Developing the RASTEP Model: A Methodological Approach and Case Study of the M310 PWR Reactor

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Abstract: The RASTEP (RApid Source TErm Prediction) is a decision support software tool that incorporates already compiled information, in the form of probabilistic data and deterministic plant response and source term analyses, from the level 1 and 2 PSA and supplement it with real-time information on observed plant conditions, thereby also following along the lines of the IAEA standards for Emergency Preparedness & Response (EP&R). The RASTEP tool is designed to support decision-making during emergency situations providing emergency teams or decision-makers additional insights and support to take the most appropriate emergency protective actions based on the information currently available, even if some of the details are unknown or yet to be realized.

The RASTEP software employs Bayesian Belief Networks (BBN), which incorporate causal relationships between initiating events, safety systems and its dependencies, emergency team and operator actions and plant response with live observations from the plant.

RASTEP is capable of modeling causes and effects in complex accident scenarios characterized by numerous potential variables, incomplete data, and high levels of uncertainty.

This paper presents a methodology for RASTEP model development using the design type generic RASTEP model for the M310 Pressurized Water Reactor (PWR) as an example. It outlines the process of BBN model development, including the collection and interpretation of PSA L1 and L2 data, integration of accident analysis data, and identification of source terms and its representation in the RASTEP software.

Keywords: Emergency preparedness, Bayesian Belief Network, RASTEP, Source Term.

1. INTRODUCTION

The RASTEP (RApid Source TErm Prediction) is a decision support software tool that is based on integration of inputs from probabilistic and deterministic safety analyses (Figure. 1). RASTEP is capable of modelling causes and effects in complex cases where there are lots of potential variables, certain data is incomplete, and the level of uncertainty is high. The tool is based on Bayesian Belief Networks (BBNs), representing probabilistic and deterministic relations among observations, events, and process variables. The BBN model connects known data and expert judgements with observations of the ongoing situations and maps the outcome to pre-calculated scenarios. Due to inherent properties of BBNs, the tool can always provide a best estimate of the situation at hand, irrespective of available information, relying on data and expert judgements already built into a plant model.

RASTEP user answers a series of formulated questions on specific parameters of the affected plant. As circumstances develop, new or updated information on specific system parameters can be entered. RASTEP applies that data to the corresponding systems in the model, resulting in a continually renewing diagnosis of the overall state of the affected plant and the potential development of this state (including the source term), thereby supporting decision-making at national and local authorities (Figure 4).

Bayesian Belief Networks (BBN) represent an established method of modelling uncertain relations among random variables and capturing the relationships between these variables using Bayes’ theorem. The BBN approach is to take prior beliefs at the outset and when information on the progression of an event becomes available, modify, and update those beliefs.

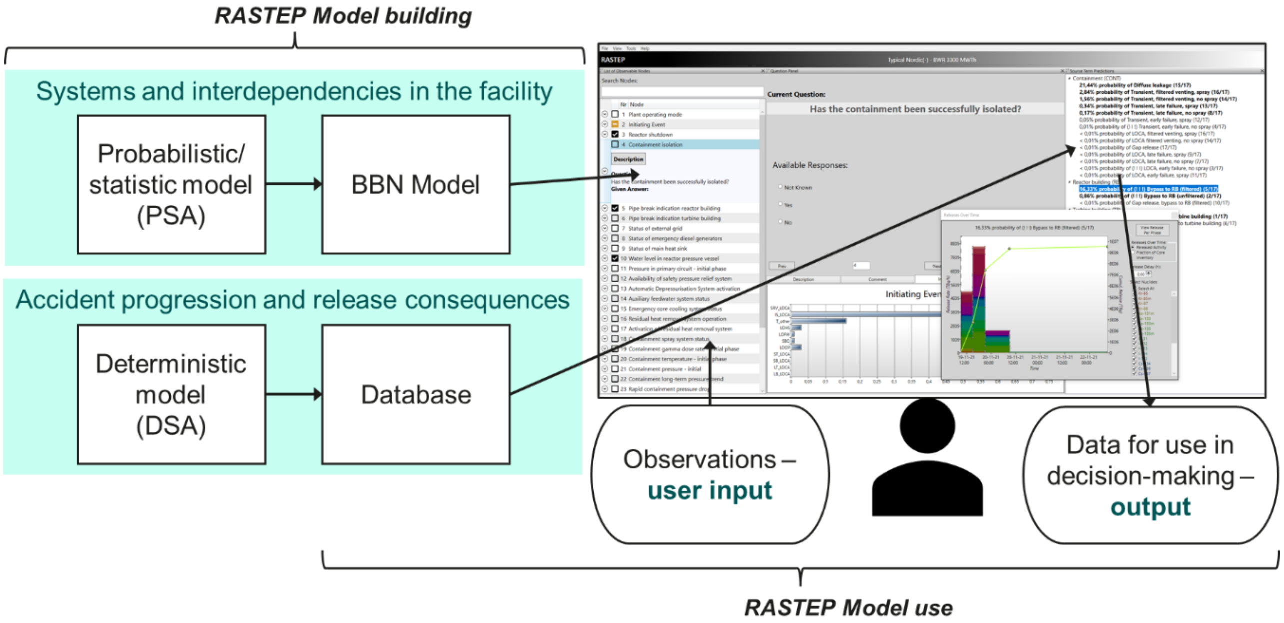

Figure 1. RASTEP Overview

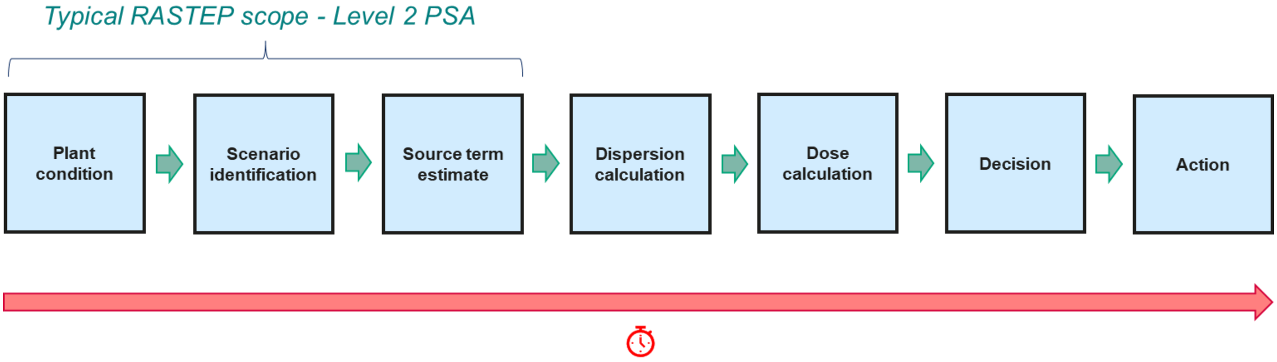

Figure 2. RASTEP in emergency preparedness context [3]

This paper presents a brief overview of the process of RASTEP model development using the design type generic RASTEP model of the M310 Pressurized Water Reactor (PWR) as an example. Section 2.2 outlines the process of development of the M310 Bayesian Belief Network, including the collection and interpretation of PSA L1 and L2 data. Section 2.3 presents the process of integration of deterministic accident analysis results and source terms and its representation in the RASTEP software. Section 2.4 presents the process of model validation and verification.

2. RASTEP MODEL DEVELOPMENT

2.1. RASTEP Model of a Generic Type M310 Reactor

A RASTEP model consists of a Bayesian Belief Network (BBN) model and a source term file, that contains post-processed source term data for different release categories.

The process of RASTEP model development, in general, follows the footsteps of PSA model development and includes such steps as familiarization with the safety design of the plant and collection relevant information; identification of relevant initiating event groups; identification of possible release paths; identification of relevant preventive and mitigative safety functions and safety systems; identification of manual operator actions (within the Emergency Operating Procedures (EOPs) and Severe Accident Management Guidelines (SAMGs)); deterministic analysis for identification of system requirements and quantification of the consequences (such as core damage, or the magnitude of the source term released to the environment).

The M310 reactor is a 900MWe (2895MWth) 3-loop pressurized water reactor. The reactor containment consists of a single wall prestressed reinforced concrete with inside steel liner. The containment is fitted with the system for manual containment pressure relief through a filter to ensure containment integrity and limit release of radioactive materials to the environment.

2.2. Bayesian Belief Network

The Bayesian Belief Network of the M310 PWR is organized into sub-networks. Sub-networks are, as a general rule-of-thumb, structured to reflect the accident progression and important safety functions. Each of the sub-networks may include several nodes.
The following sub-networks are included in the M310 PWR BBN model.

- Initiating events
- Core cooling
- Residual heat removal
- Fuel status
- Primary system
- Secondary system
- Containment status
- Source terms

Where the initiating events subnetwork is used to identify the initiating event based on the symptoms in the primary and secondary cooling systems and the containment (such as water levels, containment or secondary side gamma dose rates, pressure and temperature measurements in different systems).
The core cooling and residual heat removal subnetworks, together with the primary and secondary systems subnetworks typically represent the systems responsible for primary/secondary side coolant inventory control and residual heat removal, status of operator actions (e.g. RCS depressurization) and other relevant components (such as position of the Main Steam Isolation Valves (MSIVs), steam generator atmospheric relief valves, etc.).
The fuel status subnetwork typically consists of measurements and indicators of ongoing core damage.
The containment status subnetwork consists of the nodes that represent measurements and indicators for the containment overpressure protection and fission products retention systems, as well as measurements and SAMG operation actions relevant to the containment threats, such as long- and short-term pressure trends in the containment, hydrogen concentration, etc., that can affect the containment function and determine the mode of fission products release to the environment. An example of the RASTEP model structure is depicted in Figure 3.

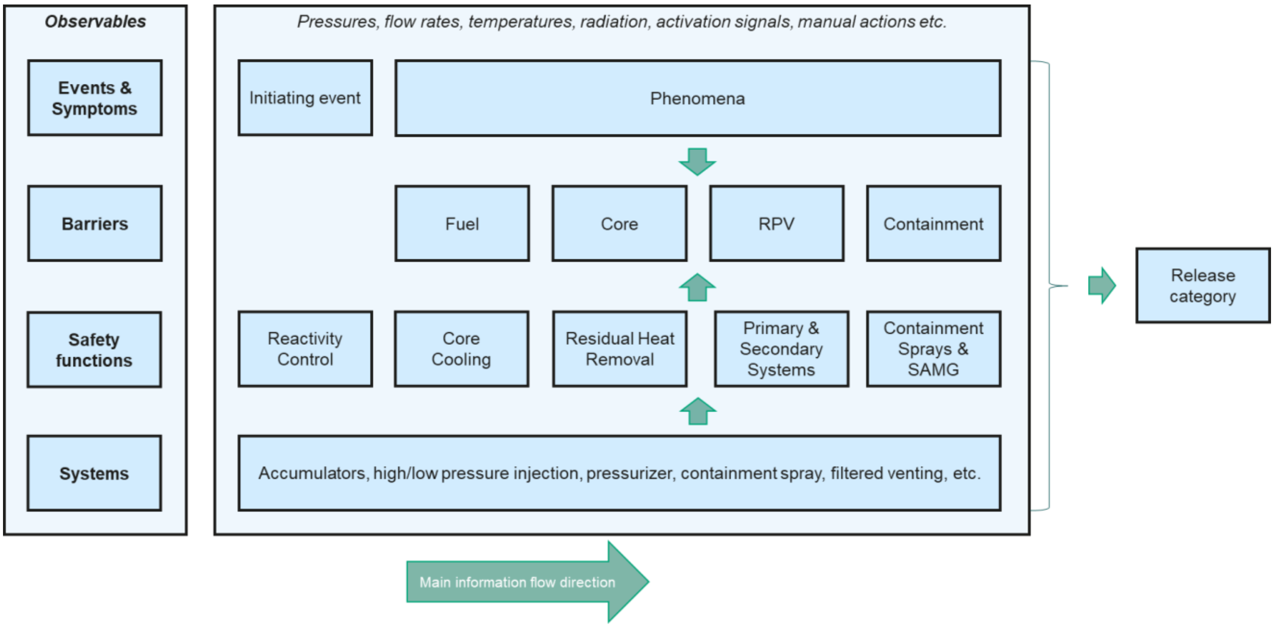

Figure 3. RASTEP Model structure – Release from containment example [3]

Initiating events

The scope of RASTEP models is typically limited to internal events during full power operation. Some initiating events are grouped as it has been judged unnecessary to discriminate between them for severe accident source term estimation. Some initiating events were screened out either due to very low contribution to the Core Damage Frequency (CDF) and Large Early Release Frequency (LERF) or the scope of RASTEP model (e.g. initiating events during shutdown, room events, site events). The resulting initiating event set for the M310 PWR RASTEP model is shown in Table 1.

Table 1. RASTEP IE groups of M310 Reactor.

RASTEP model IE group	**M310 Initiating event**
Large LOCA	Large LOCA
Medium LOCA	Medium LOCA
Small LOCA	Small LOCA
Small LOCA PRZ	Pressurizer LOCA
Steam line break	Steam line break
Feedwater line break	Feedwater line break
SGTR	Steam Generator Tube Rupture (SGTR)
	Steam line break induced SGTR
Loss of offsite (AC) power	LOOP
Loss of ultimate heat sink	Total Loss of ultimate heat sink
Loss of feedwater	Loss of feedwater Loss of compressed air
Other transients	Spurious reactor trip Transient on primary loop Transient on secondary loop

The relevant symptoms, in the form process parameters response in the primary and secondary systems, containment, etc., are typically based on deterministic analysis results and EOPs and SAMGs (entry conditions for EOPs/SAMGs instructions).

Safety functions and safety systems

To develop the RASTEP model for the M310 PWR, the PSA L1 event trees and PSA L2 accident progression event trees were investigated, to identify important safety functions, as well as system requirements for different initiating event groups. The resulting safety functions and safety systems are shown in Table 2.

Table 2. M310 Reactor design safety functions and safety systems relevant for RASTEP model.

Safety Function	**Safety System/Equipment**
Reactivity Control	Control Rods
	Boron Injection System
Core cooling, primary inventory control	Low pressure injection systems
	High pressure injection system
	Accumulators (3 hydro accumulators are respectively connected to the three cold legs of the RCS)
	Boron injection tank and boron surge tank
	Boron recirculation
	Pressurizer
	RWST
Residual heat removal	High pressure injection system
	RHR heat exchangers
	Primary feed & bleed
Primary depressurization	PORVs
	Pressurizer relief tank
Secondary system isolation	Main Steam Isolation Valves
Secondary system inventory control / heat sink	Condenser
	Atmospheric relief valves
	Feedwater system
	Auxiliary feedwater system

Safety Function	Safety System/Equipment
	Secondary system feed & bleed
Containment Isolation	Containment isolation system
Hydrogen management	Passive Autocatalytic Recombiners
Containment overpressure protection and fission products retention	Containment spray system
	Containment filtered venting system

Safety systems are typically modelled within their respective safety function subnetworks. The typical scope of RASTEP models does not include the modelling of separate trains or detailed representations of system dependencies, such as the component cooling system or compressed air/nitrogen systems. Instead, these dependencies are typically accounted for through underlying Conditional Probability Table (CPT) values derived from fault tree analyses using specific settings of boundary conditions and node dependencies. AC power dependencies, however, are typically modelled as part of the initiating events modelling and are included in the Bayesian Belief Network (BBN), as illustrated in the example of BBN modelling of the emergency core cooling systems in Figure 4.

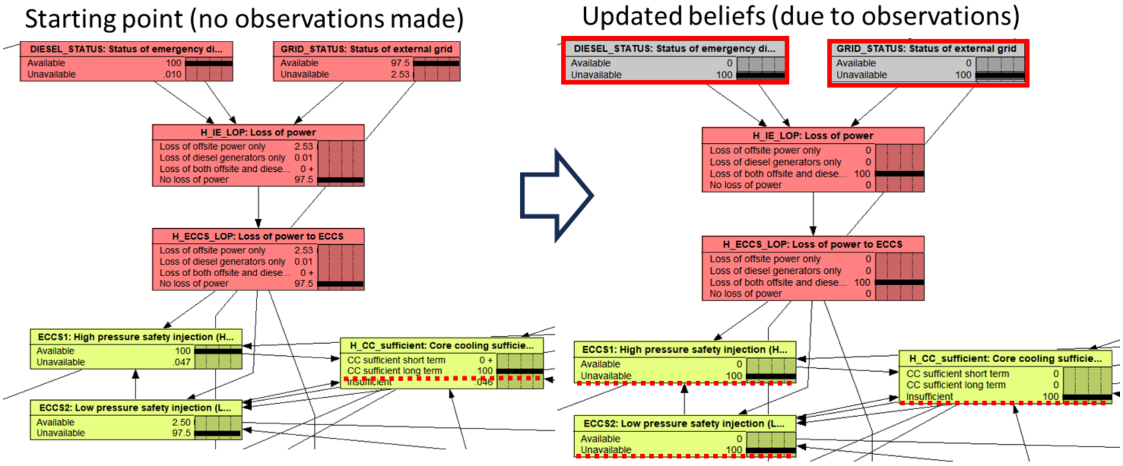

Figure 4. M310 BBN modelling of High- and Low-Pressure Safety Injection Systems

The observable symptoms/indicators for safety systems performance (such as readings from flowmeters, pressure gauges, etc.) are typically based on EOPs/SAMGs (control process parameters).

Source terms

The source terms subnetwork represents the M310 PWR RASTEP model release categories based on the typical Level 2 PSA release categories for PWR containments with filtered venting. The nodes of the source terms subnetwork are the output nodes of the BBN, with each state connected to a precalculated source term. These nodes gather information from other subnetworks and correlate it with the source terms. The BBN calculates likelihood values associated with different source terms, which are then displayed in the RASTEP GUI as a ranking of the most probable modes of radioactive release to the environment given the provided observations.

Table 3. Containment release category set and source term simulation cases

RASTEP model release category	Source term simulation case
Early failure, spray	Transient or reactor trip with loss of core cooling leading to fuel melt. Containment spray successful. A physical phenomenon such as hydrogen explosion or steam explosion leads to containment failure before or at the time of RPV melt-through.
Early failure, no spray	Transient or reactor trip with loss of core cooling leading to fuel melt. Containment spray fails. A physical phenomenon such as hydrogen explosion or steam explosion leads to containment failure before or at the time of RPV melt-through.
Late failure, spray	Transient or reactor trip with loss of core cooling leading to fuel melt. Containment spray successful. A physical phenomenon such as hydrogen explosion or steam explosion leads to containment failure after the time of RPV melt-through.

RASTEP model release category	Source term simulation case
Late failure, no spray	Transient or reactor trip with loss of core cooling leading to fuel melt. Containment spray fails. Containment pressure increase and failure to open filtered venting line leads to containment failure after the time of RPV melt-through.
Containment vent, spray	Transient or reactor trip with loss of core cooling leading to fuel melt. Containment spray initially failing, leading to increasing containment pressure and opening of filtered venting line. Containment spray recovered late (after opening of filtered venting).
Containment vent, no spray	Transient or reactor trip with loss of core cooling leading to fuel melt. Containment spray fails. Containment pressure increases until the filtered venting line is opened.
Basemat melt-through	Transient or reactor trip with loss of core cooling leading to fuel melt. Containment spray and/or recovery of safety injection limits containment pressure and filtered venting is not needed. Core debris not sufficiently cooled after RPV melt-through, leading to basemat melt-through.
Diffuse leakage	Transient or reactor trip with loss of core cooling leading to fuel melt. Containment spray and/or recovery of safety injection limits containment pressure increase. The containment remains intact without opening of the filtered venting line.
LOCA, early failure, spray	LOCA with loss of core cooling leading to fuel melt. Containment spray successful. A physical phenomenon such as hydrogen explosion or steam explosion leads to containment failure before or at the time of RPV melt-through.
LOCA, early failure, no spray	LOCA with loss of core cooling leading to fuel melt. Containment spray fails. A physical phenomenon such as hydrogen explosion or steam explosion leads to containment failure before or at the time of RPV melt-through.
LOCA, late failure, spray	LOCA with loss of core cooling leading to fuel melt. Containment spray successful. Physical phenomena such as hydrogen explosion or steam explosion leads to containment failure after the time of RPV melt-through.
LOCA, late failure, no spray	LOCA with loss of core cooling leading to fuel melt. Containment spray fails. Containment pressure increase and failure to open filtered venting line leads to containment failure after the time of RPV melt-through.
LOCA, containment vent, spray	LOCA with loss of core cooling leading to fuel melt. Containment spray initially failing, leading to increasing containment pressure and opening of filtered venting line. Containment spray recovered late (after opening of filtered venting).
LOCA, containment vent, no spray	LOCA with loss of core cooling leading to fuel melt. Containment spray fails. Containment pressure increases until the filtered venting line is opened.
LOCA, basemat melt-through	LOCA with loss of core cooling leading to fuel melt. Containment spray and/or recovery of safety injection limits containment pressure and filtered venting is not needed. Core debris not cooled after RPV melt-through, leading to basemat melt-through.
LOCA, diffuse leakage	LOCA with loss of core cooling leading to fuel melt. Containment spray and/or recovery of safety injection limits containment pressure increase. The containment remains intact without opening of the filtered venting line.

Table 4. Secondary system release category set and source term simulation cases

RASTEP model release category	Source term simulation case
SGTR, dryout, melt release	SGTR with loss of core cooling leading to fuel melt. Venting of the secondary system to the atmosphere. Scrubbing of fission products in the steam generator is not credited due to low water level.
SGTR, dryout, gap release	SGTR with partial loss of core cooling, leading to gap release but no fuel melt. Venting of the secondary system to the atmosphere. Scrubbing of fission products in the steam generator is not credited due to low water level.
SGTR, poolscrub, melt release	SGTR with loss of core cooling leading to fuel melt. Venting of the secondary system to the atmosphere. Scrubbing of fission products in the steam generator is credited.
SGTR, poolscrub, gap release	SGTR with partial loss of core cooling, leading to gap release but no fuel melt. Venting of the secondary system to the atmosphere. Scrubbing of fission products in the steam generator is credited.

Node types and information used in the BBN model

The nodes in the M310 BBN can be classified into two categories:

- Observable nodes, that can be further subdivided into:
    - Type A observable nodes, that represent observable measurements of process parameters (e.g. mass flow rates, pressures, dose rates). The conditional probability tables in these nodes typically incorporate the likelihood of false measurements.
    - Type B observable nodes, that represent human (operator) actions, where the CPT values are based on human error probabilities (HEP) from PSA.
    - Type C observable nodes, which represent more complex qualities of system response, e.g. such as availability, where the state of the node is typically determined by the observations. The CPT values in this case can be both deterministic (0 and 1 probabilities) or probabilistic, based on PSA (fault tree analysis).
- Hidden nodes that collect information from other nodes and model system dependencies, system requirements or plant conditions that cannot be directly observed (e.g. steam explosion). The CPT tables for these nodes can be:
    - Deterministic, which employ 0 or 1 probabilities in the conditional probability tables (CPTs). Such nodes typically employed to model logical relations between other nodes (to model system dependencies on other systems or observations (such as measurements, performance of manual actions, etc.); or system requirements as in event tree analysis in PSA, where different outcomes represent different branches in the event tree).
    - Probabilistic nodes based on PSA (system availabilities under different conditions calculated using fault tree analysis, probabilities of phenomena) or expert judgment.

The Bayesian Belief Network was implemented in the Norsys Netica software [1].

3.3. Deterministic Analysis Results and Source Term Information

Analysis of the accident sequences and the source terms released to the environment, as presented in Tables 3 and 4, was performed using the MAAP model of the M310 PWR. The deterministic analysis results were used in the development of the RASTEP model, to define observable nodes states based on the predicted behaviour of the primary and secondary cooling systems, and the containment during the accident progression. The source terms released to the environment were post-processed, to account for radioactive decay of fission products and implemented in the RASTEP model.

RASTEP supports free phasing in time of all source term data. Assuming that all accident sequences start with reactor scram at t=0, the phasing used in the M310 PWR RASTEP model source term set is given by times 2, 6, 12, 24, 48 h, and end of simulation resulting in 6 phases. The length of the first phase is loosely connected to the definition of relevant emergency action levels (EAL) for the M310 design, where some of the EALs are evaluated over 1 h.

Furthermore, the RASTEP source terms also include data for release height and thermal power (for input to plume lift calculation in atmospheric dispersion models) and Iodine speciation. The cumulative release of I-131 has been calculated for each source term and used as consequence severity ranking to be displayed in the RASTEP GUI. As the M310 PWR model contains 20 source terms, these are ranked from the most severe in terms of total I-131 release, denoted by (1/20) in the RASTEP GUI, to the least severe in terms of total I-131 release, denoted by (20/20) in the RASTEP GUI.

3.3. Model Verification and Validation

The current RASTEP model verification and validation scheme is based on a verification questionnaire for the BBN and a source term consistency check, which relies on deterministic analysis results.

The verification questionnaire includes a set of tests specifically designed to perform verification of the model response to different initiating events (e.g. SBO or LOCA) or loss of specific safety functions (e.g. loss of core cooling systems (primary inventory control) or residual heat removal systems).

The source term consistency check is performed manually for different initiating event groups and release categories, determining the response of the plant under different conditions using deterministic analysis results, and comparing the model's response by feeding this information into the RASTEP model in the form of answers to different observable nodes in the BBN. An automated approach for the source term consistency check using integral response code calculations is under development [2].

3. RESULTS

Case SBO – Diffuse Leakage

MAAP simulation results of the RASTEP release category Diffuse Leakage were used to inform the M310 PWR RASTEP model on accident progression. The observations entered are listed together with predictions of initiating events and release categories according to the source term phasing timespans, as presented in Table 5. Initiating event and release category predicted states are listed in order of decreasing likelihood, only listing those with predicted likelihood above 10%.

The prediction stabilizes to the correct release category during the second phase, from 2 to 6 h. As this is an accident scenario with recovery of AC power, it is crucial to enter the observation of confirmed core melt in connection with updating the observation on diesel generator availability (Otherwise, the core status prediction will return to intact, and the source term prediction will be no release).

The release category prediction is sensitive to the combination of observations on long-term containment pressure trend, containment spray availability and H2 concentration, where also the release category Basemat Melt-through appears in some combinations. This modelling can be improved by implementing more detailed information on long-term SAMG strategies for the M310 design.

Table 5. M310 PWR BBN verification against MAAP simulation for release category Diffuse Leakage

Timespan [h]	**Observations**	**Initiating event (> 10% likelihood)**	**Release category (> 10% likelihood)**
0 - 2	External grid unavailable Diesel generators unavailable SG level falling Containment pressure increasing	LOOP	Containment vent – no spray Early failure – no spray
2 - 6	Current primary pressure low Accumulators emptied Containment pressure steady Core exit temperature > 1200 C Containment H2 > 4% Core melt confirmed Diesel generators available	LOOP	Diffuse leakage Late failure – spray Early failure spray
6 - 12	Containment pressure decreasing Containment spray available	LOOP LOCA	Diffuse leakage Late failure – spray Early failure spray

Case LOCA – LOCA Containment Venting – No spray

MAAP simulation results of the RASTEP release category LOCA containment vent – no spray, were used to inform the M310 PWR BBN model on accident progression. The observations entered are listed together with predictions of initiating events and release categories according to the source term phasing timespans, as presented in Table 6. Initiating event and release category predicted states are listed in order of decreasing likelihood, only listing those with predicted likelihood above 10%.

The prediction stabilizes to the correct release category during the fourth phase, from 12 to 24 h, when information on increasing containment pressure is given. In this case, information on normal dose rate in secondary system is required to get the correct initiating event prediction. This is due to 1) that SGTRs have higher a priori likelihood than larger LOCAs and 2) that the model does not treat LOCA size assessment as an observable.

Table 6. M310 PWR BBN verification against MAAP simulation for release category LOCA containment vent – no spray

Timespan [h]	**Observations**	**Initiating event (> 10% likelihood)**	**Release category (> 10% likelihood)**
0 - 2	Initial containment pressure high Containment temperature high Initial SG water level falling Initial primary pressure falling Initial secondary pressure falling Current primary pressure low HPSI and LPSI unavailable Core exit temp > 1200 C Containment spray unavailable Containment pressure steady Containment H2 > 4%	SGTR LOCA	LOCA basemat melt-through LOCA early failure no spray LOCA late failure no spray
2 - 6	Core exit temp below 600 C Core melt confirmed Secondary dose rate normal	LOCA	LOCA basemat melt-through LOCA early failure no spray LOCA late failure no spray
6 - 12	No new information	LOCA	LOCA basemat melt-through LOCA early failure no spray LOCA late failure no spray
12 - 24	Containment pressure increasing	LOCA	LOCA containment vent no spray LOCA early failure no spray

Case SBO – Late Failure No Spray

MAAP simulation results of the RASTEP release category Late failure no spray was used to inform the M310 PWR BBN model on accident progression. The observations entered are listed together with predictions of initiating events and release categories according to the source term phases timespans as presented in Table 7. Initiating event and release category predicted states are listed in order of decreasing likelihood, only listing those with predicted likelihood above 10%.

The prediction of correct release category during the second phase, from 2 to 6 h, is dependent on the observation of failure to vent the containment. When this is entered, the most likely release category switches from containment vent no spray to late failure no spray. At this stage, the likelihood of early failure spray as the second most likely outcome is also dependent on an observation of current primary pressure.

Table 7. M310 PWR BBN verification against MAAP simulation for release category Late Failure No Spray

Timespan [h]	**Observations**	**Initiating event (> 10% likelihood)**	**Release category (> 10% likelihood)**
0 - 2	External grid unavailable Diesel generators unavailable SG level falling Containment pressure increasing	LOOP	Containment vent – no spray Early failure – no spray
2 - 6	Current primary pressure low Accumulators emptied Core exit temperature > 1200 C Core melt confirmed Failure to vent containment	LOOP	Containment vent – no spray Late failure – no spray

4. CONCLUSION

The RASTEP model development process was demonstrated using the RASTEP model for the Chinese M310 PWR plant design type. In particular, the process of BBN model development, including the collection and interpretation of PSA L1 and L2 data, integration of accident analysis data, and identification of source terms and its representation in the RASTEP software was outlined.

The M310 RASTEP model provides the most likely sequence and end state after a nuclear accident and estimates the source term released to the environment.

The RASTEP tool can be used for prognosis of source terms unlike the conventional estimates in the industry, where the source terms are based on measured dose rates without the ability of prognosis. Thus, it provides an independent view of possible scenarios in real time. RASTEP also enables its users to perform What-If analyses in conjunction with severe accident sequences. Thereby, the capabilities of the tool make it well-suited for the needs of any emergency response organization or nuclear operator.

Acknowledgements

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