ENGINEERING & LICENSING BRIEFING

Regulatory Guide 1.203

Best Estimate Plus Uncertainty (BEPU)

Evaluation Model Development and Assessment Process

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Executive Summary

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Briefing Objectives

- **Regulatory Framework:** Overview of the EMDAP framework outlined in NRC RG 1.203.
- **Statistical Rigor:** Define the best-practice approach for establishing Probability Density Functions (PDFs).
- **Combination of Uncertainties:** How individual parameter variations are mathematically aggregated to prove safety limits.

Key Deliverables

- Traceable, documented basis for statistical inputs.
- Computation of valid 95/95 safety bounds.

Methodology Focus

1. PIRT Process
2. Data Sourcing
3. Combination

Regulatory Shift: BEPU & RG 1.203

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The BEPU Philosophy: Historically, safety codes used punitive, worst-case deterministic assumptions (e.g., Appendix K). The NRC now encourages **Best Estimate Plus Uncertainty (BEPU)** approaches, using realistic physics paired with rigorous statistical quantification.

The Evaluation Model (EM): Under RG 1.203, an Evaluation Model is not just a computer code. It is the entire suite of:

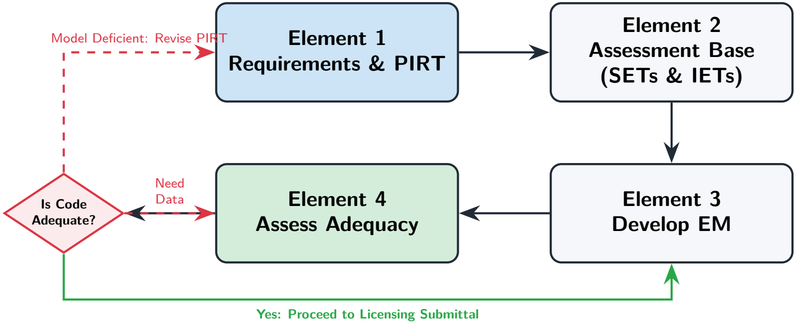
- The physical code (e.g., RELAP, TRACE, VERA).
- The spatial nodalization scheme.
- The numerical solution techniques.
- **The specific uncertainty methodology.**

Why use BEPU?

- Recovers trapped safety margin.
- Allows for reactor power uprates.
- Improves operational flexibility without compromising the licensing basis.

The 4 Elements of EMDAP

Evaluation Model Development and Assessment Process



- **Iterative Strictness:** RG 1.203 requires that if the code cannot predict reality within established uncertainty bounds, developers must loop back to fix the code, gather more experimental data, or revise the PIRT.

Step 1: Establish Requirements (PIRT)

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Phenomena Identification and Ranking Table (PIRT): Before assigning math to uncertainties, a panel of experts determines what parameters actually affect the Figures of Merit (e.g., Peak Cladding Temperature).

1. Identify

List every conceivable parameter and physical phenomenon that could affect the transient.

2. Rank

Rank by Importance (High, Medium, Low) and Knowledge Level (Known, Partially Known, Unknown).

3. Focus

Only build rigorous PDFs for **High Importance** parameters to optimize computational resources.

Low Importance = Held at Nominal or Deterministic Biased

Element 1: PIRT Execution Example

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Component	Phenomenon	Importance	Knowledge Level
Core	Post-accident Heat Transfer	**High**	**Medium**
Core	Decay Heat Profile	**High**	High
Downcomer	3D Flow Mixing	**High**	**Low**
Pressurizer	Flashing	Low	High

Actionable Output

High Importance + Low/Medium Knowledge = **Knowledge Gap**. EMDAP requires focusing resources, experimental testing, and EM development specifically on these gaps.

Elements 2 & 3: Data and Code Development

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Element 2: Assessment Base

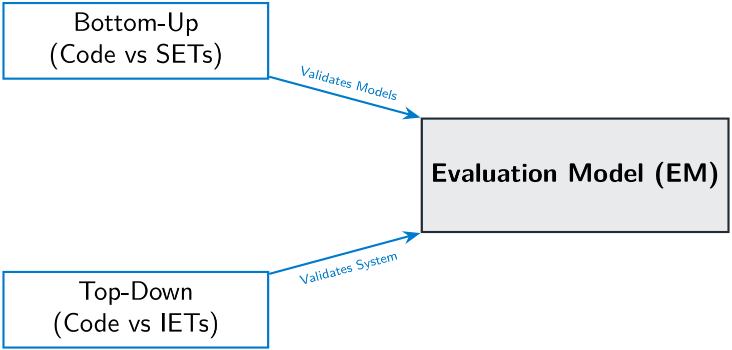
- Gather experimental data to validate the phenomena identified in the PIRT.
- **Separate Effects Tests (SET):** Isolate a single phenomenon (e.g., heat transfer in a single heated pipe).
- **Integral Effects Tests (IET):** Scaled-down facilities that simulate the whole plant (e.g., LOFT, ROSA) to capture system interactions.

Element 3: Develop the EM

- Build the mathematical models, spatial nodalization schemes, and numerical solvers.
- Establish the code architecture and closure relations.
- **Scaling:** Ensure the code scales properly from a small test facility to a full-size commercial reactor.

Element 4: Assess EM Adequacy

How do we prove the code works? RG 1.203 requires a dual-pronged approach:



- **Bottom-Up:** Prove individual closure equations work using Separate Effects Tests.
- **Top-Down:** Prove the code handles complex system interactions using Integral Effects Tests and actual plant transient data.

Defining Probability Density Functions (PDFs)

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The Core of BEPU Licensing: Defining the PDFs is arguably the most highly scrutinized step in a BEPU submittal.

The Risk of Flawed Inputs: If your input distributions are flawed, your 95/95 safety limits are invalid. The NRC expects a rigorous, traceable, and heavily documented basis for every single distribution fed into a statistical engine.

Three Data Categories

1. Manufacturing Tolerances
2. Operating Conditions
3. Modeling Uncertainties

Defining Input Distributions (PDFs)

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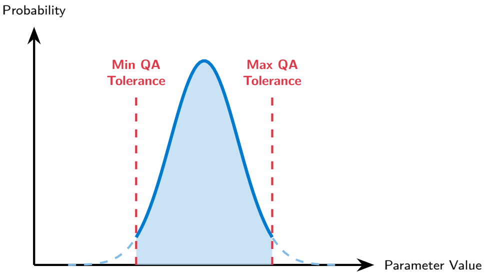
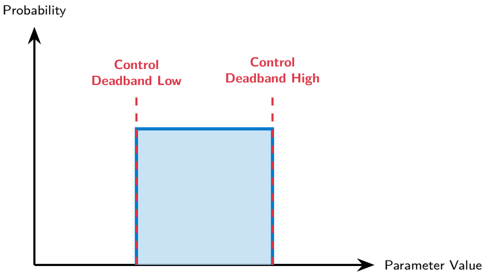


Truncated Normal
(e.g., Pellet Diameter)



Uniform Distribution
(e.g., System Pressure)

Rule: Never sample physically impossible states. Tail truncation is required.

Category 1: Manufacturing Tolerances

Fuel and Core Geometry The Approach: Do not guess these; rely on the actual Quality Assurance/Quality Control (QA/QC) data from the fuel fabrication facility.

- *Examples:* Pellet enrichment, theoretical density, clad outer diameter, fuel rod pitch.

PDF Selection Rules

- **Truncated Normal:** QA data forms a Gaussian curve, but QA rejects items outside tolerance bands. Truncate the PDF to avoid impossible configurations.
- **Uniform:** If historical QA data is lacking (e.g., novel LEU+ fuel), the NRC expects a Uniform distribution between min/max limits.

Category 2: Operating Conditions

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Plant State and Boundary Conditions The Approach: Base these strictly on the reactor's Technical Specifications, instrument uncertainties, and control system deadbands.

- *Examples:* Core thermal power, primary pump mass flow rate, core inlet temperature, system pressure.

PDF Selection Rules

- **Normal:** Used for instrument errors. If a thermocouple is accurate to $\pm 2^\circ$F (95% confidence), map to a Normal distribution where $2\sigma = 2^\circ$F.
- **Uniform:** Used for control bands. If automated systems allow pressure to float between 1490 and 1510 psia before actuating, use Uniform across that 20 psi band.

Category 3: Modeling Uncertainties

Code and Correlation Flaws The most difficult category. No computer code is perfect. You must quantify how wrong your Evaluation Models are when compared to actual physical experiments.

- *Examples:* Heat transfer coefficients, two-phase friction multipliers, gap conductance models.

The Approach: Simulate historical validation tests and plot **Predicted vs. Measured** results.

PDF Selection Rules

- **Bias & Variance:** Data scatter provides the standard deviation; consistent over/under-prediction provides the "bias".
- **Lognormal:** Often required if a parameter strictly cannot be less than zero (e.g., friction multipliers).

Step 3: Checking for Parameter Correlations

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The Trap of Independence: A common trap in BEPU analysis is treating all variables as completely independent. If your statistical sampler randomly picks values without knowing they are related, it will simulate physically impossible reactors.

The Problem

Example: Fuel pellet density and fuel pellet diameter are often inversely correlated in manufacturing. Sampling a maximum diameter and a maximum density simultaneously could exceed the total allowed uranium mass per rod.

The Fix

Construct a **covariance matrix**. When programming the sampling engine (like DAKOTA or RAVEN), input the covariance matrix so that if it samples a high diameter, it restricts the available sample space for density.

Step 4: The PDF Justification Document

For NRC licensing under RG 1.203, every single PDF must have a heavily documented "pedigree."

The Uncertainty Quantification Report: This document must detail the following for every parameter fed into the engine:

1. **Definition:** What the parameter is.
2. **PIRT Rank:** Why it was ranked High importance.
3. **Raw Data Source:** E.g., "Vendor QA report 2024," "Instrument Cal-Spec," or "Validation Test Suite B".
4. **Mathematical Fit:** E.g., Normal, $\mu = 1500$, $\sigma = 4.5$.
5. **Goodness-of-Fit Test:** E.g., Passing a Shapiro-Wilk test to mathematically prove the data actually fits the chosen PDF.

The Challenge of Combining Uncertainties

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The Objective: Once individual PDFs for all High-Ranked PIRT parameters are justified, they must be mathematically combined to yield a single total uncertainty statement for the Figure of Merit (FOM).

Why is this difficult?

- **Non-linearity:** Reactor transients are highly non-linear. Doubling an input error does not simply double the output error.
- **Synergistic Effects:** Parameters interact during an accident (e.g., pump flow and decay heat interacting with system pressure).

Methods of Combination

1. Square Root of Sum of Squares (SRSS)
2. Response Surface Methodology (RSM)
3. Direct Monte Carlo Sampling

Combination Method 1: SRSS

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Square Root of the Sum of the Squares (SRSS)
The traditional, simplistic method for combining statistical variations.

$$U_{total} = \sqrt{U_1^2 + U_2^2 + U_3^2 + \cdots + U_n^2}$$

Limitations for BEPU:

- **Strict Independence:** It assumes parameters do not influence each other.
- **Linearity Assumption:** It assumes the output responds linearly to inputs, which is rarely true in complex nuclear safety transients (e.g., LOCA).

Rarely accepted for complex EMs *NRC*

Note: RG 1.203 requires extensive justification if linear SRSS is used to combine phenomenological uncertainties.

Combination Method 2: Response Surface Methodology

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Response Surface Methodology (RSM) Used historically when running a full-scale Evaluation Model 10,000 times was too computationally expensive.

The Process

1. Run the EM a limited number of times using an experimental design (e.g., Latin Hypercube).
2. Fit a mathematical surrogate model (polynomial) to the outputs.
3. Perform Monte Carlo sampling on the *fast surrogate*, not the slow EM.

Drawbacks:

- The surrogate polynomial may fail to capture sudden cliff-edge effects (which are common in multi-phase flow).
- Introduces an extra layer of "fitting uncertainty" that must be quantified.

Combination Method 3: Direct Monte Carlo Sampling

The Modern Standard: With modern computing clusters, we bypass surrogates and directly sample the physics code.

How it works: A sampling engine (like DAKOTA or RAVEN) randomly pulls values from all defined input PDFs simultaneously, passes them to the Evaluation Model, runs the transient, and records the Figure of Merit.

Advantage: Naturally captures all non-linear physics and correlations.

Requirements

Requires vast computational resources, but eliminates surrogate fitting errors.

Non-Parametric Order Statistics (Wilks' Formula)

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The Question: How many times (N) must we run the Monte Carlo simulation to prove safety?

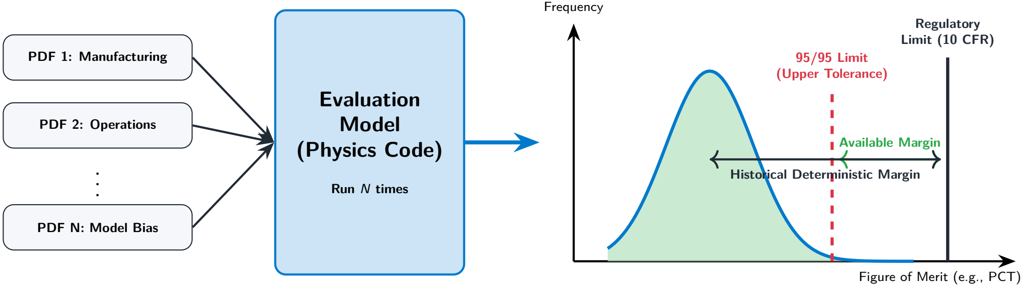
Wilks' Theorem: Allows us to determine the tolerance limit of a distribution without knowing the shape of that distribution (non-parametric).

Crucially, the required number of runs (N) is **independent of the number of input parameters**.

Common N Values (95/95 Limit)

- **1st Order ($N = 59$):** The worst-case result out of 59 runs bounds 95% of the population with 95% confidence.
- **2nd Order ($N = 93$):** The second-worst result out of 93 runs bounds the 95/95 limit.
- **3rd Order ($N = 124$).**

Establishing the 95/95 Safety Limit (Monte Carlo)



BEPU Benefit: Safely recovering margin previously lost to deterministic assumptions.

Summary & References

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The BEPU Philosophy: RG 1.203 shifts safety analysis away from unphysical assumptions toward realistic physics, bounded strictly by mathematically combined uncertainty matrices.

NRC Submittal Checklist

1. Is the PIRT complete?
2. Are scaling distortions quantified?
3. Are PDFs sourced from QA or Test data?
4. Are correlations defined via covariance?
5. Is uncertainty quantified and combined to the 95/95 limit?

Key Regulatory Resources

- Regulatory Guide 1.203, *Transient and Accident Analysis Methods*.
- NUREG/CR-5249, *Quantifying Reactor Safety Margins* (CSAU).

Industry Tools

- RELAP5-3D
- TRACE
- RAVEN / DAKOTA