

Severa Decision Support Tool Development in Project NARSIS

Luka Štrubelj, Klemen Debelak

GEN energija d.o.o.

Vrbina 17

8270, Krško, Slovenia

Luka.strubelj@gen-energija.si, klemen.debelak@gen-energija.si

Marko Bohanec

“Jožef Stefan” Institute

Jamova cesta 39

1000, Ljubljana, Slovenia

marko.bohanec@ijs.si

Ivica Bašić, Ivan Vrbanić

APOSS, Analize pouzdanosti i sigurnosti sustava d.o.o

Repovec 23B

49210 Zabok, Croatia

basic.ivica@kr.t-com.hr, ivan.vrbanic@zg.t-com.hr

ABSTRACT

The project NARSIS – New Approach to Reactor Safety ImprovementS – is making scientific steps towards addressing the update of some elements required for the safety assessment of nuclear power plants. These improvements mainly concern:

- Natural hazards characterization, in particular by considering concomitant external events, either simultaneous-yet-independent hazards or cascading events, and the correlation in intra-event intensity parameters.
- Vulnerability of the elements to complex aggressions, with the integration of new approaches such as vector-based fragility surfaces and reduced models.
- Better treatment of uncertainties through adoption of probabilistic framework for vulnerability curves and non-probabilistic approach to constraining the “expert judgments”.
- Develop decision support tool for severe accident management.

In the first step, the referential nuclear power plant (NPP) is identified: pressurized water reactor NPP with two loops. In the second step, the severe accident management guidelines for referential NPP are characterized. In the third step, the relevant scenarios are identified, hazard-induced damage states defined and state-specific accident progression event tree for demonstration purposes are developed. In the fourth step, the applicable deterministic analyses of severe accidents are performed. In the last, fifth, step, the decision support tool for severe accidents – Severa is developed. Its purpose is a prototype demonstration-level decision support system aimed at supporting the technical support center (TSC) while managing a severe accident. Severa represents, stores and monitors selected physical measurements of the NPP. It assesses the current state of barriers: core, reactor coolant system, reactor pressure vessel and containment. The prediction of future accident progression, if no action is undertaken is one of basic functions. The support tool provides a

list of possible management recovery strategies and courses of action. The applicability and feasibility of possible actions in the given situation is identified. For each action the prediction of the consequences in terms of probability of the last barrier (containment) failure and estimated time window for failure. At the end, Severa evaluates and ranks the feasible actions, providing recommendations for the TSC.

1 INTRODUCTION

Eighteen academic, research and industrial European institutions from Slovenia (GEN, JSI), Croatia (APOSS), Italy (ENEA, UNIPI), France (CEA, BRGM, IRSN, EDF, Framatome – ex Areva NP), Austria (NUCCON), Poland (NCBJ, WUT), Germany (KIT, Framatome – ex. Areva), Finland (VTT), The Netherlands (TU Delft, NRG) and United Kingdom (EDF Energy) are working on the project NARSIS – New Approach to Reactor Safety ImprovementS [1]. The project is funded by European Commission and has started in autumn 2017, with the duration of 4,5 years. The main vision of the consortium is to fill some gaps identified in existing external events probabilistic safety analyses (PSA) and to improve parts of the existing methodologies by 3 points: (1) to adapt most up to date frameworks and methodologies already existing or under development outside of nuclear community; (2) to use knowledge and experience on recent national and international projects; (3) to develop demonstration cases at the real NPP scale. The main results are the development of an integrated risk framework for safety analyses and the development of a decision-making tool for demonstration of nuclear facility management. The integrated risk framework consists of:

- Scenarios comprising single or multiple external hazards. Hazards are combined or cascading and include earthquake, flooding (height of external flooding due to increased river flow or precipitation), extreme weather and others,
- The physical and functional fragilities and interdependencies between systems/equipment are considered with aging effects,
- Human factors are considered and may play important role during severe accidents.
- A decision-support tool is developed to demonstrate nuclear facility management during severe accidents due to external natural events.

The project is structured into seven work packages (WP):

WP1: External hazards characterisation,

WP2: Fragility assessment of main NPPs critical elements,

WP3: Integration and safety analysis,

WP4: Applying & comparing various safety assessment approaches on a virtual reactor,

WP5: Supporting tool for severe accident management,

WP6: Dissemination, recommendation, and training,

WP7: Project management and coordination.

The work package (WP5) deals with the development of decision support tool for severe accident management and its demonstration. First, the referential nuclear power plant (NPP) was established [1]. The referential NPP is based on operating power plants in European Union. The safety systems, structures and components (SSC) of referential nuclear power plant include design basis safety SSC, safety SSC to mitigate severe accident and mobile SSC (FLEX equipment). The design basis SSC was installed during the construction of NPP and includes high pressure injection, borated water accumulators, and low-pressure safety injections, to supply cooling water and mitigate loss of coolant accident. Emergency diesel generators and batteries are intended to supply energy for operation of pumps, valves and instrumentation and control. Emergency feed water pumps are intended for reactor core cooling. The safety valves are installed at reactor coolant system to decrease pressure below

design value. The containment is a building around reactor to confine the radioactive material and prevent releases to the environment and radioactive doses to the public. After the Fukushima accident stress tests were performed on all European NPPs. New SSC were installed in NPPs all over EU, to prevent or mitigate severe accidents – accidents with core melting. Additional energy sources in terms of diesel generators and batteries are installed. The passive containment venting is installed to decrease the pressure in containment in case of low probable high-pressure scenario. The passive autocatalytic recombiners are installed to reduce the possibility of hydrogen explosions. Alternative depressurization system is installed to have high confidence for depressurization of reactor coolant system.

Next, the severe accident management guidelines (SAMG) applicable to referential NPP were described [2]. In case of deviation of important NPP measurements, defined in chapter 3, alarms go off in the control room and the operators use alarm respond procedures to respond to alarms. If they are not able to successfully correct the situation, the use abnormal operating procedures is envisaged. If the problems still persist and reactor trip is activated, it means that design basis accident is occurring and emergency operating procedures are used to activate safety SSC. If such action is not successful, the core starts to heat up due to decay heat and severe accident with core degradation or melting can occur. The management of NPP is transferred from operators in control room to the technical support center. In order to manage severe accidents, the SAMG are used by managers in the technical support center. The SAMG includes operations such as:

- Injection to steam generator, to remove decay heat from reactor coolant system.
- Depressurization of reactor coolant system, to prevent high pressure melted corium ejection, which can damage containment and causes quick rise of containment pressure and hydrogen generation.
- Injection to reactor coolant system, which assures coolant water to reactor core to remove decay heat.
- Injection of water into containment, to reduce containment pressure and possible radioactive releases.

In contrast to previously used procedures, where operators followed the procedures line by line and no decisions are needed, in SAMG the technical support center needs to take decisions. There can be large amount of information, some of them available only partially, or with high uncertainty. The technical support center managers are under stress due to a large damage in the NPP, potential releases of radioactivity and time pressure. The decision support tool Severa, developed in the project and described below, targets this accident management stage and aims at supporting the managers to make appropriate decisions with prioritization of actions in a well-justified and timely manner.

2 SCENARIO DEVELOPMENT AND INPUT DATA

The next task was to develop the hazard-induced damage states and specific accident progression event tree for demonstration purposes [3]. This includes developing accident progression logic structure for postulated hazard damage states, where damaged SSC are identified.

For this purpose, two major severe accident sequences were evaluated: high pressure or low pressure sequence. The high pressure sequence starts with an initiating event like station black out (total loss of internal and external electricity power), or loss of ultimate heat sink, where decay heat removal is absent and the depressurization of reactor coolant system fails. The core temperature starts to rise and hydrogen production starts in contact of hot steam and cladding. The core starts to melt and can be ejected, if hot leg creep failure did not occur, to

containment with reactor vessel failure at high pressure (High Pressure Melt Ejection (HPME)). The fast transfer of corium heat in containment (Direct Containment Heating (DCH)) threatens containment integrity.

The low pressure sequence starts with an initiating event like loss of coolant accident, where the water in reactor coolant system is lost, and there is no medium to remove decay heat. The containment pressure starts to increase with loss of coolant accident, which can threaten the integrity of containment. The core temperature starts to rise. The core starts to melt and reactor vessel fails at the bottom. The reactor cavity bellow the reactor pressure vessel can be flooded with water. Hot corium in contact with water can initiate steam explosions, which can threaten containment integrity. The molten corium interaction with concrete and water starts to produce hydrogen and carbon monoxide (CO), which both can form explosive mixture. Potential hydrogen and CO burn or explosion can threaten the integrity of containment.

Severe accident simulations were performed for each sequence, with different safety features available and different time of activation of safety features [4].

The assessment of potential decisions needed to be taken by technical support center, is provided. The set of attributes against which all decisions are evaluated in decision support process is identified. This includes the status of main barriers, fuel cladding, reactor coolant boundary and containment. Since the status of boundaries (e.g. fuel temperatures) is not measured directly some indirect parameters are used.

Figure 1 presents simplified severe accident progression, important phenomenology effects for both scenarios (LP and HP) including the comparison of expected (predicted by severe accident simulations with MELCOR code) time windows of each accident phase [4].

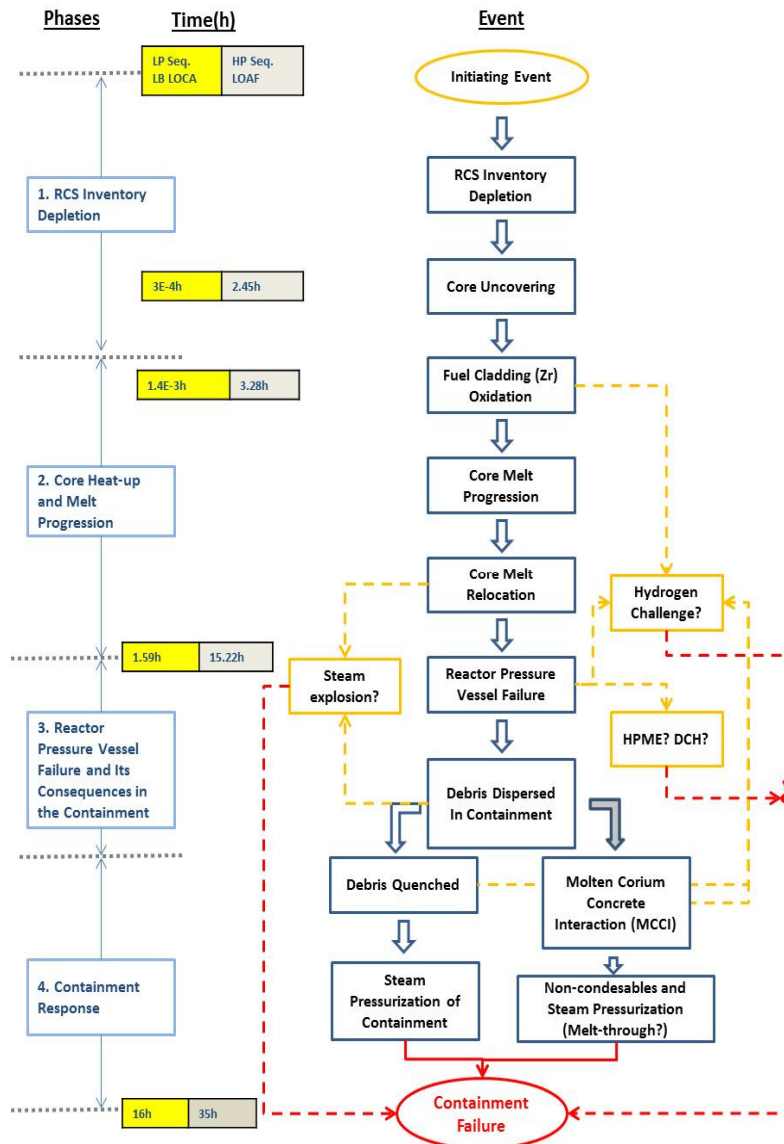


Figure 1: Severe Accident Progression and Phenomenology

3 DECISION-SUPPORT TOOL SEVERA

In the last task, a decision-support tool called Severa was developed [5]. Severa is a demonstration-level Windows application, aimed at supporting the TSC team while managing a severe NPP accident.

The operation of Severa is based on a time series of eight critical parameters that are periodically measured in the NPP [7]:

- 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]
- Lcont: Containment Water Level [m]
- H2: Hydrogen concentration [%]

On this basis, Severa makes a first major decision-support contribution by providing the following information to the TSC:

- Whether or not – and when – the conditions in the NPP require the activation of SAMGs?
- Which SAGs are relevant for the situation? Currently, Severa is restricted to three SAGs: SAG-1 (Inject into SG), SAG-2 (Depressurisation of RCS) and/or SAG-3 (Inject into RCS).
- Given the measurements, what are the expected states of the three barriers: Core, RCS, and Containment?
- What are the expected progressions of the event if no actions are undertaken by the TSC?

Time [min]	CET [°C]	SGL [%]	RPVL [%]	Prcs [MPa]	Pcont [MPa]	TCont [°C]	Lcont [m]	H2 [%]	SAGs	Seq Type	Core State	RCS State	Cont State	Possible Progressions
0	330	87.7	100.0	15.51	0.101	22	0.0	0.00			OK	OK	OK	
10	309	59.3	100.0	13.29	0.104	26	0.0	0.00			OK	OK	OK	
20	307	42.3	100.0	12.75	0.107	31	0.1	0.00			OK	OK	OK	
30	307	27.9	100.0	12.23	0.109	33	0.1	0.00			OK	OK	OK	
40	307	16.4	100.0	11.18	0.109	34	0.1	0.00			OK	OK	OK	
50	307	4.9	99.5	9.53	0.110	35	0.2	0.00			OK	OK	OK	
60	318	0.0	99.7	11.23	0.110	36	0.2	0.00			OK	OK	OK	
70	335	0.0	100.0	14.81	0.111	37	0.2	0.00			OK	OK	OK	
80	349	0.0	100.0	17.22	0.111	37	0.3	0.00			OK	OK	OK	
90	354	0.0	67.2	17.03	0.153	76	1.1	0.00			OK	OK	OK	
100	354	0.0	56.5	17.11	0.176	84	1.1	0.00			OK	OK	OK	
110	423	0.0	37.1	17.09	0.178	85	1.2	0.00			OK	OK	OK	
120	677	0.0	27.5	17.08	0.173	82	1.2	0.00	1, 2, 3	High	OK	OK	OK	
130	1,074	0.0	23.8	17.08	0.168	80	1.6	0.00	1, 2, 3	High	OK	OK	OK	
140	1,786	0.0	20.3	17.07	0.183	86	1.6	0.01	1, 2, 3	High	OX	IP	OK	CD, RCSdepr, CH, DCH, Bypass
150	1,525	0.0	13.1	17.15	0.189	87	1.6	0.03	1, 2, 3	High	OX	IP	OK	CD, RCSdepr, CH, DCH, Bypass
160	1,410	0.0	13.1	17.23	0.196	89	1.6	0.03	1, 2, 3	High	CD & OX	IP	OK	RPVmelt, RCSdepr, CH, DCH, Bypass
170	1,531	0.0	12.5	17.20	0.195	89	1.6	0.03	1, 2, 3	High	CD & OX	IP	OK	RPVmelt, RCSdepr, CH, DCH, Bypass
180	1,612	0.0	9.0	17.05	0.194	89	1.6	0.03	1, 2, 3	High	CD & OX	IP	OK	RPVmelt, RCSdepr, CH, DCH, Bypass
190	607	0.0	6.6	16.44	0.189	87	1.6	0.03	1, 2, 3	High	CD & OX	IP	OK	RPVmelt, RCSdepr, CH, DCH, Bypass
200	179	0.0	33.0	0.30	0.294	113	1.6	0.03	1	Low	CD & OX	IFD	OK	RPVmelt, CH, MCCI

Figure 2: A Severa screenshot showing the first 200 minutes of a Station Blackout event

Figure 2 shows an example of a Severa screenshot that displays the first 200 minutes of a Station Blackout event (simulated with Melcor) and Severe interpretation of time series in terms of:

- Columns CET to Lcont: Color-coded interpretation of individual measurements, where white, yellow, orange and red colours indicate the states of increasing severity, and magenta indicates an out-of-range or erroneous measurements (the real measurements in NPP have specified range, however the Melcor simulation results are not limited by measurement range).
- Column SAG: Shows SAGs relevant for the situation (multiple SAGs are possible).
- Column Seq Type: Sequence type, either low-pressure (LP) or high-pressure (HP).
- Columns Core State – Cont State: Assessed current state of the three barriers.
- Column Possible Progressions: Prediction of possible events if no actions are undertaken.

This information is generated by Severa partly by using decision rules encoded in the software and partly by a qualitative rule-based multi-criteria model [7] developed according to the method DEX [8] with decision modelling software DEXi [9].

The second major decision-support contribution of Severa is related to possible management actions and their expected consequences. In each situation, multiple actions may be available, but their choice and potential success depend of a variety of factors: preconditions for carrying out an action, current and future availability of equipment,

available time window, action adequacy, etc. Actions may be mutually exclusive and the success of some action may depend of the success of another one.

In Severa, the expected outcome of actions is assessed using a probability distribution of expected radioactive releases with respect to four categories of radioactivity release [7]:

- RC-E: Containment failure with a significant release of radioactivity is expected within several hours.
- RC-I: Containment failure with a significant release of radioactivity within several days.
- RC-L: No significant release of radioactivity is expected within several days.
- RC-N: Long-term concern (in-vessel recovery and/or intact containment).

Figure 3 shows an example of such a probability distribution, assessed by Severa for the situation at the 180's minute of the time series from Figure 2, assuming that all equipment is available and all mitigation actions can be started immediately. Notice that at that time, the station blackout event has been already in progress for about one hour.

Generally, when choosing between alternative actions, the action whose probabilities are the highest around RC-N and the lowest around RC-E is recommended for implementation.

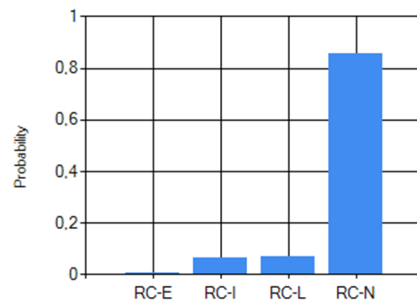


Figure 3: An example of radioactive-release probability distribution

The main model for producing such assessments is based on an accident progression event tree (APET), developed in previous stages of the project [3, 4]. In Severa, the APET is implemented in terms of an equivalent probabilistic DEX model [7]. Additionally, the expected success of actions over time is estimated using a cumulative lognormal distribution.

Each activity has an associated “success window”, determined by the 95th and 5th percentile success times.

It needs to be pointed out that, in its current version, Severa is a simplified tool which was developed in order to investigate the possibilities of this kind of support to decision-making in severe accident management, primarily for the training purposes. As any simplified tool, it has its limitation. Among the most important is a treatment of time dependency of the probabilistic parameters incorporated in its prognostic logic. A number of phenomenological probabilities are presented by values which apply at an early phase of scenario and, therefore, its use is limited to this time window. Furthermore, it relies on simplified presentation of logic models for “success paths” and system functions, as well as simplified consideration of adequacy of equipment included in the model and feedback from the implemented actions. However, even under the limitations it took quite a considerable programming effort and posed a number of challenges for the programmers. Verification and validation exercises showed that it can provide reasonable predictions of probability profiles of major release categories for the scenarios considered.

4 CONCLUSION

Severa is a simplified tool which was developed with an idea to investigate the possibilities of use of a computer tool in support of decision-making in severe accident management, primarily for the training of NPPs Technical Support Center (TSC) staff. Demonstration version of Severa is capable to evaluate potential successes of available severe accident management actions (SAGs) based on assumed time windows for successful recovery actions and predetermined probability profiles of expected major radioactive release categories for different plant status/configurations. The appropriate timely executed operator actions should reduce the early containment failure or/and minimize other types of radiological releases. The TSC staff decisions based on additional information and training with Severa tool can lead to better understanding and management of severe accidents in nuclear power plants. Although the prototype version is simplified and involves a number of limitations, the verification and validation exercises showed that it can provide reasonable predictions of probability profiles of major release categories for the scenarios considered.

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