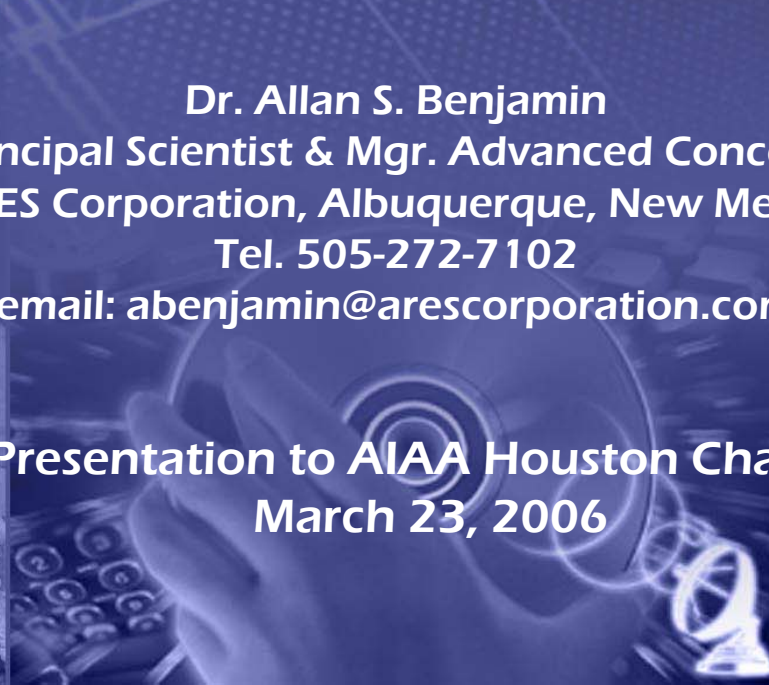




Evaluation of Return to Flight Issues for the Space Shuttle Orbiter

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Presentation to AIAA Houston Chapter
March 23, 2006



Contents of Presentation

Summary of Analysis Methods Developed and Results Obtained to Address Return to Flight Issues

- **Likelihood of Critical Fragment Impact**
 - Risk for Orbiter Windows from Aluminum Oxide & Foam
 - Risk for Orbiter Wing Leading Edge from Foam and Ice
 - Effects of Particle Orientation on Damage Thresholds for Tile
- **Confidence Level for Margin of Safety during Reentry Following an Impact that Produces a Known Amount of Damage**

Use of Petri Nets within a Monte Carlo Framework for Contingency Shuttle Crew Support (CSCS) Consumables Analysis

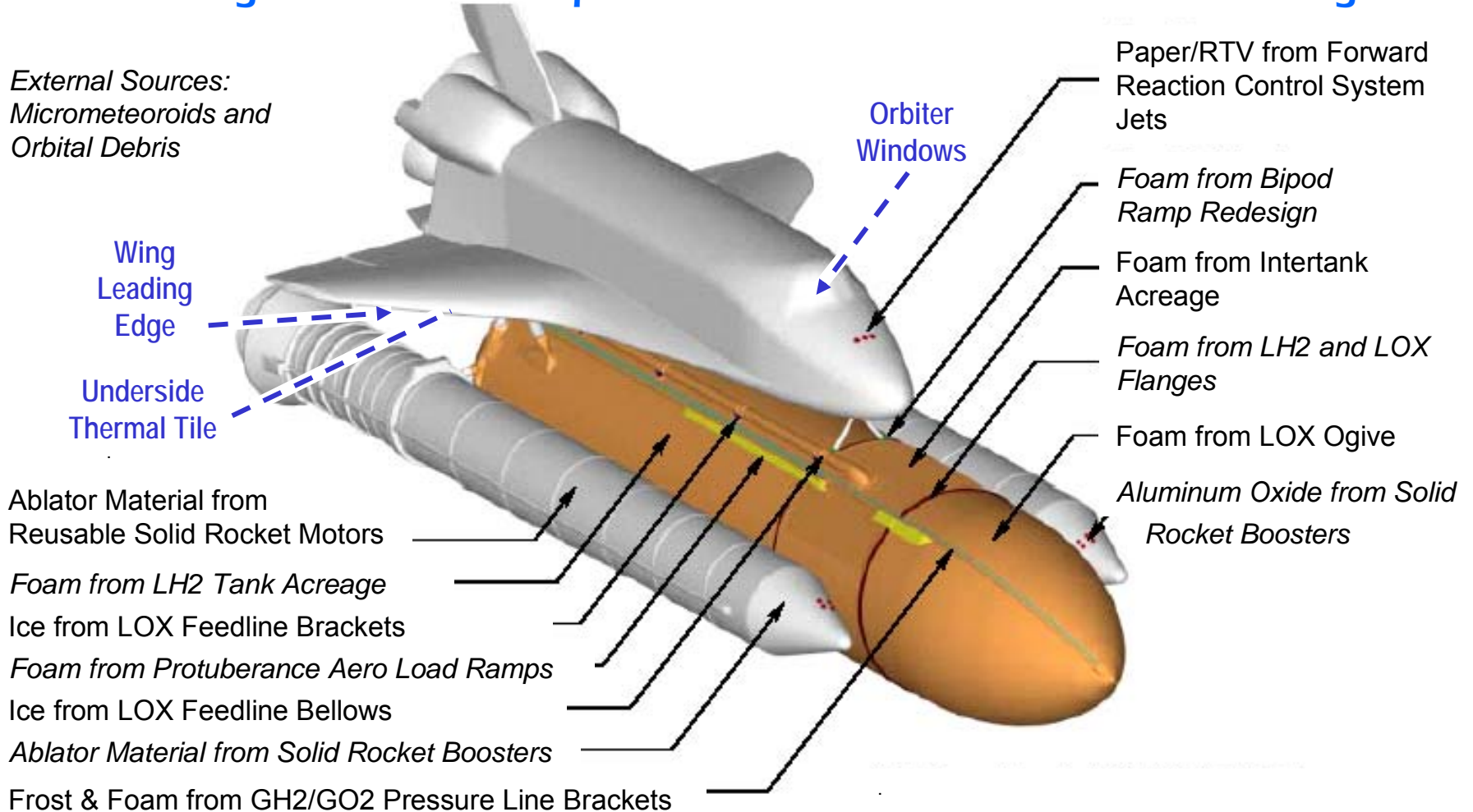
- **ARES Sampled Petri Net Tool**
- **Analysis for CO₂ During Use of ISS for CSCS as a Safe Haven**
- **Integration of Petri Net Capability with Event Trees & Fault Trees**

Three RTF Questions Addressed by ARES for Boeing

- What is the likelihood that a fragment generated from the shuttle external tank during ascent could impact the orbiter and cause critical damage?
- What are the confidence levels for the calculated margins of safety during reentry given a known amount of damage?
 - How large are the uncertainties surrounding Boeing's/NASA's detailed computations of thermal & structural responses of the orbiter during reentry following damage by a fragment impact?
- If the ISS had to be used as a safe haven following a fragment impact that disabled the orbiter for reentry, what is the probability that essential consumables (oxygen, water) and waste products (carbon dioxide) can be kept within safe limits until an alternate means of return can be provided?

Analysis of Debris Impact Risk

What is the Likelihood that a Fragment Generated from the Shuttle External Tank During Ascent Could Impact the Orbiter and Cause Critical Damage?



Orbiter Windows Debris Risk Assessment

Orbiter Windows Debris Risk Assessment: Specific Tasks

What is the likelihood that a fragment in the BSM plume or a foam fragment generated from the shuttle external tank during ascent could impact the orbiter windows and cause damage that exceeds the design safety margin?

1) Debris Generation

- Characterize and quantify debris catalog items (why and where debris is generated and in what form)

2) Debris Transport

- Evaluate and adapt Boeing transport model results (how debris is transported from external tank to orbiter windows)

3) Window Damage

- Develop correlations of experimental results for pit depths in quartz windows
- Develop correlations of pit depths that cause critical damage

4) Consequence Analysis, Integrated Qualitative Logic Model, Integrated Quantitative PRA

- Build, populate event tree models
- Quantify results to obtain probability of an impact that exceeds the design margin of safety

Orbiter Windows Debris Risk Assessment: Assumptions

What is the likelihood that a fragment in the BSM plume or a foam fragment generated from the shuttle external tank during ascent could impact the orbiter windows and cause damage that exceeds the design safety margin?

Debris Generation Assumptions

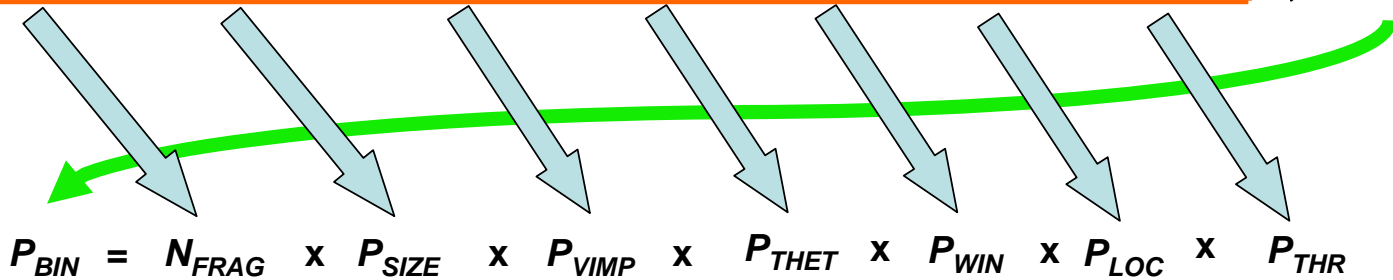
- All propellant in the BSM is expended.
- 2% (by weight) of the propellant is free aluminum particles used as the fuel source for the combustion process, and all of it is converted to aluminum oxide (Al_2O_3) particulate.
- 90% (by mass) of the Al_2O_3 particles are spherical and have a diameter between the range of 0.1 and 3 microns.
- 10% (by mass) of the Al_2O_3 particles are larger than 3 microns consisting of spherical particles up to 15 microns in diameter and irregularly shaped particles including cylinders up to 500 microns in length and 50 microns in diameter.
- The number of foam particles released and associated mass distribution are based on historical debris data collected for the liquid hydrogen (LH_2) flange region of the tank.
- The debris is uniformly distributed over the nozzle, with angular dispersion uniformly distributed between 0 to 30 degrees off center.
- The mass flux in the particle field generated at any given time is proportional to the thrust.
- The distribution of the sizes of the particles remained constant over time.

Orbiter Windows Debris Risk Assessment: Event Tree Formulation

What is the likelihood that a fragment generated from the shuttle external tank during ascent could impact the orbiter windows and cause damage that exceeds the design safety margin?

Pivot Event						
Initiating Event	Particle Size (Micron)	Impact Velocity (ft/s)	Impact Angle (deg)	Impacted Window	Impact Location	Threshold Exceedance
FRAG	SIZE	VIMP	THET	WIN	LOC	THR
<ul style="list-style-type: none"> • BSM Ignition 	<ul style="list-style-type: none"> • Range 1 • Range 2 • Range 3 • Range 4 • Range 5 • Range 6 	<ul style="list-style-type: none"> • Range 1 • Range 2 • Range 3 • Range 4 • Range 5 • Range 6 	<ul style="list-style-type: none"> • Range 1 • Range 2 • Range 3 • Range 4 • Range 5 • Range 6 	<ul style="list-style-type: none"> • Front • Middle • Side 	<ul style="list-style-type: none"> • Loc. 1 • Loc. 2 • Loc. 3 • Loc. 4 • ... • Loc. 15 	<ul style="list-style-type: none"> • Yes • No

- Bin 1
- Bin 2
- Bin 3
- Bin 4
- Etc.

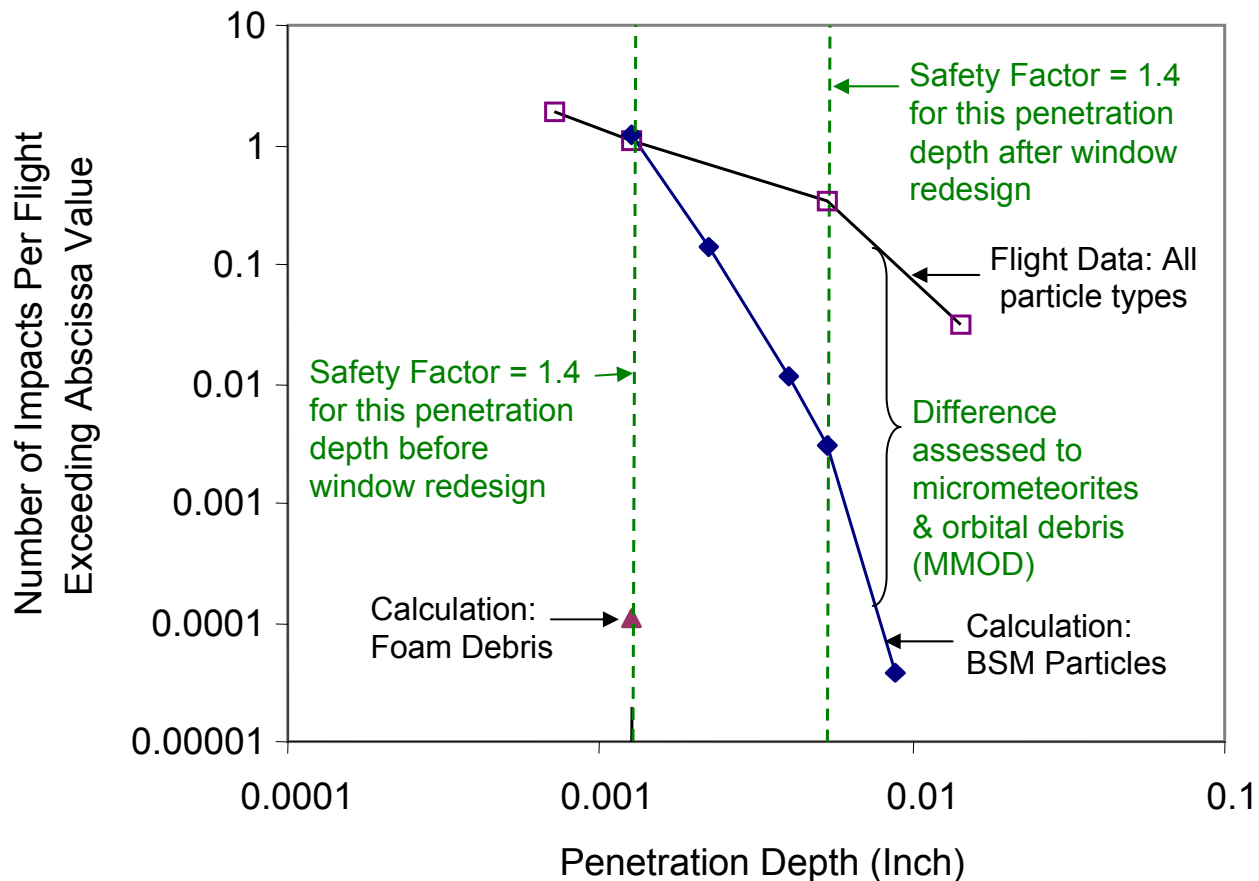


Each branch of each pivot event has a discrete probability with uncertainty

Orbiter Windows Debris Risk Assessment: Example Results

What is the likelihood that a fragment in the BSM plume or a foam fragment generated from the shuttle external tank during ascent could impact the orbiter windows and cause damage that exceeds the design safety margin?

Penetration Depth Results for Side Windows



Orbiter Leading Edge Risk Assessment

Orbiter Leading Edge Risk Assessment: Introduction

What is the likelihood that a foam or ice fragment generated from the shuttle external tank during ascent could impact the orbiter wing leading edge and cause damage that is critical but not visible to an onboard scanner?

- **Four indicators of critical damage**

- Coating loss occurs in combination with RCC delamination
- Crack goes through to substrate
- Damage extent in minimum dimension exceeds 0.015 inch
- Kinetic energy of impact exceeds threshold for critical damage (different for each group of panels)

- **Two indicators of visible damage**

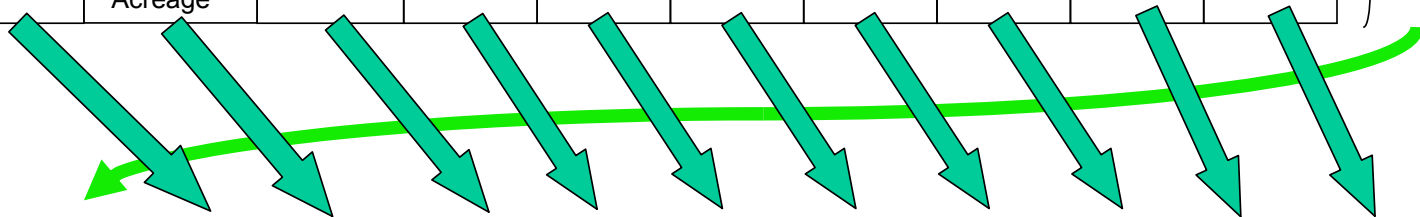
- Surface damage extent in minimum dimension exceeds 0.25 inch
- Kinetic energy of impact exceeds threshold for visible damage (different for each group of panels)

- **Kinetic energy thresholds were used for this analysis**

Orbiter Leading Edge Risk Assessment: Event Tree Formulation

The Pivot Events in the Event Tree Reflect the Inputs to the Debris Transport Analyses (DTAs)

Pivot Events										
Initiating Event	Originating Element	Originating Location	Frag. Mass (lbm)	Release Elev. (deg)	Release Azimuth (deg)	Release Velocity (ft/s)	Mach Number	Vehicle Pitch (deg)	Vehicle Sideslip (Deg)	
FRAG	ELMT	XSRC	MASS	ELEV	AZIM	VREL	MACH	ALFA	BETA	
•Foam Fragment	•Flange	•X ₁ , Y ₁ , Z ₁	•Val. 1	•Val. 1	•Val. 1	•Val. 1	•Val. 1	•STS-107 Values	•STS-107 Values	<ul style="list-style-type: none"> •Case 1 •Case 2 •Case 3 •Case 4 •Case 5 •Case 6 •Case 7 •Etc.
	•Fwd Ogive	•X ₂ , Y ₂ , Z ₂	•Val. 2	•Val. 2	•Val. 2	•Val. 2	•Val. 2			
	•Brackets	•Etc.	•Val. 3	•Val. 3	•Val. 3	•Val. 3	•Val. 3			
	•Intertank Acreage		•Val. 4	•Val. 4	•Val. 4	•Val. 4	•Val. 4			
	•Bipod Redesign		•Val. 5	•Val. 5	•Val. 5	•Val. 5	•Val. 5			
	•PALRamp		•Val. 6		•Val. 6	•Val. 6	•Val. 6			
	•LH2 Tank Acreage		...		•Val. 7	...	•Val. 7			
			•Val. 18		•Val. 8	•Val. 16	•Val. 8			



$$P_{CASE} = N_{FRAG} \times P_{ELMT} \times P_{XSRC} \times P_{MASS} \times P_{ELEV} \times P_{AZIM} \times P_{VREL} \times P_{MACH} \times P_{ALFA} \times P_{BETA}$$

Probability Distributions



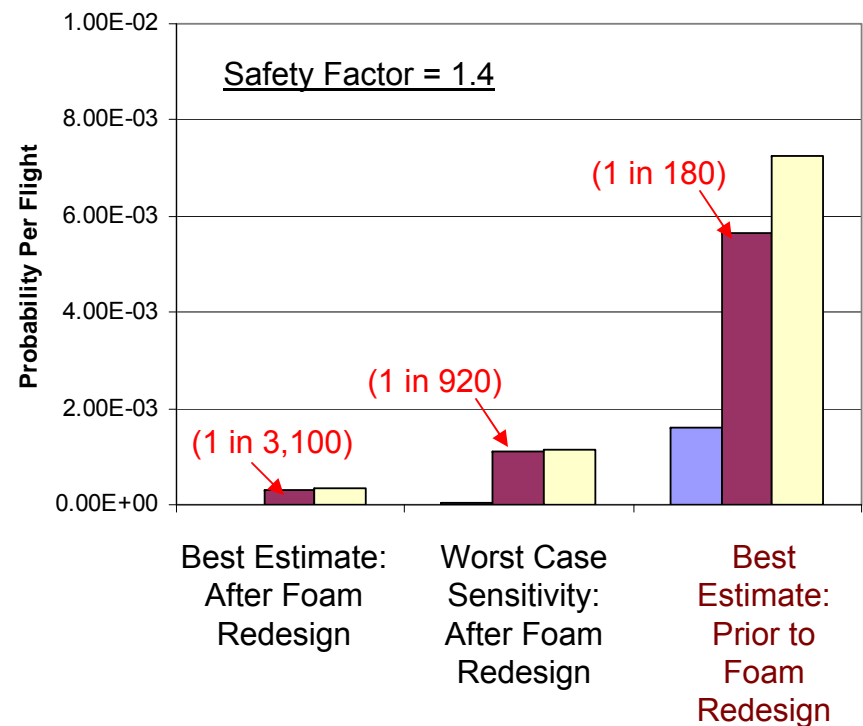
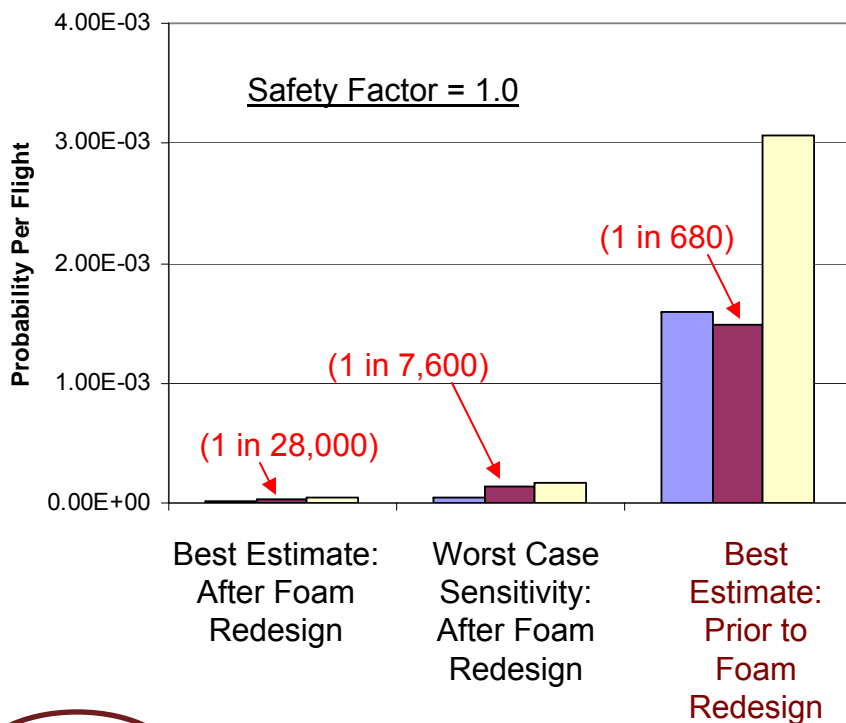
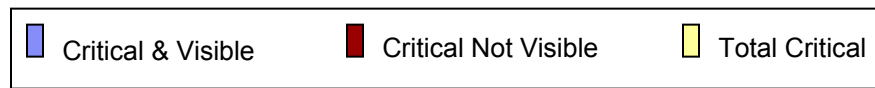
- The Probability of Each DTA Case is the Product of the Probabilities of the Pivot Events
- Dependencies Between Pivot Events Can Be Accounted for by Using Conditional Probabilities



Orbiter Leading Edge Risk Assessment: Example Results

Results for Foam

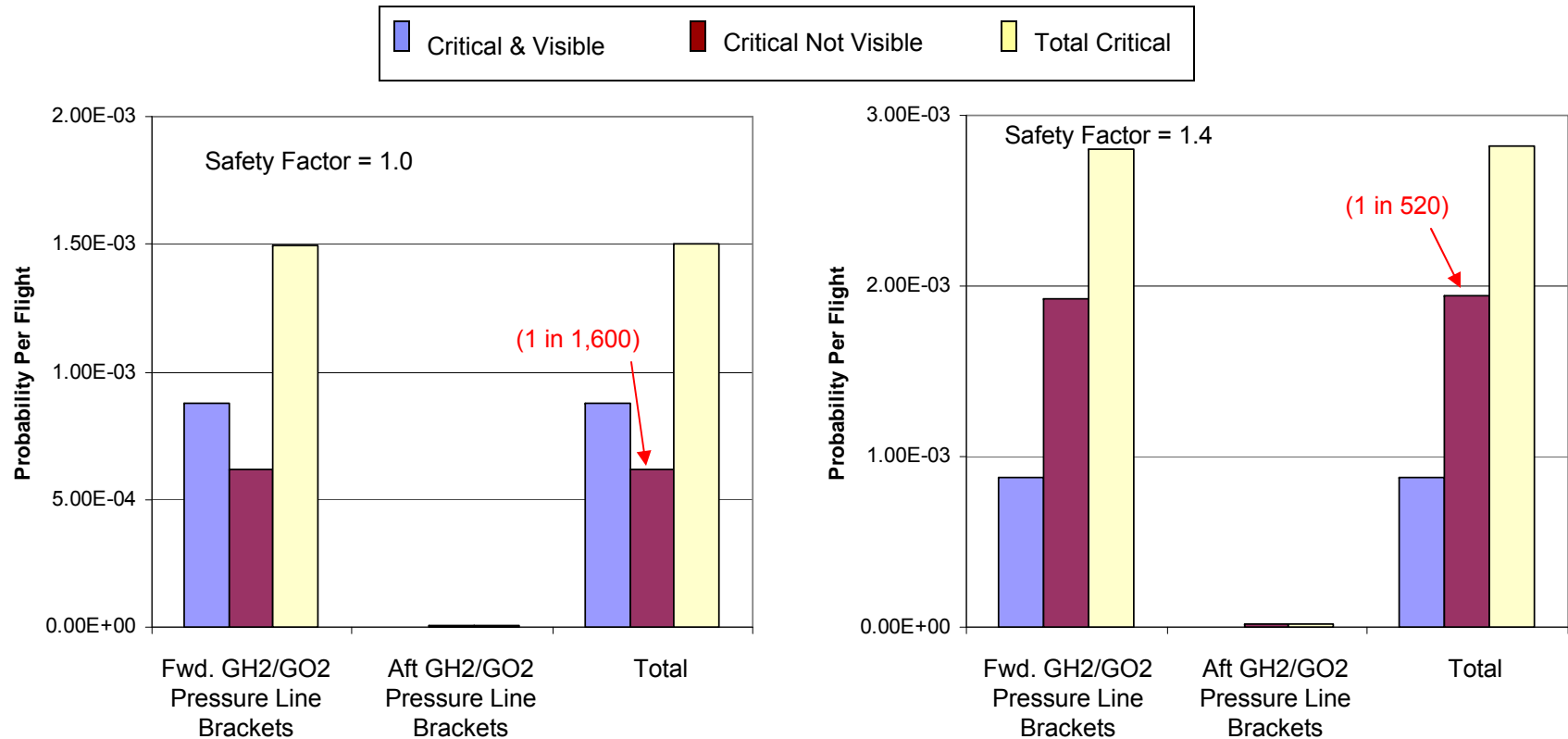
A Very Sizeable Reduction in the Probability of Critical Damage Can Be Realized if the Redesign of the Foam Insulation Succeeds in Eliminating Very Large Fragments



Orbiter Leading Edge Risk Assessment: Example Results (Cont.)

Results for Ice/Frost

An Ice/Frost Mixture on the Forward Portion of the Pressure Line Brackets May Cause More Problems than Ice Further Back on the ET Because the Longer Travel Distance Results in Higher Impact Velocities and Angles



Note: Results are Highly Uncertain Because There are No Impact Threshold Data for Frost. Assumed KE Threshold = 1.5 x Ice Value Based on Relative Densities



Orbiter Leading Edge Risk Assessment: Recommendations

What is the likelihood that a fragment generated from the shuttle external tank during ascent could impact the orbiter wing leading edge and cause damage that is critical but not visible to an onboard scanner?

Recommendations

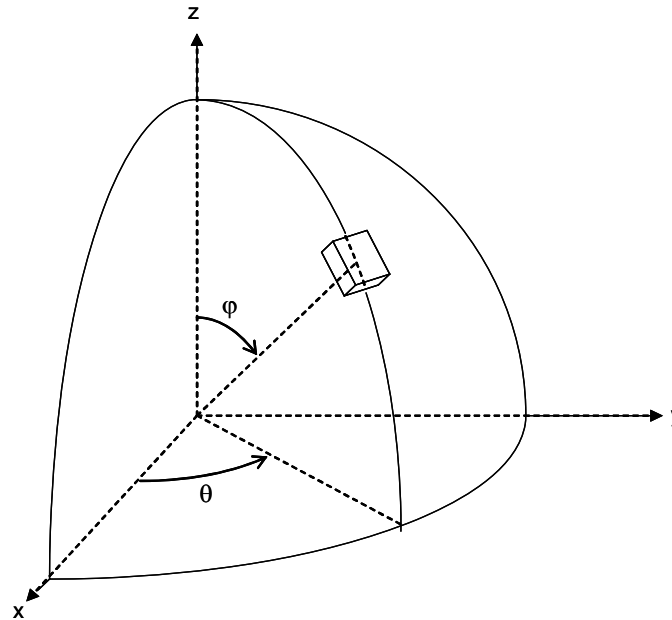
- Validation is Required to Prove that the Foam Redesign Reduces the Largest Foam Fragment to the Values Specified in NASA's Requirements
- The Effect of the Foam Redesign on the Time of Release during Flight and the Number of Particles Released Should be Investigated Through Appropriate Experiments
- The Time of Release Distribution for Ice and Frost Fragments Should be Investigated Through Appropriate Experiments
- Kinetic Energy Thresholds for Impacts by an Ice/Frost Mixture Should be Established by Modeling the Impact Dynamics of Frost in DYNA
- The Results of the Leading Edge PRA Should be Updated Periodically as New Data and Analysis Results Become Available

Effect of Debris Orientation on KE Threshold for Critical Damage

Effect of Debris Orientation on KE Threshold for Critical Damage

- The kinetic energy threshold for critical damage should be treated as a function of two random variables: the orientation of the fragment and the local material properties. Previously it was considered to be a function of only material properties.
- Orientation can be defined by two angles in a spherical coordinate system: latitude, ϕ , and longitude, θ .

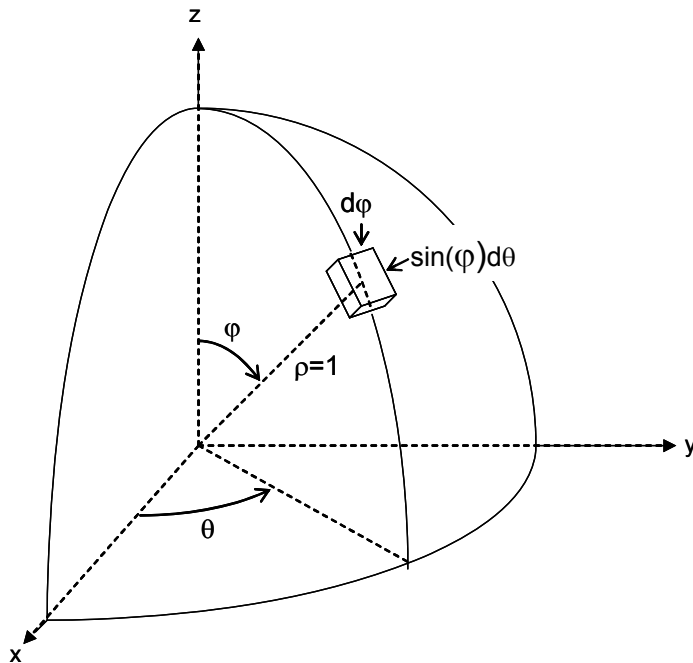
Fragment Orientation in Spherical Coordinates



Math Derivation for Effect of Debris Orientation: Ice Debris

- The orientation for ice fragments is considered to be random, based on experimental data
- This means that the probability of φ and θ lying within a certain range $[\varphi \pm \frac{1}{2} \Delta\varphi, \theta \pm \frac{1}{2} \Delta\theta]$ is proportional to the area of a unit sphere subtended by that range
- Therefore, the joint density function for angles φ and θ is given by the following equation:

$$f_{\varphi,\theta}(\varphi,\theta) = \frac{\sin(\varphi)}{2\pi \int_0^\pi \int_0^{2\pi} \sin(\varphi) d\varphi d\theta} = \frac{\sin(\varphi)}{4\pi}$$



- The marginal distribution for φ is

$$f_{\varphi}(\varphi) = \int_0^{2\pi} f_{\varphi,\theta}(\varphi,\theta) d\theta = \frac{\sin(\varphi)}{2}$$

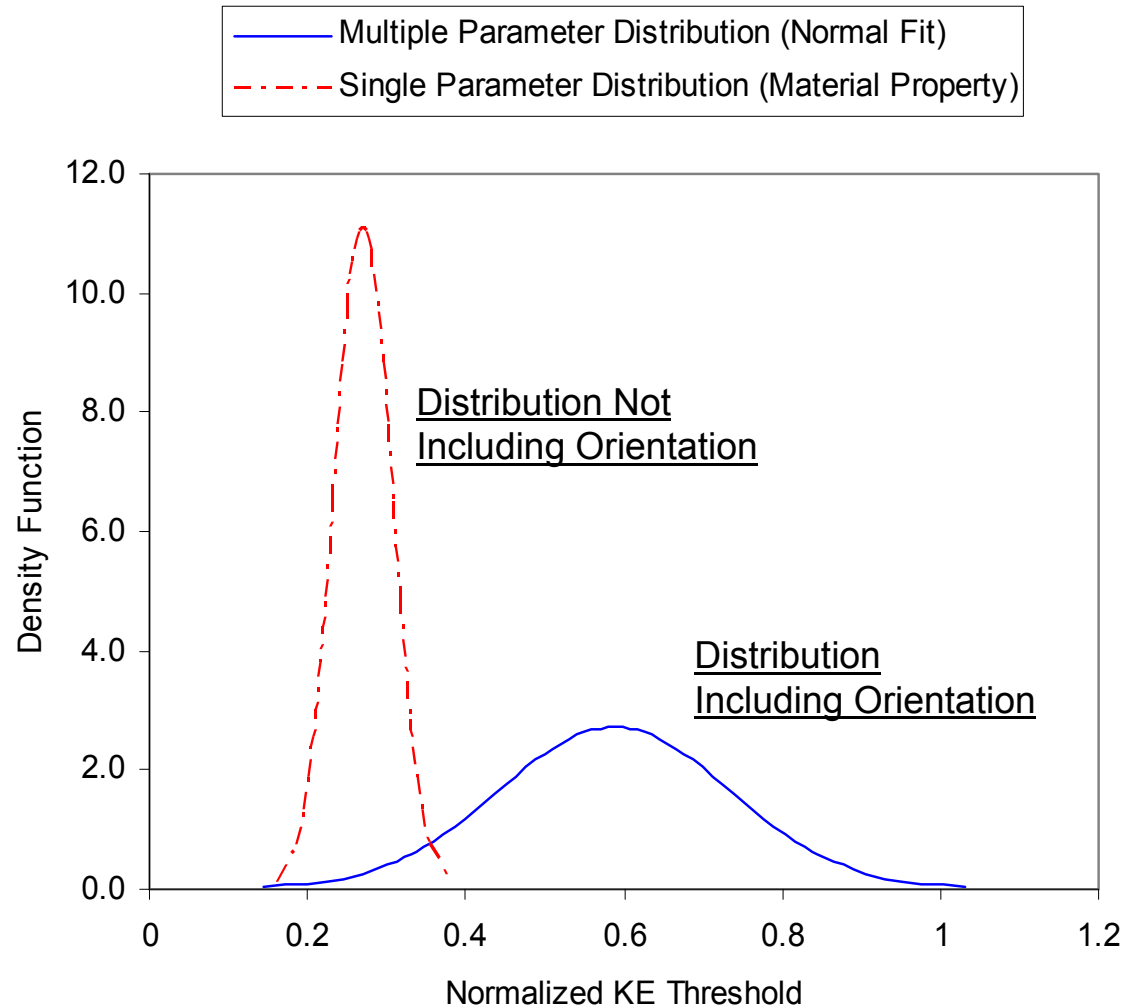
- The marginal distribution for the KE threshold, K , is

$$f_K(K) = f_{\varphi}(\varphi) \left| \frac{d\varphi}{dK} \right|$$

- From analysis of experimental data, $K = 0.549 \sin(\varphi) + 0.167$. Substituting this into the preceding equation we obtain

$$f_K(K) = \frac{K - 0.167}{(0.549)^2 \sqrt{1 - \left(\frac{K - 0.167}{0.549}\right)^2}} \quad \text{for } 0.167 \leq K \leq 0.716, \text{ and } = 0 \text{ elsewhere}$$

Effect of Debris Orientation on KE Threshold: Ice Debris



Effect of Debris Orientation on KE Threshold: Conclusions

Conclusions

- The kinetic energy threshold is a function of two random variables: the orientation of the fragment and the local material properties
- For Ice Debris, Including Orientation Effects Increases the Kinetic Energy Threshold by a Factor of About 2.0
- For Foam Debris, Including Orientation Effects Increases the Kinetic Energy Threshold by a Factor of About 1.2

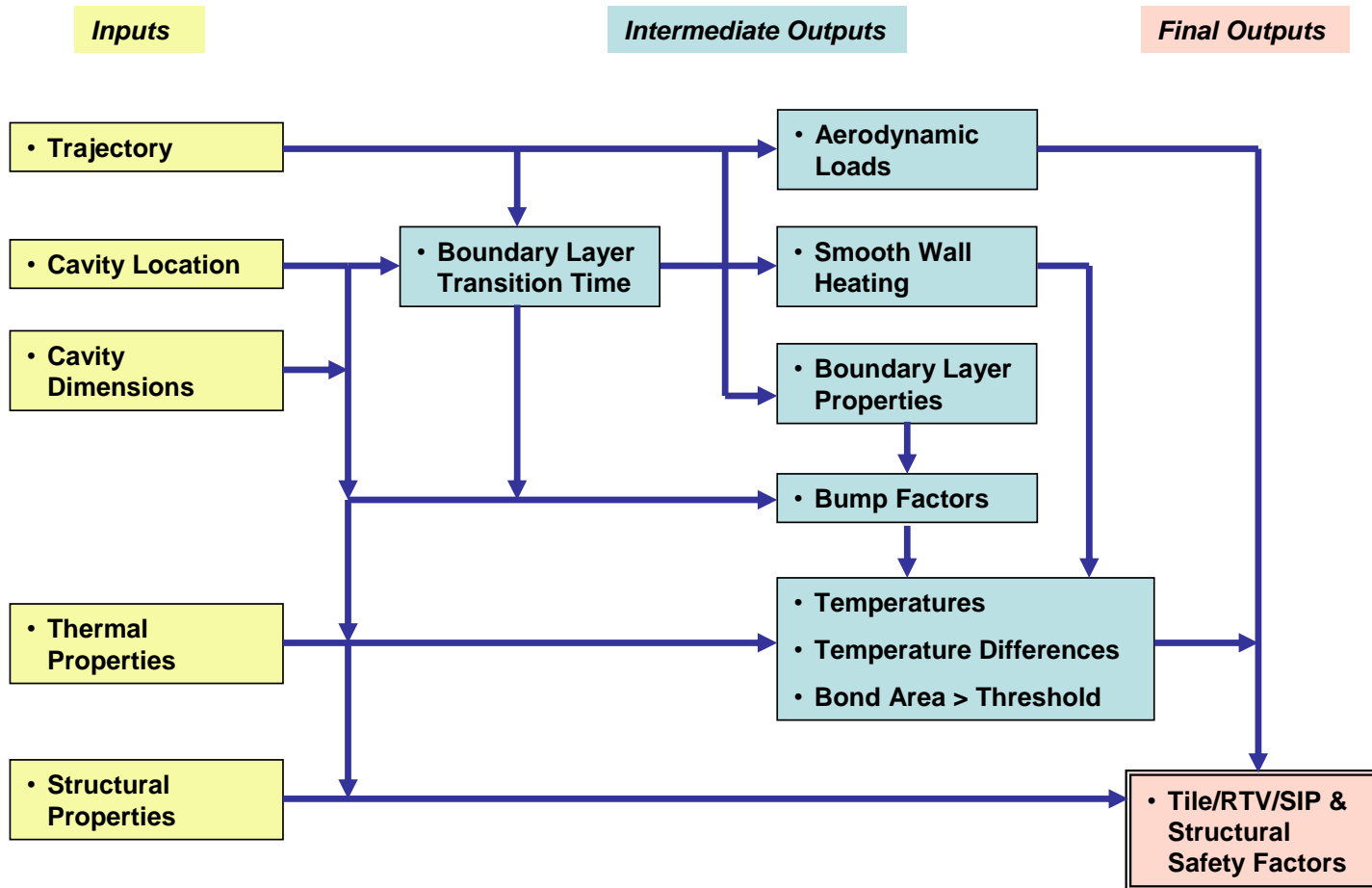
Analysis of Confidence Levels for Computed Margins of Safety

Analysis of Confidence Levels for Computed Margins of Safety

What are the Confidence Levels for the Calculated Margins of Safety During Reentry Given a Known Amount of Damage?

Scope of Study

Flow of Information for Detailed Calculation of Safety Factors



Analysis of Confidence Levels for Computed Margins of Safety

What are the Confidence Levels for the Calculated Margins of Safety During Reentry Given a Known Amount of Damage?

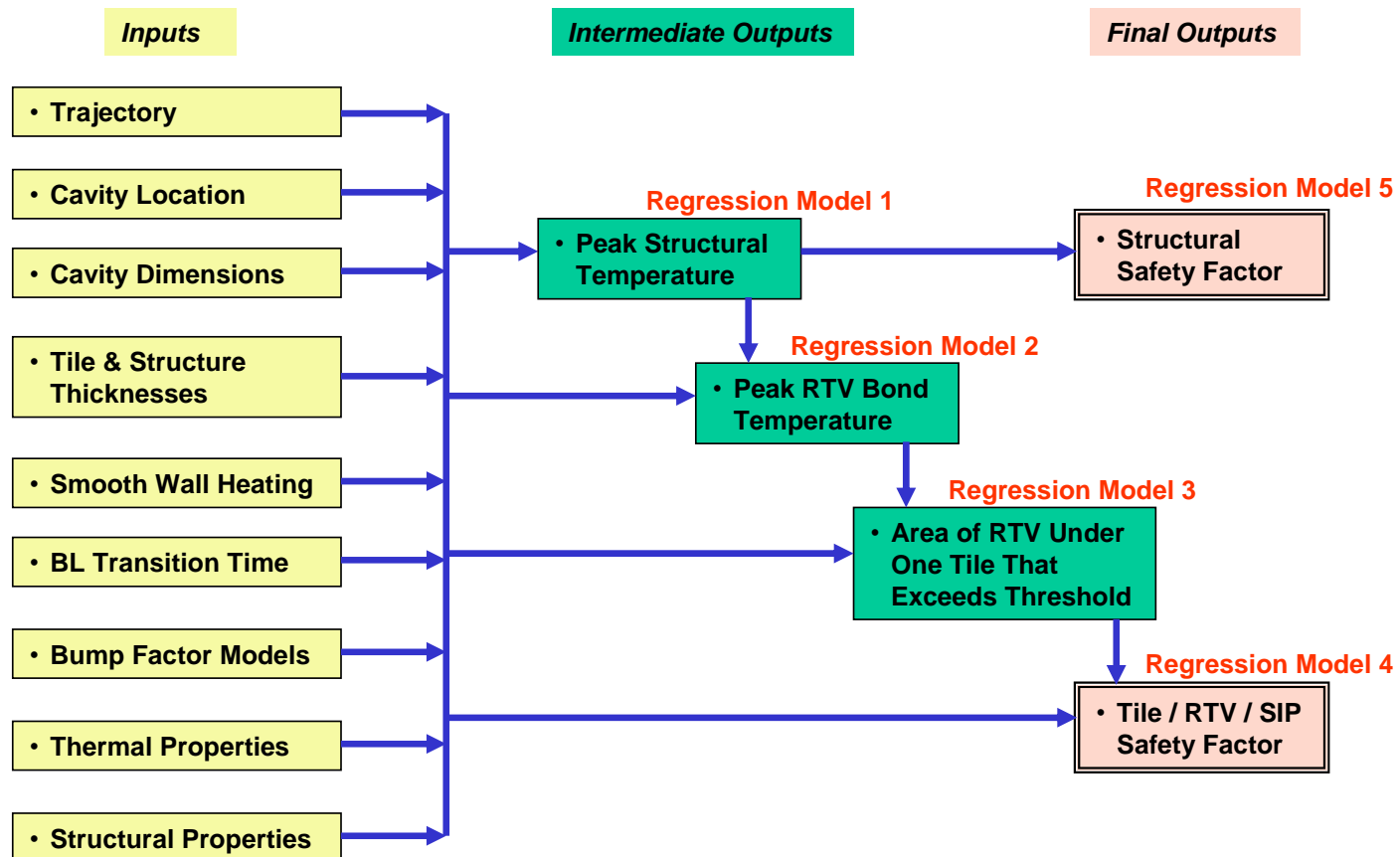
Method Employed

- Collaborated with Boeing to Produce ~2000 End-to-End Deterministic Calculations
- Performed Multiple-Parameter Regression Analyses with up to 23 Parameters to Develop Response Surfaces that Simulate Boeing Results
 - Needed to Reduce Running Time for Uncertainty Analysis
- Formulated Uncertainty Distributions for Code Inputs and Model Variations Using Available Data and Expert Opinion
- Performed Monte Carlo Analysis Using the Response Surfaces to Propagate Inputs to Outputs

Analysis of Confidence Levels for Computed Margins of Safety

What are the Confidence Levels for the Calculated Margins of Safety During Reentry Given a Known Amount of Damage?

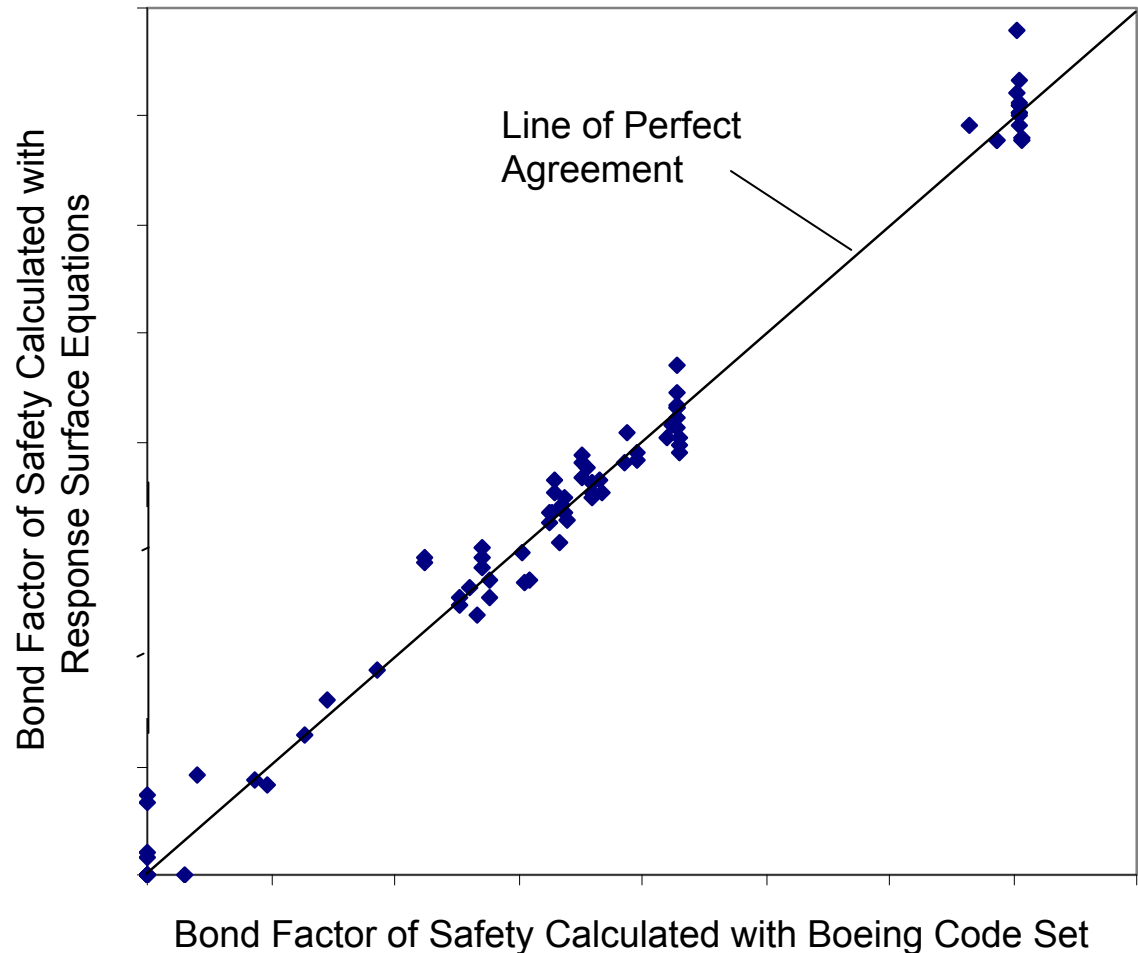
Flow of Information for Response-Surface Based Calculation of Safety Factors



Analysis of Confidence Levels for Computed Margins of Safety

RTV Factor of Safety to from Entry Insertion to Mach 5, Body Point 2510

Comparison of Boeing Code Calculations and Corresponding Response Surface Approximations



Analysis of Confidence Levels for Computed Margins of Safety

What are the Confidence Levels for the Calculated Margins of Safety During Reentry Given a Known Amount of Damage?

Scenario Variations Considered

- Cavity Location, Acreage Only (X, Y)
- Cavity Dimensions (Depth, Length, Width, Entrance Angle, & Side Angle)
- Trajectory (Vehicle Weight)

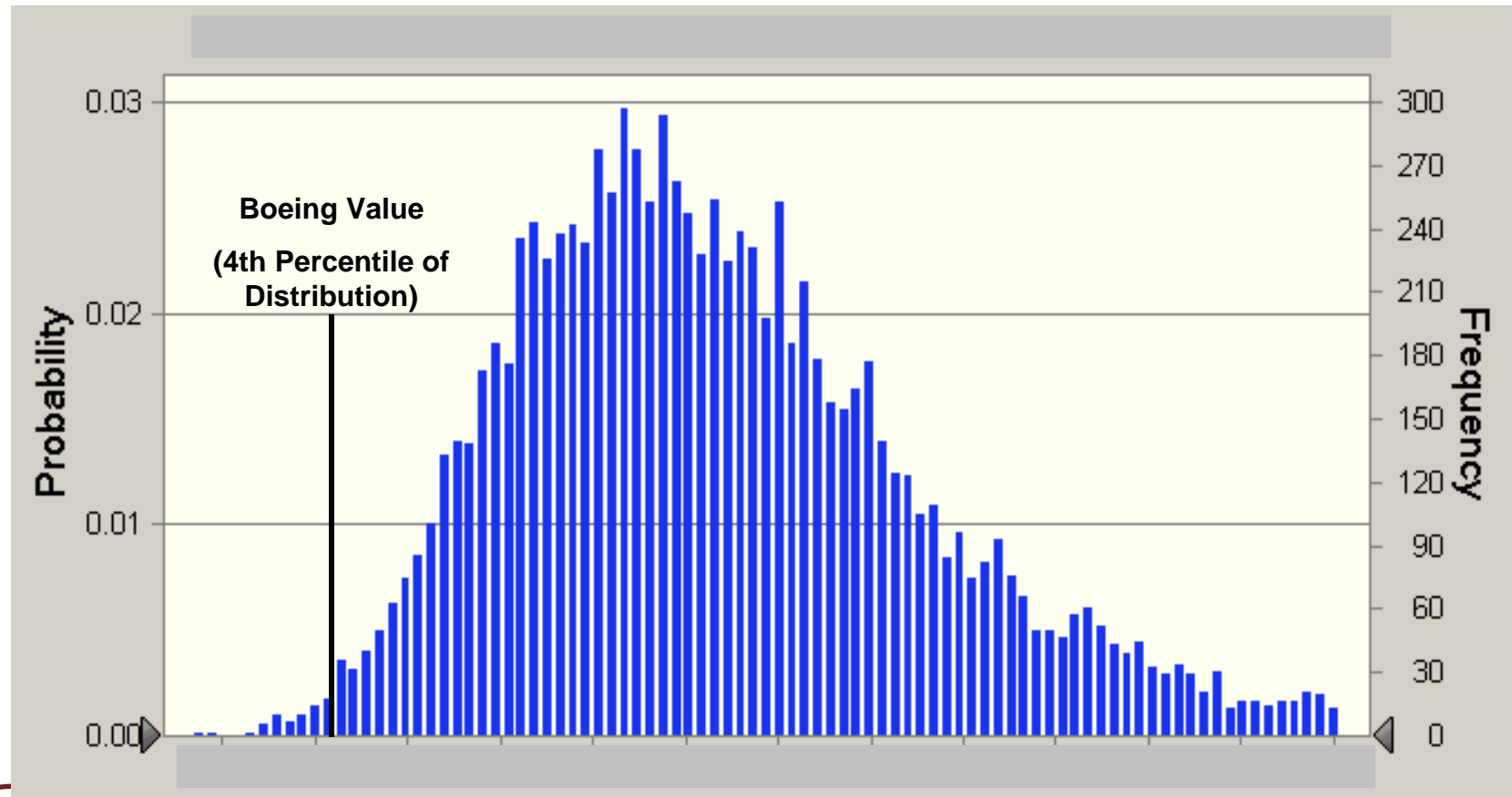
Uncertainties Considered

- Simplified Model Dimensions (Depth, Length, Width, Entrance Angle, & Side Angle)
- Inaccuracies Produced by Simplified Model Approximation (Evaluated at ARES Using COSMOS)
- Inaccuracies Produced by Incompleteness of Cavity Scan Data
- Inaccuracies Produced by F.E. Cell Size and Acreage Not Included in Model
- Boundary Layer Transition Time
- Smooth Body Heating
- Cavity Heating Augmentation Factors, Including Bump Factor and Possible Gap and Catalysis Effects
- Damaged Tile Emissivity & Thermal Conductivity
- SIP Thermal Conductivity & Secant Modulus
- Tile / Bond / SIP Strength

Analysis of Confidence Levels for Computed Margins of Safety

What are the Confidence Levels for the Calculated Margins of Safety During Reentry Given a Known Amount of Damage?

Structural Factor of Safety (at TD) for Example Cavity at BP 2510



Analysis of Confidence Levels for Computed Margins of Safety

What are the Key Uncertainty Issues for the Calculated Margins of Safety During Reentry Given a Known Amount of Damage?

Tile/RTV/SIP Factor of Safety

Assumptions	Contribution to Variance
Cavity Height Increment Due to Incomplete Scan	52.2%
Cavity Bump Factor Model	24.8%
Ultimate Strength Model	10.8%
Tile Thermal Conductivity	2.8%
Smooth Wall Heat Rate	< 2% *
SIP Thermal Conductivity	< 2%
Cavity Side Angle	< 2%
RTV & Struct. Temp. Impact Due to Simplified Geometry Approx.	< 2%
Cavity Height	< 2%
Struct. Temp. Impact Due to Finite Mesh Size & Modeled Acreage	< 2%
Boundary Layer Transition Time	< 2%
Cavity Width	< 2%
Uncoated Surface Emissivity	< 2%
Cavity Entrance Angle	< 2%
Cavity Length	< 2%

Structural Factor of Safety

Assumptions	Contribution to Variance
Cavity Bump Factor Model	70.5%
Cavity Height Increment Due to Incomplete Scan	12.8%
Tile Thermal Conductivity	6.8%
Struct. Temp. Impact Due to Finite Mesh Size & Modeled Acreage	2.6%
Ultimate Strength Model	< 2% *
Boundary Layer Transition Time	< 2%
Smooth Wall Heat Rate	< 2%
Uncoated Surface Emissivity	< 2%
RTV & Struct. Temp. Impact Due to Simplified Geometry Approx.	< 2%
SIP Thermal Conductivity	< 2%
Cavity Side Angle	< 2%
Cavity Length	< 2%
Cavity Height	< 2%
Cavity Width	< 2%
Cavity Entrance Angle	< 2%

* Values < 2% Are Considered to Lie Within the Noise of Statistical Uncertainty Due to Sample Size Limitations



Viability of Using ISS as a Safe Haven

Viability of Using ISS as a Safe Haven

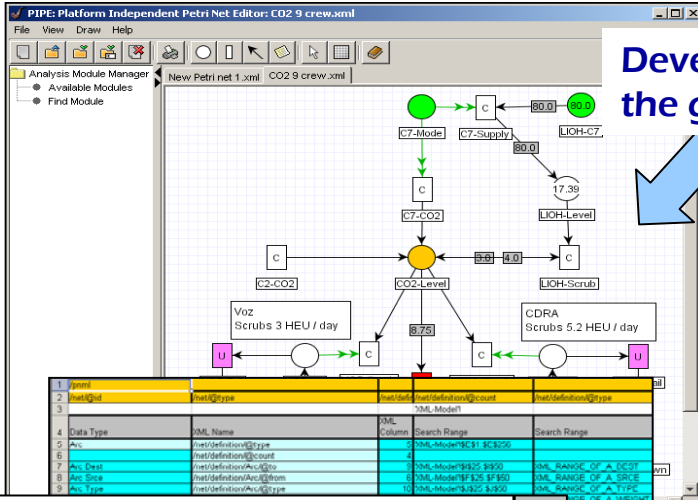
Problem Statement



- If the Shuttle Orbiter experiences a critical and irreparable debris impact on liftoff and cannot safely enter, the crew can take refuge in the ISS safe haven for some weeks
- ARES was tasked by JSC to quantify the risks associated with depleting consumables (O₂, H₂O) or exceeding safe CO₂ levels onboard ISS in the event of a contingency 9-crew situation (2 ISS + 7 Shuttle)
- The problem involves interactions between several pieces of machinery with random failures and uncertain repair times – how should it be modeled?
 - Dynamic fault trees
 - Monte Carlo Excel models
 - →Petri Nets

Viability of Using ISS as a Safe Haven (Cont.)

ARES Sampled Petri Net Tool



Development of a Petri Net with the ARES tool starts in the graphical user interface (PIPE).

Once the net is configured, the data is imported into an MS Excel/VBA platform via an XML interface. In the Excel tool, users set run parameters (simulation time, number of Monte Carlo runs, etc.) and specify the statistics to be recorded.

Simulation Parameters:

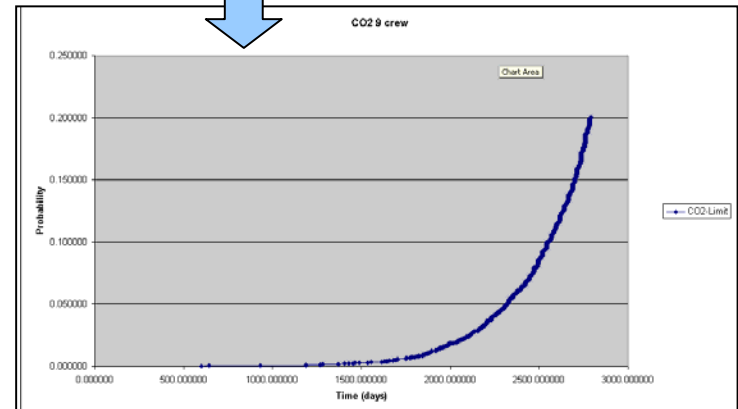
- Time Limit: 8766
- Trials: 5000
- Sampling: Use New Random Sequence
- Model: CO2 9 crew.xml
- Results: Record All Events

Microsoft Excel - CO2 9 crew After

ID	Name	Recorded	Limit	Start	Count
P1000002	VOZ-Up	FALSE	-1	1	1
P1000003					
P1000004					
P1000006					
P1000007					
P1000008					
P1000009					
P1000010					
P1000011					

Following a simulation, probability curves are automatically configured as Excel charts.

Step	Current	Simulation	Probability	P1000002	P1000003	P1000004	P1000006	P1000007	P1000008	P1000009	P1000010
Number	Time	Time	Unused	VOZ-Up	Crew	VOZ-Down	CO2-Level	CDRA-Up	CDRA-Down	LIQH-Level	LIQH
2020	2017	14.46.39.0	2781.890110	1.000000	2.000000	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000
2021	2018	14.46.39.0	2783.178613	1.000000	2.000000	0.000000	7.000000	1.000000	0.000000	0.000000	0.000000
2022	2019	14.46.39.0	2784.000000	1.000000	2.000000	0.000000	8.000000	1.000000	0.000000	0.000000	0.000000
2023	2020	14.46.39.0	2784.000000	1.000000	2.000000	0.000000	9.000000	1.000000	0.000000	0.000000	0.000000
2024	2021	14.46.39.0	2785.555495	1.000000	2.000000	0.000000	9.000000	1.000000	0.000000	0.000000	0.000000
2025	2022	14.46.39.0	2787.429571	1.000000	2.000000	0.000000	9.000000	1.000000	0.000000	0.000000	0.000000
2026	2023	14.46.39.0	2790.927143	1.000000	2.000000	0.000000	10.000000	1.000000	0.000000	0.000000	0.000000
2027	2024	14.46.39.0	2794.130228	1.000000	2.000000	0.000000	10.000000	1.000000	0.000000	0.000000	0.000000

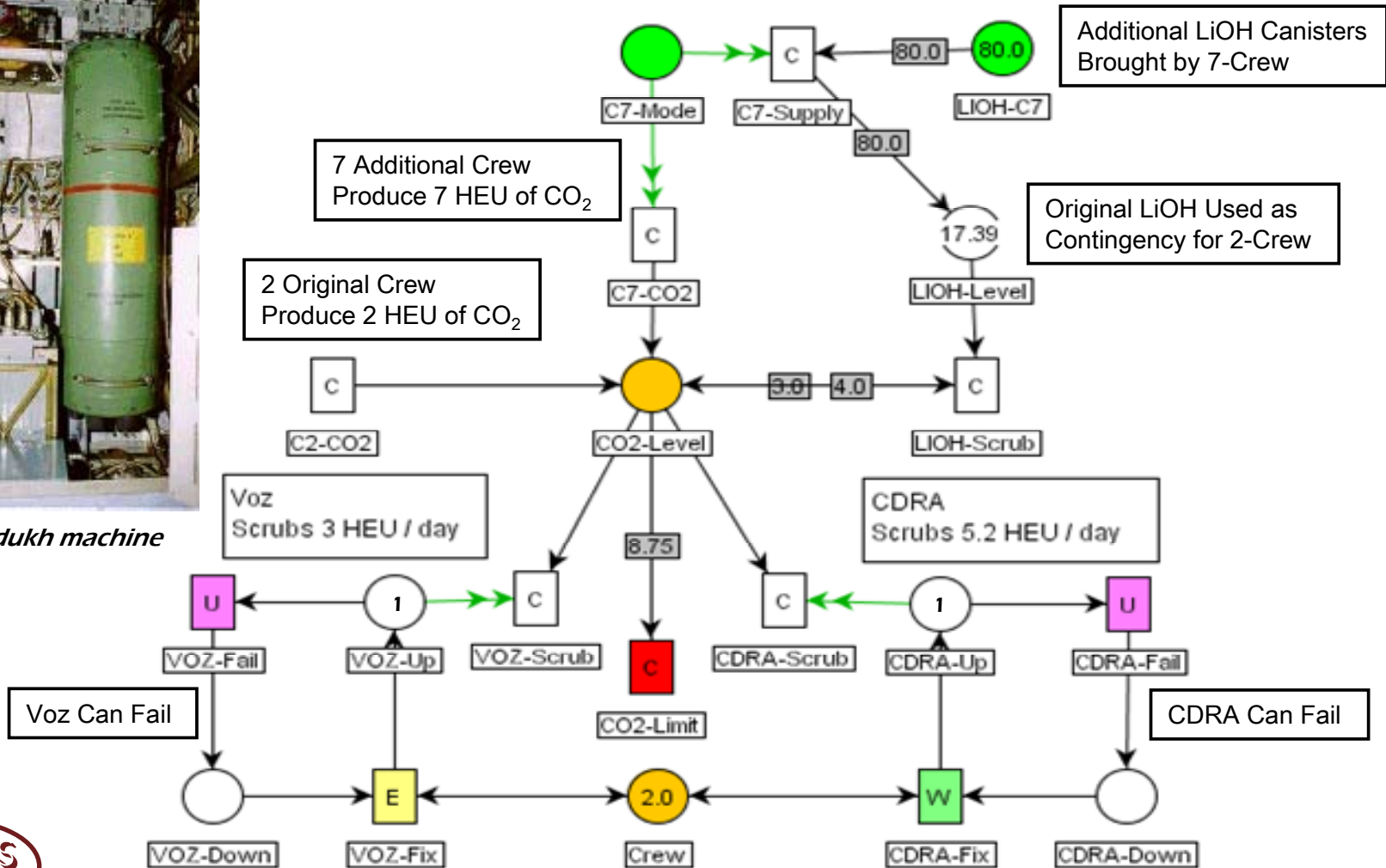


Viability of Using ISS as a Safe Haven (Cont.)

Consumables Petri Nets: CO₂



Vozdukh machine



Additional LiOH Canisters Brought by 7-Crew

7 Additional Crew Produce 7 HEU of CO₂

2 Original Crew Produce 2 HEU of CO₂

Original LiOH Used as Contingency for 2-Crew

Voz Scrubs 3 HEU / day

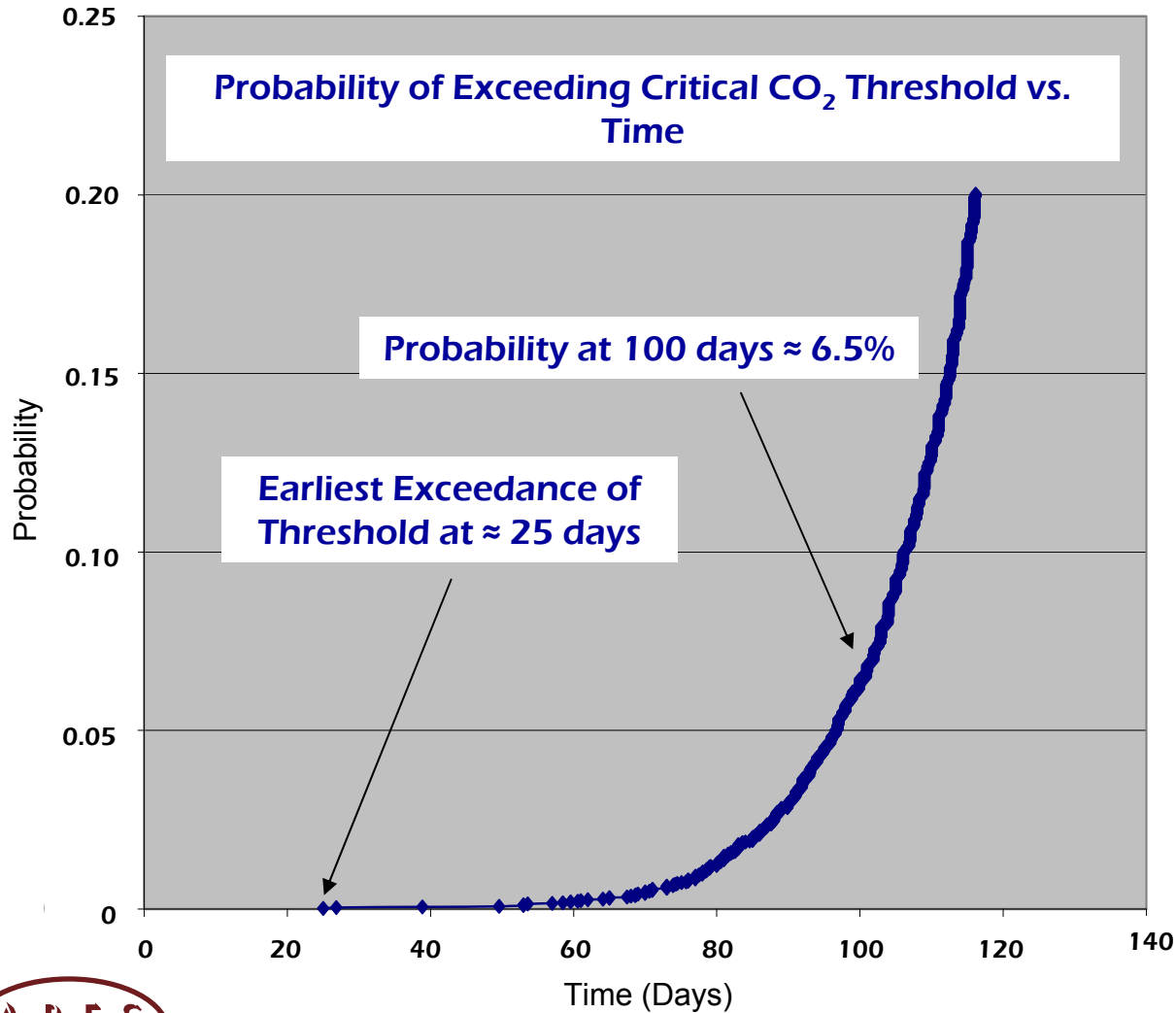
CDRA Scrubs 5.2 HEU / day

Voz Can Fail

CDRA Can Fail

Viability of Using ISS as a Safe Haven (Cont.)

Results for CO₂ Model



Since failure and repair times are different on each run through the model, every simulation is different. Monte Carlo analysis with 10,000+ runs through the model yields probabilities of events of interest.

Each dot on the chart represents a single run through the model. The scarcity of dots at early times can be attributed to the small probability of failing both CO₂-removal equipment very early in the simulation and also experiencing slow repair times.

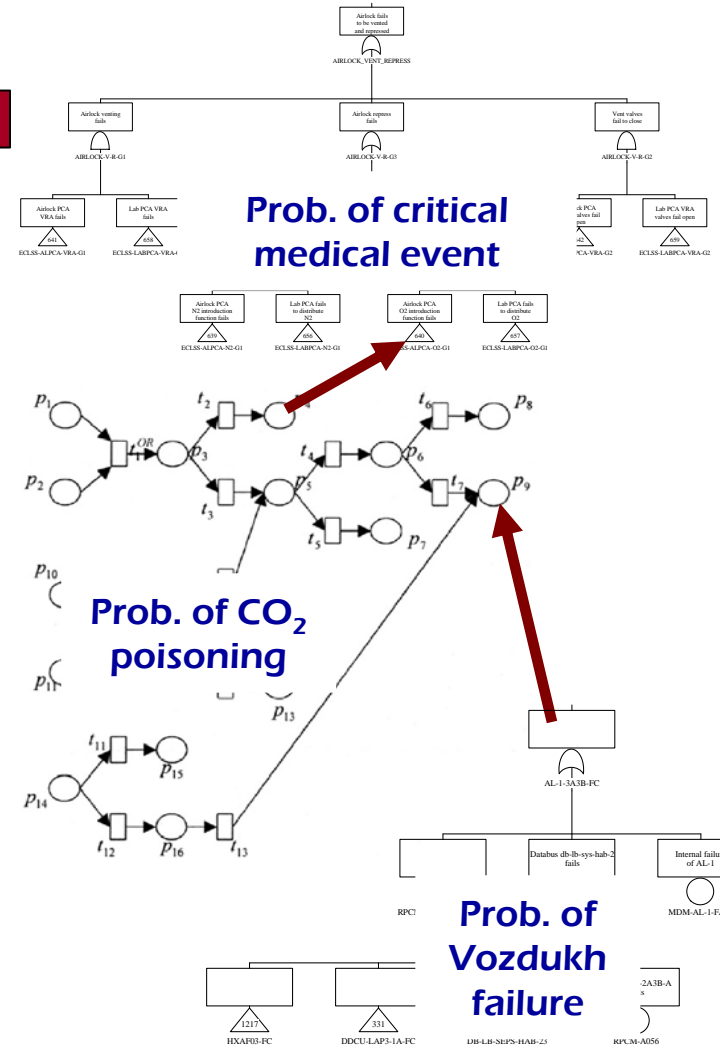
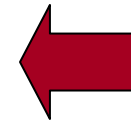
Viability of Using ISS as a Safe Haven (Cont.)

Integration of Petri Nets with PRA Models

CRV or CRV support systems fail	CRV or CRV support systems fail FT	CRV less than 6 months old?	CRV repair successful?	CRV operable for crew evacuation	Can CRV be unblocked and jettisoned	#	END-STATE-NAMES	
RE	CRV	CRV-SSP02	CRV-REP	CRV-OP	CRV-RETTIS	1	OK	
							2	OK
							4 T <= 170	LOM-RS-SOYUZ-T
							5 T <= 156	LOM-DC1-PORFT-T
							6 T <= 120	EVAC-SOYUZ-T

CRV - Soyuz Crew Return Vehicle (CRV) or CRV support systems fail 2005-04-08 Page 83

Prob. of evacuation



Because simulation is computationally intensive, stand-alone Petri Nets are ill-equipped to handle very large models with hundreds of events and high-reliability hardware.

Therefore, a process that couples Petri Nets with fault trees and event trees, at both inputs and outputs, enhances the power and flexibility of an event-tree based PRA model.

Summary

Summary and Impact of Analyses Performed for Return to Flight

Questions Addressed by RTF Analyses	Results of the Analyses and Value to NASA
◆ Do the orbiter windows need to be replaced by thicker panes to provide increased protection against impacts from particulate matter generated during ascent?	◆ Analysis showed the answer to be yes for the two side windows. Was a factor in NASA's decision to replace those windows before flight STS-114.
◆ Is there a significant probability that particulate debris could cause damage to the orbiter wing leading edges that is large enough to be critical but not large enough to be detected?	◆ Analysis showed that ice or an ice-frost mixture emanating from the forward portions of the external tank might have a relatively high probability of causing critical damage that cannot be detected. Was a factor in NASA's decision to provide additional protection against ice formation.
◆ Are the current kinetic energy thresholds for critical tile damage excessively conservative because of worst-case assumptions about particle orientation?	◆ Analysis showed that not accounting for random particle orientation causes the thresholds to be evaluated much too conservatively, by a factor of more than two for ice debris. Was a factor in NASA's decision to proceed with STS-114.

Summary and Impact of Analyses Performed (Cont.)

Questions Addressed by RTF Analyses	Results of the Analyses and Value to NASA
<ul style="list-style-type: none">◆ What is the confidence level accompanying the decision about whether the orbiter can safely endure reentry following damage to the tile, based on predictions by the best available suite of computer codes?	<ul style="list-style-type: none">◆ Created a tool for calculating the uncertainty distributions surrounding the computed safety margins for reentry. The tool has increased NASA's ability to make informed, real-time judgments about the likelihood that reentry will be successful.
<ul style="list-style-type: none">◆ What is the probability distribution for the amount of time available, if the shuttle crew has to take refuge on the ISS, before consumables run out or toxic levels become excessively high?	<ul style="list-style-type: none">◆ Created a finite state computer tool to analyze this problem. Results showed that there is a high enough probability that sufficient time is available to warrant the return to flight.