Reliability Engineering
Applications and Case Studies

Fayssal M. Safie, Ph. D.,

NASA R&M Tech Fellow

Marshall Space Flight Center

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Agenda

- **Reliability Engineering Overview**
  - Reliability Engineering Definition
  - The Reliability Engineering Case
  - The Relationship to Safety, Mission Success, and Affordability
  - Design VS. Process Reliability
  - Reliability Prediction VS. Reliability Demonstration
  - Uncertainty Analysis VS. Statistical Confidence
  - Reliability VS. Probabilistic Risk Assessment (PRA)
- **Applications and Case Studies**
  - **Conceptual System Reliability Trade Studies**
    - The ARES V Conceptual Design Case
  - **Development Issues**
    - The Roller Bearing Inner Race Fracture Case
  - **Technical Issues**
    - The High Pressure Fuel Turbo-pump (HPFTP) First Stage Blade
  - **Integrated Failure Analysis**
    - The Columbia Accident
- **The NASA Engineering Center (NSC) Reliability and Maintainability Engineering Training Program**
- **The Reliability Challenges**

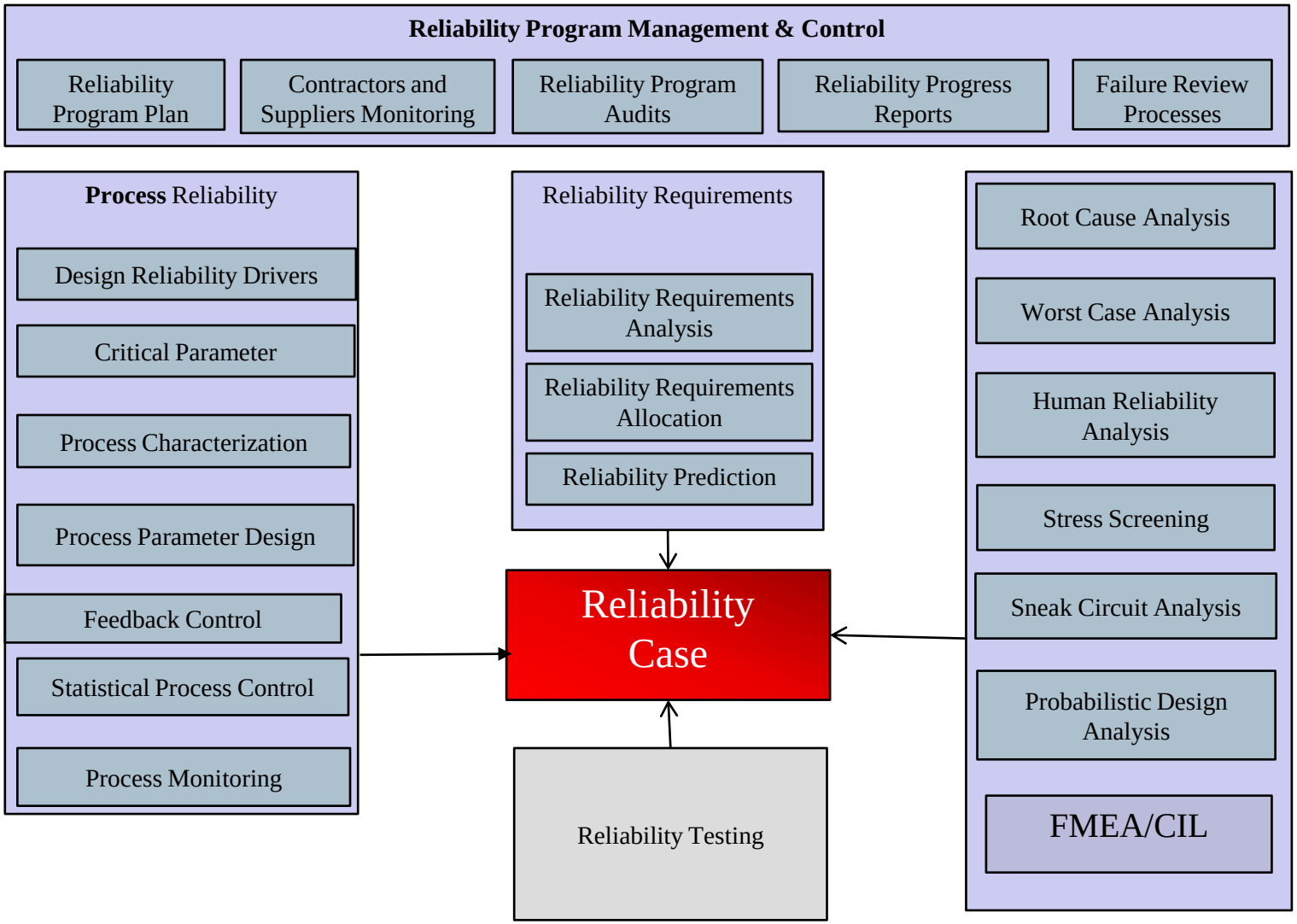
Background

Reliability Engineering Definition

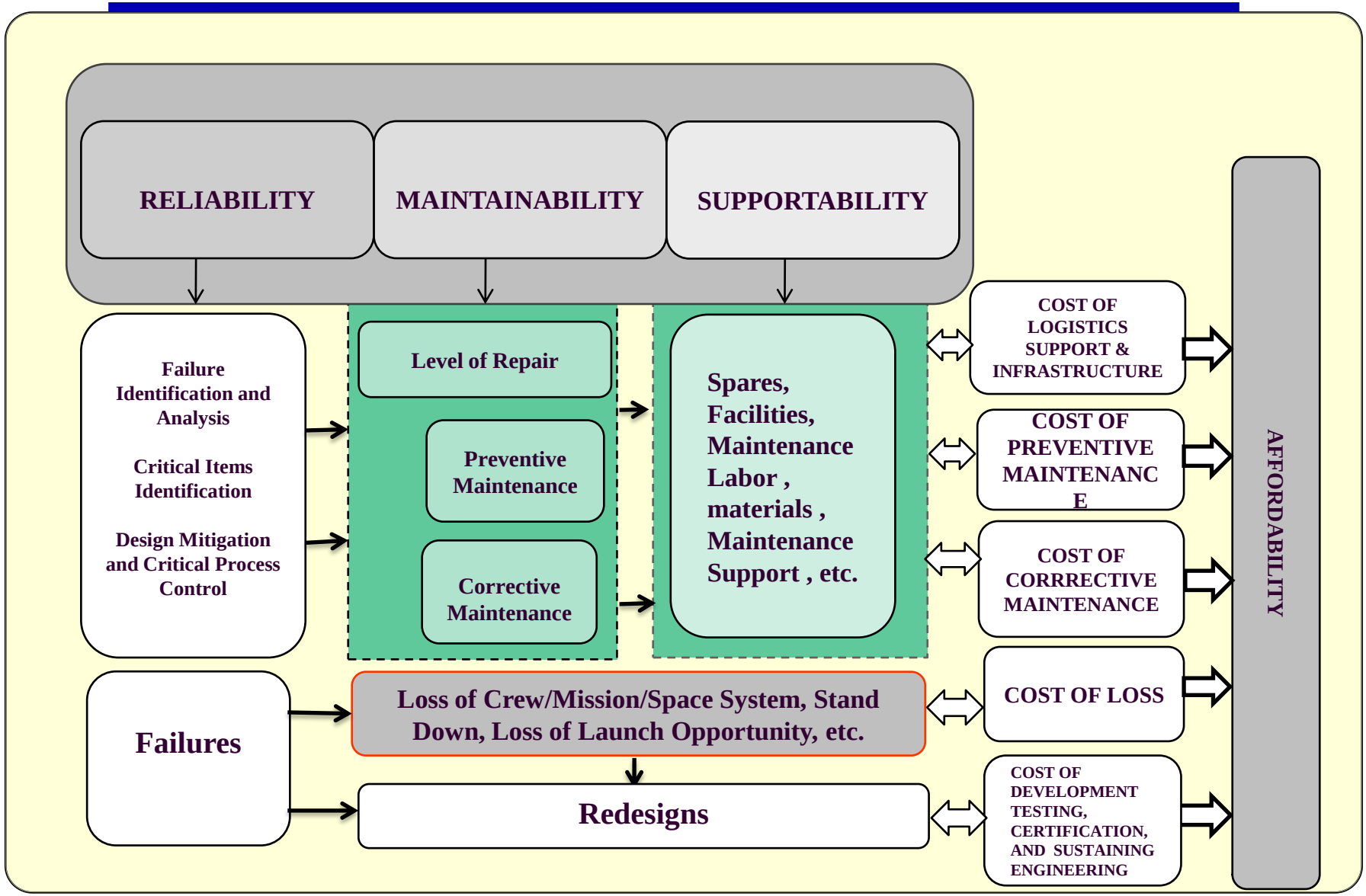
- **Reliability Engineering is**:
  - The application of engineering and scientific principles to the design and processing of products, both hardware and software, for the purpose of meeting product reliability requirements or goals.
  - The ability or capability of the product to perform the specified function in the designated environment for a specified length of time or specified number of cycles
- **Reliability as a Figure of Merit is:** The probability that an item will perform its intended function for a specified mission profile.
- Reliability is a very broad design-support discipline. It has important interfaces with most engineering disciplines
- Reliability analysis is critical for understanding component failure mechanisms and identifying reliability critical design and process drivers.
- A comprehensive reliability program is critical for addressing the entire spectrum of design engineering and programmatic concerns to sustainment and system life cycle costs.

Background

The Reliability Engineering Case



The Relationship to Safety, Mission Success, and Affordability



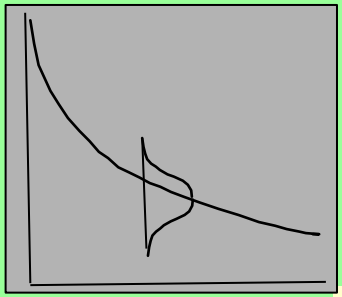
Design Reliability VS. Design Reliability

Design VS. Process Reliability

"Design Right and Built Right

Reliability

Materials Properties

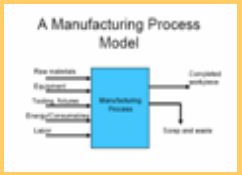


Material Models

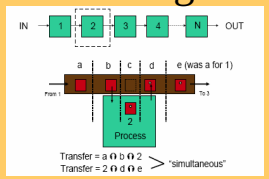
Design Reliability

Process Reliability

Processing



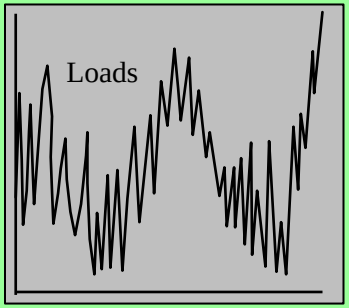
Manufacturing Models



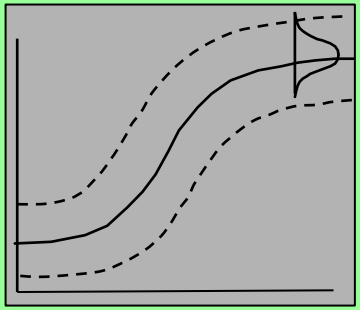
Processing Models

Loads & Environments

Operations

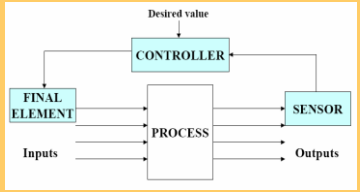


Historical data and models

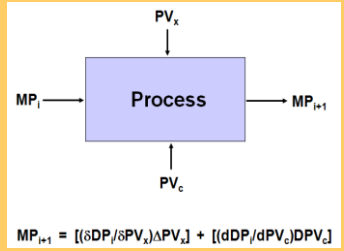


Operating conditions

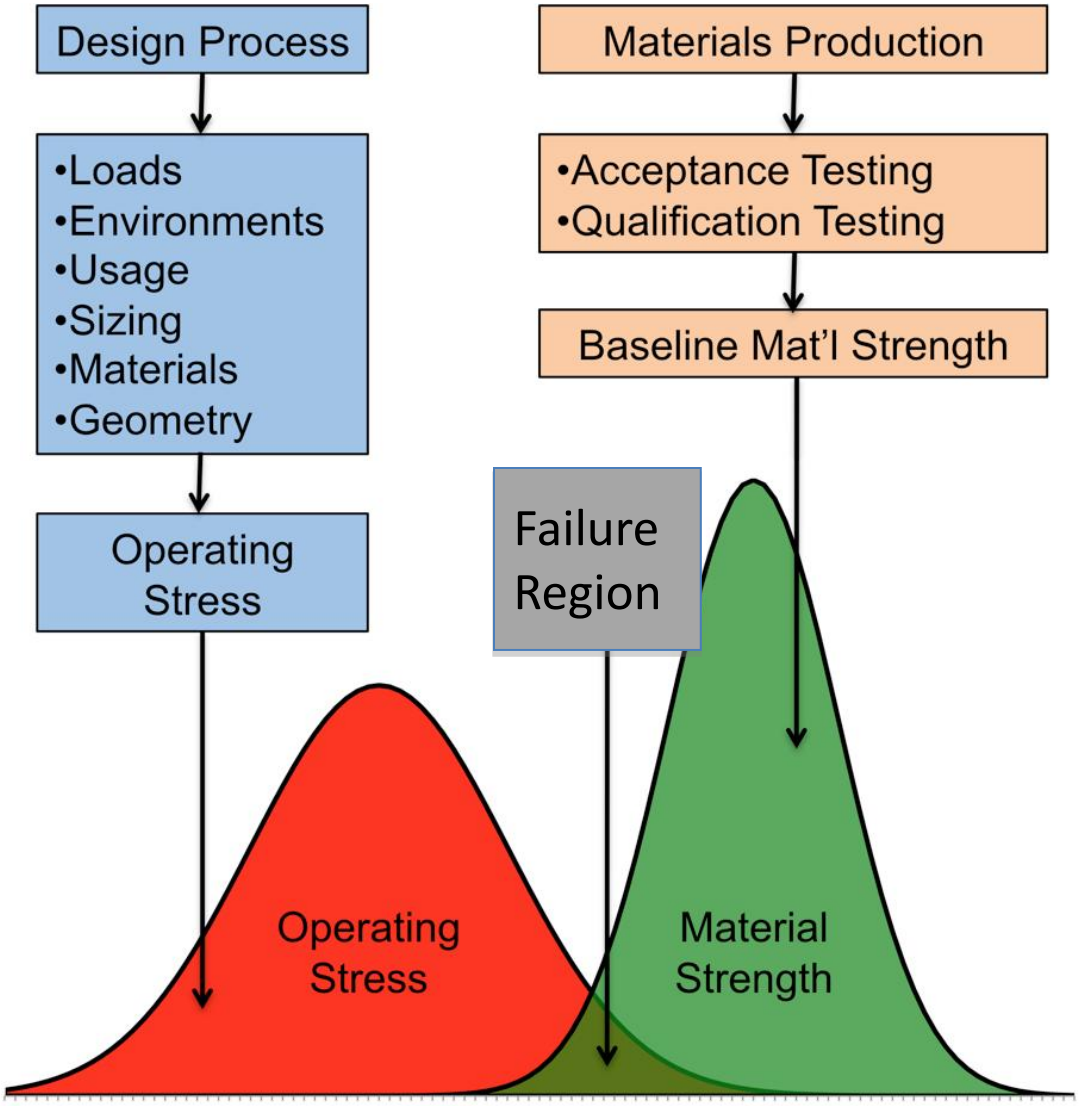
Process Control



Process Characterization

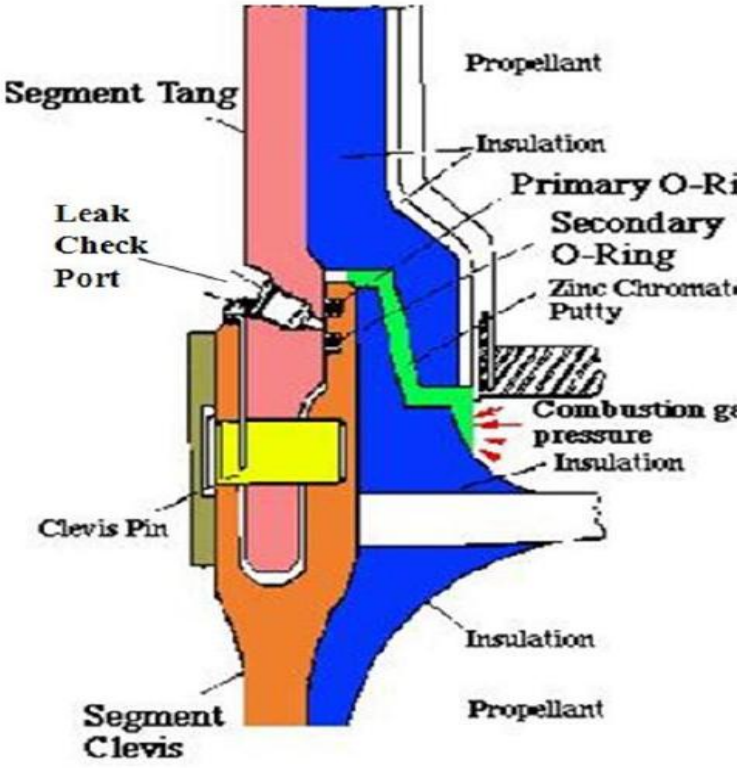


Design Reliability



The Challenger Accident
The Problem

- **Causes and Contributing Factors**
  - The zinc chromate putty frequently failed and permitted the gas to erode the primary O-rings.
  - The particular material used in the manufacture of the shuttle O-rings was the wrong material to use at low temperatures.
  - Elastomers become brittle at low temperatures.



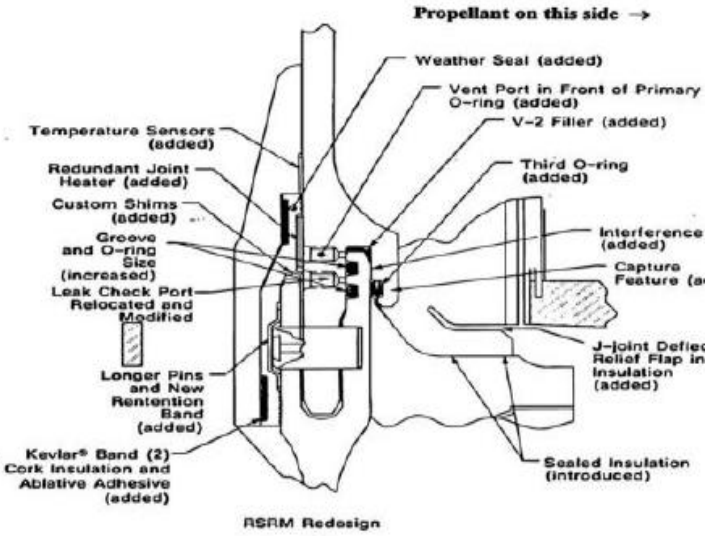
The Challenger Accident

Redesigned Field Joint

The redesign of the joint/seal shown here added a third O-ring and eliminated the troublesome putty which served as a partial seal.

Bonded insulation replaced the putty [Lewis, 1986].

A capture device was added to prevent or reduce the opening of the joint as the booster inflated under motor gas pressure during ignition.



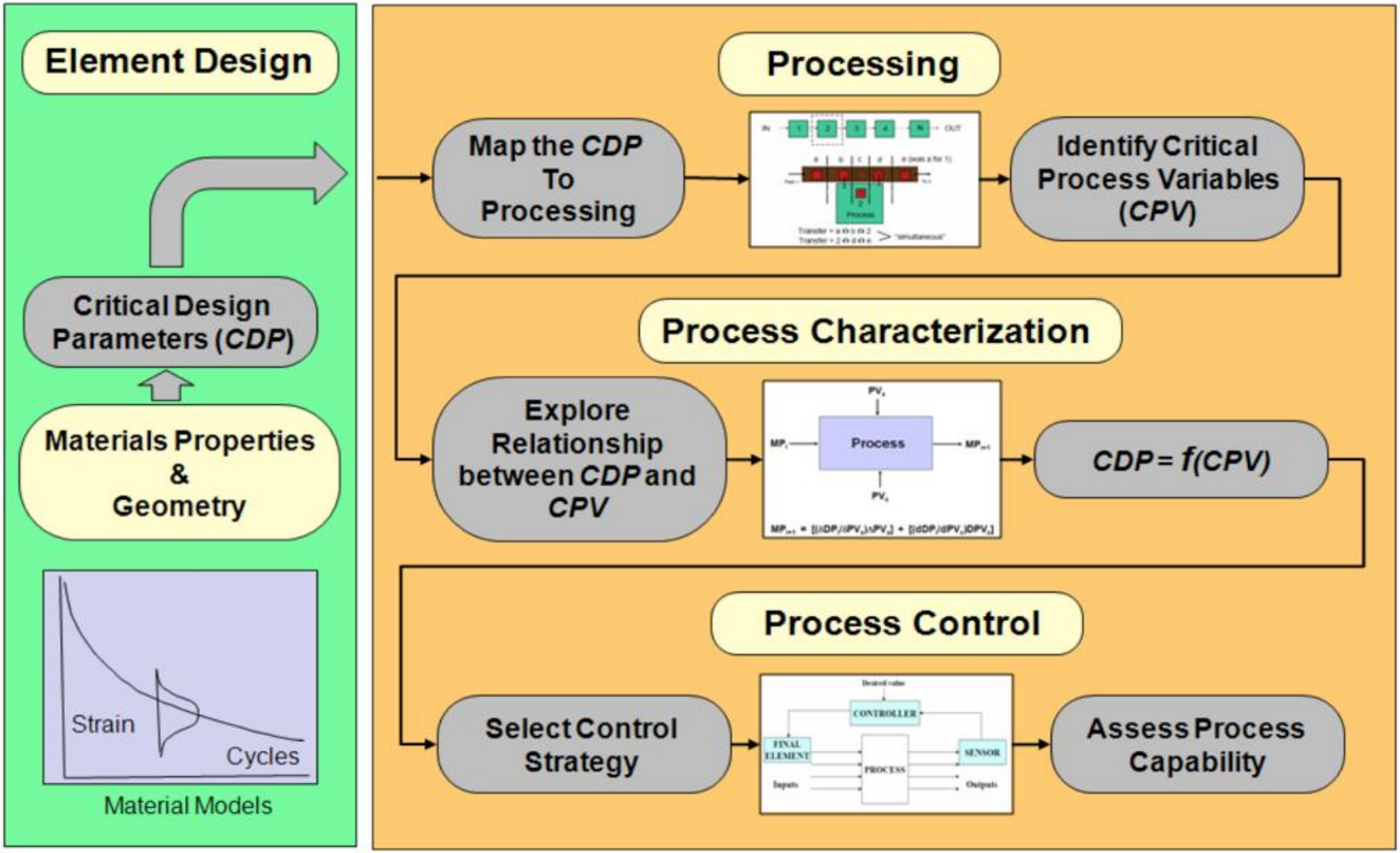
The third O-ring would be added to seal the joint at the capture device.

The former O-rings would be replaced by rings of the same size but made of a better performing material called fluorosilicone or nitrile rubber.

Heating strips were added around the joints to assure the O-rings did not experience temperatures lower than 75 degrees Fahrenheit regardless of the surrounding temperature.

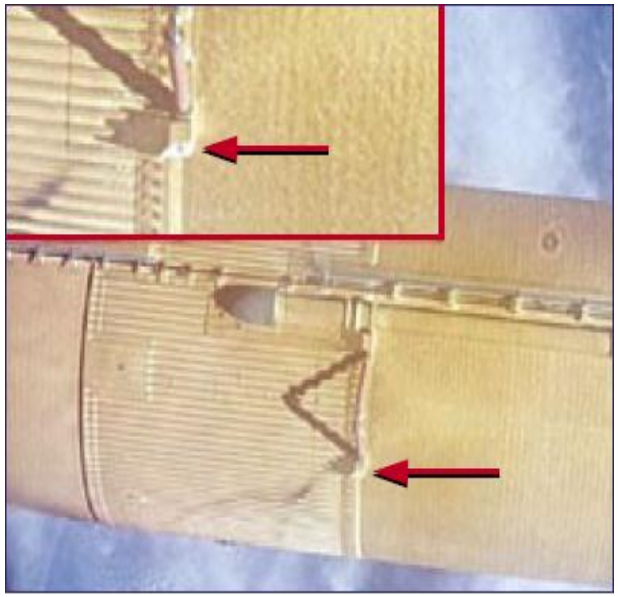
The gap openings which the O-rings were designed to seal were reduced to 6 thousandths of an inch from the former gap of 30 thousandths of an inch.

Process Reliability



The Columbia Accident

- **Causes and Contributing Factors**
  - Breach in the Thermal Protection System caused by the left bipod ramp insulation foam striking the left wing leading edge.
  - There were large gaps in NASA's knowledge about the foam.
  - cryopumping and cryoingestion, were experienced during tanking, launch, and ascent.
  - Dissections of foam revealed subsurface flaws and defects as contributing to the loss of foam.

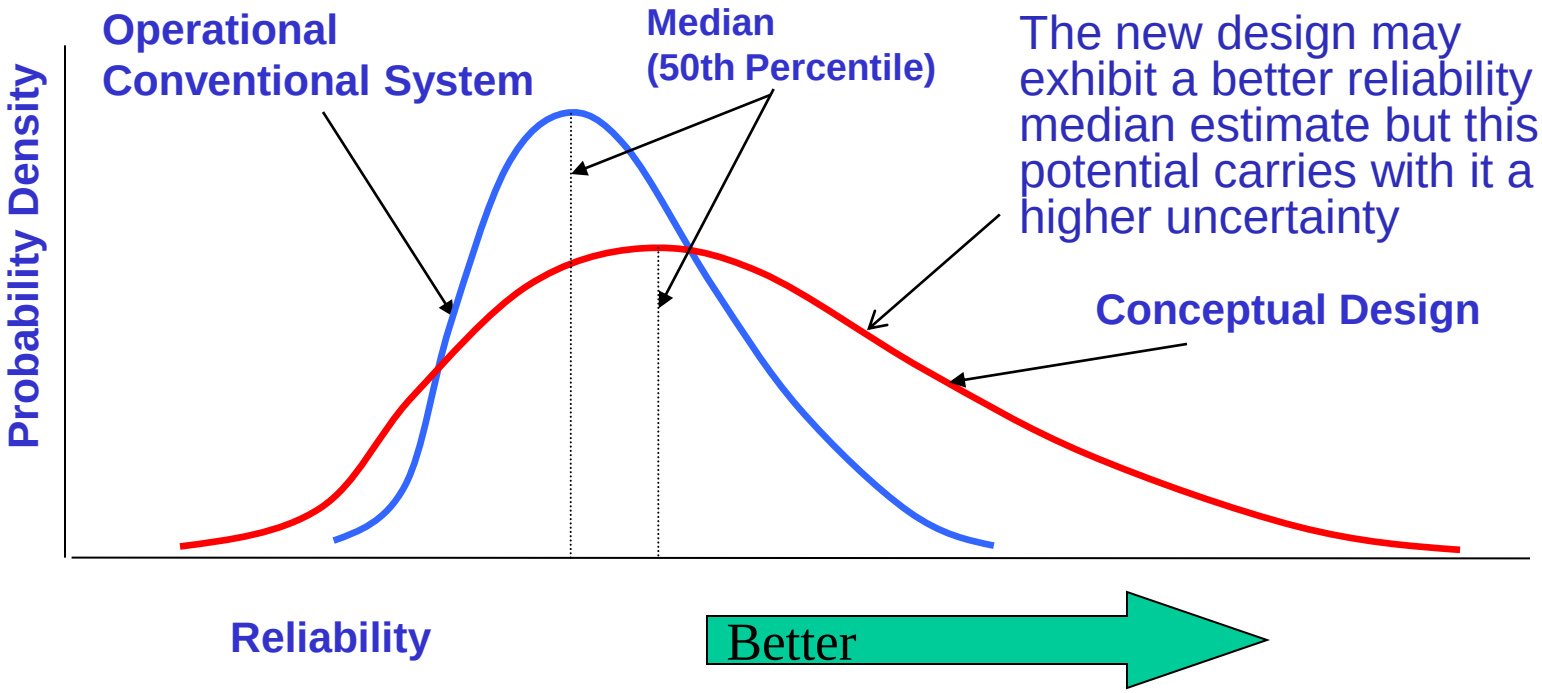


Reliability Prediction VS. Reliability Demonstration
Uncertainty Analysis VS. Statistical Confidence

Reliability Predictions

- **Reliability prediction is the process of quantitatively estimating the reliability of a system using both objective and subjective data.**
- **Reliability prediction is performed to the lowest level for which data is available. The sub-level reliabilities are then combined to derive the system level prediction.**
- **Reliability prediction during design is used as a benchmark for subsequent reliability assessments.**
- **Predictions provide managers and designers a rational basis for design decisions.**
- **Reliability prediction techniques are dependent on the degree of the design definition and the availability of historical data. Examples are:**
  - Similarity analysis techniques: Reliability of a new design is predicted using reliability of similar parts; where failure rates are adjusted for the operating environment, geometry, material change, etc.
  - Physics-based techniques: Reliability is predicted using probabilistic engineering models expressed as loads and environment vs. capability
  - Techniques that utilize generic failure rates such as MIL-HDBK 217, Reliability Prediction of Electronic Equipment.

The Uncertainty Distributions

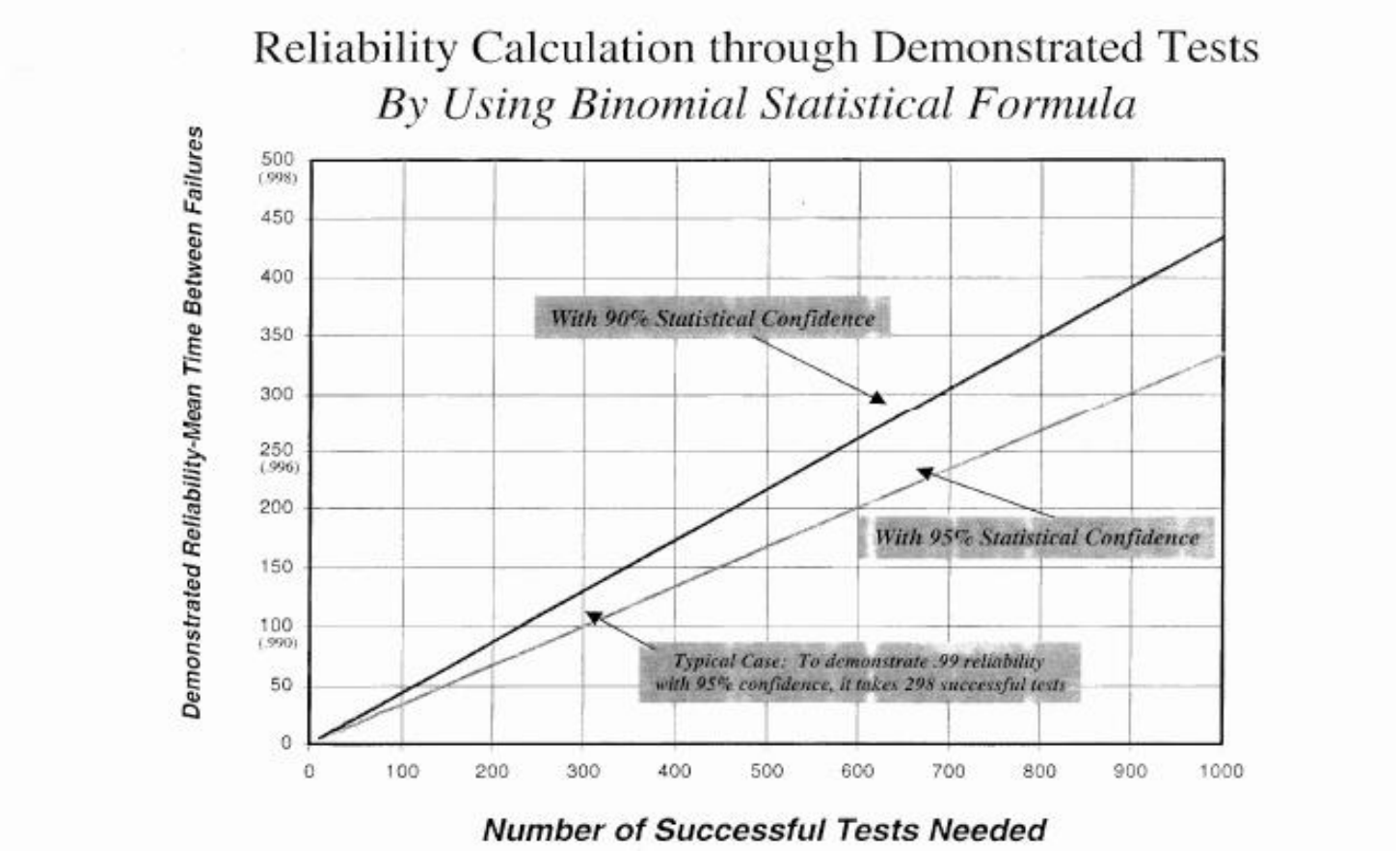


- **Probabilistic analyses deal with uncertainties of estimates**
- **For low-probability events, uncertainty distributions are, in general right-skewed (tail to the right)**

Reliability Demonstration

- Reliability Demonstration is the process of quantitatively estimating the reliability of a system using objective data at the level intended for demonstration.
- statistical formulas are used to calculate the demonstrated reliability or to demonstrate numerical reliability goal with some statistical confidence.
- Models and techniques used in reliability demonstration include Binomial, Exponential, Weibull models.
- Reliability growth techniques, such as the U.S. Army Material Systems Analysis Activity (AMSAA) and Duane models can also be used to calculate demonstrated reliability.
- Historically, some military and space programs employed this method to demonstrate reliability goals. For example, a reliability goal of .99 at 95% confidence level is demonstrated by conducting 298 successful tests.

Statistical Confidence



Reliability VS. Probabilistic Risk Assessment

Probabilistic Risk Assessment (PRA)

- **Reliability: The probability that an item will perform its intended function for a specified mission profile.**
- **Risk: The chance of occurrence of an undesired event and the severity of the resulting consequences.**
- **Probabilistic Risk assessment (PRA) is the systematic process of analyzing a system, a process, or an activity to answer three basic questions:**
  - What can go wrong that would lead to loss or degraded performance (i.e., scenarios involving undesired consequences of interest)?
  - How likely is it (probabilities)?
  - What is the severity of the degradation (consequences)?

Scenario	Likelihood (Probability)	Consequence
S_1	p_1	C_1
S_2	p_2	C_2
S_3	p_3	C_3
⋮	⋮	⋮
S_N	p_N	C_N

Risk assessment is the task of generating the triplet set

$$R \equiv \text{RISK} \equiv \{\langle S_i, P_i, C_i \rangle\}$$

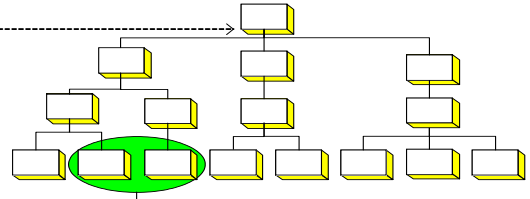
The PRA Process

Defining the PRA Study Scope and Objectives

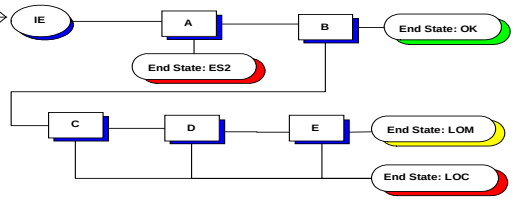
End State: LOC

End State: LOM

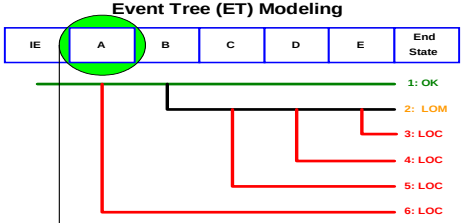
Initiating Events Identification



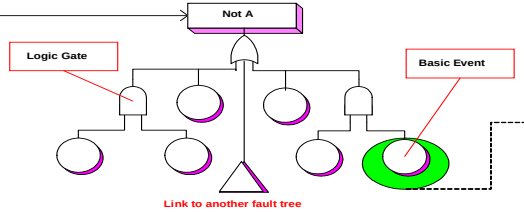
Event Sequence Diagram (Inductive Logic)



Event Tree (ET) Modeling



Fault Tree (FT) System Modeling



Mapping of ET-defined Scenarios to Causal Events

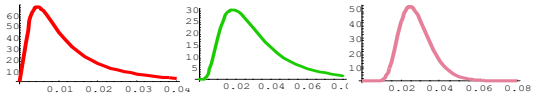
- Internal initiating events
- External initiating events
- Hardware failure
- Human error
- Software error
- Common cause failure
- Environmental conditions
- Other

One of these events

AND

one or more of these elementary events

Probabilistic Treatment of Basic Events



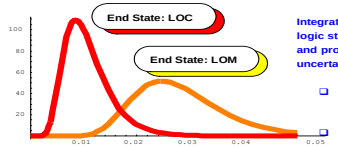
Examples (from left to right):
Probability that the hardware x fails when needed
Probability that the crew fail to perform a task
Probability that there would be a windy condition at the time of landing

The uncertainty in occurrence frequency of an event is characterized by a probability distribution

Model Logic and Data Analysis Review

Domain Experts ensure that system failure logic is correctly captured in model and appropriate data is used in data analysis

Model Integration and Quantification of Risk Scenarios



Integration and quantification of logic structures (ETs and FTs) and propagation of epistemic uncertainties to obtain

- minimal cutsets (risk scenarios in terms of basic events)
- likelihood of risk scenarios uncertainty in the likelihood estimates

Technical Review of Results and Interpretation

Communicating & Documenting Risk Results and Insights to Decision-maker

- Displaying the results in tabular and graphical forms
- Ranking of risk scenarios
- Ranking of individual events (e.g., hardware failure, human errors, etc.)
- Insights into how various systems interact
- Tabulation of all the assumptions
- Identification of key parameters that greatly influence the results
- Presenting results of sensitivity studies
- Proposing candidate mitigation strategies

Ref., ESD 10011, Cross Program Probabilistic Risk Assessment Methodology

Reliability Prediction vs. PRA

Category	Reliability Prediction	PRA
What It Is	***Methodology to Predict Reliability***	***Methodology to Predict System/Mission Accident Risk***
Discipline	***Reliability Engineering***	***System Safety***
Domain	***Space Flight System Design***	***Space Flight Mission***
Objective	***Successful*** Space Flight ***System Function***	Space Flight Mission Accident Scenarios, i.e., ***Accident Avoidance***
Measure	***Probability of Success*** (e.g., 0.999)	***LOC/LOM***(e.g., 1/500)
Focus	***How the Space Flight System can Fail***, i.e., Loss of System Function, the Causes, and the Effects	***How and to What Extent Accident Risk Propagates from Hazards/Failure Events***, i.e., Hazardous/Failure Events and their Consequences
How It's Done	***FMEA*** (Failure Modes, Mechanisms, Loads/Environments) → ***RBD's/Failure Logic Diagrams → Probability & Statistics***	***Hazards/Failure Mode Effects →Event Sequence Diagrams → Event Trees → FTA → Probability & Statistics***
Input	Space Flight System Design and Process (e.g., manufacturing) Data, FMEA	Space Mission Data, Hazard Analysis/FTA, Failure Modes/Effects, Reliability Predictions (i.e., ***Uses Output from Reliability Prediction***)
Users	Engineering Design, Program Management, Maintenance Planning/Logistics Support, System Safety/PRA (i.e., ***Input to PRA***)	Engineering Design, Mission Design, Program Management

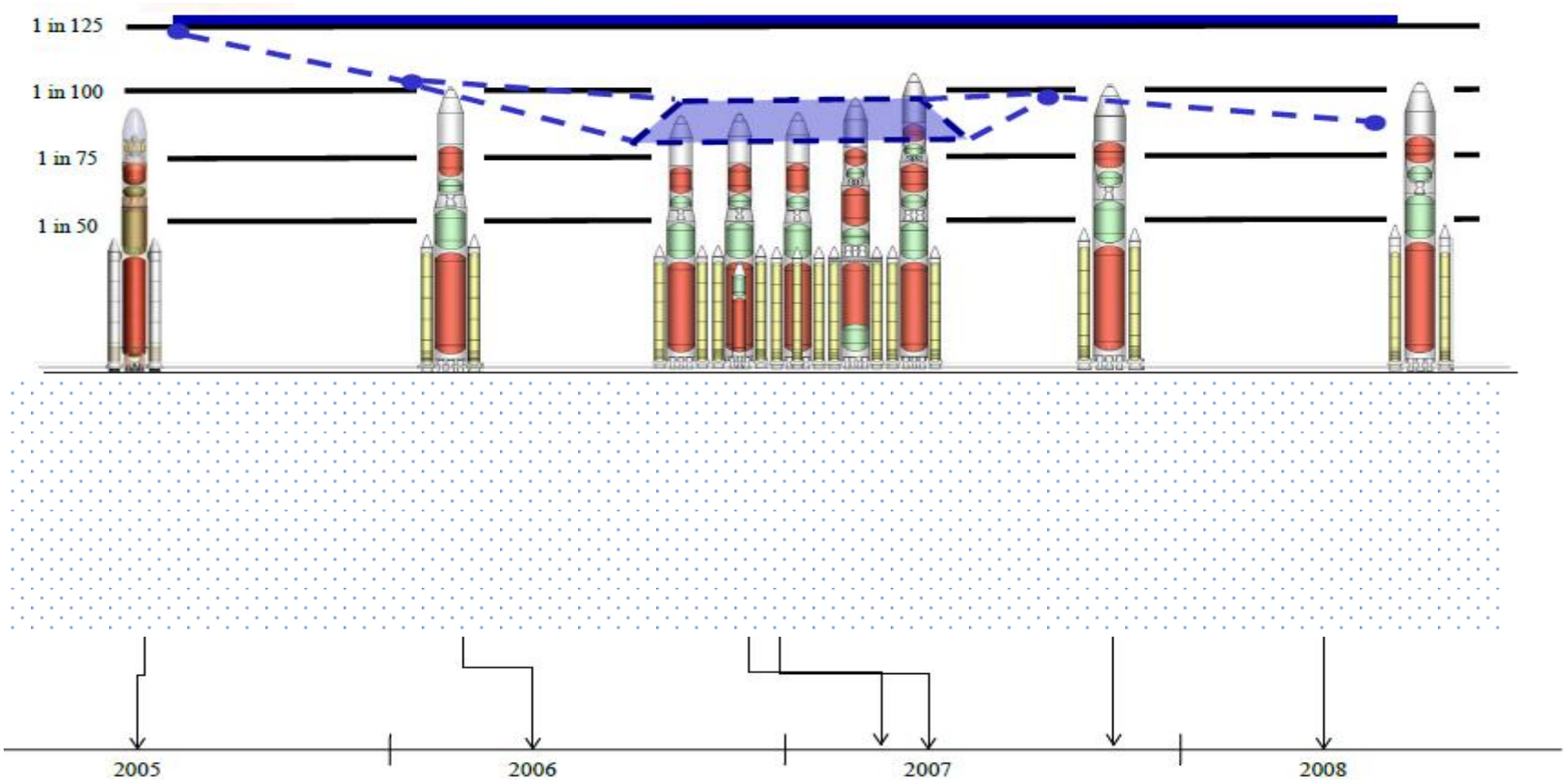
Reliability Engineering Applications

Reliability Engineering Applications

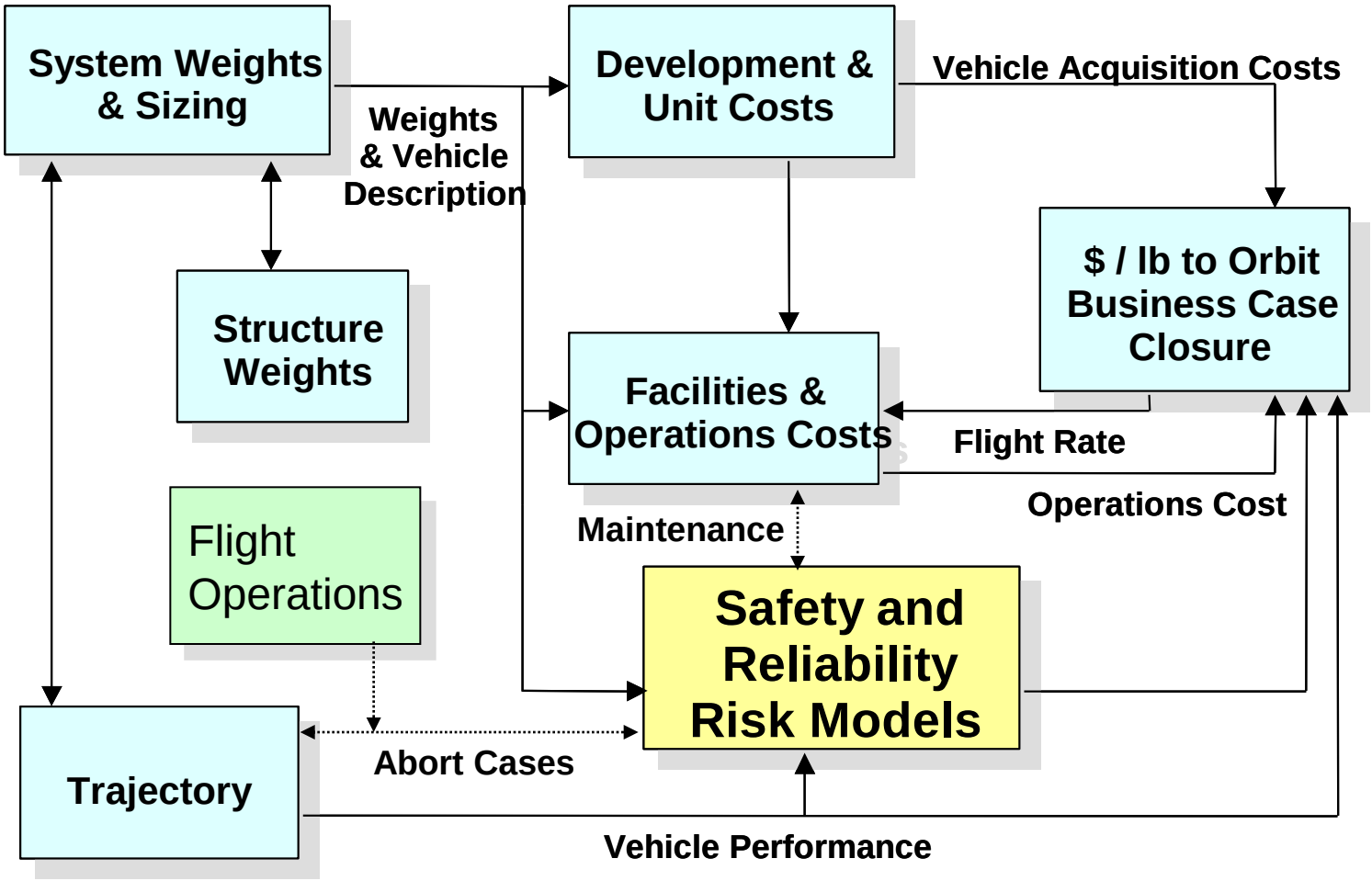
- **Applications and Case Studies**
  - The ARES V Conceptual Design Case - Reliability Trade Studies
  - The Orion Electrical Power System (EPS) Case - Failure Tolerance
  - Complex Reliability problems using simulation
    - The Space Shuttle External Tank (ET) Welds Case
    - The Space Shuttle Auxiliary Power Unit (APU) Case
  - The Space Shuttle Main Engine (SSME) Reliability Tracking Case – Reliability Growth
  - The SSME Single Flight Reliability Case - Life Limit Extension
  - The Roller Bearing Inner Race Fracture Case - Physics-based Reliability
  - The High Pressure Fuel Turbo-pump (HPFTP) First Stage Blade Cracks Case – A Weibull/Weibayes Application
  - The Columbia Accident - Integrated Failure Analysis

Conceptual System Reliability Trade Studies
The ARES V Conceptual Design Case

Reliability Trades During Conceptual Phase



Vehicle Concept Assessment Methodology



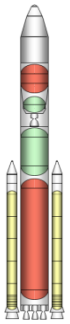
Reliability Methodology

The Process

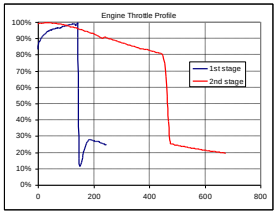
Mission Profile

Event	Time (sec)	Alt (km)
Liftoff		
Maximum Q		
SRB Separation		
Shroud Separation		
Main Engine Cutoff		
EDS Ignition		
EDS Engine Cutoff		

Vehicle Configuration

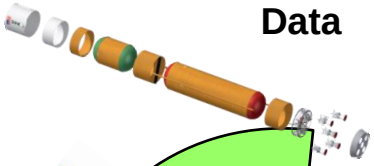


Subsystem Parameters

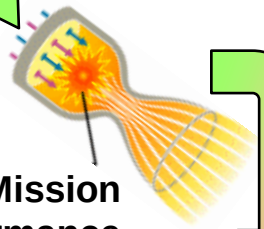


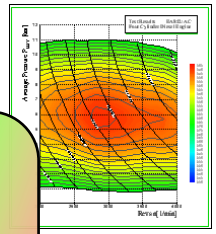
Advanced Concepts Office Design Input

Ares V Subsystem Data



Reliability Database





Reliability Algorithms

Mission Performance Data

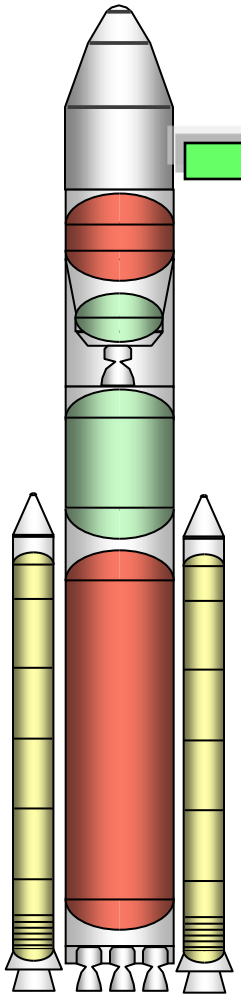
System Analysis Integration

Reliability Evaluation Results

Reliability Methodology - *Notional*

The Input / Output

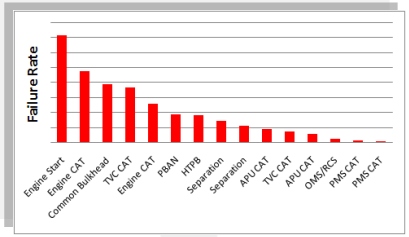
INPUT



Configuration

- No. of engines?
- Engine type?
- Burntime?
- Power Level?
- No. of segments?
- Propellant type?
- Mission Profile

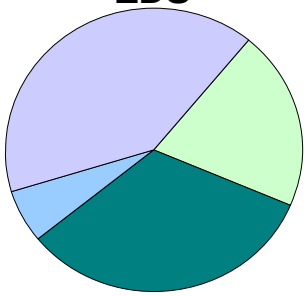
Reliability Data



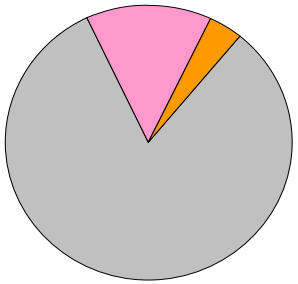
OUTPUT

System-Level Results

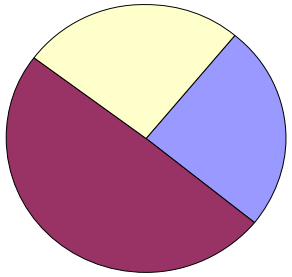
EDS



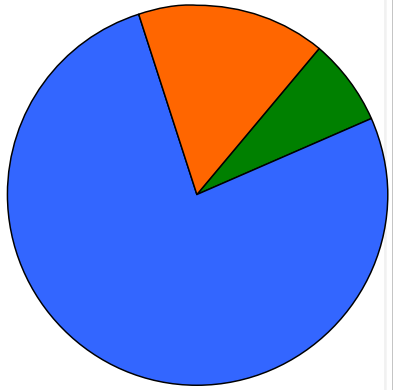
Core



Strap-On



Vehicle Results



- EDS
- Core
- Strap-On

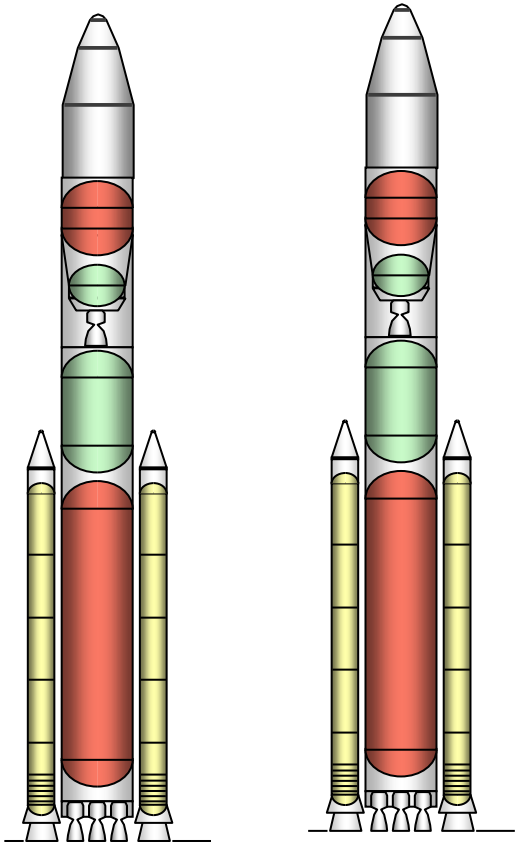
- EDS Air-Start
- EDS Non-Cat
- EDS Cat
- EDS Other
- Core Non-Cat
- Core Cat
- Core Other
- SRB
- RSRM
- Strap-On Separation

Launch Vehicle Comparison

Booster Stage (each)
2 / 5 - Segment SRM

First Stage
5 / RS-68

Second Stage
1 / J-2X

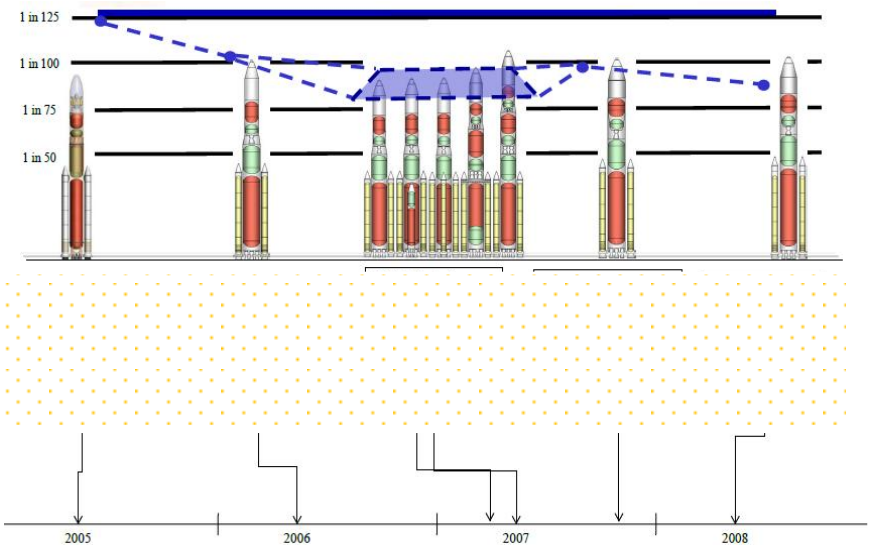


Booster Stage (each)
2 / 5 - Segment SRM

First Stage
6 / RS 68

Second Stage
1 / J-2X

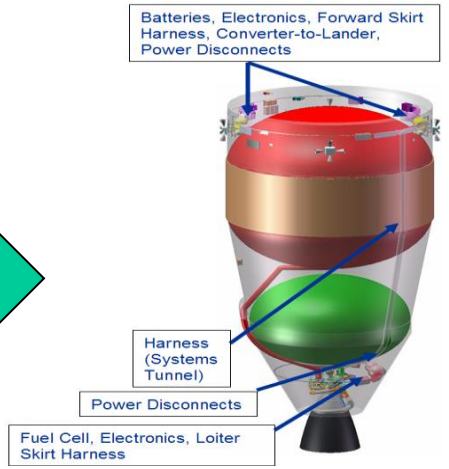
Earth Departure Stage (EDS)



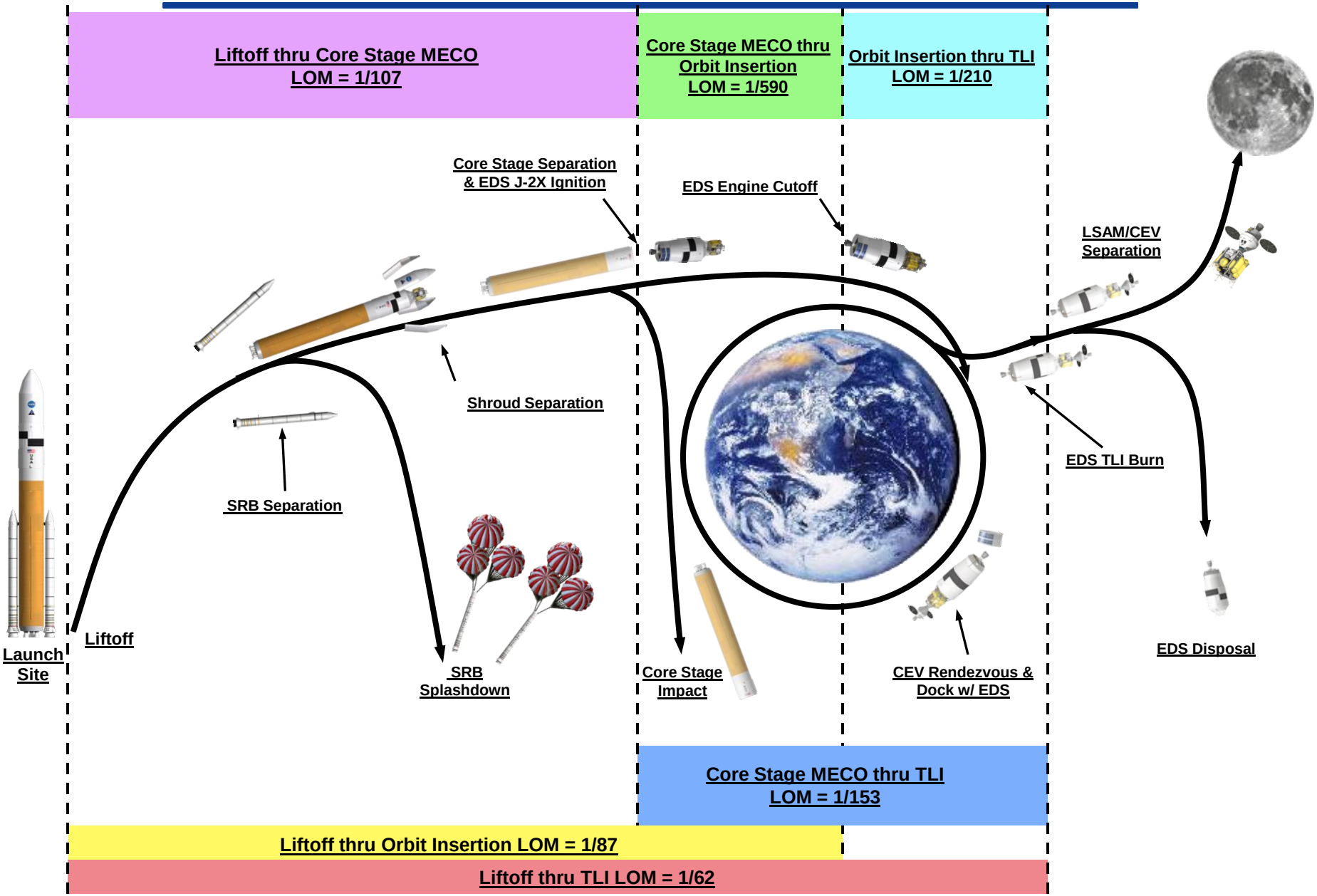
Performance-based reliability analysis provided supporting data in key architecture, element, subsystem, and component design decisions.

Earth Departure Stage

Solar Array to Fuel Cells



Mission Reliability Over the Mission Profile



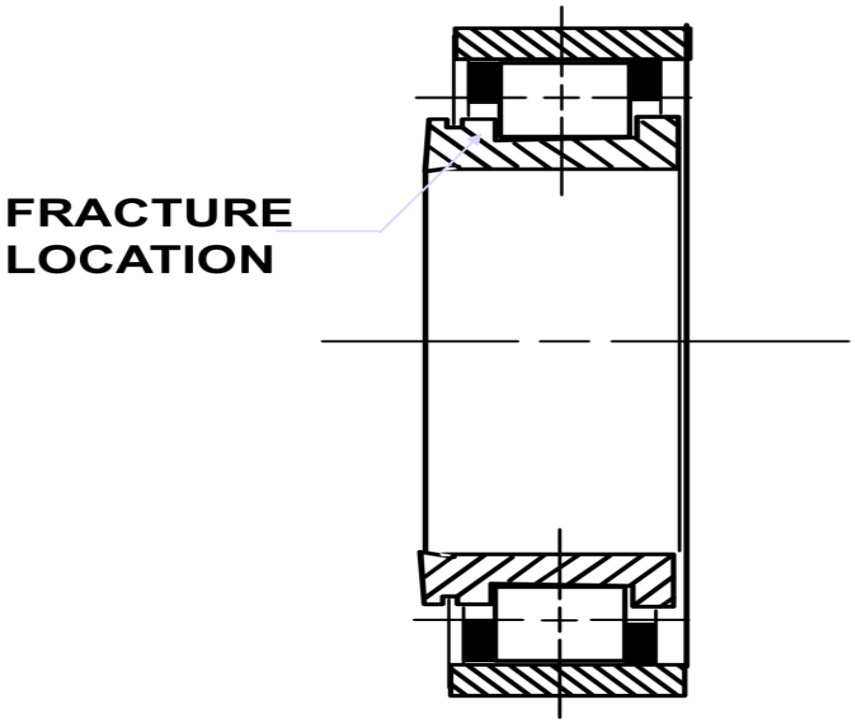
Concluding Remarks

- **Reliability is a critical system parameter that needs to be considered upfront in the design process along with performance and cost.**
- **Adopting a "Design for Reliability" philosophy is key in achieving NASA ambitious goals in safety and affordability.**
- **Reliability trade studies are part of a risk informed process to support architecture capability studies and conceptual design trades.**

Development Study
The Roller Bearing Inner Race Fracture Case

Background

During rig testing the AT/HPFTP Bearing experienced several cracked races. Three of four tests failed (440C bearing races Fractured)

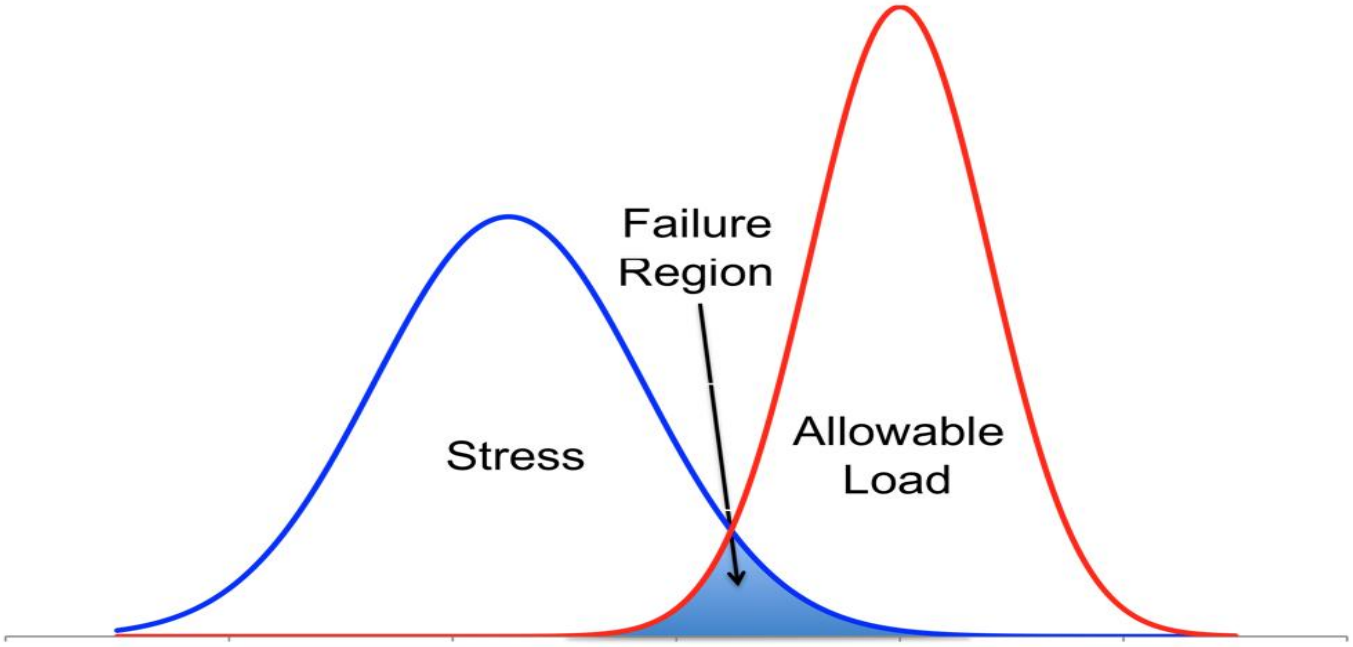


Objective

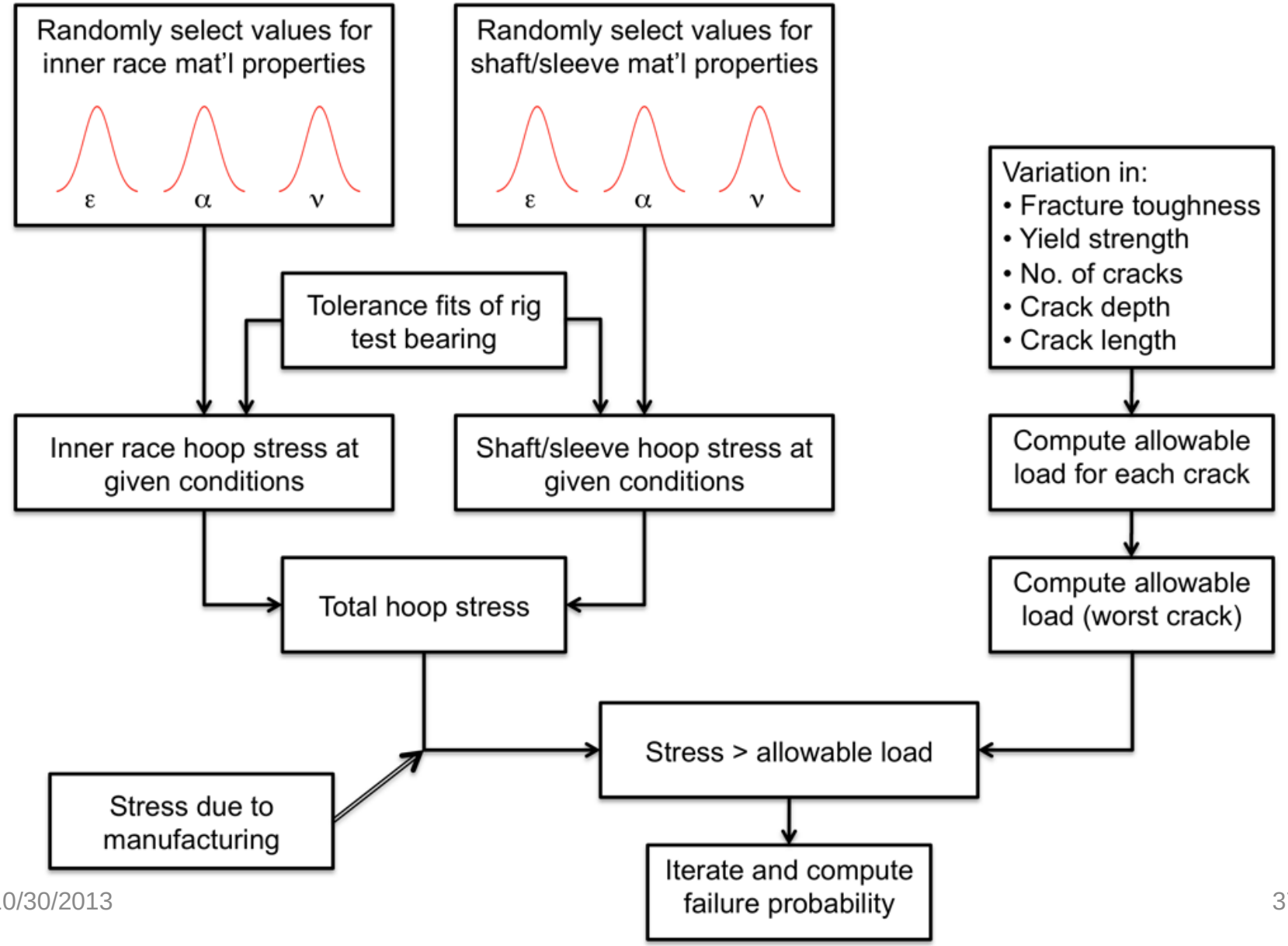
- In this application, an analysis was done for the Pratt & Whitney Alternate Turbo-pump Development (ATD) to assist in a High Pressure Fuel Turbo-pump (HPFTP) roller bearing inner race fracture problem.
- In particular, the questions which needed to be addressed were:
  - The probability of failure due to the hoop stress exceeding the materials capa-bility strength was acceptable.
  - The effect of manufacturing stresses on the fracture probability.
- There were two different materials under consideration; the 440C (current material) and the 9310.

Probabilistic Engineering Analysis

- Probabilistic engineering analysis is used when not enough no failure data is available and the design is characterized by complex geometry or is sensitive to loads, material properties, and environments.



The Analytical Approach
The Simulation Model



The Simulation Model

- Since this failure model is a simple overstress model, only two distributions need to be simulated: the hoop stress distribution and the materials capability distribution.
- In order to calculate the hoop stress distribution it was necessary to determine the materials properties variability.
- Of those materials properties that af-fected the total inner race hoop stress, a series of equations was derived which mapped these life drivers (such as modulus of elasticity, coefficient of thermal expansion, etc.) into the total Inner race hoop stress.
- In order to derive these equations, several sources of information were used which included P&W computer "design programs, equations from engineering theory, manufacturing stress data, and engineering judgment. This resulted in a distribution of the total hoop stress.

The Simulation Model

- In a similar fashion, a distribution on the materials ca-pability strength was derived.
- In this case, life drivers such as fracture toughness, crack depth/length, yield strength. etc. were important. The resulting materials capability strength distribution was then obtained through a similar series of equations.
- The Monte Carlo simulation in this case would calculate a random hoop stress and a random materials capability strength. if the former is greater than the later, a failure due to overstress occurs in the simulation. Otherwise, a success is recorded.
- The simulation was run for two different materials: 440C (current material) and 9310.
- After several thousand simulations are conducted, the percent which failed are recorded.

The Analysis Results

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

*ideal + abusive grinding
**Probabilistic Structural Analysis

The results of this analysis clearly show that the 9310 material was preferred over the 440C in terms inner race fracture failure mode.

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 X 10/100k = 5 fail/100k firings.

The Roller Bearing Inner Race Fracture Case

Conclusion

- The results of this analysis clearly showed that the 9310 material was preferred over the 440C in terms of the inner race fracture failure mode.
- Manufacturing stresses effect for the 440C material was very significant.
- Material selection has a major impact on Reliability.
- Probabilistic engineering analysis is critical to perform sensitivity analysis and trade studies for material selection and testing.

Technical Issues

The Roller Bearing Inner Race Fracture Case

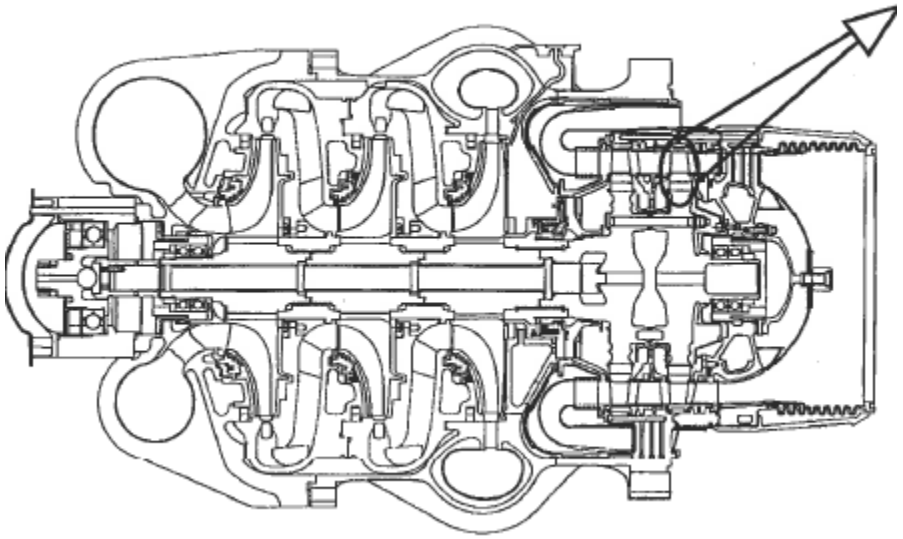
HPFTP
First Stage Turbine Blade Cracks

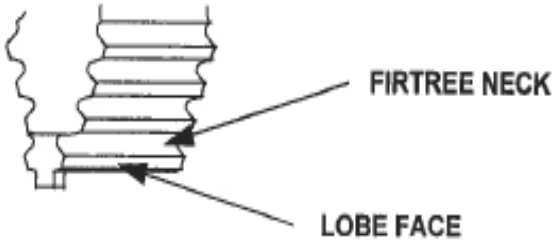
Objective

- Determine the Space Shuttle flight risk due to a HPFTP first stage turbine blade failure

HPFTP
First Stage Turbine Blade Cracks

HPFTP





HPFTP
First Stage Turbine Blade Cracks
Background

- A crack was found in a first stage turbine blade in HPFTP development unit 2423 during dye penetrant inspection 1/19/96.
- The subject blade had accumulated 20 starts and 9,826 seconds of operation.
- A total of 34 blade set of the current configuration have been dye penetrant inspected, with no other crack being found (see Database: Case 1).
- Metallurgical evaluation of blade:
  - Fracture is hydrogen assisted cracking
  - Fracture origin approximately in middle of bottom firtree lobe- starting on pressure side
  - No clear evidence of crack progression (striations)
  - Radial crack appears to be secondary - origin at intersection of transverse crack.
  - Similar to previous firtree lobe cracking
  - Pressure side of bottom lobe (face) has little evidence (visually) of shot peening

HPFTP
First Stage Turbine Blade Cracks

Assumptions

- A crack in a blade is a failure
- Only last dye penetrant inspection times are used (34 sets)
- One failure (crack) at 20 starts and 9826 seconds

HPFTP
First Stage Turbine Blade Cracks

Database

Last dye penetrant inspection for current blade configuration

Starts	Seconds	Starts	Seconds
46	22,241	15	7,604
21	10,394	27	7,344
28	11,314	5	2,337
17	13,997	15	7,302
38	13,269	8	3,759
32	13,028	10	6,308
20	9,826	11	4,792
25	12,362	8	4,178
21	10,219	11	4,076
30	10,139	5	2,402
22	9,822	5	2,337
19	9,314	4	2,110
17	9,011	5	1,871
28	8,577	4	1,851
21	8,285	5	1,612
19	8,250	4	1,598
36	7,839	2	600

HPFTP
First Stage Turbine Blade Cracks
Firtree Lobe Crack

Analysis Results

A Blade Crack is Considered a Failure

STS-75 Risk Summary for HPFTP First Stage Turbine Blade

STS-75 Engine	HPFTP Unit #	Based on Starts		Based on Time	
		Reliability	Risk	Reliability	Risk
ME-1	4112R1	0.999486	1 / 1,944	0.999436	1 / 1,773
ME-2	2128	0.999882	1 / 8,475	0.999943	1 / 17,507
ME-3	4016R1	0.999221	1 / 1,283	0.999517	1 / 2,070
3 Engine Cluster		0.998589	1 / 708	0.998896	1 / 906

- The starts and run time for the three pumps:
  - 2 STARTS/817 SEC
  - 2 STARTS/780 SEC
  - 4 STARTS /1856 SEC
- Weibull model was used for reliability predictions

The Roller Bearing Inner Race Fracture Case

Conclusion

Rationale For Flight

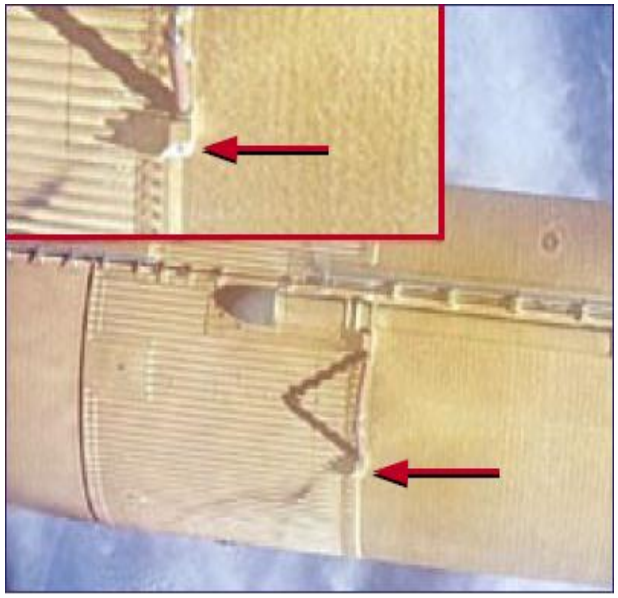
- Manufacturing records review for the flight set showed no discrepancies
- Fleet leader blade set with 22241 seconds and 46 tests
- 53 blade sets tested greater than the flight units.
- Flight Reliability was assessed and risk was accepted by Shuttle program.

The NASA Reliability and Maintainability Engineering Training Program

Integrated Analysis
The Columbia Accident Case

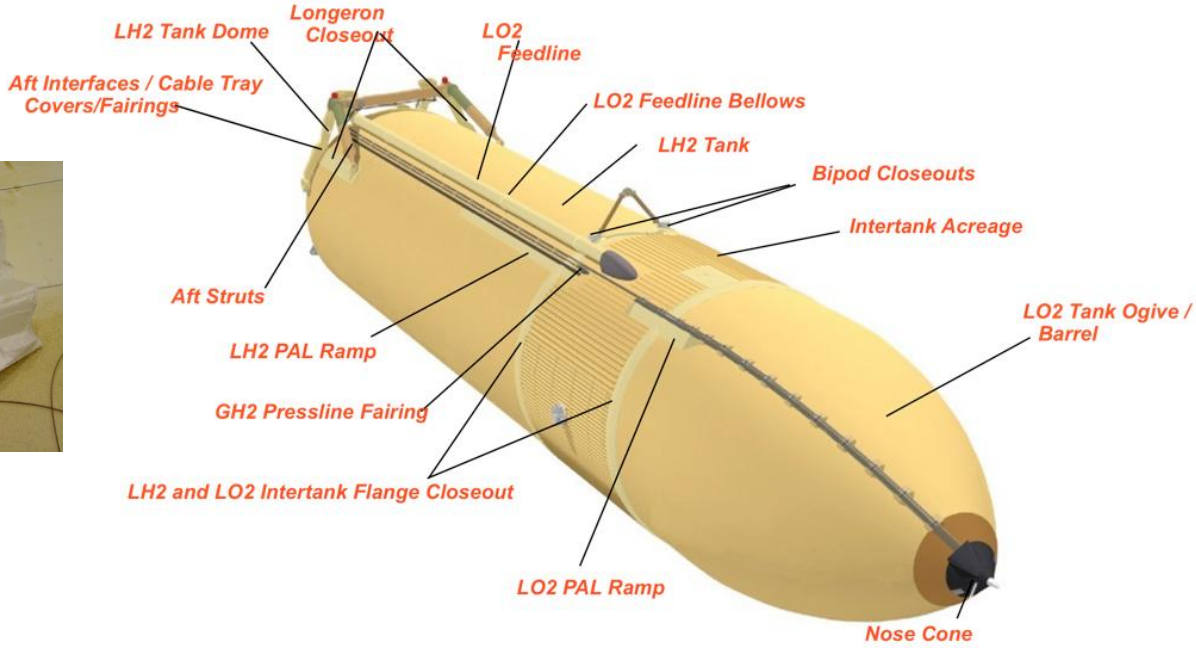
The Columbia Accident

- Causes and Contributing Factors
  - Breach in the Thermal Protection System caused by the left bipod ramp insulation foam striking the left wing leading edge.
  - There were large gaps in NASA's knowledge about the foam.
  - cryopumping and cryoingestion, were experienced during tanking, launch, and ascent.
  - Dissections of foam revealed subsurface flaws and defects as contributing to the loss of foam.



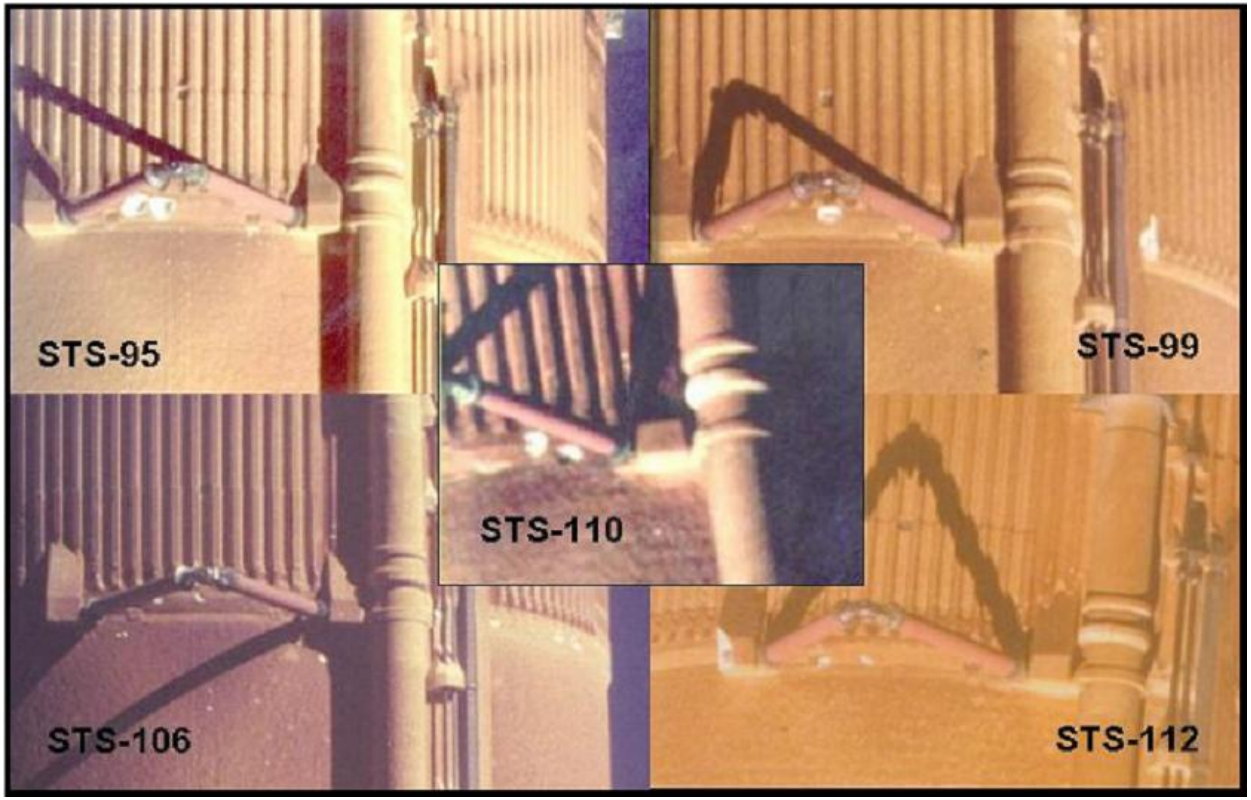
Background
ET Thermal Protection System

- The ET thermal protection system is a foam-type material applied to the external tank 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.

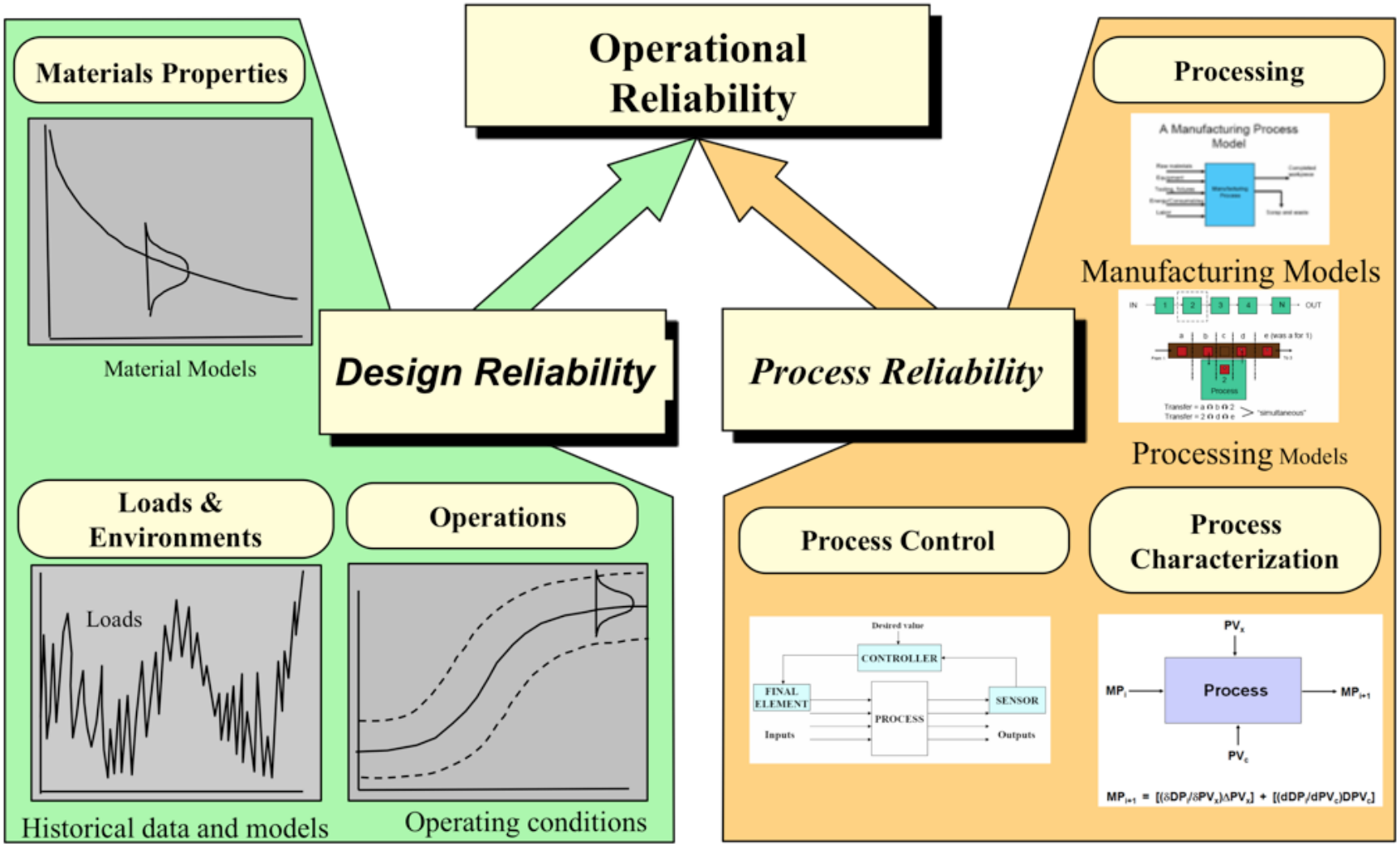


The Issue

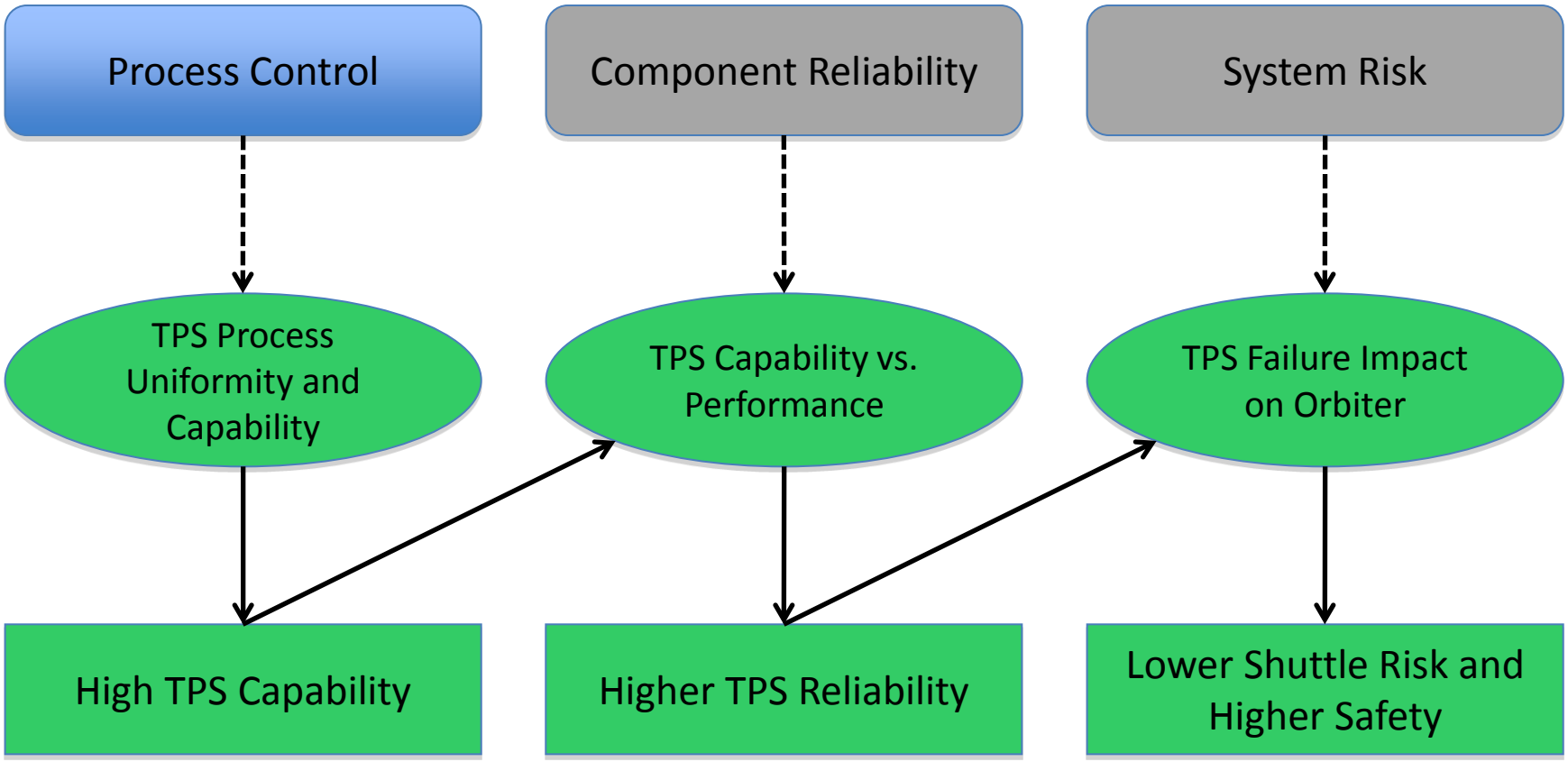
Foam Flight Photos



The Foam Reliability



The Technical Approach
The Relationship



Reliability of the ET 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.

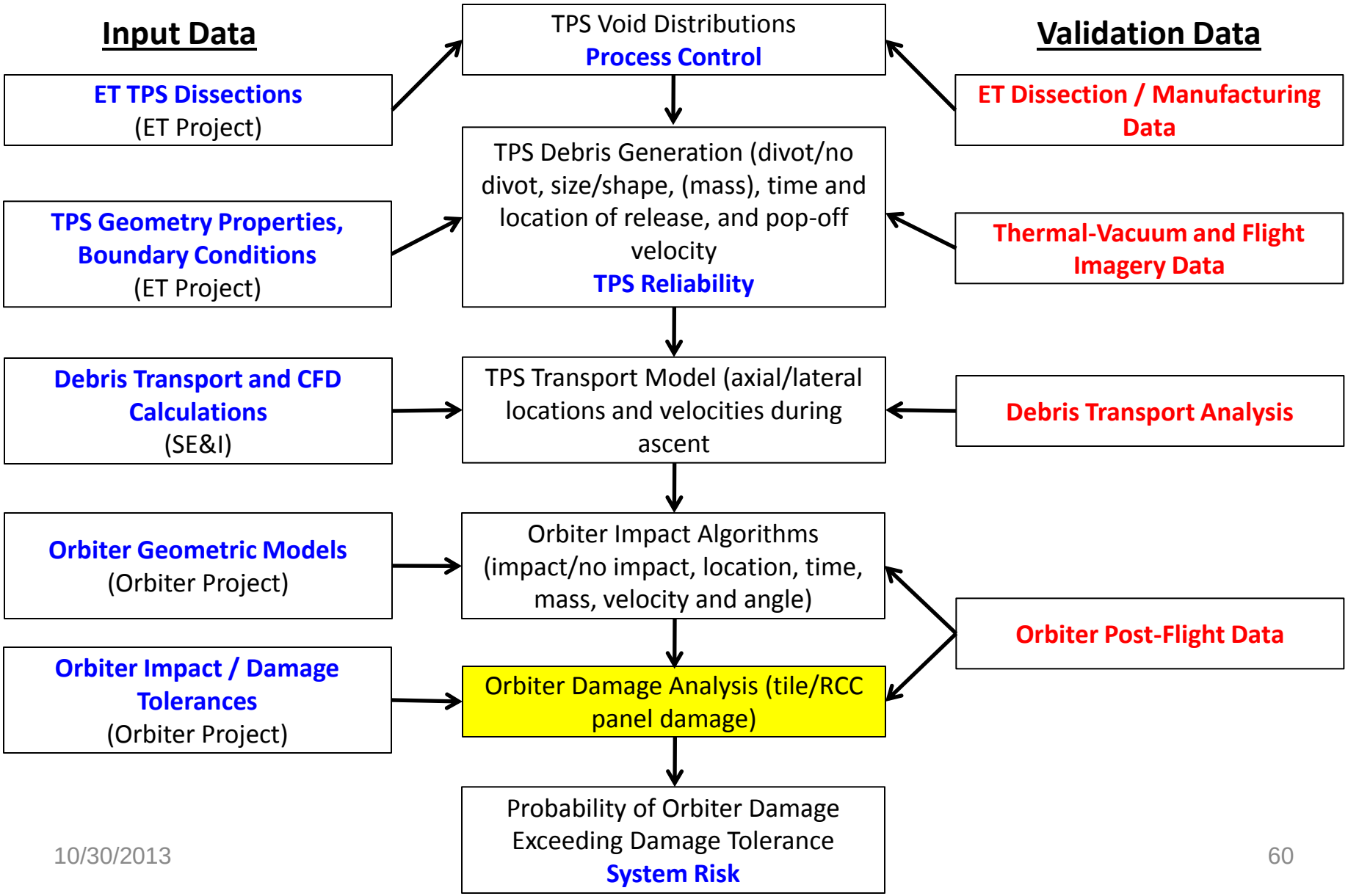
Foam Spray Process Evaluation

- Process variability was evaluated after the fact
- Dissection data collected after the Columbia accident showed excessive variability (Coefficient of variation is greater than 100%)
- Within tank variability was high, and tank to tank variability could not be fully characterized
- Defect/void characterization was difficult and statistics derived had high level of uncertainty
- The natural variation of the process was not well understood
- The relationship between process control variables and defects is not known
- For certification, a max expected void size was derived based on statistics and engineering analysis including a penalty factor for the unknowns in process control

Evaluation of Redesigned Components and Process Enhanced Foam

- Conducted verification and validation testing sufficient enough to understand and characterize the process variability and process capability
- Evaluated process capability for meeting the specification
- Evaluated process control for process uniformity
- Statistical evaluation of the data showed that significant improvements were made in process uniformity and process capability, including significant reduction in the coefficient of variation (COV) of the process critical output parameters (e.g. void frequency and void sizes)
- Void characterization was still difficult because of limitation of the data and lack of good definition of the right tail of the data distribution

The Data, Models, Analysis, and the Results



The Columbia Accident Case
The Conclusion

- The clear messages from the Columbia accident and the ET TPS foam experience are:
  - It is critical to understand the relationship between process control, component reliability, and system safety.
  - Inadequate manufacturing and quality control can have a severe negative impact on component reliability and system safety.
  - Process design should be considered upfront in the overall design process.
- Physics based Risk Assessment is critical to understand failure mechanism, integrated failures, etc..

Reliability and Maintainability (R&M) Engineering
The NSC STEP Training Resource

Fayssal Safie, Ph.D.
R&M Engineering Tech Fellow
MSFC/QD01

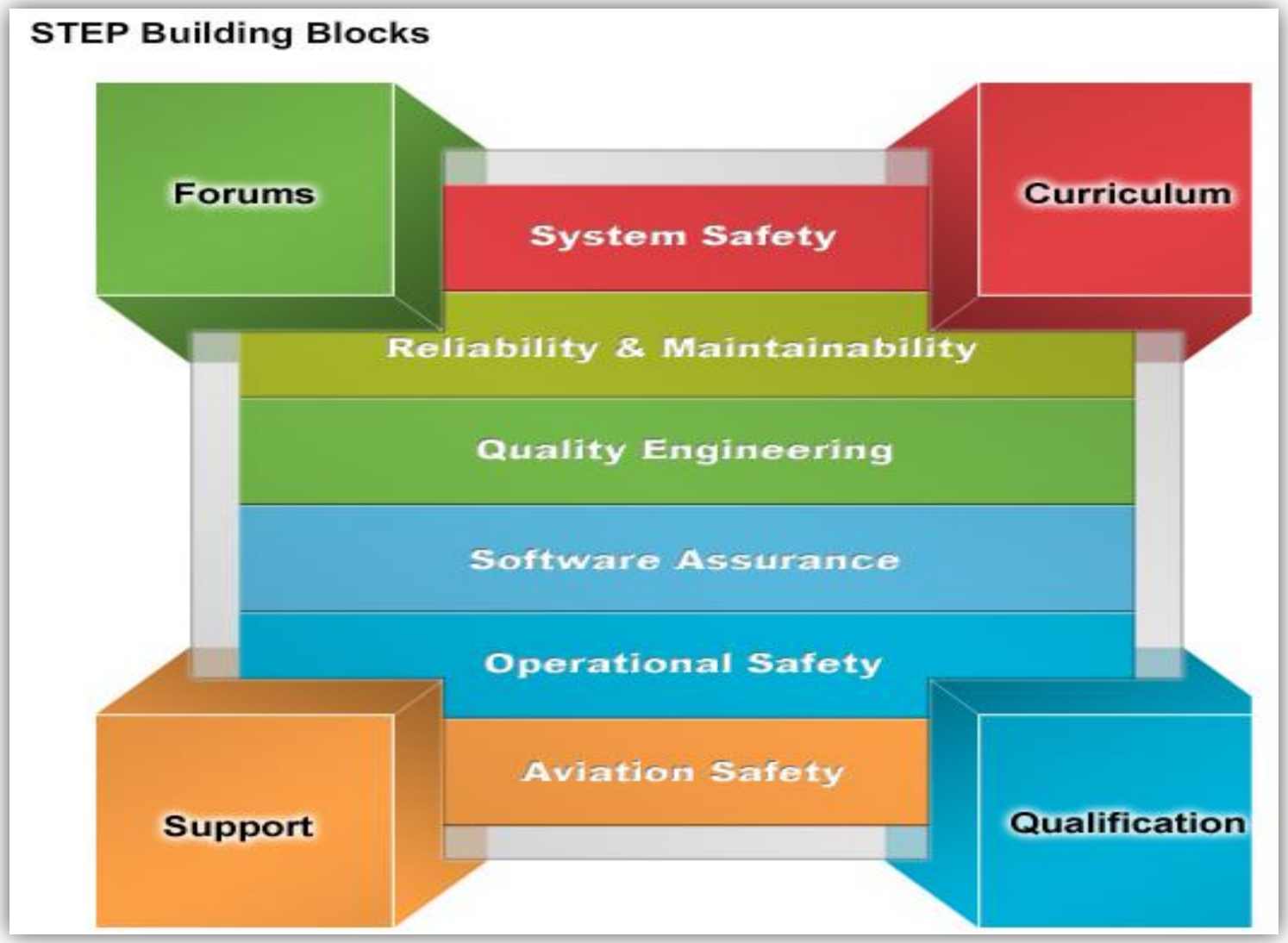
Agenda

- The Safety and Mission Assurance Technical Excellence Program (STEP) Overview
- The Reliability and Maintainability (R&M) Engineering Curriculum
- The “Design for Reliability “ five Modules Training Course
- Other Selected R&M Courses

STEP Overview

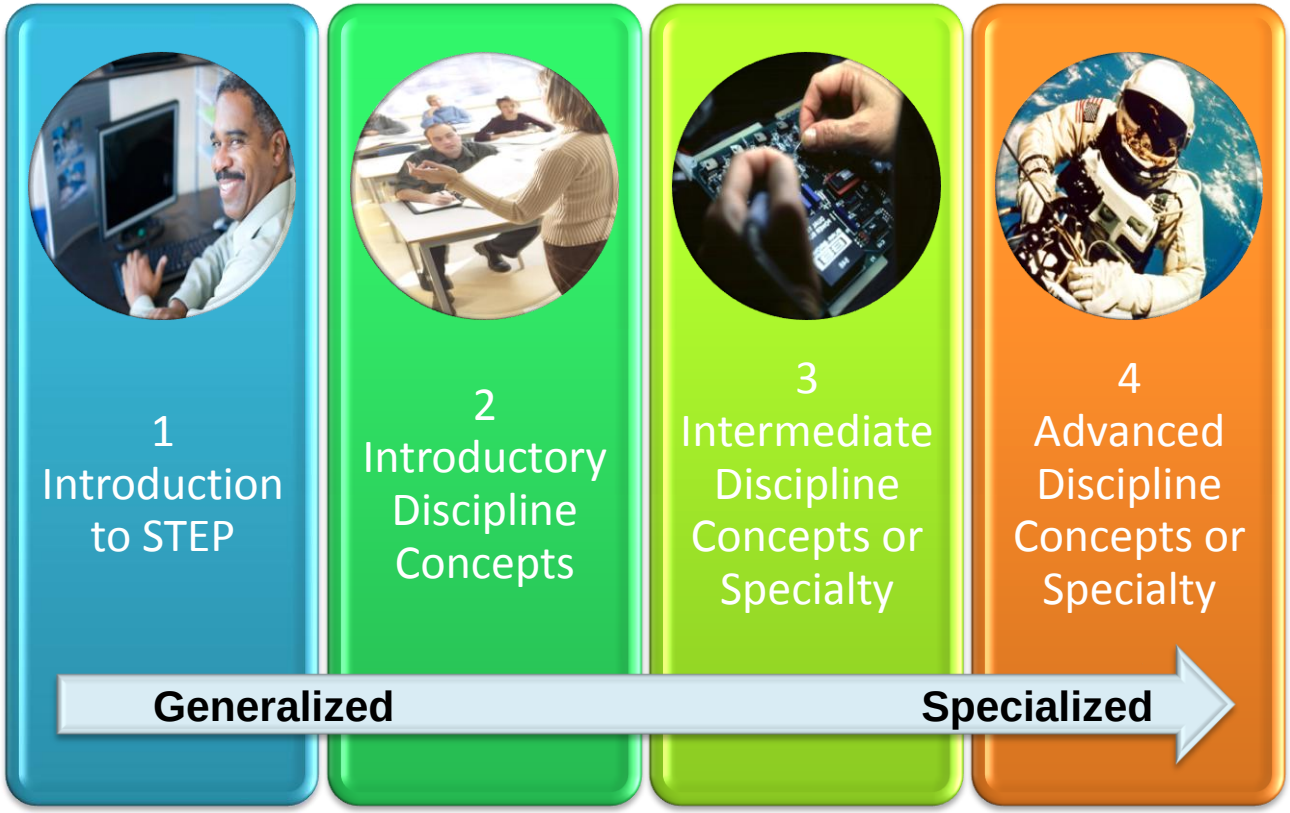
- **STEP, the Safety and Mission Assurance Technical Excellence Program, is a professional education program:**
  - Developed by the NASA Safety Center
  - Structured, career-oriented professional development
  - Focused on the six disciplines
  - Four curriculum levels
  - Combination of online and instructor-led courses

STEP – A Complete Curriculum



The STEP Curriculum

- **The STEP Curriculum is delivered across four levels with increasing specialization.**



The STEP Curriculum

- A complete curriculum plan for each discipline by level:
  - Courses & Descriptions
  - Readings & Resources
  - OJT Experiences
  - Domain Training

https://nscstep.nasa.gov/docs/Flash/PDFs/RMCourseOfStudy.pdf

R&M Curriculum – Level 2

- **A Minimum of 100 Hours Required**
  - **80 Required Discipline Training**
    - Design For Reliability
    - Design For Maintainability
    - R&M Principles and Planning
  - **20 Hours of Elective Courses**
    - Material Control
    - Metrology and Calibration
    - Introduction to Safety and Health Management
    - Introduction To Software Testing
    - Etc.

R&M Curriculum – Level 3

- **A Minimum of 137 Hours Required Discipline Training**
  - **103.5 Hours Required**
    - FMEA/CIL and FMECA
    - Basic Fault Tree Analysis I
    - Data Collection and Analysis I
    - Maintainability and Supportability Analysis and Integration
    - Testing and Demonstration I
    - Reliability, Availability, and Maintainability Modeling I
    - Root Cause Analysis
    - System Safety I
    - Completing The Investigation And Mishap Report
    - Mishap Investigation Roles And Responsibilities
    - Probabilistic Risk Assessment Methods (PRAM) for Practitioners and Managers
  - **33.5 Hours (minimum) of Level 3 Elective Courses**
    - Design of Experiments Overview
    - Drawings, Dimensions, & Tolerances SMA
    - Electrical Safety Basics
    - Etc.

R&M Curriculum – Level 4

- **A Minimum of 137 Hours Required Discipline Training**
  - **106 Hours Required**
    - Data Collection and Analysis II
    - Human Reliability Analysis
    - Parts and Materials Assessment (IEEE, Mechanical, Parts Stress/Derating)
    - Physics of Failure (Failure Mechanisms)
    - R&M Testing and Demonstration II
    - Reliability, Availability, and Maintainability Modeling II
    - Software Reliability Toolkit and Software Failure Modes And Effects Analysis (FMEA)
  - **31 Hours (minimum) of Level 3 Elective Courses**
    - Operational Aircraft Performance and Flight Test Practices
    - Safety of Complex Electronics
    - Statistical Quality Control
    - Risk Assessment of Space Systems
    - Etc.

NSC Website


SMA Technical Excellence Program (STEP) - Windows Internet Explorer
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STEP Supervisor Guide
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Learn how the STEP development team created STEP, from forming the teams that first developed the program's structure to creating specific courses.
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Reliability Challenges

- Having the right mix of Reliability engineering skills to support long duration manned missions beyond LEO
- Creating consistent methodologies for reliability allocations, predictions, demonstration, and analysis.
- Integrating reliability, maintainability, and supportability (RMS) analyses, a key to reduce sustainment cost and achieve high system availability for future NASA programs and projects.
- Embedding reliability engineers in the design engineering community to effectively help the design process.
- Training our engineering community to have a better understanding of the language of probability, statistics, and reliability engineering.