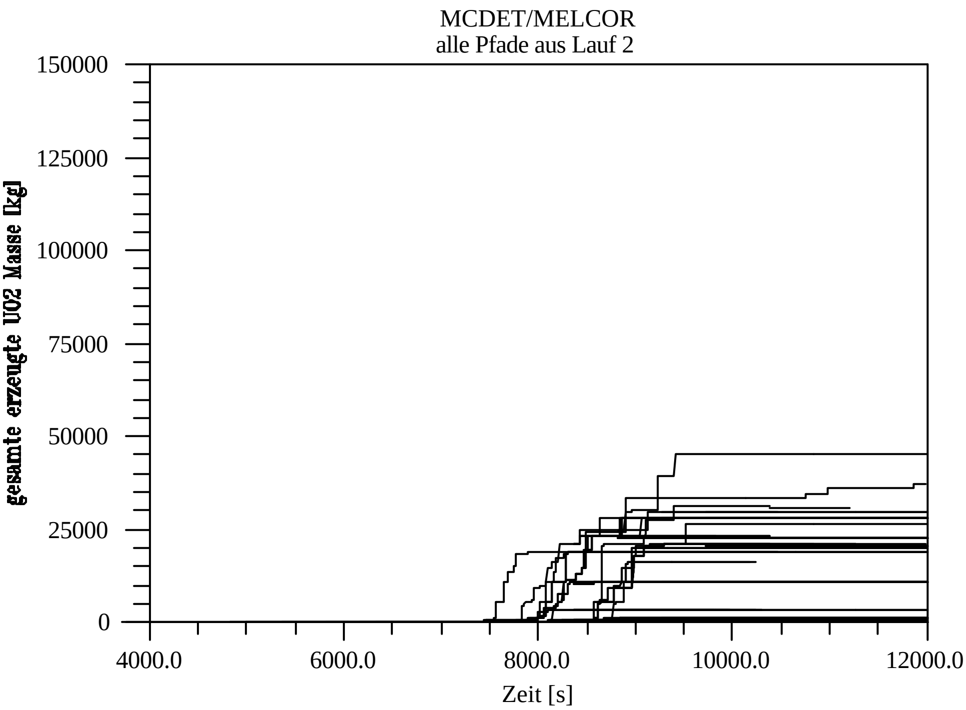

Fig. 3: Dynamic event tree no. 2 of the sample presented in the time/state plane for the state variable "total generated UO_2 melt mass"

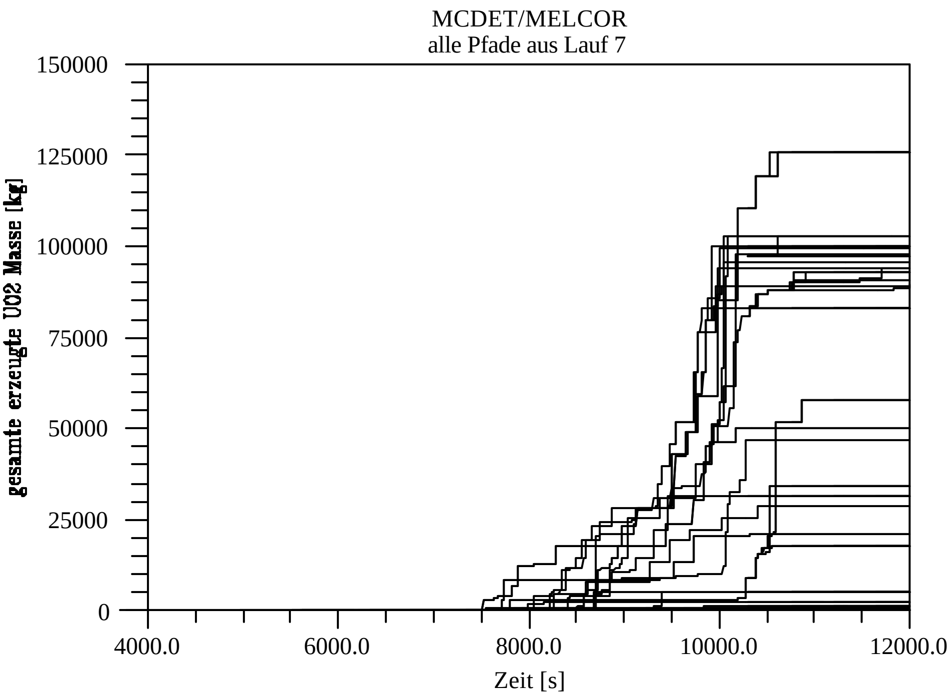

Fig. 4: Dynamic event tree no. 7 of the sample presented in the time/state plane for the state variable "total generated UO_2 melt mass"

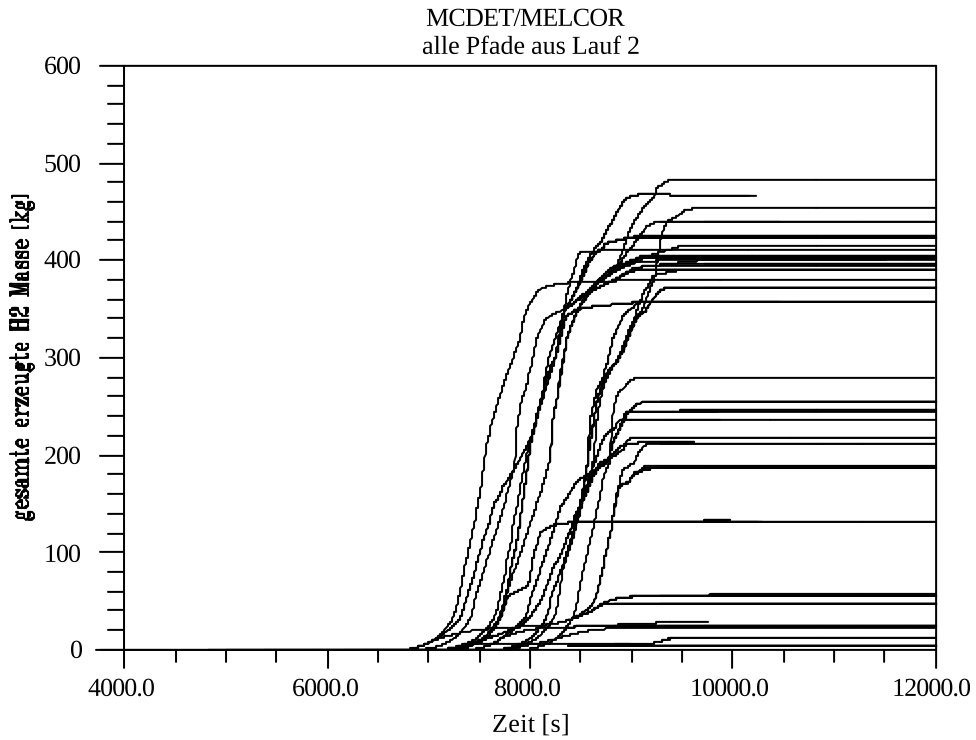

Fig. 5: Dynamic event tree no. 2 of the sample presented in the time/state plane for the state variable "total generated H_2 mass"

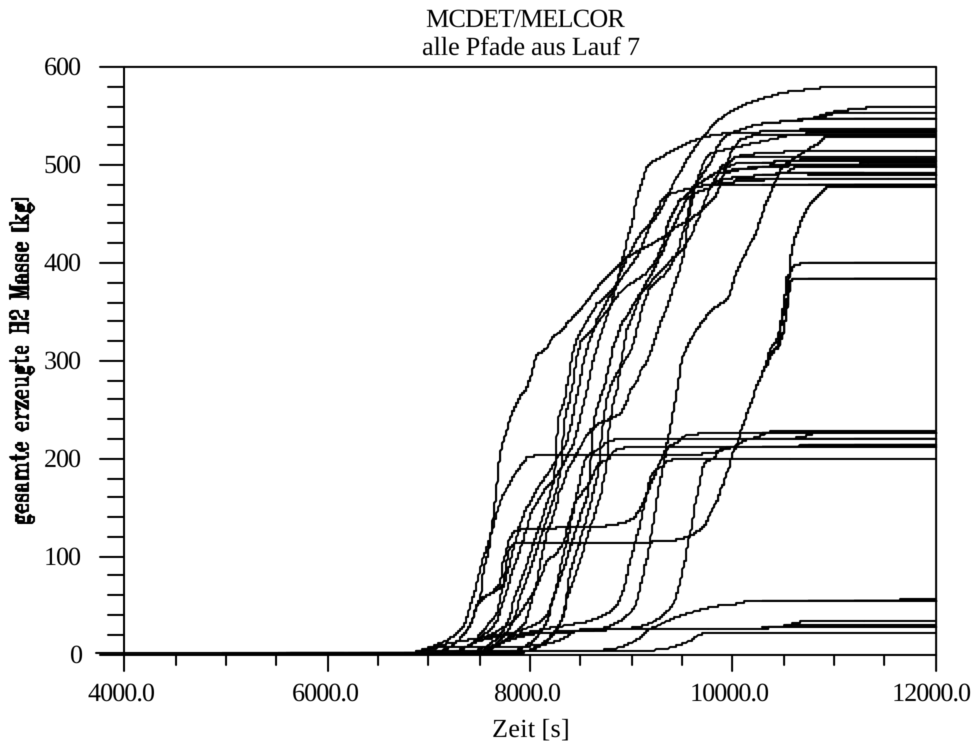

Fig. 6: Dynamic event tree no. 7 of the sample presented in the time/state plane for the state variable "total generated H_2 mass"

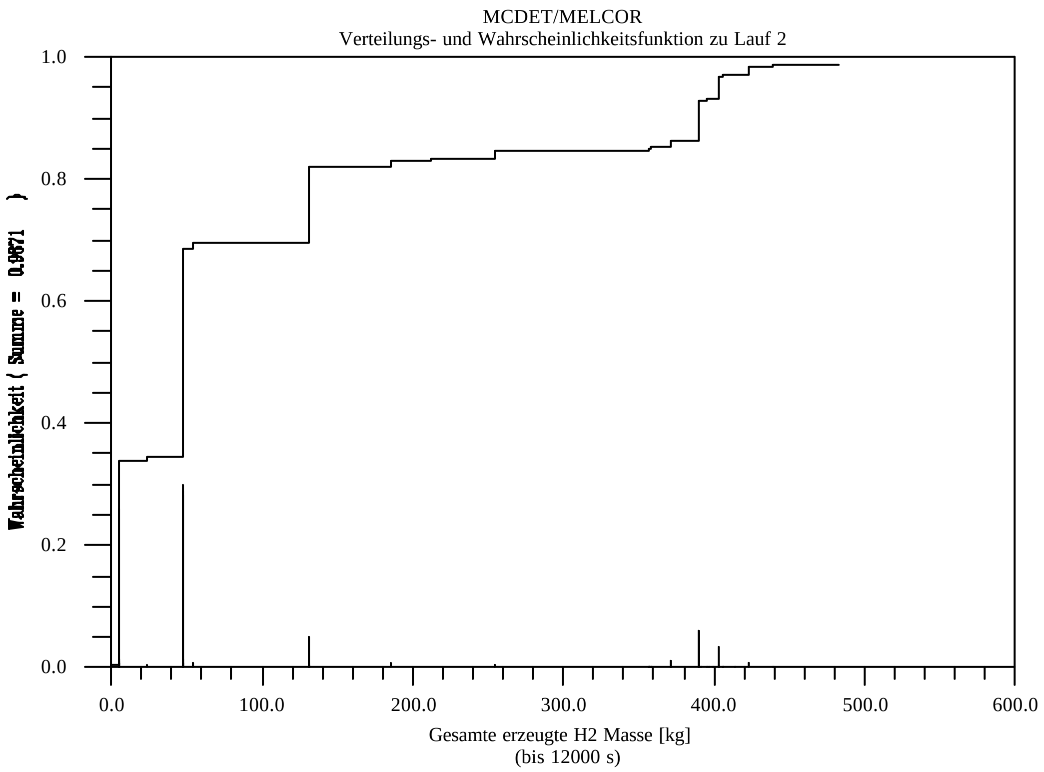

Fig. 7: Conditional probability distribution of the state variable “total H_2 mass generated up to 12000 s” from the dynamic event tree no. 2 of the sample

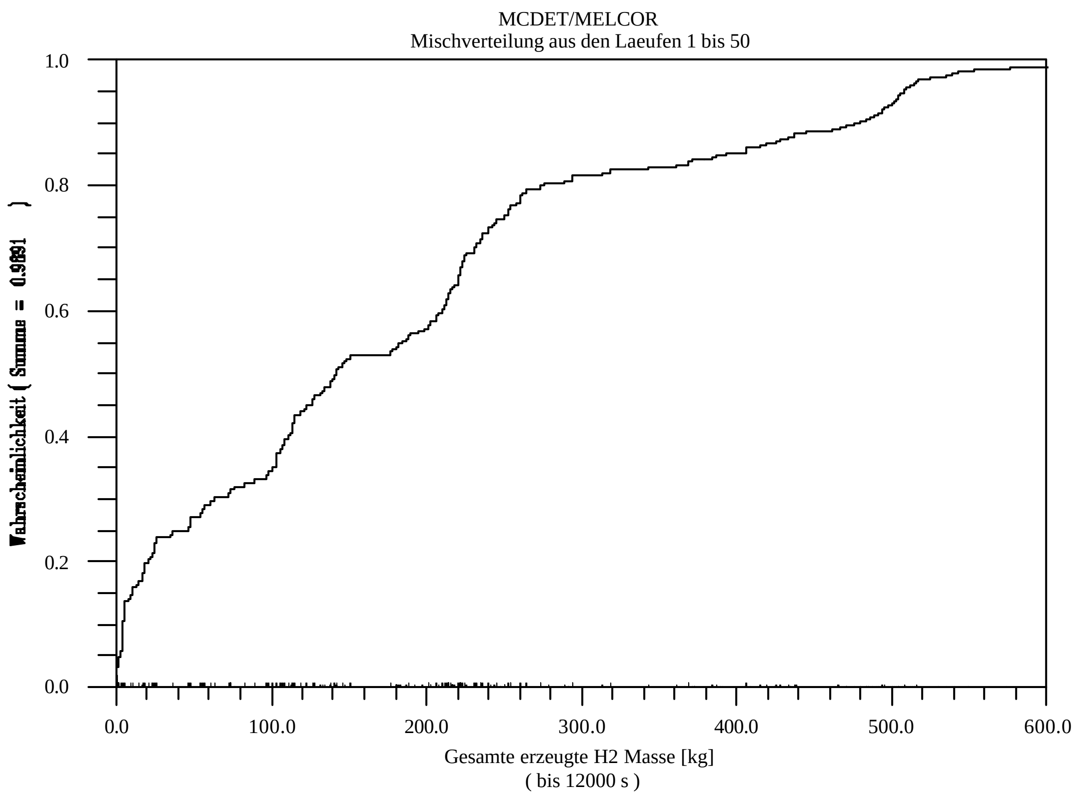

Fig. 8: Conditional probability distribution of the state variable “total H_2 mass generated up to 12000 s” from all dynamic event trees in the sample

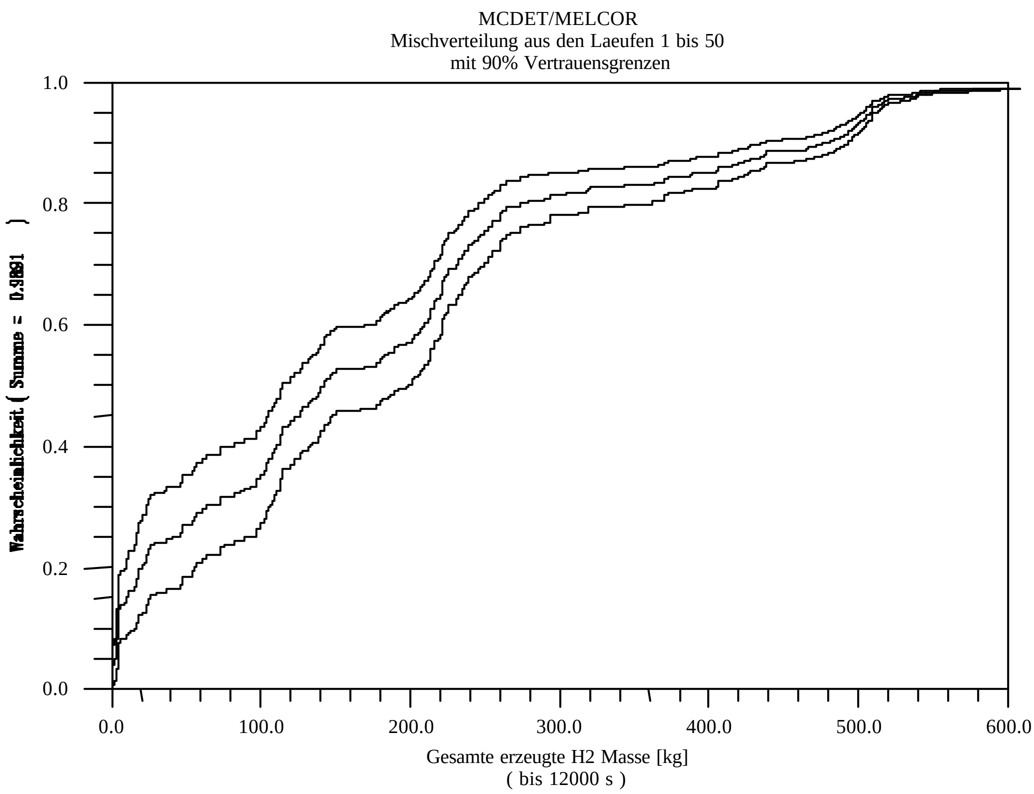

Fig. 9: Band of local 90% confidence intervals for the cumulative probabilities of the state variable "total H_2 mass generated up to 12000 s"; The intermediate curve is the probability distribution in Fig. 8.

even wider spectrum of paths with corresponding consequence magnitudes and probabilities, as can be seen from the comparison of the two trees in Figs. 3 and 4 as well as in Figs. 5 and 6. It is to be remembered that the conventional PSA performs only a few dynamics calculations (i.e. follows only a few paths). The conditional probability distribution in Fig. 8 is the kind of result a PSA needs for its assessments. Such distributions are only available from a probabilistic dynamics analysis. They provide an approximate summary of the stochastic variability of the accident consequence magnitudes within the continuous dynamic event tree that evolves from the initiating event.

At this point it should be mentioned that this illustrative probabilistic dynamics analysis provided many interesting insights into the possible spectrum of accident sequences following an SBO. Among these are also some unexpected results which require detailed investigation by the experts in order to decide whether they are due to the particular model representation of the plant in MELCOR or whether they are founded in the physics of the accident. MCDET will next be applied in a PSA for a BWR. This application in tandem with MELCOR will be restricted to high pressure plant damage states where the impression is that the spectrum of accident sequences resulting from the interactions of various processes is not satisfactorily captured by the conventional event tree analysis.

The modeling of the stochastics in actions of the operating crew has so far been restricted to distributions of execution times and to failure probabilities in MCDET. These distributions and probabilities can be specified with full reference to their dynamics context. All the necessary dynamics, systems and component state information is available at each point of time. Information on the reaction of the system and process dynamics to human actions is immediately available for the evaluation of the interaction with the crew. Obviously, a so-called crew module is a necessity for the probabilistic dynamics analysis. An example of such a module is published in [4,12]. The long term goal of methods development for probabilistic dynamics [13] should be the capability to perform a dynamic PSA. Development of an MCDET module for the interactions of the operating crew with the plant and with the process dynamics is the next important step in this direction.

References

1. G. Cojazzi, The DYLAM approach for the dynamic reliability analysis of systems, Reliability Engineering and System Safety 52 (1996) 279-296.

2. N. Siu, Risk assessment for dynamic systems: An overview, Reliability Engineering and System Safety 43 (1994) 43-73.

3. K.S. Hsueh. A. Mosleh, The development and application of the accident dynamic simulator (ADS) for dynamic probabilistic risk assessment of nuclear power plants, Reliability Engineering and System Safety 52 (1996) 297-314.

4. T. Shukri, A. Mosleh, S.H. Shen, Implementation of a Cognitive Human Reliability Model in Dynamic Probabilistic Risk Assessment of a Nuclear Power Plant (ADS-IDA), UMNE-97,Center for Technology Risk Studies, University of Maryland, College Park (1997).

5. E.M. Asensio, A.P. Mulas, J.M. Izquierdo-Rocha, On the application of the ISA methodology to the study of accident sequence precursors, Proceedings of the ESREL'97 conference, C.G. Soares (ed.), Elsevier Science, 1997.

6. K. Andersson, P. Pyy, Integrated Sequence Analysis – Experiences from a Nordic Study and Recommendations for Methodological Development, Proceedings of PSAM-4, A. Mosleh and R.A. Bari (eds.), Springer Verlag, Berlin, 1998.

7. E. Hofer, M. Kloos, B. Krzykacz-Hausmann, J. Peschke, M. Sonnenkalb, Methodenentwicklung zur simulativen Behandlung der Stochastik in probabilistischen Sicherheitsanalysen der Stufe 2, Abschlußbericht, GRS-A-2997, Gesellschaft für Anlagen- und Reaktorsicherheit, Germany (2001).

8. J. Devooght, C. Smidts, Probabilistic dynamics as a tool for dynamic PSA, Reliability Engineering and System Safety 52 (1996) 185-196.

9. E. Hofer, M. Kloos, B. Krzykacz-Hausmann, J. Peschke, M. Woltereck, An Approximate Epistemic Uncertainty Analysis Approach in the Presence of Epistemic and Aleatory Uncertainties, to appear in Reliability Engineering and System Safety (2002).

10. Nuclear Reactor Commission, "MELCOR 1.8.4 - Reference Manual", USA, Washington, (July 1997).

11. M. Sonnenkalb, Unfallanalysen für DWR vom Typ KONVOI (GKN-2) mit dem Integralcode MELCOR 1.8.4, GRS-A-2954, Gesellschaft für Anlagen- und Reaktorsicherheit (mbH), Köln (2001).

12. Y.-H. Chang, A. Mosleh, Dynamic PRA Using ADS with RELAP5 Code as Its Thermal Hydraulic Module, Proceedings of PSAM-4, A. Mosleh and R.A. Bari (eds.), Springer Verlag, Berlin, 1998.

13. P.E. Labeau, C. Smidts, S. Swaminathan, Dynamic reliability: towards an integrated platform for probabilistic risk assessment, Reliability Engineering and System Safety 68 (2000) 219-254.