Source Term Prediction Software in Case of Severe Accidents: FaSTPro for Shutdown States

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Abstract: In the event of a severe accident in a nuclear power plant, when airborne radioactive particles may be released to the environment (so-called source term), emergency disaster control authorities have to take measures early enough in order to protect the general public. Computerized analytical tools to guide and assist the plant crisis team or an external emergency team for estimating radioactive releases are helpful and time saving in such events. In case of a severe accident, information about expected source terms should quickly be transmitted to the authorities via data transmission or ready-made forms to make forecasts of the radiological situation, e.g., with the decision support system RODOS .

Keywords: PRA Level 2, PRA-Application, Source Term, Severe Accidents, Shutdown States.

1. INTRODUCTION

In the event of a severe accident in a nuclear power plant (NPP) during which airborne radioactive substances may be released to the environment (so-called *release*), emergency disaster control authorities have to initiate procedures in order to ensure the protection of the public whereby the time of initiation is crucial. These procedures may range from recommendations to stay indoors, to take iodine tablets, up to the evacuation of the areas probably affected by the release, or the long-term resettlement of those people living in the vicinity of the NPP [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 source term.

The source term provides data on the expected amount and type of radioactive releases in a NPP accident. These data can be applied using dispersion codes, such as ARTM [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” [2].

For core melt accidents most nuclear power plants in Germany apply the GRS software FaSTPro (*Fa*st *S*ource *T*erm *Pro*gnosis) for predicting and transmitting source terms. A newly developed version of FaSTPro, built especially for shutdown states, is presented in this paper.

GRS has developed the analytical tool FaSTPro 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 (*Bundesamt für Strahlenschutz,* BfS) through electronic data transmission or pre-fabricated forms. For example, it is possible to transfer the data directly to the RODOS decision support system [3,4] used by BfS which in turn is used to provide forecasts of the radiological situation.

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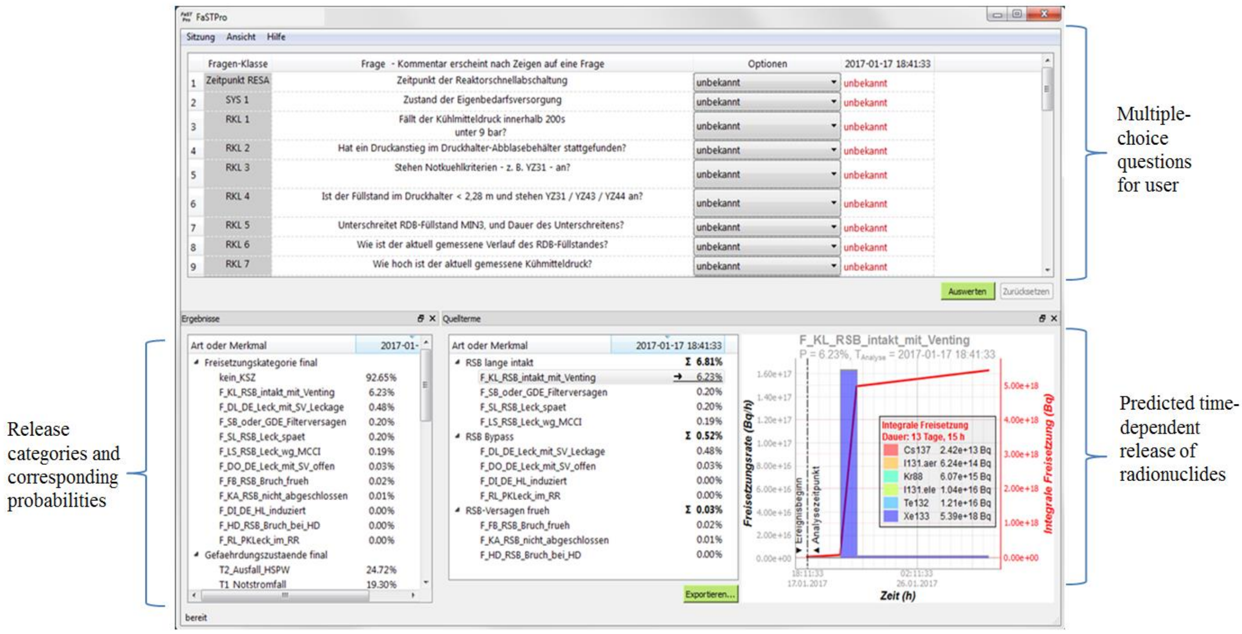
RODOS is a real-time online decision support system which is used within the European Union (EU) in order to improve off-site emergency management. It offers comprehensive decision support for international countermeasures after a severe accident. The software calculates pathways of exposure to human [4] by means of radiation from a radioactive cloud, from the ground and exposure through incorporation of radionuclides (inhalation and ingestion).

2. THE GRS-SOURCE TERM PREDICITION SOFTWARE FASTPRO

When starting the source term prediction software FaSTPro 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 to the underlying Level 2 PSA results and generates a result in a synthesis of both concepts [5,6].

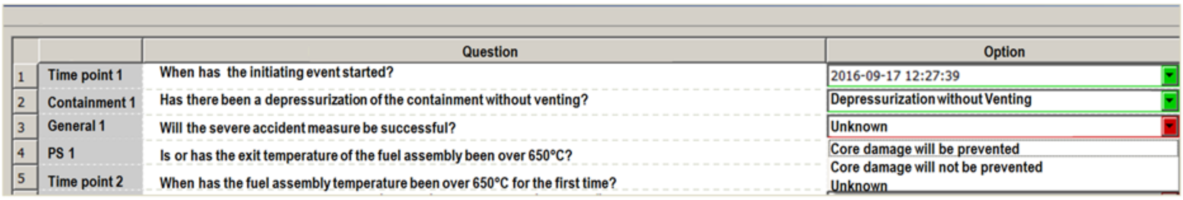
The general user interface (GUI) of the prediction software consists of several moduls (see Figure 1). One unit is dedicated to the multiple-choice questions which have to be answered by the user as far as possible respectively as soon as new/further information about the plant status is available. When giving answers, the user is alerted by warning messages in case one given answers is inconsistent with another one. The software structure allows the user to dismiss questions at any time and to change the previously given answers.

Figure 1: Basic Principles of FaSTPro - Graphical Display of the FaSTPro User Interface



Currently about 40 questions regarding the status of a nuclear power plant with pressurized or boiling water reactor (PWR/BWR) are implemented in general FaSTPro versions. These questions (see Figure 2) partly concern the status of the systems, e.g., questions about the status of the auxiliary station service, the steam generators, 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 calculations and will not be affected by internal time calculations of the prediction software.

Figure 2: Example of the Multiple Choice Questions Asked to the User



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

Some questions also concern the status of systems outside the containment, 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 procedures or the hints about a containment failure. For any question, the software offers context related and plant specific explanations of the questions realized to the user by short help texts.

The prediction software FaSTPro calculates the probabilities of the event tree end states of the accident and displays them to the user consisting of the hazard states, the core/fuel 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 materials to the environment. All source terms have been derived or taken from extensive accident simulations performed with MELCOR [7] that are documented in [9] taking into account calculations and estimations of 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. In addition, 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 either in a report form or as a set of data readable by the RODOS program.

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 NPP fleet in the frame of (Periodic) Safety Reviews (PSR), i.e. information about the different accident sequences and the corresponding occurrence probabilities of the accident scenarios already exists, which is a prerequisite for generating a plant specific source term prediction software.

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 BBN basically consists of nodes and connections. Nodes can consist of questions being asked to the user [5,8].

3. CONSIDERATION OF LOW POWER AND SHUTDOWN PLANT OPERATIONAL STATES

One of the main activities for enhancing the prognosis software was an exemplary extension of the underlying BBN in order to cover also low power and shutdown plant operational states (POS), e.g. by the integration of deviating barrier conditions for the containment (normal operation or a failure considering the air lock for example) or the primary circuit (upper head of the RPV (*r*eactor *p*ressure *v*essel) sealed or removed). These characteristics of the shutdown states affect the possible release paths (e.g., open air lock) and physical phenomena which do not occur during full power operation such as the air ingress to the RPV resulting in a specific chemical reaction with Zircaloy. The connection of the reactor refuelling cavity with the spent fuel pool (SFP) and the different loads of the reactor/SFP are also specific for the shutdown modes.

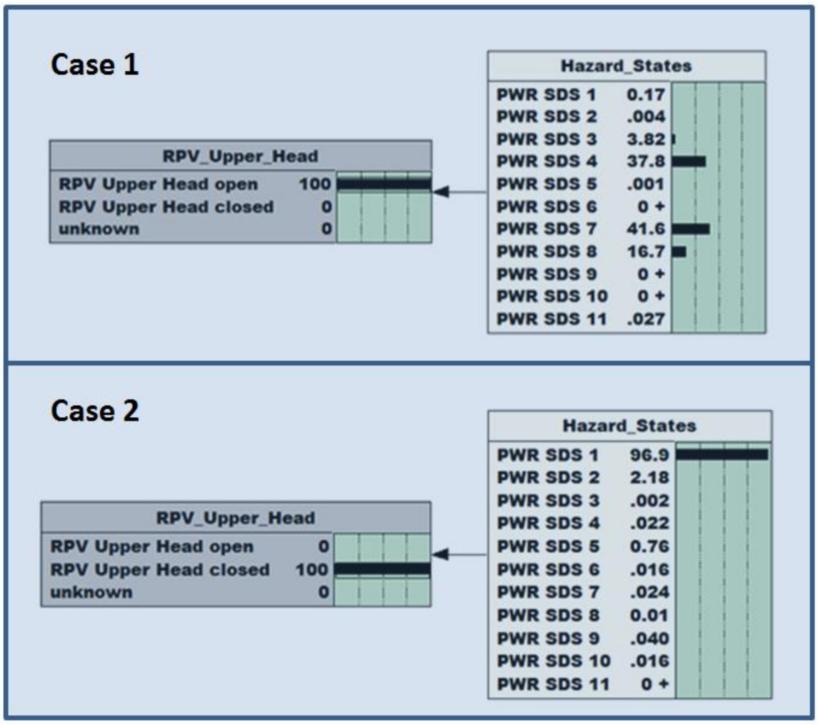
In previous versions of the source term prediction software FaSTPro, the condition of barriers (e.g. the containment or the air lock) has been deduced from plant status observations at the control room, e.g. on the pressure inside the containment.

In the enhanced version being the subject of this paper, the BBN has been extended by means of further explicit knots (and therefore questions) in relation to the shutdown states of the plant. The answers given to these questions are transmitted to the underlying BBN and therefore affect the calculated probability for certain accident scenarios or release categories respectively (see Figure 3). Further information about the use of the BBN and its connection to Level 2 PSA can be found in [5] and [6].

As an example of the modifications the multiple-choice list in FaSTPro (see Figure 1) was extended by a question regarding the status of the RPV head. The user can answer the question either by “RPV Upper Head open, “RPV Upper Head closed“ , or “unknown“ (see left side of Figure 3).

Depending on the answer given to this question, the probability distribution of the hazard states inside the BBN changes (see case 1/2 and the right side of Figure 3). The underlying hazard states “PWR SDS 1” to “PWR SDS 11” are taken from previous MELCOR simulations of NPP shutdown scenarios documented in [9].

Figure 3: Different Probabilities for PWR SDS Cases (SDS = Shutdown States) in the “Hazard_State” Knot Depending on the Answer Given to the Question about the Status of the RPV Upper Head



As an example for the final results of the FaSTPro source term calculations the release category “F_KA_Containment_and_Annulus_Failure” is shown in Figure 4. This release category describes an accident sequence without a containment bypass but with a release via containment failure and an annulus failure opening a path for the radionuclides into the environment.

The time dependency is depicted on the x-axis whereas the release rate is depicted on the y-axis (left-hand side, shown in black) and the integral release respectively (right-hand side, shown in red). The distribution of radionuclides is shown in a histogram, indicating in this case a high release of Xenon (Xe-133, blue color). The releases of the remaining nuclides indicated in the legend are smaller. The exact starting time of the event and the time of the analysis are shown via dotted lines. 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 the gaseous phase.

Figure 4: Histogram of the Temporal Radionuclide Distribution for the Release Category "F KA_Containment_and_Annulus_Failure"

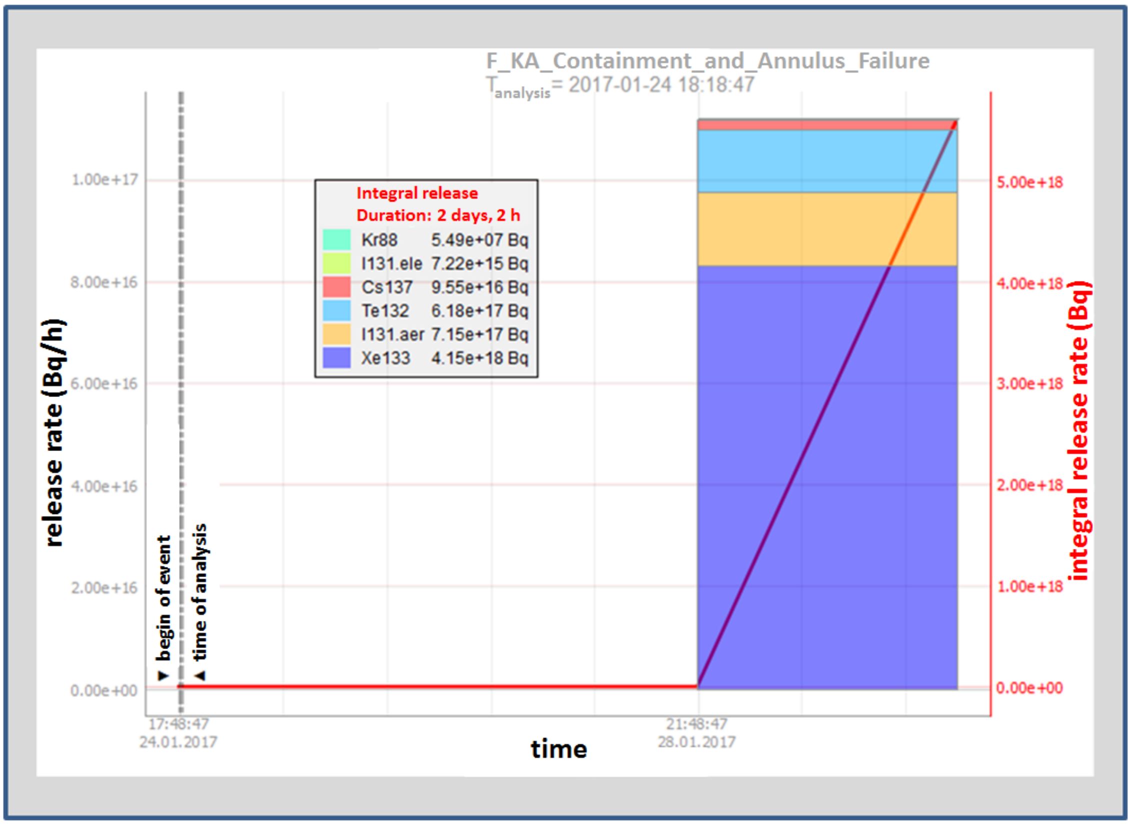


Table 1 provides the source terms for the release path "F_KA_Containment_and_Annulus_Failure". This table shows the releases of the radionuclides Kr-88, Xe-133, I-131, Te-132 and Cs-137 for one phase (phase with a release due to containment failure). Start and end of the phase are also shown in Table 1 (T_b= 100 h and T_e= 150 h, in each case related to the start of the initiating event), no second release period exists in this scenario.

Within the release of the first period, over 90 % of the noble gas core inventory is released to the environment; for I-131, Te-132 and Cs-137 the release fraction values vary between 20 % and 35 %.

Table 1: Kr-88, Xe-133, I-131, Te-132 and Cs-137 and Releases into the Environment for the Release Category „F_KA_Containment and Annulus failed"

PWR, "F_KA_Containment_and _Annulus_Failure"	**Kr-88 [Bq]**	**Xe-133 [Bq]**	**I-131 [Bq]**	**Te-132 [Bq]**	**Cs-137**
Release from begin of containment failure (T_b= 100 h) until the end of release (T_e= 150 h)	$5.5\ 10^{7}$	$4.2\ 10^{18}$	$7.2\ 10^{17}$	$6.2\ 10^{17}$	$9.6\ 10^{16}$

4. METHODOLOGICAL ENHANCEMENT FOR TIME DEPENDENT CORE INVENTORY

In previous versions of the source term prediction software FaSTPro the time dependent radionuclide decay of the core inventory has not been fully taken into account, since it was only considered between the initiating event of the severe accident and the release of radionuclides into the environment. The composition of the core inventory changes during the operation of the NPP. The current composition depends on physical parameter such as the decay chains and the half-life periods of the radionuclides and also on the current fuel composition and the time duration between the last shutdown of the plant and the initiating event of the severe accident. This last relation has been implemented into the software as the status of the core inventory at the initiating event influences directly the possible release of radionuclides during and after a severe accident.

Calculation results of the software KORIGEN [11] from the Institute for Nuclear and Energy Technologies (IKET) at the Karlsruhe Institute of Technology (KIT) were used to inlcude the temporal changes of the core inventory. These were taken from the report by the German SSK (*S*trahlen*s*chutz*k*ommission, German for radiation protection commission) “Leitfaden für den Fachberater Strahlenschutz der Katastrophenleitung bei kerntechnischen Notfällen” (pp. 81) [12]. The underlying tables were implemented in FaSTPro. The data sets of FasSTPro not only consider the radionuclides Xe-133, Kr-88, I-131 (gaseous and aerosol), Cs-137 and Te-132 but also e.g., Kr-85, Kr-85m and Kr-87.

An important variable for the calculation of the radionuclide activity is the knowledge of the time interval of the last shutdown Δt_{SD} of the NPP (either due to an overall maintenance inspection or due to refueling etc.). The tables in the SSK report [12] consist of datasets for time intervals Δt_D of 8 up to 28 days. The differences in activity are stronger dependent on the operational interruption time period Δt_{SD} for noble gases and iodine.

The implemented algorithm calculates the operating period of the plant Δt_P with time stamp information given by the user of the software. These time stamp information are given for the time point of the previous start of the operation and the current time point of shutdown of the NPP. The SSK-tables with values for the radionuclide activities are given for operational periods of $\Delta t_{OP=}$ 1, 2, 3, 10 or 100 days of operation and have been implemented into FaSTPro for the different release categories. In case of time periods in between these given values the calculation uses interpolation.

The released activity of radionuclides also depends on the time period after the end of the chain reaction. This time interval (turn-off duration) Δt_{OD} is calculated from user given time stamps for the time of reactor scram or shutdown and the prognosed time point of release of radionuclides into the environment. The time dependent core inventory values are implemented into the software for 0, 6, 24, 120 and 240 h. The activity of the radionuclides in relation to the turn-off duration Δt_{OD} is calculated using a linear interpolation.

These calculations are implemented for all release categories of the low power and shutdown plant operational states [13]. As a result the radionuclide activity and radioactive release into the environment is predicted more precisely.

5. CONCLUSION

This paper introduced an enhanced version of the source term prediction software FaSTPro having been extended to low power and shutdown phases of PWR type NPPs and calculating radionuclide activities more precisely due to considering time dependent core inventory compositions.

For a prediction of radionuclide releases after a severe accident during a shutdown phase of a NPP a special FaSTPro version has been developed. This was done by adding specific questions to the list of multiple choice questions regarding e.g. the barrier function of the RPV, the containment or the air lock and connecting them to the underlying probabilistic BBN of FaSTPro.

The source term prediction software bases on a synthesis of two inputs. On the one hand, probabilistic data (originating normally from a Level 2 PSA, in this case from plausible expert estimations) and on the other hand the current plant status with information about the status coming from the control room.

An additional component of the new version is the extension of the software with an implemented estimation procedure to adjust the prognosed source term to the actual development of the severe accident scenario. This has been realized by the integration of a time dependent core inventory composition.

The enhanced and extended version of the GRS analysis tool for a source term prediction now allows for a prognosis of the release of radionuclides into the environment also at shutdown states of NPPs. It therefore improves plant-external emergency preparedness e.g. at crisis centers.

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