INL/CON-18-45360-Revision-0

RISK-INFORMED EXTERNAL HAZARDS ANALYSIS BY EEVE TOOLKIT

C. Parisi, S. Prescott, Z. Ma, J. Coleman, R. Szilard, C. Smith

May 2018

The INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance

INL/CON-18-45360-Revision-0

RISK-INFORMED EXTERNAL HAZARDS ANALYSIS BY EEVE TOOLKIT

C. Parisi, S. Prescott, Z. Ma, J. Coleman, R. Szilard, C. Smith

May 2018

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy

Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

RISK-INFORMED EXTERNAL HAZARDS ANALYSIS BY EEVE TOOLKIT

C. Parisi, S. Prescott, Z. Ma, J. Coleman, R. Szilard, C. Smith
Idaho National Laboratory
2525 Fremont Avenue, 83415 Idaho Falls, USA
carlo.parisi@inl.gov

ABSTRACT

Introducing risk-informed safety analyses for external events can bring sensible benefits to the nuclear power industry easing the regulatory burden introduced in the aftermath of the Fukushima accident. In the framework of the US-DOE Light-Water Reactor Sustainability program, Risk-Informed Margin Characterization project (LWRS-RISMC), research activities were conducted at INL for developing and applying a toolkit for performing risk-informed external hazards analysis. The "EEVE" (External EVEnts) toolkit, a chain of INL and state-of-the-art codes, was set-up and applied for simulating earthquake-induced transients with internal flooding in a PWR. This was done using methodology set-up for evaluating new data and determining critical areas that would benefit most from advanced analysis methods. The methodology is agnostic and it can be applied to other external hazards than just seismic and flooding (e.g., high winds, intense precipitation, etc.). The first step was the deterministic calculations for evaluating the propagation of a set of earthquakes and for determining the effects on a fire suppression system in an auxiliary building. These deterministic calculations were performed using the LS-DYNA and the OPENSEE structural mechanics codes. Probability failures and event trees of a generic 3-loops Westinghouse PWR were derived from a generic SAPHIRE model. Seismically induced Loss of Offsite Power, Station Blackout, and fire suppression piping failure events were considered. SAPHIRE code allowed a pre-screening of all possible branches of the event tree and a selection of those with the largest Core Damage Frequency increase for further analysis using dynamic PRA methods. INL`s EMRALD code performed dynamic PRA calculations of the identified sequences, integrating risk analysis with on-line deterministic safety analysis results (seismically-induced internal flooding calculations by NEUTRINO code and system analysis by RELAP5-3D code). RELAP5-3D Best-Estimate calculations coupled with RAVEN statistical code were used for deriving limit surfaces as function of relevant transient parameters. This data was used by EMRALD for determining the final core status (core damage/core safe). Finally, the coupling of seismic, flooding, system thermal-hydraulic, uncertainty quantification and probabilistic risk analysis for an advanced risk-informed external hazards analysis was demonstrated. Results showed the sensible decrease in the level of conservatism achieved using the developed risk-informed methodology, which allowed also improving the evaluation of the failure modes and failure probabilities of different components.

1. INTRODUCTION

Design of nuclear power plant (NPP) facilities to resist external hazards has been a part of the regulatory process since the beginning of the NPP industry in the United States (US), but has evolved substantially over time. The original set of approaches and methods were entirely deterministic in nature and focused on a traditional engineering margins-based approach.

However, over time probabilistic and risk-informed approaches were also developed and implemented in US Nuclear Regulatory Commission (NRC) guidance and regulation [1]. As a result, today, the US regulatory framework incorporates deterministic and probabilistic approaches for a range of different applications and for a range of natural hazard considerations.

Although the US regulatory framework has continued to evolve over time, the tools, methods and data available to the US nuclear industry to meet the changing requirements have not kept pace. Development of a new set of tools and methods that incorporate current knowledge, modern best practice, and state-of-the-art computational resources would lead to more reliable assessment of facility risk and risk insights (e.g., the structure, system, and component (SSC) and accident sequences that are most risk-significant), with less uncertainty, and reduced potential conservatisms. New tools would also benefit risk-informed approaches to assessing and managing margin.

In the framework of the US Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) program, Risk Informed Margin Characterization Pathway (RISMC), a research effort for developing advanced tools, data and methods has been launched [2]. Goals of the LWRS-RISMC Pathway are twofold:

1) develop and demonstrate a risk-assessment method coupled to safety margin quantification that can be used by NPP decision makers as part of their margin recovery strategies;
2) create an advanced "RISMC toolkit" that enables more accurate representation of NPP safety margin.

In particular, activities devoted to the study of external events were initiated, with the scope of performing an advanced risk analysis of accidental events caused at a NPP, pressurized water reactor (PWR) or boiling water reactor (BWR) by a combination of natural external hazards, for example earthquake and flooding [3].

For achieving such goal, a detailed roadmap has been identified. As a results of these activities, the "EEVE" (External EVEnts) toolkit, a chain of INL and state-of-the-art codes, was set-up and applied for simulating earthquake-induced transients with internal flooding in a generic three-loops PWR. A general methodology was also conceived for evaluating new data and determining critical areas that would benefit from advanced analysis methods.

In this paper we present the developed methodology and the results from the first application of the EEVE toolkit. We then show how the application of advanced codes and risk-informed analysis can lead to the decrease of undue conservatisms and to a better evaluation of the failure modes and failure probabilities of different components.

2. METHODOLOGY

The first step was the development of a non-hazard specific methodology workflow (see Figur below) so that it could be applied to whatever external hazard safety analysis (earthquake, high wind, external flooding, etc.). Following this workflow, a safety analyst is able to focus work on the correct areas by using existing models and data (traditional Fault Trees and Event Trees) with new data and methods in stages to determine if continued analysis may be significantly beneficial.

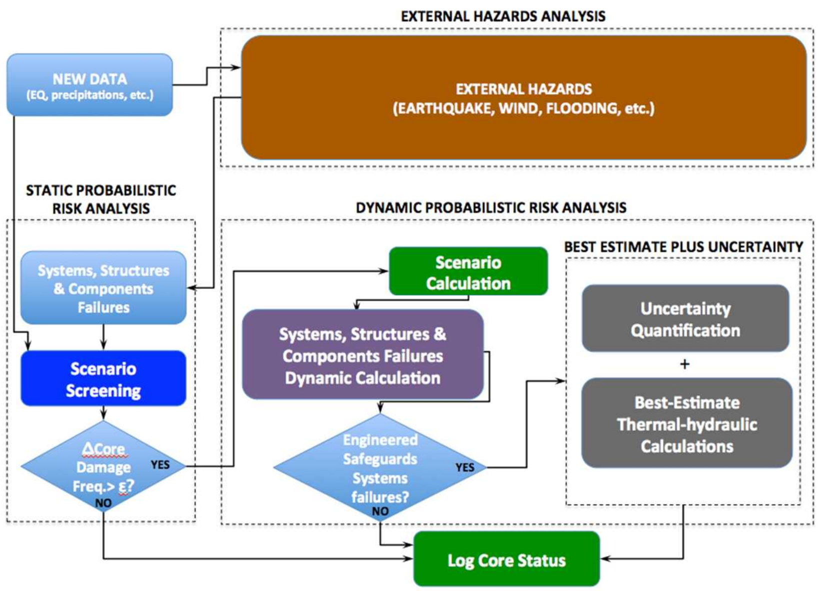

Figure 1. External Events Methodology Workflow.

The External Events (EE) generating hazards for the NPP are simulated in the top block. Deterministic software is to be used for determining the mechanical effects on the system, structure or components (SSC) of a NPP. The derived SSC failure modes and probabilities are then used for informing the available static probabilistic risk assessment (PRA).

When new data is available or hazard identified (e.g., new precipitation models, new earthquake (EQ) hazard curves, degraded piping, etc.), the new SSC failure modes and probabilities along with a conservative or maximum failure rates from any physics based models, are calculated and the static PRA tool is used to assess any positive increase in core damage frequency (CDF). If such increase is greater than a user-defined threshold, the significant failure sequences are identified as needing additional modeling for the dynamic PRA tools for performing a more detailed risk evaluation. The dynamic PRA tools re-simulate the selected scenarios performing dynamic calculations of the SSC failure modes (e.g., calculating the flooding and water spray of a pipe break). If safety-significant components are affected by the selected SSC failure then Best-Estimate Plus Uncertainty (BEPU) calculations are run for determining the core status (core damage/core safe).

Every time the workflow is run, an update of the core status (i.e., the CDF probability) is performed. The developed workflow is consistent with the safety analyses options listed by the International Atomic Energy Agency (IAEA) in its Safety Guide [4] and it corresponds to the option 4 of Table 1.

Table 1. Options for Safety Analyses.

Option	Computer Code	Availability of Systems	Initial and Boundary Conditions
1) CONSERVATIVE	Conservative	Conservative Assumptions	Conservative Input Data
2) COMBINED	Best Estimate	Conservative Assumptions	Conservative Input Data
3) BEST ESTIMATE	Best Estimate	Conservative Assumptions	Realistic + Uncertainty
4) RISK INFORMED	Best Estimate	Derived from PRA	Realistic + Uncertainty

3. THE "EEVE" TOOLKIT

EEVE toolkit is based on a set of INL state-of-the-art tools and it leverages computer technology being developed at the Idaho National Laboratory (INL) (e.g., [5], [6]). The list of computer codes applied for achieving a combined deterministic and probabilistic analysis is shown in Table 2.

Table 2. EEVE Toolkit main codes

Tools	Function	Block
SAPHIRE	Static PRA	Static PRA
EMRALD	Dynamic PRA	Dynamic PRA
NEUTRINO	3D Flooding Simulation	
RELAP5-3D	System TH / 3D Neutronics	BEPU
RAVEN	Sensitivity/Uncertainty	

It should be noted that external events codes are application-specific. The application case presented in this paper focused on seismic risk. The structural mechanics codes that were used for performing seismic-PRA are reported in Table 3. The corresponding EEVE workflow used for this study, which includes evaluation of seismic and internal flooding risks, is shown in Figure .

Table 3. EEVE Toolkit – External hazards analysis codes for seismic risk

Tools	Function	Block
LS-DYNA	Non-Linear Soil Structure Interaction	External Hazards Analysis (Seismic)
	Building Response	
OPENSEES	Pipeline stress & strains	

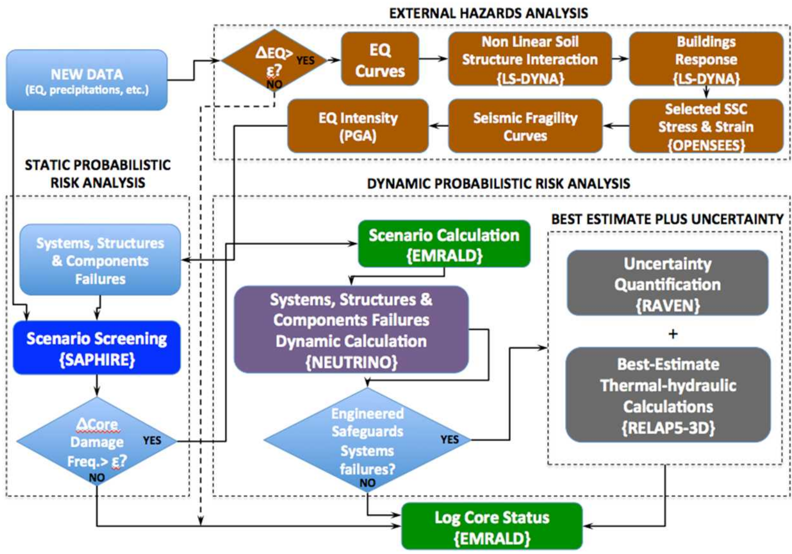

Figure 2. Workflow and tools for EEVE Toolkit.

The scheme above shows that in order to perform a new complete risk-informed EE hazard analysis, the change in the CDF evaluated by the static PRA has to be greater than a threshold indicated by the safety analyst. Of course a threshold set to zero implies to re-perform the analysis every time. The five steps that were followed for the case presented in this paper are:

1) External Hazards Analysis. Seismic PRA analysis:
   a. Use updated Earthquake (EQ) curves
   b. Perform Non-Linear Soil Structure Interaction (NLSSI) and calculate the Building Dynamic Response by the LS-DYNA code [7]
   c. Calculate the selected SSC (fire suppression pipelines) stress & strain by OPENSEES code [8]
   d. Derive the new Seismic Fragility Curves for the SSC (failure probability vs. peak ground acceleration)
2) Static PRA:
   a. update SSC failure probabilities
   b. calculate, using the SAPHIRE code [9], if the updated SSC failure probabilities lead to a significant increase of CDF
   c. if yes, perform dynamic PRA calculations for updating CDF with Best Estimate (BE) methods
3) Dynamic PRA:
   a. run selected scenarios using dynamic PRA code EMRALD [10]
   b. perform flooding calculations for determining failure modes and probabilities for selected SSC using the NEUTRINO code [11]
   c. if failures of safety relevant components are detected, then perform BEPU of NPP affected transients

4) BEPU:

   a. run NPP scenario using BE system thermal-hydraulic code RELAP5-3D plus uncertainty code RAVEN [12].

5) Determine core status (failed/safe) and update the CDF metric (EMRALD code).

In the following sections, we describe the application of the methodology and of the EEVE toolkit to a generic 3-loops PWR. We studied a set of earthquake-induced scenarios (loss-of-offsite power, station blackout) including possible effects generated by an earthquake-induced internal flooding.

4. MODELING A GENERIC 3-LOOPS PWR

4.1 STRUCTURAL MODELING

We focused our investigation on the analysis of an EQ effects on an auxiliary building of a NPP. The seismic analysis methodology we applied is reported in [13]. LS-DYNA code allowed calculating the acceleration for all three translational directions at 25 selected nodes of the auxiliary building model. A fire-suppression system (FSS) was selected for evaluating EQ-induced effects. A three-dimensional (3D) model of the FSS located in two switchgear rooms of the auxiliary building was developed using the OPENSEEES software. After the identification of locations of failures, seismic fragility analysis was carried out, in order to generate the seismic fragility curves at the failure locations. Seismic fragility curves for all these damage states were derived, obtaining for several points of the piping system the probability of failure versus the Peak Ground Acceleration (PGA) (e.g., see Figure 3).

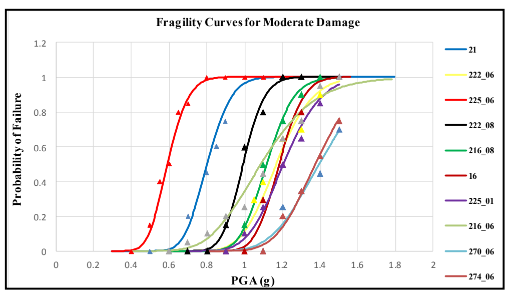

Figure 3. Fragility curve (moderate damage) for the X direction input.

4.2 STATIC PRA MODELLING

A generic internal events PRA model developed using SAPHIRE code for a typical PWR plant was obtained and revised. External events were added and few relevant sequences were selected for performing dynamic PRA analysis. A generic seismic hazard vector was used to derive the seismic initiating event frequencies as a function of seismic acceleration (g-level). The defined seismic acceleration range was then partitioned into three categories, or bins, to represent three discrete seismic event scenarios with increasing intensity. Those three seismic scenarios were then used for developing three corresponding seismic event trees. Among hundreds of seismic accident sequences in the SAPHIRE model, four Loss-of-Offsite Power (LOOPs) were selected and converted to the dynamic PRA model for EMRALD code runs (see Table 4). The criteria used for selecting those four sequences were 1) their relatively higher frequencies and 2) the inclusion of important mitigating systems such as the Auxiliary Feedwater (AFW) and the safety injection systems. These four sequences could also easily demonstrate the impact of RISMC approach for seismic induced flooding scenarios and each one can be initiated by any of the three seismic bins. Details of the 4 sequences are provided in [14].

Table 4. Selected Sequences and Static PRA frequencies.

SEQUENCES	EQK 2-02-05	EQK 2-15	EQK 2-16-03-10	EQK 2-16-45
SAPHIRE Sequence Probability (BIN1 to BIN3)	2.74E-10	4.60E-12	5.26E-09	3.99E-10
	3.84E-09	9.54E-09	3.46E-08	1.04E-07
	1.04E-07	3.76E-07	2.77E-07	1.58E-06

4.3 INTRODUCING NEW DATA & FAILURE MODES

In order to test the developed methodology, we introduced a new seismic hazard vector and new failure modes (i.e., the seismic-induced failure in the switchgear rooms 1 & 2). This new data caused a general increase of failure probabilities for each of the sequences reported in Table 4. In particular, the greatest increase was seen in the Bin 2 and 3, therefore only sequences belonging to these bins were selected for dynamic PRA modeling and implemented in the EMRALD code.

4.4 DYNAMIC PRA MODEL

4.4.1 EMRALD model

The EMRALD model was built in several stages and it linked the seismic data, the 3D fluid simulations and the thermal hydraulics data into the PRA analysis. The dynamic PRA model consisted of component diagrams, system diagrams, and a plant response diagram. Every component for the key systems was determined using the failure rates for each of the components basic events. The logic for the system diagrams was also modeled after the corresponding fault tree, along with all relevant common cause events added to the logic model. The plant response diagram couples the system evaluations into the desired sequences along with the 3D flooding simulation and the system thermal-hydraulic [14].

4.4.2 NEUTRINO 3D flooding simulation model

For the demonstration case presented in this paper, flooding analysis were carried out with a 3-D model of two switchgear rooms. The model consisted of a 3-D polygon model of a floor of the facility and other rigid objects representing components. The critical components susceptible to water damage included four battery units, two 4kV switchgear units, two 125V DC distribution panels and four Uninterruptible Power Supply (UPS) units. Dynamic particle emitters were used to simulate a rupture from the water based FSS (see Figure 4).

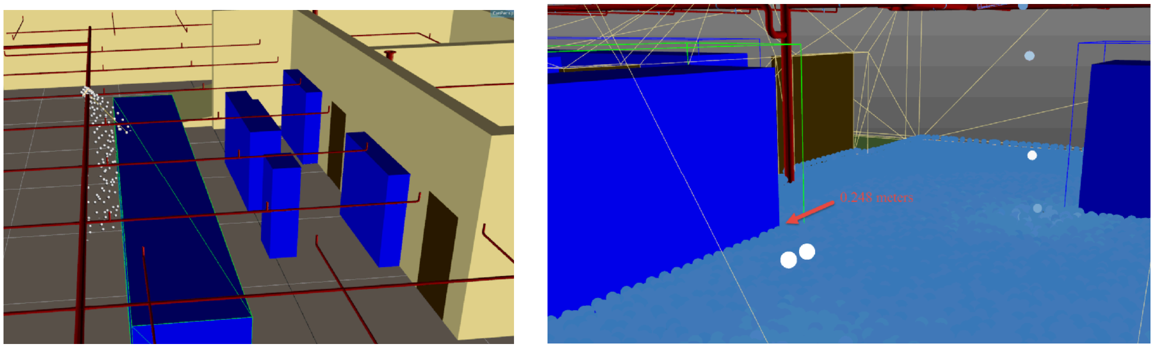

Figure 4. NEUTRINO flooding scenarios simulations.

4.4.3 RELAP5-3D/RAVEN model

Two of the sequences identified by the SAPHIRE PRA analysis in Table 4 were selected for system thermal-hydraulic (SYS-TH) simulation. The two sequences are the EQK-2-02-05 (LOOP) and the EQK-2-16-45 (LOOP→Station Blackout, (SBO)). Each of these main sequences can branch-off in other different sub-branches depending by the type of failures (e.g. the MCP seal leakage rate, battery failure time), the operator/emergency crew actions (emergency injection time, recovery of ECCS). Therefore, a RELAP5-3D model was developed for deterministic calculations of such events as function of selected parameters. The RELAP5-3D SYS-TH code modeled a generic 2.5 GWth 3-loops Westinghouse PWR, representative of the US LWR fleet.

Details of the RELAP5-3D calculations are reported in [14]. As it can be guessed, manual calculations of all the possible PRA sub-branches is almost impossible because the large number of input-decks/outputs that the safety analyst should manage. Therefore, an automatic determination of the various Limit Surfaces (LS) (i.e., the surface, in the n-dimensional space of our problem, dividing the safe fuel conditions from the failed ones) has been performed with the help of RAVEN code "*LimitSurfaceSearch*" algorithm. LS search is based on the use of a Reduced Order Model (ROM) or Surrogate Model (SM). The initial observations (in this case, RELAP5-3D calculations) are used for training the ROM, which is then employed for the determination of the LS. Exploration of the n-dimensional space of the problem using the ROM is not-computationally expensive and several algorithms from machine learning are available [12]. Thus, automatic LS search for the PRA LOOP 2-02-05 and SBO 2-16-45 sequences were performed. The parameters that were sampled are reported in Table 5. All the parameters distributions were assumed uniform.

Table 5. Sampled Parameters for LS identification.

Sequence	**Sampled Parameter**	**Number of Points**	**Interval**
LOOP 2-02-05	MCP seal leakage	6	21 to 480 gpm
	SG depressurization	16	13000 to 42000 s

			(~3.6 hr to ~1.6 hr)
SBO 2-16-45	Battery Failure time	4	0.0 to 3600 s
	Emergency Crew Recovery time	4	7200.0 to 14400 s (2 hr to 4 hr)

The following step was the determination of the SYS-TH code and model uncertainties. A simplified UQ analysis based on the order-statistics was performed and 4 (epistemic) uncertainty parameters were considered for testing the codes and the methodology. The final LS for each of the sequences of Table 5 became a 6-dimensional surface (4 epistemic uncertainty parameters + 2 transient-related random parameters), so the projection of the failed points on a two-dimensional surface (battery failure time versus crew recovery time) identified the boundaries between failed/safe state, e.g. see Figure 5. This uncertainty-informed LS was not used for the final calculations by EMRALD.

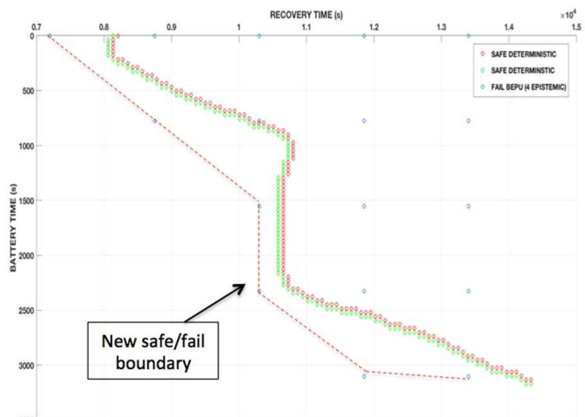

Figure 5. Limit Surface for SBO Including Epistemic Uncertainties.

5. EEVE TOOLKIT RISK-INFORMED CALCULATIONS RESULTS

The simulations from the combined EEVE codes were run on a HPC computer cluster. EMRALD code managed the calculation flow, running NEUTRINO 3-D flooding calculations and using RELAP5-3D/RAVEN LS results. A first relevant outcome we found from the analysis of the EMRALD log files, was that the application of combined EMRALD/RELAP5-3D calculations (without NEUTRINO) could contribute to a sensible reduction of the level of conservatism in our static SAPHIRE PRA model. In particular, if we compare the number of core failures obtained by SAPHIRE and EMRALD/RELAP5-3D for the sequences LOOP 2-02-05 and SBO 2-16-45, we obtain (see Table 6):

Table 6. Core failures reduction for the LOOP 2-02-05 and SBO 2-16-45 using EMRALD/RELAP5-3D.

Sequence	Reduction of Core Failures
LOOP 2-02-05	-7.3%
SBO 2-16-45	-34%

or a reduction of the core failures for both sequences, with a more important reduction for the SBO sequence. Performing a full analysis using the whole suit of EEVE toolkit codes could lead to a further sensible decrease of the CDF. First, we combined the sequences results belonging to the most intense earthquake bins or bin-2 and bin-3. Then we calculated the CDF increase for the reference SAPHIRE calculations (column 2 of Table 7) by introducing new failure modes (switchgear room (SWGR) pipe rupture by earthquake). The CDF for this new scenario was calculated using stand-alone static PRA SAPHIRE code and EEVE toolkit plus dynamic PRA calculations. The third and fourth columns of Table 7 show the corresponding CDF increase. The fifth column of Table 8 show the CDF reduction introduced by EMRALD and the RISMC methodology.

Table 7. SAPHIRE and EMRALD Results, CDF increase.

Sequence Case (Bin2+ Bin3)	**CDF No SWGR Pipe Failure, [SAPHIRE]**	**ΔCDF SWGR Pipe Failure [SAPHIRE]**	**ΔCDF SWGR Pipe Failure [EMRALD+NEUTRINO+ RELAP5-3D/RAVEN]**
LOOP 2-02-05	5.65E-07	9.940E-08	8.540E-09
LOOP 2-15	1.94E-06	8.350E-06	3.51E-09
SBO 2-16-03-10	2.09E-06	1.758E-06	1.48E-09
SBO 2-16-45	9.68E-06	1.277E-05	4.560E-10

Table 8. SAPHIRE and EMRALD Results, Absolute CDF values.

Sequence Case (Bin2+ Bin3)	**CDF No SWGR Pipe Failure [SAPHIRE]**	**CDF SWGR Pipe Failure [SAPHIRE] (S1)**	**CDF SWGR Pipe Failure [EMRALD+NEUTRINO+RELAP5-3D/RAVEN] (E1)**	**CDF Reduction EMRALD vs. SAPHIRE (1-E1/S1)*100**
LOOP 2-02-05	5.65E-07	6.64E-07	5.74E-07	-14%
LOOP 2-15	1.94E-06	1.03E-05	1.94E-06	-81%
SBO 2-16-03-10	2.09E-06	3.85E-06	2.09E-06	-46%
SBO 2-16-45	9.68E-06	2.25E-05	5.74E-07	-97%

It should be noted that further CDF reduction for sequences LOOP 2-15 and SBO 2-16-03-10 could be eventually achieved by introducing also for them the RELAP5-3D/RAVEN calculations. A counter effect to the CDF reduction can be played by the introduction of UQ results. In fact, as we briefly mentioned in section 4.4.3, introduction of uncertainty (BEPU calculations) reduces the "fuel safe area" of the LS determined by RELAP5-3D/RAVEN (see Figure 5). Therefore, for every sequence, more CD cases could be found by EMRALD. Another insight from the application of the EEVE toolkit and the developed methodology is the possibility to identify from the most vulnerable SSC's for the analyzed scenario. In particular, the application of 3D NEUTRINO flooding simulation allowed us to determine rank the vulnerability of the main electric components of the SGWR.

Table 9 shows the frequency of a component failure given that at least one component failed due to pipe rupture, and where adding resiliency to a component would make the largest impact in risk reduction. Multiplying this failure percentage by the probability of a pipe rupture would give the probability of component failure due to pipe rupture.

Table 9. Component Failures from EEVE.

3D Component	**Counts**	**Failure %**
480V bus #1	30320	97.0768%
UPS 1 B	209	0.6692%
125VDC Panel 1	515	1.6489%
4KV bus #1	160	0.5123%
480V bus #2	27	0.0864%
UPS 1 A	2	0.0064%

6. CONCLUSIONS

In this paper we presented a demonstration of a Risk-Informed External Hazards analysis for a generic PWR. First we proposed a toolkit (EEVE) and a methodology for performing a risk-informed safety analysis, focusing on earthquake-induced accidents. Then we showed the developed models, which are based on advanced tools. The results presented in the previous sections, demonstrate the capabilities achieved by the EEVE toolkit in performing multi-physics and multi-scale simulations combining advanced seismic, PRA and BEPU analyses.

The following relevant points could be highlighted from this work:

1) combination of advanced PRA analysis (static and dynamic) and the use of BEPU can allow the industry to significantly improve operating and accident management procedures, better quantify the safety margins and help in finding out new risk scenarios;
2) the developed methodology presented here has the ability to use existing models and data. This can result in a work optimization and in an efficient use of resources when e.g., new data is available; moreover, the methodology workflow can be easily adapted for studying different kinds of external events risks;
3) the use of 3D flooding analysis tools like NEUTRINO can provide extremely realistic flooding simulations;
4) the use of HPC and machine-learning algorithms coupled to system TH codes can significantly ease the work of a safety analyst in handling the large amount of data that is generated when dealing with complex problems;
5) in general, the level of conservatism can be sensibly reduced, enhancing the economy and the safety level of a NPP.

Several parts of EEVE could be further improved in the next future. In particular researches are being focused on increasing the efficiency of the EMRALD sampling strategy, performing direct coupling between codes (e.g. EMRALD-RELAP5-3D/RAVEN) and optimizing RAVEN LS search algorithms. The ultimate goal is to have EEVE calculations (deterministic and probabilistic) carried out on a single HPC machine, thus leveraging the parallel calculation architecture.

ACKNOWLEDGMENTS

This manuscript has been authored by Battelle Energy Alliance, LLC under Contract No. DE-AC07-05ID14517 with the U.S. Department of Energy, Office of Nuclear Energy. The authors acknowledge the contributions of Bob Konsbab of SC Solutions LLC, Marietta (GA), the research team led by prof. Abinav Gupta at North Carolina State University, Raleigh (NC), and Ram Sampath, director of R&D of Centroid LAB, Mar Vista (CA).

REFERENCES

[1] U.S. NRC. “Procedural and Submittal Guidance for the Individual Plant Examination of External Events (IPEEE) for Severe Accident Vulnerabilities.” U.S. NRC, Washington, D.C., 1991.

[2] Szilard, R. H., Smith, C. L., & Youngblood, R. “RISMC Advanced Safety Analysis Project Plan.” Idaho National Laboratory, Idaho Falls, 2014.

[3] Szilard, R., & al. “Industry Application - External Hazard Analyses - Problem Statement.” Idaho National Laboratory, Idaho Falls, 2015.

[4] IAEA. “Deterministic Safety Analysis for Nuclear Power Plants.” Specific Safety Guide, IAEA, Vienna, 2009.

[5] Gaston, D., Hansen, G., & Newman, C.. “MOOSE: A Parallel Computational Framework for Coupled Systems for Nonlinear Equations”. *International Conference on Mathematics, Computational Methods, and Reactor Physics.* Saratoga Springs, NY, 2009.

[6] RELAP5-3D(c) Code Development Team. “RELAP5-3D code Manual Volume I: Code Structure, System Models and Solution Methods.” Manual, Idaho National Laboratory, Idaho Falls, 2015.

[7] LS-DYNA. (2013). *LS-DYNA Software Version smp R7.00.* Livermore Software Technology Corporation. Livermore: Livermore Software Technology Corporation.

[8] University of California. “OpenSees.” Retrieved 09 27, 2017, from http://opensees.berkeley.edu, 2017.

[9] Smith, C. L., & Wood, S. T. “Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE).” Idaho National Laboratory, Idaho Falls, 2011.

[10] Prescott, S., Smith, C., & Samptah, R. “Incorporating dynamic 3D simulation into PRA” Idaho National Laboratory, Idaho Falls, 2014.

[11] Sampath, R., Montanari, N., & Akinci, N. “Large-scale solitary wave simulation with implicit incompressible SPH”, *Journal of Ocean Engineering and Marine Energy,* 2016.

[12] Alfonsi, A., Rabiti, C., Mandelli, D., Cogliati, J., Wang, C., Talbot, P. W., et al. “RAVEN Theory Manual and User Guide.” Idaho National Laboratory, Idaho Falls, 2017.

[13] Spears, R., & Coleman, J. “Nonlinear Time Domain Soil-Structure Interaction Methodology Development”, Idaho National Laboratory, Idaho Falls, 2014.

[14] Parisi, C., Prescott, R., Ma, Z., Spears, R., Szilard, R., Coleman, J., Kosbab, B., “Risk-Informed External Hazards Analysis for Seismic and Flooding Phenomena for a Generic PWR”, INL/EXT-17-42666, Idaho National Laboratory, Idaho Falls, 2017.