10 CFR 50.46c Rulemaking: A Novel Approach in Restating the LOCA Problem for PWRs

Cesare Frepoli(1), Joseph P. Yurko(1), Ronaldo H. Szilard(2), Curtis L. Smith(2) and Robert Youngblood(2)

(1) FPoliSolutions, LLC, 4618 Old William Penn Hwy, Murrysville, PA 15668, USA
*frepolc@fpolisolutions.com

(2) PO Box 1625, Idaho Falls, ID 83415-3870
ronaldo.szilard@inl.gov

Abstract

The USNRC is considering a rulemaking that would revise requirements in 10 CFR 50.46 (aka the ECCS rule). Experimental work sponsored by the USNRC suggested that the current regulatory acceptance criteria on ECCS performance during design-basis accidents are actually nonconservative for higher burnup fuel: that embrittlement mechanisms not contemplated in the original criteria exist, and the 17% limit on oxidation is not adequate to preserve the level of ductility that the NRC originally deemed to be warranted for adequate protection. The new rule imposes new acceptance criteria, and is expected to be in effect as early as 2016. An implementation plan was developed which, once the rule is amended, will give individual plants up to 24, 48 or 60 months to comply, depending on the status of each plant's analysis of record, the effort involved, and existing analytical margin to the limits.

The new rule may challenge US LWR fleet operational flexibility and economics. Within the DOE Light Water Reactor Sustainability (LWRS) Program, the INL is pursuing an initiative which is focused on industry applications using Risk-Informed Safety Margin Characterization (RISMC) tools and methods applied to issues that are of current interest to the operating fleet. The mission of RISMC is to provide cost-beneficial approaches to safety analysis by leveraging modern methods, augmented tools (a combination of existing and new), and repurposed data (existing, but used in a new way).

The objectives of this paper are to revisit and redefine the LOCA problem in light of the new rule, to propose a novel, RISMC-based approach to risk-inform the licensees' response to this rulemaking, to fully characterize LOCA effects, and potentially to optimize operational flexibility under the new rule. The goal is a Risk-Informed Margin Management (RIMM) tool for the industry to cope with the challenges associated with the more restrictive LOCA rule, the 10 CFR 50.46c. Uncertainty analysis for the RIMM Integrated Evaluation Model (IEM) will be performed with algorithms derived from the machine learning community. These techniques will enable responsive sensitivity and optimization studies.

Keywords: 10 CFR 50.46, LOCA, RISMC, RIMM

1. BACKGROUND

The 10 CFR 50.46 rule defines the acceptance criteria for emergency core cooling systems for light-water nuclear power reactors. To comply with the rule, the industry calculates the E*CCS cooling performance with an acceptable evaluation model. The analysis must include a number of postulated loss-of-coolant accidents of different sizes, locations, and other properties sufficient to provide assurance that the most severe postulated loss-of-coolant accidents are calculated*[1].

Currently, the NRC allows two alternative methods to demonstrate compliance with the rule. A prescriptive, deterministic, and conservative[2] method, Appendix K to Part 50, provides required and acceptable features for the ECCS Performance Evaluation Models (EMs). Alternatively, Best-Estimate-Plus-Uncertainty (BEPU) methods can be used. For BEPU licensing analyses, the evaluation model must include sufficient supporting justification to show that the analytical technique realistically describes the behavior of the reactor system during a loss-of-coolant accident.

Bias and uncertainties in the EM are derived from comparisons to applicable experimental data. The analysis also needs to account for the uncertainties in design inputs.

The rule requires that the *[…] uncertainty must be accounted for, so that, when the calculated ECCS cooling performance is compared to the criteria set forth in paragraph […], there is a high level of probability that the criteria would not be exceeded.* […]

Regulatory Guides 1.157 [1] and 1.203 [2] provide guidance on how to set up such methods in order to meet USNRC expectations.

LOCA methods are still constructed outside a risk-informed paradigm in the sense that safety analysis is formulated to support findings regarding reasonable assurance of adequate protection based on a specific surrogate for "safety." In particular, specific "design-basis" accidents serve as proxies for a certain portion of the spectrum of challenges to plant safety functions; satisfactory performance in these types of accidents (as demonstrated based on conservative analysis) is considered to be evidence of a certain kind of "safety."

As a result, BEPU methods today still contain a high degree of conservatism, mostly to cover a lack of knowledge in some phenomena and to ease licensing and implementation. For some purposes, lack of knowledge is compensated by layers of conservativism to enable the practical execution and licensing of the analysis required to demonstrate the safety of the engineered device.

Despite these conservative biases, in the last decade the use of best-estimate plus uncertainty Loss of Coolant Accident (LOCA) methodologies has become the *de-facto* standard in the

---

[1] Text italicized is a direct reproduction of the 10 CFR 50.46 rule language

[2] Note that potential sources of "non-conservativism" in the Appendix K of 10 CFR 50.46 rule were identified in 2001 by the USNRC in support of Risk Informed Regulation (http://pbadupws.nrc.gov/docs/ML0217/ML021720716.pdf)

industry. More than 75% of the Pressurized Water Reactor (PWR) fleet in the United States (U.S.) is currently analyzed using best-estimate methods. The implementation of BE LOCA methods in the US enabled power uprate and increase operational flexibility of the power plants. A review of the power uprates can be found in [3].

In the US PWR fleet, the two main methodologies applied are the AREVA realistic Large-Break LOCA (LBLOCA) [4] [5] and Westinghouse Electric Company (WEC) LBLOCA EM [6] [7] [8].

The historical evolution of these methods can be followed in the publically-available literature. Westinghouse first introduced BEPU methods for license application in the early 1990's, in response to the introduction by the NRC of the CSAU methodology, which was proposed in the late 80's [9] [10]. The evolution of AREVA Realistic LBLOCA methodology can be found in the review paper by Martin et al. [5]

As far as the uncertainty treatment, early versions of the BEPU approach (1990's) by WEC followed very closely the CSAU roadmap, which suggested the use of the response surface technique, a crude surrogate of the relationship between inputs and outputs. The AREVA method was the first to receive approval of the replacement of the response surface technique proposed by the CSAU with the non-parametric order statistics approach (Wilks' approach). In the industry, this is typically referred to as the Wilks's approach, since the theoretical work stems from the 1940's work by Wilks on how to determine tolerance limits in the manufacturing industry.

In the early 2000's, following this trend, WEC started the development of ASTRUM as the new generation of LBLOCA EM. The ASTRUM Topical Report was submitted to the NRC for review on June 2, 2003, and the SER was received November 5, 2004.

The introduction of the AREVA Realistic LBLOCA EM in the early 2000's, shortly followed by the WEC ASTRUM EM, presents some important features which distinguish them from previously approved methods in the industry:

1) Allowance of sampling the break size as one of the uncertainty parameters.

2) Allowance of sampling the burnup for the assemblies in the core, or often presented as sampling "time in cycle" as an uncertainty parameter.

3) Direct Monte Carlo sampling of uncertainties with minimum sample and use of non-parametric order statistics to infer probabilistic statements to comply with 10 CFR 50.46 acceptance criteria.

Soon after ASTRUM received NRC approval [11], in 2005 WEC began the development of the Full Spectrum LOCA [12]. The FSLOCA Topical Report, WCAP-16996-P, was submitted to the NRC in November 2010 and is still under NRC review.

In parallel to power uprates, a trend of improving fuel utilization over the years has led to an increase of discharge burnup of the fuel, which almost doubled in the last two decades. The current regulatory limit is 62 MWd/kg; however, the limit is likely to be increased in the future.

The NRC and the industry overall gathered a significant amount of data and information relative to fuel degradation effects under extended irradiation. As a result, a wealth of information on the behavior of fuel at high burnup was collected over the same time period. Oxidation, embrittlement, and deformation of fuel and fuel cladding under LOCA conditions have been extensively investigated.

A detailed review of these findings is beyond the scope of this paper; however, significant literature and regulatory material are available. This research expanded the knowledge base to support a better understanding of LOCA-related phenomena.

LOCA separate-effects methods and tests have been carried out to gather knowledge on cladding creep, diffusion constants for α to $\alpha+\beta$ and $\alpha+\beta$ to β transformation temperatures, ductility, the effect of hydrogen and oxygen on residual cladding ductility, and integral quench tests for strength. LOCA phenomena such a ballooning, burst, oxidation, fuel relocation and possible fracture at quench have been further investigated. Methods for LOCA oxidation testing and details of high-temperature oxidation behavior of cladding material are available. This also includes two-sided oxidation and ring compression for ductility, in-reactor and out-of-reactor cladding deformation experimental data, experimental studies of coolability of a deformed core under LOCA conditions, and additional data for validation of transient fuel performance computer codes.

As a result of these findings, the NRC has been considering a rulemaking that would revise requirements in 10 CFR 50.46 (the 10 CFR 50.46c ECCS rule). The work sponsored by the NRC suggested that the current regulatory acceptance criteria are actually nonconservative for higher burnup fuel (i.e., that embrittlement mechanisms not contemplated in the original criteria exist, and the 17% limit on oxidation is not adequate to preserve the level of ductility that the NRC originally deemed to be warranted for adequate protection).

Draft Regulatory Guide DG-1263 [13] defines an acceptable analytical limit on peak cladding temperature and integral time at temperature for the zirconium-alloy cladding materials tested in the U.S. Nuclear Regulatory Commission's (NRC's) loss-of-coolant accident (LOCA) research program. For example, Figure 1 from the DG-1263 (reproduced here as Figure 1) develops the analytical limit that will replace the current 17% limit. The hydrogen content (ppm) depends on the burnup value and material characteristic of the cladding, i.e. performance to embrittlement under irradiation for a specific cladding alloy. The ductile-to-brittle threshold, defined in the figure, is an acceptable analytical limit on integral time at temperature (as calculated in local oxidation calculations using the Cathcart-Pawel (CP) correlation [14].

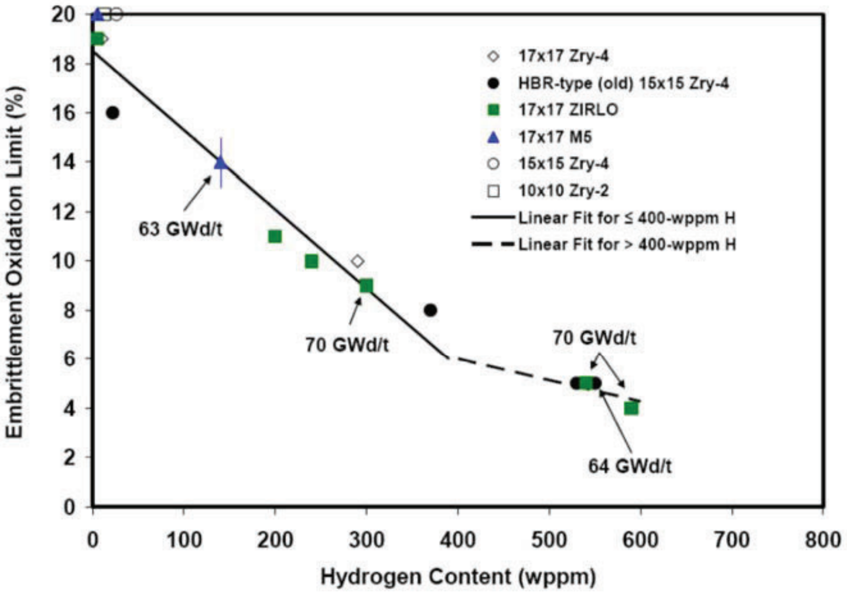

Figure 1. Ductile-to-brittle transition oxidation level (CP-ECR) as a function of pretest hydrogen content in cladding metal for as-fabricated, prehydrided, and high-burnup cladding materials. Samples were oxidized at ≤1,200 °C ±10 °C and quenched at 800 °C. For high-burnup cladding with about 550-wppm hydrogen, embrittlement occurred during the heating ramp at 1,160–1,180 °C peak oxidation temperatures (Ref. 8).

Figure 1 – Figure 1 from DG-1263 (ADAMS Accession Number ML12284A323)

The draft rule was published on the Federal Register in 2014 [15]. This rule is what is referred to as 10 CFR 50.46c.

Assuming that the ECCS rulemaking goes forward in essentially its current form, licensees will eventually need to perform and submit revised accident analysis that addresses the new acceptance criteria.

Overall, the rule is expected to be more restrictive than the current rule; therefore, the industry is responding by improving their methods to prevent undue restriction to the operation of the plants. Moreover, while best-estimate methods for LOCA safety analyses have been accepted by the regulators under the current rule, there are several issues and limitations still under debate which can be potentially exacerbated under the new rule.

2. REVIEW OF CURRENT LOCA ANALYSIS PROCESS

A LOCA safety analysis involves several disciplines which are computationally loosely (externally) coupled, in order to facilitate the process and maintenance of legacy codes and methods. A cursory review of a few examples of analyses performed by vendors such as AREVA and Westinghouse Electric Company (WEC) helps to define the state of the art in the industry.

The key disciplines involved are:

- Core Design
- Fuel Rod Design
- Containment
- Fluid systems and NSSS design.

A review of publically available input assumption lists is useful to identify the stream of inputs and outputs parameters across these disciplines.

Model and input uncertainties are propagated in the chain of analyses, where LOCA resides at the end of the data stream and the analysis is intended to demonstrate compliance with the ECCS design acceptance criteria. The demonstration is achieved by searching for the limiting case within the issue space. Limiting case is here intended to be the limiting case in a minimum sample that is sufficient to satisfy the rule - 95/95 probability of not-exceedance of the 10 CFR 50.46 limits – for acceptable parameter ranges over which the analyst is allowed to sample.

Given that the limiting case has appropriate margin to acceptance criteria, it can then be argued that ECCS performance is adequate. Classically, identification of the limiting case has been done manually, and the complexity of the problem has led to numerous instances in which the analysis of record was based on a non-limiting case.

The paper by Frepoli [9] describes the evolution of the LBLOCA analysis and how it is currently performed in the industry. In a nutshell, once data is gathered and the NPP model developed, the analysis is fully automated with the simulation of several instances of LOCA scenarios which represent realizations randomly sampled following a crude Monte Carlo procedure. The procedure considers the most important sources of uncertainties which have been properly characterized with their own probability density functions. About 40 uncertainty parameters are typically considered in a LOCA analysis [9]. Figure 2 depicts the process. The vector ***x*** is the vector of randomly sample input settings, while the vector ***y*** is the vector of the outcomes, typically the target figures of merit (FOMs), such as Peak Clad Temperature (PCT), (Maximum Local Oxidation (MLO) and Core-Wide Oxidation (CWO)).

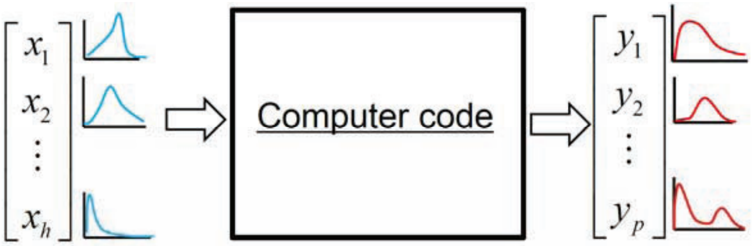

Figure 2 – Monte Carlo Forward Propagation of Uncertainties

The outcome of the analysis results in a sample of results which can be collected as shown in Figure 3 which presents sample results from a typical WEC ASTRUM analysis [9] (left) and a typical AREVA Realistic LBLOCA analysis [16] (right).

The red marks on the left and square on the right identify double-ended guillotine cases while the other are split breaks which stretch down to an equivalent break size of 1.0 ft^2 assumed to be minimum size of a large break. Noticeable the two methodology differ in the break type and size sampling approach.

The compliance is demonstrated by ensuring that the maximum PCT value, the maximum MLO value and maximum CWO value in the 124-set are below the acceptance criteria, which in the current rule are respectively 2200 ºF, 17% and 1%. The procedure guarantees that a joint probability of 95% on the three criteria is satisfied with 95% confidence.

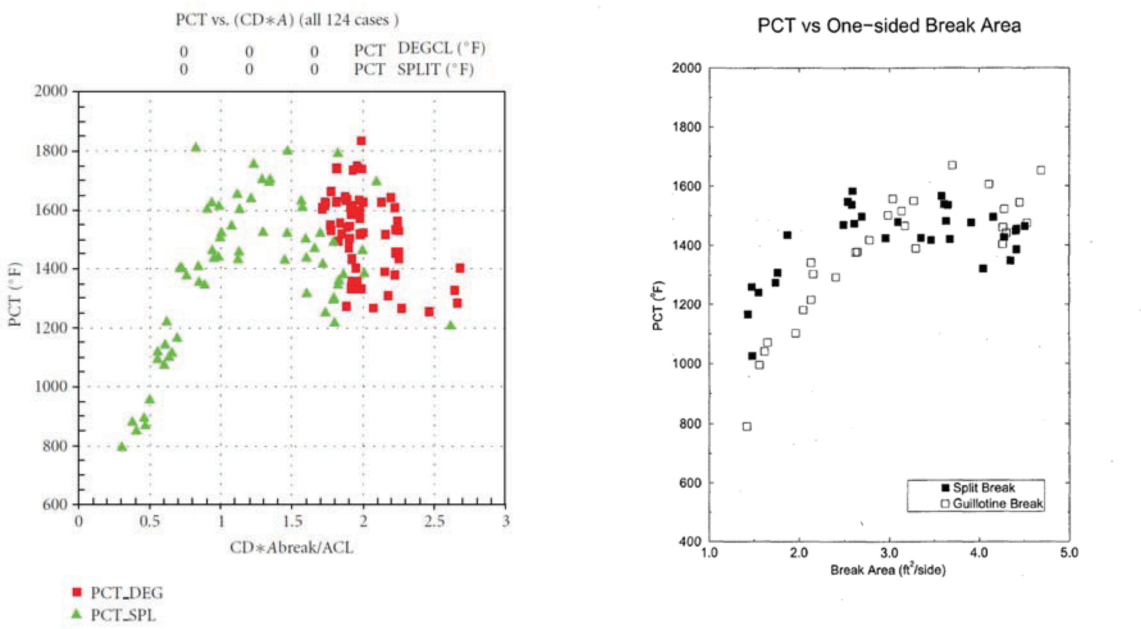

FIGURE 7: Peak clad temperature (PCT) from the ASTRUM 124 run set.

Figure 3-8 PCT versus Break Size Scatter Plot from 59 Calculations

Figure 3 – Scatter Plots for PCT in a Typical WEC ASTRUM (left, Figure 7 from Frepoli [9]) and AREVA Realistic LBLOCA Analysis [16]

3. DEFINITION OF THE LOCA PROBLEM UNDER THE NEW RULE

Section 2 described how the industry has been addressing the LOCA rule so far. The analytical work required to demonstrate compliance with 10 CFR 50.46 is typically performed by the vendors on behalf of the licensees (plant operators). Over the years, methodologies evolved from a deterministic Appendix K approach to Best-Estimate Plus-Uncertainty (BEPU) methods which spun off from the CSAU work in the 1980's.

As stated in Section 2, the requirement to identify the "limiting case" has been deemed satisfied if input and model uncertainties are sampled within realistic, albeit conservative ranges, and combined via Monte Carlo (MC) techniques. Compliance is demonstrated by a 95/95 joint-probability statement from the sample of simulations with respect to the three main acceptance figure of merits (FOM): PCT, Maximum Local Oxidation and Core-Wide Oxidation.

The re-definition of the LOCA problem translates into two key questions:

1) Can we envision an analytical tool/methodology that can help in addressing LOCA 'legacy' issues that the industry is facing?

2) Can this advanced tool fit well in the context of the new rule (10 CFR 50.46c)?

The 'legacy' issues are the intrinsic limitations in the current approach to the LOCA problem which are expected to escalate under the proposed new rule change, because the FOM is a much more complex multi-dimensional variable than a simple PCT or maximum local oxidation limit.

The recognized limitations in established industry methods are:

1. There is little knowledge on why the so-called limiting case is limiting. The applicant is simply interested in the final probabilistic statement that the ECCS design is acceptable under the rule.
2. The result, specifically the 95/95 estimate, is strongly impacted by the limits of the sample size, seed issues, and unquantified risk of exceedance of the regulatory limit. For purposes of assessing "adequate protection," this has typically been justified, considering the several layers of conservative biases embedded in the methodology.
3. There is no information or a simple method to perform global sensitivities. The sample size (statistics) is too small to provide a reliable answer.
4. There is limited information on which parameters are important.
5. Impact assessments on plant design changes and design optimization studies are extremely cumbersome, lengthy, and unresponsive, unless design changes are small enough that they can be addressed by engineering judgment.
6. There is limited information on the actual probability of exceeding a limit in a given design. Compliance with the rule within the licensing basis of an approved EM is the primary objective of the licensee.

Vendors and plant owners operate in a heavily regulated environment. The economics prevent deviations from well established procedures within the licensing basis of the Evaluation Models. The multi-physics problem is solved via operator splitting procedures. Interfaces across the disciplines and processes do not easily adapt to a new fully integrated method. The propagation of uncertainties across the various functional groups is addressed by defining bounding assumptions at the interfaces, which limits the possibility that the impact on an issue in a specific discipline crosses over to the other physics.

Moving forward, the industry is expected to develop better standardized databases and improved interfaces across the various engineering disciplines as more automation is implemented in those processes. This will enable consideration of new paradigms to manage the uncertainties across the various disciplines with a truly multi-physics approach to the LOCA problem.

In addition to legacy issues, the new rule will challenge historical assumptions in the LOCA analysis which add complexity to the process of updating the Analysis of Record (AOR). For example, the characteristics of the Hot Assembly (HA), a surrogate for the most limiting fuel assembly in the core at the time when the LOCA is postulated to occur, will require either sophisticated trade studies or, alternatively, the full core to be explicitly accounted for in the analysis. The applicant may always choose a very bounding approach for the sake of analysis process simplification or ease of licensing. However, in that case, a significant amount of margin may be trapped in an analytical space and removed from plant operator discretion.

4. THE RISK INFORMED MARGIN MANAGEMENT METHODOLOGY

Within the RISMC Pathway of the DOE LWRS Program [17], the Risk-Informed Margin Management (RIMM) project [18] is expected to create value by anticipating industry trends and focusing on developing a methodology that effectively addresses the above-discussed limitations in the way LOCA analysis are conducted today. The primary goal of the RIMM is to explore an integrated approach for knowledge and uncertainty management, as illustrated in Figure 4. The resulting analytical tool is called RIMM Integrated Evaluation Model (RIMM IEM). The functional requirements and vision for the RIMM IEM are briefly presented in this paper.

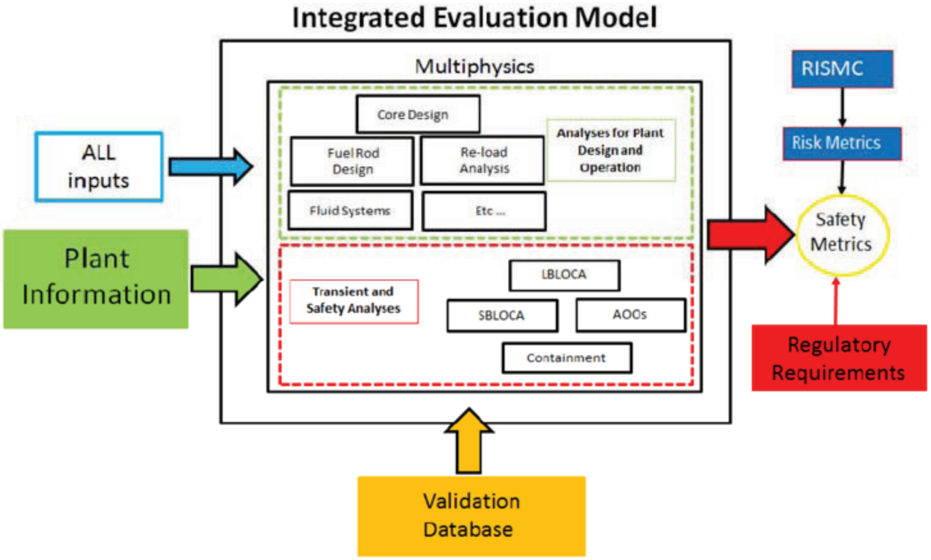

Figure 4 – Flow Chart of the RIMM Integrated Evaluation Model

Each of the physics domains in the IEM is traditionally analyzed separately in each functional group of the organization. Data is passed from one functional group to another via formalized interface procedures. The RIMM IEM methodology attempts to remove those interfaces, allowing the information to pass seamlessly between the various disciplines. As will be described below, current industry practices provide considerable resistance to such a framework. Overcoming those hurdles allows the RIMM IEM to capture as much as the current state of knowledge as possible.

4.1 Resistance to Integration

The classical nuclear safety analysis that is done for licensing purposes has relied on the following two kinds of simplifications:

- Focus on a selected set of events that are supposed to envelope probabilistically significant events of potential concern
- Analyze those events in a systematically conservative way: introduce approximations and assumptions that tend to make the results worse than reality; therefore, if system performance is found to be acceptable for a given event within that body of approximations and assumptions, there is a high probability that it really is acceptable for that event.

It is also noted that, even when safety analyses are performed within the BEPU framework, by necessity (incomplete knowledge and licensing demand) conservativisms are added in the analysis, and, in many circumstances, are unquantified. These limitations trap *de-facto* potential operating margin in analytical space. The new 10 CFR 50.46 is expected to be more restrictive than the current rule and will exert further pressure on the licensees to develop a better understanding of the actual margin available in their plant to continue in their path of keeping the nuclear option economically viable.

The propagation of uncertainties across the various functional groups is complex. This is typically addressed defining bounding assumptions at the interfaces to limit the possibility that an issue in a specific domain (error discovered, design change or other) might cross over to another domain. Such processes and interfaces do not easily adapt to new integrated methods and cannot fully leverage the progress that has been made in computation and numerical algorithms. Also, there is a difficulty in absorbing new knowledge in the processes that are now recognized by regulators and the industry as a whole. In other words, the methods are ‘not responsive’ or limited in their responsiveness. Economic factors and regulatory risk considerations tend to freeze the technology.

Even state-of-the-art BEPU methods provide little information on the actual margin available in the plants. Most margin resides in engineering judgment and grossly conservative assumptions which were built to deal with the ‘imperfect knowledge.’

4.2 RIMM IEM Value Proposition

The trend toward a better risk-informed paradigm when dealing with safety analyses has been facing considerable resistance because of the above considerations. The RIMM project is expected to facilitate a paradigm shift and anticipate industry trends toward a risk informed approach. The process starts by developing a methodology that effectively addresses the limitations in the *status quo* presented above. The vision for the RIMM IEM is summarized in the following propositions:

1. Provide analytical capabilities for the plant operator to enable rapid risk-informed decisions on considered changes within the LOCA issue space (as regulated under the new 10 CFR 50.46c). The goal is to reduce the response cycle by at least an order of magnitude.

2. Enable factoring current knowledge into the process to enhance safety and operation optimization, two objectives not necessarily in conflict.

3. Quantify currently unquantified uncertainties and trend to a truly realistic representation of the LOCA which provides insights on the design otherwise distorted by undue biases.

4. Develop new knowledge and understanding of the LOCA scenario, which is currently obscured by the engineering assumptions of classical licensing calculations. Enable a more effective ‘exploration’ of the issue space.

5. Eliminate the issues associated with the so-called Wilks’ approach (variability in the estimator, i.e. risk of under-prediction of or over-prediction of FOM, lack of knowledge in what’s truly limiting in the design, incapacity to perform sensitivity studies, impact assessment etc.)

6. A ‘plug-and-play’ design philosophy of the multiphysics toolkit which enables plant owners and vendors to consider and further develop RIMM Framework for use within their established codes and methods.

4.3 RIMM IEM High Level Functional Requirements

The RISMC is now sufficiently matured to offer a potential solution to the LOCA problem and provide to the plant operator a vehicle to manage the margins and inform decisions when compliance with 10 CFR 50.46 is challenged by changes in the operational envelope.

The RIMM IEM will leverage use of well-established analytical tools such as RELAP5-3D coupled with core physics and fuel rod performance tools. A large set of simulations will be performed in high performance computational platforms at INL. Uncertainty analysis for the RIMM IEM will be performed with algorithms derived from the machine learning community [19]. These techniques will enable responsive sensitivity and optimization studies.

The current method proposes to use emulators to act as very fast approximations to the input/output relationship. After an initial set of computer code evaluations required to build or train the emulator, it is used in place of the computer code in the Monte Carlo sampling scheme. A crude emulator-based approach to UQ was proposed as part of the original CSAU method for propagating uncertainties [20] (the response-surface technique). One advantage of the new emulators considered in this work is the inclusion of an estimate of the emulator’s own predictive uncertainty.

Following the nomenclature from various references, approximations to the behavior of the computer code (simulators) are referred to as emulators. An important example is the Gaussian

Process (GP) regression model [21], [22], [23]. As an emulator, the GP is considered a Bayesian non-parametric non-linear model. The GP has many useful and beneficial mathematical properties that have helped to promote its widespread adoption as an emulator.

Here, the GP emulator procedure is integrated into a Monte Carlo sampling scheme. The initial set of computer code training runs is performed by choosing specific sets of input values. The training set requires Design of Experiment type techniques, but typically space-filling Latin Hypercube Sampling is used [23]. A typical "rule of thumb" is to use of the order 10 training runs per input [21].

The emulator-based technology will allow the analyst, plant operator, to probe information from a pre-set large training database of simulations. The database is 'elastic' in the sense that "new information" is added to the "knowledge database" as it becomes available. Also the plug-and-play concept will enable a quick replacement of the simulator codes with method of choice by user. In other words the methodology "Framework" is independent on the specific computer codes selected to represent the different physics.

When the design change is within the envelope of the training set, the fast-running Framework can be used to infer a prediction rather than re-running the entire set of simulations.

Note that the RIMM IEM is not intended to replace licensing AORs, but rather to replace or aid the 'engineering judgment' applied in managing those AORs. In other words, the RIMM IEM is a margin management tool. This objective is achieved by representing the plant realistically with as many uncertainties included as possible. The uncertainties included in the analysis are chosen by considering and managing the entire body of knowledge - the "Knowledge Database" -which goes beyond regulatory and licensing concerns. The issue of unknown unknowns is typically treated adding conservative biases. However the issue related to model discrepancy and scaling distortion and their impact to uncertainty quantification is beyond the current scope of the project and will be considered in later stages.

A multigenerational development plan has been developed. The focus in 2015 is an early demonstration of the RIMM concept (eDemo). The eDemo is intended to provide confidence of the technical maturity in the RISMC methodology (essential for broad industry adoption) and encourage strong industry stakeholder interaction and support for the following phases. Later phases will focus more attention on validation and calibration of the IEM methodology.

5. CONCLUSIONS

This paper provides a definition of the "LOCA problem" in the context of the proposed 10 CFR 50.46c rulemaking. A roadmap to the demonstration of the application of the RISMC methodology of the RIMM Industry Application #1 (Integrated Cladding/ECCS Performance Analysis [24]) is provided. The outcome is the development of the RIMM IEM introduced in this paper. Section 4 lists the RIMM IEM high level functional requirements and suggests the value proposition for the industry.

In a nutshell, the RIMM IEM is expected to be a margin management tool for the industry to cope with the challenges associated with the more restrictive LOCA rule, the 10 CFR 50.46c which is expected to be amended in 2016. The industry will need to comply with the new rule within the following five to ten years and the RIMM IEM is anticipated to be a valuable tool for plant operators and vendors to facilitate these activities.

The RIMM IEM is not intended to replace licensing AORs, but rather to replace or aid the 'engineering judgment' which is typically applied in the management and maintenance of those AORs. The goal is an analytical and computational device that can represent a power plant realistically with all the uncertainties included and that considers all physical disciplines involved in an integrated fashion, i.e. an Integrated Evaluation Model (IEM). The tool will enable a plant operator to manage the entire body of knowledge – here called the "Knowledge Database" - to inform decisions that minimize or manage the risks of exceeding the LOCA criteria while allowing a safe and economical operation of the plant by eliminating or reducing the need for expensive re-analyses. At a minimum, the RIMM IEM tool will be a very valuable tool to inform licensees and regulator about real margin available in their plants on an interim basis while new license-grade evaluation models are being rolled out.

6. REFERENCES

[1] U.S. Nuclear Regulatory Commission, "Regulatory Guide 1.157 - Best-Estimate Calculations of Emergency Core Cooling System Performance," U.S. NRC, Washington D.C, 1989.

[2] NRC, "http://pbadupws.nrc.gov/docs/ML0535/ML053500170.pdf," 2005. [Online].

[3] "http://www.nrc.gov/reactors/operating/licensing/power-uprates.html," [Online].

[4] B. Dunn and e. al., "Realistic Large Break LOCA Methodology for Pressurized Water Reactors, Revision 2," AREVA NP Inc., 2010.

[5] P. R. Martin and L. D. O'Dell, "Development Considerations of AREVA NP Inc.'s Realistic LBLOCA Analysis Methodology," *Science and Technology of Nuclear Installations,* vol. 2008, p. 13, 2008.

[6] M. Y. Young, S. M. Bajorek, M. E. Nissley and L. E. Hochreiter, "Application of Code Scaling Applicability and Uncertainty Methodology to the Large Break Loss of Coolant," *Nuclear Engineering and Design,* vol. 186, no. 1-2, 1998.

[7] M. E. Nissley, "Method for Satisfying 10 CFR 50.46 Reanalysis Requirements for Best-Estimate LOCA Evaluation Models," Westinghouse Electric Compnay, LLC, Pittsburgh, PA, 2004.

[8] M. E. Nissley, C. Frepoli, K. Ohkawa and K. Muftuoglu, "Realistic Large-Break LOCA Evaluation Methodology Using the Automated Statistical Treatment of Uncertainty Method (ASTRUM)," Westinghouse Electric Company, Pittsburgh, PA, 2003.

[9] C. Frepoli, "Review Article - An Overview of Westinghouse Realistic Large Break LOCA Evaluation Model," *Science and Technology of Nuclear Installations,* vol. 2008, p. 15, 2008.

[10] C. Frepoli and K. Ohkawa, "Westinghouse Experience in Licensing and Applying Best-

Estimate LOCA Methodologies within the Industry: Past, Present and Future," in *Workshop on Best Estimate Methods and Uncertainty Evaluations*, Barcelona, Spain, 2011.

[11] U.S. Nuclear Regulatory Commission, "Safety Evaluation by the Office of the Nuclear Reactor Regulation Topical Report WCAP-16009-P. Revision 0, "Realistic Large Break LOCA Evaluation Methodology Using Automated Statistical Treatment of Uncertainty Method (ASTRUM)"," U.S. NRC, Washington, DC, November 5, 2004.

[12] C. Frepoli and e. al., "Realisitic LOCA Evaluation Methodology Applied to the Full Spectrum of Break Sizes (FULL SPECTRUM LOCA Methodology)," Westinghouse Electric Company LLC, Pittsburgh, PA, 2010.

[13] NRC, "http://pbadupws.nrc.gov/docs/ML1228/ML12284A323.pdf," [Online].

[14] J. V. Cathcart, P. R. E. and a. et., "Zirconium Metal-Water Oxidation Kinetics IV. Reaction Rate Studies," ORNL/NUREG-17, 1977.

[15] " Proposed Rules," Federal Register, Vol. 79, No. 56, Monday, March 24, 2014.

[16] NRC, "http://pbadupws.nrc.gov/docs/ML0933/ML093350101.pdf," 2009. [Online].

[17] D. Mandelli and C. Smith, "Light Water Reactor Sustainability Program – Risk- Informed Safety Margin Characterization Methods Development Work, INL-EXT-14-33191," September 2014.

[18] R. Szilard, C. Smith and R. Youngblood, "Light Water Reactor Sustainability Program – RISMC Advanced Safety Analysis Project Plan FY2015-FY2019, INL-EXT-33186," September 2014.

[19] C. Rasmussen and C. Williams, Gaussian Processes for Machine Learning, Springer-Verlag, 2004.

[20] B. Boyack and e. al., "Quantifying Reactor Safety Margins," 1989.

[21] "[Online], Managning Uncertainty in Complex Models Toolkit," [Online]. Available: http://www.mucm.ac.uk/.

[22] D. Higdon, M. Kennedy, J. Cavendish, J. Cafeo and R. Ryne, "Combining field data and computer simulations for calibration and prediction," *SIAM Journal on Scientific Computing,* vol. 26, pp. 448-466, 2004.

[23] D. Higdon, J. Gattiker, B. Williams and M. Rightley, "Computer model calibration using high-dimensional output," *Journal of the American Statistical Association,* vol. 103, no. 482, 2008.

[24] D. Mandelli, C. Smith, M. Z. T. Riley, J. A. A. Nielsen, C. Rabiti and J. Cogliati, "INL/EXT-14-33191 - Light Water Reactor Sustainability Program, Risk-Informed Safety Margin Characterization Methods Development Work," INL, 2014.