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.
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
Overview, cont.’d

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
Current Process Flow

ORU operating hours → Bayesian Update Process → Posterior ORU failure rate (1/MTBF) → Poisson Process

ORU failures → Spares

Prior Error factor → Posterior Error factor

ORU Probability of Sufficiency

Air Lock
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

- ORU operating hours
- ORU failures
- Prior Error factor

Bayesian Update Process:
- Posterior ORU failure rate (1/MTBF)

Log Normal Process:
- Spares
- Posterior Error factor

ORU Probability of Sufficiency
Confidence in the Probability Estimate

PACT
PACT Results

• 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

**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.

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

Confidence and Probability of Sufficiency through 2020

![Graph showing confidence and probability of sufficiency through 2020. The graph includes lines for Sufficiency, Epistemic Uncertainty/Accepted Risk, Error Factor 1 (Poisson), Error Factor 1.36, and Sufficiency Target.]
Results: IPEHG

Confidence and Probability of Sufficiency through 2020
Pump Module

Confidence and Probability of Sufficiency through 2020

![Graph showing confidence and probability of sufficiency through 2020.](image)
Hydrogen Dome

Confidence and Probability of Sufficiency through 2020

![Graph showing confidence and probability of sufficiency through 2020. The graph displays various confidence levels and their corresponding probability of sufficiency. The x-axis represents confidence in probability of sufficiency, and the y-axis represents probability of sufficiency (failures < spares). The graph includes lines for sufficiency, epistemic uncertainty/accepted risk, error factor 1 (Poisson), error factor 3.13, and sufficiency target.]
Confidence and Probability of Sufficiency through 2020
Confidence and Probability of Sufficiency through 2020