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

Name of Forum: AIAA SPACE 2012 Conference & Exposition
Date: September 2012

Leif Anderson, Boeing L&M
Neil Box, ARES S&MA
Katrina Carter-Journet, ARES S&MA
Denise DiFilippo, Boeing L&M
Sean Harrington, Boeing L&M
David Jackson, NASA L&M
Michael Lutomski, NASA S&MA
Background

• Sparing Assessment
  – Prior to Shuttle retirement, spares had already been purchased and pre-positioned on-orbit to meet the critical ISS functional requirements to the previously expected life of 2015.
  – 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.
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—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.
   - 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

We propose an approach to revise confidence targets and account for both categories of uncertainty, an approach we call Probability and Confidence Trade-space (PACT) evaluation.
Current Process Flow

1. ORU operating hours
2. Bayesian Update Process
3. Posterior ORU failure rate (1/MTBF)
4. Poisson Process
5. ORU Probability of Sufficiency
6. ORU failures
7. Prior Error factor
8. Spares
9. Posterior Error factor
Current Model of ISS Sparing Risk

- **Probability of Sufficiency (POS)**
  - Accepted Risk
  - Sufficiency
  - Un-quantified Confidence in POS
PACT: Proposed Process Flow

- ORU operating hours
- ORU failures
- Prior Error factor
- Bayesian Update Process
- Posterior ORU failure rate (1/MTBF)
- Log Normal Process
- ORU Probability of Sufficiency
- Spares
- Posterior Error factor
- Confidence in the Probability Estimate
PACT Model of ISS Sparing Risk

Previously Accepted Risk

Quantified Confidence in POS

Previously Unidentified Epistemic Uncertainty

Probability of Sufficiency (POS)

Previously Accepted Risk “Now Sufficient”
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.’

• 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.
  – Decision options:
    1. We may accept the probability and our confidence as is.
    2. We may relax our confidence for a higher desirable POS value, or we may consider a lower desirable POS value in favor of a higher confidence level.

Alternately, we may influence the ORU POS and confidence estimates by assuming additional spares or by changing the projected horizon time for the analysis.
Figure shows what number of ‘events’ sparing quantities should cover to meet the targets: 90/90 TARGET: 1.36 events, 75/75 TARGET: 1.02 events, 60/60 TARGET: 0.91 events
Summary

• When introducing PACT Evaluation, we define the epistemic uncertainty characterizing ISS sparing assessments. We hereby acknowledge what we can realistically know about an ORU’s true failure rate given the various methods used to predict ORU reliability.

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

Acknowledgement:
The researchers extend our utmost gratitude to Dr. William E. Vesely, of NASA Headquarters, whose technical expertise, advice, and encouragement was a catalyst to our efforts for completing this phase of our work.
Backup
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. Develop the **capability to optimize** 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
Testing PACT: Case Study

- **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
  - **Remote Power Control Mechanism (RPCM T5 Ext)** – large population of installed units and spares providing rich operational experience including failures and redesign
  - **Improved Payload Ethernet Hub Gateway (IPEHG)** – small internal ORU, no operational experience
  - **Pump Module Assembly (PMA)** – 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
  - **Solar Array Rotary Joint Drive Lock Assembly Drive Lock Assembly (SARJ-DLA)** – external ORUs with redundancy, similar function differing failure rates, SARJ DLA modeled in the Usable Power function hierarchy
  - **Thermal Radiator Rotary Joint Drive Lock Assembly Drive Lock Assembly (TRRJ-DLA)** – external ORUs with redundancy, similar function differing failure rates, TRRJ DLA modeled as a separate ORU

- **Statistics:**
  - The posterior error factor range for entire ISS population of ORUs: 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 Ext Improved Payload</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>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 SARJ Drive Lock Assembly (SARJ-DLA)</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>TRRJ Drive 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>
Results: RPCM Type V Ext

Confidence and Probability of Sufficiency through 2020

RPCM Type 5 - External: Poisson Distribution

- Sufficiency
- Epistemic Uncertainty/Accepted Risk
- Error Factor 1 (Poisson)
- Error Factor 1.36
Results: IPEHG

Confidence and Probability of Sufficiency through 2020

![Graph of IPEHG: Poisson Distribution]

- **Sufficiency**
- **Epistemic Uncertainty/Accepted Risk**
- **Error Factor 1 (Poisson)**
- **Error Factor 4**
Pump Module

Confidence and Probability of Sufficiency through 2020

Pump Module: Poisson Distribution

Confidence in Probability of Sufficiency (Failures < Spares)

Probability of Sufficiency (POS) (Failures < Spares)

- Sufficiency
- Epistemic Uncertainty/Accepted Risk
- Error Factor 1 (Poisson)
- Error Factor 2.61
Hydrogen Dome

Confidence and Probability of Sufficiency through 2020

Hydrogen Dome: Poisson Distribution

Confidence in Probability of Sufficiency (Failures < Spares)

Probability of Sufficiency (POS)

1% 3% 5% 10% 25% 40% 50% 60% 70% 75% 80% 90% 95% 99%

Sufficiency  Epistemic Uncertainty/Accepted Risk  Error Factor 1 (Poisson)  Error Factor 3.13
SARJ DLA

Confidence and Probability of Sufficiency through 2020

SARJ DLA: Poisson Distribution

Confidence in Probability of Sufficiency (Failures < Spares)

Probability of Sufficiency (POS) (Failures < Spares)

- Sufficiency
- Epistemic Uncertainty/Accepted Risk
- Error Factor 1 (Poisson)
- Error Factor 4
Confidence and Probability of Sufficiency through 2020

TRRJ DLA: Poisson Distribution

- Sufficiency
- Epistemic Uncertainty/Accepted Risk
- Error Factor 1 (Poisson)
- Error Factor 4
## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT</td>
<td>Confidence Target</td>
</tr>
<tr>
<td>EF</td>
<td>Error Factor</td>
</tr>
<tr>
<td>IPEHG</td>
<td>Improved Payload Ethernet Hub Gateway</td>
</tr>
<tr>
<td>ISS</td>
<td>International Space Station</td>
</tr>
<tr>
<td>kF</td>
<td>K Factor</td>
</tr>
<tr>
<td>MTBF</td>
<td>Mean Time Between Failure</td>
</tr>
<tr>
<td>ORU</td>
<td>Orbital Replacement Unit</td>
</tr>
<tr>
<td>PACT</td>
<td>Probability and Confidence Trade-space</td>
</tr>
<tr>
<td>POS</td>
<td>Probability of Sufficiency</td>
</tr>
<tr>
<td>PMA</td>
<td>Pump Module Assembly</td>
</tr>
<tr>
<td>PT</td>
<td>Probability Target</td>
</tr>
<tr>
<td>RPCM</td>
<td>Remote Power Control Mechanism</td>
</tr>
<tr>
<td>SARJ DLA</td>
<td>Solar Array Rotary Joint Drive Lock Assembly</td>
</tr>
<tr>
<td>TRRJ DLA</td>
<td>Thermal Radiator Rotary Joint Drive Lock Assembly</td>
</tr>
</tbody>
</table>