Conceptual Design of a Decision Support Tool for Severe Accident Management in Nuclear Power Plants

Marko Bohanec
Jožef Stefan Institute
Dept. of Knowledge Technologies
Jamova cesta 39
SI-1000 Ljubljana, Slovenia
marko.bohanec@ijs.si

Ivan Vrbanić, Ivica Bašić
APoSS
System Reliability and Safety Analyses
Repovec 23B
HR-49210 Zabok, Croatia
ivan.vrbanic@zg.t-com.hr
basic.ivica@kr.t-com.hr

Klemen Debelak, Luka Štrubelj
GEN energija, d.o.o.
Trg republike 3
SI-1000 Ljubljana, Slovenia
{klemen.debelak, luka.strubelj}@gen-energija.si

ABSTRACT

Safety is one of the major concerns connected with the operation of nuclear power plants. Severe accidents are very rare, but may cause very large consequences. The prevention and management of accidents requires carefully designed safety plans, guidelines and decision support tools. In this paper, we present a conceptual design of a decision support system for severe accident management. The system is aimed at providing essential information to the accident management team, in terms of the assessment of the damage state, prediction of possible progressions of the accident, and assessment of available management actions and their consequences. The system will employ components and models developed through probabilistic safety assessment and qualitative multi-criteria decision modeling. The software is being developed in the context of the EU H2020 project NARSIS. Its first prototype is expected in 2020.

Keywords

Nuclear Power Plant Safety, Severe Accident Management, Decision Support System, Probabilistic Safety Assessment.

1. INTRODUCTION

Electric energy is an indispensable resource in the modern world. Global electricity demand in 2018 increased by 4%, or 900 TWh, growing nearly twice as fast as the overall demand for energy [1]. About 11% of the world's electricity is generated by about 450 nuclear power plants (NPPs), and about 60 more are under construction [2]. NPPs provide high power output with relatively low operational costs and low impacts on the environment [3]. In the unlikely case of a severe accident, NPP may, however, cause significant and long-term consequences to people, the environment or the facility [4]. Those may include casualties, severe effects on individual's health, emitting radioactive isotopes to the environment, or melting the reactor core [5]. In spite of the remarkable reliability of current NPP safety procedures, the 2011 Fukushima Daiichi accident highlighted a number of challenging issues [6], among others the need (1) to seek out and act on new information about hazards, including combined natural events (such as the earthquake and tsunami in Fukushima), and (2) improve nuclear plant systems, resources, and training to enable effective responses to severe accidents.

Some of these challenges are addressed in an ongoing EU H2020 project NARSIS (*New Approach to Reactor Safety ImprovementS*) [7]. The project involves 18 partners from 9 European countries and aims to improve the current Probabilistic Safety Assessment (PSA) procedures by elements that take into account coincidental external events, vulnerability of the elements to complex aggressions, and better treatment of uncertainties through adoption of probabilistic framework for vulnerability curves and non-probabilistic approach to constraining the "expert judgments". PSA is, together with its deterministic counterpart, DSA, the main analytical method used for assessing nuclear safety, which allows practitioners to better understand the causes that can initiate nuclear accidents and to identify the most critical elements of the systems [7].

One of the goals of NARSIS is to develop a prototype Decision Support Tool for Severe Accident Management (hereafter called Severa). Severa will be aimed at supporting the NPP Technical Support Center (TSC), which is responsible for managing severe accidents through the assessment of the current situation, identifying and assessing available management actions and their consequences, selecting the actions, and monitoring the NPP response. In this stressful and complex decision situation, Severa will, based on measurements of operational parameters and using various insights or information from PSA models, assess the damage state of NPP barriers, predict possible progressions of the accident, and assess the available management actions. In this way, it will help the TSC to select the most appropriate management actions in a given situation, considering the likelihood of their successful implementation and possible impacts on the NPP and its environment.

Severa is currently under development, to be completed in 2020. In this paper, we present its conceptual design. We first describe the addressed decision problem. In section 3, we formulate the requirements for Severa and describe its intended use in a decision-making loop. In section 4, the main building blocks of Severa are proposed and described. Section 5 concludes the paper.

2. PROBLEM DESCRIPTION

A *severe accident* is characterized by circumstances that can cause severe core degradation, damage to the nuclear fuel, reactor pressure vessel and the NPP containment structures, possibly leading to a release of radioactivity to the environment. A severe accident may be initiated by internal (e.g., multiple equipment failures) or external (e.g. natural hazard) events, leading to NPP damage states that cannot be handled by normal operation procedures. In this case, a timely, accurate and well-justified management response is essential for preventing and mitigating the consequences of the event. For such situations, modern NPPs provide an extensive set of Severe Accident Management Guidelines (SAMGs), carefully designed and frequently reviewed written procedures for mitigating severe accidents.

SAMGs are meant to be activated in rare cases when critical parameters considerably exceed the normal operating values, for instance in the case of an unlikely accident scenario, under which the core exit temperature would exceed 650 °C. In such a case, the TSC would be formed, and the responsibility for accident management transferred from the operators in the control room to the TSC, so that the SAMGs would be used by the TSC members. The TSC would then be faced with the situation in which it has to diagnose the NPP status and recommend a sequence of management actions. Depending on the type of the accident, decisions may be time-critical and may need to be made in time windows measured in minutes after the accident.

The NPP is a complex system, and such would be decision making in real situations. At a very basic level, however, we consider that the NPP contains various barriers that prevent the emission from radioactive fuel and debris into the environment. The most important are three barriers: (1) Cladding of fuel in the Reactor Core (RC), (2) Reactor Coolant System (RCS), and (3) Containment. Accident management actions strive to prevent or minimize structural or operational damage to these barriers, for instance by identifying possible actions to decrease the core temperature or reactor pressure vessel and containment pressure. The main management strategies thus include actions such as (1) inject water into the steam generator, (2) depressurize the RCS, (3) inject water into the RCS and control containment conditions (pressure and temperature). The actual implementation of these strategies may vary depending on the current NPP status, available resources (e.g., external power supply), available equipment (e.g., mobile water pumps) and available staff. In a given situation, some of the actions may be unfeasible, may have negative effects on accident progression, or cannot resolve the problem within the required time constraints. All these factors, together with potentially severe consequences of wrong decisions, lead to an extremely complex decision problem that poses a large burden on the TSC team.

3. REQUIREMENTS FOR SEVERA

The objective of Severa is to provide an effective software tool for decision-support in the NPP severe accident management, relying on the PSA techniques and the current status of SAMGs. Severa will address the decision-analysis and decision-support needs of the TSC, once it has been formed and SAMGs have been activated. Severa is expected to support the following functions:

- Provide means to represent, store and monitor selected physical measurements of the NPP.
- Assess the current state of the vital NPP barriers: Core, RCS/Reactor Vessel, and Containment.
- Predict the future accident progression in the case that no action is undertaken by the TSC.
- Provide a list of possible management recovery strategies and courses of actions.
- Assess the applicability and feasibility of possible actions in the given situation.
- For each action: predict the consequences in terms of probability of the last barrier (containment) failure and estimated time window for failure.
- Evaluate and rank the feasible actions, providing recommendations for the TSC.

In the framework of NARSIS, only a prototype implementation of Severa is foreseen. It will be used mainly to demonstrate the feasibility of developing such a tool for actual NPPs and its potential for managing and reducing the residual risk from NPPs operation. It may also improve the training of TSC members. Due to the complexity of the decision problem, Severa will be further restricted to reasonably small, but relevant, subsets of system parameters and management actions. Severa's performance will be tuned and measured on the "Virtual NPP": an artificial, somewhat simplified, but sufficiently realistic NPP architecture, defined in the NARSIS project for research and testing purposes.

Severa is foreseen to be used in repeated decision-making cycles. Each cycle is expected to take about 10 to 20 minutes and will consist of the following main steps:

1. Monitor and assess the NPP status: relevant parameters (e.g., primary system or containment), and availability and performance of plant systems.
2. Collect the information concerning the current status of plant damage and accident progression; e.g., which barriers are challenged or may be soon, which functions are not available.
3. Identify possible alternatives (action courses); identified action courses should include the actions which are required by the SAMGs and should consider the availability of plant systems/functions and time window necessary for the action.
4. For each identified alternative establish the answers to the set of plant status questions, i.e., establish the input for the tool for each alternative action.
5. Quantify (assess, evaluate) each alternative using the models implemented in the tool.
6. Compare the alternatives based on the results from the tool and select the alternative to proceed with.
7. Implement the selected actions and observe plant's response.

4. CONCEPTUAL DESIGN

At the highest level, Severa will consist of two parts (Figure 1):

I. *Monitoring*: Observing and assessing the situation "as-is", without any human intervention.

II. *Management*: Facilitating the decision-analysis and decision-support activities of the TSC.

4.1 Monitoring

The objective of the monitoring part is to provide information about the current state of important NPP barriers and possible progressions of events. It consists of three modules: Input Parameters (IP), Diagnostic Module, and Prognostic Module.

4.1.1 Input Parameters

This module provides means to store and manage a time series of physical parameters, which are measured at critical operational points in the NPP:

- CET: Core Exit Thermocouples [°C]
- SGL: Steam Generator Level [m]
- RPVL: Reactor Pressure Vessel Level [%]
- Prcs: Reactor Coolant System Pressure [MPa]
- Pcont: Containment Pressure [MPa]
- Tcont: Containment Temperature [°C]
- H2: Hydrogen concentration [%]

Each parameter is represented in terms of a numerical measurement (e.g., SGL = 8.9 m, H2 = 0.21 %) and color-coded severity level (green, yellow, orange, red). The latter is determined by a discretization of the former. The orange and red levels denote a severe situation and generally require the activation of SAMGs.

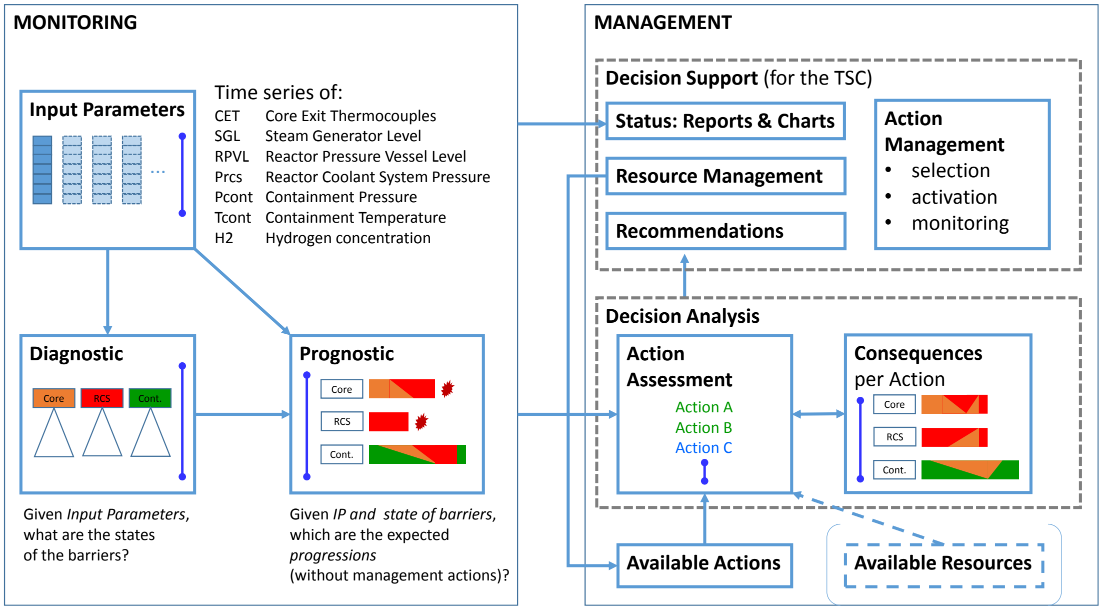

Figure 1: Building blocks of Severa. The symbol indicates the current time.

Even though these parameters can be measured continuously, a typical time granulation is expected to be about 10 to 20 minutes, corresponding to the expected time cycle of using the system.

4.1.2 Diagnostic Module

The purpose of this module is to determine the status of each of the three barriers: Core, RCS (vessel) and Containment. Each barrier has an individual set of possible states. For instance, states of the Core are OX (cladding oxidation), CD (core damage), EX (corium ex-vessel) or OK. For comprehensibility, the states are color-coded, too.

Barrier states are determined from the values of IP. They form a time series, which corresponds to the granularity of the IP, i.e., each set of barrier states corresponds to each IP vector.

Employed methods: Basic information about determining barrier states will be provided in terms of tables and/or decision trees. In Severa, states will be determined using DEX hierarchical models [9]: one model for each barrier. Decision rules in the DEX models will facilitate probabilistic assessment of states [9], for instance in cases of missing or inaccurate IP measurements.

4.1.3 Prognostic Module

Given the IP and outcomes of the Diagnostic Module, the purpose of the prognostic module is to predict the future progression of the barrier states if no management actions are undertaken. The progression information include:

- Identification of the future state(s) for each barrier.
- Estimation of time until the next state change.
- Time series of probabilistic distributions of predicted future states.

Methods: A combination of PSA modelling methods, primarily event trees and probabilistic assessment models [10].

4.2 Management

The management part of Severa will provide decision-analysis and decision-support functionality for the TSC. The main purpose is to inform the TSC about the current state of the NPP and to give advice about possible recovery actions and their consequences.

The management part of the system is particularly concerned with *management actions*. These represent possible decision alternatives, which are at the TSC's disposal at a given situation and time frame. The TSC has to consider the possible actions and assess their feasibility and consequences with respect to the integrity of the barriers. The TSC may select an action (possibly leading to a series of actions), allocate the necessary resources, and monitor the progress while the action is being carried out.

To help performing these activities, Severa will provide databases of available actions and resources, and two modules, called Decision Analysis Module and Decision Support Module.

4.2.1 Database of Available Actions

This database provides a collection of possible recovery actions envisioned in the SAMGs. Only a subset of actions may be feasible in a given situation. Thus, each action has associated a number of properties (or even models), aimed at determining:

- *Applicability* (relevance, entry conditions): Is the action relevant for recovering the current situation?
- *Feasibility*: Is the action feasible given the current IP, barrier states, available resources and available time for recovery?
- Possible *impacts* and *consequences* in terms of probability of barrier (containment) failure in a given time window.

4.2.2 Database of Available Resources

This is a foreseen collection of resources available for carrying out any actions, including material resources (electric energy supply, availability of pumps and generators, etc.) and human resources. The availability of resources primarily influences the feasibility, completion time and expected success of actions. When an action is activated, the corresponding resources are allocated or spent.

Because resources are usually vast and very specific to individual NPPs, this database will not be implemented explicitly in the Severa prototype; the availability of resources will be modelled implicitly through manual input to the decision analysis module.

4.2.3 Decision Analysis Module

Among all the available management actions, only a few of them may actually be relevant in a given situation. The purpose of the Decision Analysis Module is to:

- Identify actions that are applicable and feasible in the current situation.
- Predict possible consequences in terms of probability of barrier failure and assessed time window for failure.
- Assess the quality of actions according to multiple criteria.
- Make a priority ranking of actions to be recommended to the TSC.

In principle, the consequence prediction will be done similarly as in the Prognostic Module, that is, in a reusable way. The difference is that the Prognostic Module assumes no actions and the Decision Analysis Module depends on a specific action. The unification is foreseen by defining a special action *status-quo*, to be used in the diagnostic stage.

Methods: Actions will be described in terms of multiple parameters, whose probabilistic values will be assessed through a series of plant status and phenomenological questions [10]. An APET (Accident Progression Event Tree) [10], implemented as a DEX probabilistic model [9], will be employed to assess the expected probabilities of eventual radioactive emissions.

4.2.4 Decision Support Module

This module directly supports the decision-making process of the TSC, providing the following functionality:

- *Presenting* all the relevant information that comes from the other parts of the system, in a transparent and user-friendly way, mainly using charts and reports. This information includes:
  - *IP values* presented in tables and charts,
  - *diagnostic* and *prognostic* information from the monitoring subsystem,
  - *action recommendations* in terms of action ranking and assessment of consequences.
- *Resource management*: Allows the TSC to provide additional input data about resources that is needed in order to assess the feasibility and expected consequences of actions. For instance, the TSC may indicate that some resources are unavailable and cannot be used in recovery actions. For reasons that cannot be measured or determined by the system, the TSC may also manually enable or disable specific actions.
- *Action Management*: Actual selection, activation and monitoring of actions.

5. CONCLUSION

The immediate goal of the decision support system, whose conceptual design has been presented above, is to demonstrate the feasibility of developing such a tool, using the PSA and decision-modeling methods, for actual NPPs. The approach is novel in attempting to operationalize SAMGs for a specific severe accident situation, focusing on decision-support needs of the TSC.

Ultimately, such tools are expected to substantially contribute to severe accident management in NPPs as tools for the training of TSC members and as decision-support tools in real situations. The main contributions include:

- providing a timely and best available information about the state of NPPs barriers and potential future developments of the event;
- information support to the TSC team in an extremely difficult and stressful decision situation;
- operationalization of SAMGs for a specific situation;
- reducing the risk of overlooking important management actions and, consequently, making wrong decisions.

Further work will be focused on the implementation of the system (to be completed in 2020) and its experimental evaluation using the NARSIS' specification of the "Virtual NPP". The evaluation will address both the aspects of verification (compliance of Severa with the SAMGs) and validation (meeting the needs of the TSC in severe accident management). The latter will be assessed by comparing the performance of the TSC on selected accident scenarios with and without the support of Severa.

6. ACKNOWLEDGMENTS

This work has been carried out within the NARSIS project [7], which has received funding from the European Union's H2020-Euratom Program under grant agreement N° 755439.

7. REFERENCES

[1] Global Energy & CO2 Status Report, https://www.iea.org/geco/electricity/

[2] Nuclear Power in the World Today, https://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx, Updated February 2019.

[3] Nuclear Energy: Pros & Cons, https://www.renewableresourcescoalition.org/nuclear-energy-pros-cons/

[4] Nuclear and radiation accidents and incidents, https://en.wikipedia.org/wiki/Nuclear_and_radiation_accidents_and_incidents

[5] Staff, IAEA, AEN/NEA. International Nuclear and Radiological Events Scale Users' Manual, 2008 Edition (PDF). Vienna, Austria: International Atomic Energy Agency. p. 184. Archived from the original (PDF) on May 15, 2011. Retrieved 2010-07-26.

[6] Committee on Lessons Learned from the Fukushima Nuclear Accident for Improving Safety and Security of U.S. Nuclear Plants; Nuclear and Radiation Studies Board; Division on Earth and Life Studies; National Research Council. Washington (DC): National Academies Press (US); 2014.

[7] NARSIS, *New Approach to Reactor Safety ImprovementS*, EU Horizon 2020 project H2020-RIA-755439 (2017-2020) http://www.narsis.eu/

[8] Bohanec, M.: *DEXi: Program for Multi-Attribute Decision Making, User's Manual*, Version 5.00. IJS Report DP-11897, Jožef Stefan Institute, Ljubljana, 2015. http://kt.ijs.si/MarkoBohanec/pub/DEXiManual500p.pdf

[9] Trdin, N., Bohanec, M.: Extending the multi-criteria decision making method DEX with numeric attributes, value distributions and relational models. *Central European Journal of Operations Research* 26(1), 1–41, DOI: 10.1007/s10100-017-0468-92018, 2018.

[10] Vrbanić, I., Bašić, I., Štrubelj, L., Debelak, K., Bohanec, M.: *Definition of Hazard-Induced Damage States and Development of State-Specific APETs for Demonstration Purposes*, NARSIS Deliverable D5.3, 2019