Contract No.: FIKR-CT2001-00139

Title: A Rapid Source Term Indicator Based on Plant Status for Use in Emergency Response

Introduction

Development of tools for use in rapid accident diagnosis and subsequent radiological source term forecasting at Nuclear Power Plants (NPPs) is increasingly desired by off-site emergency planning and response personnel across Europe. Availability of such analytical tools would enhance the efficiency in preparing accident response options and result in a more appropriate off-site response.

Recent developments in Decision Support Systems for emergency response, within the European Union and elsewhere, have been predominantly concerned with improvements of models for dispersion, radiological consequence assessment or countermeasures planning. An area which is not so well developed is the assessment of the plant status and the associated source term. Of immediate concern to the emergency response team and the incident controller is a timely estimate of the likely release of radioactivity to the environment. This should be based on the status of the plant and take account of the way in which the plant is likely to behave, either passively or as a result of operator actions. The STERPS (**S**ource **Term** Indicator Based on **P**lant **S**tatus) project is based on the premis that information on plant status can be deduced from key plant observations using a probabilistic based model.

Work performed in the current project demonstrates that the use of Bayesian Belief Networks (BBNs) show promise in meeting this requirement. This approach is very much focussed on providing direct support to the DSSNET, for use in off-site emergency management. As such it contributes directly to the stated objective for Key Action 2 (Nuclear Fission) in the area of radiological protection / off-site emergency management, which is: to improve the efficacy and coherence of off-site emergency management in Europe, including enhanced decision support tools, development of better methods for predicting releases to the environment based on plant status, and for data and information exchange.

Objectives

The aim of the STERPS project is to begin the development of a practical and effective probabilistic system for the rapid and early diagnosis of plant status and estimation of source terms from potential accident scenarios at NPPs. Within this remit, there are two main project objectives:

- To further develop the probabilistic approach to source term estimation (begun in FP4 under the auspices of RODOS) based on BBN analysis.
- To deliver a robust software tool to support the use of BBNs.

Results

Prototype software was developed as part of the FP4 RODOS project specifically to demonstrate the feasibility of the approach, based on a rigid structure specific to the

Westinghouse SNUPPS type PWR and populated with data based on the Sizewell 'B' PWR in the UK. The main emphasis of the current project is to enhance and extend the application capability and flexibility. This is achieved by removing all plant dependent data from the software executables and by the incorporation of additional observables, plant systems and potential Severe Accident Management (SAM) measures into the model file. This generic source term prediction module (consisting of the user interface, belief network engine and supporting model file) is subsequently referred to as the SPRINT (**S**ystem for the **PR**obabilistic **I**nference of **N**uclear power plant **T**ransients) application.

Work Package 1: Plant Specific Input Data for the development of a generic Belief Network

The key plant parameters for inclusion in the probabilistic model were identified through a systematic consideration of fission product transport and retention phenomena in the identified plant compartments. Plant systems, which are available for the mitigation of accidents, and currently implemented SAM strategies at the reference plants were also considered. This logic helped to capture the similarities and differences in design concepts and / or plant layouts that might impact on the probabilistic logic model.

Physical volumes and potential fission product transport pathways are relatively well understood and documented. It was found that the basic elements for all the reference plants could be included in one generic scheme. The main differences arose from the varying locations of the interfacing safety systems and the NSSS in PWR and BWR designs. Some secondary containment/confinement spaces are relatively complex and this may result in several alternative release pathways through the space, each with potentially different deposition/filtration mechanisms.

Transferring information on key plant observables that allow the user to infer the likely plant status and/or operability of plant systems is key to this approach. The observables to be included in the model were identified through a review of those plant state parameters likely to be reported (either automatically or manually) by the reference plants in the event of an accident.

Work Package 2: Development of Belief Networks and Supporting Software

The starting point for building a probabilistic-based model, to describe the fission product transport and release phenomena during an accident sequence, is a description of the logical relationships between various key plant parameters. These relationships are represented by a graphical network that consists of nodes and directed links between the nodes. In this case, the directed links usually represent a causal connection between two nodes. Beside the network structure itself, the Conditional Probability Tables (CPTs) supporting the network contain the data that define the strength of influence of a parent node on a daughter node. This is the essence of so-called Bayesian belief networks.

The concept of using belief networks to assess plant status is novel. It is useful to consider the relative advantages of both the deterministic and probabilistic approaches. In traditional plant analysis, the source term (or estimated release of radioactivity into the environment) is calculated on a deterministic basis by assuming the parameters that define the input conditions (based on initiating events and assumed systems response) and using the calculated event progression based on the accident phenomenology in the analytical models. When using the deterministic approach to source term prediction for emergency response, the same constraints apply; i.e. a single, deterministic scenario to describe the plant status must be agreed before any predictive source term calculation can start. This is appropriate where the plant status can be positively and uniquely identified, based on instrument readings, as is typically the case for design basis faults. However, and particularly in Beyond Design Basis conditions, this is not always the case: instrumentation may be operating beyond its' designated range (and so provide unreliable readings) or it may fail altogether. In order to make source term predictions in this situation, decisions about the reliability of conflicting instrument readings and suitable substitutions for any missing information must be made in 'real time' before any source term calculation can be carried out.

In the probabilistic model the 'input' nodes represent plant parameters / conditions that are observable, at least in principle, while others represent conditions that are intrinsically unobservable. When any observation is made, probabilistic inference is used to determine the implications that observation has for other nodes, both observable and unobservable. Therefore, the probabilistic element of these methods can overcome unknown or missing information by resorting to prior probabilities determined by the plant experts who set up the model. This overcomes the need for making data substitutions in a 'real time' stressful environment. One of the other major benefits of using probabilistic methods is that it alerts the user to the existence of alternative possible plant states, based on the known and unknown plant parameters. Thus, the outcome is typically a number of possible plant states each with an associated source term estimate and probability ranking.

The SPRINT approach uses the observations from the NPP to interrogate a database of pre-calculated source terms, typically compiled from existing plant specific analyses. The basis for this interrogation is the belief network model of plant behaviour. The end points of this model are mapped onto the database of pre-calculated source terms. This approach has the advantage of exploiting available plant analyses to provide approximate source term predictions very rapidly. However, the draw back is that it can only use the pre-existing source terms stored in the repository file. Hence, in this respect, it is not as flexible as a code generating source terms in real time. Customisation of the SPRINT application has been carried out for 5 PWR plants (of Westinghouse, KWU, and VVER design) and a single BWR (ABB Atom BWR-75).

Another important aspect of the STERPS programme is to demonstrate the practicality of interfacing a BBN model for plant state diagnosis to a fast running deterministic tool for real time accident progression analysis and source term prediction. This more dynamic approach has potential benefits but is technically more complex. A prototype tool has been developed for automated accident diagnosis and source term prediction that is based on the linking of a specific BBN approach (mimicing the event tree from a level 2 PSA) to the existing ADAM (Accident Diagnostics and Management) system. This approach has been named SABINE (Source Term Assessment by Belief Network).

Work Package 3: Verification of Belief Networks

The conclusions of the plant specific belief network verification task are:

- The BBN technique is a promising method for a quick diagnosis of accident progression and radioactive releases, based on actual plant parameter observations.
- The results of the plant specific networks which have been developed within this project show reasonable trends. However, early in an accident sequence the prognosis of further events is sometimes poor. This is not due to deficiencies of the method itself, but rather it points to more fundamental difficulties in monitoring plant conditions or in other cases the lack of resources to adequately explore existing information.
- The current plant specific networks developed for use with SPRINT are considered suitable for demonstration purposes, however direct application at specific plants or national crisis centres requires additional work. To reach this goal, additional efforts need to be expended in order to explore and to better implement the existing knowledge-base on accident progression behavior into plant specific networks.
- The SABINE plant specific network, developed for interfacing with a deterministic severe accident prediction model, demonstrates the feasibility of a coupled analysis combining the BBN inference capability with the deterministic accident progression models and real time source term calculations of more mechanistic severe accident codes.

The main objective of the formal verification study was to determine a methodology, and to develop the methods, for performing a mathematical analysis of the SPRINT belief networks. Due to the work performed in this study, the methods now exist to perform two different types of sensitivity study: sensitivities oriented to observables, allowing us to distinguish between more and less important user inputs, and sensitivities oriented to network parameters, allowing us to distinguish between more and less important values in the conditional probability tables.

For a full consideration on sensitivity, the results from the both types of sensitivity analysis should be considered, e.g. a case where an important input observation is associated with a highly sensitive parameter value should be identified as 'weak point' or critical point of the network for further consideration. Thus, the results of such sensitivity analysis depend strongly on both network parameter values and on a realistic context or case. These results help to identify parameters which are crucial to the diagnostic process and, thus, influence additional work to make them more robust. Sensitivity analysis was carried out for one output node in the generic model to illustrate the usefulness of the methodology and demonstrate the methods. The next step should be the application of the methodology for a full verification of a plant specific BBN. The main requirement for this would be a sufficiently large family of realistic cases (contexts).

Work Package 4: User Manual and Project Software

The final software deliverable is supported by a detailed explanatory user manual for the operation of the SPRINT source term package. Information is given on:

- Methodology of plant status diagnosis and source term estimation,
- Architecture, installation and operation of the SPRINT software,
- Modifications made during the development of reactor design specific models.

Implications

Development of tools for use in rapid accident diagnosis and subsequent radiological source term forecasting 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 result in a more appropriate off-site response.

Work performed in the current STERPS project demonstrates that the use of BBNs show promise in meeting this demand. This project is based on the premis that information on NPP plant status can be deduced from key plant observations using a probabilistic based model. One of the major benefits of using a probabilistic model (rather than a deterministic model) is that it alerts the user to the existence of alternative possible plant states based on the known and unknown plant observations. Thus the outcome is typically a number of possible alternative plant states each with an associated environmental source term and probability ranking.

A generic system entitled SPRINT has been developed to demonstrate the use of probabilistic methods for plant status diagnosis and source term estimation. Adaptation of SPRINT has been carried out for 6 reference plants. This systems is currently based on manual input of plant observations and judgments by an operator or analyst, from which a corresponding plant state is deduced by inference in the BBN. Conditional probabilities in the BBN embody expert judgment about the likely plant state corresponding to observations, and source terms are mapped to each final plant state based on pre-existing calculations performed for the specific NPPs. The SPRINT development is very much focussed on providing direct support to DSSNET. The software and the associated data files provide a highly customisable interface to powerful but affordable BBN software. The files on the STERPS CD represent the state of development at the end of this project - logically the next step is demonstrating the concept in an end user environment. It is planned to do this during 2004-5 in a demonstration project that is part of the much larger FP6 EURANOS Integrated Project.

The practicality of interfacing a BBN model for plant state diagnosis to a fast running deterministic tool for real time accident progression analysis and source term prediction has been demonstrated. This is based on the linking of a specific BBN approach (mimicing the event tree from a level 2 PSA) to an existing fast running accident analysis code. This approach has been named SABINE.

Co-ordinator: E Grindon (National Nuclear Corporation (NNC) Ltd, UK)

Partners: M.L. Ang (NNC Ltd, UK), M. Bednardski (Silesian University of Technology, P), S.C. Bubb (NNC Ltd, UK), A. Bujan (VUJE Trnava a.s., SK), W. Cholewa (Silesian University of Technology, P), W Frid (Royal Institute of Technology, SE), G Horvath (VEIKI Institute for Electric Power Research, HU), H. Kahlert (ERI Consulting & Co.), M Khatib-Rahbar (ERI Consulting & Co.), C.G. Kinniburgh (NNC Ltd, UK), M. Knochenhauer (Impera Consulting, SE), M Kulig (Enconet Consulting G.m.b.H., A), H. Löffler, (GRS m.b.H., D), B. Pütter (GRS m.b.H., D), J. Slaby (VUJE Trnava a.s., SK), M.L.F. Slootman (NRG, NL), M. Zavisca (ERI Consulting & Co.).