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Using Bayesian Belief Network (BBN) Modelling for Rapid Source Term Prediction – RASTEP Phase 1

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September 2012

Abstract

The project is connected to the development of RASTEP, a computerized source term prediction tool aimed at providing a basis for improving off-site emergency management. RASTEP uses Bayesian belief networks (BBN) to model severe accident progression in a nuclear power plant in combination with pre-calculated source terms (i.e., amount, timing, and pathway of released radio-nuclides). The output is a set of possible source terms with associated probabilities. In the NKS project, a number of complex issues associated with the integration of probabilistic and deterministic analyses are addressed. This includes issues related to the method for estimating source terms, signal validation, and sensitivity analysis. One major task within Phase 1 of the project addressed the problem of how to make the source term module flexible enough to give reliable and valid output throughout the accident scenario. Of the alternatives evaluated, it is recommended that RASTEP is connected to a fast running source term prediction code, e.g., MARS, with a possibility of updating source terms based on real-time observations.

Key words

BBN, Bayesian Belief Network, Severe Accidents, Source Terms, Level 2 PSA, Signal Validation

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USING BAYESIAN BELIEF NETWORK (BBN) MODELLING FOR RAPID SOURCE TERM PREDICTION – RASTEP PHASE 1

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Summary:

The project presented in this report is connected to the development of RASTEP, a computerized source term prediction tool aimed at providing a basis for improving off-site emergency management.

RASTEP uses Bayesian belief networks (BBN) to model severe accident progression in a nuclear power plant in combination with pre-calculated source terms (i.e., amount, timing, and pathway of released radio-nuclides). The output is a set of possible source terms with associated probabilities.

In this report, several "complex issues" associated with the integration of probabilistic and deterministic analyses are addressed. One major task is how to make the source term module flexible enough to give reliable and valid output throughout the accident scenario. Of the alternatives evaluated, it is recommended that RASTEP is connected to a fast running source term prediction code, e.g., MARS, with a possibility of updating source terms based on real-time observations.

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ABBREVIATIONS

ADAM	Accident Diagnosis Analysis And Management
ASTRID	Assessment of Source Term for emergency response based on Installation Data
BBN	Bayesian Belief Network
BWR	Boiling Water Reactor
CAMS	Computerized Accident Management System
CPT	Conditional Probability Table
DBN	Dynamic Bayesian Network
DPSA	Dynamic Probabilistic Safety Assessment
DSA	Deterministic Safety Assessment
EdF	Electricité de France
ENSI	Swiss Federal Nuclear Inspectorate
EOP	Emergency Operating Procedure
ERI	Energy Research Incorporated
ET	Event Tree
FAI	Fauske and Associates
FT	Fault Tree
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit GmbH
HRP	OECD Halden Reactor Project
IRSN	Institut de radioprotection et de sûreté nucléaire
KTH	Kungliga Tekniska Högskolan (Royal Institute of Technology)
LENA/ARGOS	ARGOS is an information system for enhancing Crisis Management for incidents with chemical, biological, radiological, and nuclear (CBRN) releases.
LOCA	Loss Of Coolant Accident
LWR	Light Water Reactor
MAAP	Modular Accident Analysis Program
MELCOR	An integrated, engineering-level computer code used to model the progression of postulated accidents in light-water reactors, as well as non-reactor systems (e.g., spent fuel pool and dry cask).
MARS	MAAP Accident Response System
MCDET	Monte Carlo Dynamic Event Tree
NKS	Nordic Nuclear Safety Research
NPP	Nuclear Power Plant
OECD/NEA	OECD Nuclear Energy Agency
PEANO	Process Evaluation and Analysis by Neural Operators
PLASMA	Plant Safety Monitoring Assessment System
PSA	Probabilistic Safety Assessment
PWR	Pressurized Water Reactor
RASTEP	Rapid Source Term Prediction
RELAP	Reactor Excursion and Leak Analysis Program
SABINE	Source Term Assessment by Belief Network
SAMG	Severe Accident Management Guideline
SKI	Statens kärnkraftsinspektion (now part of SSM)
SPRINT	System For The Probabilistic Inference of Nuclear Power Plant Transients
SSI	Statens strålskyddsinstitut (now part of SSM)
SSM	Strålsäkerhetsmyndigheten
STERPS	Source Term Prediction Based On Plant Status
USNRC	United States Nuclear Regulatory Commission

1. INTRODUCTION

Development of tools for use in the fast, online event or accident diagnosis and subsequent radiological source term forecasting at nuclear power plants is increasingly desired by off-site emergency planning and response personnel. Availability of such analytical tools would enhance the efficiency in preparing accident response options, and online implementations would be invaluable in quickly predicting likely offsite consequences and result in a more appropriate off-site response.

Large uncertainties are inherent in severe accident situations at nuclear power plants. In trying to model severe accident situations a mixture of probabilistic and deterministic approaches are typically used. Thus probabilistic safety assessment (PSA) models are used for creating an over-all logical model representing the reaction of the plant to various challenges, and identifying critical event sequences leading to unacceptable radioactive releases. Deterministic analyses are used to determine critical aspects related to physical phenomena during progression of a severe accident, to the time and composition of releases, etc.

The project presented in this report is connected to the development of RASTEP, a computerized source term prediction tool aimed at providing a basis for improving off-site emergency management.

The name RASTEP stands for Rapid Source Term Prediction. RASTEP uses Bayesian belief networks (BBN) to model severe accident progression in a nuclear power plant. The output is a set of possible source terms with associated probabilities. RASTEP basically consist of two fundamentally different parts, i.e., a BBN model used to predict plant states and release paths, and a source term definition part used to characterise the source term (height, composition, amount, timing, etc.). The BBN model is based on prior information from the plant PSA model which is iteratively updated based on plant observables, e.g., pressure or temperature measurements. The source term definition and the modelling of the severe accident progression uses information from deterministic severe accident analysis tools, e.g., MAAP. The tool shall interface with commonly used off-site dose calculation tools, e.g., LENA and/or ARGOS. The approach chosen aims at facilitating decision making in a situation with incomplete, unreliable, or partly contradictive information.

1.1 Previous work

The work is partly based on a pilot project performed in 2001-2005 within the EU project STERPS, which was part of the EU framework programmes 5 and 6 [1, 2]. Nordic participation in the EU project was through the Royal Institute of Technology in Stockholm (KTH), with Wiktor Frid (professor at KTH at the time; now at SSM) as project manager, with the participation of Scandpower (Michael Knochenhauer), and extensive in-kind participation from OKG. There are also parallel RASTEP activities performed by the Swedish Radiation Safety Authority (SSM).

The previous work and SSM activities are described more in detail in Chapter 2.

1.2 Aim and objectives of the NKS project

There are several sub-steps defined within the RASTEP project. In brief, these are:

1. Definition of user interface
2. Definition of BBN functionality
3. Source term definitions
4. Signal validation
5. Application to plants. The basic part of the application of RASTEP involves development of generic BBN models for Swedish BWR:s and PWR:s, followed by specific plant applications.
6. Dissemination of results. Activities 2011-2012:
    - Presentation at the IDPSA Workshop in Espoo, Finland, November 2011.
    - Conference paper and presentation at PSAM 11-ESREL 2012; Helsinki, Finland; June 2012.
    - Project seminar at SSM October 17, 2012.
    - Participation in the Cooperation in the CAPS-WGAMA project (*International benchmarking project initiated by OECD/NEA of fast-running software tools for the estimation of fission product releases during accidents at nuclear power plants*).

Activities addressed in the NKS project are focusing on "complex issues", mainly connected to items 2-4 above, to be carried out in two project phases (Phase 1: July 2011 to June 2012; Phase 2: July 2012 to June 2013). Thus, the objectives of the NKS project are to support further studies in the following areas:

A. Definition and evaluation of a dynamic source term module for use within RASTEP, i.e., research on feasible fast running deterministic codes for online/dynamic, calculation and recalculation of source terms. Examples of candidates are, alongside with MAAP, MARS, ADAM, and MELCOR. The background to this area is that it's the current source term predicting abilities of RASTEP are not flexible enough.
B. Comparisons between different codes to elucidate practical aspects of changing from the current PSA level 2 based paradigm, with beforehand calculated (assumed typical/representative) source terms, to a dynamic one where the *actual source term* is to be captured.
C. Definition of BBN Functionality incl. methods for sensitivity analyses and definition of complex CPT:s (see below).
D. Signal validation of input to the BBN, i.e., the assessing the validity of observables.

The major part of phase 1 deals with task A, i.e., the feasibility of making the source term analysis less static. The fundamentals were chiselled out in a master thesis project, run by Scandpower in co-operation with Uppsala University, and finalized in early 2012. A comprehensive presentation of the results of this part of the study is found in Chapter 3. Several state-of-the-art approaches were reviewed, including dynamic BBN:s, genetic algorithm Dynamic PSA (DPSA) methods, as well as the feasibility of plugging fast running deterministic codes into a future version of the existing source term module. The latter alternative seems to be the most promising, however facing two major challenges:

– Firstly, one important strength of RASTEP is that it is probabilistic, i.e. it will provide a prediction of what accident sequence is to be expected even if only scarce information is available along with a pre-calculated source term based on a typical case. Now, updating this source term will be feasible only well into the accident scenario, with a considerable amount of information (based on observables) available. This means that at some point the user has to rely more on the deterministic forecast, than the probabilistic. Yet, it is not clear how to make this balancing.
– Secondly, the technical problem of plugging the code into RASTEP has to be solved.

Thus, it is all reduced to a matter of conceptual and technical integration. To resolve this is the first objective of phase 2, followed up within the frame of a second master thesis project, this time in co-operation with Chalmers Institute of Technology starting in September 2012 (see Section 7.1 for a project abstract). This part of the study will be interconnected with further comparisons between different codes (item B above). There is certainly a need for understanding the problem complexity associated with connecting a dynamic source term predictor to RASTEP as well as the possibility of combining different codes serving different purposes, e.g., it might be that for purposes of developing a robust and general source term, calculation run time not being an issue, MAAP could be the best alternative, whereas it will not serve the purpose of online calculations. Thus, it is not only a matter of probabilistic/deterministic, but one of changing from one code to another as well. The study will primarily be carried out using MAAP and MELCOR, mainly because these codes are widely used internationally for severe accident analyses, and both are currently at the disposal of the project.

The tasks mentioned in item C and D, related to BBN functionality and to signal validation, have also been addressed in this first phase of the project, however much work is yet to be done. The tasks of finding a "semi quantitative method" of defining complex CPT:s and a method for sensitivity analysis of the BBN, in order to, e.g., identify nodes that are "driving the result", are planned to be carried out within the frames of two master thesis projects, respectively. Abstracts of these studies are presented in Sections 7.3 and 7.4. One or both of these MSc projects are planned to be included in phase 2 of the NKS project.

Task D has been planned to be dealt with within a joint activity between Scandpower and IFE Halden, the objective being to investigate the feasibility of adapting PEANO, a tool for signal validation, to RASTEP, along with a strategy of screening out invalid input, i.e., observables. Such a filtering procedure would certainly be powerful if it were combined with a method of BBN sensitivity analysis, since combining the knowledge of importance and validity might increase the quality of the output drastically, as it is minimizing the risk of drawing inaccurate conclusions. A detailed outline of task D is presented in Chapter 5. However, since fast running source term prediction codes such as, e.g. MARS, are providing this very functionality, it is of interest to await the result of the second master thesis (item A, autumn 2012). If these tools are not promising in this respect, or if further elucidation is needed, the feasibility study on PEANO-RASTEP may be resumed.

Thus, the beginning of phase 2 will be devoted to elucidating the conceptual and technical aspects of plugging a fast running code into RASTEP, involving necessary comparisons between MAAP and MELCOR, as well as to further preparation of studies on BBN sensitivity analysis and determination of complex CPT:s.

1.3 Project organisation

The SSM project manager is Wiktor Frid. NKS activity leader and Scandpower project manager is Michael Knochenhauer. Expertise on signal validation is planned to be provided by IFE Halden. In addition, the activity will include expertise related to PSA, severe accident analysis and programming (BBN, Netica, source term characterisation, input and output interface, LENA/ARGOS interfaces).

End users will be represented through a reference group, including experts in severe accident analysis and emergency preparedness from SSM and the Swedish utilities (Forsmark, Ringhals, and Oskarshamn). If possible, information exchange will also be organised with some of the previous STERPS partner, e.g., with GRS in Germany.

2. RASTEP – AN OVERVIEW OF SSM ACTIVITIES

2.1 Background and relation to previous work

The work is partly based on a pilot project performed in 2001-2005 within the EU project STERPS, which was part of the EU framework programmes 5 and 6 [1, 2]. Nordic participation in the EU project was through the Royal Institute of Technology in Stockholm (KTH), with Wiktor Frid (professor at KTH at the time; now at SSM) as project manager, with the participation of Scandpower (Michael Knochenhauer), and extensive in-kind participation from OKG. The STERPS project 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. The analysis used the generic BBN software Netica (developed by Norsys Inc.), with the user interface SPRINT (System for the Probabilistic Inference of Nuclear Power Plant Transients), which was developed within the STERPS project for handling of the BBN. The user interface includes a set of questions and background information, which are used in order to gain information about crucial plant parameters during the course of a severe accident. SPRINT also includes graphical presentation of analysis results, both in terms of node probabilities and as characteristics for radioactive releases (amount, composition, and timing).

Within the project BBN tentative models were developed and tested for a number of different reactor types. Oskarshamn 3 was the only boiling water reactor (BWR) in the project, and a rather detailed outline of a BBN model was developed for the unit. The BWR model was tested at an emergency preparedness exercise at Oskarshamn 3 in March 2005. It has later been demonstrated and presented at SKI, SSI and Forsmark.

During 2008 and 2009 a pre-project was performed by SSM (Swedish Radiation Safety Authority) to analyze the potential for further developing what was achieved in the STERPS project into a functioning tool; this project was given the name RASTEP. A review of experiences from the STERPS-project was included in the pre-project. The review included contacts with organisations that have further developed their STERPS models, especially GRS in Germany. Requirements and expectations regarding functionality and user interfaces were discussed with stakeholders within SSM. Finally an initial study was made concerning prerequisites and possibilities for an accommodated computerized tool that will be used for modelling, review and use of the BBN model. A reference group with members from SSM and the Swedish nuclear power plants has been connected to the project.

2.2 Objectives of the SSM project

The pre-project performed by SSM resulted in the proposal for a radical re-composition of the BBN structure suggested in the EU STERPS project, see Figure 1, which also gives a good view of the general lay-out of a BBN. Other aspects of BBN modelling are the identification of relevant PSA information (prior information) and of relevant observables (plant status parameters, such as pressures, temperatures, water levels etc.), as well as possibilities of measuring the sensitivity of the output with respect to the state of specific nodes (answering questions like “What nodes are driving the result?”). Finally, the definition of a relevant and defendable set of conditional probabilities related to BBN nodes has proved to be a major challenge, and needs to be further explored.

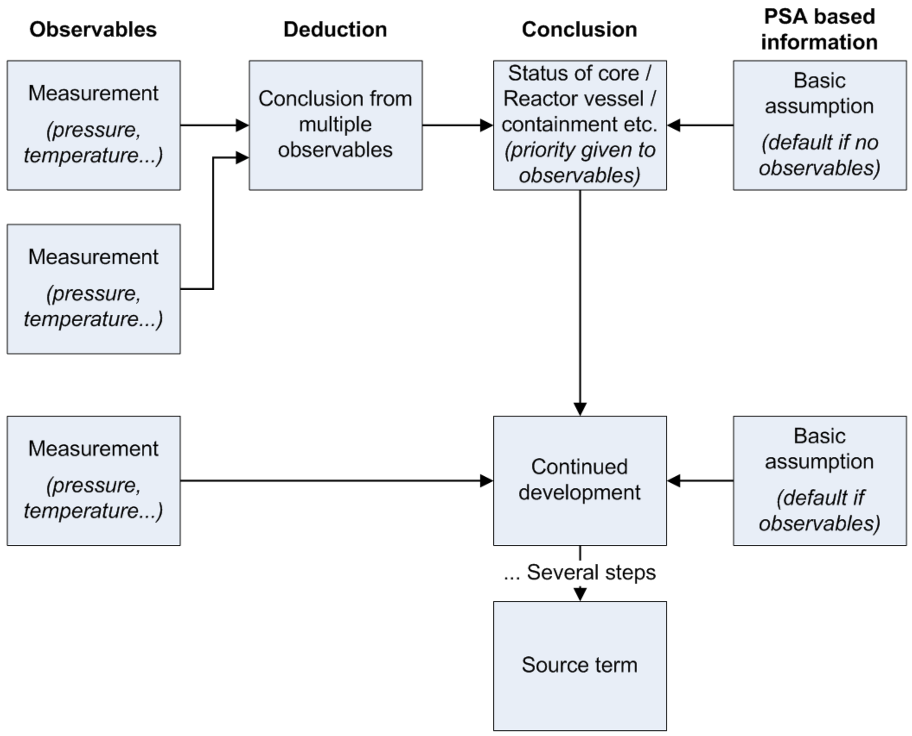

Figure 1 RASTEP – Suggested basic structure of BBN model

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

- Development and documentation of an analysis methodology, including the necessary QA procedures and procedures for validation and verification of developed BBN models.
- Development of RASTEP with required functionality, including required user and program interfaces.
- Definition of procedures for update and maintenance of the specific NPP models in RASTEP.
- Development of a generic RASTEP model for Swedish BWR:s and PWR:s, aiming at producing general models that can be reasonably easy adapted to all Swedish reactors.
- Development of RASTEP models for all Swedish nuclear power plants.

2.3 Scope of the SSM project

The first phase of the SSM project (2009) focused on creating the basis for a generic BBN model for Swedish BWR:s, using Oskarshamn 3 as a first case. In doing this, the project created a structured general framework for developing BBN models for nuclear power plants (NPP). Phase two (2010) consisted of two parts; finalization of the Oskarshamn 3 BWR model conditional probability tables (CPT:s) and initiation of source term definition based on MAAP calculations in level 2 PSA. Phase three (2011) consisted of an integration of the Oskarshamn 3 BWR model and the user interface SPRINT, a validation and verification process of the Oskarshamn 3 BWR model, an initiation of a specific PWR BBN model and an outline for a design specification of a user interface for RASTEP. In the on-going fourth phase earlier developed models are used as a basis for modelling of Oskarshamn 2 and Ringhals 3 NPP:s.

2.4 Basic features of RASTEP in the SSM project

Below, the basic features of RASTEP as developed in the SSM project are described, as well as the main objectives of the SSM project [13].

2.4.1 User interface and software tool

In a computer based decision support tool intended for use during severe accident conditions, relevant and easily used interfaces will be important. This includes both input interfaces (creation of model, running of model) and output interfaces, including interface with offsite consequence analysis tools such as LENA/ARGOS, ADAM, etc.

As previously stated, the RASTEP model include two fundamentally different parts, firstly the BBN model used to predicts plant states and release paths, and secondly the source term module that characterises source terms (height, composition, timing etc). The time being, the SPRINT user interface developed within the STERPS project is used to illustrate the model. This interface will eventually be replaced by a specially developed RASTEP software interface with considerably extended functionality and user interfaces.

In the interface the user answers questions about plant observables. The answers are in terms of node states and they are entered into the corresponding network node as a finding. Then the BBN Engine, Netica, find beliefs for all the other variables in the network. The tool scheme is depicted in Figure 2. The figure suggests automatic transfer of data from the NPP into RASTEP.

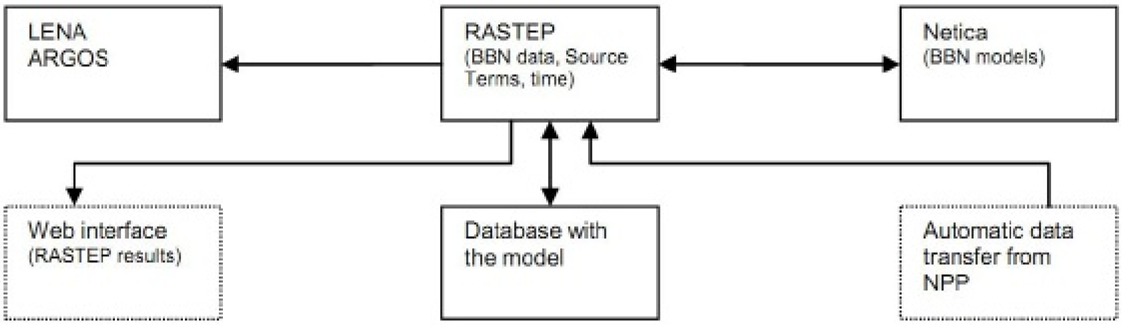

Figure 2. Schematic overview of RASTEP

2.4.2 Functionality

Initially, RASTEP is developed only for use in power operation mode meaning that the start-up, shut-down and cold shut-down states are considered at this time. The model considers all initiating event categories considered in the plant PSA, but some simplified regroupings can be performed without loss of precision. Loss of coolant accident (LOCA) events are divided into "large" or "small" based on system requirements from the emergency core cooling and auxiliary feed water systems. The network considers loss of external power both as an initiating event and as a grid level consequence of other initiating events. The end states of the network are radioactive releases that are associated with defined release paths and source terms that should be in agreement with release paths and source terms modelled in the level 2 PSA.

The users of RASTEP are assumed to be part of the SSM emergency preparedness organisation and the primary aim is to provide SSM with an independent view of the accident progression and possible off-site consequences. SSM interacts with the plant and the local emergency preparedness organisation when using RASTEP. Furthermore, training is a useful area of usage.

It is important to consider at what stage in an accident sequence SSM might start using RASTEP. The starting point has been set to the time of the failure of the "first line of defence" which means the failure of one or more of the systems for fission control, pressure control, core cooling and residual heat removal. The output from RASTEP is intended to be used with off-site consequence analysis tools (such as LENA or ARGOS).

2.4.3 Mapping of plant characteristics

To create a RASTEP plant model the mapping of plant characteristics is essential. This task aims to give a general understanding of relevant plant design characteristics and of systems designed to mitigate severe accidents. Key plant parameters to include in the BBN are identified via systematic consideration of fission product transport. Systems and management strategies for accident mitigation are also considered. These are the same mapping procedures that should be part of performing a level 2 PSA and RASTEP results should be in agreement with Level 2 PSA results. Furthermore, "observables" are identified. This refers to variables indicating something about the status of the plant during a severe accident, typically these are instruments measuring the pressure, temperature, radiation or water level at certain locations.

2.4.4 Source term definition

The STERPS project defined source terms in a complex excel spread-sheet model depicting a set of pre-calculated source terms, which were associated with various end states of the BBN. This proved to work well in some cases, but was often perceived to be too inflexible.

For this reason, improving the source term definition functionality of RASTEP has been defined as one of the complex issues to be addressed in the NKS project. This includes the exploration of various approaches, including the improvement of the functionality of the STERPS simplified spreadsheet approach, but also looking at more sophisticated approaches, such as interfacing RASTEP with a deterministic source term prediction code, e.g., MELCOR, MAAP or ADAM. Such codes would use as input the characteristics of the accident initiator and the availability of various systems, and calculate the various phenomenological outcomes and their resulting radiological source terms for the alternative scenarios (with different probabilities).

2.4.4.1 Source term prediction

The output from RASTEP is a set of possible plant states that are ranked depending on probability. Each plant state has an associated source term. The source terms are derived from a set of pre-calculated plant specific source terms (from PSA level 2), which have been mapped to each final plant state when creating the RASTEP model. The source terms are mainly characterised by:

- Amount (Becquerel per radionuclide Xe-133, I-131, Te-132, Mo-99, Cs-137, Rb-88)
- Chemical composition (radionuclides included)
- Iodine specification (fractions of elemental, organic and aerosol iodine)

- Release height and thermal energy
- Division of the total time into 4 time spans which correspond to the occurrence of some major changes in the characteristics of the release (as modelled in MAAP)

In the use of the software, the user is prompted to answer questions about the accident scenario; these answers are entered as findings into the corresponding node in the BBN after which inference is performed. This changes the joint probability distribution of the network and hence the source term probabilities.

The questions are used to provide the network with information on the boundary conditions of the plant. This includes knowledge of parameters such as pressure, temperatures, water levels, radiation and system statuses etc. A set of alternative answers is presented to each question. The following are some examples of questions asked to the user:

- Is the containment oxygen level below 2 %?
- What is the long term pressure trend in the containment?
- Has the decision been made to manually vent the containment?
- Has the containment pressure exceeded the set point for automatic overpressure protection?
- Is the venting system 362 in operation?

Figure 3 and Figure 4 show the two main user interfaces of SPRINT, i.e., the question path defining the BBN status and the source term interface showing the outcome.

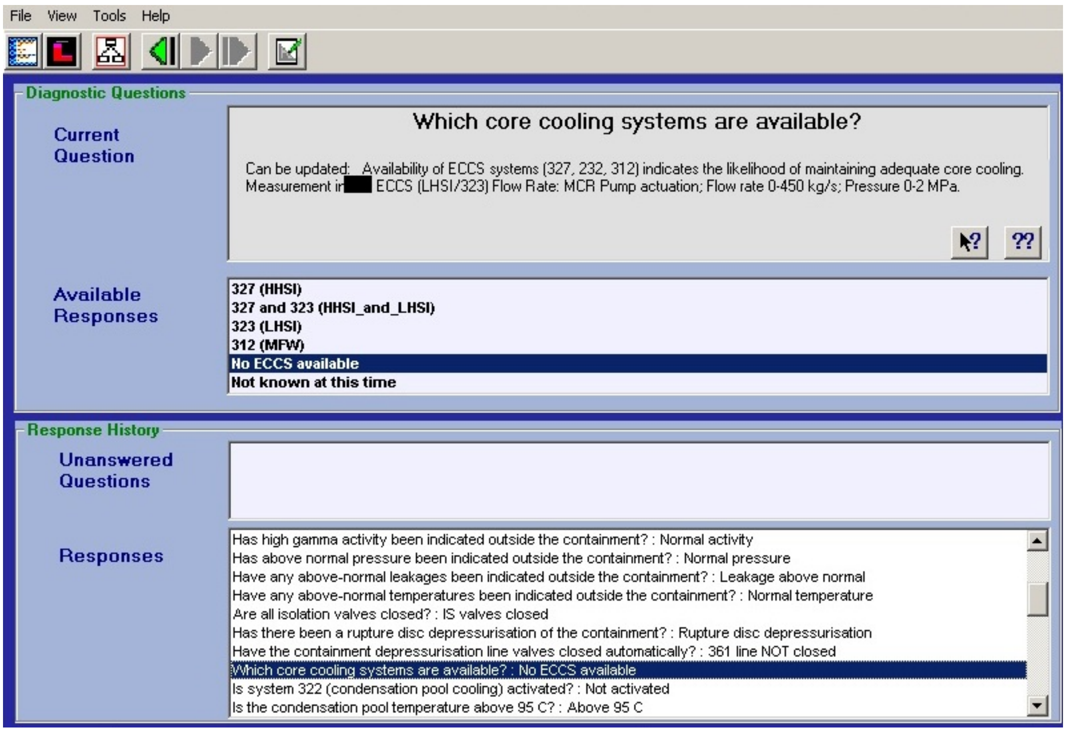

Figure 3. User interface of SPRINT

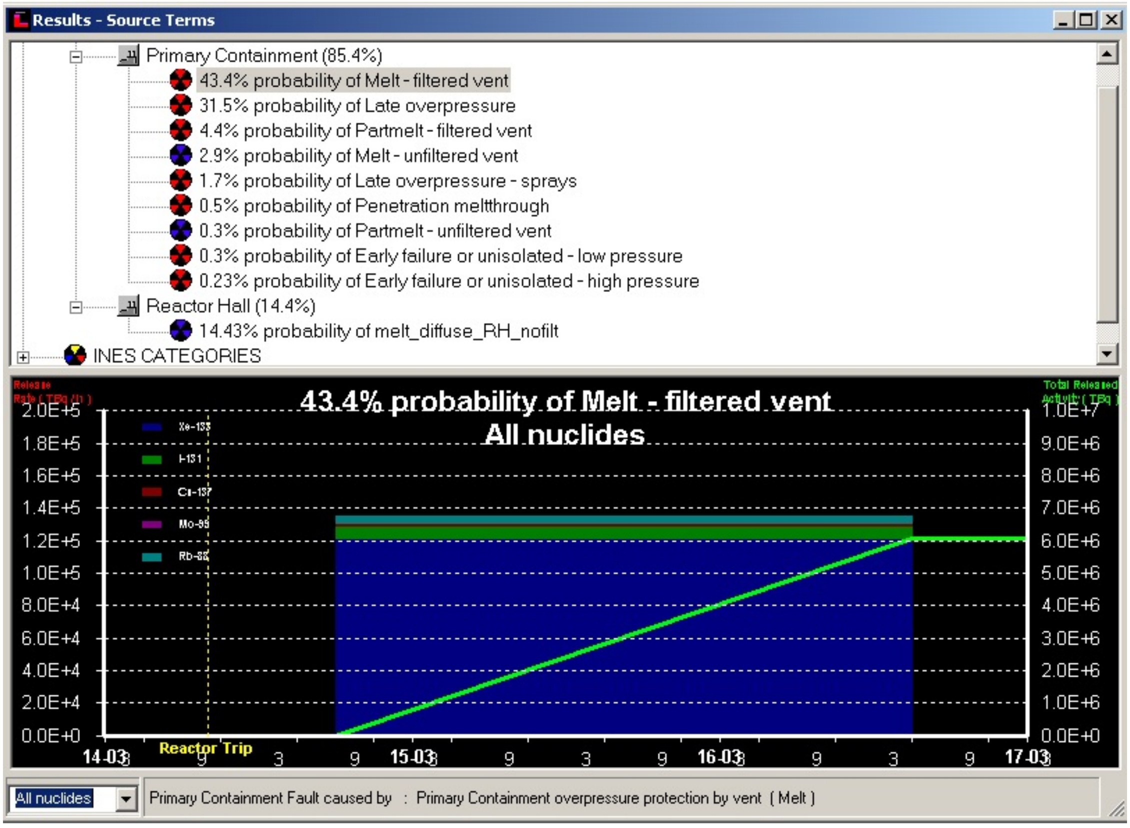

Figure 4. Presentation of source terms and their associated probabilities

2.5 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 [23].

The nodes in a Bayesian network are graphical representations of events that exist in real life and they are termed variables or states. Relations between such nodes are represented with and arc drawn between the nodes. If there is a causal relationship between two variables then the arc will be directional, directed from the cause variable to the effect variable. Figure 5 shows a Bayesian network where the variables X and Y are conditionally independent, given variable Z.

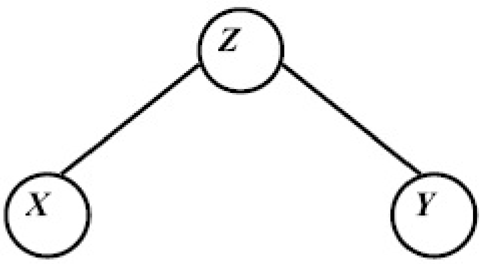

Figure 5. Simple Bayesian Network

All of the nodes in the network are associated with a probability distribution function which dimensions and definitions are dependent on the arcs that lead into the node. Bayesian networks can be considered as a special case of the more general class called graphical models where nodes represent random variables and the absence of arcs represents conditional independence assumptions between variables. In a Bayesian network, one node is used for each scalar variable, which may be discrete, continuous or propositional (true/false). Nodes that are connected are referred to as *parents* and *children*. In Figure 5 X and Y would be the children of Z. For instance, the arc between Z and X indicates that:

- Z causes X, or
- Z partially causes or predisposes X, or
- X is an imperfect observation of Z, or
- Z and X are functionally related, or
- Z and X are statistically correlated

There are 3 basic axioms in probability theory:

1. $0 \leq P(X) \leq 1$
2. $P(X) = 1$ if and only if X is certain
3. If X and Y are mutually exclusive, then $P(X \cup Y) = P(X) + P(Y)$

as well as a fundamental rule of probability calculus:

$$P(X,Y) = P(X|Y)P(Y) \qquad \text{Equation 1}$$

where P(X,Y) is the probability of the joint event $X \cap Y$.
This leads us to *Bayes' theorem* (hence the name Bayesian networks) that is used to compute the posterior probability ($P(X|Y)$) given the prior probability (P(X)) and the likelihood ($P(Y|X)$) that Y will be realized if X is true:

$$P(X|Y) = \frac{P(Y|X)P(X)}{P(Y)} \qquad \text{Equation 2}$$

X represents hypothesis and Y represents evidence. If X and Y are conditionally independent of each other then we can write the following:

$$P(X|Z,Y) = P(X|Z) \qquad \text{Equation 3}$$

Furthermore, Bayesian networks can be considered a knowledge base which explicitly represents beliefs about the elements included in the system and the relationships existing between these elements. The purpose of having such a knowledge base is to infer some belief or to draw conclusions about events in the system. One important property of a Bayesian network is that the graph can be thought of as representing the joint probability distribution for all the variables included. Considering the network as a whole, the conditional probabilities, the structure of the network and the joint probability distribution can be used to determine the likelihood of each node being in one of its states. Performing this procedure is called marginalisation and the ability to change these marginal probabilities is one of the great powers of belief calculations using Bayesian networks. The effects of observations propagate throughout the entire network and in every step the probabilities of a different neighbouring node are updated.

There is a vast body of literature on the subject of probability theory to which the reader is advised for more details on the mathematical framework of Bayesian theory.

2.5.1 Example Bayesian network

There are different modelling tools in order to create Bayesian network models. For RASTEP, Netica has been used and this section will demonstrate how a Bayesian network modelled in Netica may appear. The network presented in Figure 6 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 are the disease symptoms.

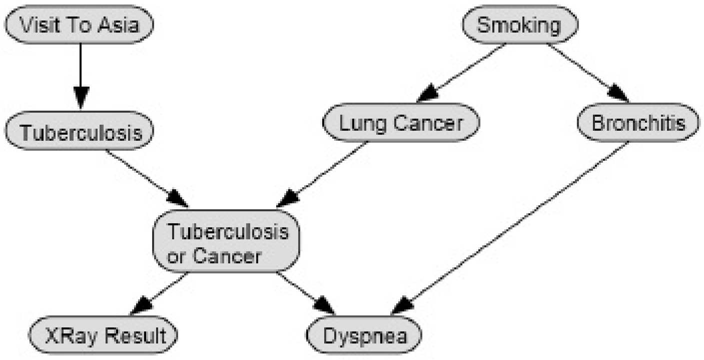

Figure 6. Network representing medical diagnosis example

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 for the node. The conditional probability tables increases 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 be based 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 conditional probability table for the node lunch cancer. Table 1 shows such a conditional probability table.

Table 1. Conditional probability table

Parent node(s)	**Child node: Lung cancer**	
Smoking	Lung cancer	No Lunc 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 have been made (generic case). The "Visit to Asia" and "Smoking" nodes include prior beliefs based on which the state probabilities in the other nodes are calculated. Figure 7 shows the generic case of the network.

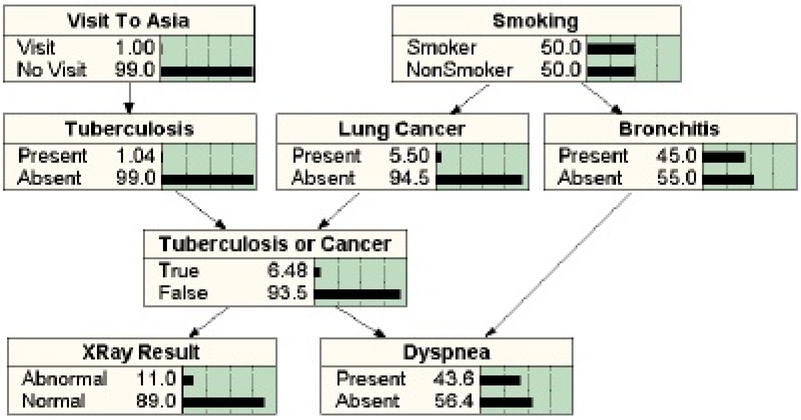

Figure 7. Generic case of the network

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 have 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 8 shows the network for this case.

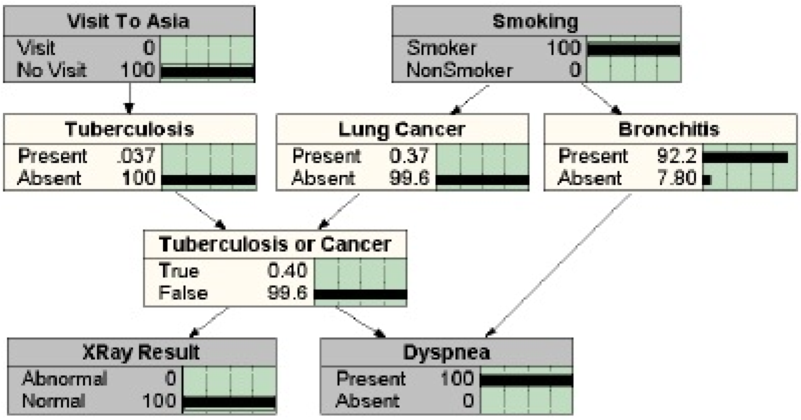

Figure 8. Specific case of the network

2.6 Basic BBN structure for Swedish BWR:s

Figure 9 gives a simplified overview of the Oskarshamn 3 BBN, showing the main blocks of the network and the most important interrelations within the block. Sub-networks are as far as possible structured in an order that reflects the accident progression, i.e., Initiating event – Core cooling – Residual heat removal – Fuel status – Reactor pressure vessel status – Containment status (Reactor/Turbine building status) – Source term. In the complete network, each of the sub-networks includes a number of nodes.

As indicated in the figure, the starting point of the network is the identification of the initiating event of the accident sequence. Thereafter, the probability of a number of different release paths is estimated based on the status of a number of fundamental blocks (fuel status, status of important safety systems, containment status, etc.), as well as of the success or failure of severe accident mitigation systems and of severe accident management actions.

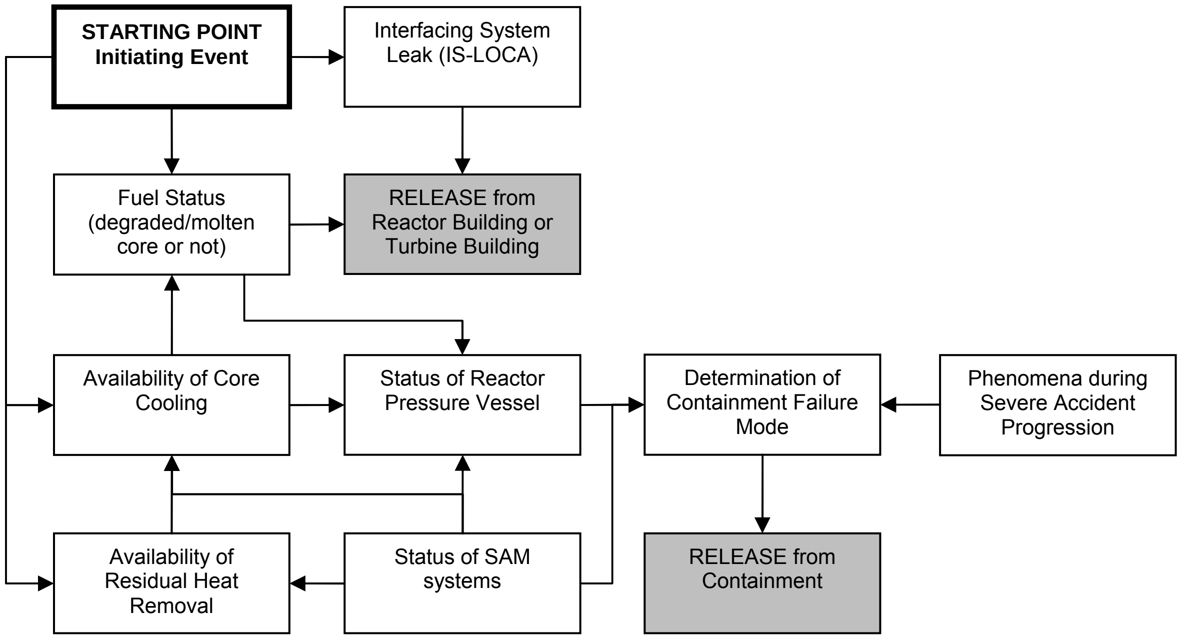

Figure 9 Basic BBN structure for Swedish BWR:s

Sub-networks are as far as possible structured in an order that reflects the accident progression. The following main blocks have been defined:

1. Initiating event
2. Core cooling
3. RHR
4. Fuel status
5. RPV/RCPB status
6. Containment status
7. Reactor building status
8. Turbine building status
9. Source terms

3. DEFINITION AND EVALUATION OF A DYNAMIC SOURCE TERM MODULE FOR USE WITHIN RASTEP: A FEASIBILITY STUDY

This chapter is largely based on a master thesis project performed by Per Alfheim at Scandpower in collaboration with Uppsala University, spring 2012 [33].

3.1 Introduction

As previously described RASTEP is based on two modules, each with its own fundamental purpose:

- One module that predicts states in the nuclear power plant, using a Bayesian Belief Network, in order to predict the probability of different source terms.
- One module that characterizes source terms (Chemical composition, amount, height and timing of the release)

In its current design, the source term information is stored in a spread sheet. These source terms have been pre-calculated in the deterministic code MAAP (Modular Accident Analysis Program) [10] during level 2 Probabilistic Safety Assessment (PSA) studies. This approach has proven functional in some cases but generally it is too static. Because of this there is a desire for increased functionality in the source term module. The purpose of the sub-project and thesis work performed as part of the first phase of the NKS-RASTEP project was to:

- Identify the need for improvement
- Evaluate possible ways of improving the RASTEP source term module

The initial mapping was directed towards defining the "meaning" of improvement and dynamics in terms of the RASTEP source term module i.e. determining in what ways enhancements can be made.

The work process included three parts:

- Identification of the need for improvement
- Identification of possibilities
- Evaluation of feasibility of possible solutions

The first part involved interviews and discussions with people involved in the development of RASTEP alongside with a literature study for deepened knowledge of the underlying methodologies (e.g. deterministic and probabilistic safety assessment). The second part involved processing of information acquired from literature and discussions in order to determine in what ways the source term module might be changed. Lastly, the third part of the work has been to evaluate, based on both the collected information and the opinions of the people involved, the suitability of the identified methods. Implementation of the identified methods was not part of the project.

3.2 Stating the problem

To understand why there is an interest in enhancing the source term module of RASTEP one need to understand how the source term prediction presently is carried out. The foundation of the current RASTEP source term module is the PSA level 2 for the analysed plant, where severe accident sequences have been modelled in accordance with state of the art practice. From the PSA, release categories are defined and associated with plant end-states. This causes an inherent static behaviour of RASTEP.

Consider an actual severe accident where RASTEP, in its present design, is supposed to be used for accident mitigation. If the predictions of RASTEP differ significantly from the progression of the actual observed accident, then they are practically meaningless since the source terms predicted by RASTEP are based on predefined sequences which have been assumed to be the most likely ones, with no possibility of changing the outcome afterwards, "on-the-fly".

Furthermore, modelling of accidents in PSA level 2 are performed in a highly conservative manner. Therefore, the time progression in the PSA may differ from that in real accident scenarios. Also, potential worst case scenarios might be omitted. With this in mind, it becomes obvious that RASTEP would benefit from the ability to "adapt" the source term prediction to the progression of an actual accident. While it naturally is impossible to make highly detailed predictions of the exact characteristics of any release in case of an accident, it is still desired that RASTEP be more dynamic/accurate.

Given the above mentioned conditions, the objective of this sub-project was to define and evaluate how the source term predictions can be made more dynamic (adaptive to actual accident progressions) as opposed to just basing it on predefined values from PSA level 2, which because of their static nature may be inadequate in the actual use of RASTEP.

The ultimate goal is to make RASTEP a more dynamic tool in terms of source term prediction so that it will be more effective and useful in the emergency preparedness organization. As a part of this development, this sub-project aims at providing a basis to proceed from when enhancing the predictive abilities of RASTEP.

3.3 Approaches to a dynamic source term module

The task of identifying how the source term module can be improved relates to a wide variety of subjects. Different methods have been considered and investigated. Some are not feasible in the short term but (as will be discussed later) they are still of importance and deserve to be covered within the scope of the sub-project. However, four main areas have been identified in total. In this section these areas are briefly described along with a discussion of how they are to be considered in order to contribute to the source term module.

As previously mentioned, not all of these methods are easily implemented, but since RASTEP will most likely continue to be developed over time, all of the methods have the potential to be used provided sufficient adaptation work is performed. Following in Section 3.4 is a review of the state-of-the-art methods while this section serves as an introduction. The methods that are considered to be the most feasible at the moment will be described in more detail in Section 3.5.

3.3.1 Linking RASTEP to a fast-running deterministic code

There are several integrated deterministic codes for plant diagnostics and prediction of source terms in the event of a severe accident, being used in PSA level 2 (e.g. MAAP/MELCOR). However, these codes may be inappropriate for use together with RASTEP for different reasons such as difficulties with creating an interface between the code and the plant data to be used as input, or time-consuming execution. There is also a variety of codes similar to the ones used in PSA level 2, but tailored for use in accident situations. Such codes are used in different constellations for accident management around the world.

When it comes to linking such a fast-running deterministic code with RASTEP, the idea is that the output from the Bayesian network model or plant data transferred from the NPP will be used as input to the code. In this sense, the source term prediction will be dynamic since the code execution will be performed "on-the-fly" as compared to in advance (static approach). As discussed in chapter 2.4, RASTEP currently uses source terms that are pre-calculated in MAAP, often using conservative assumptions.

There are several reasons for the increased general interest in using computerized tools for various safety related tasks. For instance the more extensive use of advanced computer technology associated with modernization projects at NPPs simplifies handling of station parameters. Another reason is that the external emergency preparedness organization needs more effective tools in order to complete their tasks. Several research and development projects have been carried out, including some European Commission (EC) projects, in order to develop computerized tools for more accurate source term prediction [21].

3.3.2 Using dynamic probabilistic safety assessment methods

Dynamic probabilistic safety assessment (DPSA) methods are concerned with probabilistic dynamics and dynamic reliability. Probabilistic dynamics concern dynamics (evolution of the physical variables e.g. during a severe accident) and their interactions with the random evolution of parameters (e.g. component behaviour or NPP operating states). Dynamic reliability methods aim to provide a framework for explicitly capturing the influence of time and process dynamics on scenarios. In summary, DPSA attempts to simulate the actual plant/operator response by addressing the mutual effect of the time-dependent plant physical variables, system configuration and operator actions over the course of an accident scenario.

It should be mentioned that there are no actual DPSA methods used in the safety analyses of nuclear power plants today. However, research has been ongoing during the last decades and in early 2012 a project proposal was sent to the EC in order to start up a joint research project aiming at creating an European framework for the use of DPSA methods. In the light of this project, the umbrella term "Integrated Deterministic/Probabilistic Safety Assessment" has been proposed in order to label the different existing DPSA methodologies. The EC project is intended to run over 4 years and some 20 different organisations from all over the world are involved [4].

One of the aims of DPSA is to make it possible to identify "worst case scenarios" and vulnerable events that have not been considered or have been foreseen in the traditional safety analysis. Therefore the envisioned use of DPSA methods, with respect to the RASTEP source term module, would be to provide more insight into the accident sequences that are considered in RASTEP and to the extent to which timing is of importance for the outcome of the sequences. This could possibly make possible a more accurate source term prediction.

Apart from identification of possible use of DPSA methods within the context of RASTEP, this report will serve as a mapping of the field of research with particular emphasis on methods considered relevant for RASTEP.

3.3.3 Expanding the Bayesian network to a dynamic Bayesian network

A dynamic Bayesian network (DBN) is a Bayesian Belief Network (BBN) that incorporates nodes that can change over time [29]. RASTEP is currently based on a regular, static Bayesian Belief Network (see Appendix B: *Bayesian Networks*). However, since the evolvement of a severe accident is very much a dynamic process it would be interesting to investigate how timing could be introduced into the Bayesian network. One issue that has been recognized with RASTEP is the fact that the BBN represents a snap-shot of the current situation given its current input status. Hence, it lacks memory of its previous states. Since a DBN accounts for the "stream" of observations used as input to the network this might be a way to introducing a time factor to the network.

The use of dynamic Bayesian networks for risk analysis in nuclear power plants has been successfully shown in [29] where a loss of feed water transient was modelled using a DBN linked with the deterministic code RELAP5.

3.3.4 Adjusting the existing source terms based on accident progression

This approach considers ways of being able to modify the pre-calculated source terms that are included in the spreadsheet based on the characteristics of the accident that is in progress. Thus, if the prediction of the Bayesian network does not correspond to the actual accident progression, it is of interest to provide means of altering the prediction in order to make it more realistic (hence more useful during the continued progress). More information of how this could be done is provided in Section 3.5.2.

3.4 Review of state-of-the-art methods

In this section a more extensive coverage of the methods described in Section 3.3 will be provided. Regarding DPSA methods the two approaches covered are considered the most comprehensive ones that could actually be beneficial for RASTEP in some sense.

3.4.1 DPSA / Dynamic probabilistic safety assessment

A mapping of the research field within dynamic probabilistic safety assessment has been made. This section describes the two methods considered most interesting from the point of view of RASTEP. As mentioned in Section 3.3.2, methodologies from DPSA will most likely be implemented in traditional nuclear safety analysis in the future. In this sense, they are of interest within the scope of RASTEP.

3.4.1.1 **Introduction**

Dynamic Probabilistic Safety Assessment (DPSA) is a family of methods which uses probabilistic and deterministic approaches that are tightly linked together. The reason for this is to be able to address aleatory uncertainties (stochastic aspects of a scenario) and epistemic uncertainties (modelling aspects) in a consistent way. DPSA methods are being developed because it was early realized that there are inherent limitations in the static, logical models used in traditional PSA when resolving time dependent interactions between:

- Physical phenomena
- Control logics
- Operator actions
- Equipment failures

These interactions may affect the order and timing of event sequences. PSA aims at quantifying probabilities of known threats, and is not suited for revealing unknown vulnerable sequences. Since PSA models are based on events that have been thoroughly simulated with deterministic plant simulations, after being identified by expert judgement, threats that are not part of the accident scenario simulations will remain unknown. In cases where the threat is known, there might be scenarios with significant timing factors and process-system feedback loops that are challenging to account for in the static ET/FT approach.

DPSA can provide additional help in order to reduce and quantify uncertainties efficiently [4].

Below is a description of the DPSA methods that are considered most comprehensive and possibly useful in view of RASTEP.

3.4.1.2 **Monte Carlo Dynamic Event Tree**

The Monte Carlo Dynamic Event Tree (MCDET) method is a combination of Monte Carlo simulation and dynamic event tree analysis [15]. The method makes possible an approximate treatment of continuous random transitions and also of discrete random transitions with many transition alternatives. Estimation of the approximation error is also provided.

Two characteristics can be attributed to a transition, "when" it occurs and "where to" it goes. Both cases may be deterministic, discrete and random, or continuous and random. The discrete and random "where" and/or "where to" are generally dealt with by dynamic event tree analysis. Continuous and random "where" and/or "where to" are dealt with by Monte Carlo simulation. Transitions of deterministic "when" (set point transitions) are handled by the general control module of the deterministic code (e.g. MELCOR). This module also contains the points in time/state where automatic actions of the safety systems are initiated (set points).

In the MCDET method, any scalar output quantity Y of some dynamic model h (with aleatory uncertainties) can be represented as Y=h(**V**) where V is the set of all stochastic variables involved. **V** is divided into two subsets, $\mathbf{V_d}$ and $\mathbf{V_s}$. $\mathbf{V_d}$ is the subset of selected discrete variables handled by event tree analysis and $\mathbf{V_s=V \backslash V_d}$ is the subset of all remaining variables, i.e. all continuous variables as well as the remaining discrete variables. The variables in $\mathbf{V_d}$ may be regarded as representing the discrete system states into which the aleatory transitions may take place. The variables in $\mathbf{V_s}$. may be regarded as representing the continuous aleatory times at which these transitions may occur.

The computational procedure of the MCDET approach may be regarded as consisting of two main parts:

- Generate a value vs. of the variables from subset $\mathbf{V_s}$. by Monte Carlo simulation.
- Perform the computer model runs with the value $\mathbf{V_s}$. for the variables from subset $\mathbf{V_s}$. and with all possible combinations of all discrete values of the variables from subset $\mathbf{V_d}$ (considered as paths of an event tree)

The MCDET is implemented as a stochastic module that may be executed together with some deterministic code. For each element of the Monte Carlo sample, a discrete dynamic event tree is generated and time histories of all dynamics variables along each path (together with the path probability) are computed. Each tree in the sample provides a conditional probability distribution. The mean distribution over all trees in the sample is the final result.

In summary, the MCDET method allows:

- To be connected as a module to dynamics codes such as MELCOR
- Consideration of many stochastic influences
- Consideration of continuous stochastic transitions via Monte Carlo methods
- Handling of different dependencies of stochastic elements (time, status, history of accident)
- Use of parallel processors for speed

Implementation of the MCDET method could be feasible both in terms of RASTEP and more general safety analysis tasks.

3.4.1.3 Genetic Algorithm Dynamic Probabilistic Safety Assessment

One of the crucial points in the development of DPSA is to apply an algorithm for efficient search and exploration of the practically infinite plant scenario (event) space in order to identify vulnerable scenarios. The space is infinite because all parameters are dependent on time. Discrete parameters, e.g. success or failure of systems, become continuous which causes the number of possible combinations of scenarios to increase infinitely. Hence, the need for an efficient search algorithm [30].

Exploration of the event space may be regarded as a search for vulnerability. This effectively means identifying feasible sequences of initiating events, component failures, plant control and safety systems operation that lead to failure of some safety barrier (e.g. fuel cladding, pressure vessel, containment etc.). In Genetic Algorithm Dynamic Probabilistic Safety Assessment (GA-DPSA) a risk goal (e.g. core damage, containment leakage) and the corresponding critical values of safety parameters (e.g. peak cladding temperature, containment pressure etc.) is used as a fitness function to guide the search process. Since a NPP is a very complex and nonlinear system, the "landscape" of the fitness function is also nonlinear, containing many local optima. Two typical tasks exist for the DPSA analysis:

- Identification of a worst case scenario with the most severe violation of safety limits. This corresponds to the global maxima of the fitness function.
- Identification of "failure domains" i.e. sub-domains in the plant scenario space. In a failure domain, the fitness function exceeds certain thresholds that normally are associated with the safety limit.

In the GA-DPSA approach a genetic algorithm (GA) is used to guide the exploration process. GA is a concept from biology to perform global optimization. The computational procedure is as follows. The GA fitness function **Y** is defined by critical values of system parameters (e.g. cladding temperature, containment pressure) that set the limits of the performance of safety barriers (cladding failure, fuel degradation, reactor pressure vessel failure and loss of containment integrity). To apply the method, one needs to adapt the NPPs event space and its parameters, referred to as **X**, in order to analyze typical accidents. Varying the parameters **X** provides exploration of the scenario space in order to find a set of values (target) that will result in some certain degree of core damage, $\mathbf{Y_{TAR}}$.

The GA-DPSA can, like other DPSA methods, have a scheduling module which is able to make decisions on branching of certain stochastic variables. The branching is based on the analysis of the history and instantaneous plant states. This means that, for instance, the failure probability of a valve or pump can be related to the local temperature and/or pressure.

The GA is a stochastic method, and therefore provides ways of estimating the probability $\mathbf{P(Y>Y_{TAR})}$ for which the search criterion (core damage degree) is satisfied ($\mathbf{Y>Y_{TAR}}$). In the search, the parameters are biased towards $\mathbf{Y>Y_{TAR}}$. Because of this the GA method can be regarded as performing adaptive biasing i.e. adaptive exploration of the event space.

It should be mentioned that definition of the GA parameters and the GA implementation schemes are experienced-based procedure, meaning that they must be carried out an iterative, manner using "rules of thumbs" or "educated guesses". This is important in order to increase completeness and comprehensiveness of the scenario space description and efficiency of the simulations. Because of this, further research is needed to develop recommendations regarding the implementation of GA for different classes of NPP accidents.

3.4.1.4 **Discussion**

The presented DPSA methods are both interesting and relevant to the ongoing development of nuclear safety analysis at a general level. Their specific usability to RASTEP would be to provide deeper insight into the accident sequences that are currently considered in the BBN model. They have a potential to provide means of adding more "nuances" and precision to the source term prediction. It should be noted however that the methods do not present a way of making "on-the-fly" calculations of source terms based on real plant data but rather a refinement of the pre-calculated source terms.

In looking at the potential usability of these methods, it is also important to consider that the methods of DPSA are still at a very early stage and not suitable at the moment to be used for further development of RASTEP. However, given the consensus in the nuclear safety community that DPSA methods would be extremely useful as a complement to traditional safety analysis it is probably only a matter of time before they might in fact be applicable. Therefore, in the future development of RASTEP, it is recommended to follow the ongoing development and re-investigate the feasibility of DPSA methods.

3.4.2 Computerized tools for source term assessment

3.4.2.1 **Mapping of tools**

This section provides a description of computerized tools with the main purpose of being used in accident situations for fast source term prediction. The scope of this review is based on previous studies by SSM [21] where computerized tools for source term prediction have been investigated. The main aim has been to identify tools suitable for use within RASTEP. The assessment is based on the following criteria:

- Maturity level of the tool (is the tool used today?)
- Possibility to link the tool to RASTEP

3.4.2.2 **ASTRID**

The ASTRID system (Assessment of Source Term for emergency response based on Installation Data) was developed within an EC project in the 5th framework programme during 2001-2004. It consists of two parts: (i) a methodology for analysing an ongoing accident in a light water reactor (LWR), (ii) a software tool to support this methodology.

The method aims at performing a thorough analysis of the plant status. It is based on the concept of safety barriers (i.e. fuel/cladding, reactor coolant pressure boundary, containment/filters). For each barrier critical safety functions that ensure the integrity of the barrier are defined. The next step is to identify the safety systems used for these functions. During an accident, the status of the barriers is considered intact, degraded, lost, or unknown. In the beginning of the work process, it is critical to determine to what extent the safety barriers have been degraded. Then potential source terms can be estimated through the prediction of possible scenarios.

The purpose of the tool is to monitor the evolvement of the accident, predict the behaviour of the reactor as well as to predict possible source terms. The results from the analysis are supposed to be used for accident mitigation measures such as decision making and input for dispersion calculations.

Project status
After the completion of the EC project, efforts have been made to develop ASTRID further. However, there seem to have been little success in this ambition. One of the developers,

Institut de radioprotection et de sûreté nucléaire (IRSN), drew the conclusion in 2008 that ASTRID could not be considered mature enough to be used [14]
GRS also further developed the tool and used it in emergency training for a German boiling water reactor (BWR); the development was cancelled however [19]. In order to use the code with regard to Swedish conditions further development would be needed and resources allocated to the maintenance of the code.

3.4.2.3 **ADAM**

ADAM (Accident Diagnostics, Analysis and Management) is a tool designed for both online accident diagnostics and offline accident simulation. ADAM is developed by Energy Research, Inc. (ERI) and financed mainly by the Swiss federal nuclear safety inspectorate (ENSI) [18]. ADAM consists of 4 modules:

- Pikett Ingenieur (ADAM-PI),
- Online Diagnostics (ADAM-D),
- Offline Accident Management and analysis (ADAM-A),
- Source Term Prediction ADAM-STEP.

ADAM-PI is unique to the version of ADAM that is being used at ENSI. It presents important process parameters and information regarding the status of the reactor and the containment. Furthermore it uses simplified conditions for diagnostics and the acquired information is presented graphically. Very little training is therefore required to use the module. ADAM-D provides more advanced means of diagnosis of the accident scenario.

A set of parameters is transferred to ADAM from the plant and then used to derive other parameters. Different safety margins are then evaluated such as the margin to core damage, containment break etc. The evolvement of events in the reactor, containment and reactor building can be monitored via alarms that are initiated when pre-defined threshold values are exceeded. ADAM-A makes possible a prognosis of the sequence of events as well as the source term via simulation of different accident scenarios for different boundary conditions. The result may be used as input to the ADAM-D module but this module is also suitable for training and educational purposes. The ADAM-STEP module is designed to make a fast prediction of the source term based on transferred plant parameters and user input.

Project status
ADAM is actively used at ENSI. ADAM-D is used for support in decision making by the authorities or at the affected power plant. The implementation of the ADAM system has streamlined the tasks of the emergency preparedness organisation and its possibilities to rapidly acquire a reliable overview of the plant status and possible accident scenarios. Apart from ENSI, the ADAM system is also implemented at the Slovakian and Hungarian authorities [21].

3.4.2.4 **SABINE**

SABINE (Source Term Assessment by Belief Network) was developed within the STERPS project and like ADAM it was developed by ERI with financing from ENSI. The purpose of SABINE was to link the BBN (the concept used in STERPS) with the ADAM system. The BBN uses available observable parameters and user input in order to derive the most likely combinations of boundary and initial conditions that may have caused the accident scenario at hand. Then the tool combines this set of possible initial conditions and remaining observable parameters and initiates the ADAM-A module that generates a list of possible source terms and their probabilities [31]. The BBN conceptualization for SABINE is demonstrated in Figure 10.

Project status
ENSI have abandoned the plans of using SABINE in their emergency preparedness organisation in favour of using the ADAM system (as discussed in Section 3.5.1.2). Because of this ERI has chosen not to develop the system further. However, in test cases the system was able to correctly diagnose the set of initial- and boundary conditions of the scenario [17].

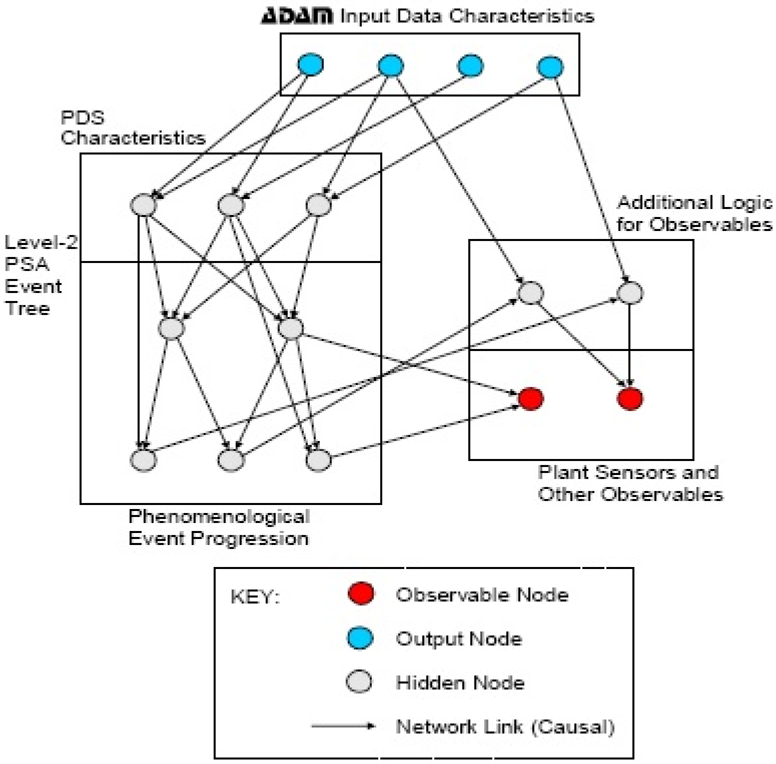

Figure 10. BBN Conceptualization for SABINE

3.4.2.5 **SESAME**

The French organisation IRSN has together with the French nuclear industry developed a methodology for diagnosis and prognosis of plant status and source terms. To support the methodology, the SESAME software tool was developed. Diagnosis of the plant status performed in SESAME is based on parameters that are transferred online from the plant. These are used by experts in order to evaluate critical safety functions and barriers. Different tools implemented in SESAME are then used to calculate a variety of parameters such as pipe break size (in case of LOCA), time until core uncovered and risk of hydrogen combustion. The prognosis is based on evaluation of the assumed availability of the safety systems in combination with extrapolation [16].

Project status
Not known; also no information available on IRSN homepage.

3.4.2.6 **TOUTEC/CRISALIDE**

The French power company EdF (Electricité de France) have developed a set of tools and simplified models called TOUTEC and CRISALIDE.

The tools aim to support the SESAME methodology developed together with IRSN (mentioned in chapter 3.4.2.5) and are aimed to be used in the national emergency preparedness organisation in Paris for diagnosis and prognosis during an accident. The tools have been developed for all French pressurized water reactors (PWR) [12]. The application of the code begins with the use of TOUTEC in order to complement the accident manual (currently used by EDF in accident situations) via simplified computational models and relations that can be used for unburdening and reduction of computational tasks in a critical situation. The most important parameters that are calculated are pipe break-sizes, time to core uncovered and risk of hydrogen combustion. After this stage the models in CRISTALIDE are used to provide more detailed calculations of some critical safety parameters (time to core uncovered, containment pressure, source term during the following 24 hours). With CRISALIDE one can account for different boundary conditions concerning the availability of safety systems as well as operator actions.

Project status
Not known; also no information available on IRSN homepage.

3.4.2.7 **MARS**

MARS (MAAP Accident Response system) is developed by the US company FAI (Fauske and Associates, LLC) who also developed the integrated severe accident code MAAP [5]. MARS is used for online, continuous surveillance of the plant status via interpretation of plant parameter values in order to detect deviations from the desired operational mode. In case of such a deviation, MARS shall diagnose the plants response to the event and follow the status of the plant in order to determine the evolvement and possible deterioration of the event. MARS shall also dynamically initiate MAAP with information from the diagnosis procedure. MAAP can then predict the plant response and its future state.

Project status
The MARS system is implemented and used at the Consejo de Seguridad Nuclear (CSN) in Spain which currently is the only user of the MARS software in the world. However, there are plans of implementing MARS at the NPPs in Oskarshamn, Sweden [6].

3.4.2.8 **CAMS**

CAMS (Computerized Accident Management System) is a tool that was developed within the OECD Halden Reactor Project (HRP) in order to provide support for decision making in emergency situations and during normal operation of NPPs [7]. The aim of the tool is to identify plant status, predict the evolvement of the accident and to provide support regarding emergency planning. Envisioned users of the tool are operators and the emergency preparedness organisation. As a part in the development of CAMS efforts were put into the integration of the MAAP code with the CAMS system. The envisioned structure for this purpose is shown in
Figure 11.

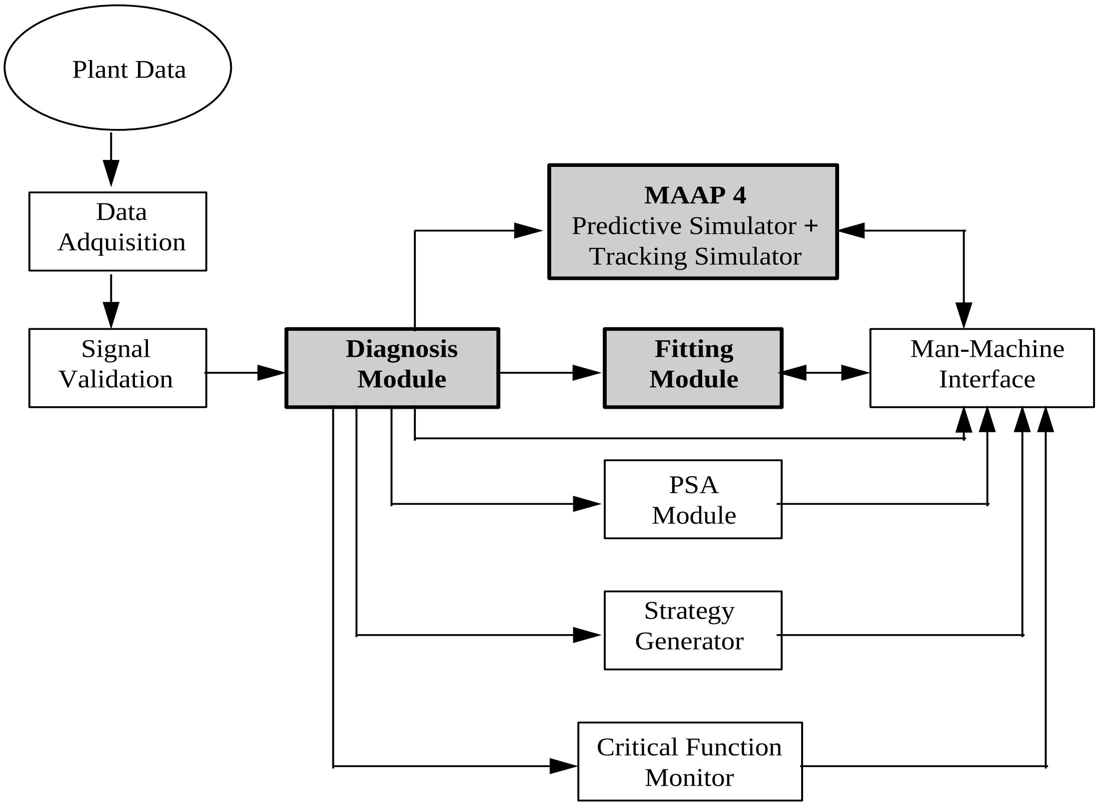

Figure 11. Structure for the use of MAAP with CAMS

The three main modules of the tool are the diagnosis module, the fitting module and the predictive simulator. The tracking simulator provides estimation of values that are not directly measured and calculates the initial values needed for the predictive simulator. The predictive simulator calculates the future evolution of the scenario (using the MAAP code). To include the MAAP code, the diagnosis and fitting modules were added to the original tool. The diagnosis module receives plant data which gives the user the ability to identify the status and conditions of the plant during the accident. The fitting module compares the plant state obtained from MAAP calculations with the information processed through the diagnosis module. In this way, the simulated scenario can be adjusted to the observed (real) data.

Project status
Investigations on how to implement MAAP with CAMS (as discussed above) were carried out in 2001-2003. It was concluded that this was possible and that CAMS would provide a good basis. However, the project aimed at developing such a tool was never initiated.

3.4.2.9 PLASMA

PLASMA (Plant Safety Monitoring Assessment System) was, like CAMS, developed within the OECD Halden Reactor Project. PLASMA is a computerized support system aimed at providing support to the control room during deviations from normal operation and during accidents [21]. It is mainly targeted at the operators in the control room. The system provides information to the operators regarding; (i) the current safety status of the plant, (ii) online monitoring of the critical safety function status, (iii) displays, in a computerized form, the emergency operation procedures (EOP) and those parameters which are referenced in the EOPs.

Project status
During 2000 the system was implemented at the simulator and Unit 1 and 2 of the Paks NPP in Hungary.

3.4.2.10 **Simplified version of MELCOR**

The United States Nuclear Regulatory Commission (NRC) initiated a project aimed at developing a fast-running version of the integrated severe accident analysis code MELCOR. However, this project was cancelled [9].

3.4.2.11 **Discussion**

Using the selection criteria presented in Section 3.4.2.1 MARS and ADAM are judged to be of potential relevance for the purposes of RASTEP. The reasons are the following:

- Both tools are actively used (MARS in Spain, ADAM in Switzerland, Slovakia and Hungary). This ensures continuous development and improvement of the tools.
- Both tools are suited for the task of being linked to RASTEP (see Section 3.5).
- The other codes considered are not as mature or have not been developed beyond a feasibility or pilot stage.

3.4.3 Dynamic Bayesian Networks

Events are usually not determined at a single point in time, but can be described through a set of sequential observations. The field of statistics dealing with this type of problem is generally known as time-series analysis [23]. Dynamic Bayesian networks (DBN) extend the standard Bayesian network formalism (for more information on Bayesian networks see Appendix B: *Bayesian Networks*) by providing an explicit discrete temporal dimension. This type of network represents a probability distribution over the possible histories of a process.

Consider a set of time-dependent state variables $X_1....X_n$ and a Bayesian network *N* constructed on basis of such variables. Then a dynamic Bayesian network is essentially a replication of *N* over two time-slices t and t + Δ, where Δ is the discretization step, with the addition of arcs that represents the transition model [8]. Figure 12 and Figure 13 illustrate the difference.

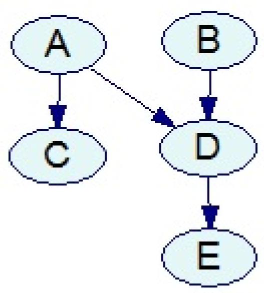

Figure 12. Simple Bayesian Network

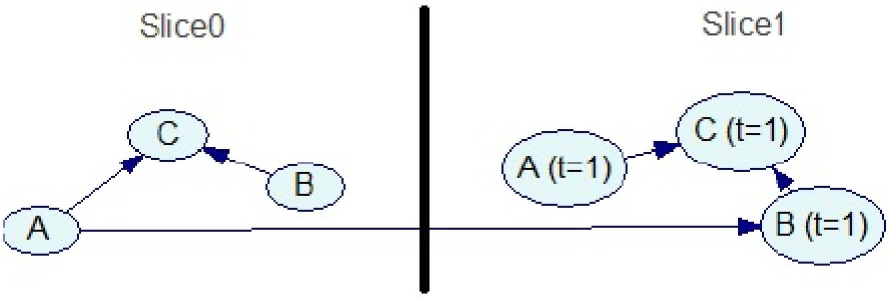

Figure 13. Dynamic Bayesian network expanded over two time-slices

In Figure 13, for any given slice, node C is completely determined by node A and B and node B is at any given slice dependent on the value of node A in the preceding slice. Arcs reaching between slices are referred to as inter-slice arcs or temporal arcs and they indicate the dependence of the nodes that are time dependent [29].

When it comes to the analysis of a dynamic Bayesian network there are different kinds of algorithms available. Let X_t be a set of variables at time t and $y_{a:b}$ a stream of observations from time point a to b. Then the following tasks can be performed:

- Filtering/monitoring: Computation of $P(X_t|Y_{0:t})$. In other words tracking the probability of the system state taking into account the stream of observations.
- Prediction: Computation of $P(X_{t+h}|y_{0:t})$ for some horizon h > 0. This means predicting a future state while taking into account the observations up to now.
- Smoothing: Computation of $P(X_{t-l}|y_{0:t})$ for any $l < t$ in other words estimating what happened l steps in the past given all the available observations

Another important task that could be performed using a dynamic Bayesian network is called *pruning*. This feature is based on the networks possibility to change its structure and connections over time.

Pruning of the network consists of some of the following actions:

- Deleting states from some node
- Removing the connection between two nodes
- Removing a node from the network

It should however be noted that this task is difficult to implement [23].

There are lots of successful demonstrations of the applicability of DBNs. For instance in fault diagnosis of automotive systems [24] and fault management of telecommunication systems [28]. Research aimed at supporting reliability engineers in the field of applying the DBN formalism is also ongoing, see for instance [8], [25]. Of particular interest for the scope of RASTEP is the work performed in [29] where a loss of feedwater transient has been modelled using a dynamic Bayesian network linked to the RELAP5 code. A 2-slice dynamic Bayesian network, illustrated in Figure 14, was used for this purpose.

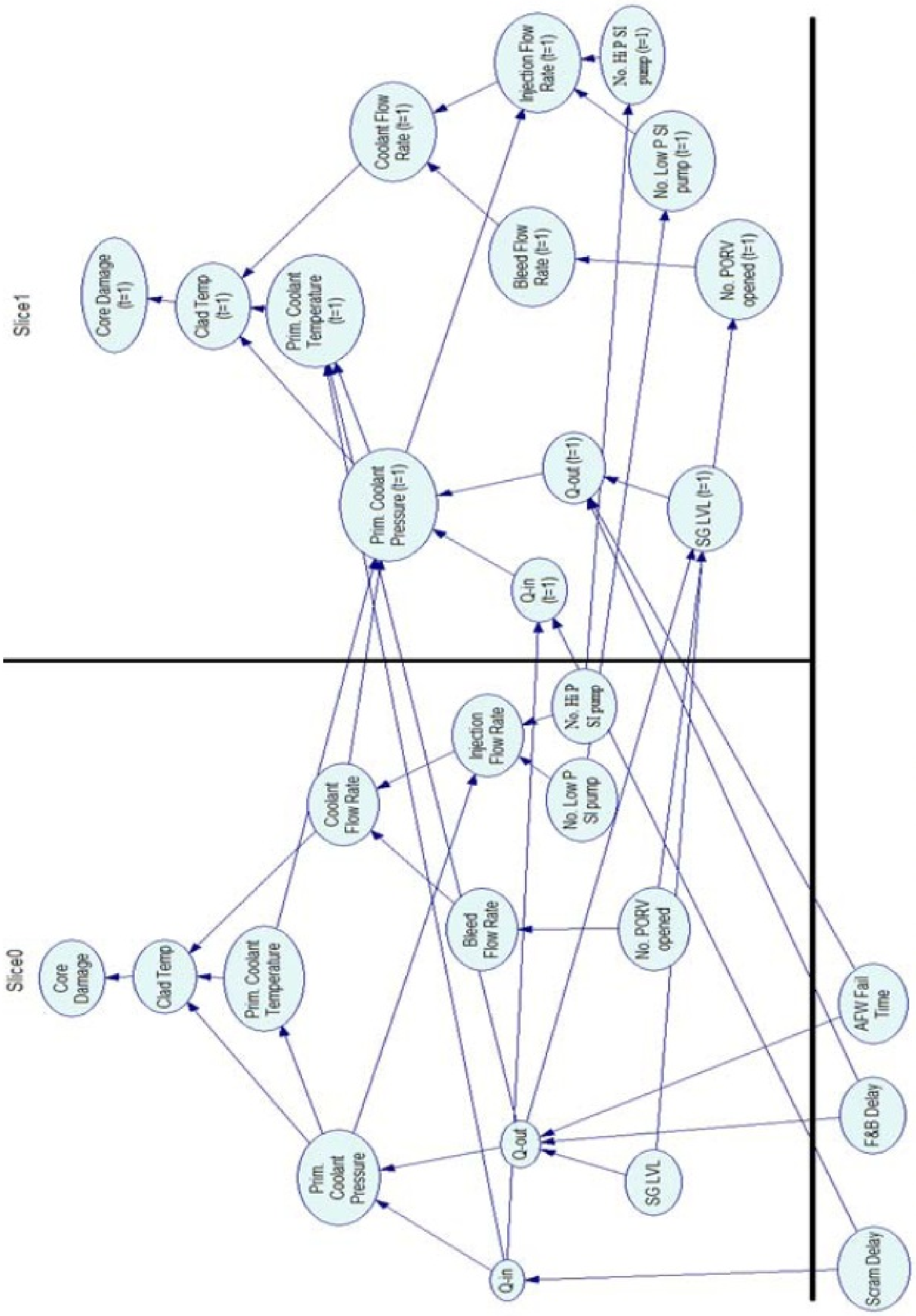

Figure 14. Dynamic Bayesian network model for analyzing loss of feed water scenario.

On a general level there are two main features that a DBN possibly could bring into RASTEP, i.e., memory and a more accurate source term prediction. However, it would be a daunting task to actually convert the static Bayesian network currently constituting the basis for RASTEP into a dynamic Bayesian network. Creating and validating one static model is a complex matter already. However, it may be possible to consider DBN techniques in the long-term development of RASTEP.

Using a 2-slice DBN could be a way of bringing memory into the model. Basically one only needs to duplicate the already existing static BBN for a second slice only that now dependencies are also allowed to come from the nodes in the previous slice. The crucial task will be to identify which nodes that will be given time-dependence and the main difficulty will probably lie in constructing the inter-slice conditional probability function (i.e. between slices). The intra-slice probability functions in the RASTEP BBN are well defined at this point. When creating a DBN it is also crucial not to introduce time-dependence between too many nodes as this will increase the complexity of the model drastically [20].

As discussed in Chapter 2, RASTEP uses observables i.e. observations of different plant parameters which are entered (manually or automatically) as findings in the nodes. Based on this information, inference is carried out and the most probable plant state based on the observed information will be determined. One of the problems identified with RASTEP is that the BBN only provides a "snapshot" of the current situation; hence there is no "memory". The DBN formalism accounts for the "stream" of observations i.e. the observed information as it is gathered over time. In combination with the inter-slice conditional probability tables a time component is in this way introduced into the model. A consequence of this is that the most likely plant state might be predicted more accurately and consequently the source term might also be predicted more accurately.

3.4.4 Discussion

All of the methods (as listed in Section 3.3) present a challenge and possibility for further research in their own right, and may therefore not be given an equal amount of attention within the scope of this sub-project. Therefore an assessment of the importance of each method has been performed. The outcome of the assessment is based on considerations of availability and functionality. Availability suggests that the method is actually accessible within reasonable effort. Regarding functionality it is also of importance that the method adds sufficient new functionality while still remaining accessible.

As discussed in Sections 3.4.1.4 and 3.4.3 both *DPSA methods* and the *DBN formalism* present very interesting abilities, but at the same time they do not match the availability/functionality criteria very well. At the present time, these methods are too immature and imply too complex tasks for implementation. *Linking RASTEP to a fast-running deterministic code* and providing means of *altering the pre-defined source terms based on accident progression* on the other hand fit the criteria better. As indicated in Section 3.4.2.11 there are two codes (MARS and ADAM) that suit the purposes of RASTEP and there are also ways of being able to alter the pre-defined source terms (see Section 3.5.2).

Based on the assessment, the methods are ranked in the following way according to relevance for application within RASTEP:

1. Linking RASTEP to a fast-running deterministic code
2. Adjusting the existing source terms based on accident progression
3. Using DPSA methods
4. Expanding the Bayesian network to a dynamic Bayesian network

In the next chapter the most promising methods in the short term (i.e. method 1 and 2) will be discussed in more detail. Method 3 and 4 will not be further discussed.

3.5 Selected methods

3.5.1 Linking RASTEP to a fast-running deterministic code

As discussed in Section 3.4.2.11 there are two software tools that are considered most promising from the point of view of RASTEP development, MARS, and ADAM. In this section the tools and their respective abilities will be described more in detail to provide an understanding for how they work and how they could be linked with RASTEP.

3.5.1.1 **MARS**

MARS uses data in the form of about 75 signals from the plant computer or by manual entry, to generate the necessary information to start the MAAP accident simulation [27]. The initialization is the foundation for the MARS tracker module. When using MARS for training purposes the plant data could be replaced by other tools which simulate the plant response, i.e. a control room simulator or other calculation tools. The incoming plant data (real or simulated) will go through two steps of processing, verification and conversion.

In the process of verification, the signals that are determined to be of poor quality will be discarded. In this case, the user will be notified and another method for determining a representative value will be used. For instance, if some parameter of the primary system that is required by MARS is discarded, the remaining parameters of the primary system will be used to estimate a representative value. Also, the user may manually input a value based on information that is available offline or from some other source (e.g. a BBN in the case of RASTEP)

In the initialization routine, the processed plant data is first used to estimate the approximate accident state, i.e., whether or not the core is uncovered, the core has been damaged, the vessel has failed etc. Identifying the time to such events is crucial because the availability of reliable instrumentation as well as the methods for initialization vary depending on the accident progression. As an example, initialization of the fuel parameters is different after core damage compared to initialization before core uncovered with no indication of previous fuel damage.

When the accident state has been (approximately) identified, values for several thousand parameters that are required by MARS will be calculated based on plant data.

<u>Tracking</u>
The purpose of the MARS tracking function is to make sure the computer simulation actually follows the plant behaviour. In that sense, the tracking function is the basis for the predictor function. The tracking function will at first perform an assessment of the symptoms of the accident in order to determine the plant status and the types of accident initiators.

Having this information as well as the evolving set of plant data, the tracker performs necessary calculations to guide the MAAP code in such a way that it tracks the behaviour of the plant. A comparison of the plant data to the tracker is performed over multiple time intervals in order to assess how well the simulation compares to the actual plant status. If there are differences, beyond thresholds specified by the user, the tracker corrector logic is applied. This means that the tracker simulation is modified as differences between the tracker simulations and actual plant data occur. The modifications performed vary from stopping a system, in the case where no information is known about the system, to stopping and re-initializing the simulation.

The tracking module also attempts to identify the potential root cause of the accident. For instance, if the tracker identifies a loss of coolant accident (LOCA), the information generated by the tracker about the break size (of the pipe) and elevation may be used to determine possible locations for the LOCA.

Predictors

The MARS predictors have been developed in order to predict the future plant state based on current plant status. The information generated by the tracker is used by the predictor to perform the necessary calculations. For instance, the predictions can be used to estimate the time before a major change in the accident state (core uncovered, core damage, reactor pressure vessel failure, or containment failure), efficiency of possible accident management strategies etc.

When the tracker has a sufficient understanding of the status of the plant, the predictors may be started automatically or manually. The calculations of the predictors can be performed assuming a wide variety of operator actions. The first predictor will perform its analysis based on the assumption that the operators use their training and follow the emergency operating procedures (EOP). The next predictor will analyze the plant in both the short and long term assuming no additional actions from the operators. The rest of the predictors may be used to analyze the effects of accident management guidelines or some other methods.

The predictors can provide information such as:

- Minimum injection flow rates for success
- Timing of vessel and containment failure
- Effects of operator actions
- Future accessibility of plant buildings based on predicted radiation levels

Instrumentation

Understanding and utilising available plant instrumentation values is crucial when it comes to managing an accident. One needs to obtain at least approximate values for those parameters which are difficult or impossible to know in detail. However, it is also very important to be able to discard instrumentation values that appear to be of poor quality (determined by MARS). MARS provides means of addressing these issues. The MARS tracker and predictor functions can provide approximate values and trends, based on the current plant configuration and postulated future plant states, for the variables that are impossible or hard to determine. The capability to analyze the available plant data in order to determine its validity is a key feature of MARS. If the confidence level for some variable is low, then the user will be notified and MARS will take appropriate steps in order to use representative values. Figure 15 shows the graphical user interface of MARS.

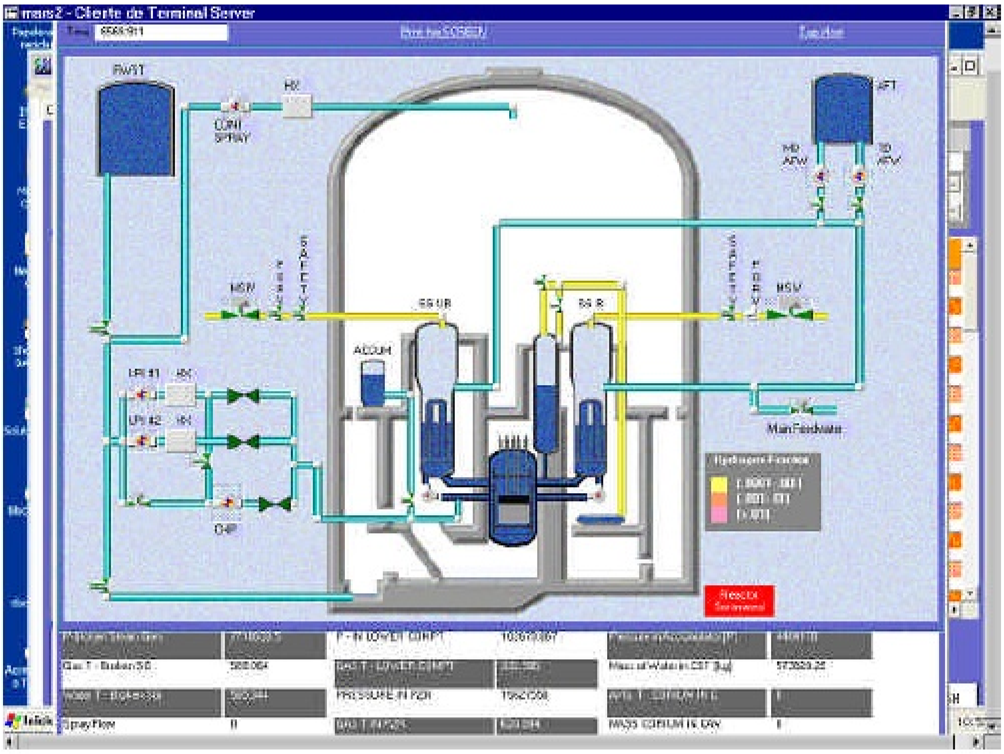

Figure 15. Example of MARS Graphical User Interface

Modelling of operator actions

Once the predictors are initialized, the MARS user may change the predictor simulations in order to model operator actions or additional plant accident management procedures. For instance, the user can model the loss of a given safety system to determine its effect on the overall accident progression.

3.5.1.2 ADAM

The accident management and analysis module of ADAM includes extensive mathematical models for the simulation of a large variety of accidents. The various mechanistic models included in ADAM have a sufficient level of detail to provide accurate results, while at the same time remaining simple enough to be fast-running [32].

Diagnostics module

In the diagnostics module of ADAM real-time signals corresponding to typically 20-30 plant parameters are transmitted to the regulatory authority and fed into the ADAM diagnostics system. A set of alarms are displayed in ADAM in order to monitor the state of the plant during the course of an event. Additional information is provided to monitor the reactor state, the reactor coolant system and the most probable accident conditions. This information provides insight into the state of the plant. In

Figure 16, the basic logic of the ADAM diagnostic module is shown. As can be seen in the figure, initialization and validation of plant signals is the starting point of the diagnostics module. Thereafter, identification of accident conditions and accident type will take place (e.g. LOCA of a given size or steam generator tube rupture etc).

The signals used for the accident identification depends on the plant type and typically include: pressure, water levels, and radiation levels inside the reactor coolant system, steam generators and/or the containment building.

After the accident identification, the diagnostics module will calculate all the thermodynamic properties of the reactor coolant system as well as of the containment. Then the reactor safety systems, the status of the emergency core cooling systems and the possibility of feed water injection will be evaluated. This process if followed by calculation of different safety margins. A margin is defined as the time remaining until a certain pre-specified condition occurs. Typical margins that are calculated include:

- Core uncovered
- Containment venting
- Containment failure
- Suppression pool saturation
- Suppression pool depletion
- Condensate storage tank water depletion
- Hydrogen combustion

Finally, the different end states and alarms of the reactor and the containment are identified based on an analysis of available online data.

<u>Accident management and analysis module</u>
This part of ADAM includes extensive mathematical models for simulation of a large set of accidents, including accidents that lead to reactor pressure vessel failure, molten core-concrete interaction, and containment pressurization.

The mechanistic models in ADAM include:

- Non-equilibrium, separated flow thermo-hydraulics
- Heat transfer to various steel and concrete structures
- Parametric fuel heat-up, meltdown, relocation and debris quenching
- Fission products release, transport through the reactor coolant system and containment into the environment
- Fission product revaporization
- Hydrogen and carbon oxide generation, transport and combustion
- Molten core-concrete interaction
- Emergency core cooling system and decay heat removal systems
- Radionuclide decay and transmutation for 60 risk dominant (predetermined) nuclides

<u>"What-if-analyses"</u>
Like MARS, ADAM also includes provisions for assessing the impact from operator actions. In this way accident management strategies and their consequences can be assessed. Typical procedural alternatives that are considered as part of the severe accident management guidelines (SAMG) include the actions listed in Table 2.

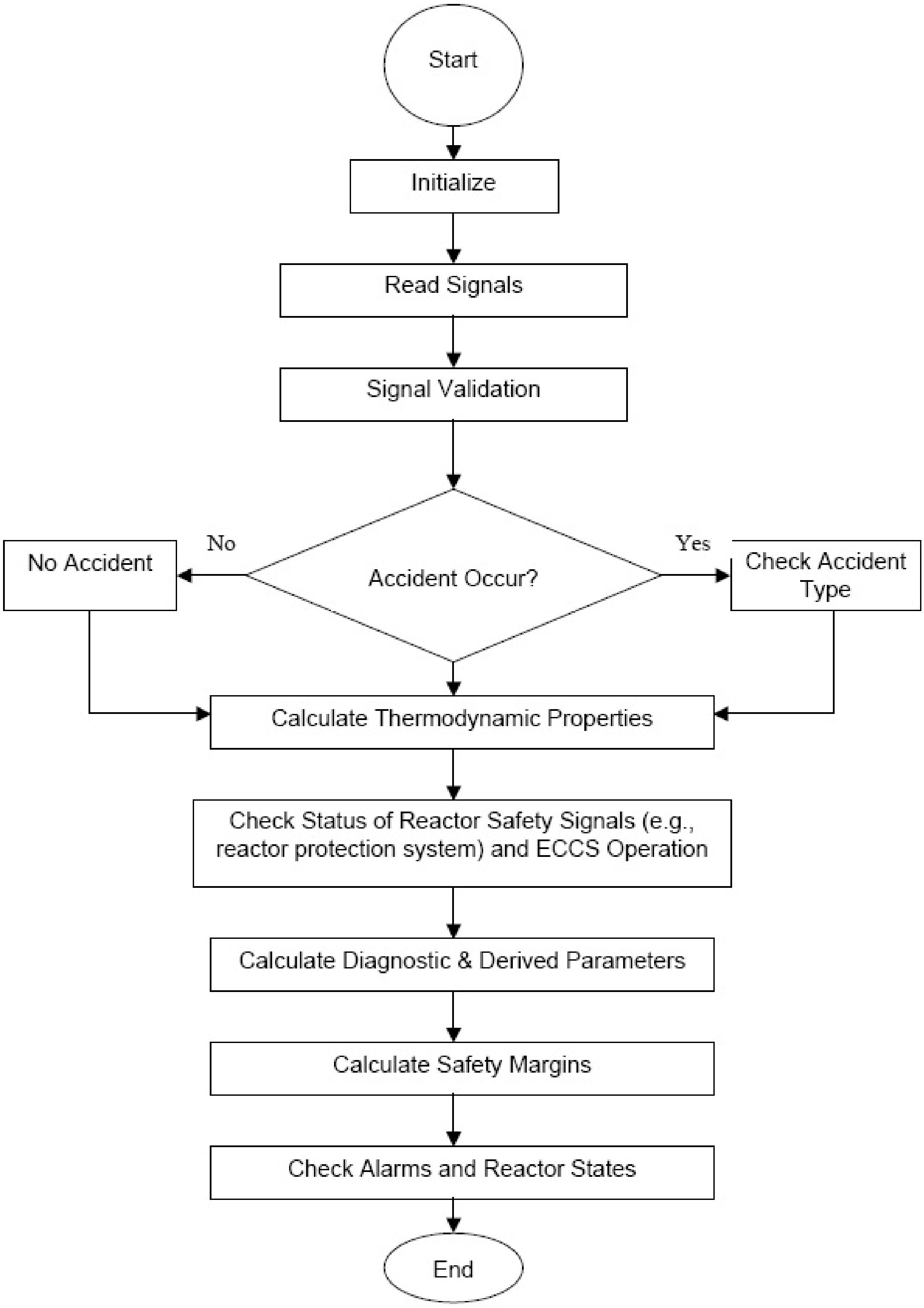

Figure 16. Schematics of the ADAM diagnostics module

Table 2. Typical SAMG procedural alternatives considered in ADAM

SAM Action	Accident phase	"What if" & "impact" issues addressed
Addition of water to a degraded core	In-vessel	– Time of water injection was changed – Rate of water addition was changed – Impact on metal oxidation – Impact on fission product release
Manual RCS depressurization	In-vessel	– Impact on core cooling (use of low pressure systems) and damage progression – Impact on hydrogen generation – Time of depressurization was changed
Isolation of steam generators following SGTR	In-vessel	– Time of diagnostics and leak detection changed – Time of isolation was changed – Impact on damage progression – Impact on environmental release
Addition of water to damaged steam generators	In-vessel	– Impact of quantity and rate of water addition – Impact of water addition on fission product releases
Recovery of containment isolation prior to core damage	In-vessel	– Detectability/diagnostics issues – Impact on damage progression – Impact on fission product release – Impact on hydrogen combustion
Flooding of lower containment region	Ex-vessel	– Impact on core debris cooling – Impact on hydrogen combustion – Impact on lower head failure – Impact on containment loading – Impact on fission product release and transport
Containment venting	Ex-vessel	– Manual vs. automatic vent actuation – Impact of time of venting on release of fission product and activity to environment – Can manual venting be used to control hydrogen combustion
Containment Heat Removal Systems	Ex-vessel	– Time of actuation/recovery and impact on containment integrity

3.5.1.3 **Code comparison**

MARS and ADAM serve the same purpose, i.e. to provide a way of evaluating the status of the NPP during an accident and make it possible to predict the evolvement of the accident as well as the source term. Both codes also provide the feature of modelling the impact of operator actions on the overall accident progression. The methodology is quite similar; collection of plant data is performed (automatically or manually) and the gathered information is used to provide an immediate diagnosis of the status of the plant. As more information becomes available, the tools initiate deterministic simulations that predict how the accident most likely will evolve. This is the approach adapted in most software tools aimed at diagnosing NPPs during accidents. The envisioned version of CAMS (see Section 3.4.2.8) that was planned to be linked with MAAP basically used the same approach.

The main difference between ADAM and MARS is the algorithm used to perform the actual calculations. ADAM uses an internally developed algorithm used only in the ADAM software. As mentioned in Section 3.5.1.2 this algorithm uses simplified mechanistic models to perform calculations of the accident scenario. According to ERI they are still good "enough" to produce valuable result which has been shown in benchmarking activities [32]. MARS on the other hand is based on the same algorithm as is used in the MAAP code, which has a long history of calculating plant states under all conditions from normal operation to severe accidents. This extensive MAAP experience is of course a strong feature, showing that the code is actively used and maintained. According to FAI [26]the computational power available today allows the MARS algorithm to be executed at high speed without simplifications introduced into the physical modelling.

On a general level however, both codes could be used as a part of RASTEP using the BBN (or plant signals) as input to initiate the respective tool (this is discussed in chapter 3.5.1.4).

3.5.1.4 **Interface between RASTEP and a deterministic code**

Using plant data directly as input
The most straight-forward approach of initiating either ADAM or MARS is by using live plant data transmitted directly from the NPP as input. This is the approach adapted by ENSI and CSN for instance. The advantage and power of the BBN approach is evident in situations where there is a lack of reliable information (i.e. plant data). In such situations the BBN is able to use the available information together with level 2 PSA input to determine the most likely plant state. In a situation where reliable plant data is continuously transferred from the NPP, this information could be used to initiate MARS or ADAM. Figure 17 demonstrates the schematics of using ADAM or MARS fed with plant data transferred directly from the NPP.

In the approach implemented by ENSI, ADAM is primarily used for source term prediction and an older and simpler way of estimating the source term is used for double-checking [21]. However, using the BBN as a mere "back-up" solution would not imply making full use of the BBNs powerful ability to predict the plant state. A clear distinction between ADAM/MARS and the BBN must be made since the former are deterministic tools and the latter a probabilistic tool. This means that to some extent, they represent different and complementary abilities. In order to use MARS/ADAM together in RASTEP as suggested in Figure 17, the box entitled "Evaluation" must be clearly defined. The BBN will probably be most useful in the beginning of the accident sequence in order to efficiently determine the plant state. The deterministic code is most useful later on, when more information is available, in order to simulate the evolvement of the accident scenario. A set of criteria that determines when "enough" information is available to start the deterministic simulations will most likely need to be defined.

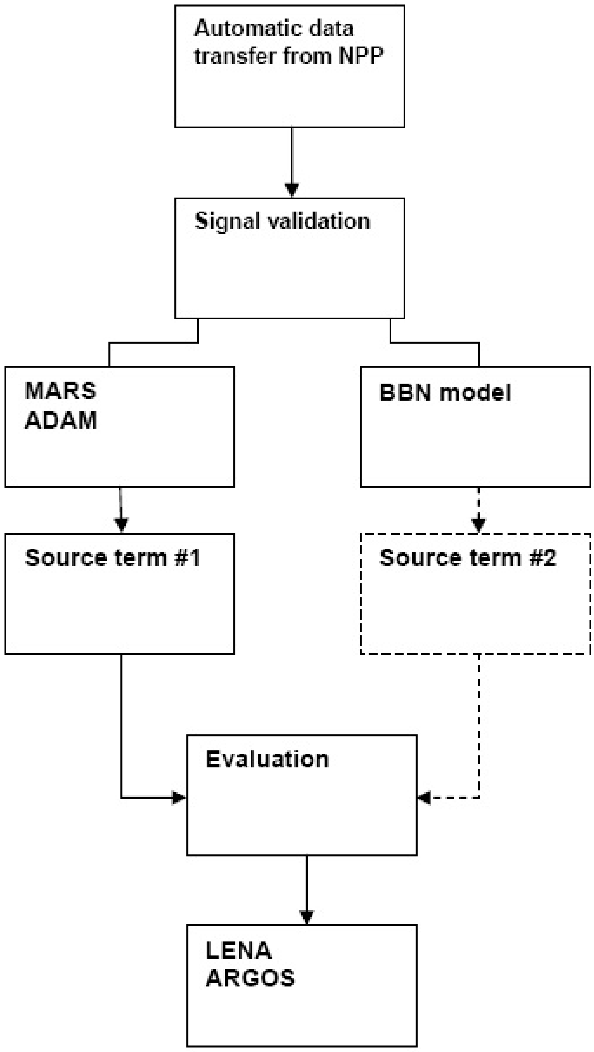

Figure 17. MARS/ADAM using plant data directly as input

Using the BBN to generate input

The other option of linking RASTEP to MARS or ADAM is to use the BBN to feed either tool with data. In this approach, the BBN will be assigned the role to diagnose the initial and boundary conditions of the accident scenario based upon plant observations. The RASTEP BBN approach is comprised of a set of sub-networks aimed at modelling the following:

- Initiating Event
- Core Cooling
- Residual Heat Removal
- Fuel Status
- Reactor Pressure Vessel Status
- Containment Status
- Auxiliary Building Status
- Secondary Circuit Status
- Source Term

In its current design the source term sub-network and its nodes is what might be considered the output from the network. By linking the BBN to MARS or ADAM a different approach would be used. Based on the observables, which might be considered input to the network, the BBN will be used to infer the initial and boundary conditions of the accident.

All of the sub-networks consist of two types of nodes; hidden and observable. Plant data is entered as observable nodes and after the BBN performs inference the states in the hidden nodes will assigned updated probabilities. For purposes of demonstration some of the nodes included in the RASTEP initiating event sub-network are described in Table 3.

Table 3. Sample nodes of sub-network Initiating Event

Node title	**Node name**	**Description**
H_INIT	Initiating Event	Contains the prior likelihood of the designated initiating events. These are Loss Of Coolant Accident (LOCA) based on the system requirement of system 327, IS LOCA, Loss of offsite power (TE), Loss of feedwater (TF) and transients (T other).
H_IE_LOCA	LOCA initiator (size)	Identification of LOCA size based on indicators.
CONT_GA	Containment gamma activity	A containment gamma activity that is "above setpoint" indicates a leak of primary coolant has occurred.
CONT_P	Drywell pressure	A pressure that is > 0.2 MPa indicates that a leak has occurred from a high pressure system into the containment.

The observable nodes (i.e. CONT_GA and CONT_P) in this case will receive data in the form of instrument readings for gamma activity and containment pressure respectively. Hidden nodes such as H_INIT and H_IE_LOCA on the other hand will tell us (based on the data entered as observables) if a LOCA has occurred as well as an indication of the size of the break. This type of information is what will be regarded as *output* from the network and sets the boundary conditions for MARS or ADAM.

No detailed mapping of the exact information needed to be extracted from the BBN has been performed. However, both codes need initial (i.e. the accident initiating event) conditions as well as plant parameters such as:

- Pressure
- Temperature
- Radiation levels
- System statuses

Such information is retrievable from the hidden nodes in the respective sub-networks (as indicated using Table 3 as example), and hence the BBN should be possible to use to initiate ADAM or MARS. Figure 18 shows the schematics of this approach.

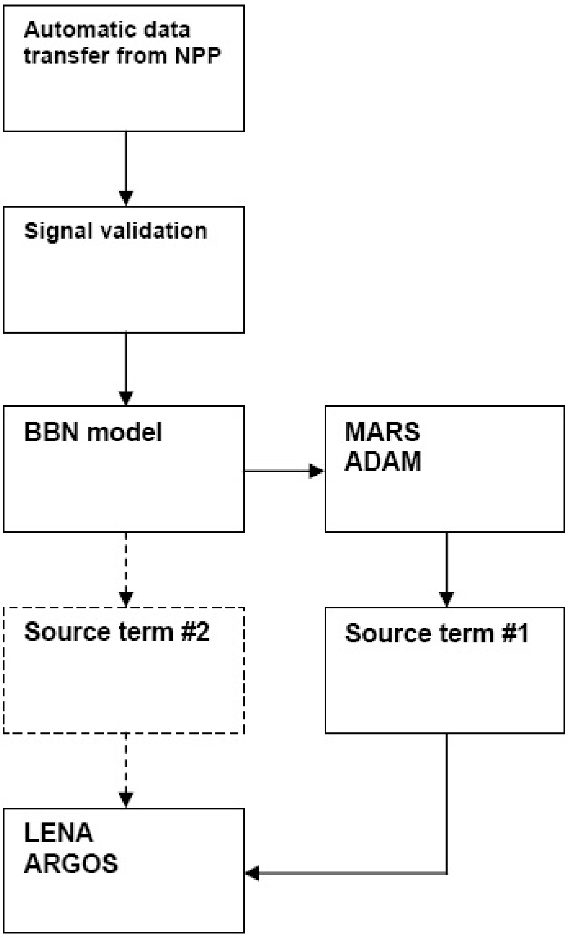

Figure 18. Using BBN generated input for MARS/ADAM

This way of generating input data to ADAM/MARS also raises issues that need to be further analysed. By using the BBN in this way one will clearly take advantage of the probabilistic abilities of the BBN i.e. to efficiently determine the plant state. However, just as when using plant data directly as input to ADAM/MARS, some criteria must determine when the deterministic code will be used instead of the pre-defined source terms. There is also the possibility to actually use plant data directly (from the start of the sequence) as inputs to ADAM/MARS and in this way obtain source term data for double-checking purposes. Another important aspect is how to combine information about the different plant states (as generated by the BBN) in order to obtain a reliable source term. The BBN will generate a spectrum of possible plant states (with different associated probabilities) and it probably not necessary to evaluate each of these with ADAM/MARS.

3.5.2 Adjusting the existing source terms based on accident progression

3.5.2.1 **Modification of pre-defined source terms**

This method aims at introducing the ability to modify the pre-defined source terms stored in the spread sheet model (as described in Section 2.4.4). This approach was also chosen by GRS in Germany in their further development of the original SPRINT software into the software tool QPRO (Quelltermsprognose) [22] introduced similar features.

- The fixed set of source terms applied in RASTEP is characterized by quantity and a division into a fixed number of time sections (often four).

The set of source terms is quite static. Thus, to change the quantity of the release, new simulations must be performed. On the other hand, the timing of the accident sequence can be more easily modified. This does not imply changing the actual time progression of the (pre-calculated) accident, as that would also require the execution of new simulations, but rather a way of adjusting the timing of the pre-defined accident sequence to fit the actual time progression of an analysed accident scenario. This could be done by letting the user enter a set of characteristic times such as:

- At what time did scram occur?
- At what time was the coolant level at the top of the core?
- At what time was damage in buildings observed?

With this information the time axis of the pre-defined accident scenario can be shifted in order to better fit the real timeline of accident progression..

3.5.2.2 **Identification of critical parameters**

A method similar to the one presented above (Section 3.5.2.1) but more extensive is the identification of "critical parameters". Critical meaning parameters that are of great importance for the outcome of the sequence and that might be conservatively modelled in the PSA or in the deterministic calculations, e.g. condensations pool temperature (or other parameters affecting condensation pool temperature). One would like to provide a means of being able to perform alterations of the source terms in the excel sheet (timing and magnitude) based on the deviation of such critical parameter values compared to the values used in the MAAP calculations that have generated the pre-defined source terms.

However, this approach is most likely not viable due to the complexity of the physical processes constituting an accident scenario. If one parameter is drastically changed in a given accident scenario, the entire outcome will probably be entirely different. The only way to find out in what way the source term will change is to perform a new simulation with the new accident conditions as input.

Another approach of a similar nature would be to perform a closer examination of the MAAP cases that have generated the source terms that now constitute the look-up table in the excel sheet. MAAP relies on two fundamental files, a *parameter file* and an *input file.* The parameter file determines the modelling of all the plant characteristics. This includes qualities such as material properties, geometric relationships, heat sinks etc. The parameter file is plant specific. The input file contains information on the accident sequence that is being modelled and differs between analysis cases. It contains information on the availability of different safety systems etc. Conservatism, as discussed above, can be considered to be "built-in" in the parameter file, because this is where all the information regarding the properties of different systems is specified. Consider the capacity of some Emergency Core Cooling System (ECCS) for instance. The flow rate is tested on a regular basis and might differ from time to time. If the DSA shows that the core will be sufficiently cooled at a flow rate below the interval measured when testing the system, this value will be specified in the MAAP parameter file.

A review of the MAAP parameter file could be performed in order to identify modelling parameters where conservatism is judged to be substantial. By performing relevant changes to these parameters one would obtain more of a "best estimate" parameter file (i.e. realistic) that could be used to re-execute the MAAP cases that are included in RASTEP. Parameters that are known to be conservatively modelled and that would imply a reasonable amount of effort to identify might include pump capacity, valve capacity, delay time, and rupture disc properties.

This approach would imply an extension of the current (Excel) look-up table in which each source term will be supplemented by an alternative accounting for modelling conservatisms in the "standard" MAAP calculations. Figure 19 illustrates this concept.

The reasoning behind this approach illustrates the complexity of problems of the RASTEP source term module but also the reason for the interest in DPSA methods. DSA and RASTEP have two different purposes; DSA is supposed to be performed in a conservative manner while the outcome of RASTEP is intended to be as realistic as possible. The above described method is effectively aiming at the same as DPSA. This particularly applies to the GA-DPSA method described in chapter 3.4.1.3. In that approach, the aim is to discover worst case scenarios and sub-domains of the plant scenario space where some safety limit is violated. In order to apply this method to actual accident PSA sequences one needs to closely examine the sequences in the PSA and identify parameters and states where timing is of crucial importance and will influence the outcome of the sequence. Effectively, the aim is to avoid cliff edge effects.. The same idea constitutes the reasoning behind the concept in Figure 19.

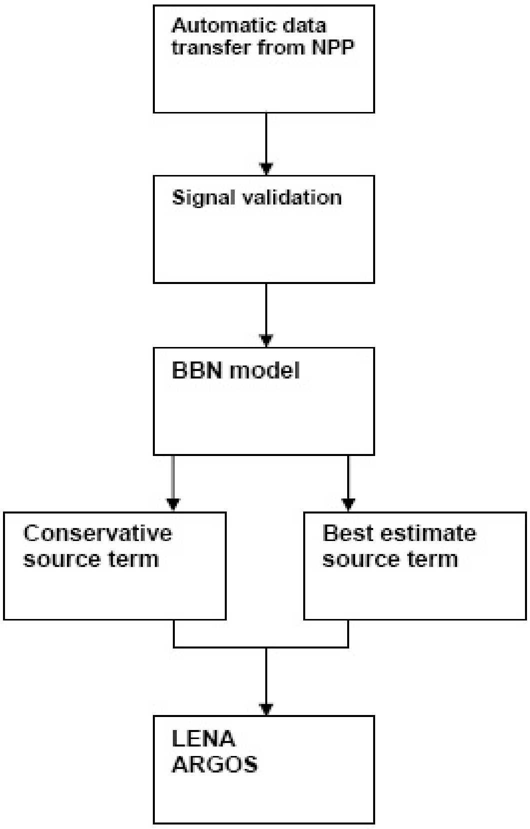

Figure 19. Conservative versus best estimate source term

3.6 Assessment of selected methods

3.6.1 Definition of a dynamic source term module

The mapping and reviewing activities performed within the sub-project have generated a set of criteria that should be associated with a dynamic source term module for use within RASTEP. The source term module should be:

1. *Realistic* – i.e. conservatism should be reduced
2. *Accurate* – i.e. live plant data shall be used as basis for the predictions
3. *Predictive* – i.e. able to evaluate "what-if" scenarios and their possible outcome
4. *Adaptable* – i.e. able to re-evaluate a given scenario by performing new calculations

The following sections will address the methods discussed in chapter 3.5 based on the above listed criteria, considering both usefulness and feasibility.

3.6.2 Linking RASTEP to a fast-running deterministic code

3.6.2.1 **Evaluation**

Considering the criteria in chapter 3.6.1 this method fulfils all with the exception of criterion 1 (realism). This is due to fact that the tools will still be based on plant models that constitutes the basis for the calculations. For instance in the case with MARS the plant model from MAAP and consequently the modelling strategy adapted there will be used. As discussed in chapter 3.5.2.2 this causes inherited conservatism. However, using ADAM or MARS still provide a great advantage in being able to perform "on-the-fly" calculations using live plant data. The ability of the respective tool to perform "what-if-analysis" e.g. to examine the influence of some operator action is also highly attractive.

3.6.2.2 **Feasibility**

Two things need to be considered when judging on the feasibility of this method; (i) Which tool to be used (ii) Which approach to use to generate input to the tool. When it comes to the choice of tool, MARS has the great advantage of being based on MAAP. There are already MAAP models for Swedish power plants (e.g. Oskarshamn) and consequently a large body of modelling competence is available. The developers of MAAP (FAI) regularly visit the Oskarshamn site, so feedback on the MARS system (if used) would be easily available. For ADAM on the other hand, plant specific models would have to be created from scratch. Due to licensing agreements there is no possibility to test the system for evaluation purposes. Thus, MARS seem to be the better choice.

Regarding the generation of input data, the easiest way would be to feed the tool directly with live plant data. At the moment, no system for transmission of plant signals (from the NPP to SSM) is in operation. However such a transmission system will most likely be implemented within the next 2-3 years [11]. Using the BBN to generate input data would utilise the BBNs ability to infer the most likely plant state, which is a powerful asset.

Even if systems for transmission of live plant data are implemented it could still be beneficial to use the BBN to feed ADAM or MARS with data as the BBN will be able to determine the initial and boundary conditions of the plant in an effective manner. However, to realise this approach a means of extracting the necessary information must be developed and implemented.

3.6.3 Adjusting the existing source terms based on accident progression

3.6.3.1 **Evaluation**

The method of introducing the ability to modify the source terms stored in the spread sheet model is probably the most easily accessible method in the short term. . However, this method does not address the complex issues discussed in chapter 3.5.2.2 and does not solve the issue with conservatism in the pre-defined source terms.

To tackle the inherent conservatism in the pre-defined source terms one would need to investigate the MAAP parameter files and re-perform the MAAP simulations in order to evaluate how they differ when changing parameter values that originally was conservatively modelled. This task is also relevant when considering linking RASTEP to MARS (see chapter 3.5.1.4). If MARS was to be used with RASTEP it could be interesting to use a best-estimate parameter file as a basis for the MAAP engine.

3.6.3.2 **Feasibility**

The method of modifying the pre-defined source terms is probably the most feasible considering the low level of complexity of the tasks needed to be performed (mapping of what functionality to add followed by Microsoft Excel programming).

Review of the MAAP parameter file aiming at identifying conservatively modelled parameters requires more effort. It is estimated that about 100-200 parameters need to be evaluated.

4. COMPARISON OF CODES

There is a need for understanding the problem complexity associated with connecting a dynamic source term predictor to RASTEP as well as the possibility of combining different codes serving different purposes. For example, it might be that for purposes of developing a robust and general source term, calculation run time not being an issue, MAAP could be the best alternative, whereas it will not serve the purpose of online calculations where the *actual source term* during an evolving accident sequence is to be captured. The opposite might be true of a simplified but fast running code.

Since both aspects might be crucial to a software like RASTEP, i.e., that is intended to support decision making in the very beginning of, as well as a bit into, an accidental scenario, the possibilities of using different codes in parallel, or even integrated, have to be elucidated.

Thus, changing from the current PSA level 2 based approach, with beforehand calculated (assumed typical/representative) source terms, to an approach based on dynamic calculation might not only be a matter of probabilistic vs. deterministic, but also one of changing from one code to another. Particularly interesting are differences in sequences used to draw qualitative conclusions, and sequences where the results are close to a threshold value resulting in large effects from small changes.

4.1 MAAP vs. MELCOR

The study will primarily be carried out as a comparison between existing MAAP calculations used in PSA and the same analysis cases calculated with MELCOR, since this is open source.

To simulate severe accidents and make comparisons with MAAP-results, a model of the power plant to be analyzed is needed. A MELCOR model of Oskarshamn 3 already exists, elaborated by KTH in cooperation with SSM and OKG, and is placed at the project's disposal on courtesy of the stakeholders. In exchange all the results produced will be provided to SSM. The MELCOR agreement also makes NRC entitled to all reports produced based on MELCOR results.

4.2 Definition of cases for MAAP-MELCOR comparison analysis

The study will be based on MAAP analysis cases available via the Level 2 PSA of Oskarshamn 3. Based on existing MAAP cases and the questions to be answered about the codes a set of cases to analyse with MELCOR have been worked out.

The criteria for selection of the cases are:

- The cases are already analysed by MAAP for Oskarshamn 3.
- The cases represent the two basic internal initiator types for the PSA level 2 events, i.e., Loss of Coolant Accidents (LOCA) and transients.
- The cases cover both low pressure vessel failure and high pressure vessel failure scenarios.
- The important in-vessel phenomena are present in the selected cases.
- The important ex-vessel phenomena are present in the selected cases.

Based on the above criteria two main cases (A1 and B1) are selected. Depending on the progress, two variations of these main cases (A2 and B2) may be analyzed to further supplement the study.

Case	Initiating event	Failed system/function	Available system/function	Sequence no. in O3 MAAP
A1	Transient (TSxD)	System 327, 323, 322, 362	System 314/ADS, system 358, 361/RI	7
B1	LOCA (Steam line break)	System 327, 323, 322, 362, 322-independent	System 314/ADS, system 358, 361/RI, manual depressurization by 362 after 20 hours	24
A2	Transient (TSxD)	System 327, 323, 322, 362, 314/ADS	System 358, 361/RI	7c
B2	LOCA (Steam line break)	System 327, 323, 322, 362	System 314/ADS, system 358, 361/RI, manual start of 322-independent after 2 hours	25

The following phenomena are identified as essential, and will be studied in the MELCOR simulations to give a comparison with the MAAP results.

Phenomenon	Quantity	Models being compared	Covered by cases
Core uncovered	Time to core uncovered	Thermal hydraulics	All
Fuel melt	Time to fuel melt	Thermal hydraulics Fuel heat-up modelling	All
Failure of core support structure	Time to core support structure failure	Fuel melt process Melt relocation model	All
	In-vessel pressure increase upon core support structure failure	Thermal hydraulics Metal-water reaction model	All
	Hydrogen generation upon core support structure failure	Metal-water reaction model	All
Vessel failure	Time to vessel failure	Vessel failure mechanism and criteria	All
	Mode of vessel failure (not a quantity)		All
	Containment pressure increase upon vessel failure	Melt relocation to cavity	All
	Ex-vessel hydrogen generation upon vessel failure	Melt relocation to cavity Corium-concrete interaction Metal-water reaction	All
Corium-concrete interaction	Hydrogen generation after vessel failure	CCI-model	All
	Concrete erosion depth vs. time (if available in MELCOR)	CCI-model	All
Ex-vessel coolability	Corium temperature vs. time	Corium cooling model	All
	Steam generation vs. time		All

Phenomenon	Quantity	Models being compared	Covered by cases
Containment failure	Time to containment failure	Combined	A1, A2
Effect of drywell spray	Containment pressure vs. time	Model for spray, droplet distribution, steam condensation etc	B2

5. SIGNAL VALIDATION

A critical aspect affecting the uncertainty in the estimates of a rapid source term prediction tool is the availability of correct measurement information from the monitored plant. This involves the validation of plant measurements (pressures, temperatures, ...) at the starting point, and during accident progression, to update the predictions of the BBN models. Since input of plant information via automatic signal transfer is an option, the NKS project involves the evaluation of different possibilities and aspects of signal validation.

Research on signal validation techniques for online instrument channel monitoring has been a central activity at IFE and at the Halden Reactor Project for the past fifteen years, where techniques and tools have been developed and tested in numerous applications, e.g., [3]. The typical application of these techniques has been during normal operation for the online monitoring of the calibration status of instrumentation. A research challenge in the proposed project would be to investigate the applicability of these techniques to a severe accident situation.

Signal validation in combination with the possibilities of sensitivity analysis applied to specific nodes would be a powerful tool, addressing questions like "What nodes are driving the result and what can be said about the validity of the information/observations defining the states of these nodes?".

A study aimed at evaluating the feasibility of using the IFE-COSS software PEANO for signal validation together with RASTEP has been outlined. However, since some fast running source term prediction codes, e.g. MARS (see Section 3.5.1.1), also provide functionality for signal validation, this might provide an alternative approach for exploring the issue.

Below, the preliminaries of the proposed joint venture with IFE Halden are outlined.

5.1 Background

5.1.1 Signal validation and rapid source term prediction

The discussion on implementing a module for signal validation into software like RASTEP was introduced by SSM in the, now closed, CAMS project. The idea has been adopted and concretized in the course of the RASTEP project.

IFE Halden has a long tradition of signal validation through the work of its department COSS (Computerized Operation Support Systems), and that the features of one of its most important software, PEANO, together with the acquired know-how of the development team speaks in forward of a successful joint venture.

5.1.2 IFE-COSS and PEANO

PEANO was developed by IFE-COSS as part of the OECD Halden Reactor Project. PEANO is a software for sensor condition monitoring with *real-time signal validation and reconstruction* as one featured application. The methodology is based on Fuzzy clustering and Neural network models where:

- Auto-Associative Neural Networks are used to extract information from interrelated measurements and generate estimates of expected measurement values.
- Possibilistic Pattern Classification is used to obtain a reliability estimate that indicates if the current process state is within the model limits.
- Estimates are used to detect sensor faults and generate reconstructed values.

One important task is that the network is trained in the target area of the assigned problem.

5.1.3 Expected functionality

In the RASTEP project, the main purpose of adding a module for signal validation to the software is:

1. The validation and filtering of information communicated from the in-plant computer into the Bayesian Belief Network (irrespective of whether the information is transferred automatically or entered manually).
   Together with functionality that allows instant sensitivity analysis of the BBN, it may be concluded to what extent the resulting predictions are affected by non-reliable/incorrect information. Nodes in the BBN that contain such information, given they are driving the result, may be eliminated or suppressed.
2. The possible re-construction of invalid signals.
   Re-construction of signals may be valuable in situations where only scarce information has been fed into the BBN, or the information is critical, and some underlying signal has been shown to be incorrect.

5.2 Aim and scope of the proposed study

The aim of the proposed work is to evaluate the feasibility of using PEANO, either the methodology in general or the code itself, together with RASTEP to enhance the production of reliable source term predictions.

Examples of issues that will be addressed are:

- How is the neural network trained with respect to severe accident scenarios?
- To what extent are "ordinary data" valid as a basis of experience?
- May one use simulators, e.g. MAAP, to produce data as a basis of experience to train the network?
- Is there a need of expanding the number of pre-calculated MAAP analysis cases used in RASTEP to serve the purpose of signal validation?
- Is there any conceptual obstacles in using reconstructed signals as input to a (probabilistic) tool that is designed to handle uncertain/incomplete information?
- What are the preliminary possibilities to integrate PEANO and RASTEP with respect to methodological, technical, and organizational aspects?

5.2.1 Delimitations

The sub-project will deal with technical and conceptual possibilities of applying methods for signal validation in the relevant range of application, i.e. real-time monitoring and analysis of severe accident scenarios.

The sensitivity of the BBN, as well as its importance for the usability of signal validation, is itself an interesting topic. However, only the conceptual aspects of BBN sensitivity will be highlighted in so far as they are crucial for the feasibility of signal validation. Technical aspects of BBN sensitivity are left out of scope.

6. CONCLUSIONS

Phase 1 of the NKS project has focused on methods to enhance the source term module of RASTEP. The results indicates that there are four main methods that could be used to enhance the source term module of RASTEP in different aspects. These are:

1. Linking RASTEP to a fast running deterministic code
2. Adjusting the existing source terms based on accident progression
3. Using DPSA methods
4. Extending the BBN to a dynamic Bayesian network (DBN)

All of these methods present challenges and would need to be further investigated in order to be implemented in RASTEP.

Methods 3 and 4 are not considered feasible in the short term due to the complexity associated with implementation of those methods.

Method 2 is probably the most easily accessible method altogether. However, it does not address the complex issues discussed in chapter 3.5.2.2 and does not meet the challenge with conservatisms in the pre-defined source terms. Yet, it is still relevant as a complement to method 1 as long as pre-defined source terms have to be used in the beginning of the scenario.

Method 1, i.e., linking RASTEP to a fast running deterministic code, is considered the most interesting one. This is due to the fact that implementation of this method would provide the most benefits for RASTEP and would allow the information gained from the BBN to be truly used dynamically in order to evaluate the evolvement of an accident scenario. Therefore it is concluded that:

- An investigation on how to implement method 1 should be performed.
- Ideas from method 2 should be considered as they might be useful in terms of complementing method 1.
- Methods 3 and 4 are not further explored, but might prove useful at a later stage.

It is also essential that further evaluation of fast running deterministic codes involve aspects of signal validation, which needs to be considered in planning activities dealing with signal validation. In addition to the topics dealt with in Chapters 3 to 5 it is suggested that efforts are made towards enhancing the BBN functionality, i.e., to lay the basis for sensitivity analysis and determination of complex CPT:s. This last part may only be partly achievable within the project budget; detailed planning will be done during phase 2.

Topics for phase 2 thus are suggested to be:

- Linking RASTEP to a fast running deterministic code (including Master Thesis #2)
- Further comparisons of codes
- Evaluation of the most promising way of implementing signal validation.
- Issues related to BBN functionality (probably only partly within phase 2):
    - BBN sensitivity (including Master Thesis #3)
    - Complex CPT:s (including Master Thesis #4)

Suggestions of how to proceed with these topics are gone through in Chapter 7.

7. FUTURE WORK – ACTIVITIES IN PHASE 2

7.1 Overview

Project phase 2 is planned to include the following sub-projects, each of which is further described in a short section below:

- Linking RASTEP to a fast running deterministic code
- Sensitivity wrt parameters and model structure
- Complex CPT:s
- MAAP vs. MELCOR
- Signal validation

7.2 Linking RASTEP to a fast running deterministic code

In order to link RASTEP to a fast running deterministic code further studies will be performed to determine the schematics of such a solution. There are in general two ways of using a deterministic code with RASTEP:

- *Parallel use*: The deterministic code is fed with data directly from the plant
- *Integrated use*: The deterministic code is fed with data generated by the BBN

In the case of *parallel use* the main issue that need to be addressed is how to interpret the aggregated information acquired from the BBN and the deterministic code? Typically the BBN will be better in the early stage of an accident (lack of information) and the deterministic code will be better later on when more reliable information is available.

In the case of *integrated use,* the strength of the BBN, i.e. to determine the plant status, will be used more distinctly. Some key questions that need to be addressed are:

- At what stage in the accident sequence will the source term calculated by the deterministic code be considered reliable? (The same consideration as in parallel use).
- Will it still be useful to use the deterministic code for "parallel" calculations using data directly from the plant as input?
- How is information from the different plant states to be combined in order to generate a reliable source term?
- How many source terms need to be calculated?

Apart from these issues it might also be considered whether to use a "best-estimate" MAAP parameter file (as discussed in section 3.5.2.2) as basis for the accident simulations (provided MARS is used as deterministic code).

- In order to investigate the suggested questions tests need to be performed using the actual deterministic code. Consequently it will also be necessary to investigate how to (technically) link the deterministic code to RASTEP.

In order to provide means of adjusting the pre-defined source terms (see chapter 3.5.2.1) investigations should be carried out to determine:

- What characteristic times that the user can enter (analysis of the included MAAP sequences will most likely be necessary).
- How to perform the required Microsoft Excel programming tasks.
- The above mentioned suggestions relate to the methods identified as most feasible. However, there are interesting possibilities for further studies relating to GA-DPSA (see chapter 3.4.1.3). To lay the foundation for application of the GA-DPSA method,

the accident sequences included in RASTEP need to be analysed with particular emphasis on parameters with crucial importance for the outcome of the sequence.

This would be the first step in order to apply the GA-DPSA method to the specific accident sequences included in RASTEP. Furthermore, the mathematical framework as well as the computer infrastructure necessary for execution of the method needs to be specified. Collaboration with KTH will be necessary for this task.

Finally, when evaluating the above mentioned alternatives, it is essential to take into account functionality of integrated signal validation.

7.3 Sensitivity wrt parameters and model structure

RASTEP is designed to support decisions in case of a severe accidental scenario. Hence, it is crucial that the predictions are as credible and reliable as possible, which in turn increases the requirements on validity, robustness, and transparency of the BBN.

As part of this sub-activity, a proposed Master Thesis project will analyse sensitivity and uncertainty regarding parameters as well as model structure for the BBN:s developed within the RASTEP project. It is also important to evaluate and suggest how parameters and model structure may optimize the updating procedure and the prediction of source terms.

Finally, the knowledge of node importance will be powerful combined with a method of determining the validity of the input. An important objective thus is to create a conceptual interface between the sensitivity analysis and the method for signal validation.

7.4 Complex CPT:s

The Bayesian network in RASTEP consists of nodes categorised based on the kind of information they process, which in turn determines how the node's conditional probability tables (CPT:s) are defined. Sometimes, the values are based on plant specific PSA:s. In other cases, qualitative information in terms of expert judgment, etc., is used. Developing such *complex* CPT:s is time consuming and the process, as well as the result, is difficult to verify.

As part of this sub-activity a proposed Master Thesis will develop a systematic, semi-quantitative method for determination of probabilities in a BBN in cases where mainly qualitative information is available. The method will address aspects such as prioritising information, uncertainties and applicability.

7.5 MAAP vs. MELCOR ctd.

In phase 1 a comparisons between MAAP and MELCOR has been defined and outlined. The next step will be to perform MELCOR simulations for some important accident sequences (see Section 4.2) and to analyze the results, including comparison with the corresponding MAAP results.

7.6 Signal validation

Since fast running source term prediction codes such as, e.g. MARS, are providing functionality for signal validation, this sub-activity will be resumed in January 2013 when the results of sub-project related to Linking RASTEP to a fast running deterministic code are at hand.

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Abstract

The project is connected to the development of RASTEP, a computerized source term prediction tool aimed at providing a basis for improving off-site emergency management. RASTEP uses Bayesian belief networks (BBN) to model severe accident progression in a nuclear power plant in combination with pre-calculated source terms (i.e., amount, timing, and pathway of released radio-nuclides). The output is a set of possible source terms with associated probabilities. In the NKS project, a number of complex issues associated with the integration of probabilistic and deterministic analyses are addressed. This includes issues related to the method for estimating source terms, signal validation, and sensitivity analysis. One major task within Phase 1 of the project addressed the problem of how to make the source term module flexible enough to give reliable and valid output throughout the accident scenario. Of the alternatives evaluated, it is recommended that RASTEP is connected to a fast running source term prediction code, e.g., MARS, with a possibility of updating source terms based on real-time observations.

Key words: BBN, Bayesian Belief Network, Severe Accidents, Source Terms, Level 2 PSA, Signal Validation

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