A PROBABILISTIC APPROACH FOR SOURCE TERM PREDICTION IN CASE OF SEVERE ACCIDENTS

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In case of an accident, an early prediction of the expected releases of radioactive materials into the environment (source term) is crucial for a timely decision on short-term plant external protection of the public and civil protection measures. A computer software to guide and assist the plant crisis team or an external emergency team in order to estimate the radioactive release is helpful and time saving in case of a severe accident.

Results from plant specific PSA up to Level 2 are available for all plants in Germany from Periodic Safety Reviews, including probabilities and source terms of potential accident sequences. Bayesian Belief Networks (BBN) can be used to combine PSA results and actual plant related observations during an accident. The underlying PSA represents the basis of the calculations. This level of knowledge gets updated with the information available to the user concerning the status of the plant. In addition, the underlying PSA probabilities for the occurrence of source terms are adjusted according to actual observations. The result from this combination is an improved and more accurate prediction of the probability for accident sequences to be expected in a severe accident.

I. INTRODUCTION

In the event of a severe accident in a nuclear power plant (NPP) during which airborne radioactive substances may enter the environment (so-called release), emergency disaster control authorities have to take measures early enough in order to protect the population. These may range from recommendations to stay indoors, to take iodine tablets up to the evacuation of the areas affected by the release, or the long-term resettlement of the people living in the vicinity of the NPP (Ref. 1). The measures needed to be taken in the specific case depend on the exact time, when an area is expected to be contaminated with which amount of radioactive substances. This depends on the weather conditions that prevail at the time of release as well as on the so-called source term.

The source term provides data on the expected amount and type of radioactive releases in an NPP accident. These data can be applied using dispersion codes, such as ARTM (Ref. 1) in such a way, that a prediction can be made on the distribution of the radioactive substances under given weather conditions. While the weather forecast data can be obtained quickly from pertinent services, the source term and its prediction are the result of a complex calculation process. In Germany, the determination of the source term and its forwarding to responsible authorities in the course of the accident is the responsibility of the operator, which is laid down in the Basic Recommendations for Disaster Control in the Vicinity of Nuclear Facilities (Ref. 2).

GRS has developed a computer code, which predicts potential source terms in the event of an NPP accident. The source terms can quickly be transmitted to the supervisory authorities or other regulatory institutions, such as the Federal Office for Radiation Protection (BfS) through data transmission or pre-fabricated forms. There is, e.g., the possibility of transferring the data directly into the RODOS decision support system (Ref. 3) of BfS, which, in turn, is used to make forecasts of the radiological situation.

RODOS is a real-time online decision support system, which is used within the European Union to improve off-site emergency management. It offers comprehensive decision support for international countermeasures after a severe accident.

The software calculates pathways of exposure to human (Ref. 4) by means of radiation from a radioactive cloud, from the ground and exposure through incorporation of radionuclides (inhalation and ingestion).

II. MAJOR STEPS OF THE PAST AND CURRENT DEVELOPMENT OF THE SOURCE TERM PREDICTION SOFTWARE

The objective of the development of source term prediction software is to develop a helpful supporting tool for crisis team members to predict source terms, that could be released in the process of a severe accident.

The development of the GRS source term prediction software has its origins in the EU program STERPS (Source Term Indicator Based on Plant Status for Use in Emergency Response) based on an international cooperation of researchers funded by the EU from 2001 to 2003. The software was enhanced taking into account experiences of emergency exercises and severe accident research.

Recent improvements of the software have been done by means of a modernized general user interface (GUI) and by the usage of a modern platform independent programming language (Python), which offers full development opportunities.

The GRS source term prediction software is designed to be applicable at severe nuclear accidents in NPPs, at the point of time when core damage is expected or already existing. Source term in this context is defined as a radioactive release to the environment, described by the following three characteristics:

- The source term consists, amongst other data, of the total amount of released radioactivity in Becquerel (Bq).
- The source term contains the release height of the relevant reference nuclides (e.g. Kr-87, Xe-133, I-131, Te-132, Cs-137) and their individual amount of radioactivity, which are important in the context of the weather dependent distribution of radioactive materials in the environment after their release from the NPP.
- The source term contains the time dependent sequence of the release, split up for the different phases such as venting, design leakage or bypass phase.

The accident and emergency management demands a diagnosis of the disturbed plant status on short notice with a possible lack of information about the plant status at the very same time. In some NPPs, the necessary source term prediction of the expected release from a plant might be performed by a member of a crisis team at the NPP based on various documents such as emergency handbooks, tables or printed graphs of relevant physical parameters. The process of determining necessary data from the graphs is prone to error, particularly if the underlying stressful emergency situation for the crisis team member is considered.

The subsequent external actions in scenarios involving a core melt are different from country to country and depend on their national regulations. In Germany, the NPP licensee is obliged to deliver a source term prediction in order to manage external emergency plant measures. External emergency plans like the distribution of iodine tablets to the population or evacuations of certain areas will be implemented depending on the released amount of radioactivity and the meteorological situation.

In this context, a plant external emergency measure might be too late if, it is based on a radioactive release which already occurs. For the above mentioned reasons, a prediction of the release source term at short notice is crucial. In principle, the following methods are available:

- calculations of accident scenarios in advance, summarized in tables and handbooks,
- fast-running simulation tools (however, these are only for experts and can be nevertheless time consuming), cf. Ref. 5,
- probabilistic methods based on plant specific PSA (*P*robabilistic *S*afety *A*nalysis), cf. (Ref. 6) .

In Germany, a source term prediction based on Level 2 PSA results and plant specific parameters is recommended by the “Strahlenschutzkommission” (SSK, German abbreviation for Commission on Radiological Protection). It is specifically recommended to use software at the crisis center of the operator, which allows for a prediction of the source term at an early stage. The following requirements are defined in the SSK recommendation (Ref. 6):

- The procedure shall use the plant specific Level 2 PSA as well as the corresponding plant status as basis.
- The procedure shall even be applicable with an incomplete knowledge of the plant status.
- The demand of the ease of usability shall ensure an error-free use even under severe accident conditions.
- The uncertainties of the accident sequences shall be accounted for by corresponding calculations of probabilities.
- The radionuclides relevant for a calculation of radiation exposure shall be given. The amount of the release as well as the thermal energy of the release shall be given by the software.

The prediction software by GRS is based on the probabilistic methods approach.

It is necessary to consider, that there are uncertainties regarding the estimated sequence of accident events. First, there is a lack of information about the plant state, as measurement devices are possibly failing. This represents an epistemic (knowledge) uncertainty. Moreover, there is a high risk of miscommunication between the several people involved. In addition, the uncertainty of accident related phenomena such as possibility and time of hydrogen combustions, exact time of the melting of the RPV (*r*eactor *p*ressure *v*essel) or a potential containment failure are difficult to calculate in advance. Finally, there is an uncertainty of the success of plant internally initiated emergency measures like re-feeding of the core or total containment isolation or the restoration of power supply and the estimated sequence of accident events.

With regard to emergency management, the prediction software can be easily applied by new users of the software and the results can directly be fed into consequence analyses. Certainly the probabilistic approach does not deliver a "point estimate result", but rather provides a set of possible source terms together with the related probabilities. This should be kept in mind in the decision making for emergency management based on the predicted results.

The philosophy behind the prediction tool is the application of Level 2 PSA in order to enable an improved source term prediction with a minimum of time and effort. Level 2 PSA has been performed for the entire German NPPs in the frame of the (Periodic) Safety Reviews, i.e. there already exist information about the different accident sequences and the corresponding probabilities of occurrences for the accident scenarios, which is a prerequisite for generating plant specific source term prediction software.

III. BASIC PRINCIPLE OF THE STRUCTURE OF THE SOURCE TERM PREDICTION SOFTWARE

A schematic overview of the approach is shown in Figure 1. In order to calculate the probability distributions of the different scenarios, the observations of the user are merged and compared to the Level 2 PSA results. In case the deductions from observations are contractionary to the input from PSA, more value will be attached to the observations with a higher emphasis. As it can be seen in Figure 1, individual observations like pressure and temperature measurements (blue) in a single system, e.g. the reactor coolant system or the containment, might get combined to a conclusion from these observations. This synthesis of observation and input from PSA constitutes the result of the software for a particular issue.

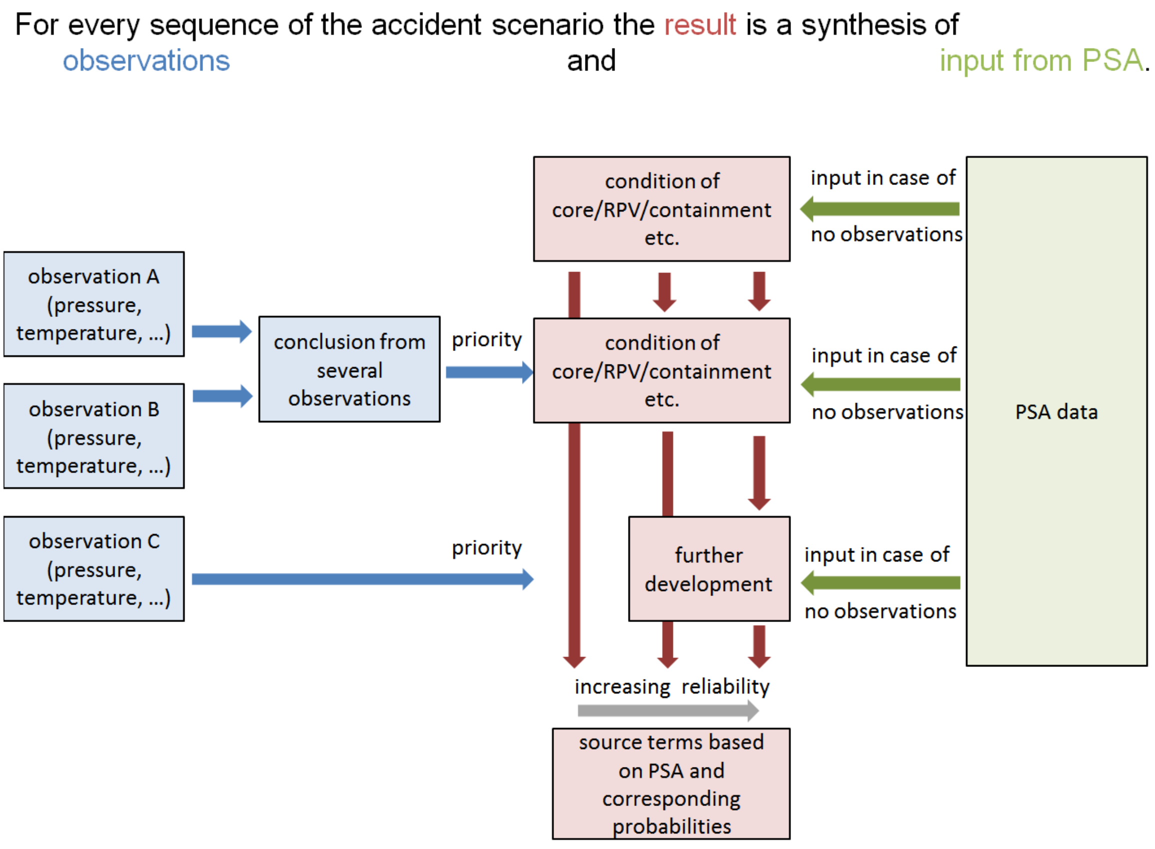

Figure 1. Structure of the BBN: the combination of observations (blue) and Level 2 PSA (green) result in a prediction for source terms (red)

This result is then taken as boundary condition and will affect the outcome of the subsequent steps of the model and therefore be relevant for the next calculations regarding the further development of the process. The results will finally result in a prediction for the probability of a given set of source terms. The more input from user answers the final calculation contains, i.e. the more questions are answered by the user, the more accurate the final result will be (grey arrow).

The correlation between observations and PSA results is realized via a Bayesian Belief Network (BBN). In the frame of Level 2 PSA a knowledge base of possible accident sequences and source terms and their probabilities is given. This knowledge is implemented in a BBN in order to link actual observations and measurements in case of an accident.

A practical example for the functionality of such a BBN can be found in Figure 2 to Figure 4. The BBNs shown are generated with the software Netica™ by Norsys Software Corporation™ (Ref. 7). A BBN basically consist of nodes and connections. Nodes can consist of questions being asked to the user. In this example the nodes "Pressurizer Level", "Containment Pressure" and "Core Temperature" are such questions (e.g., "Is the current pressurizer level either constant or increasing, or is the level decreasing?" for the "Pressurizer_Level" node)".

Furthermore, the nodes can also consist of PSA results (e.g., "Initiating Event PSA") or they can represent conclusions from previous observations (e.g., "LOCA exists"). The following step is the intermediate result of the calculation (e.g., "Initiating Event Final"). The nodes are connected with links (black arrows) that indicate dependencies.

In the first example (Figure 2) a case is shown in which the BBN calculates the probabilities of the occurrence of a loss of coolant accident (LOCA) in dependence of the answers given by the user. In this specific case, the user is asked about the pressurizer level, the containment pressure and the core temperature. The first two nodes on the left side ask questions about pressurizer and the containment; the answers for these can indicate the existence of a LOCA and will therefore influence the initiating event (being either a LOCA or a transient). The underlying PSA result is also connected to the first result of the calculation. This node is then connected to the core damage PSA node ("CD_IE_PSA"), which itself connects to the final core damage node ("CD_Final"). This calculation node is influenced by the answer given by the user concerning the core temperature ("Core_Temperature").

All nodes result in the final result node, that consists of the final source terms (Source_Terms), i.e. a source term for LOCA accidents involving core damage (Source Term CD LOCA), a source term resulting from accidents involving transients resulting in core damage (Source Term CD Trans) and a source term that does not result in core damage (Source Term No CD). In this last source term, the source is radioactivity originating rather from e.g. internal radioactive depositions in the reactor coolant system being released to the environment during an accident.

Figure 2 shows the results of the BBN, if the answer "Unknown" is given by the user (indicated by the 100 % value next to the "Unknown" value). In this example, the nodes "Pressurizer_Level", "Containment_Pressure" and "Core_Temperature" have been answered by the user leading to the probability of a LOCA to be 100 %" Unkown" (cf. node "LOCA_Exists"). In this case, it can be seen, that the underlying PSA results are transferred directly to the intermediately calculated nodes "Initiating_Event_Final" and "CD_Fnal", being 20 % for "LOCA" and 80 % for "Transient" in the "Initiating_Event_Final" node or 26 % for "Yes" and 74 % for "No" in the "CD_Final" node respectively.

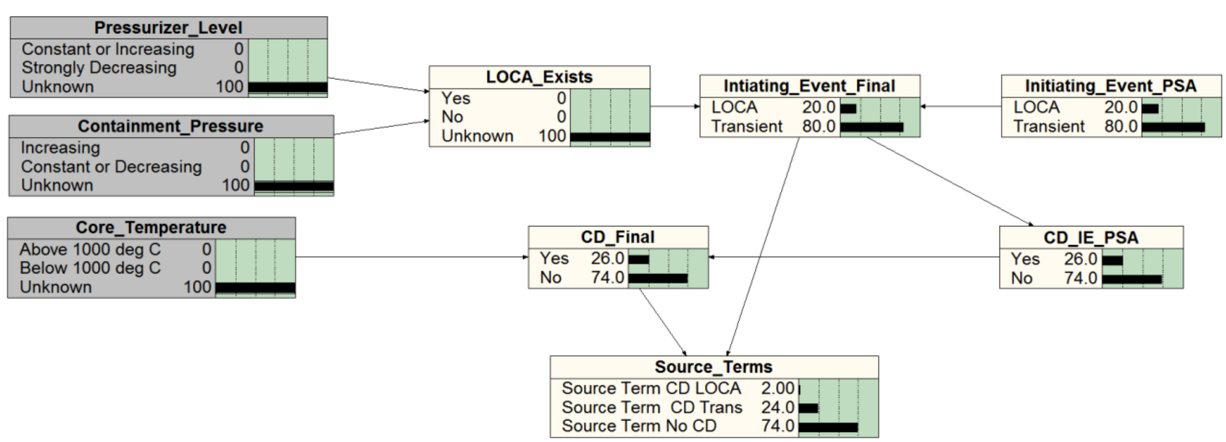

Figure 2. Example of a BBN: direct takeover of PSA values in case the user answers "Unknown"

Figure 3 shows the behavior of the net, when the user answers the nodes "Pressurizer_Level", "Containment_Pressure" and "Core_Temperature" with "Strongly Decreasing", "Increasing" and "Above 1000 deg C" respectively. These answers result from observations that strongly indicate a LOCA case, which is also visible in the net by the result "Yes" being 100 % in the node "LOCA_Exists". This is combined with the PSA result from the node "Initiating_Event_PSA", assuming, that the information coming from the node "LOCA_Exists" has a weight of 99 %. Here the source term probability for a LOCA rises from a previous value of 2 % (Figure 2) to 98.3 % (Figure 3).

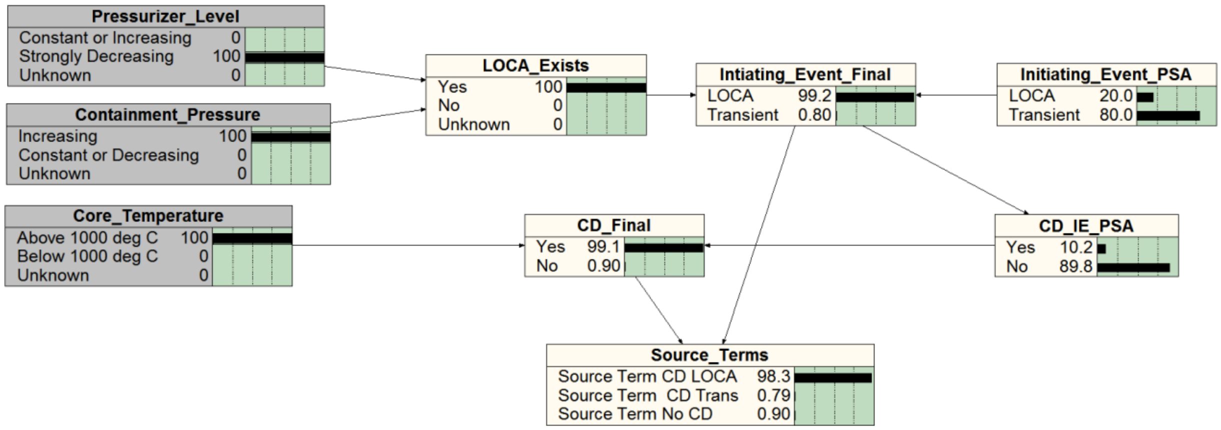

Figure 3. Example of a Bayesian net: LOCA case resulting from the answers given by the user

Figure 4 shows the behavior of the net, when the user answers the nodes "Pressurizer_Level", "Containment_Pressure" and "Core_Temperature" with "Constant or Increasing" , "Constant or Decreasing" and "Above 1000 deg C" respectively. These answers resulting from observations indicate a transient case, which is also visible in the net by the result "No" being 100 % in the node "LOCA_Exists". Here the source term probability for a LOCA decreases to 0.2 % whereas the source term "Source Term CD Trans" rises from a previous value of 0.79 % (Figure 3) to 99.1 % (Figure 4).

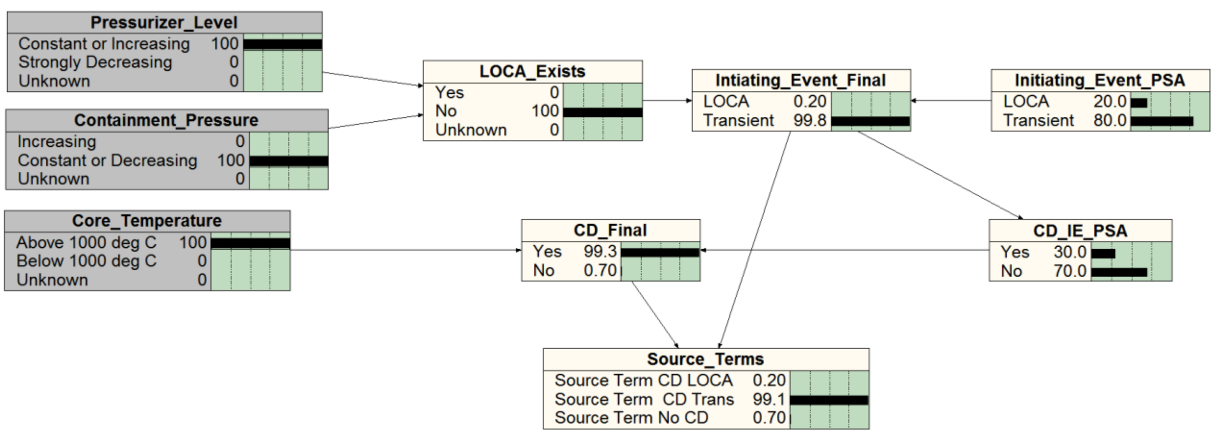

Figure 4. Example of a Bayesian net: Transient case resulting from the answers given by the user

The examples given in Figure 2 to Figure 4 demonstrate that the final result depends on the answers given by the user as well as on the underlying Level 2 PSA results.

IV. USE OF THE SOURCE TERM PREDICTION SOFTWARE

Starting the source term prediction software the user is asked to answer multiple-choices questions about the status of plant. The source term prediction software combines the answers given by the user and the underlying PSA Level 2 results and generates a result in a synthesis of both concepts.

The general user interface (GUI) of the prediction software consists of several units. One unit is dedicated to the multiple- choice questions, which have to be answered by the user as far as possible. When giving answers, the user is alerted by warning messages in case one given answers is inconsistent to another. The software structure allows the user to dismiss questions at any time and to change the previously given answers.

The prediction software consists of about 40 questions about the plant status of a PWR. A part of them deals with the status of the systems, e.g. questions about the status of the auxiliary station service, the steam generators, main steam activity or the secondary system. Other questions ask for explicit time points, e.g. time of scram, expected time of venting, expected time of a failure of the containment. This time point information is directly connected to the prediction of the temporal development of the accident. In case the user provides a time point, this will be dominant in the further calculations and not be adjusted by internal time calculations of the prediction software.

Another set of questions deals with relevant events, which are linked to the accident, like a rise of the core temperature above 650 °C, indicating subsequent core damage. There are also questions dealing with the status of the containment, like questions about the pressure inside the containment, a possible rise of activity inside the containment or the success of general containment isolation.

Other questions deal with systems outside the containment like e.g. water spray systems or the condition of the reactor building annulus. Finally, general questions are added, in order to estimate the further accident sequence, e.g. about the prospect of success of emergency measures or the hints about a containment failure. For any question, the software offers the user context related and plant specific explanations to the questions, realized by short help texts.

The prediction software calculates the event tree end states of the accident and displays them to the user, consisting of the hazard states, the core damage states and the source terms of the release categories listed with the calculated probability of occurrence. The source terms are the most important result for the prediction of a release of radioactive material in the environment. All source terms have been derived or taken from extensive accident simulations performed with MELCOR (Ref. 8) taking into account different possible accident scenarios. In this context, they are grouped according to given aspects such as “containment fine”, “bypass” or “containment fail”. The most probable case is emphasized by an arrow, to help the user choosing the final source term, which should be selected. Also the development of the radioactive release over time is displayed to the user. The user can choose to export the calculated data set with the source terms in either a report form or a set of data readable by the RODOS program.

Figure 5 shows an example of the distribution of a predicted source term over time.

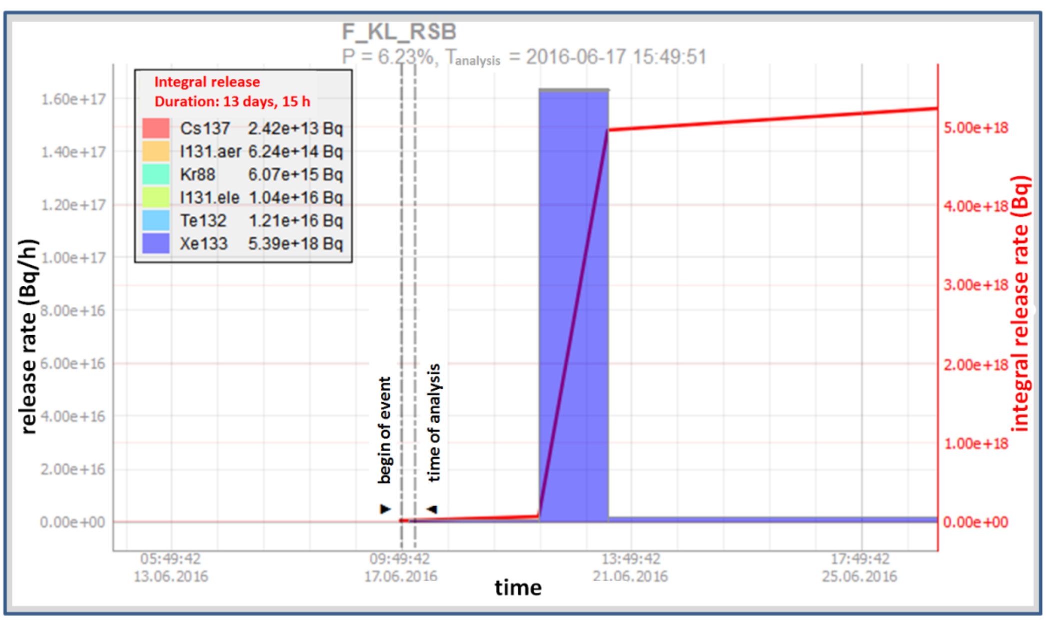

Figure 5. A graphical display of the predicted time-dependent release of radionuclides calculated with the source term prediction software (example)

The time dependence is depicted on the x-axis, whereas the release rate is depicted on the y-axis (left-hand side, shown in black) or the integral release respectively (right hand side, shown in red). Here the distribution of radionuclides is shown in a histogram, indicating in this case a high release of xenon (Xe-133, blue color). The remaining nuclides indicated in the legend are substantially smaller and therefore not visible in this graph. The program itself allows for a magnifier function, which will show the nuclides. The exact time of the beginning of the event and the time of the analysis are shown via dotted lines. The software is programmed in a manner, that the legend will show the related data for different phases (before the release, during the release (e.g. venting) and after the release (e.g. leakage). The legend shows the calculated activities in Becquerel for the reference nuclides iodine, cesium, krypton, tellurium and xenon. Iodine is calculated in its aerosol phase as well as its elemental phase. The calculated probability for the scenario to result in this venting release category is p = 6.23 %.

The software calculates all probabilities for the entire source terms and indicates the source term with the highest activity release, whose probability exceeds 10 %.

The requirements for user skills to apply this software tool are kept deliberately low, as it was considered in the development, that there is hardly any user experience in software handling and a stressful situation. Its calculation time is minimal as it is in the range of seconds depending on the usage of an up-to-date PC.

All questions and answers are recorded; therefore the accident sequence over time can be deduced later. A prepared form is available for the status report to the national German authorities, which already fulfills the formal needs. In addition, an export data set for the source terms can be generated, that is able to be processed with the decision support system RODOS.

The current versions have been further developed and improved regarding the scenarios considering shutdown states of the NPP and the corresponding scenarios e.g. an open containment or an open RPV. Furthermore the core inventory has been modelled more precisely considering phenomena like a buildup of radioactive nuclides after shutdown (Ref. 9), (Ref. 10). The software is being continuously enhanced and improved by implementing further MELCOR calculations regarding external hazards scenarios and the spent fuel pool.

V. CONCLUSIONS

In this paper, the GRS prediction software is introduced, showing its underlying probabilistic approach to predict a possible radioactive release into the environment during a severe accident. By combing user given answers concerning the status of the NPP and a basic Level 2 PSA by using a Bayesian Belief Network (BBN), the software predicts the most probable accident scenario and the corresponding release. The use of such prediction software has been recommended by the German Commission on Radiological Protection (SSK) in Germany.

The fast-running GRS code has been improved and modernized to provide a user interface for input of observations and output of source term prognoses. The final source terms can be provided as an already formatted report and as code, which can be instantly read by decision support programs used by the corresponding authorities dealing with contamination in the environment and plant external measures.

With a computational time of a few seconds only, the improved software creates a list of possible source terms with their corresponding probabilities. Selected source terms can be graphically displayed within the user interface and exported for direct use in consequence analyses.

The GRS source term prediction software is easy to use, also for applicants that might have hardly any practice with the software. The prediction software is a tool to help and support the crisis team at the nuclear power plant during a severe accident. In this way national authorities are better prepared when deciding external emergency procedures such as evacuations or the distribution of iodine to the public.

However, as all release categories represent a large number of sequences, there is also an inherent uncertainty in the calculation due to this binning. Further improvements of the underlying time calculations in the software with a more accurate implementation of the real time behavior of the source terms are intended. Mainly the discretization of the currently time averaged graphs has to be programmed in more detail, in order to calculate the releases more accurately, for example during venting scenarios or during long lasting phases of release. More detailed time trends can be derived from further MELCOR calculations, in order to calculate the amount of release of radioactive nuclides and the corresponding time points of the release more precisely.

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