RASTEP – A novel tool for nuclear accident diagnosis and source term prediction based on PSA and Bayesian Belief Networks

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Abstract: RASTEP (RApid Source TErm Prediction) is a software tool that provides an independent view of the progression of an accident at a nuclear power plant and the possible off-site consequences to the public and the environment. It gives a real-time picture of the affected plant's status, possible developments of the scenario, and details on the expected radiological source term. It has been developed in cooperation between Lloyds Register (LR) and the Swedish Radiation Safety Authority (SSM).

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 uncertain relations among variables and capturing the probabilistic relationship between these variables.

The RASTEP user answers a series of questions on specific parameters of the affected plant. As circumstances develop, new or updated information on specific system parameters are 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.

Keywords: Emergency response, RASTEP, BBN, FASTNET, source term.

1. INTRODUCTION

Development of tools for use in the fast, online diagnosis of an event or an accident, and in the subsequent radiological source term forecasting at nuclear power plants, is increasingly desired by off-site emergency planning and response personnel.

The RASTEP (RApid Source TErm Prediction) tool has been developed in a multi-year project and it is tailored to the needs of the Swedish Radiation Safety Authority (SSM). As a result, however, the capabilities of the tool make it well-suited for the needs of any emergency response organization or nuclear operator. The tool is based on a probabilistic plant model using the Bayesian Belief Network (BBN) methodology.

The outcome of the EU-project STERPS (Source Term Indicator Based on Plant Status) has been used as the starting point for the RASTEP project. STERPS had the objective to develop a computer-based tool for rapid and early diagnosis of plant status and subsequent estimation of the possible environmental releases, based on a probabilistic plant model using the Bayesian Belief Network (BBN) methodology. Within this project, BBN models were developed and tested for different reactor types whereof a Swedish boiling water reactor (BWR) was the only BWR in the project, and the model created for that BWR was tentative.

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A number of Master thesis projects have also been performed in parallel with development of the RASTEP tool, addressing a number of complex issues related to the definition of the source term as well as to the creation and quantification of BBN models.

RASTEP is one of the tools that are evaluated in the EU project FASTNET (FAST Nuclear Emergency Tools, www.fastnet-h2020.eu). FASTNET started in 2015 and is scheduled to run for four years. It involves a consortium of 20 partners from 18 countries (including the US, Canada and the Russian Federation) as well as the IAEA as a third party. The main focus of the project is on reliable prediction of severe accident progression and anticipation of the radioactive release of a nuclear accident.

2. AIM AND SCOPE OF THE RASTEP PROJECT

2.1. Project aim

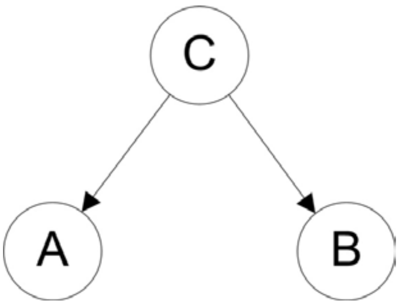
The basic aim of the RASTEP project is to develop a tool for rapid source term prediction for practical use in severe accident situations, considering the specific needs of SSM's emergency organization, including definition of the necessary administrative infrastructure which includes:

- Development and documentation of an analysis methodology, including necessary QA procedures, as well as procedures for validation and verification of the BBN models.
- Development of RASTEP with specified functionality, including the required software tool and user interface.
- Definition of procedures for update and maintenance of the specific nuclear power plant (NPP) models in RASTEP.
- Development of RASTEP models that can be applied to all Swedish nuclear power plants (in some cases, a model may be used for more than one plant, after modifications).

3. SHORT INTRODUCTION TO BAYESIAN BELIEF NETWORKS

Bayesian networks are well-known and established as a way of representing problems involving uncertain relations among a collection of random variables. These networks can be considered as a knowledge base which explicitly represents beliefs about elements included in the system and the relationships between these elements. The purpose of such a knowledge base is to infer some belief or draw conclusions about events in the system. The network is built on Bayes' theorem, which in turn originates from the foundations of probability theory. A simple Bayesian network is illustrated in Figure 1.

Figure 1: Simple Bayesian Network

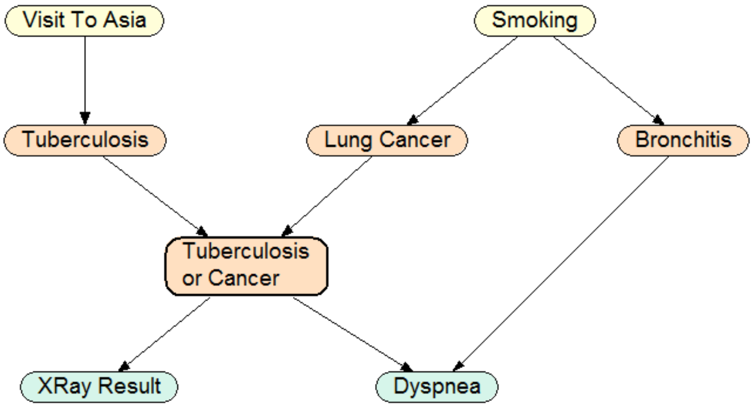


Bayes' theorem is used to calculate the posterior probability P(A | B) given the prior probability P(A) and the likelihood P(B | A) that B will be realized if A is true. In Bayes' theorem, equation (1), A represents the hypothesis and B represents the evidence.

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \quad (1)$$

The network presented in Figure 2 represents a medical diagnosis example where the two top nodes are "*predispositions*" which influence the likelihood of the illnesses following below. In the bottom of the network there are disease symptoms and examination results.

Figure 2: Network representing medical diagnosis example



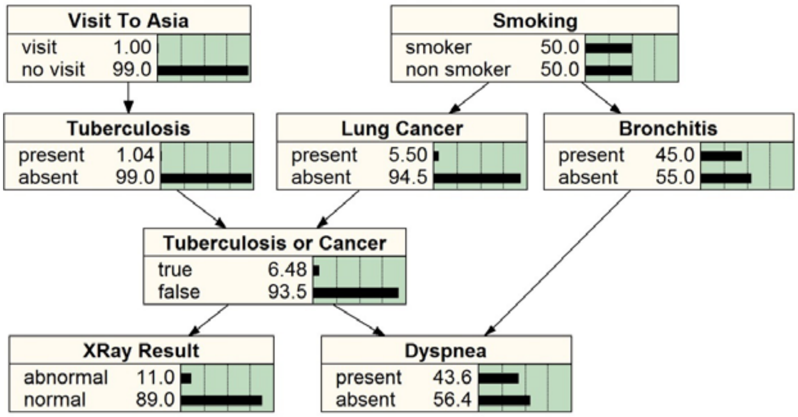
Each of the nodes in the network has different states, e.g., smoker/non-smoker for the node "*Smoking*" and every node state has a default probability. This information is summarized in a so-called Conditional Probability Table (CPT) for the node. The CPTs increase in size as the number of parent nodes and states increases. Default probabilities can be based either on statistics (for the "*Visit to Asia*" and "*Smoking*" nodes) or on the status of the parent nodes (every other node). For instance, the probability of "*Lung Cancer*" depends on if the patient is a smoker or not. This information is represented in a CPT for the node "*Lung Cancer*". Table 1 shows such a conditional probability table.

Table 1: Conditional Probability Table (CPT)

Parent node: Smoking	**Child node: Lung cancer**	
	Lung cancer	No lung cancer
Smoker	10%	90%
Non-smoker	1%	99%

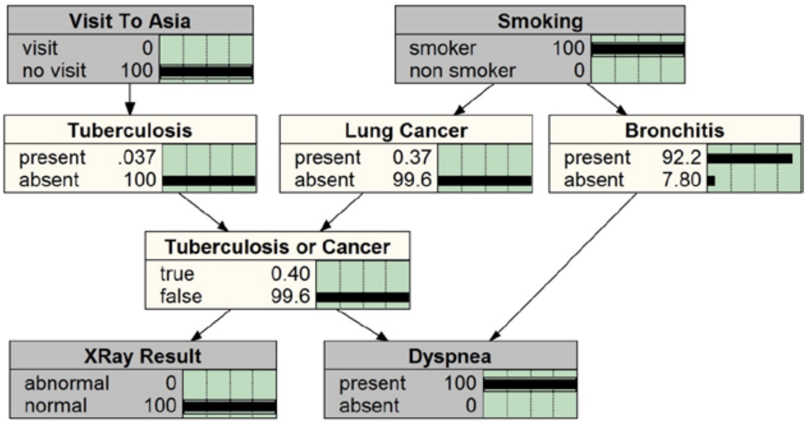
After belief update has been performed, the network will display the state probabilities for every node (as percentages). The starting point in this example is before any observations that have been made (generic case). The "*Visit to Asia*" and "*Smoking*" nodes include prior beliefs based on the state probabilities in the other nodes which are calculated. Figure 3 shows the generic case of the network.

Figure 3: Generic case of the network



Now the network is applied to a specific case in which observations are made and entered as findings (input) in the observable nodes. The observations consist of questions that are asked to the patient as well as of medical examinations. In our example the diagnosis involves a smoker who has not visited Asia and whose medical examination has shown normal X-ray results but suggests presence of Dyspnea. Based on this information, after belief updating, the network shows that a high probability of bronchitis prevails. Figure 4 shows the network for this case.

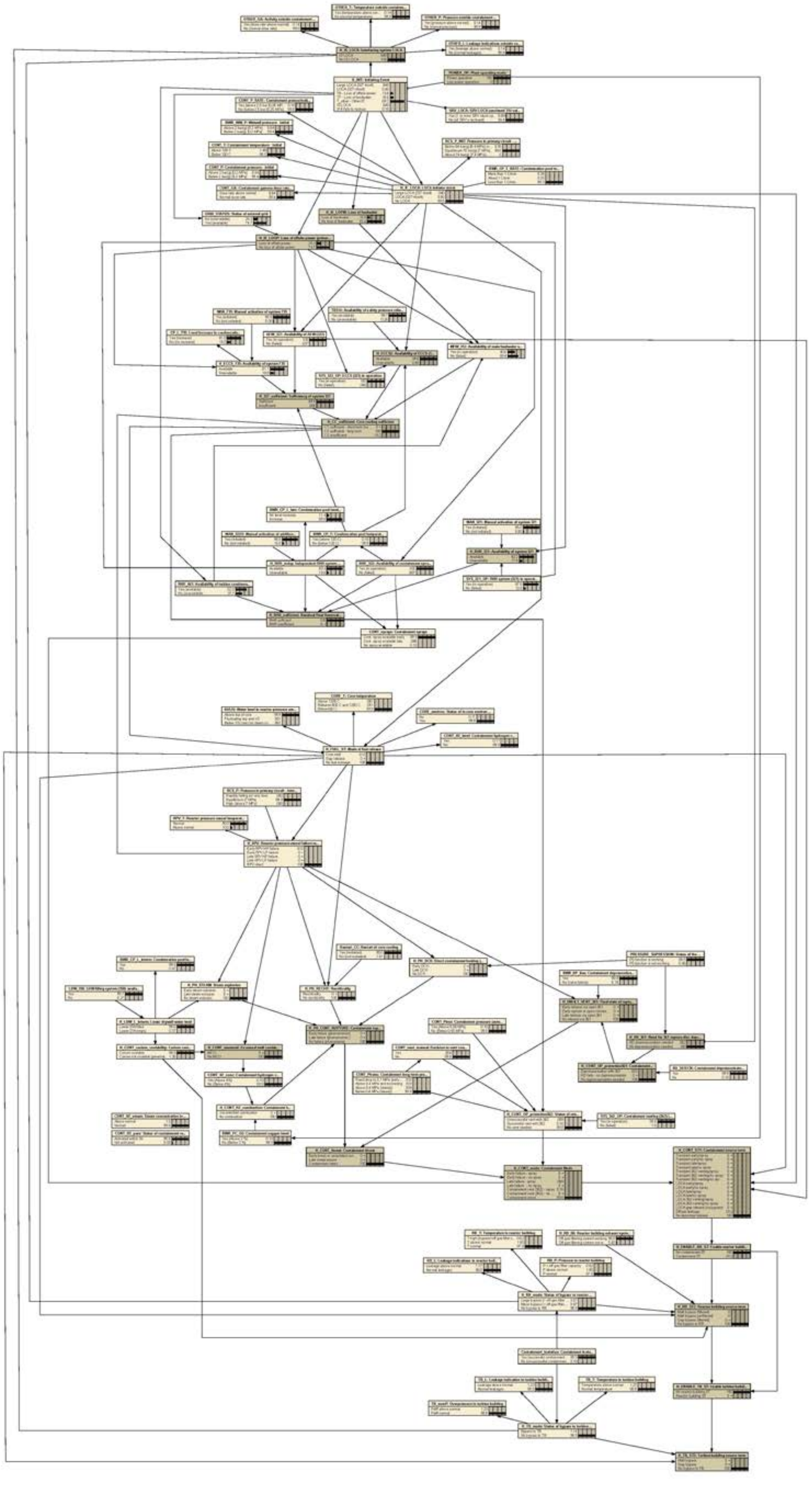
Figure 4: Specific case of the network



4. NUCLEAR POWER PLANT BBNs

The BBN models used by RASTEP are generated using the software Netica [1], in which all nodes, connections and CPTs are defined. The typical large-scale structure of a NPP BBN as displayed by the Netica user interface is shown in Figure 5.

Figure 5: Typical BBN of a NPP model as shown by Netica



There are obviously a large number of nodes and connections present in the NPP models which makes them complex to maintain and modify. In order to improve the readability and maintainability of the BBN, the nodes are grouped into subnetworks, representing important systems or collections of systems in the plant. A typical set of subnetworks for a NPP BBN model is given in Table 2.

Table 2: Typical BBN subnetworks

Subnetwork No.	Representation
1	Initiating events
2	Core cooling
3	Residual heat removal
4	Fuel
5	Reactor pressure vessel
6	Containment
7	Source terms

The nodes used in the models are either deterministic or probabilistic. The former represent logical relations such as:

“*if neither offsite power nor diesel generators are available, then no AC power is available*”

while the latter represent probabilistic relations such as:

“*the probability of a large break LOCA is P*”

The latter is typically based on a probabilistic safety assessment (PSA) or its underlying data. Technically, a deterministic node is a probabilistic node with probabilities of only 0 or 100 % in the CPT.

Furthermore, the nodes of the BBN are either “*observable*” or “*hidden*”. An observable node represents a quantity that can be measured or observed in the physical plant, such as the availability of offsite power. Observable nodes are often coupled to questions which are displayed by the RASTEP user interface to gather information for belief updating during an accident scenario. Hidden nodes, on the other hand, represent quantities that are not directly observable but have an important role to play in the probabilistic assessment of the accident progression, such as the current conditional probability of containment rupture.

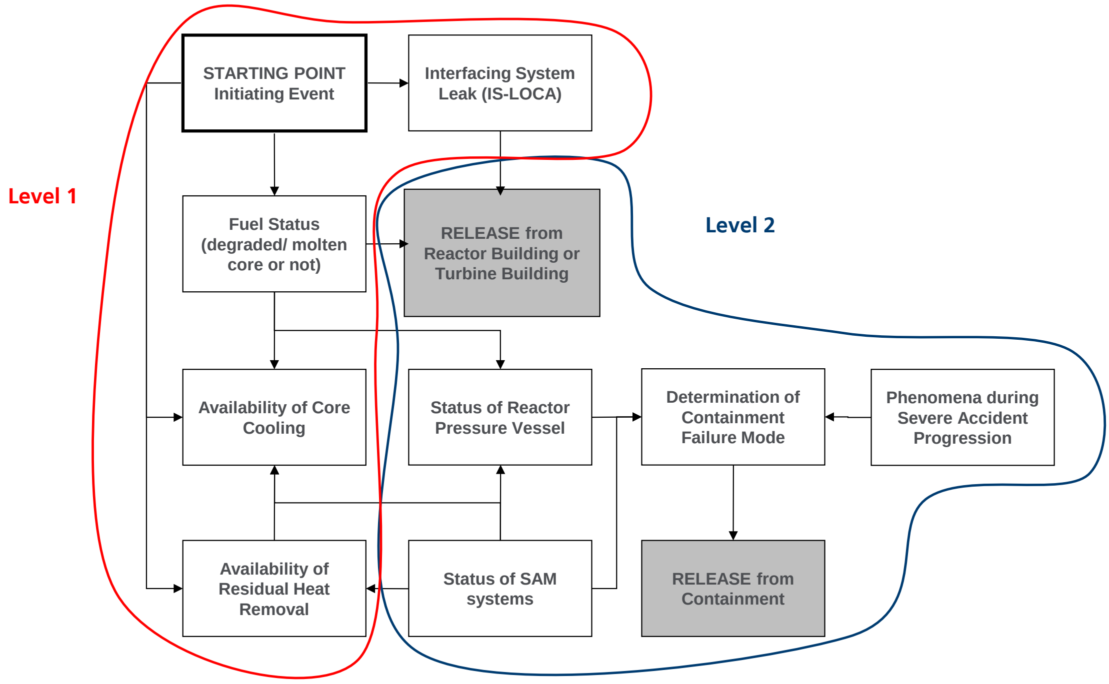
The input for the CPTs of the model can be obtained through several ways, depending on the node function:

- PSA – the CPT is based on PSA data [†] (this type of node is mostly used for observables),
- BELIEF – the CPT is based on expert judgment [‡],
- DETERMINISTIC – the CPT contains only zeros and ones (this type of node is mainly used for logic inside the model).

In Figure 6, the general model structure of a BBN for a BWR is displayed together with visualization of what parts of the BBN that draw information from Level 1 and Level 2 PSA respectively.

[†] It shall be noticed that uncertainties from the PSAs are currently not considered in RASTEP. It is however something that will be taken into consideration in future development of RASTEP, i.e. if it is possible to take PSA uncertainties into account and how these should be represented in that case.
[‡] For an expert it can be difficult to assign probabilities for events that are very rare. Different methods for expert elicitation of probabilities have therefore been developed; *(1) Elicitation of a single probability* and *(2) Elicitation of a full conditional probability table*. The methods used are explained in more detail in section 6.3 in [2].

Figure 6: General model structure – BWR example



5. INTRODUCTION TO THE RASTEP TOOL

RASTEP [2] is a single, dynamic tool that models an accident in a nuclear power plant by predicting plant states, probabilities of various event sequences, and assessing potential radioactive releases. These estimates are essential for effective off-site emergency response planning, involving national regulators, local authorities and the NPP operator. RASTEP is capable of modelling causes and effects in extremely complex cases, involving many variables, where data may be missing or incomplete and the level of uncertainty is high.

In an emergency situation, RASTEP works by asking the user a series of questions on specific parameters of the affected plant. The answers are fed into a pre-loaded model of the plant, mapping interconnections between all significant systems. As circumstances develop, RASTEP is able to absorb new or updated information on specific system parameters and apply that data to the corresponding systems in the model. The result is a continually renewed real-time diagnosis of the overall state of the affected plant and the potential development of this state, including the source term, should radioactive releases occur.

RASTEP models include two main components:

- A BBN including initiating events, barriers, safety functions with related data and a number of predefined release categories.
- Customized pre-calculated source terms based on deterministic simulations of pre-defined release categories.

The RASTEP models use a starting point that represents reactor shutdown (scram) and failure of "*first line of defense*", i.e. failure of systems that are expected to work in case of a normal disturbance. The model end points (results) consist of presentations of possible scenarios including their likelihood, release paths, source terms, and timing.

The screenshot of the user interface in Figure 7 shows RASTEP's emergency "dashboard". Different panels provide real-time information on system status, predictions of different source terms and visualization of releases of different radionuclides over time, with one section dedicated to dialogue with the user.

Figure 7: RASTEP's emergency 'dashboard': A clear, real-time picture of events at an effected nuclear power plant

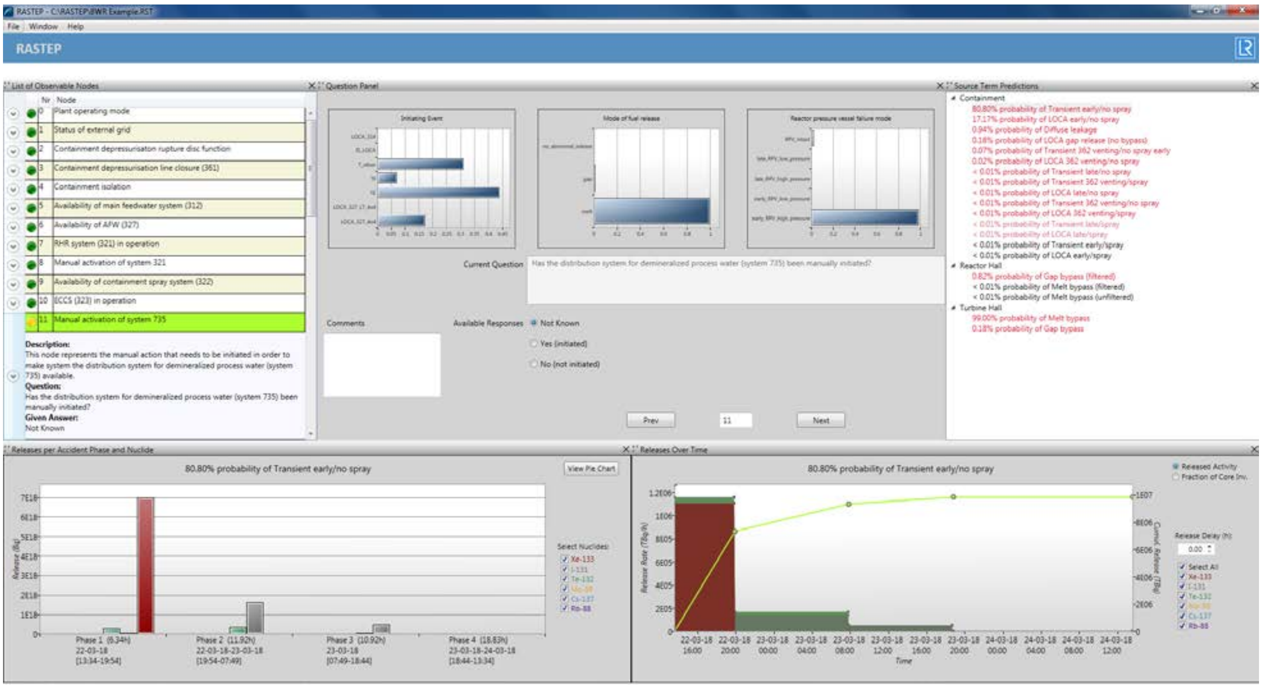
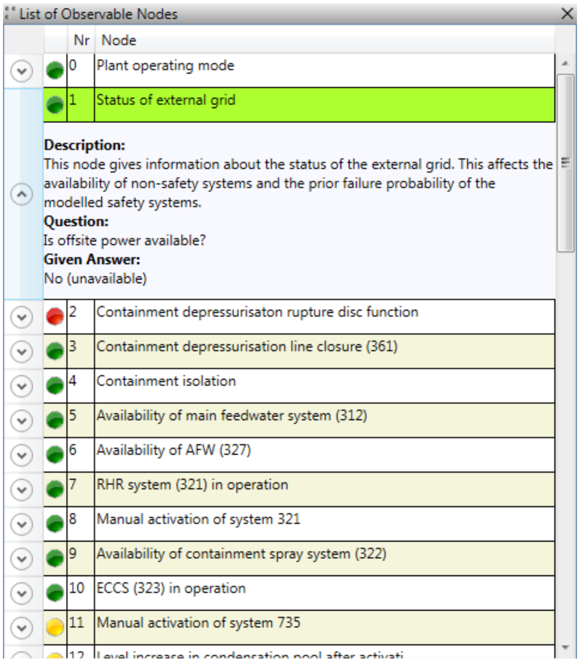


Figure 8 displays the panel of observable nodes and the questions they are linked to. The user is asked to provide answers to these questions whenever information is available or known. The green row highlights the currently selected node/question. The leftmost column contains a check icon that shows what question have been answered (●), not answered (●), or for which information is not known (●). The answer is provided in the question panel through a set of possible answers that match the CPTs in the BBN model.

Figure 8: RASTEP interface – List of Observable Nodes



In Figure 9 the Question Panel is displayed. In this panel the user can navigate through the questions and provide answers using the radio buttons and write comments. Based upon the currently provided answers, the Question Panel also provides a visualization with likelihoods of the occurred initiating event, the mode of radioactive release from the fuel, and the failure mode of the reactor pressure vessel (if any).

Figure 9: RASTEP interface – Question panel

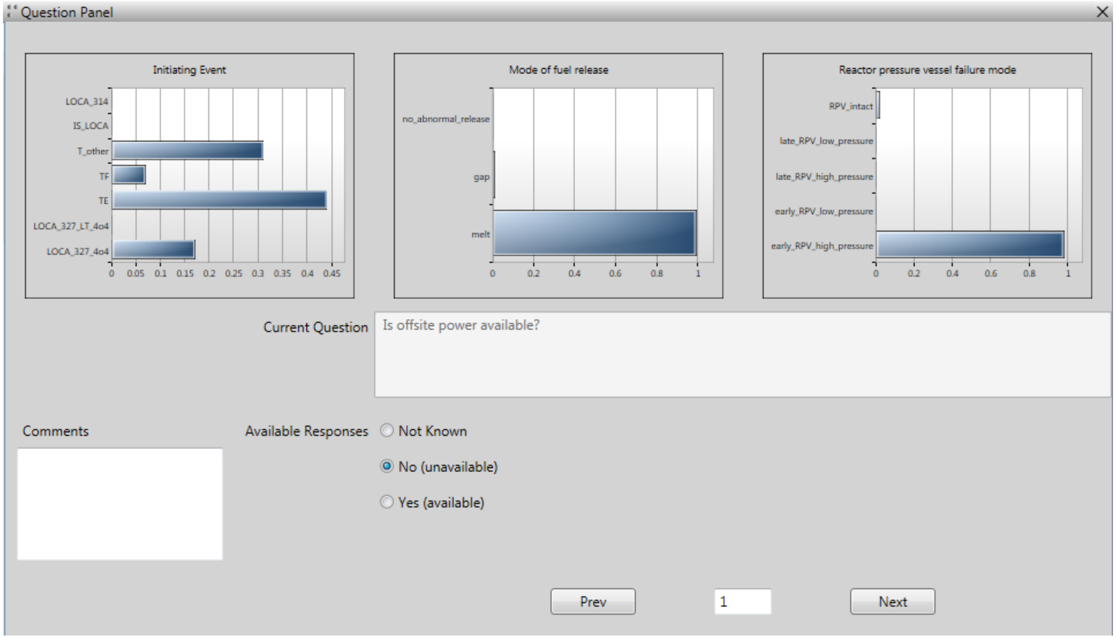


Figure 10 shows the Source Term Predictions panel where the user is provided with information about likelihood of possible scenarios for different release paths. The user can click on any of the displayed scenarios and study its predicted source term including its timing, see Figures 11 and 12.

Figure 10: RASTEP interface – Source Term Predictions

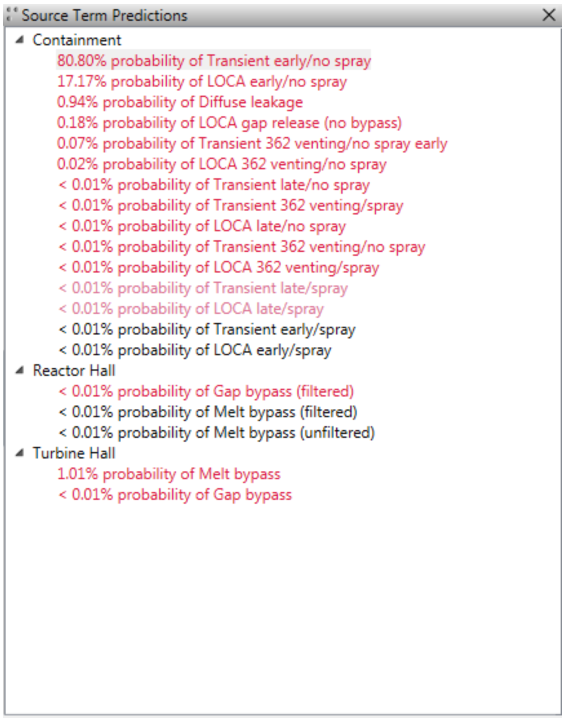


Figure 11: RASTEP interface – Source Term Visualization (1)

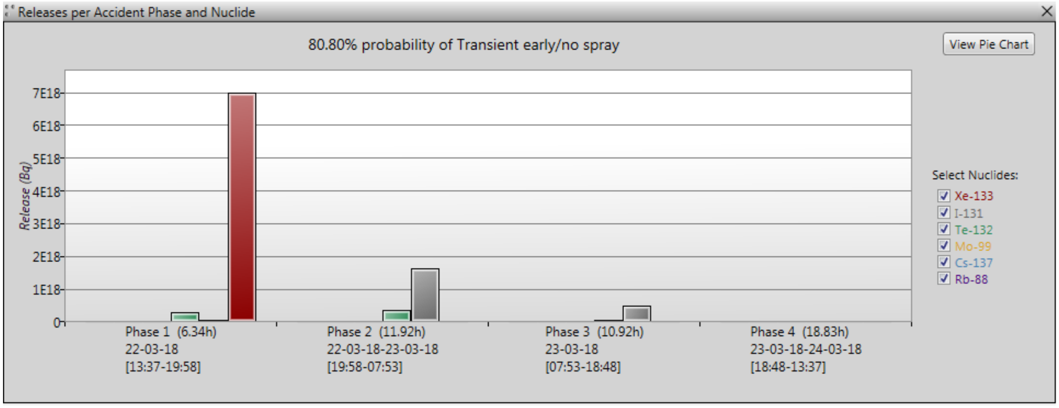
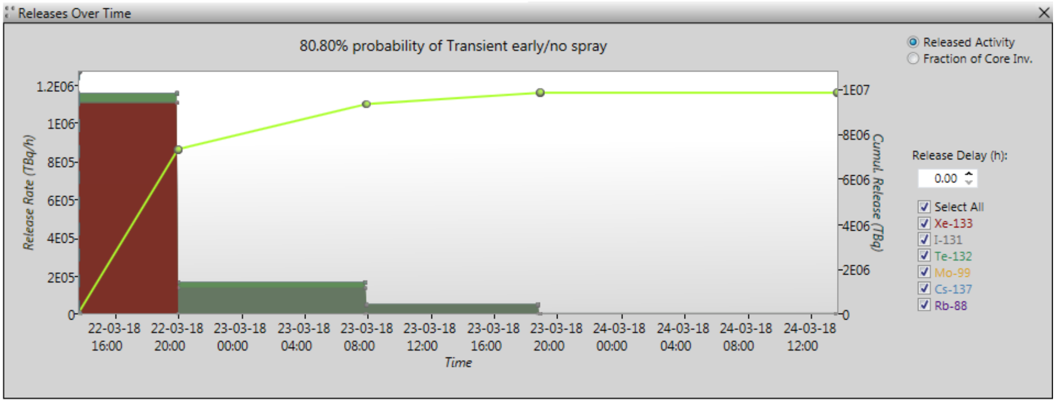
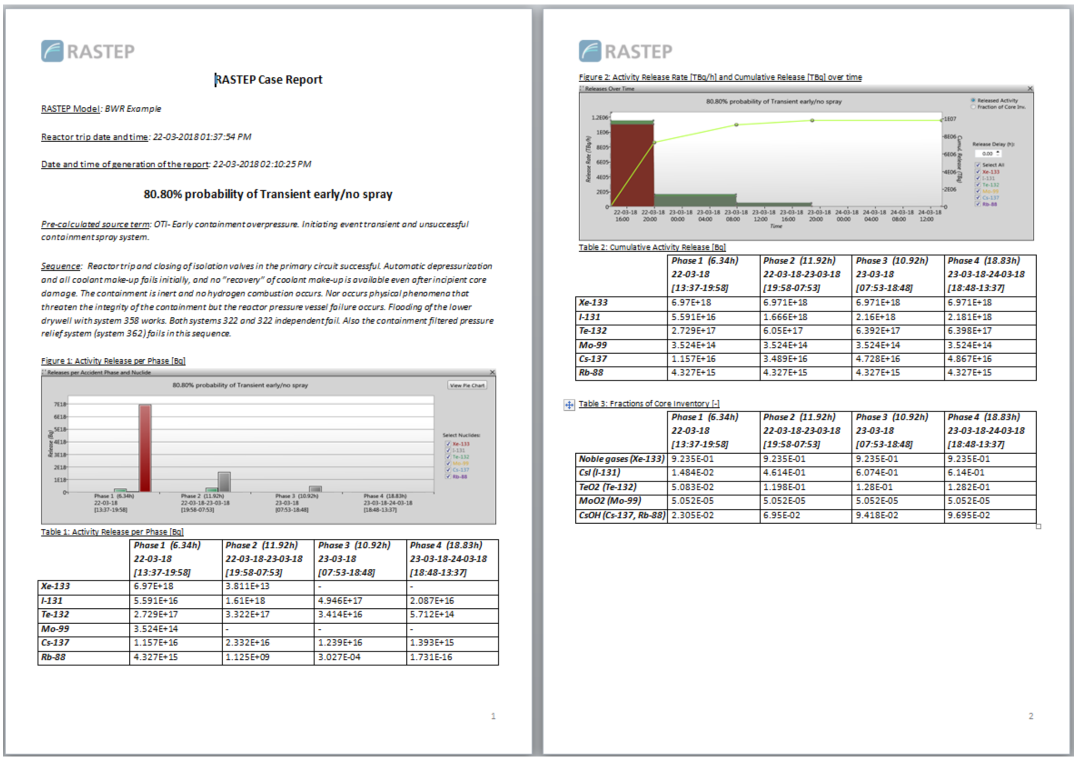


Figure 12: RASTEP interface – Source Term Visualization (2)



Another function in RASTEP is the Source Term Printout. As shown in Figure 13, this function allows the user to produce a document reporting all relevant data for a specific source term.

Figure 13: RASTEP interface – Source Term Printout



RASTEP

RASTEP Case Report

RASTEP Model: *BWR Example*

Reactor trip date and time: *22-03-2018 01:37:54 PM*

Date and time of generation of the report: *22-03-2018 02:10:25 PM*

80.80% probability of Transient early/no spray

Pre-calculated source term: OTI- Early containment overpressure. Initiating event transient and unsuccessful containment spray system.

Sequence: Reactor trip and closing of isolation valves in the primary circuit successful. Automatic depressurization and all coolant make-up fails initially, and no "recovery" of coolant make-up is available even after incipient core damage. The containment is inert and no hydrogen combustion occurs. Nor occurs physical phenomena that threaten the integrity of the containment but the reactor pressure vessel failure occurs. Flooding of the lower drywell with system 358 works. Both systems 322 and 322 independent fail. Also the containment filtered pressure relief system (system 362) fails in this sequence.

Figure 1: Activity Release per Phase [Bq]

Table 1: Activity Release per Phase [Bq]

	Phase 1 (6.34h) 22-03-18 [13:37-19:58]	Phase 2 (11.92h) 22-03-18-23-03-18 [19:58-07:53]	Phase 3 (10.92h) 23-03-18 [07:53-18:48]	Phase 4 (18.83h) 23-03-18-24-03-18 [18:48-13:37]
Xe-133	6.97E+18	3.811E+13	-	-
I-131	5.591E+16	1.61E+18	4.946E+17	2.087E+16
Te-132	2.729E+17	3.322E+17	3.414E+16	5.712E+14
Mo-99	3.524E+14	-	-	-
Cs-137	1.157E+16	2.332E+16	1.239E+16	1.393E+15
Rb-88	4.327E+15	1.125E+09	3.027E-04	1.731E-16

1

RASTEP

Figure 2: Activity Release Rate [TBq/h] and Cumulative Release [TBq] over time

Table 2: Cumulative Activity Release [Bq]

	Phase 1 (6.34h) 22-03-18 [13:37-19:58]	Phase 2 (11.92h) 22-03-18-23-03-18 [19:58-07:53]	Phase 3 (10.92h) 23-03-18 [07:53-18:48]	Phase 4 (18.83h) 23-03-18-24-03-18 [18:48-13:37]
Xe-133	6.97E+18	6.971E+18	6.971E+18	6.971E+18
I-131	5.591E+16	1.666E+18	2.16E+18	2.181E+18
Te-132	2.729E+17	6.05E+17	6.392E+17	6.398E+17
Mo-99	3.524E+14	3.524E+14	3.524E+14	3.524E+14
Cs-137	1.157E+16	3.489E+16	4.728E+16	4.867E+16
Rb-88	4.327E+15	4.327E+15	4.327E+15	4.327E+15

Table 3: Fractions of Core Inventory [-]

	Phase 1 (6.34h) 22-03-18 [13:37-19:58]	Phase 2 (11.92h) 22-03-18-23-03-18 [19:58-07:53]	Phase 3 (10.92h) 23-03-18 [07:53-18:48]	Phase 4 (18.83h) 23-03-18-24-03-18 [18:48-13:37]
Noble gases (Xe-133)	9.235E-01	9.235E-01	9.235E-01	9.235E-01
CsI (I-131)	1.484E-02	4.614E-01	6.074E-01	6.14E-01
TeO2 (Te-132)	5.083E-02	1.198E-01	1.28E-01	1.282E-01
MoO2 (Mo-99)	5.052E-05	5.052E-05	5.052E-05	5.052E-05
CsOH (Cs-137, Rb-88)	2.305E-02	6.95E-02	9.418E-02	9.695E-02

2

6. THE FASTNET PROJECT

6.1. Introduction to FASTNET

The overall objectives of the FASTNET project (www.fastnet-h2020.eu) are:

- to set-up a severe accident scenarios database,
- to qualify a common graduated response methodology that integrates several tools and methods to:
  - evaluate the source term,
  - ensure both diagnosis and prognosis of severe accident progression,
  - make connections between the FASTNET tools and others systems that use source term definition for further assessments,
- to communicate to the public the emergency management approaches, measures and resources in Europe.

In order to be implemented in any emergency center in Europe, all currently operating nuclear power plant concepts (PWR of Gen II and III; BWR of Gen II; VVER 440 and 1000; CANDU), as well as a concept of spent fuel pool facilities (SFP) in Europe, are covered.

The FASTNET project consists of six Work Packages (WPs) which are outlined in table 3 below.

Table 3: FASTNET work packages

WP	Name	Lead	Description
WP1	Scenarios database	LEI	Elaboration of a common database of pre-calculated scenarios on all concepts of existing NPPs in Europe including SFP facilities.
WP2	Emergency preparedness	LR	Evaluation and improvement of two types of existing approaches; the deterministic approach (3D/3P) and approaches using BBN (RASTEP, ASTEC inversion).
WP3	Emergency response	IRSN	• Development of specific parameterizations files describing all concepts of existing NPPs in Europe including SFP facilities which will be included with the PERSAN and RASTEP tool to allow the fast calculation of source terms for any situation, • improvement of the BBN approaches to foster their implementation in emergency centers.
WP4	Emergency exercises	NRPA	Preparation and realization of two series of emergency exercises: • the best evaluation of the ongoing situation, its evolution and its consequences, • protection of the population.
WP5	Dissemination	ENEA	• Sharing of knowledge, including a scenarios database and reference methods and tools beyond the Consortium, • education and training through workshops.
WP6	Management	IRSN	Project overall administrative and financial management.

6.2. RASTEP in FASTNET

The overall aim of the FASTNET project is to develop a common set of tools and methodology to be used in case of a severe accident (SA) at a nuclear power plant in the European Union. More specifically, the FASTNET project aims at developing and qualifying a response methodology integrating several tools and methods for both diagnosis and prognosis of severe accident progression as well as estimation of consequences. In this framework, the Bayesian Belief Network approach for predicting the source term plays a vital role, and the reference tool for this approach is the RASTEP tool, owned and developed by Lloyd’s Register.

To comply with the goals of FASTNET, generic RASTEP models for the different types of NPPs that are present in the EU as well as a spent fuel pool concept are created. Although the models are more generic than the ones developed for the Swedish plants, the same principal approach as described above is adopted.

Lloyd's Register cooperates closely with the Swedish Radiation Safety Authority within the FASTNET project.

7. CONCLUSION

Within the RASTEP project, multiple plant-specific BBN models have been and are still being developed. The project has been ongoing for more than 10 years, and during that time a structure and framework have been created in order to develop the BBN models, to validate and verify the inputs and outputs (the results), and to develop a software tool that can be used by emergency preparedness organizations.

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

[1] Norsys, 1997, *NETICA Application for Belief Networks and Influence Diagrams – User's guide*, Norsys Software Corp., 1997, Vancouver.

[2] Knochenhauer, M., Hedtjärn Swaling, V., Di Dedda, F., Hansson, F., Sjökvist, S. and Sunnevik, K. *Using Bayesian Belief Network (BBN) Modelling for Rapid Source Term Prediction – Final Report*, NKS-293, ISBN 978-87-7893-369-0, (2013)