# 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)?

# BACKGROUND

- 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.

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Space Shuttle Safety and Mission Assurance Office
NASA Johnson Space Center, Houston, Texas

# 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:** SLEP Risk Trades (2003) · HST Manifest Decision (2006/2007) · STS-128 Flight Rationale (2008) · STS-131 Flight Rationale (2010)

**Mean Probability of LOCV**

| Mean Probability of LOCV | Description | Model |
|---|---|---|
| 1:70 | 1987 Proof of concept study for applying PRA to Space Shuttle. Scope was limited to APUs for Orbiter and SRB | |
| 1:55 | 1988 First somewhat integrated PRA conducted on the Space Shuttle. Done in support of Galileo Mission. (Ascent Only). | Galileo 1988 |
| 1:73 | 1993 Update of the Galileo study results to reflect then current test and operational base of the shuttle. (Ascent Only) | Phase 1 1993 |
| 1:131 | 1995 First major integrated (multi phase) shuttle PRA. Done with input from prime contractors. | Shuttle PRA 1995 |
| 1:234 | 1998 Unpublished analysis using QRAS. No integration of elements. Limited to three Orbiter systems and the Propulsion elements | Shuttle PRA 1998 |
| 1:78 | 2003 Integrated PRA with all elements, 18 Orbiter Systems, MMOD and human actions included. Presented to Peer review Team. | SPRAT PRA Iteration 1.5 2003 |
| 1:61 | 2004/2005 Integrated PRA with all elements, 18 Orbiter Systems, MMOD and human actions included. Peer reviewed. | *SPRAT PRA Iteration 2.0 2004/2005* |
| 1:67 | 2005 Integrated PRA with all elements, 18 Orbiter Systems, MMOD and human actions included. Peer reviewed. Updated Pre-valve modeling | *SPRAT PRA Iteration 2.1 2005* |
| 1:77 | 2006/2007 Updated SPRA iteration 2.1 with Inspection with Repair and Crew Rescue. Updated MMOD and Ascent Debris Modeling | *SPRAT PRA Iteration 2.2 2006/2007* |
| 1:81 | 2008 Updated SPRA iteration 2.2 with Abort modeling, Rendezvous and Docking. Updated Functional Data, MMOD and Ascent Debris | *SPRAT PRA Iteration 3.0 2008* |
| 1:85 | 2009 Updated SPRA iteration 3.0 with corrected APU Hydrazine Leak Probabilities | *SPRAT PRA Iteration 3.1 2009* |
| 1:89 | 2010 Updated SPRA iteration 3.1 with updated MMOD, Ascent Debris, Orbiter Flight Software, Incorporated Orbiter Review Summit Comments | *SPRAT PRA Iteration 3.2 2010* |

# BACKGROUND

- 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)

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Space Shuttle SR&QA Office
NASA Johnson Space Center, Houston, Texas

## Comparison of Upgrades

Presenter
Date 01/20/2004 Page 1

| | Current Estimated Shuttle Risk (1) | Current Estimated Risk Contribution | Proposed Upgrade Estimated Risk Contribution | Overall Shuttle Risk Estimate With Proposed Upgrade | Percent Change from Current Estimate |
|---|---|---|---|---|---|
| AHMS | 1.28E-02 | 1.14E-03 | 6.94E-04 | 1.24E-02 | -3.5 |
| AHPS | 1.28E-02 | 1.22E-03 | 4.50E-06 | 1.16E-02 | -9.5 |
| SSME CWN (2) | 1.28E-02 | 1.20E-04 | 4.78E-05 | 1.27E-02 | -0.6 |
| Helium APU | 1.28E-02 | 2.34E-04 | 9.05E-05 | 1.27E-2 | -1.1 |

(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

✓ **Assessed the risk of each proposed upgrade <u>and</u> compared relative changes in risk**

# Shuttle Service Life Extension Program (SLEP)

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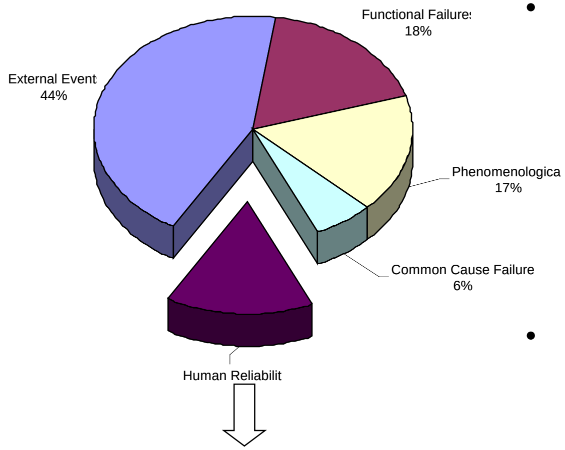
NASA Johnson Space Center, Houston, Texas

| Autonomous Shuttle Risk Evaluation | Presenter | |
|---|---|---|
| | Date 1/26/04 | Page 1 |

### Orbiter Risk Estimates



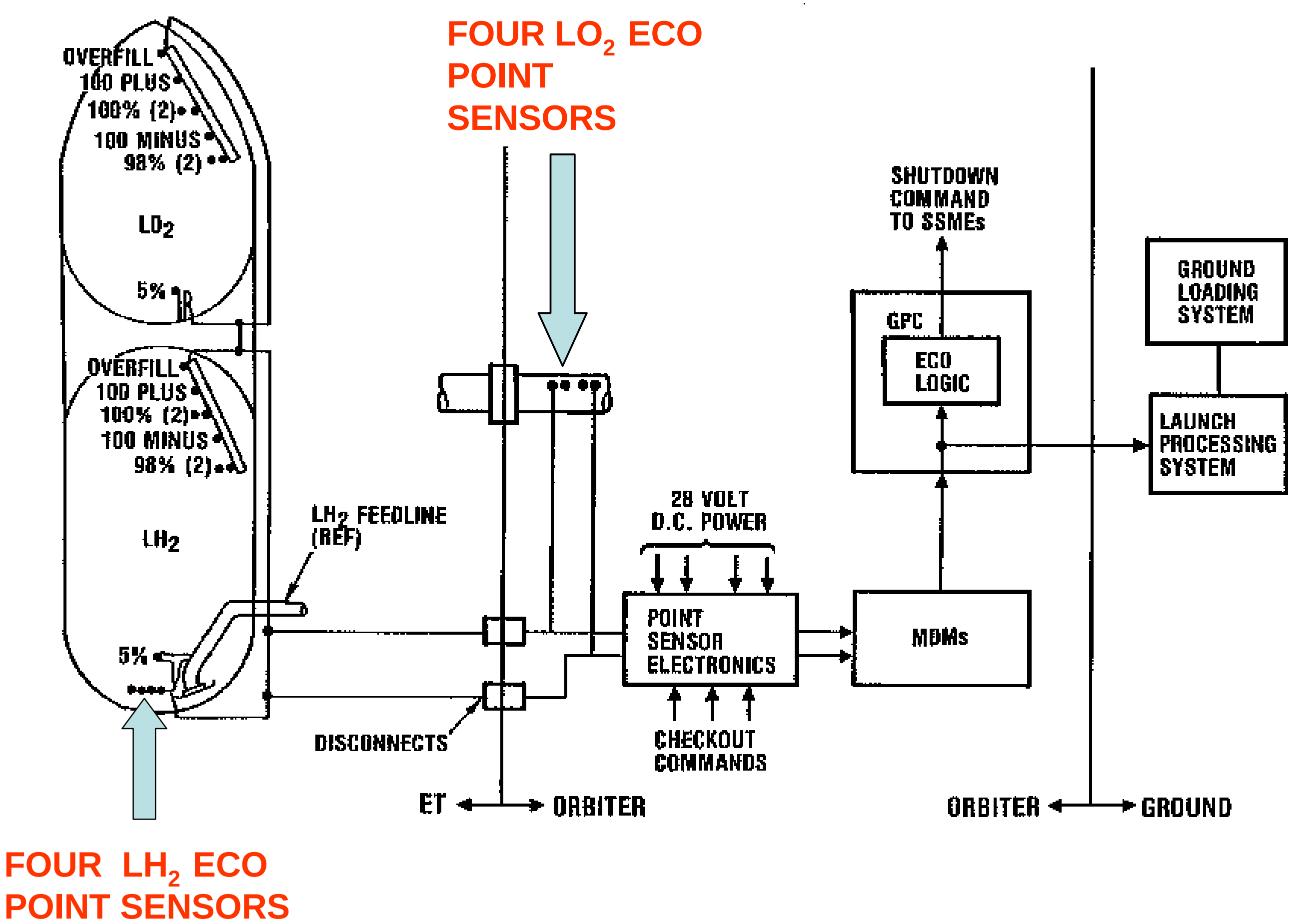

- Preliminary Shuttle Probabilistic Risk Assessment (SPRA) results show crew actions during entry are a risk driver.
  - Contributions were developed with the assistance of the Astronaut Office (Dom Gorie).
  - Results / methods are currently undergoing an independent review.
- These actions are or could be automated, potentially reducing the risk of entry.

- 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

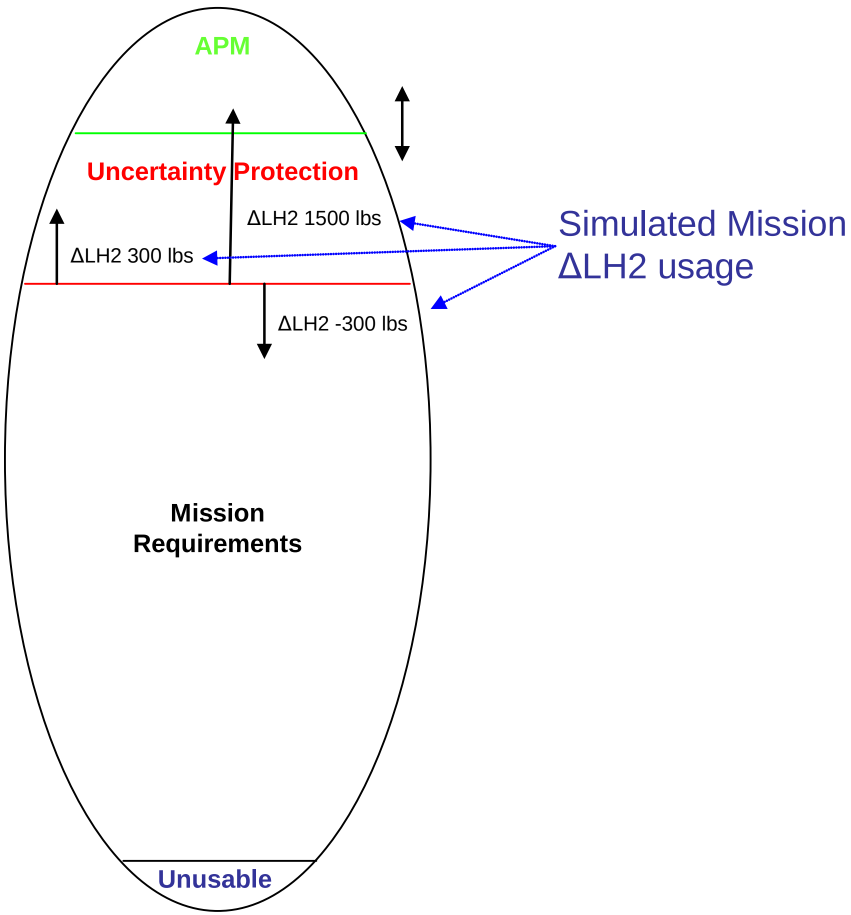
✓Showed that ~70% of calculated risk due to crew error occurs during entry, descent, and landing

# Engine Cutoff (ECO) Sensors



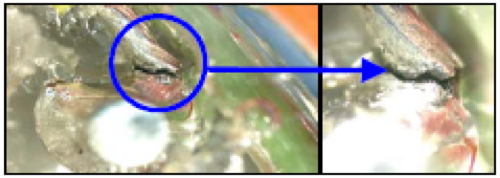

- ✓ Assessed the risk of changing the Launch Commit Criteria (LCC) for these ECO sensors from requiring four of four sensors to only requiring three of four sensors.
- ✓ Pointed out the need to better understand the other side of the risk trade when a launch is scrubbed due to ECO sensor failures, i.e., scrub turnaround risk.

# Probability of LH2 Low Level Cutoff (STS-122)



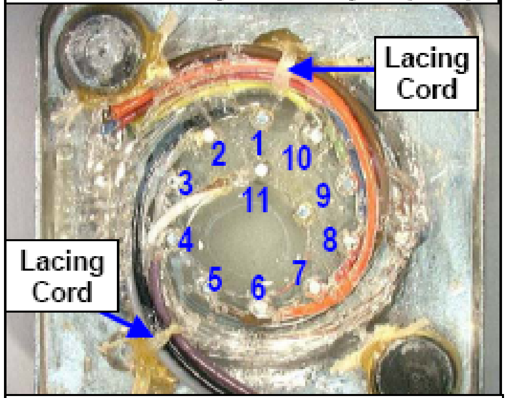

- ✓ Shuttle Program Manager requested and used
- ✓ Model used historical data in a simulation model
- ✓ Shuttle Program Manager could see it impact of adding Ascent Performance Margin (APM) on risk

# Solid Rocket Booster Power Bus Isolation Supply Analysis



Wire Broken at Pin 10 Post

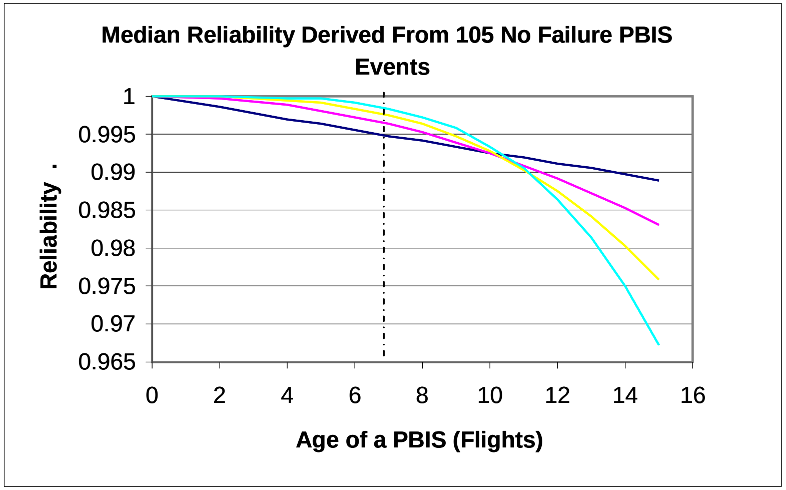
Destructive Physical Analysis (DPA)




Critical Pins: 2, 3, 4, 5, 6

Non Critical Pins: 1, 7, 8, 9, 10, 11

PBIS T2 Transformer Leads

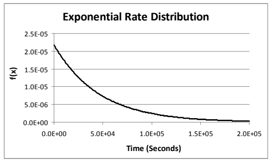



- ✓ **Emphasized the need to implement a design change that would eliminate the failure in future flights**

# Main Propulsion Flow Control Valve

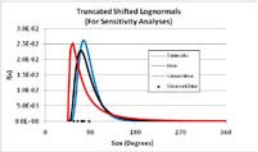
**INPUTS**

**Failure Rate**




**Chance of multiple failures**

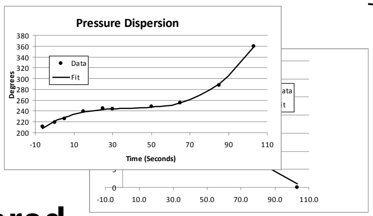
**Poppet Break Size Distribution**

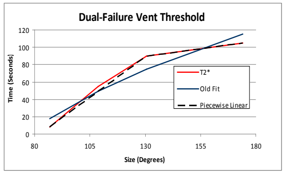



**# of failures, size and time**

**Compared to Thresholds**

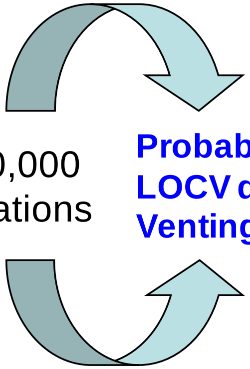
**Thresholds**




3 poppet failures are assumed to vent if occur before 120 seconds

5,000,000 replications

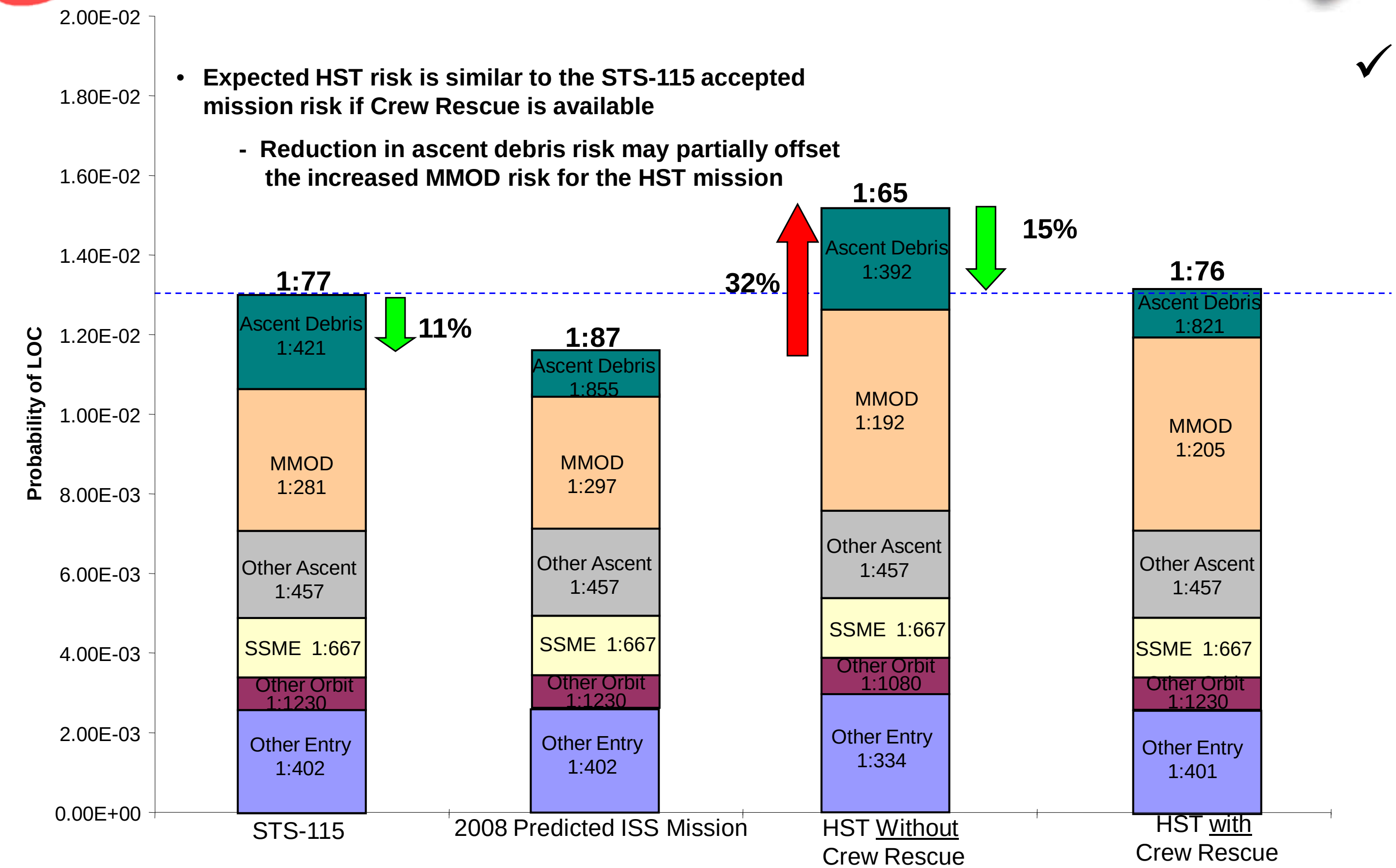


**Probability of LOCV due to Venting**

- ✓ **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

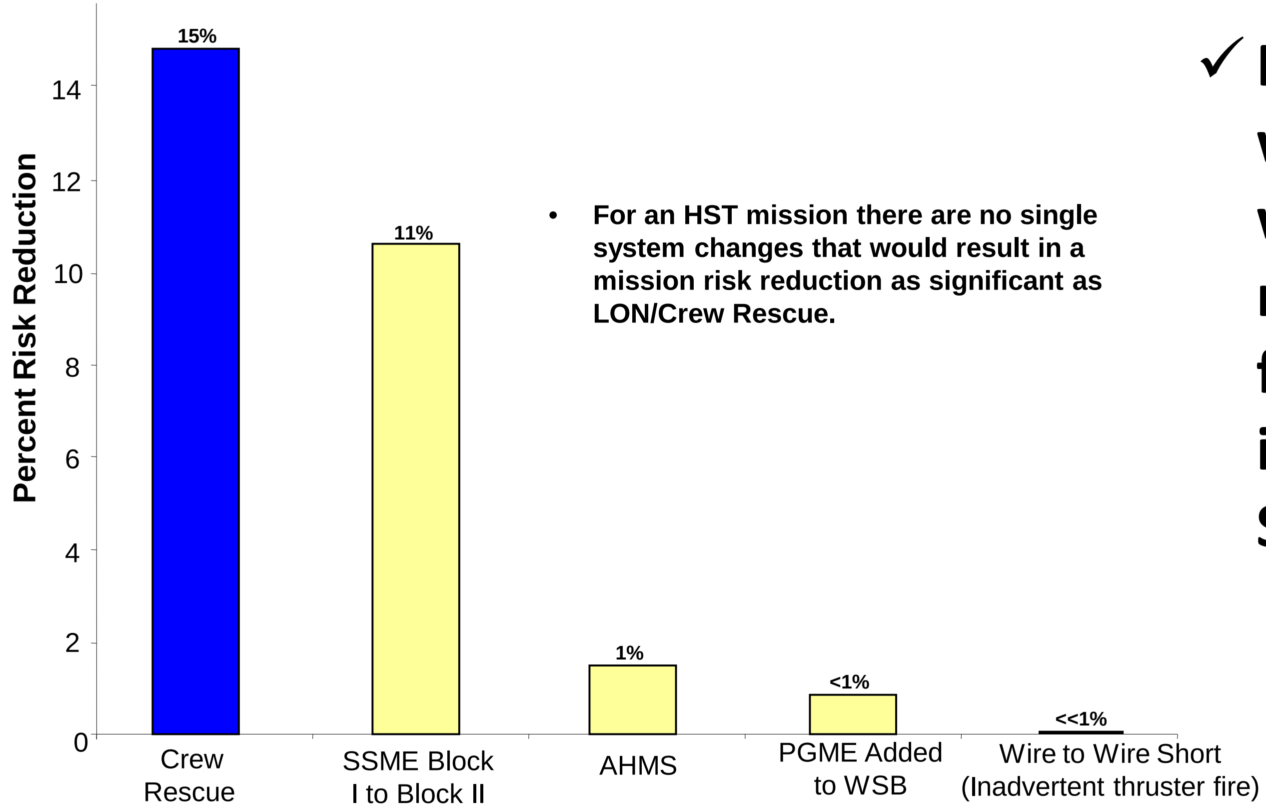



✓ **Analysis compared HST risk with and without crew rescue to other Shuttle missions in order to help NASA Administrator decide whether or not the HST mission was an acceptable risk**

Oct 27, 2006

# Hubble Space Telescope (HST) Manifest Decision (2)

## RISK REDUCTION COMPARISON

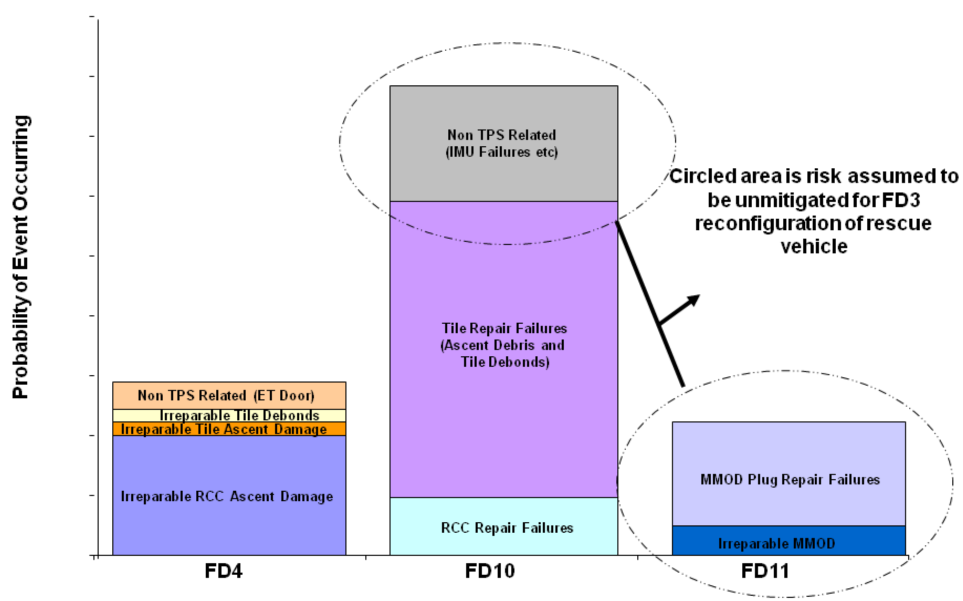



✓ **Risk reduction with crew rescue was compared to risk reductions from implemented Shuttle upgrades**

# Probability of Launch on Need

✓ **Assisted the Shuttle Program Manager with making an informed decision not to release the HST rescue vehicle**

PROBABILITY OF NEEDING CREW RESCUE BY DECISION FLIGHT DAY



# STS-128 Power Controller Assembly Risk Presented at L-2

## STS-128 PCA FAILURE RATE RESULTS

| | | OV103 | | | Weibull (β=2.024, η=25538) | | |
|---|---|---|---|---|---|---|---|
| | | S/N | ASSEMBLE | Cycles | P(f) | 5th | 95th |
| | FPCA-1 V070-763320 | -032 / 266775 | | | | | |
| K1 | AC Inverter 1, Phase A | 127 | 4/16/1982 | 6100 | 1.8E-05 | 8.4E-06 | 3.3E-05 |
| K2 | AC Inverter 1, Phase B | 128 | 4/16/1982 | 6100 | 1.8E-05 | 8.4E-06 | 3.3E-05 |
| K3 | AC Inverter 1, Phase C | 126 | 4/16/1982 | 6100 | 1.8E-05 | 8.4E-06 | 3.3E-05 |
| K11 | RJDF Bus A | 092 | 11/14/1979 | 1245 | 3.6E-06 | 1.6E-06 | 6.6E-06 |
| | FPCA-2 V070-763340 | -013 / J12867 | | | | | |
| K1 | AC Inverter 2, Phase A | 096 | 1/20/1981 | 6300 | 1.9E-05 | 8.7E-06 | 3.5E-05 |
| K2 | AC Inverter 2, Phase B | 112 | 1/20/1981 | 6300 | 1.9E-05 | 8.7E-06 | 3.5E-05 |
| K3 | AC Inverter 2, Phase C | 117 | 1/20/1981 | 6300 | 1.9E-05 | 8.7E-06 | 3.5E-05 |
| K13 | RJDF-1 Bus B PWR (RPC#36) | 111 | 1/20/1981 | 1245 | 3.6E-06 | 1.6E-06 | 6.6E-06 |
| | FPCA-3 V070-763360 | -019 / EJ3166 | | | | | |
| K-1 | AC Inverter 3, Phase A | 212 | 10/12/1978 | 6900 | 2.1E-05 | 9.5E-06 | 3.8E-05 |
| K-2 | AC Inverter 3, Phase B | 214 | 10/12/1978 | 6900 | 2.1E-05 | 9.5E-06 | 3.8E-05 |
| K-3 | AC Inverter 3, Phase C | 215 | 10/12/1978 | 6900 | 2.1E-05 | 9.5E-06 | 3.8E-05 |
| K-6 | RJDF-2B Manif F4/F5 Drivers | 216 | 12/10/1985 | 1245 | 3.6E-06 | 1.6E-06 | 6.6E-06 |
| | MPCA-1 V070-764400 | -039 / ER1634 | | | | | |
| K4 | SPARE | 221 | 7/11/1989 | 700 | 2.0E-06 | 9.1E-07 | 3.6E-06 |
| K5 | ODS/ECLSS | 228 | 7/11/1989 | 1180 | 3.4E-06 | 1.6E-06 | 6.2E-06 |
| | MPCA-2 V070-764430 | -033 / F71099 | | | | | |
| K4 | SPARE | 103 | 3/31/1980 | 700 | 2.0E-06 | 9.1E-07 | 3.6E-06 |
| K5 | ODS/ECLSS | 106 | 3/31/1980 | 1180 | 3.4E-06 | 1.6E-06 | 6.2E-06 |
| | APCA-1 V070-765310 | -003 / AM6520 | | | | | |
| K1 | Reaction Jet Driver Bus A | 138 | 11/10/1982 | 1245 | 3.6E-06 | 1.6E-06 | 6.6E-06 |
| | APCA-2 V070-765320 | -009 / F66222 | | | | | |
| K1 | Aft Payload Bay Power B | 137 | 3/29/1982 | 700 | 2.0E-06 | 9.1E-07 | 3.6E-06 |
| K2 | RJDA Manif Drivers Bus B | 180 | 2/9/1984 | 1245 | 3.6E-06 | 1.6E-06 | 6.6E-06 |
| | APCA-3 V070-765330 | -013 / J43296 | | | | | |
| K1 | Aft Payload Bay Power C | 072 | 10/10/1979 | 700 | 2.0E-06 | 9.1E-07 | 3.6E-06 |
| K2 | RJDA Manif Drivers | 079 | 10/10/1979 | 1245 | 3.6E-06 | 1.6E-06 | 6.6E-06 |

**Failure rates between 2.0E-06 and 2.1E-05 per cycle**

### 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**

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

### 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 contactor s 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**

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

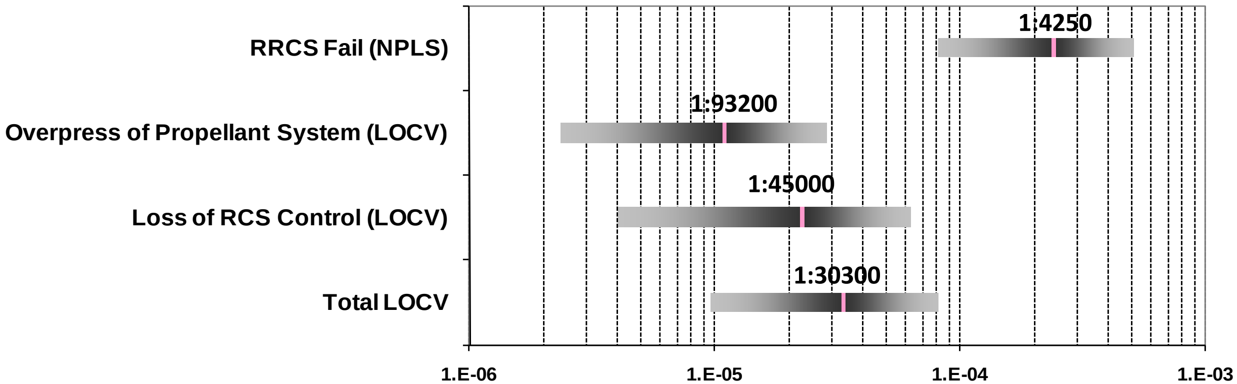
### KEY ASSUMPTIONS

- Assumes 0.5 cycles for AC inverter contactor, 1.5 cycles for RJD contactor and 1.5 cycles for ODS and Payload contactors 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

**Important to inform managers of the analysis assumptions**

# STS-131 Helium Isolation Valve Risk

## FAILURE SCENARIO RISK UNCERTAINTIES

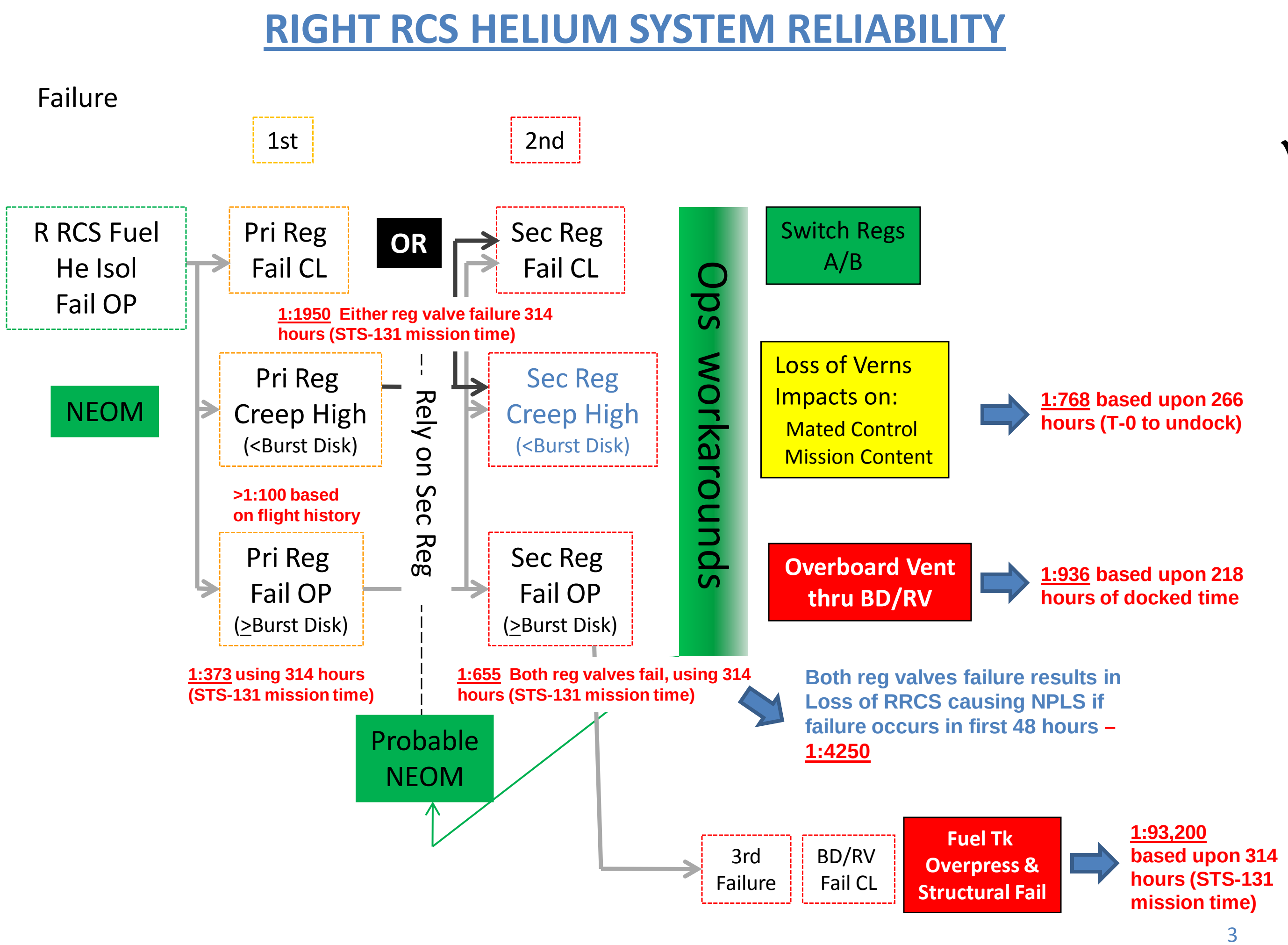



- Given the failed helium isolation valve failed open, the identified risk scenarios have various mission impacts as shown in backup chart 6.
- **Loss of Right RCS Function** is failure of both regulators and assumes a mission time of **48 hours** (prior to reaching 82% which is expected late FD2, early 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.

2

✓ **Analysis was used to support STS-131 flight rationale at the HQ Flight Readiness Review**

# Right RCS Helium System Reliability




- ✓ **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