Understanding the Elements of Operational Reliability
A Key for Achieving High Reliability

Fayssal M. Safie, Ph. D.
Marshall Space Flight Center
Huntsville, Alabama, USA

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Mission Success Starts with Safety

Agenda

• Introduction
• Reliability Engineering Major Areas
  - Reliability Engineering Interfaces
• Design Reliability
• Process Reliability
• Reliability Applications
  - A Probabilistic Engineering Analysis Case Study
  - A Process Reliability Case Study
• Concluding Remarks
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Reliability Engineering Major Areas

- Reliability
- Reliability Analysis
- Reliability Testing and Verification
- FMEA/CIL
- Reliability, Allocation, Modeling, and Prediction
- Reliability Requirement
- Reliability Program Planning and Control
- Reliability Growth
- Reliability Databases
Reliability Engineering Major Interfaces

- Risk Management
- Maintainability Engineering
- Quality Engineering
- Supportability Engineering
- System Safety Engineering
- Test and Evaluation
- Engineering Design
Inherent Reliability versus Operational Reliability

- **Inherent Reliability** is the level of reliability inherent in the system as designed and manufactured (See design and process reliability).

- **Operational Reliability** is the reliability actually observed during operation.

- Failure occur due to weaknesses in the design, flaws in the materials, defects from the manufacturing processes, maintenance errors, improper operation, changes in operating concept, etc.

- The level of inherent reliability is determined through analysis and test (the "actual" system or prototypes). Although the design and development team attempts to simulate the actual operating environment, it is difficult if not impossible to account for some aspects of operation.

- If the operating environment is substantively different from that defined during design, more failures or failure modes may occur than were addressed during design and manufacturing.
Introduction - The Metric

**Reliability**: The probability that an item will perform its intended function for a specified mission profile.

HIGH RELIABILITY MEANS:

- **DESIGN IT RIGHT**
  - ESTABLISH DESIGN RELIABILITY REQUIREMENTS AND DEVELOP A PLAN WHICH SHOWS HOW REQUIREMENTS WILL BE MET
  - USE QUALITATIVE AND QUANTITATIVE ANALYSIS METHODS AND TOOLS TO VERIFY THAT REQUIREMENTS ARE MET

- **BUILD IT RIGHT**
  - ANALYZE THE MANUFACTURING, ASSEMBLY, AND TEST PROCEDURE CONCURRENT WITH THE DESIGN PROCESS
  - USE CONCURRENT ENGINEERING TO GET EVERYONE INVOLVED UP-FRONT
Design and Process Reliability

Reliability

Design Reliability

Process Reliability

Materials Properties

Processing Models

Material Models

Manufacturing Models

Loads & Environments

Process Control

Operations

Process Characterization

Loads

Historical data and models

Operating conditions

Process
Design Reliability

Design Process
- Loads
- Environments
- Usage
- Sizing
- Materials
- Geometry

Operating Stress

Materials Production
- Acceptance Testing
- Qualification Testing

Baseline Mat’l Strength

Failure Region

Operating Stress

Material Strength
Process Reliability

- **Element Design**
  - Critical Design Parameters (CDP)
  - Materials Properties & Geometry

- **Processing**
  - Map the CDP To Processing
  - Identify Critical Process Variables (CPV)

- **Process Characterization**
  - Explore Relationship between CDP and CPV
  - CDP = f(CPV)

- **Process Control**
  - Select Control Strategy
  - Assess Process Capability

Material Models

Strain vs. Cycles
A Probabilistic Engineering Analysis Case Study
Probabilistic Engineering Analysis

• Probabilistic engineering analysis was used in the study to predict the probability of inner race over-stress, under the conditions experienced in the test rig, and estimate the effect of manufacturing stresses on the fracture probability.

• Probabilistic engineering analysis is used when failure data is not available and the design is characterized by complex geometry or is sensitive to loads, material properties, and environments.

• During rig testing the AT/HPFTP Bearing experienced several cracked races.

• Summary of 440C race fractures/tests: 3 of 4 fractured
Turbo-pump Bearing Simulation Model

1. Randomly select values for inner race mat'l properties
   - ε
   - α
   - ν

2. Randomly select values for shaft/sleeve mat'l properties
   - ε
   - α
   - ν

3. Tolerance fits of rig test bearing

4. Inner race hoop stress at given conditions

5. Shaft/sleeve hoop stress at given conditions

6. Total hoop stress

7. Stress due to manufacturing

8. Variation in:
   - Fracture toughness
   - Yield strength
   - No. of cracks
   - Crack depth
   - Crack length

9. Compute allowable load for each crack

10. Compute allowable load (worst crack)

11. Stress > allowable load

12. Iterate and compute failure probability
# Turbo-pump Bearing Simulation Results

<table>
<thead>
<tr>
<th>Test Failures</th>
<th>Race Configuration</th>
<th>Failures in 100,000 firings**</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 of 4</td>
<td>440C w/ actual* mfg. stresses</td>
<td>68,000</td>
</tr>
<tr>
<td>N/A</td>
<td>440C w/ no mfg. stresses</td>
<td>1,500</td>
</tr>
<tr>
<td>N/A</td>
<td>440 C w/ ideal mfg. stresses</td>
<td>27,000</td>
</tr>
<tr>
<td>0 of 15</td>
<td>9310 w/ ideal mfg. stresses</td>
<td>10</td>
</tr>
</tbody>
</table>

*ideal + abusive grinding  
**Probabilistic Structural Analysis

It is estimated that 50% of the through ring fractures would result in an engine shutdown. The shutdown 9310 HPFTP Roller Bearing Inner Race Failure Rate is then: $$0.50 \times 10/100k = 5 \text{ fail}/100k \text{ firings.}$$
The Message

• Probabilistic engineering analysis is critical:
  • To understand the uncertainty of the design and identify high risk areas
  • To perform sensitivity analysis and trade studies for reliability optimization.
  • To identify areas for further testing.
A Process Reliability Case Study
External Tank (ET) Thermal Protection System (TPS)

- The ET TPS is a foam-type material applied to the ET to maintain cryogenic propellant quality, minimize ice and frost formation, and protect the structure from ascent, plume, and re-entry heating.
- The TPS during re-entry is needed because after ET/Orbiter separation, premature structural overheating due to loss of TPS could result in a premature ET breakup with debris landing outside the predicted footprint.
Reliability of TPS

• The reliability of the TPS is broadly defined as its strength versus the stress put on it in flight.
• High TPS reliability means less debris released and fewer hits to the orbiter, reducing system risk.
• Process control, process uniformity, high process capability are critical factors in achieving high TPS reliability.
• Good process uniformity and high process capability yield fewer process defects, smaller defect sizes, and good material properties that meets the engineering specification—the critical ingredients of high reliability.
Impact of Process Reliability

**Input Data**
- ET TPS Dissections (ET Project)
- TPS Geometry Properties, Boundary Conditions (ET Project)
- Debris Transport and CFD Calculations (SE&I)
- Orbiter Geometric Models (Orbiter Project)
- Orbiter Impact / Damage Tolerances (Orbiter Project)

**Validation Data**
- ET Dissection / Manufacturing Data
- Thermal-Vacuum and Flight Imagery Data
- Debris Transport Analysis
- Orbiter Post-Flight Data

**TPS Void Distributions**

**Process Control**

**TPS Debris Generation**
- (divot/no divot, size/shape, (mass), time and location of release, and pop-off velocity)

**TPS Reliability**

**TPS Transport Model**
- (axial/lateral locations and velocities during ascent)

**Orbiter Impact Algorithms**
- (impact/no impact, location, time, mass, velocity and angle)

**Orbiter Damage Analysis**
- (tile/RCC panel damage)

**Probability of Orbiter Damage Exceeding Damage Tolerance**

**System Risk**
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Impact of Process Reliability

- **Process Control**
  - TPS Process Uniformity and Capability
  - High TPS Capability

- **Component Reliability**
  - TPS Capability vs. Performance
  - Higher TPS Capability

- **System Risk**
  - TPS Failure Impact on Orbiter
  - Lower Shuttle Risk and Higher Safety
The Message

• The clear message from the Columbia accident and the ET TPS foam experience is that inadequate manufacturing and quality control can have a severe negative impact on component reliability and system safety.

• It is critical to understand the relationship between process control, component reliability, and system safety upfront in the design process.
Concluding Remarks

• Quantitative Reliability Engineering analysis involves more than just reliability predictions and reliability demonstration that are performed against a given program or project requirements.

• Quantitative Reliability Engineering analysis can play a key role in supporting a broad range of applications. It is critical in addressing design and manufacturing deficiencies.

• High Reliability means design it right and build it right.