Best Estimate Plus Uncertainty Methods Applied to Hydraulic System Models

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INTRODUCTION

This paper demonstrates the application of Best-Estimate Plus Uncertainty (BEPU) methodology to a steady state hydraulic system model of a Client's Auxiliary Service Water (ASW) system. The application of this methodology resulted in significant flow margin recovery compared to traditional analysis techniques.

Background

The driving event for the analysis is a posited scenario at a US nuclear power plant in which damage is sustained to the plant by a tornado. The scenario assumes (1) a station blackout (SBO) of all Units, (2) damage to main steam relief valves (MSRV), and (3) the loss of the Emergency Feedwater System (EFW), which usually supplements the normal Service Water (SW) system in case of an accident. An ASW system is available to supply additional flow in the case of EFW system failure.

For the tornado scenario examined herein, the output value of interest is the flow rate supplied to a single Unit's steam generators by the ASW system. Preliminary sensitivities performed using an existing computer model for the ASW system indicated the system could be challenged to supply sufficient flow margin under tornado scenarios. This model included many conservative assumptions and accounted for all uncertainties in the inputs by setting them at a bounding value. Simultaneously applying all these conservatisms is unrealistic and not representative of expected system performance for this scenario.

It was determined that much of the conservative margin applied to the model inputs was various sources of measurement uncertainty, as well as inputs that are naturally represented by a range of potential values, rather than a single value. Applying an ordered statistics (or non-parametric) approach with Monte Carlo sampling statistically accounted for the uncertainties present in many of the model inputs and provided a bounding estimate of a specified tolerance level. This allowed for a more realistic characterization of the range of expected system performance relative to a traditional deterministic analysis, while simultaneously recovering margin lost to unnecessary conservatism.

Parameter Selection

The posited scenario and existing hydraulic model were reviewed to identify the important phenomena and model inputs that had the largest effect on the steam generator flow rate. This mini-PIRT (Phenomena Identification and Ranking Table) identified the following parameters: system suction and discharge water levels, parasitic flow rates to components such as air ejectors, component resistances within piping, variation of the frequency of the electricity provided by the diesel generators, the setpoint pressure tolerances of the MSRVs, the pump performance curves, and uncertainty in the measured flow rates that are used as indicators to control valves throttling flow to various systems.

Sensitivity studies were performed to supplement the mini-PIRT and quantitatively assess the impact of various parameters on the calculated results. Only the model inputs with significant impact were included in the Monte Carlo sampling during the final analysis. All others remained at their original values. The final list of parameters for sampling includes 2 separate control valve flows, steam generator pressure, emergency diesel generator (EDG) frequency, and ASW pump performance. The process to determine the range and distribution of each parameter is detailed in the next section.

Uncertainty Quantification

The next step was to quantify the uncertainty range and statistical distributions for each of the parameters based on available information, including manufacturing specifications and test data. In the absence of more refined data, the most conservative probability distribution to use when sampling a parameter is the uniform distribution. All parameters in this study that either do not exhibit a predictable distribution shape, or if data does not exist to justify another type of distribution, were assumed to have a uniform distribution. Furthermore, instrument measurement uncertainty is generally considered to be random within its allowable range. In the absence of adequate test data that could define the probability of different values within that range, it must be assumed that any value is equally likely, so a uniform probability distribution is used.

Separate valves control the amount of flow to external systems or components. The setpoints on these valves must consider the measurement uncertainty attributable to the instrumentation used to measure the flow rate in the pipes. Operators adjust the valve position to the specified flow rate as indicated by the instrumentation, but due to the uncertainty in that instrumentation the actual flow rate of the water moving through the piping could fall within a range of values. The flow uncertainties for the control valves 1 and 2 were determined to be [-7.52%, 6.94%] and [-5.73%, 4.62%], respectively. This is based on available data from the manufacturer. All values are equally likely to occur, implying a uniform distribution. These uncertainties are asymmetric about the setpoint, with a slightly increased amount of flow uncertainty in the lower bound compared to the upper bound. Since the uniform distribution is symmetric, sampling from the shown ranges will approach a mean value that is lower than the stated nominal valve setpoint; however, since the range represents all allowable flows, all of which are equally likely to occur, this is expected and appropriate.

The maximum possible steam generator pressure is taken to be the setpoint of the lowest available MSRV with a tolerance of [-1.00%, 1.00%]. The pressure will not rise above this setpoint if the MSRV is not damaged in this scenario. The setpoint tolerance is treated as a random variable with a uniform distribution since adequate data about the setpoint tolerance variations was not available.

During the posited scenario, the pumps in the ASW system will likely be powered by the EDGs. The frequency of the electricity provided by the EDGs may increase or droop slightly, which directly affects any electric motors using that electricity. A change in frequency proportionally affects the rotational speed (n) of the pump. That change in speed affects the performance (the developed head H at flow rate Q) of the pump through the pump affinity laws.

$$Q_2 = \left(\frac{n_2}{n_1}\right) Q_1 \quad \text{and} \quad H_2 = \left(\frac{n_2}{n_1}\right)^2 H_1 \qquad (1)$$

According to plant procedures, the acceptable range for the EDG frequency is [-1.00%, 1.00%]. Past results of testing performed by the Client were evaluated and it was found that the actual range was significantly narrower than the procedurally acceptable range. Test data shows that the values of the frequency have never exceeded a range of [-0.17%, 0.83%]. Fig. 1 shows a histogram of the test results.

The overall width of the tested frequencies is well within the test procedure acceptable range and shows that the actual frequency variations have a much narrower spread than that range; however, with respect to a nominal frequency value, Fig. 1 shows that the frequencies recorded during testing are skewed above nominal (0%). This skew could be the result of many factors, such as equipment measurement bias, governor settings bias, testing conditions, etc. For example, many of the tests were performed while the system is synced to the grid, which may skew the frequency at which the generator is producing power. In order to account for this and other potential unknown biases, for the purposes of sampling, the tested frequency range was adjusted to be centered about the nominal. This new range after adjustments is [-0.67%, 0.67%]. The adjustment of the range from the original high skew to the centered range is a conservative adjustment, since the lower allowed frequencies reduce the overall performance of the ASW system.

The histogram does not show a well-formed probability distribution shape, so the values within the narrowed range must be treated as equally likely to occur, thus a uniform probability distribution is used.

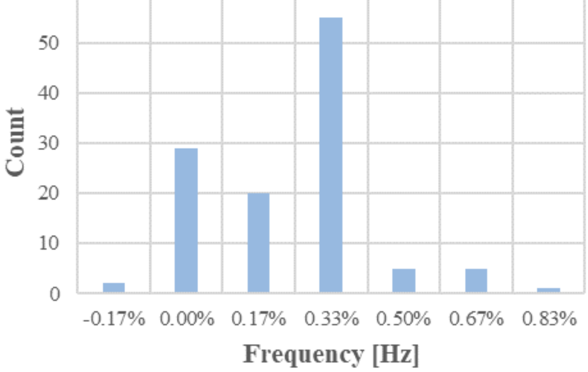

Fig. 1. Histogram of EDG frequency test results since 2011.

There are multiple pumps present in the ASW system, but the dominant pump is referred to as the ASW pump. The ASW pump is modeled using a flow vs. head curve. This curve is biased to account for various factors affecting performance, including measurement uncertainty and performance degradation. The measurement uncertainty portion of the pump performance quantifies the uncertainty in the instrumentation for indicating pump flow. The reported range for this uncertainty is [-3.04%, 3.04%] based on instrumentation documentation. It is considered random and no data is available to indicate that any value within the calculated uncertainty range is more likely to occur than another, so a uniform distribution is used.

Meanwhile, the performance degradation of the pump is due to physical wear or damage over time. The ASW pump is not subject to substantial normal wear, since it is a standby pump that only runs during an accident event or during testing. Separate Client analysis determined that the current, as-installed state of the pump shows no measurable pump performance degradation. Therefore, the pump performance degradation relative to the normal operation curve will be taken to be a constant value of zero.

Ordered Statistics

An ordered statistic (or non-parametric) method provides a bounding estimate of a specified tolerance level. A tolerance level consists of a specified quantile, or probability, (α) with a specified confidence level (β). A 95% probability with a 95% confidence (or 95/95 bound) has been applied within the nuclear industry and has been accepted by the USNRC for various applications, including loss-of-coolant accident (LOCA) analysis (see Ref. [1-3]).

For a one-side tolerance limit with p = 1 (*i.e.*, 1st order approach, where the "worst" case corresponds to the bounding estimate of the specified tolerance level), the number of samples (N) is determined from:

$$1 - \alpha^N \geq \beta \qquad (2)$$

Using the 95/95 bound as the acceptance criteria, the minimum number of sample sets (N) is 59. Higher order approaches (*e.g.,* $p > 1$) could be applied to reduce the variance in the estimated of the tolerance level (see Fig. 1 of Ref. [4]); however, a 1st order approach is known to be a more conservative approach (Ref. [4]).

Solution Methodology

The solution methodology applies an input sampling software (DAKOTA) together with steady state piping system modeling software (PROTO-FLO) to perform the BEPU analysis.

The DAKOTA (Design Analysis Kit for Optimization and Terascale Applications) software, Version 6.9, which is developed by Sandia National Laboratories (SNL), was used to perform the random input sampling required to perform BEPU analysis. DAKOTA has been successfully used in the past in BEPU LOCA methods and therefore was adopted here. It generates random samples for a given set of parameter ranges and distribution types to model the uncertainty in the inputs. These input samples are then propagated into the system flow model.

The hydraulic system in this study is modeled using PROTO-FLO^{TM} Version 5.03, which is developed and maintained by Zachry Nuclear Engineering. PROTO-FLO is designed for thermohydraulic modeling of nuclear plant piping systems and is widely used throughout the industry to model safety-related nuclear plant pipe systems such as Service Water, Component Cooling Water, Emergency Feedwater, and many others. It fully complies with nuclear QA requirements, including 10CFR50 Appendix B, 10CFR21, and ASME NQA-1.

PROTO-FLO provides capabilities that allow for both the creation of defined system alignments, as well as solving a large set of cases automatically as a batch. Batch processing allows a user to define a custom set of steps that allows for flexible automation of repetitive analyses. These capabilities are essential to efficiently apply Monte Carlo methods. When the batch is run, selected outputs are tracked across iterations using the Trended Parameters feature. Nearly all of the model inputs varied in this analysis correspond to a single value in the model, and thus can be directly modified. The exception is the ASW pump curve. The pump curve used for a given sample set is constructed using the normal operating curve as a base, then including the constant given value for pump performance degradation and the sampled value for pump measurement uncertainty. A spectrum of pump curves were created in the model, each at a specific degradation relative to the normal operating base curve. Intervals of 10 ft of head degradation were used in this evaluation.

The finite set of pump curves represents a discrete sample space, unlike the other parameters, which are continuous. DAKOTA draws samples across a continuous range. Therefore, the sampled values from DAKOTA are binned to map the continuous sample onto the discrete range. The pump measurement uncertainty is sampled from its range, then combined with the constant performance degradation to determine a total pump degradation. Values are binned to the conservative end of the range, i.e., a value of -63 ft is binned to the -70 ft degraded pump curve. A negative value represents degraded performance.

The acceptance criteria for this analysis is a set amount of flow rate delivered to a steam generator. The delivered flow rate must be greater than this amount under all evaluated scenarios. The results from the model cases are “ordered” (e.g., $Y(1) < Y(2) < \ldots < Y(N)$) and the minimum flow rate is identified. The minimum predicted flow rate (Y(1)) from a set of 59 cases corresponds to a bounding estimate of the 95% probability with 95% confidence (95/95 bound).

RESULTS

The original bounding analysis simultaneously set all important input parameters to conservative (worst-case) values. It also assumed -4.95% of performance degradation when estimating the pump performance. A revised bounding analysis was then run assuming 0% performance degradation, which is consistent with the indications from recent pump performance testing. This provided significant margin, but still did not satisfy the acceptance criteria. Next, the effect of diesel generator frequency was considered by applying the minimum expected frequency based on recent testing rather than the more conservative value allowed by the test procedure. This also provided additional margin, but still did not satisfy the acceptance criteria. Finally, Monte Carlo methods were applied to draw 59 random samples from each input range and estimate a 95/95 bounding flow. The sampling runs were performed using the [-0.67%, 0.67%] narrowed test range for EDG frequency, zero pump performance degradation, and the rest of the input ranges as specified in preceding sections. This resulted in significant margin recovery and a flow rate exceeding the required flow acceptance criteria. The results are summarized in TABLE I.

The results demonstrate the ability of BEPU analysis methods to provide additional flow margin for an ASW system hydraulic model that contains many conservative assumptions stemming from underlying random effects, such as measurement uncertainty and tolerances. The comparable single point bounding analysis indicated the system could provide only 90.6% of the required flow while the BEPU approach with Monte Carlo sampling of important parameters could provide 110.5% of the required flow (on a 95/95 basis), both assuming zero performance degradation. This provides a more accurate estimate of expected system performance and demonstrates the potential for analytical margin recovery. Alternatively, this result corresponds to a maximum allowable pump performance degradation of about 10%, while still providing the required minimum flow on a 95/95 basis. This provides flexibility for the Client if future testing indicates the ASW pump performance does start to degrade.

Other Considerations

A 1st order approach (p=1) is known to generally provide a more conservative estimate of the bounding value, while higher order approaches (p > 1) can provide a better estimate of the specified quantile but require additional cases to be run. This is because the variance of the bounding values is reduced as the number of samples increases. To examine this effect, a sample set of 1013 was run and the results for various orders are shown in Fig. 2. The variance reduction is obvious in these results. The 95/95 bound from 1013 cases corresponds to the 40th-smallest flow and was determined to be 114% of the acceptance criteria, which provides more margin in the flow results relative to the 1st order analysis.

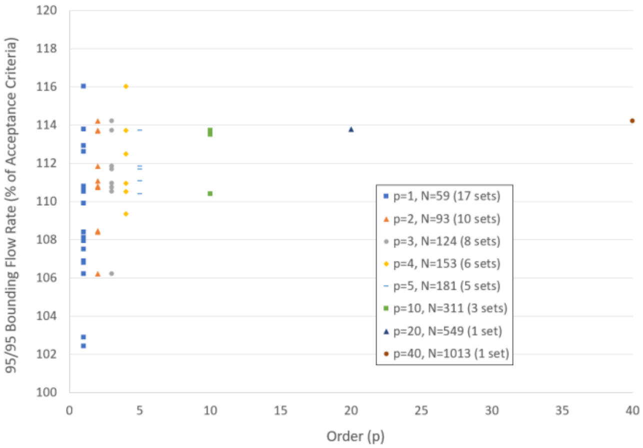

Fig. 2. Variance reduction with higher order methods.

If enough Monte Carlo samples are run, then the distribution starts to coalesce into the system's true probability density function. Or, using a stratified sampling approach, such as Latin Hypercube Sampling (LHS), it may be possible to cover the entire distribution more efficiently. In either case, it may be demonstrated that the output distribution can be modeled by a continuous equation, for example, a Gaussian normal distribution. The continuous equation would provide a more precise estimate of the probability. This has the potential to increase margin by further reducing the uncertainty of the results and allow for easier calculation of expected system performance; however, in this case, the results from the analysis did not satisfy the Shapiro-Wilk normality test.

CONCLUSIONS

This paper demonstrates the application of BEPU to recover flow margin in a Client's ASW analysis that could not satisfy the acceptance criteria using traditional analysis techniques. This combined a statistical treatment of uncertainty with refined uncertainty distributions based on available plant data to provide a 95/95 bound minimum flow rate that satisfied the acceptance criteria. This is still considered to be a conservative estimate of system performance and, as part of this process, other inputs and assumptions have been identified that could be revised, if necessary in the future, to recover additional margin.

REFERENCES

1. "Best-Estimate Calculations of Emergency Core Cooling System Performance", Regulatory Guide 1.157, U.S. Nuclear Regulatory Commission (1989).
2. FREPOLI C., "An Overview of Westinghouse Realistic Large Break LOCA Evaluation Model," *Science and Technology of Nuclear Installations*, **2008**, *498737*, 15 pages (2008).
3. MARTIN R., O'DELL L., "Framatome ANP's realistic large break LOCA analysis methodology," *Nuclear Engineering and Design*, **235**, *16*, 1713 (2005).
4. GRABASKAS D. et al, "Advantages of variance reduction techniques in establishing confidence intervals for quantiles", *Reliability Engineering & System Safety*, **149**, 187 (2016).
5. ADAMS et al., "Dakota, A Multilevel Parallel Object-Oriented Framework for Design Optimization, Parameter Estimation, Uncertainty Quantification, and Sensitivity Analysis: Version 6.0 User's Manual," SAND2014-4633, Sandia National Lab (2018, Version 6.9).
6. "PROTO-FLO Version 5.03 User Documentation," Zachry Nuclear Engineering (2017).

TABLE I. Summary of Resultant Flows

Parameter (% of nominal value)	Original Bounding Analysis	Effect of 0% Pump Degradation	Effect of Narrowed DG Frequency	BEPU (95/95 using 59 cases)
Control Valve 1 Flow	6.94%	6.94%	6.94%	[-7.52%, 6.94%]
Control Valve 2 Flow	4.62%	4.62%	4.62%	[-5.73%, 4.62%]
Steam Generator Pressure	1.00%	1.00%	1.00%	[-1.00%, 1.00%]
Diesel Generator Frequency	-1.00%	-1.00%	-0.67%	[-0.67%, 0.67%]
Pump Measurement Uncertainty	-3.04%	-3.04%	-3.04%	[-3.04%, 3.04%]
Pump Performance Degradation	-4.95%	0.00%	0.00%	0.00%
Resulting Flow (% of Acceptance Criteria)	49.5%	90.6%	97.0%	110.5%