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Probability and Confidence Trade-space (PACT) Evaluation: Accounting for Uncertainty in Sparing Assessments

Name of Forum: *AIAA Annual Technical Symposium*
Date: *May 18, 2012*

Purpose/Agenda

- **Purpose**
  - Status update on the developing methodology to revise sub-system sparing targets.

  - To describe how to incorporate uncertainty into spare assessments and why it is important to do so

  - Demonstrate hardware risk postures through PACT evaluation

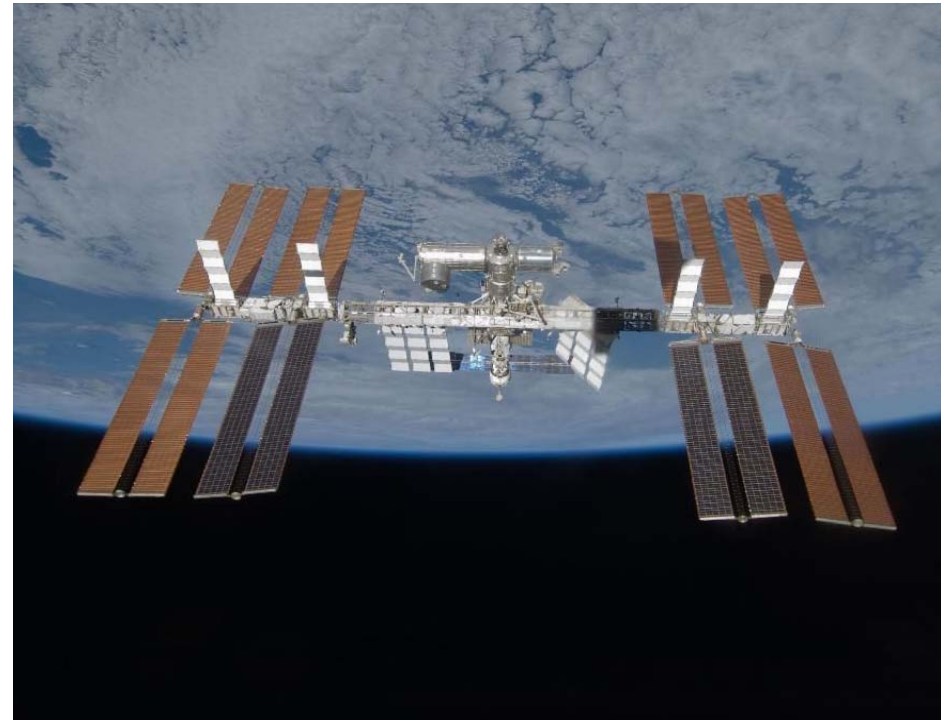- **Agenda: (list major topics of the presentation):**
  - Background
  - Key Definitions
  - Overview
  - Problem Statement
  - Review of Current Process
  - Introduction of Proposed Process
  - Analysis Examples
  - Results
  - Forward Work
  - Backup –analysis results

Background

- **Sparing Assessment**
  - Currently, an annual assessment is performed to estimate the number of spares needed to keep the International Space Station (ISS) operational until 2020 (and beyond).
  - Historically, the Spares Assessment has not included all uncertainty, specifically epistemic (lack of knowledge).

- **Propose Methodologies to Supplement Sparing Assessment**
  - *Characterize* and *quantify* uncertainty, at the Orbital Replacement Unit (ORU) level.

Key Definitions and Concepts

- **Bayesian Process**
  - A probabilistic theorem to infer an adjustment to predicted (prior) statistic given historical data.
  - ISS specific application updates predicted an ORU failure rate given operational experience resulting in an operational (posterior) ORU failure rate.

- **Error Factor**
  - A parameter of statistical distributions describing the variation and frequency of values.
  - An ISS application for Error Factor applies to estimated ORU failure rates.
  - The Error Factor weighs ORU operational experience against the predicted ORU failure rate.

- **Poisson Process**
  - A statistical technique based on the Poisson probability distribution estimating the probability that ORU failures in a projected time period do not exceed the number of ORU spares.
  - Input parameters for the Poisson Process include: ORU annual failure rate, projected time period (vehicle life), and ORU current number of spares.

- **Lognormal Process**
  - A statistical technique similar to the Poisson process but includes an additional parameter (error factor) determining the distribution variance in ORU failure rate.

- **Confidence**
  - A measure of the fidelity of an estimate
- **Epistemic Uncertainty**
  - "Epistemic uncertainty is due to **a lack of knowledge** about the processes, models, parameters, and behavior used in the analysis." (*NASA Procedural Requirements 8705.5A*)
  - "The epistemic models deal with non-observable quantities. Failure rates and model assumptions are not observable quantities." (*NASA/SP-2011-3421*)
  - Also called reducible uncertainty
  - Only epistemic uncertainty is reducible through operational experience
- **Aleatory Uncertainty**
  - Intrinsic **randomness of a phenomenon**
  - *Also called irreducible uncertainty*
  - Can not be suppressed by more accurate measurements
- **Probability of Sufficiency (POS)**
  - Likelihood that the number of current spares and/or proposed number of spares estimated to reach the end of life of the International Space Station (ISS) is less than or equal to the predicted number of ORU failures.
  - ORU POS can be calculated through the Poisson Process or Lognormal Process
- **Probability Target (PT)**
  - Desired value in POS
- **Confidence Target (CT)**
  - Desired confidence in POS *value*

Problem Statement

There are two general shortcomings to the current annual sparing assessment:

1. **The vehicle functions are currently assessed according to 'confidence targets,' which can be misleading.**
   - Confidence calculations may be overly optimistic because they only take into account natural variability, i.e. randomness in times of failure.

   - Alternatively, for projections on necessary spares through vehicle life, current implicit function confidence targets may be overly conservative or optimistic.

2. **The current confidence levels are arbitrarily determined and do not account for epistemic uncertainty (lack of knowledge) in the ORU failure rate.**
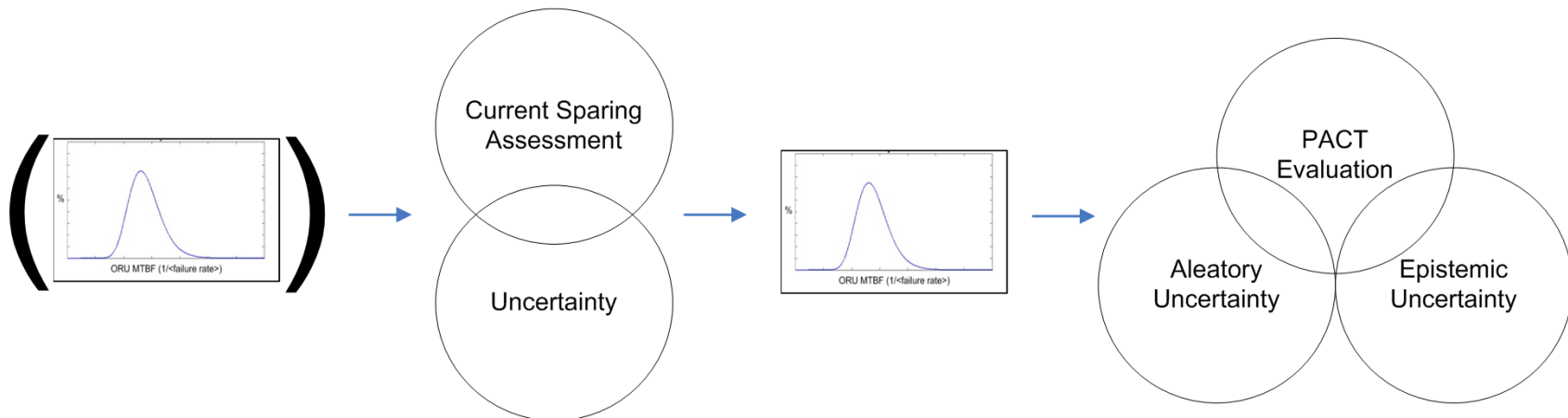   - Due to inherent uncertainty, a more robust approach is warranted.

Overview

Objective

- **Examine uncertainty, risk, and confidence for ISS Sparing Assessment**
  - Explains how robust results can be obtained where there is lack of data.
  - There are two major categories of uncertainty that impact Sparing Assessment:
    - **Aleatory Uncertainty:** Natural variability in distribution of actual failures around an Mean Time Between Failure (MTBF)
    - **Epistemic Uncertainty** : Lack of knowledge about the true value of an Orbital Replacement Unit's (ORU) MTBF
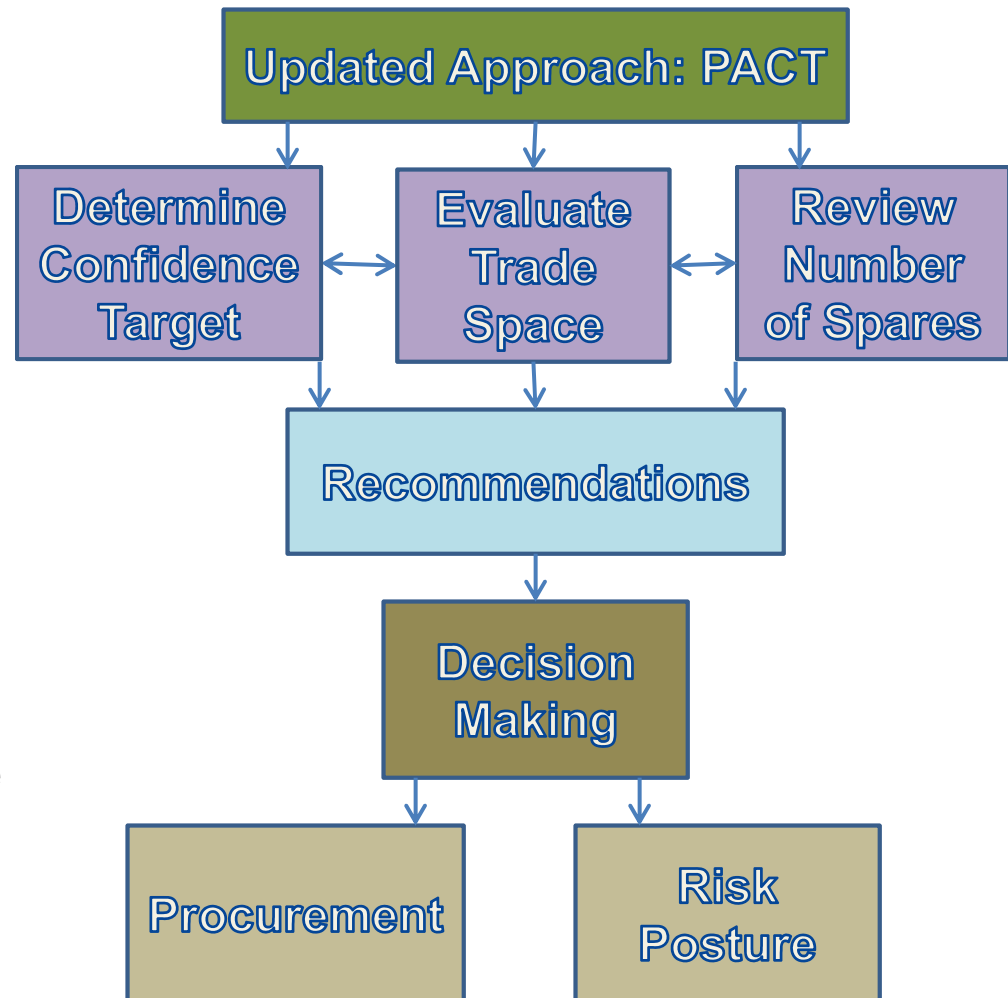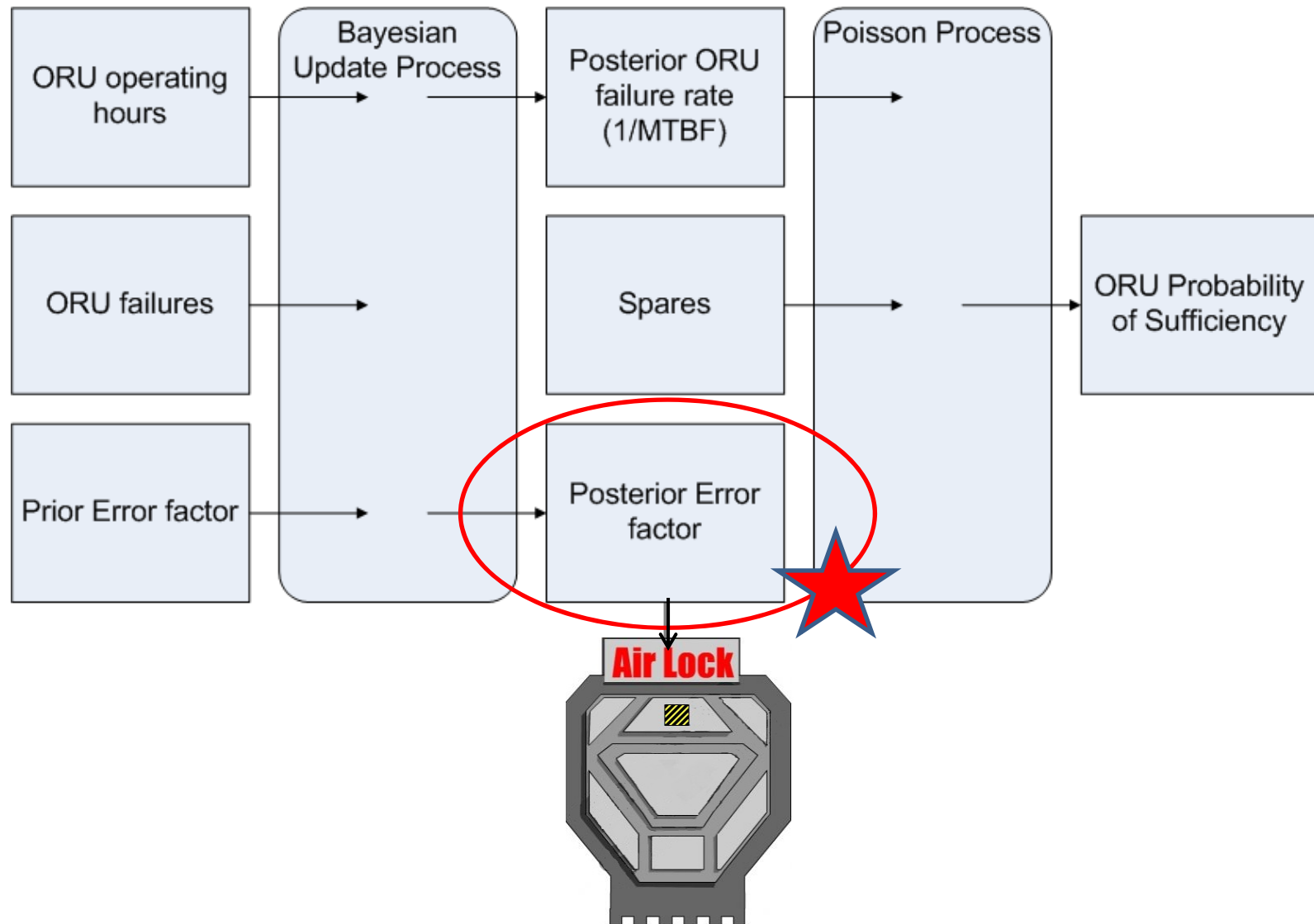
Approach

- Going forward, the team plans to recommend changes to the spares confidence and assessment that will:
  - Take into account both types of uncertainty,
  - Show the dangers of not including epistemic uncertainty in sparing evaluations
  - Make recommendations that are realistic and show how robust results can be obtained
  - Expand the approach to the function level and to include minimization of spare costs

- We therefore introduce a technique to include epistemic uncertainty

Updated Approach: PACT

| Determine Confidence Target | ↔ | Evaluate Trade Space | ↔ | Review Number of Spares |

↓ ↓ ↓

Recommendations

↓

Decision Making

↓ ↓

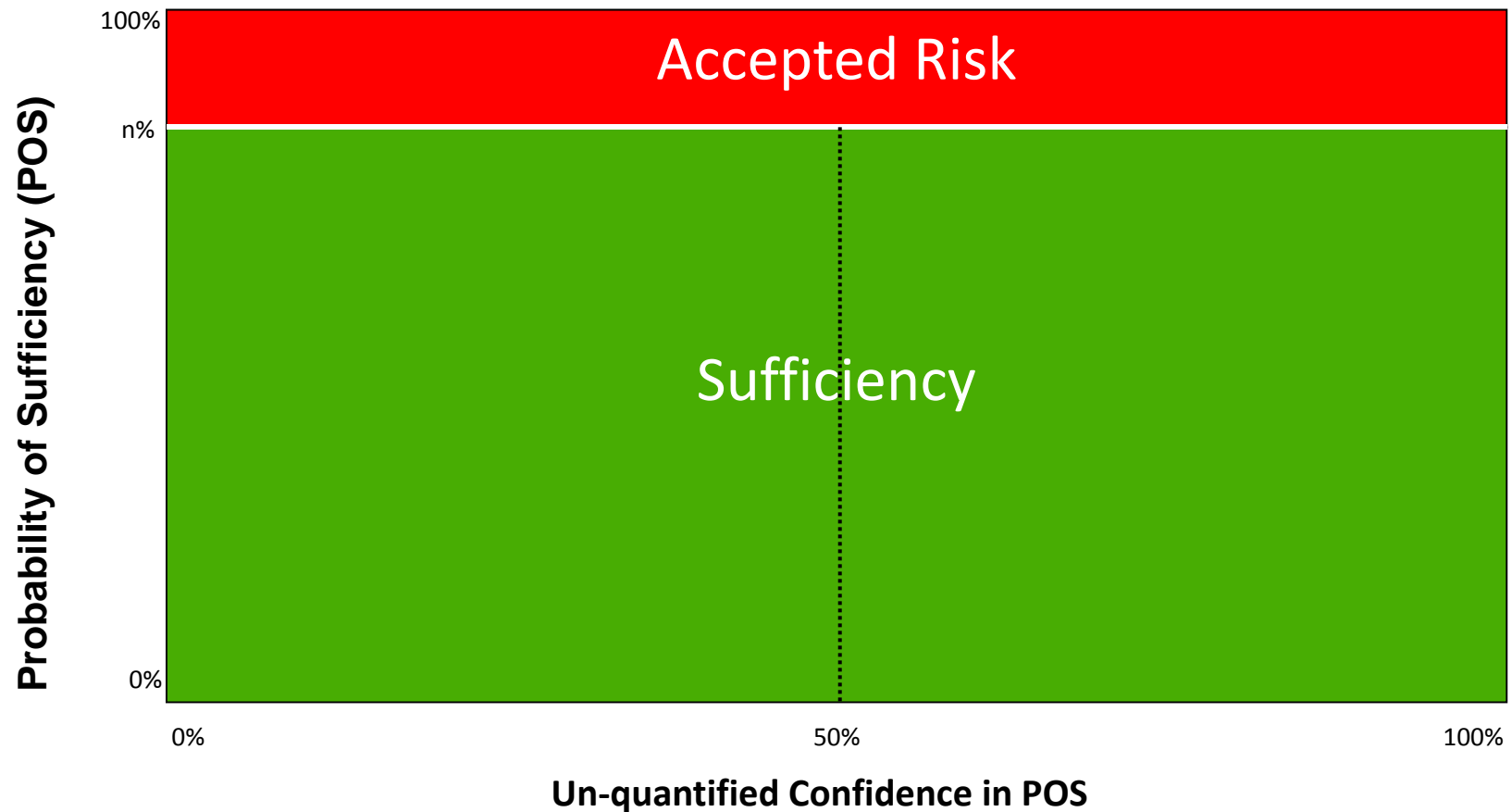**Procurement**   **Risk Posture**

Current Process Flow

Results of Current Process

- The **Bayesian** update process provides a posterior error factor (EF), which describes the epistemic uncertainty in the updated ORU failure rate and which is unused.

- The **Poisson** process provides a probability that the number of spares exceeds the expected number of failures.
  - This estimate can be considered a point along a Y-axis 0-100%

- When accounting for **epistemic uncertainty** in the ORU failure rate, we consider a corresponding "confidence value" in the probability of sufficiency estimate
  - This corresponding estimate is an added X-axis, 0-100%
  - Not including the epistemic uncertainty results in the sparing risk only being partially assessed

- These two estimates make up a **trade space**, which we use to assess sparing risk and account for epistemic and aleatory uncertainty:
  - Probability of sufficiency (POS)
  - Confidence in the probability,

Current Model of ISS Sparing Risk

Note: *50% is normally the minimum accepted confidence in the nuclear energy utility sector*

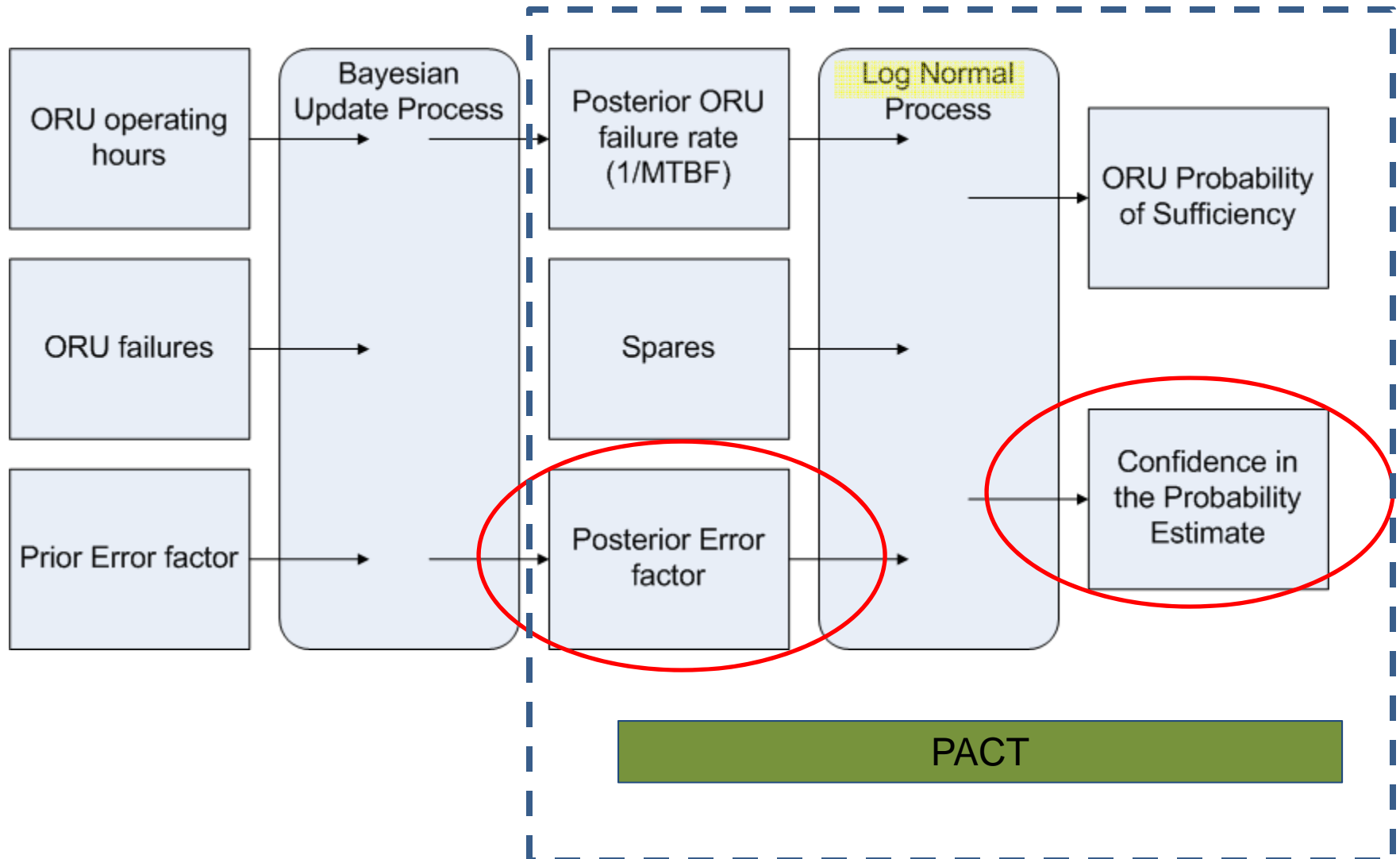# Proposed Model for Sparing Risk: PACT Evaluation

Methodology

- Explicitly account for inherent epistemic uncertainty, lack of knowledge, in the ORU failure rate by utilizing the ORU posterior error factor from the Bayesian update process.

- Use a **Lognormal** distribution to represent the uncertainty which allows use of the **Bayesian** posterior **Error Factor**
  - Higher values in the posterior error factor translate to greater levels of **uncertainty** in the ORU failure rate

  - Lower values in the posterior error factor translate to greater levels of **certainty** in ORU failure rate

Model Parameters

- **Input-** ORU failure rate uncertainty distribution

- **Output-** values of the ORU Probability of Sufficiency (POS) with the associated, explicit Confidence level
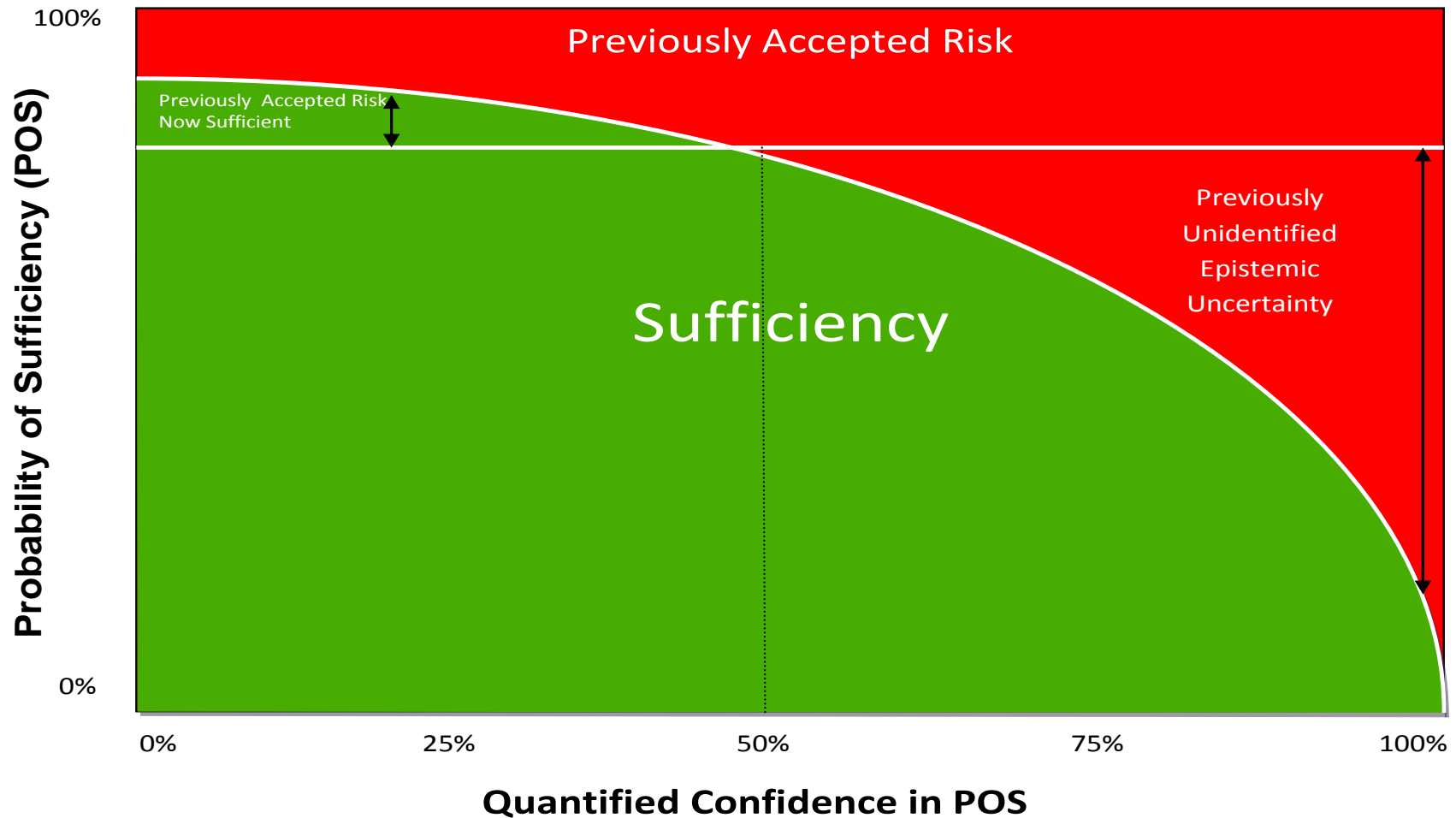
PACT: Proposed Process Flow

- **The regions describing current sparing risk- 1) accepted risk and 2) sufficiency, are no longer linear. The probability of sufficiency *straight edge* is now a curve.**
    - However, the **Lognormal** *with* **Error Factor = 1** equates to the **Poisson** process *with no* ***epistemic uncertainty***
    - Error factor = 1 represents a scenario of absolute certainty in ORU failure rate.

- **Trade Space**: Accounting for epistemic uncertainty, the trade-space is comprised of 4 regions of varying areas depending on the ORU sufficiency and level of epistemic uncertainty.
    - Area of Sufficiency
    - Area of Previously Accepted Risk
    - Area of Previously Accepted Risk that is now "sufficient"
    - Area of previously unidentified epistemic uncertainty

Introducing Uncertainty: PACT Model of ISS Sparing Risk

Note: 50% is normally the minimum accepted confidence in the nuclear energy utility sector

Benefits of the PACT

- **Using this model we can now say- 'we are *n*% confident that the ORU has *m*% probability of sufficiency through year *xxxx*.'**
  - Importantly, the intersect of the curve and straight-edge represents the underlying confidence we have carried on ORU sufficiency

- **With this knowledge, we can assess the tradeoff along the curve between the *desirable* ORU Probability of Sufficiency (POS) *value* and our *confidence* in the *value*.**
  - *At Least* **Five Options:**
    1. We may accept the probability and our confidence as is.
    2. We may relax our confidence *for a higher desirable Probability of Sufficiency (POS) value*.
    3. We may consider *a lower desirable Probability of Sufficiency (POS) value* in favor of *having* higher confidence .
    4. *We* may begin discussion on procuring more spares *to achieve a higher desirable POS value and associated confidence level*.
    5. Change the projected horizon time for the analysis.
       - Lower confidence can be accepted in cases where there is a larger sparing supply and recovery capability.
       - Shorter time intervals would allow for closer tracking.

Testing PACT

- **Objective: Selection represents a variety of ISS supportability challenges/risk impacting sparing levels**
  - Demonstrates a breadth of uncertainty: empirical basis of ORU failure rate demonstrated versus lack of operational experience

- **Case Study: 6 ORUs were analyzed in detail to understand the utilization of the proposed process**
  - **RPCM Type 5 External** –large population of installed units and spares providing rich operational experience including failures and redesign

  - **IPEHG** –small internal ORU, no operational experience

  - **Pump Module** –large external ORU, critical hardware with many hours of operation and a random failure

  - **Hydrogen Dome** –large internal ORU, no redundancy, relatively little operational experience

  - **SARJ DLA / TRRJ DLA** –external ORUs with redundancy, similar function differing failure rates, SARJ DLA modeled in the Usable Power function hierarchy, TRRJ DLA modeled as a separate ORU

- **Statistics:**
  - The average error factor for entire population of ORUs: 3.89 (range: 1.36 – 4.00)
  - ORU failure rate range: 1.98E-12 to 3.5E-4 failures/yr

PACT Analyses Results

ORU Name	MTBF	Installed Quantity	kF	Duty Cycle	Total Expected Number of Failures through 2020	Current Number of Spares	Posterior Error Factor	POS through 2020	Confidence at POS
RPCM T5 E	268,443	36	1.2	1	12.69	18	1.36	95%	54%
Improved Payload Ethernet Hub Gateway (IPEHG)	50,719	3	1.31	1	6.11	3	4	15%	66%
Pump Module Assembly (PMA)	69,065	2	1.2	1	2.74	4	2.87	86%	63%
Hydrogen Dome	49,853	1	1.3	1	2.06	4	4	95%	66%
SARJ Drive Lock Assembly (SARJ-DLA)	278,241	4	1.2	0.5	0.68	2	4	97%	66%
TRRJ Drive Lock Assembly (TRRJ-DLA)	353,926	4	1.2	0.5	0.53	1	4	90%	66%

Note: *High confidence targets are based on the minimum system configuration for each ORU. The proposed approach will be useful in re-evaluating the POS and identifying a reasonable confidence target.*

Summary

- A useful methodology has been proposed to supplement ISS sparing analysis.

- Preliminary results indicate a valuable trade space for selecting optimal targets and identifying the confidence associated with the target.

Forward Work

1. **Extend the methodology** to evaluate spare allocations for systems and functions to assure a desirable POS and confidence level for short term and long term trade-off

2. Include the **minimization of cost** and resources while assuring a desirable POS and confidence level

3. Evaluate **robust techniques** for determining desirable POS values and associated confidence levels and for handling different plausible error factors in component uncertainties
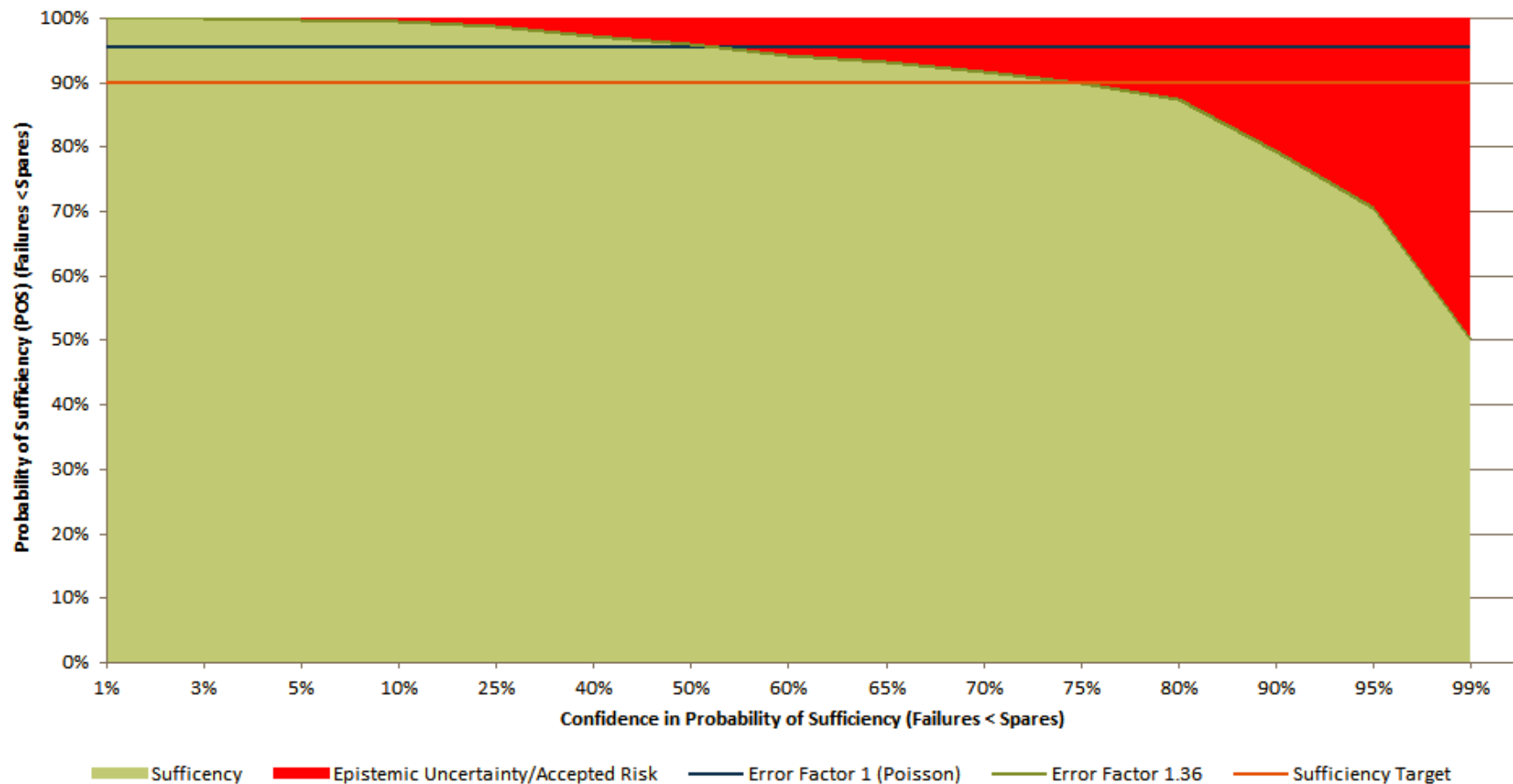
Backup

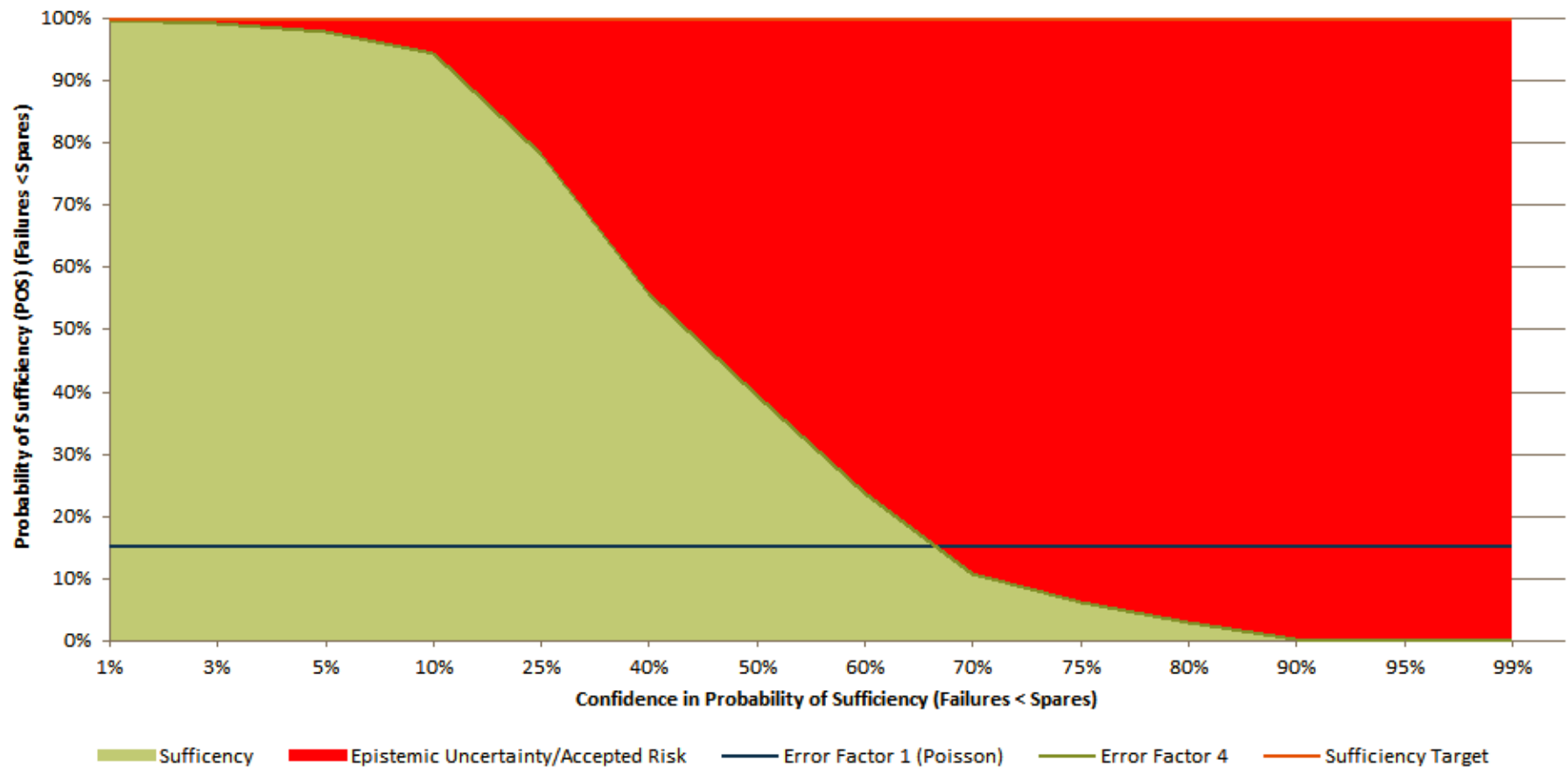Confidence and Probability of Sufficiency through 2020

Results: IPEHG

Confidence and Probability of Sufficiency through 2020

Pump Module

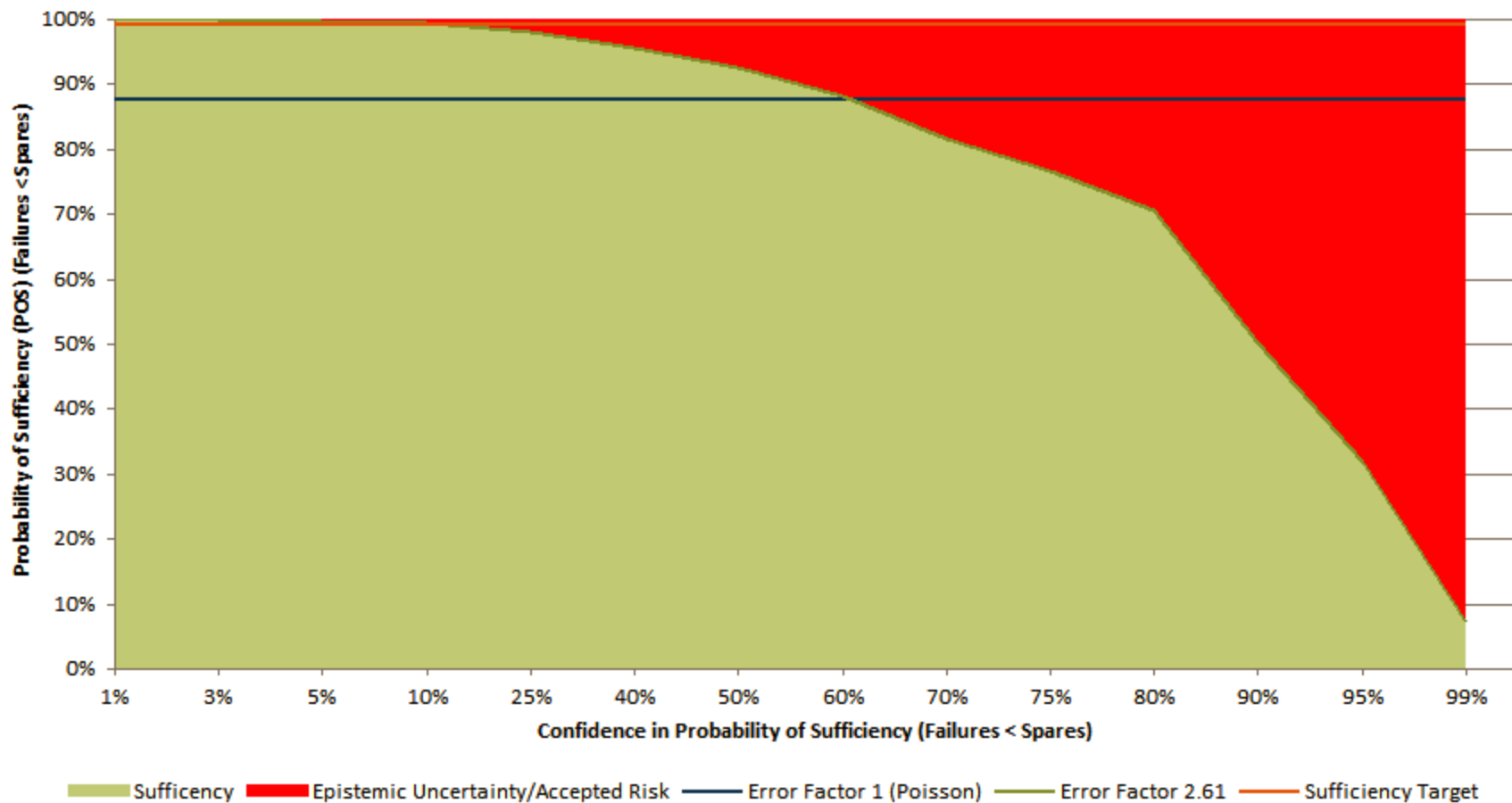## Confidence and Probability of Sufficiency through 2020

Probability of Sufficiency (POS) (Failures <Spares) (y-axis): 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%

Confidence in Probability of Sufficiency (Failures < Spares) (x-axis): 1%, 3%, 5%, 10%, 25%, 40%, 50%, 60%, 70%, 75%, 80%, 90%, 95%, 99%

Legend: Sufficiency — Epistemic Uncertainty/Accepted Risk — Error Factor 1 (Poisson) — Error Factor 2.61 — Sufficiency Target
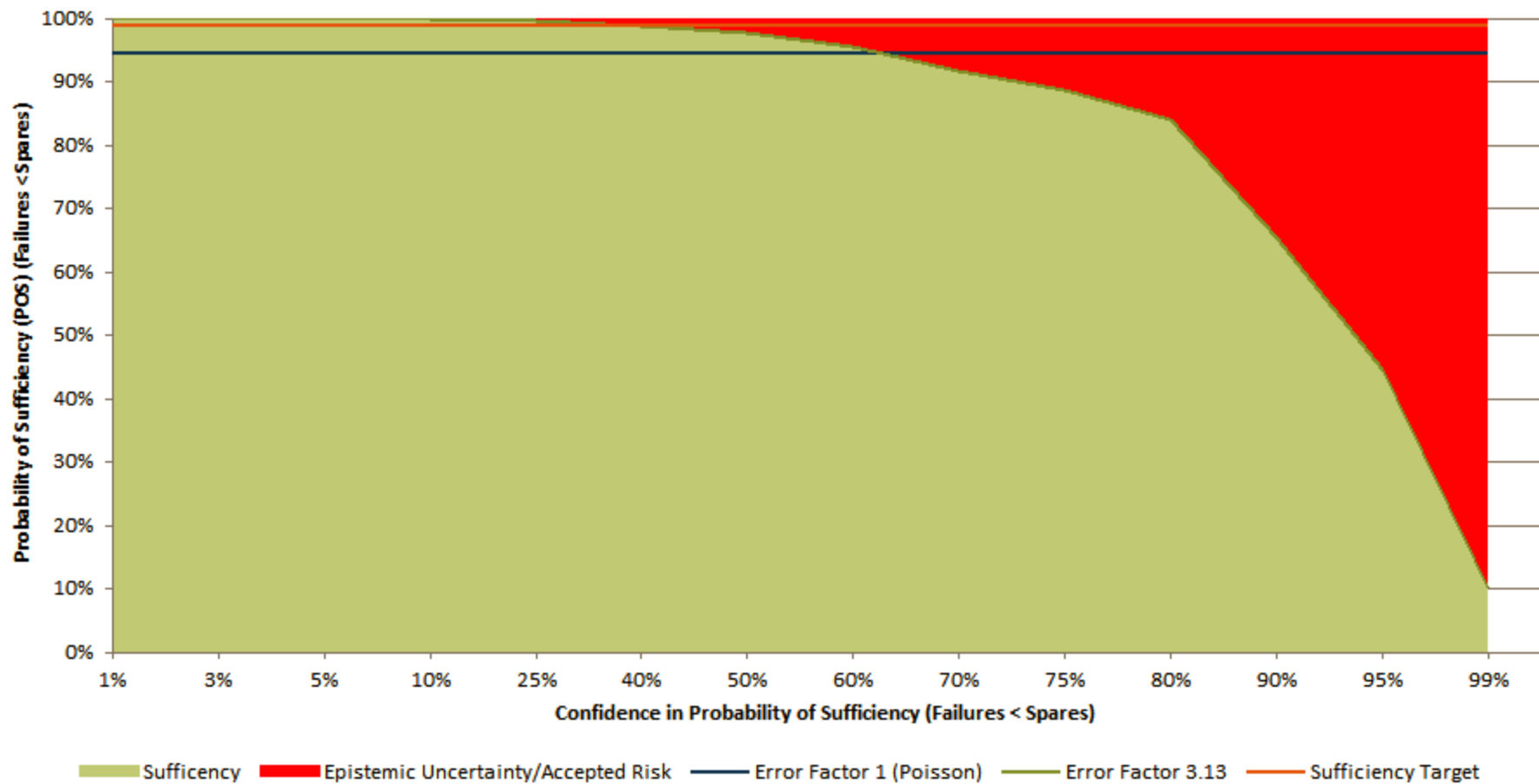
Hydrogen Dome

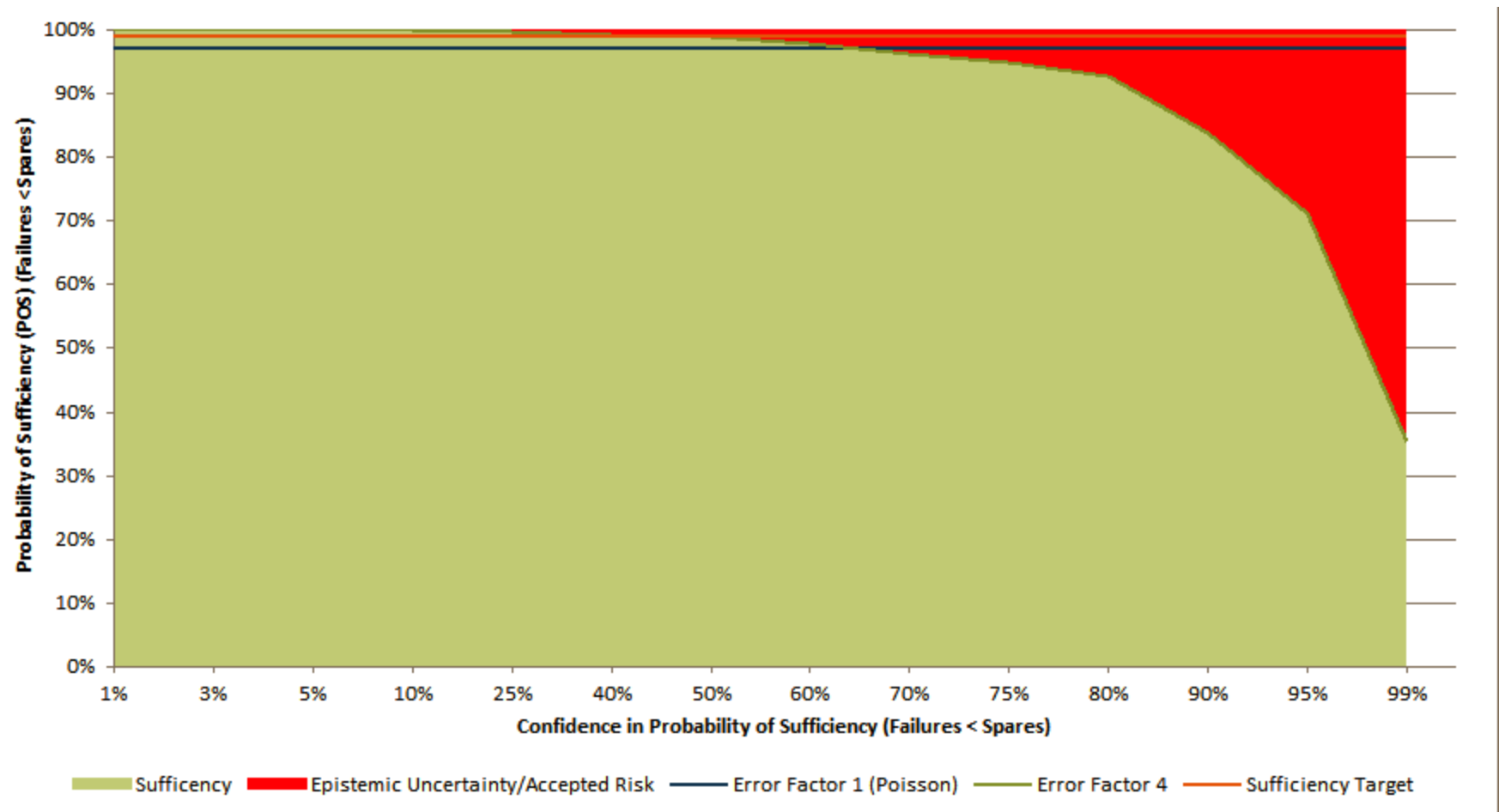Confidence and Probability of Sufficiency through 2020

Confidence and Probability of Sufficiency through 2020

TRRJ DLA

Confidence and Probability of Sufficiency through 2020