Quantification of Margins and Uncertainty for Risk-Informed Decision Analysis

Kenneth Alvin
kfalvin@sandia.gov
505 844-9329

Workshop on Risk Assessment and Safety Decision Making Under Uncertainty

Bethesda, MD

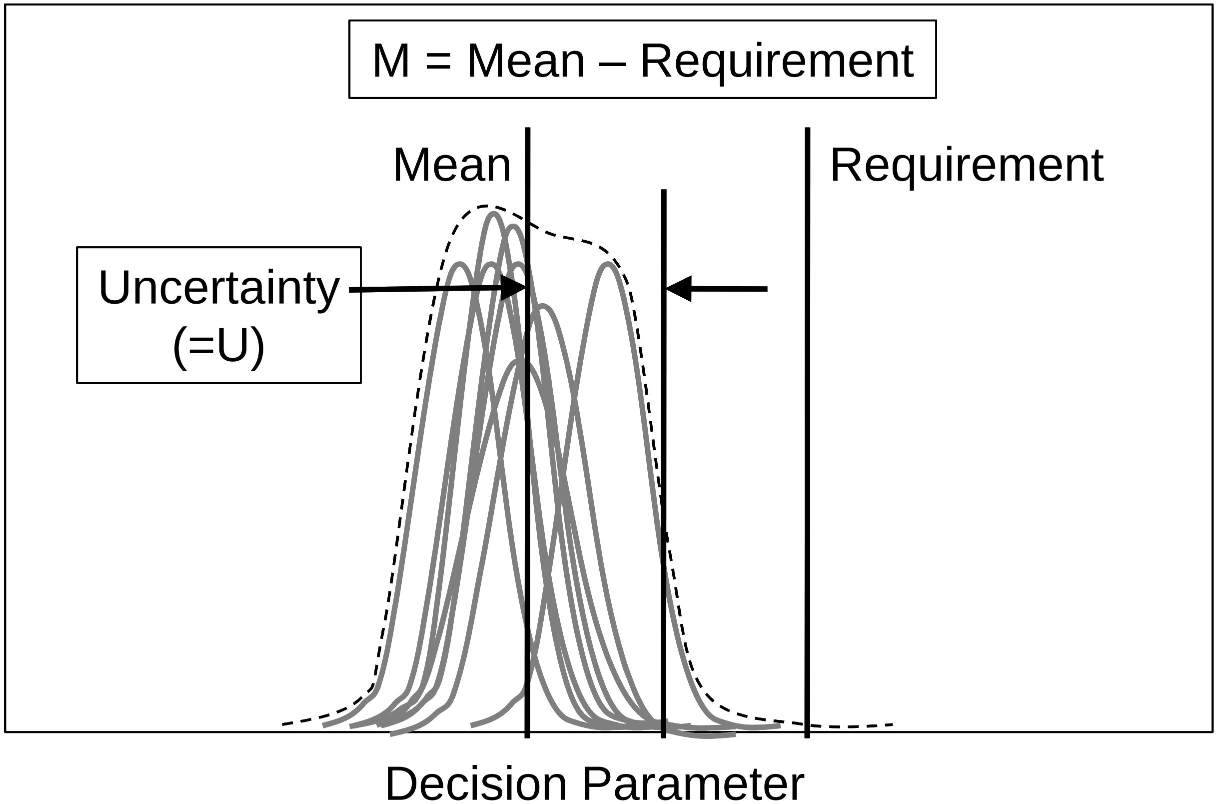
September 21-22, 2010

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Introduction: QMU at the NNSA Labs

- **QMU stands for "Quantification of Margins and Uncertainties"**
- **QMU is a basic framework for consistency in integrating simulation, data, and/or subject matter expertise to provide input into a <u>risk-informed</u> decision-making process**
- **QMU is being applied to a wide range of NNSA stockpile issues, from performance to safety**
- **The implementation of QMU varies with lab and application focus**
- **The Advanced Simulation and Computing (ASC) Program develops validated computational simulation tools to be applied in the context of QMU**

Yes, but what *is* QMU?



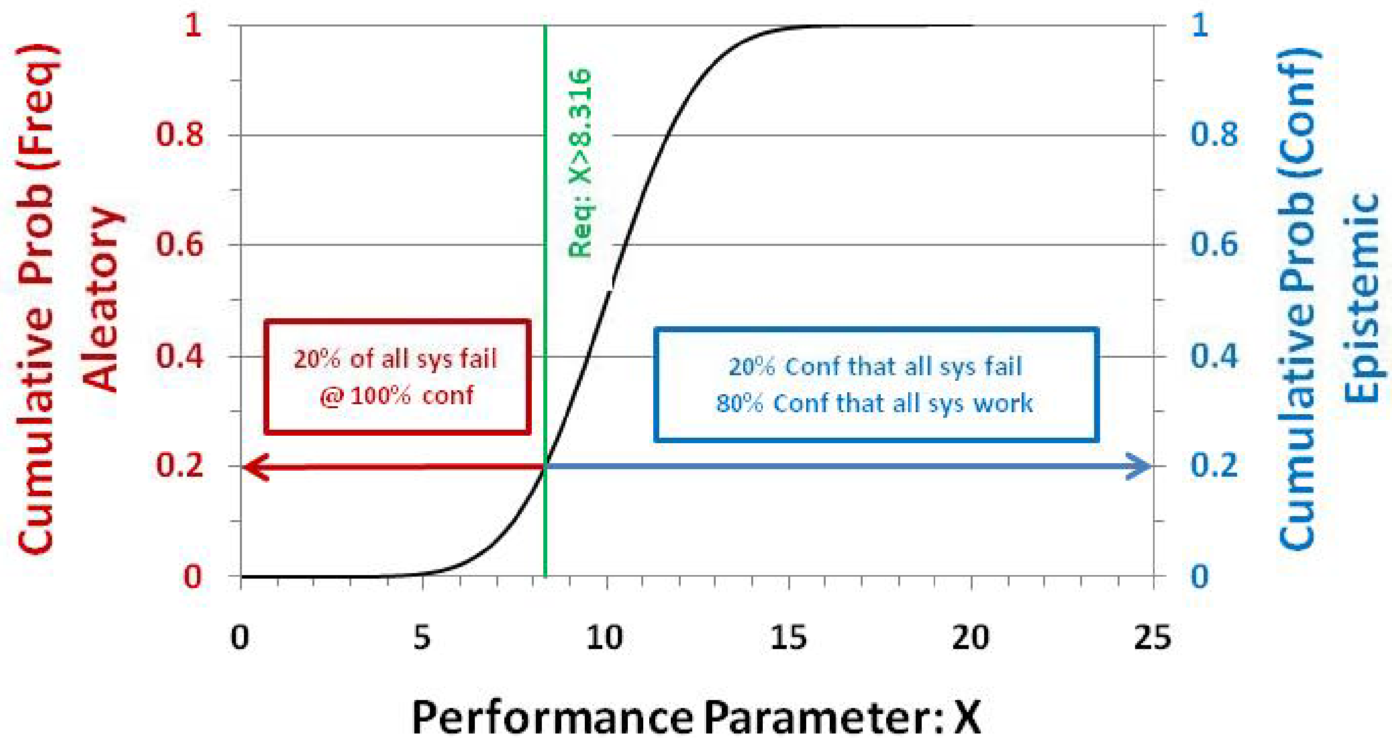
- **Confidence Factor (CF) = M/U; goal is M/U > 1**
- **M/U was thought of as a communication tool**
- **What is Mean, what is U? Open questions w.r.t QMU**

The NAS Review of QMU (2008) Concluded that the Labs Could Learn from QRA and PRA

- **QMU provides input into a risk-informed decision making process**
- **The *completeness* aspect of QMU can benefit from the structured methodology and discipline of quantitative risk assessment (QRA) / probabilistic risk assessment (PRA)**
- **In characterizing uncertainties it is important to pay attention to the distinction between those arising from incomplete knowledge ("epistemic" or systematic), and those arising from device-to-device variation ("aleatory" or random).**
- **The national security labs should investigate the utility of a probability of frequency (PoF) approach in presenting uncertainties in the stockpile**
- **A QMU methodology is *connected* if the interactions between failure modes are included**
- **The design labs should continue to focus attention on quantifying uncertainties that arise from epistemic uncertainties such as poorly-modeled phenomena, numerical errors, coding errors, and systematic uncertainties in experiment**
- **The NNSA and design labs should ensure that the certification plan for any RRW is supported by strong, timely peer review and by an ongoing, transparent QMU-based documentation and analysis in order to permit a confidence level necessary for eventual certification**

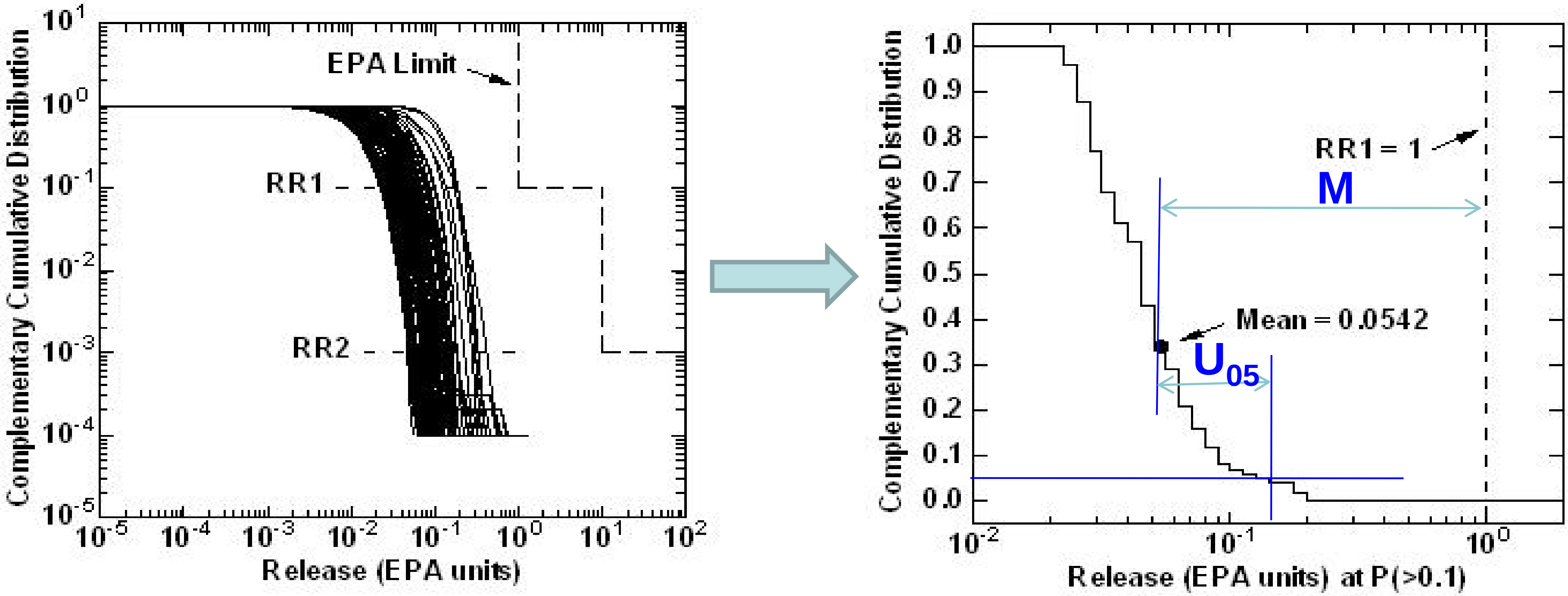
Jon C. Helton, *Conceptual and Computational Basis for the Quantification of Margins and Uncertainty*, SAND2009-3055

- **Aleatory uncertainty:** (perceived) randomness in the occurrence of future events **(frequency interpretation)**
- **Epistemic uncertainty:** Lack of knowledge wrt appropriate value to use for a quantity that has a fixed value in the context of a specific analysis **(confidence or belief interpretation)**



The distinction between aleatory uncertainties and epistemic uncertainties matters

QMU Isn't New: WIPP Performance Assessment



$M = Req - Mean = 1 - 0.0542 = 0.9458$

$U = U_{05} - Mean = 0.14 - 0.0542 = 0.0858$

$M/U = 0.9458/0.0858 = 11$ (Definition is Not Unique)

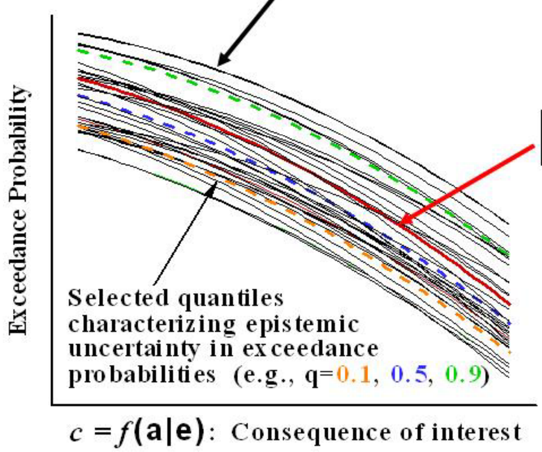
A lot of information is lost in distilling QMU into a single number, M/U

Probability-of-Frequency Provides the Necessary Mathematical Rigor Broadly Accepted by the NAS

- **Probability space (A, A, p_A) with density function d_A(a) characterizing aleatory uncertainty (each element a of A corresponds to one possible future behavior of the system under study)**
- **Probability space (E, E, p_E) with density function d_E(e) characterizing epistemic uncertainty (each element e of E corresponds to one set of possible values for epistemically uncertain analysis inputs)**

$$\left[c,\ prob_A(c<\tilde{c}\,|\,\mathbf{e})\right] = \left[c,\ \int_{\mathcal{A}} \bar{\delta}_c\left[f(\mathbf{a}|\mathbf{e})\right] d_A(\mathbf{a}|\mathbf{e})\,\mathrm{d}\mathcal{A}\right]$$

$$\text{with } \bar{\delta}_c\left[f(\mathbf{a}|\mathbf{e})\right] = \begin{cases} 1 & \text{if } c<f(\mathbf{a}|\mathbf{e}) \\ 0 & \text{otherwise} \end{cases}$$



$$\left[c,\ \overline{prob}_A(c<\tilde{c}\,|\,\mathbf{e})\right]$$

$$= \left[c,\ \int_{\mathcal{E}} prob_A(c<\tilde{c}\,|\,\mathbf{e})\, d_E(\mathbf{e})\,\mathrm{d}\mathcal{E}\right]$$

$$= \left[c,\ \int_{\mathcal{E}}\left[\int_{\mathcal{A}} \bar{\delta}_c\left[f(\mathbf{a}|\mathbf{e})\right] d_A(\mathbf{a}|\mathbf{e})\,\mathrm{d}\mathcal{A}\right] d_E(\mathbf{e})\,\mathrm{d}\mathcal{E}\right]$$

Quantiles defined by double integrals involving $\mathcal{A}$, $\mathcal{E}$ and $f(\mathbf{a}|\mathbf{e})$

Practical evaluation of the integrals is far from cookbook

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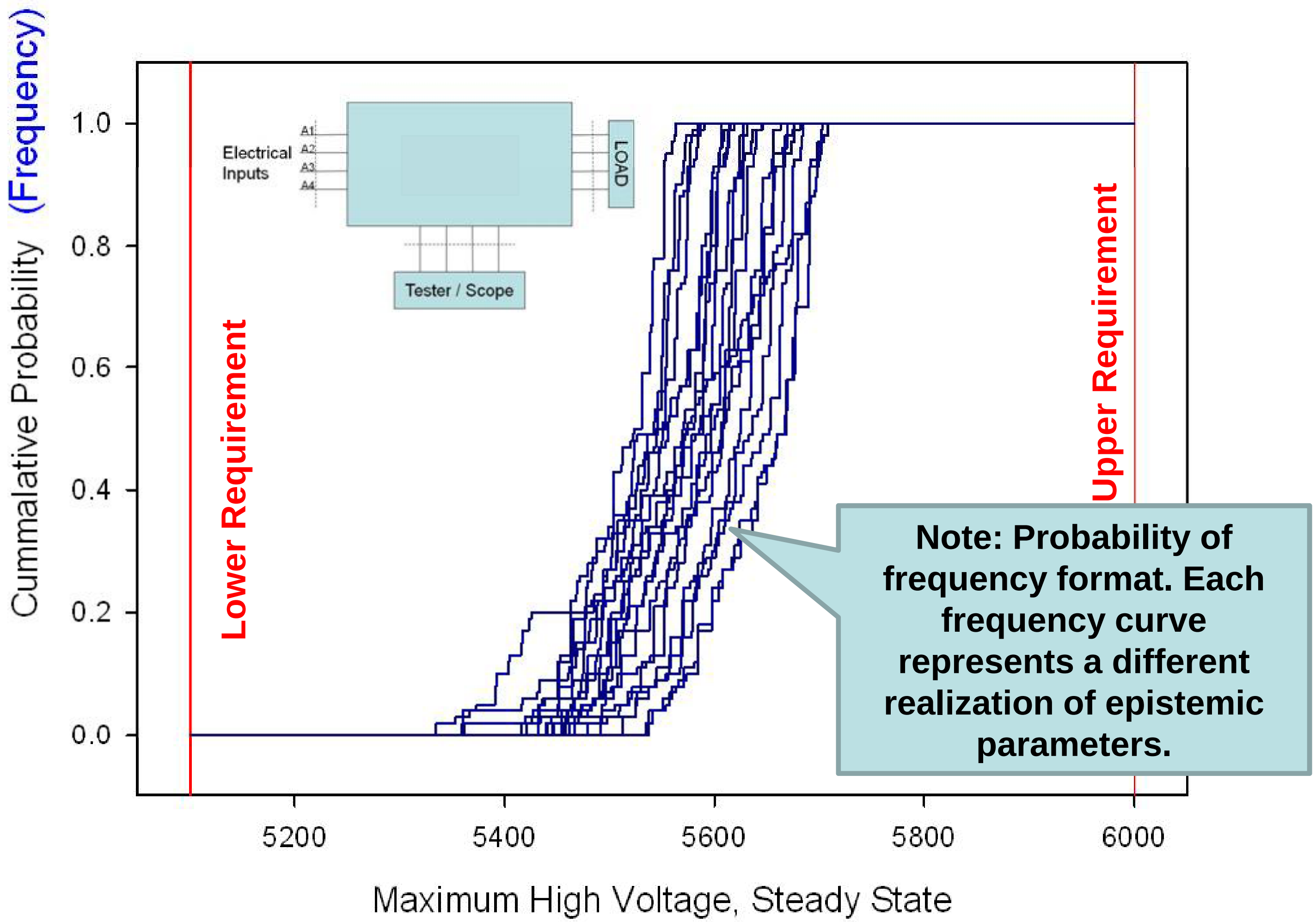
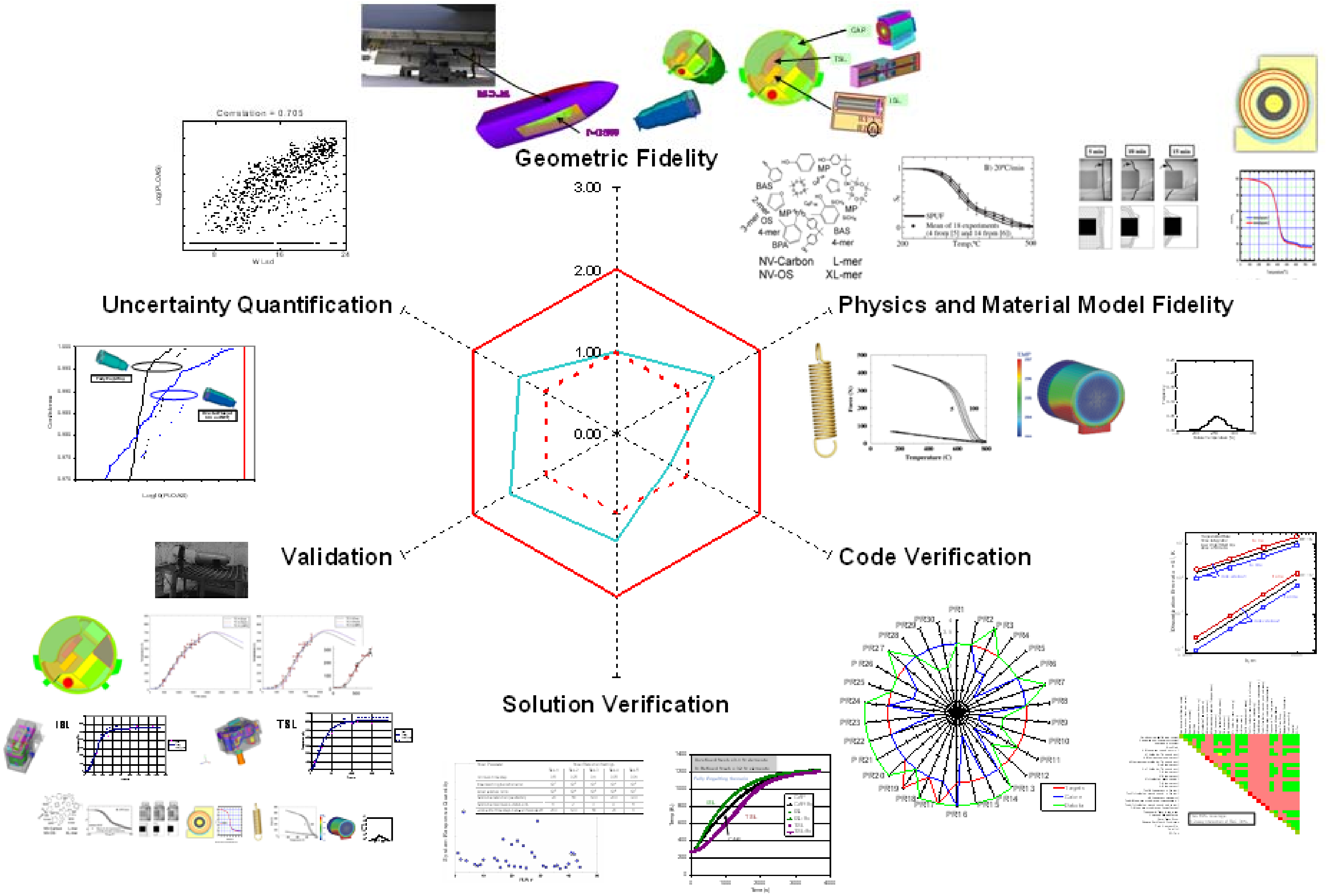
Sometimes We Rely on M&S to Assess Performance

e.g., Environmental Extrapolation, Aging, etc



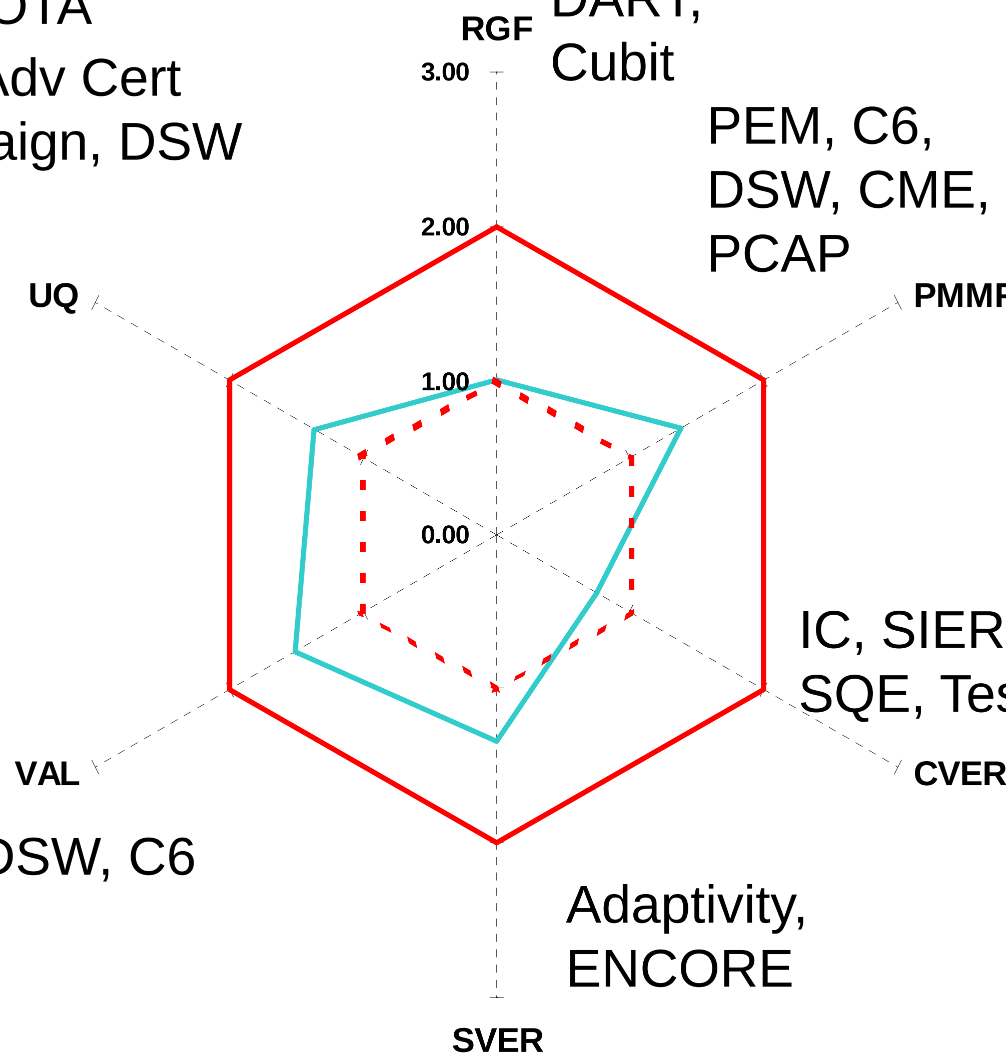
M/U> 4; therefore, the impact of this failure mode on system performance need not be assessed explicitly by representation in a reliability model

Credibility of the Modeling that Produces Simulation-based QMU Results Must be Measured and Communicated



Predictive Capability Maturity Model (PCMM)

PCMM is an Organizing Framework for Capability Development that Cuts Across Organizational and Programmatic Boundaries



DAKOTA

V&V, Adv Cert Campaign, DSW

DART, Cubit

PEM, C6, DSW, CME, PCAP

Capability/Capacity Computing

IC, SIERRA, SQE, Testing

V&V, DSW, C6

PCAP

Adaptivity, ENCORE

How Much is Enough?
A Graded Approach is Appropriate
From the Perspective of CompSim Stewardship

PCMM Practice		Maturity Level 0 Low Consequence, Minimal M&S Impact, e.g. Scoping Studies	Maturity Level 1 Moderate Consequence, Some M&S Impact, e.g. Design Support	Maturity Level 2 High-Consequence, High M&S Impact, e.g. Qualification Support
Representation and Geometric Fidelity (RGF) Are representation errors corrupting simulation conclusions?	Characterization (how close to as built are you representing the system)	• (unjustified) conceptual abstraction of the whole system	• Significant (unjustified) simplification or stylization of the system at the level of major elements	• Limited (unjustified) simplification or stylization of the system at the level of major and minor elements
	Computation Error (what impact does imperfect RGF have on computation results)	• Judgment only, numerical errors introduced because of imperfect RGF not addressed	• Sensitivity to imperfect RGF explored for some System Response Quant. (SRQs)	• Numerical errors estimated for imperfect RGF for relevant SRQs
	Verification (is what you represented really what was built)	• RGF not verified, RGF simply used without verification that it represents the actual system as built	• RGF verified only by the analysts	• RGF independently verified

Core Attribute — **Best Practices** — **Measured Against Standards Expressed in Terms of Increasing Rigor**

- **Level 0: Low consequence; minimal M&S impact (e.g., scoping studies)**
- **Level 1: Moderate consequence; some M&S impact (e.g., design support or qualification test support)**
- **Level 2: High consequence, high M&S impact (qualification decision support)**
- **Level 3: High consequence; decision making based predominately on M&S (dominant basis for qualification or certification)**

There are other ways to frame solutions to the need for a graded approach

M&S-Based QMU Results Being Used in High Consequence Decision-Making Should be Peer Reviewed

- **Increased Objectivity**
- **Assurance of Evidence Basis for Predictive Capability Assessment**
- **Hedge against "unknown unknowns" that were actually "shoulda been knowns"**

Summary and Conclusions

- QMU has the technical dimensions of Quantitative Risk Assessment (QRA)
- PoF is a NAS-accepted conceptual framework for dealing with aleatory and epistemic uncertainties
- Take a system perspective
  - Requires a consistent conceptual framework for characterizing and propagating aleatory and epistemic uncertainties
  - Reliability model is an integrating framework for weapon performance
  - Fault tree can be an integrating framework for weapon safety
- Credibility of the modeling that produces QMU results must be measured and communicated
- M&S-based QMU results should be peer reviewed