Multi-Physics Best Estimate Plus Uncertainty (MP-BEPU) Analysis Framework LOTUS and RELAP5-3D

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This work extends Best Estimate Plus Uncertainty (BEPU) beyond thermal hydraulics to include quantification of uncertainties in calculations that have multiple phenomenological areas.

Introduction

Many innovative technologies, such as longer operating cycles, higher fuel enrichment, higher burnup of discharged fuel, and power uprates, have resulted in remarkable improvements of economic performance of the existing nuclear power plants (NPP). For instance, the total additional power generated from U.S. NPP power uprates is equivalent to that of building six new 1,000-MWe NPPs. However, some of the innovations as well as plant aging have also eroded the available safety margins of these plants. The nuclear industry is able to recover the safety margin through plant equipment upgrade and modernization and by developing best estimate plus uncertainty (BEPU) modeling and simulation methodologies. The key aspect of BEPU methodology is to quantify uncertainties in the calculations with multiple disciplines involved. However, computational constraints to analyze highly complex systems, which include with many variables to be considered, have previously kept us from executing multi-physics types of schemes. The existing BEPU methodology primarily focuses on the uncertainties in thermal hydraulics. This methodology is depicted in Figure 1 using the process for loss-of-coolant (LOCA) analysis as an example:

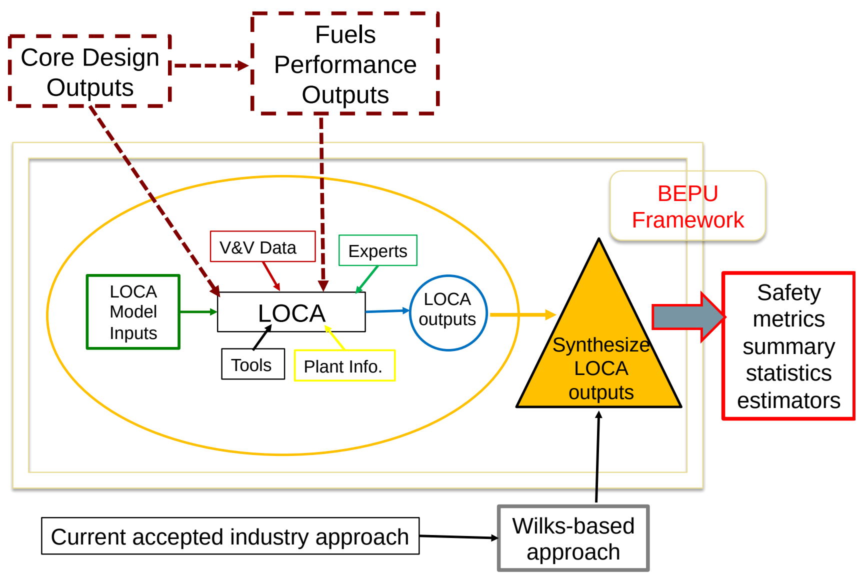

Figure 1. Schematic illustration of the current BEPU process for LOCA analysis

It is noted that current BEPU method still contains a high degree of conservatism, mostly to cover a lack of knowledge of some phenomena and to simplify licensing and implementation. Further, the propagation of uncertainties across the various disciplines is addressed by defining bounding assumptions at the interfaces that limit the possibility to consistently propagate uncertainties in multi-physics simulations. Existing BEPU methods provide limited information on the actual margin available in the plants. Most margins reside in engineering judgment and conservative assumptions, which were built to deal with the imperfect knowledge.

IMPROVEMENTS

Moving forward, the nuclear industry is expected to develop better-standardized databases and improved interfaces across the various engineering disciplines as more automation is implemented in the processes. This will enable consideration of new paradigms to manage uncertainties across various disciplines with a truly multi-physics approach to the safety analysis problem. This will become more important with industry's push to introduce accident tolerant fuel and to adapt to a flexible operating strategy, within which the fuels behavior must be considered within the context of entire plant system behavior. Fortunately, with the advancements in computing power over the past several decades, multi-physics simulations are now practical. The Risk-Informed Safety Margin Characterization (RISMC) Pathway of the LWRS Program is developing a Multi-Physics Best Estimate Plus Uncertainty (MP-BEPU) framework, called LOTUS. Uncertainties can be propagated consistently in a multi-scale and multi-physics environment to fully realize the benefits of multi-physics simulations. Taking advantage of state-of-the-art computational architectures, LOTUS aims at integrating various simulation tools in Core Design, Fuels Performance and Systems Analysis to implement complex multi-physics approaches to solve fully coupled NPP systems problems in an acceptable time.

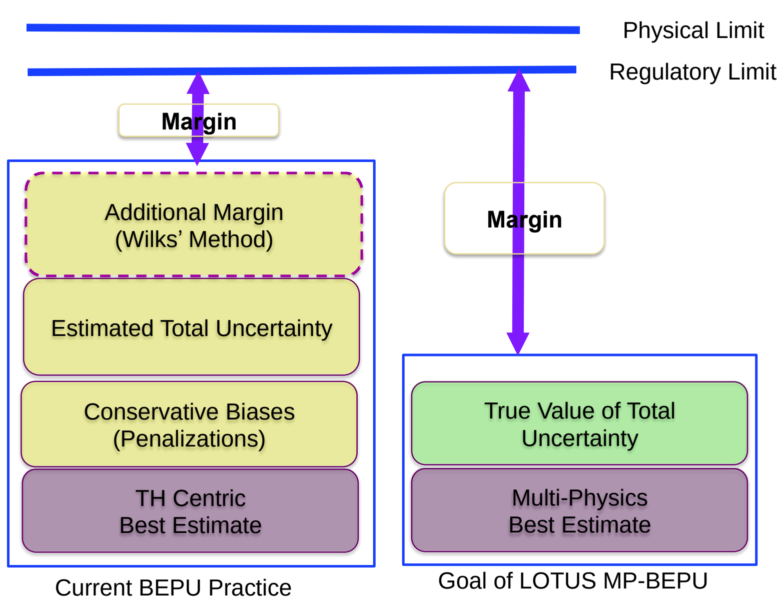

Figure 2. Paradigm shift in managing margins with LOTUS Multi-Physics BEPU

Figure 2 shows the comparison between the current BEPU approach and the MP-BEPU approach to be developed in the LOTUS framework. The column on the right in Figure 2 is the “ideal final solution” in a situation of “perfect knowledge”. In that situation, LOTUS should be able to predict the “true” best-estimate or “nominal” state of the device (given plant, scenario, etc.) and then account for all the uncertainties that can be combined in what is called the “true/theoretical value of total uncertainty”. Compliance with the acceptance criteria is demonstrated by showing that the MP-BEPU value is below the regulatory limit, which is designed by regulators to be below the physical limit.

Description of LOTUS

LOTUS, as shown in Figure 3, is envisioned as a virtual environment that is composed of many different computer codes such as VERA-CS and PHISICS for core design automation, FRAPCON/FRAPTRAN and BISON for fuels performance and RELAP5-3D and RELAP-7 for systems analysis. Since different models and assumptions have gone into different computer codes, one important aspect of the LOTUS development is to address the model inconsistencies as much as possible to minimize the impact of such inconsistencies. Another important feature to stress in the LOTUS development is that the uncertainties are propagated directly from all the uncertain design and model parameters. The interactions between the various model parameters are directly solved within the LOTUS framework. This interaction not only facilitates the automation of the process, but it is also mathematically more robust because the advanced procedure considered to propagate uncertainties and/or perform global sensitivity and risk studies requires sampled inputs to be independent.

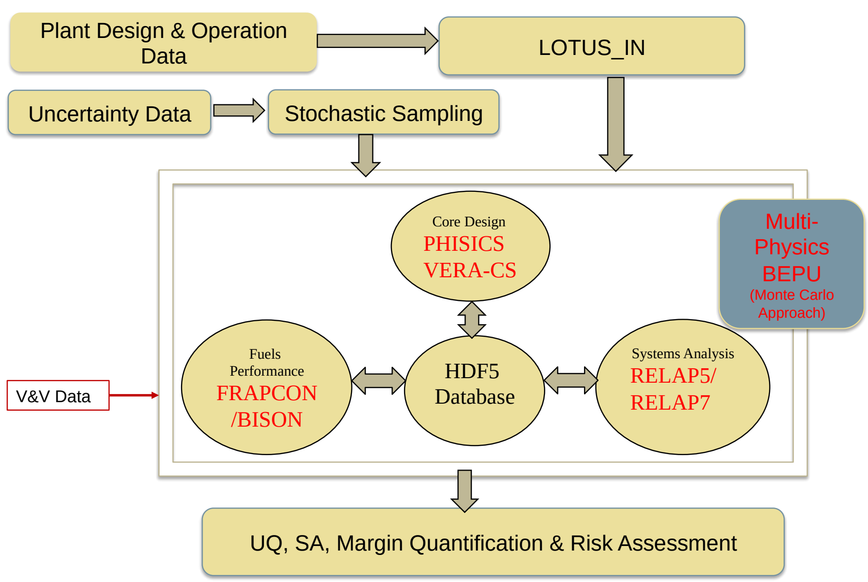

Figure 3. Illustration of LOTUS Multi-Physics BEPU (MP-BEPU) safety analysis framework.

The LOTUS vision is to move toward to a "plug-and-play" approach where the codes are simply modules 'under the hood' that provides the input-output relationship for a specific discipline. The focus shifts to managing the data stream at a system level. LOTUS is essentially a workflow engine with capability to drive physics simulators, model complex systems and provide risk assessment.

A "plug-and-play" approach will enable plant owners and vendors to consider and further customize the LOTUS framework for use within their established codes and methods. Therefore, it could potentially become the engine for license-grade methodologies. In other words, it is possible that the LOTUS technology could be advanced in the future to a level of fidelity and maturity that it could be used for some licensing or regulatory situations.

As a Best Estimate state-of-the-art reactor systems safety analysis code, RELAP5-3D plays an essential role within the LOTUS framework to perform the systems safety analysis. The coded input syntax and readily available interface for fuels performance codes simplified integration into the LOTUS framework. RELAP5-3D's relatively fast running time enables the adaptation of the full Monte Carlo simulations in managing uncertainties in LOTUS, which allows sensitivity analyses to be performed such that the impact and significance of input parameter changes can be assessed with high confidence.

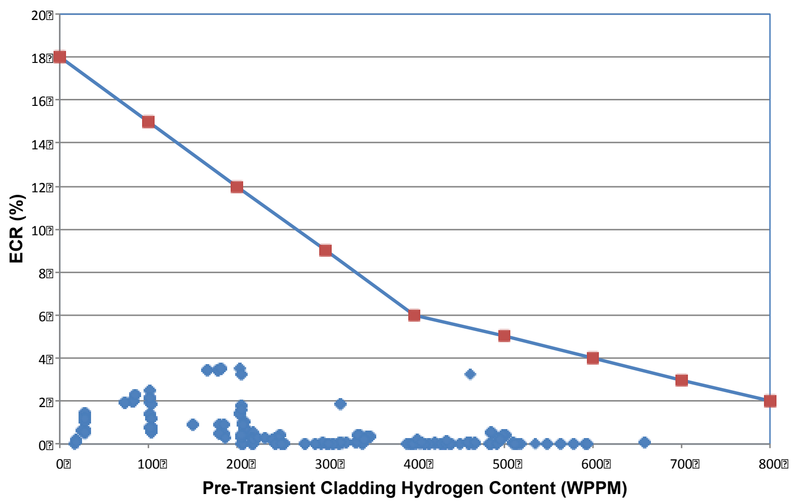

Figure 4. RELAP5-3D calculated ECR vs. acceptance criterion in NRC proposed new rulemaking in 10 CFR 50.46c.

For demonstration purpose, the LOTUS framework was applied to a generic PWR model and Large-Break Loss-of-Coolant accident (LB-LOCA) was analyzed in response to the NRC's proposed new rulemaking in 10 CFR 50.46c. Core design work was performed with the PHISICS code, achieving an eighteen months equilibrium cycle which is the subject cycle for safety analyses. FRAPCON was used for fuels performance calculations and RELAP5-3D as the systems analysis code. A PIRT table was built considering the important phenomena affecting the progression of the LB-LOCA accident. The uncertainty quantification of the LB-LOCA analyses was carried out using the Monte Carlo approach to determine the 95/95 upper tolerance limits. By randomly perturbing the input parameters using their associated probability density functions defined in the PIRT table, 1000 RELAP5-3D input files were prepared at the beginning of the cycle, and then every 100 days to the end of the cycle, respectively. All the RELAP5-3D cases were run to steady state first. LB-LOCA cases were then initiated by assuming a double-ended guillotine break at a cold leg. Figure 4 shows that the calculated equivalent cladding reacted (ECR) is in compliance with the acceptance criteria specified in the NRC's proposed new rulemaking in 10 CFR 50.46c for the generic PWR model.