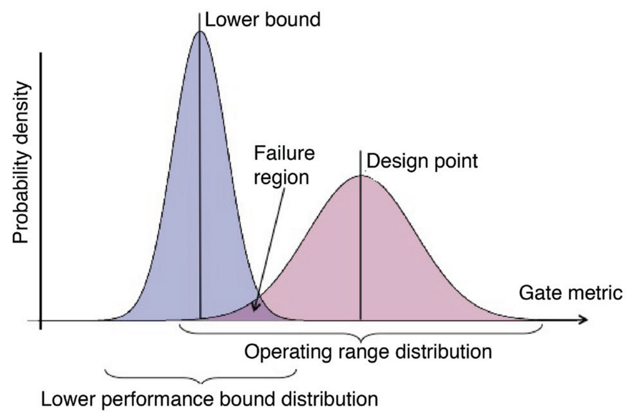
Common Framework for Quantifying Weapon System Uncertainty and Reliability within DOE/NNSA

Aparna V. Huzurbazar, Christine Anderson-Cook, CCS-6

The LANL Statistical Sciences Group, CCS-6, has a long-standing effort in research and applied methods to support the assessment of conventional and nuclear weapon stockpiles. This work has been funded long term by the Enhanced Surveillance Campaign (ESC). ESC is one of the Department of Energy/National Nuclear Security Administration's (DOE/NNSA) Engineering Campaigns that brings both an engineering and science-based predictive capability to aging of nuclear weapons and maintains critical capabilities and expertise. CCS-6 provides statistical and analytical support such as system modeling, age-aware models, tracking and trending data, and uncertainty quantification. ESC work helps the Stockpile Stewardship Program, Core Surveillance, and the Nuclear Weapons System Programs. The opportunities for statistical work encompass a broad range of areas including Bayesian statistics, reliability methods, experimental design, design and analysis of computer experiments, and complex computer modeling and simulation. This article describes our work with reliability and quantification of margins and uncertainties (QMU).

Nuclear weapons are designed with multiple objectives that include safety, security, and reliability. Here we limit our focus to reliability, which is defined as the probability of success of the weapon performing its intended function at the intended time given the required temperature range, shock and vibration exposures, altitude and speed of the release envelope, and over the designed lifetime of the weapon. The goal of the Department of Energy/National Nuclear Security Administration's (DOE/NNSA) weapon reliability assessment process is to provide a quantitative metric for this assessment. Ideally, the methods to estimate this metric should be as common as possible within the nuclear weapon complex. Researchers at LANL and SNL (New Mexico and California) worked together on a reliability uncertainty aggregation team funded by the Enhanced Surveillance Campaign (ESC, C8-LANL), Joint Munitions Program (LANL), and the Advanced Certification Campaign (SNL) from fiscal year 2008 to fiscal year 2010 to develop methodology, some of which is described here. The impact of this work includes applications to Department of Defense (DoD) systems and the current B61 Life Extension Program (LEP).

Fig. 1. Statistical view of margin and threshold distributions.



Quantification of Margins and Uncertainties (QMU) is primarily a technical framework for producing, combining, and communicating information about performance margins to support risk-informed decision-making for stockpile stewardship over the nuclear weapon life cycle [1]. The elements of such an analysis require the definition of performance thresholds, calculation of performance margins, and the quantification of uncertainty about these thresholds and margins. Our interest is in methodology for uncertainty quantification (UQ) in predictions of reliability and performance. At LANL, QMU was developed to facilitate analysis and communication of confidence in assessment or certification [2]. See Fig. 1 for a statistical view of margins and thresholds and their associated uncertainty.

Our study examined a system model representative of the complexity of the top-level models used by SNL and LANL to assess weapon reliability. Given constraints and the frequently prohibitive cost of collecting data for evaluating system reliability, alternative statistical analyses were developed to leverage the understanding gained from component and sub-system level data. It has been relatively straightforward to combine multi-level data to obtain a single point estimate of system reliability, subject to assumptions about how to combine those sources based on series or parallel structures for combining the components in the system. However, appropriately propagating the uncertainty associated with each reliability estimate based on limited testing and available data has been a more difficult challenge.

For more information contact Aparna V. Huzurbazar at aparna@lanl.gov.

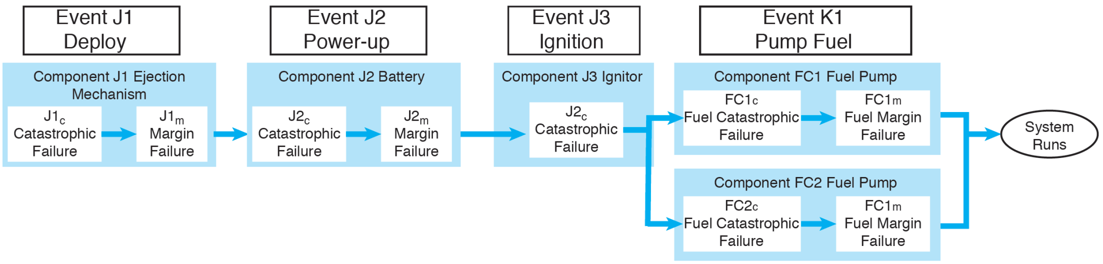


Fig. 2. System model for illustrative example in reliability block diagram format.

With a mature stockpile, limited production opportunities, and a now-extensive surveillance database, an understanding of the residual uncertainty associated with known and measurable failure modes has grown in importance. A key feature of the QMU reliability analyses is to focus not only on a point estimate of reliability, but also on the uncertainty associated with the estimate. Understanding uncertainty can and should influence subsequent decision-making. Thus the three methods presented in [3] seek to complement the NNSA point reliability and to provide a unified mechanism for assessing system-level reliability (point estimates) and reliability uncertainty (interval estimates) associated with component-level catastrophic failures and margin failures.

The authors and their collaborators, Stephen Crowder, John Lorio, James Ringland (SNL) and Alyson Wilson (Institute for Defense Analyses), developed and described different approaches for capturing reliability estimation uncertainty [3]. Three approaches are compared:
1) a historically based Method of Moments, which makes assumptions about the shape of the distribution characterizing the reliability estimate based each of the different data types and then uses these assumed distributions to combine them into an overall system estimate;
2) a Bayesian approach, which allows for related information to be combined with the observed data for each data type in order to obtain a posterior distribution, which can then be used to propagate the uncertainty between the different levels of the system model; and
3) a Bootstrap approach, which approximates the estimated component level reliabilities with an empirical distribution, and which can be sampled to combine and give an overall reliability estimate at the system level.

The different assumptions of each method, as well as their relative strengths and weaknesses are compared. With an illustrative case study and simulated data, the three approaches are implemented and compared to show common features and differences. Figure 2 shows the modeled system structure. More details about the Bayesian approach and how it can be broadly applied to more complex scenarios where multiple data sources and multiple failure modes occur on individual components are given in [4].

[1] Diegert, K. et al., *"Toward a More Rigorous Application of Margins and Uncertainties within the Nuclear Weapons Life Cycle; A Sandia Perspective,"* SAND2007-6219 (2007).
[2] Sharp, D. and Wood-Schultz, M., *Los Alamos Science* **28,** 47 (2003).
[3] Anderson-Cook, C. et al., *Reliab Eng Syst Saf* **96,** 1063 (2011).
[4] Wilson, A. et al., *Reliab Eng Syst Saf* **96,** 1076 (2011).

Funding Acknowledgement
DOE/DoD Joint Munitions Program; DOE NNSA, Defense Programs and Core Surveillance; Weapons Program, Science Campaign 8