USE OF PROBABILISTIC RISK ASSESSMENT (PRA) IN THE SHUTTLE DECISION MAKING PROCESS

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INTRODUCTION

Probabilistic Risk Assessment (PRA) is a comprehensive, structured, and disciplined approach to identifying and analyzing risk in complex systems and/or processes that seeks answers to three basic questions:

- What kinds of events or scenarios can occur (i.e., what can go wrong)?
- What are the likelihoods and associated uncertainties of the events or scenarios?
- What consequences could result from these events or scenarios (e.g., Loss of Crew and Loss of Mission)?
• The Space Shuttle Program (SSP) initiated the development of a Shuttle Probabilistic Risk Assessment (SPRA) in March 2001. Prior to that there were a number of PRA estimates for the Shuttle, but none were sponsored by the SSP.
  – Chart on next page summarizes the Shuttle PRA evolution.
• The “consequence” or metric of concern selected for the SPRA is Loss of Crew and/or Vehicle (LOCV).
• The risk contributors include hardware failures, external events, crew errors, software failures, and phenomenological events.
**SHUTTLE PRA EVOLUTION**

- The advent of established NASA requirements, standards, and tools - as well as the development of a strong Shuttle program PRA team have resulted in significant recent progress
- Iteration 3.2 is the most comprehensive and used Shuttle PRA to date

### Examples of SPRA uses:

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987</td>
<td>Proof of concept study for applying PRA to Space Shuttle. Scope was limited to APUs for Orbiter and SRB</td>
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<td>Unpublished analysis using QRAS. No integration of elements. Limited to three Orbiter systems and the Propulsion elements</td>
</tr>
<tr>
<td>2003</td>
<td>Integrated PRA with all elements, 18 Orbiter Systems, MMOD and human actions included. Presented to Peer review Team.</td>
</tr>
<tr>
<td>2004/2005</td>
<td>Updated original models to reflect current knowledge and status at the time of this analysis.</td>
</tr>
<tr>
<td>2005</td>
<td>Updated SPRA iteration 2.2 with Abort modeling, Rendezvous and Docking. Updated Functional Data, MMOD and Ascent Debris</td>
</tr>
<tr>
<td>2006/2007</td>
<td>Updated SPRA iteration 3.0 with corrected APU Hydrazine Leak Probabilities</td>
</tr>
<tr>
<td>2009</td>
<td>Updated SPRA iteration 3.1 with updated MMOD, Ascent Debris, Orbiter Flight Software, Incorporated Orbiter Review Summit Comments</td>
</tr>
<tr>
<td>2010</td>
<td>Updated SPRA iteration 3.2 with corrected MMOD, Ascent Debris, Orbiter Flight Software, Incorporated Orbiter Review Summit Comments</td>
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</tbody>
</table>

### Mean Probability of LOCV

<table>
<thead>
<tr>
<th>Year</th>
<th>Probability</th>
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<tbody>
<tr>
<td>1:70</td>
<td>1987 Proof of concept study for applying PRA to Space Shuttle. Scope was limited to APUs for Orbiter and SRB</td>
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<td>1:55</td>
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<td>1:73</td>
<td>1993 Update of the Galileo study results to reflect then current test and operational base of the shuttle. (Ascent Only)</td>
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<td>1:131</td>
<td>1995 First major integrated (multi phase) shuttle PRA. Done with input from prime contractors.</td>
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<td>1:234</td>
<td>1998 Unpublished analysis using QRAS. No integration of elements. Limited to three Orbiter systems and the Propulsion elements</td>
</tr>
<tr>
<td>1:78</td>
<td>2003 Integrated PRA with all elements, 18 Orbiter Systems, MMOD and human actions included. Presented to Peer review Team.</td>
</tr>
<tr>
<td>1:61</td>
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<td>1:81</td>
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<td>1:85</td>
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<tr>
<td>1:89</td>
<td>2013 Updated SPRA iteration 3.3 with corrected MMOD, Ascent Debris, Orbiter Flight Software, Incorporated Orbiter Review Summit Comments</td>
</tr>
</tbody>
</table>
The purpose of the SPRA is to provide a useful risk management tool for the SSP to identify strengths and possible weaknesses in the Shuttle design and operation.

- SPRA was initially developed to support upgrade decisions, but has evolved into a tool that supports Flight Readiness Reviews (FRR) and near real-time flight decisions.
LEVELS OF ASSESSMENT

• Full Scope SPRA
  – Establishes baseline risk associated with the overall mission by mission phase, as well as by vehicle elements and subsystems
  – Documented end states, assumptions, approach, and risk drivers

• Focused PRA
  – Answers specific question that doesn’t require full model, but benefits from it

• Insights
  – Knowing relative risk contributors provides input for decisions without comprehensive PRA
KEY INFORMATION FOR MANAGEMENT

• Clear presentation of analysis
  – if the audience doesn’t understand the analysis, the information will not be used
  – Difficult because many different ways people process information

• Applicable assumptions and limitations
  – PRA is only as good as the assumptions that go into the analysis, thus important to share for managers to understand the basis of the results
  – Limitations should be understood, so that the results are not misused

• Estimates of uncertainty
  – state of knowledge about the system being modeled (e.g. the real capability of the system to successfully respond to an event)
  – randomness of the probabilistic parameters (e.g. the uncertainty in estimating a failure probability of an event)
EXAMPLES
## Shuttle Service Life Extension Program (SLEP)

Assessed the risk of each proposed upgrade and compared relative changes in risk.

### Comparison of Upgrades

<table>
<thead>
<tr>
<th></th>
<th>Current Estimated Shuttle Risk (1)</th>
<th>Current Estimated Risk Contribution</th>
<th>Proposed Upgrade Estimated Risk Contribution</th>
<th>Overall Shuttle Risk Estimate With Proposed Upgrade</th>
<th>Percent Change from Current Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHMS</td>
<td>1.28E-02</td>
<td>1.14E-03</td>
<td>6.94E-04</td>
<td>1.24E-02</td>
<td>-3.5</td>
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<tr>
<td>AHPS</td>
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<td>1.22E-03</td>
<td>4.50E-06</td>
<td>1.16E-02</td>
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<td>SSME CWN (2)</td>
<td>1.28E-02</td>
<td>1.20E-04</td>
<td>4.78E-05</td>
<td>1.27E-02</td>
<td>-0.6</td>
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<tr>
<td>Helium APU</td>
<td>1.28E-02</td>
<td>2.34E-04</td>
<td>9.05E-05</td>
<td>1.27E-2</td>
<td>-1.1</td>
</tr>
</tbody>
</table>

(1) Estimate of Loss of Crew / Vehicle risk based on version 1.5 of shuttle PRA
(2) Estimates based on values used for Rocketdyne baseline analysis
Autonomous Shuttle Risk Evaluation

Preliminary Shuttle Probabilistic Risk Assessment (SPRA) results show crew actions during entry are a risk driver.

- Contributions were developed with the assistance of the Astronaut Office (Dom Gorie).
- Results / methods are currently undergoing an independent review.

These actions are or could be automated, potentially reducing the risk of entry.

Orbiter Risk Estimates

- Of the approximately 200 crew actions modeled, the top four contribute about 11% of the 15% human reliability total.

1) Crew fails to deploy landing gear
2) Crew Brakes at the Wrong Time
3) Crew Improperly Performs Pre-flare
4) Crew Lands too Hard

Space Shuttle Service Life Extension Program (SLEP)

Showed that ~70% of calculated risk due to crew error occurs during entry, descent, and landing.
Engine Cutoff (ECO) Sensors

- Assessed the risk of changing the Launch Commit Criteria (LCC) for these ECO sensors from requiring four of four sensors to only requiring three of four sensors.

- Pointed out the need to better understand the other side of the risk trade when a launch is scrubbed due to ECO sensor failures, i.e., scrub turnaround risk.
Probability of LH2 Low Level Cutoff (STS-122)

- Shuttle Program Manager requested and used
- Model used historical data in a simulation model
- Shuttle Program Manager could see it impact of adding Ascent Performance Margin (APM) on risk
Solid Rocket Booster Power Bus Isolation Supply Analysis

Emphasized the need to implement a design change that would eliminate the failure in future flights.
Shuttle Program used these risk estimates as supporting flight rationale for STS-119, combined with FCV inspection and impact testing.
Hubble Space Telescope (HST) Manifest Decision

Risk Comparisons

- Expected HST risk is similar to the STS-115 accepted mission risk if Crew Rescue is available
  - Reduction in ascent debris risk may partially offset the increased MMOD risk for the HST mission

Analysis compared HST risk with and without crew rescue to other Shuttle missions in order to help NASA Administrator decide whether or not the HST mission was an acceptable risk.
Hubble Space Telescope (HST) Manifest Decision (2)

RISK REDUCTION COMPARISON

- For an HST mission there are no single system changes that would result in a mission risk reduction as significant as LON/Crew Rescue.

Risk reduction with crew rescue was compared to risk reductions from implemented Shuttle upgrades.
Probability of Launch on Need

☑ Assisted the Shuttle Program Manager with making an informed decision not to release the HST rescue vehicle
STS-128 Power Controller Assembly Risk Presented at L-2

**STS-128 PCA FAILURE RATE RESULTS**

<table>
<thead>
<tr>
<th>S/N</th>
<th>Weibull (β=2.024, η=25538)</th>
<th>Cycles</th>
<th>P(f)</th>
<th>5th</th>
<th>95th</th>
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<tr>
<td>FPCA-1 V070-763320</td>
<td>032 / 268775</td>
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<td>MPCA-1 V070-764400</td>
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<td>AC Inverter 3, Phase B</td>
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<td>10/12/1978</td>
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<td>10/10/1979</td>
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</tbody>
</table>

**Probability of a Broken Contactor on STS-128**

**Mean – 1:7400**

95th: 1:5500

5th – 1:10000

Low Risk due to limited # of cycles in flight

Using a Random failure rate the mean probability of a broken contactor on STS-128 is: 1:4100

**Probability of a Broken Contactor on the Ground**

The probability of a SAIL contactor of ~15700 cycles old breaking in a 6 week period (Assuming 15 contactors and 2 cycles per day) is: ~1:20

The probability of a vehicle inverter contactor of ~4700 cycles old breaking in a 6 week period (Assuming 27 contactors and 4 cycles per week) is: ~1:100

**KEY ASSUMPTIONS**

- Assumes 0.5 cycles for AC inverter contactor, 1.5 cycles for RJD contactor and 1.5 cycles for ODS and Payload controllers for STS-128
- Analysis assumes failure rate based upon contactor cycles
- 5 broken contactor failures are used in the analysis
- Assumes contactor failure will result in inadvertent “off” or failure to turn “on”
- Non-latching contactors are not included in the analysis
- Contactor cycles based upon engineering judgment

Analysis was used to help Shuttle Managers decide that PCA risk was acceptable for flight

Analysis showed that it was much more likely to have a broken contactor on the ground

Important to inform managers of the analysis assumptions

Failure rates between 2.0E-06 and 2.1E-05 per cycle
Given the failed helium isolation valve failed open, the identified risk scenarios have various mission impacts as shown in backup chart 6.

- **Loss of Right RCS Function** is failure of both regulators and assumes a mission time of **48 hours** (prior to reaching 82% which is expected late FD2, early FD3) and results in NPLS.

- **Overpressurization of the Propellant System** is failure of both regulators and failure of either the burst disc or the relief valve and uses **314 hours** (STS-131 mission time).

- **Loss of RCS Control** is failure of both regulators and either cross-feed or LRCS failure and uses **48 hours** (prior to reaching 82% which is expected late FD2, early FD3).

Each scenario is developed to the point where the mission impact is reached.

No change of state in the failed isolation valve is assumed.

If both helium isolation valves are assumed to be failed open, the calculated risk for regulator fail open will double, which will impact all of the risk estimates.
Right RCS Helium System Reliability

RIGHT RCS HELIUM SYSTEM RELIABILITY

Failure

1st

R RCS Fuel He Isol Fail OP

PRI Reg Fail CL OR Sec Reg Fail CL

1:1950 Either reg valve failure 314 hours (STS-131 mission time)

Pri Reg Creep High (<Burst Disk)

>1:100 based on flight history

1:373 using 314 hours (STS-131 mission time)

Sec Reg Creep High (<Burst Disk)

1:655 Both reg valves fail, using 314 hours (STS-131 mission time)

Probable NEOM

2nd

Sec Reg Fail OP (>Burst Disk)

1:936 based upon 218 hours of docked time

Overboard Vent thru BD/RV

Both reg valves failure results in Loss of RRCS causing NPLS if failure occurs in first 48 hours – 1:4250

NEOM Ops workarounds

Switch Regs A/B

Loss of Verns Impacts on: Mated Control Mission Content

1:768 based upon 266 hours (T-0 to undock)

1:93,200 based upon 314 hours (STS-131 mission time)

>1:100 based on flight history

1:1950 Either reg valve failure 314 hours (STS-131 mission time)

3rd Failure

BD/RV Fail CL

Fuel Tk Overpress & Structural Fail

1:655 Both reg valves fail, using 314 hours (STS-131 mission time)

1:93,200 based upon 314 hours (STS-131 mission time)

1:367 using 314 hours (STS-131 mission time)

Analysis results combined with graphical display to help communicate to Management at HQ Flight Readiness Review
SUMMARY

• Showed various ways of communicating and using PRA findings in the Shuttle Program
• Stated that it is important to provide management:
  – Clear presentation of analysis
  – Applicable assumptions and limitations
  – Estimates of uncertainty
• Maintain consistency and accuracy across the program to make it relevant
• Used various levels of PRA to answer the mail
• The Shuttle Program has benefited from using PRA and others can too