|  |
| --- |
| INL/EXT-XXXXXXX  Revision: 0 |
| Implementation of Stochastic Polynomials Approach in the RAVEN Code |
|  |
| Cristian Rabiti  Paul Talbot  Andrea Alfonsi  Diego Mandelli  Joshua Cogliati |
| October 2013 |

**Disclaimer**

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the u.s. government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness, of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trade mark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. government or any agency thereof.

CONTENTS

[1. INTRODUCTION 1](#_Toc360437580)

[1.1 RAVEN: A Tool to Increase the Risk Management Capabilities for Nuclear Power Plants 1](#_Toc360437581)

[1.2 RAVEN: a Tool to Ensure the Deployment of the RISMC Concept 2](#_Toc360437582)

[1.3 RAVEN: as an Overall Control System 2](#_Toc360437583)

[1.4 Overview of the Document 2](#_Toc360437584)

[2. SOFTWARE INFRASTRUCTURE OVERVIEW 3](#_Toc360437585)

[2.1 Mathematical Formulation of the Problem 3](#_Toc360437586)

[2.1.1 System and Control Logic 3](#_Toc360437587)

[2.1.2 Modeling of Probabilistic Behaviors 4](#_Toc360437588)

[2.1.3 The Risk Weighted Formulation 5](#_Toc360437589)

[2.2 Software Infrastructure for RELAP-7 Interaction 6](#_Toc360437590)

[2.3 GUI Software Infrastructure 7](#_Toc360437591)

[2.4 Artificial Intelligence Aided Discovery Framework 8](#_Toc360437592)

[2.5 Dynamic Event Tree Approach 10](#_Toc360437593)

[3. REFERENCE PLANT ANALYSIS 11](#_Toc360437594)

[3.1 Description of the Graphical Input Process 13](#_Toc360437595)

[3.2 Control Logic Implementation 17](#_Toc360437596)

[3.3 Online Monitoring 19](#_Toc360437597)

[3.3.1 Postprocessors 19](#_Toc360437598)

[3.3.2 Visualize 20](#_Toc360437599)

[3.4 Result Analysis 21](#_Toc360437600)

[4. INTRODUCING STATISTICAL BEHAVIORS 23](#_Toc360437601)

[4.1 PWR SBO Test Case 23](#_Toc360437602)

[4.2 Modeling 24](#_Toc360437603)

[4.3 Results 25](#_Toc360437604)

[4.3.1 Explanation of the Effect on the Maximum Clad Temperature Using a Random Distribution on the Failure Temperature 29](#_Toc360437605)

[5. CONCLUSION 30](#_Toc360437606)

[5.1 References 31](#_Toc360437607)

[APPENDIX A: Station Black Out Inputs 33](#_Toc360437608)

FIGURES

[Figure 1: Deterministic (left) vs. probabilistic (right) system evolution 5](#_Toc360435381)

[Figure 2: Limit surface 6](#_Toc360435382)

[Figure 3: Software implementation 8](#_Toc360435383)

[Figure 4: Automatic process to construct the GUI interface 8](#_Toc360435384)

[Figure 5: Usage of a ROM to perform guided sampling 10](#_Toc360435385)

[Figure 6: Dynamic Event Tree Scheme 11](#_Toc360435386)

[Figure 7: Scheme of the PWR model 11](#_Toc360435387)

[Figure 8: Core Zone Correspondence 12](#_Toc360435388)

[Figure 9: Assembly Relative Power 13](#_Toc360435389)

[Figure 10: Peacock GUI for RAVEN 14](#_Toc360435390)

[Figure 11: Model of Plant with Navigation Buttons Highlighted 14](#_Toc360435391)

[Figure 12: Upper Toolbar 15](#_Toc360435392)

[Figure 13: Parameter Window with Three Sub-Windows 16](#_Toc360435393)

[Figure 14: Component Context Menu Example 16](#_Toc360435394)

[Figure 15: Generation of a controlled variable 18](#_Toc360435395)

[Figure 16: Generation of a monitored variable 18](#_Toc360435396)

[Figure 17: Generation of an auxiliary variable 19](#_Toc360435397)

[Figure 18: Tools creation 19](#_Toc360435398)

[Figure 19: Postprocessor tab 20](#_Toc360435399)

[Figure 20: Visualize tab 21](#_Toc360435400)

[Figure 21: Pump A (equal pump B) head evolution 22](#_Toc360435401)

[Figure 22: Average clad temperature in channel 1 22](#_Toc360435402)

[Figure 24: AC power recovery paths through: DGs (a), RSST (b) and 138KV line (c). Red lines indicate electrical path to power Auxiliary cooling system 24](#_Toc360435403)

[Figure 25: Recovery timings for DGs, RSSt and 138 KV line (color intensity is proportional to probability) 25](#_Toc360435404)

[Figure 26: Distribution profiles obtained from the 4000 sample for TC,fail 25](#_Toc360435405)

[Figure 27: Distribution profiles obtained from the 4000 sample for TDG1 (top left), TDG3 (top right), TRSST (bottom left) and T138 (bottom right) 26](#_Toc360435406)

[Figure 28: Temporal profiles of the clad temperature in CH1 for all the 4000 simulations 26](#_Toc360435407)

[Figure 29: Distribution of clad failure temperature (red) and maximum clad temperature reached in the simulation (blue) 27](#_Toc360435408)

[Figure 30: Max clad temperature histogram when failure is accounted for 28](#_Toc360435409)

[Figure 31: 2D limit surface 28](#_Toc360435410)

[Figure 32: 3D limit surface 29](#_Toc360435411)

[Figure 33: Combined effect of the uncertainty in the temperature failure on the maximum clad temperature recorded by the simulation 30](#_Toc360435412)

TABLES

[Table 1: Power distribution factor for representative channels and average pellet power 13](#_Toc360435413)

# INTRODUCTION

## RAVEN for Uncertainty Quantification

RAVEN, under the support of the Nuclear Energy Advanced Modeling and Simulation (NEAMS) [1] program, have been tasked to provide the necessary software and algorithmic tools to enable the application of the conceptual framework developed by the Risk Informed Safety Margin Characterization (RISMC) [2] path. RISMC is one of the paths defined under the Light Water Reactor Sustainability (LWRS) DOE program [3].

One of the most challenging requests of the RISMC framework is a holistic estimation of margins, and therefore uncertainties, in nuclear power plants (NPPs) system analysis. Those estimations, in conjunction with more accurate simulation tools, should enable an optimization process leading to safer and more economical competitive nuclear power plants.

The improvement of the accuracy of the simulations is tasked to other DOE projects like RELAP-7 [] while margin quantification and the generation of information suitable to perform safety margin managements is assigned to RAVEN.

How the uncertainty presents in the input parameters, used to build the mathematical representation of the NPP system, impacts the simulation results (uncertainty propagation) is clearly a fundamental step of the process. The uncertainty propagation analysis is a complex process and several methodologies are currently used. Clearly before deploying innovative algorithms base capabilities needs to be implemented and tested. This is the current stage of the RAVEN development project.

Earlier reports explain the implementation in RAVEN of Monte Carlo [] sampling methodologies, and also dynamic event trees []. Next step of this approaching strategy is here described and involves the implementation of the infrastructure to support the generalized Polynomial Chaos [] methodology for uncertainty propagation.

The report will cover the following subject, introduction of the generalized Stochastic Polynomial approach, description of the software implementation, and comparative analysis of clad failure probability between Monte Carlo and generalized Polynomial Chaos (gPC), in a Pressurized Water Reactor (PWR) following Station Black Out (SBO) condition.

# Generalized Polynomial Chaos

In general any response monitored of the plant (clad temperature, max pressure etc.) **U** at a given point in time could be represented as a function of the initial condition of the plant and of the values of the parameters used to construct the mathematical models. For our purpose lets’ consider a split of the input and parameter space such as and are respectively the initial condition and parameters not subjected to a probabilistic distribution while are. The dependence of from could be therefore neglected since not relevant to the discussion it will follow.

Next, we introduce the Lebesgue space equipped with measure (for simplicity for the moment we assume a one dimensional problem ),

being S the support of the measure, the scalar product in such space is therefore:

or under the assumption that the measure admit a density function

Now, if is a complete function basis on the Fourier theorem ensure that the series

is convergent being the moment of the series defined as it follows:

To reformulate the problem in space with standard measure it is sufficient to pose:

Assuming that are also a set of orthonormal polynomial with respect the measure (weighting function ) we can write the Fourier series convergent in the standard space as:

Where

The introduction of the space founds its utility when the measure is defined such as its density function is the square of the probability distribution function of ().

In this case the expected value of has an immediate formulation with respect the term of the Fourier series:

Where it has been used the property:

One of the most used cased and actually the first application of this methodology refers to the case where the is the normal distribution. For this special case the are the Hermite polynomials given by:

|  |  |  |
| --- | --- | --- |
| Order |  |  |
| 0 |  |  |
| 1 |  |  |
| 2 |  |  |
| 3 |  |  |

|  |  |  |  |
| --- | --- | --- | --- |
| Distribution | pdf | Polynomials | Support |
| Uniform |  | Legendre | [−1 : 1] |
| Normal |  | Hermite | [−∞ : ∞] |
| Exponential |  | Laguerre | [0 : ∞] |
| Beta |  | Jacobi | [−1 : 1] |