Reliability Engineering as the Bridge Between Systems Engineering, Design Engineering, and Integration and Test

PRESENTER: SAMANTHA B. RAWLINS
CO-AUTHORS: SHREYAS L. RAGHU | MICHAEL C. HALVORSON | TAMIA NEAL

ADVISOR: DR. DALE THOMAS

EMAIL: SR0134@UAH.EDU

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Complex Systems Integration Laboratory

Team Introduction

Samantha B. Rawlins
Reliability Engineering,
Systems Engineering,
Design Engineering
Integration & Test

Shreyas L. Raghu
Design Engineering,
Systems Engineering,
Reliability Engineering

Michael C. Halvorson
Systems Engineering,
Design Engineering,
Ontologies

Tamia Neal
Model-Based
Systems Engineering,
Integration & Test

Introduction

Reliability Engineering

- Provides the theoretical and practical tools to assess Reliability through associated artifacts (FMEA's/FMECA's, RBD's, FTA's, etc.) [1]
- Often underutilized by programs
  - Cost and schedule overruns, mission failure, loss of life, etc.

> *"**After the tragedy of the Apollo 1 fire**, the **reliability** of Apollo was made central by an engineering culture…"*
>
> – Jones, Reliability and Failure in NASA Missions, 2015

> *"The SSME reliability growth analysis was developed **post the Challenger accident** and has been used since then."*
>
> – F. Safie, NASA Applications and Lessons Learned in RE, 2012

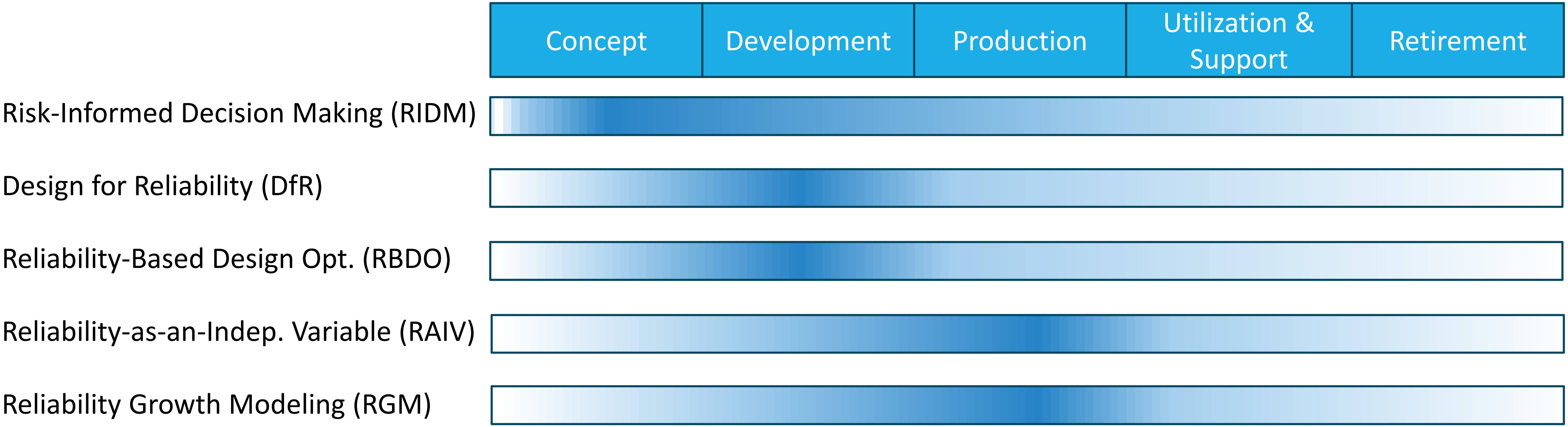
> *"a lot of the lessons from Webb are what not to do."*
>
> – R. Barron, $9B of Reliability Lessons from the JWST, 2022

> *"To a significant extent, **the success of the NERVA program**…was made possible through effective implementation of the Product Assurance Program Plan. The fact that there were very few technical setbacks in a program of such complexity, where so much could go wrong, is due to the detailed planning of **Reliability and Quality Control activities**, which anticipated problems in time to prevent them from becoming serious."*
>
> - Technical Summary Report of NERVA Program, 1972

Introduction

Challenges to Reliability Engineering [2]

- Time-Consuming, Manual, & Document-Centric
- Ambiguous Terminology & Interpretation between Reliability, Risk, and Safety
- Lacks Traceability to Design & Development Aspects



Introduction

Challenges to Reliability Engineering [2]

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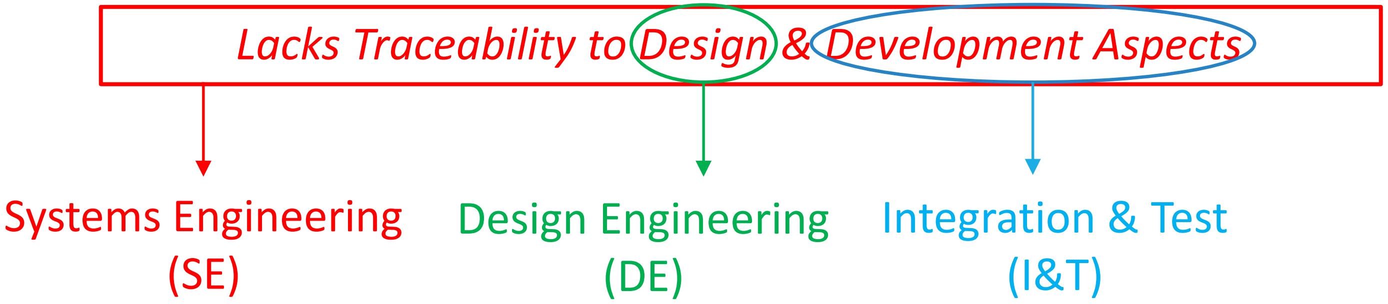
Interdependencies



Lacks Traceability to Design & Development Aspects

Systems Engineering (SE)

Design Engineering (DE)

Integration & Test (I&T)

The usefulness of Reliability Engineering needs to be explicitly illustrated to the three major engineering specialties

Systems Engineering & Reliability

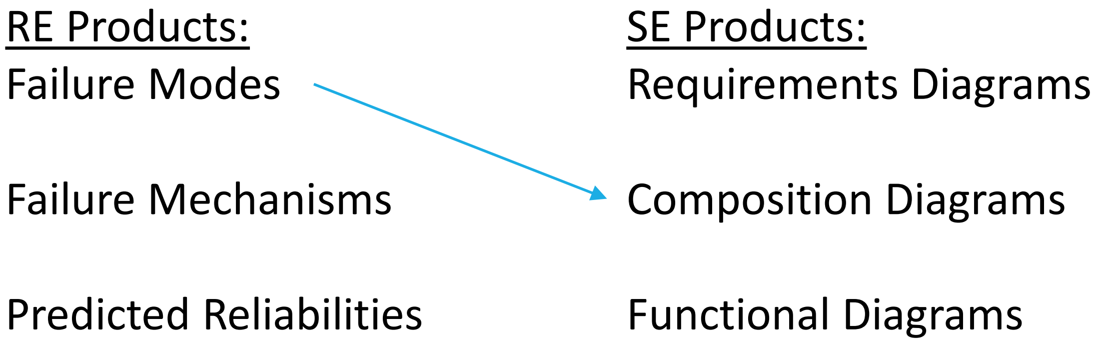
Currently:

- Also an often underappreciated discipline
- Highly subjective → Cultural shift towards Model-Based Systems Engineering (MBSE)
- Reliability is recognized as a crucial part of program success, but is consistently under-valued as a "number crunching exercise"
  - e.g. classified as a "non-functional" requirement or a "specialty discipline"

> *"[Reliability] is one of the most vital SE Decision Support activities…'The single most important factor that differentiates between effective and ineffective implementation of a reliability program is timing of the reliability effort.'"*
>
> – 2015, Wasson, *System Engineering Analysis, Design and Development*
> **Chapter 34 of 34**

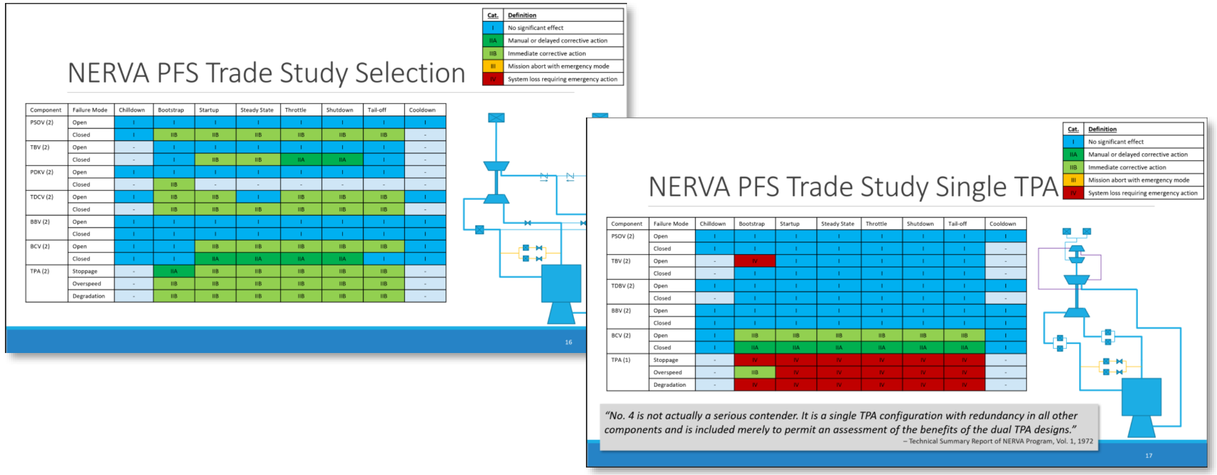
Opportunities from RE:

- Improved traceability between SE & RE artifacts offers a means of quantifying SE & supporting program-level decision making



RE Products:	SE Products:
Failure Modes	Requirements Diagrams
Failure Mechanisms	Composition Diagrams
Predicted Reliabilities	Functional Diagrams

Early Qualitative Failure Modes Analysis can Significantly Impact/Improve the Conceptual Design



NERVA PFS Trade Study Selection

Cat.	Definition
I	No significant effect
IIA	Manual or delayed corrective action
IIB	Immediate corrective action
III	Mission abort with emergency mode
IV	System loss requiring emergency action

Component	Failure Mode	Chilldown	Bootstrap	Startup	Steady State	Throttle	Shutdown	Tail-off	Cooldown
PSOV (2)	Open	I	I	I	I	I	I	I	I
	Closed	I	IIB	IIB	IIB	IIB	IIB	IIB	-
TBV (2)	Open	-	I	I	I	I	I	I	-
	Closed	-	I	IIB	IIB	IIA	IIA	I	-
PDKV (2)	Open	I	I	I	I	I	I	I	-
	Closed	-	IIB	-	-	-	-	-	-
TDCV (2)	Open	I	IIB	IIB	I	IIB	IIB	IIB	I
	Closed	-	IIB	IIB	IIB	IIB	IIB	IIB	-
BBV (2)	Open	I	I	I	I	I	I	I	I
	Closed	I	I	I	I	I	I	I	I
BCV (2)	Open	I	I	IIB	IIB	IIB	IIB	IIB	I
	Closed	I	I	IIA	IIA	IIA	IIA	I	I
TPA (2)	Stoppage	-	IIA	IIB	IIB	IIB	IIB	IIB	-
	Overspeed	-	IIB	IIB	IIB	IIB	IIB	IIB	-
	Degradation	-	IIB	IIB	IIB	IIB	IIB	IIB	-

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NERVA PFS Trade Study Single TPA

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Component	Failure Mode	Chilldown	Bootstrap	Startup	Steady State	Throttle	Shutdown	Tail-off	Cooldown
PSOV (2)	Open	I	I	I	I	I	I	I	I
	Closed	I	I	I	I	I	I	I	-
TBV (2)	Open	-	IV	I	I	I	I	I	-
	Closed	-	I	I	I	I	I	I	-
TDBV (2)	Open	I	I	I	I	I	I	I	I
	Closed	-	I	I	I	I	I	I	-
BBV (2)	Open	I	I	I	I	I	I	I	I
	Closed	I	I	I	I	I	I	I	I
BCV (2)	Open	I	IIB	IIB	IIB	IIB	IIB	IIB	I
	Closed	I	IIA	IIA	IIA	IIA	IIA	IIA	I
TPA (1)	Stoppage	-	IV	IV	IV	IV	IV	IV	-
	Overspeed	-	IIB	IV	IV	IV	IV	IV	-
	Degradation	-	IV	IV	IV	IV	IV	IV	-

"No. 4 is not actually a serious contender. It is a single TPA configuration with redundancy in all other components and is included merely to permit an assessment of the benefits of the dual TPA designs."
– Technical Summary Report of NERVA Program, Vol. 1, 1972

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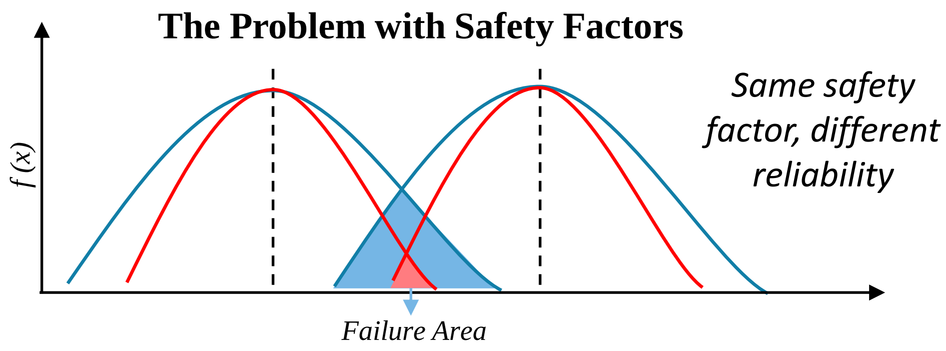
Design Engineering & Reliability

Currently:

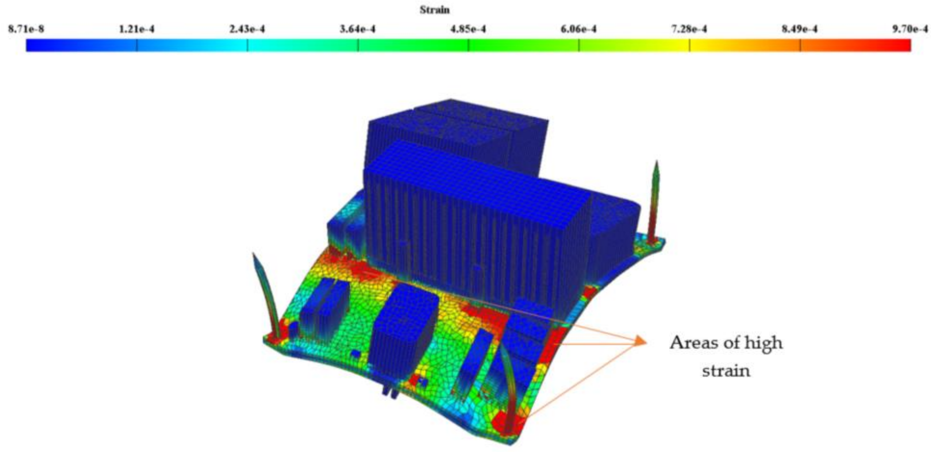
- Generate physics-based solutions that meet SE requirements
- Still highly deterministic → Safety factors are insufficient
- Most physics-based modeling tools solely evaluate performance
- Reliability highly confused with risk or safety engineering



> *"Performance of an NTP engine **depends** on the ability to demonstrate that the fuel can reliably operate"*
>
> \- Options for SMART Testing for NTP, January 2022

Opportunities from RE:

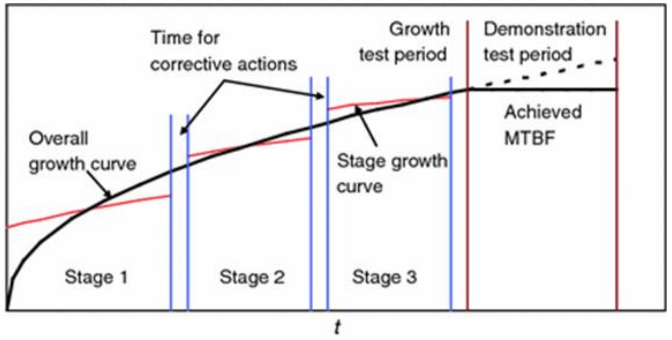
- Qualitative analysis for large-scale design changes (prior SE example)
- Quantitative analysis for small-scale design changes
  - Physics of Failure (PoF)
  - Uncertainty Consideration & Reduction
- Example: Ansys Sherlock tool for incorporating PoF into circuit board design

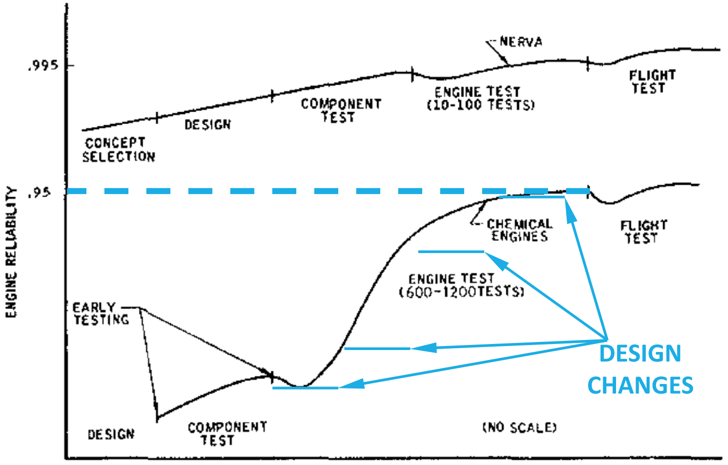


Integration and Test & Reliability

Currently:

- Highly separated from the DE & SE processes
  → No clear, formalized methodology
- Testing quickly settles into a Test-Fail-Fix routine
  - The purpose of testing becomes identifying failure modes
  - Reliability verified by demonstration, tracked via reliability growth





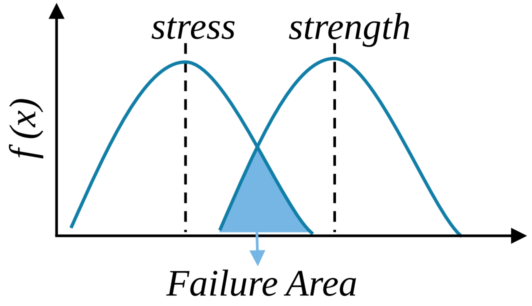
[11]

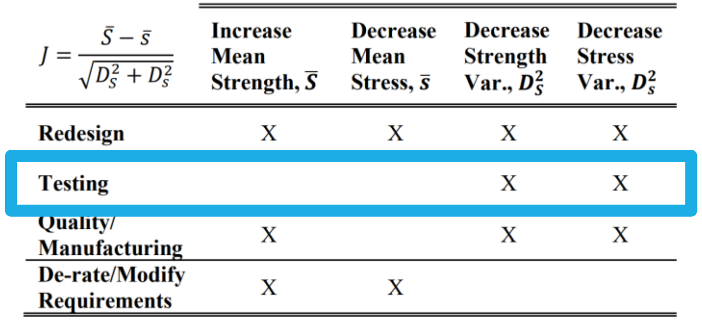
FIGURE 1 - RELIABILITY GROWTH COMPARISON ACTUAL CHEMICALS AND REQUIRED NERVA

Opportunities from RE:

- RE can be used to formalize the I&T process and explicitly integrate it with SE & DE specialties
  - The purpose of testing becomes uncertainty reduction
  - Use design reliability to drive the test program

Stress-Strength Interference Theory





$J = \frac{\bar{S}-\bar{s}}{\sqrt{D_S^2 + D_s^2}}$	Increase Mean Strength, $\bar{S}$	Decrease Mean Stress, $\bar{s}$	Decrease Strength Var., D_S^2	Decrease Stress Var., D_s^2
Redesign	X	X	X	X
Testing			X	X
Quality/ Manufacturing	X		X	X
De-rate/Modify Requirements	X	X		

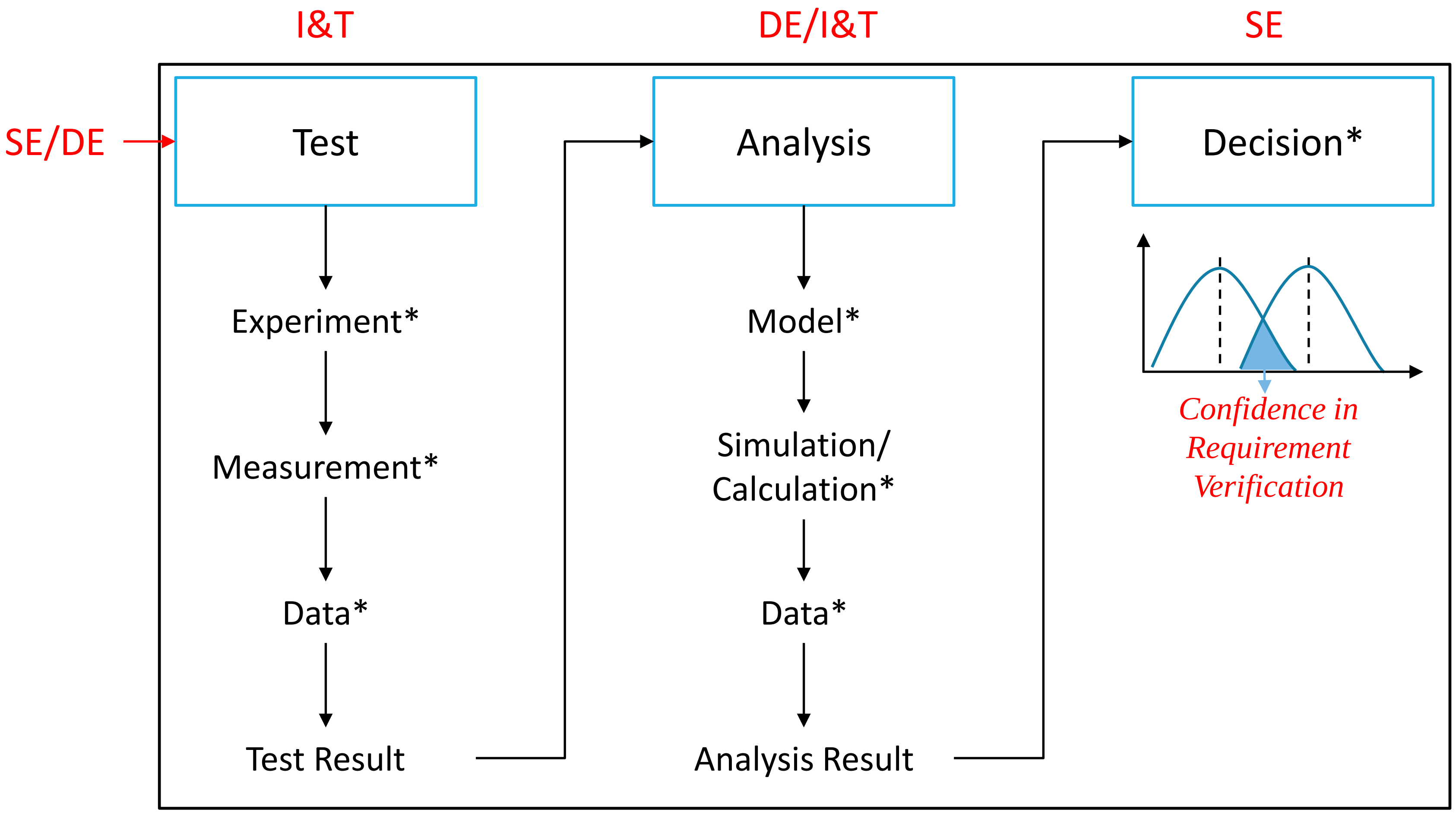
Ontological Formalization of the I&T Process

Systems Engineering Inputs:
- Requirements to be verified

Design Engineering Inputs:
- Physics-based models

Test Planning:
- Test Purpose
- Test Result
- Test Method
- Test Process

Analysis Planning:
- Computational Model
- Simulation Process
- Analysis Result



I&T

DE/I&T

SE

SE/DE

Test

Experiment*

Measurement*

Data*

Test Result

Analysis

Model*

Simulation/
Calculation*

Data*

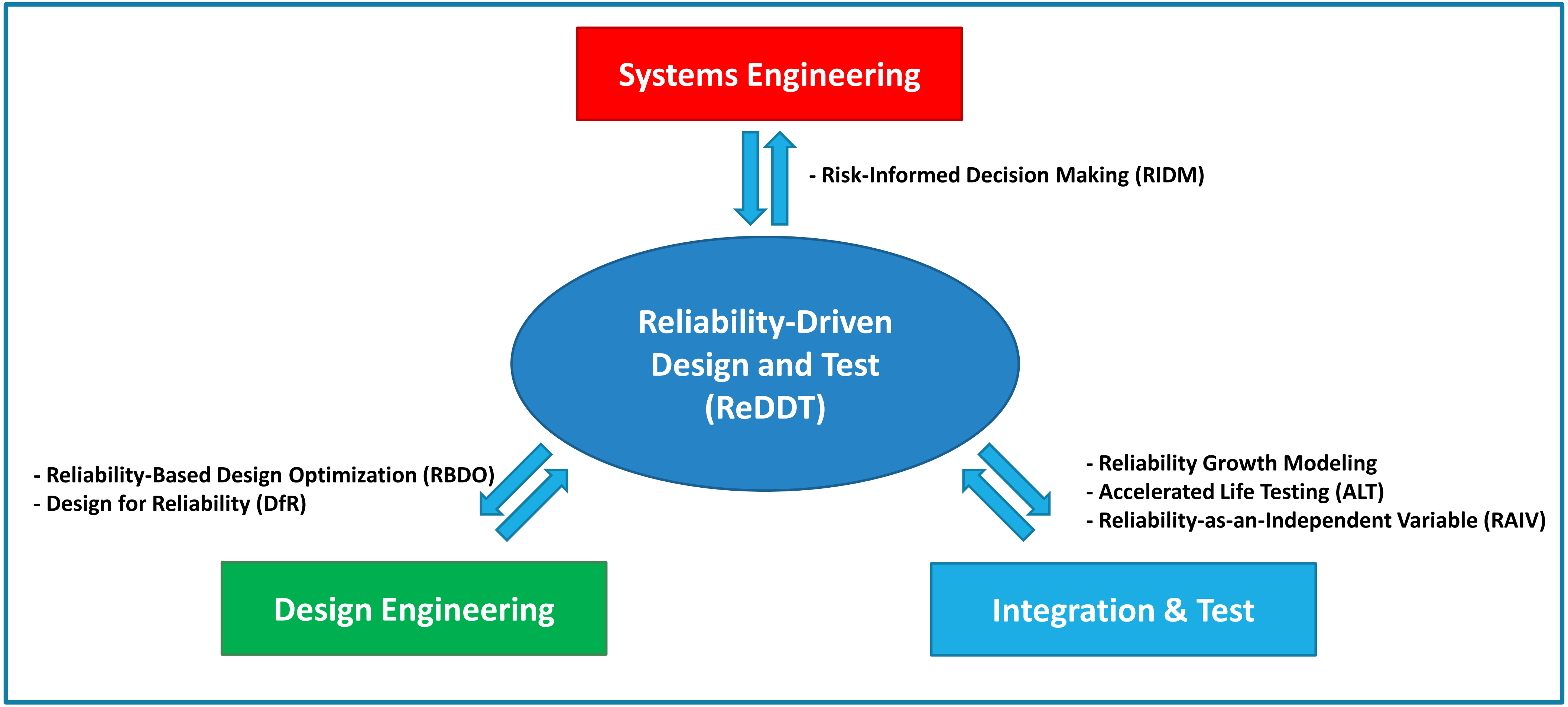
Analysis Result

Decision*

Confidence in Requirement Verification

** Indicates a source of uncertainty and opportunity for reduction*

Marriage of Specialties through *ReDDT*



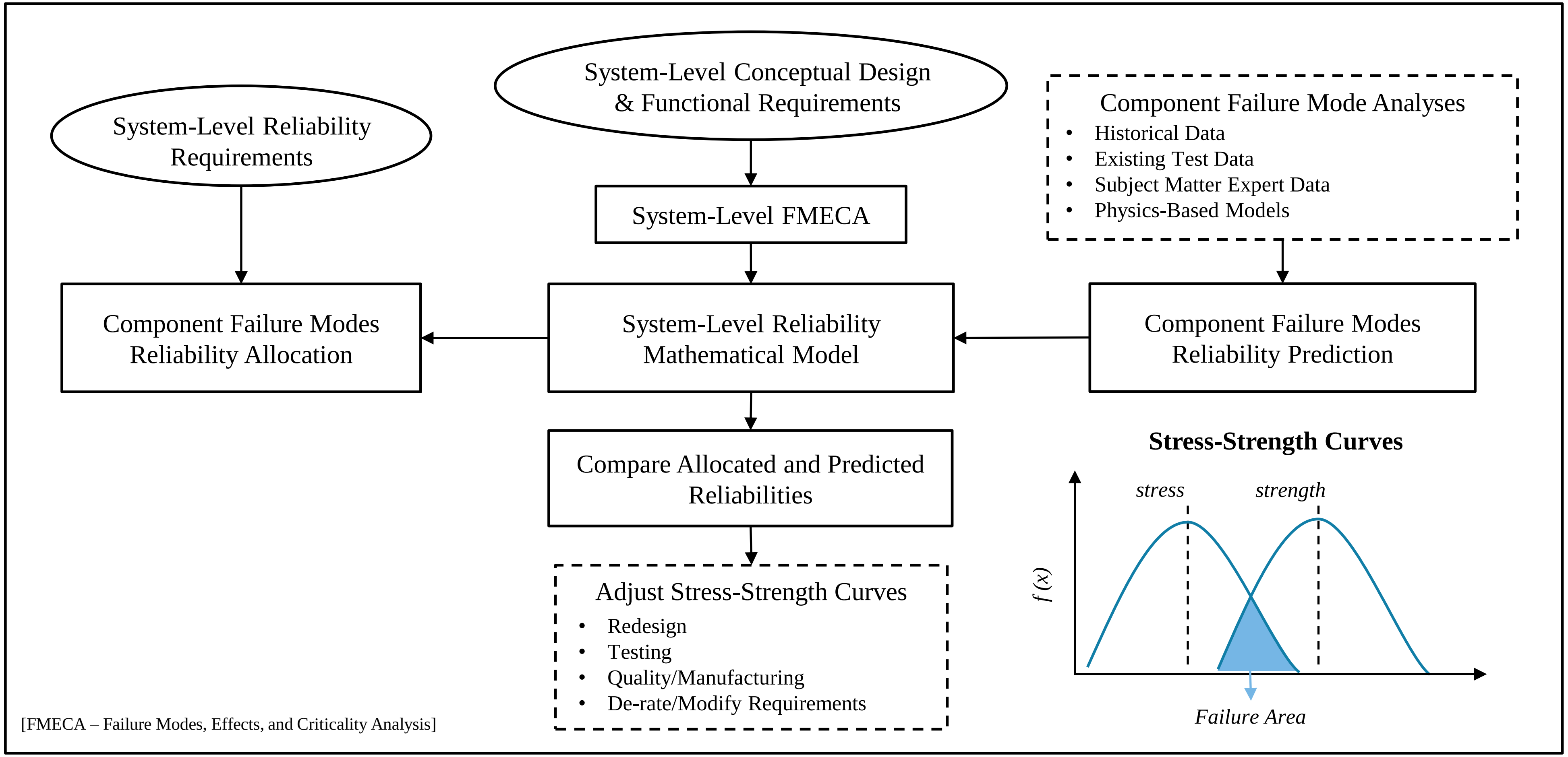
Concept of Reliability-Driven Design and Test (ReDDT) as the Bridge Between Specialties

Reliability-Driven Design & Test (ReDDT)

Step 1: Collect Inputs

Step 2: Compare Allocated & Predicted Reliabilities

Step 3: Adjust Until Requirements Met



System-Level Conceptual Design & Functional Requirements

System-Level Reliability Requirements

System-Level FMECA

Component Failure Mode Analyses
- Historical Data
- Existing Test Data
- Subject Matter Expert Data
- Physics-Based Models

Component Failure Modes Reliability Allocation

System-Level Reliability Mathematical Model

Component Failure Modes Reliability Prediction

Compare Allocated and Predicted Reliabilities

Adjust Stress-Strength Curves
- Redesign
- Testing
- Quality/Manufacturing
- De-rate/Modify Requirements

Stress-Strength Curves

[FMECA – Failure Modes, Effects, and Criticality Analysis]

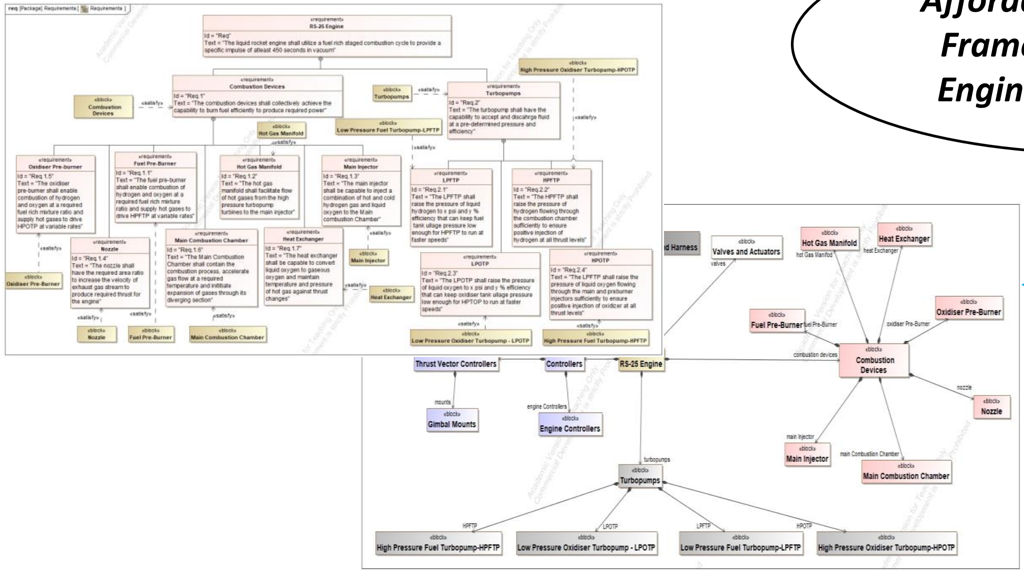
The ReDDT Process Flow

Case Study 1: RS-25 (SLS Core Stage)

Systems Engineering

Design Engineering

Affordability Modelling Framework for RS-25 Engine in SysML [3-8]


req [Package] Requirements [Requirements]

«requirement» RS-25 Engine
Id = "Req"
Text = "The liquid rocket engine shall utilize a fuel rich staged combustion cycle to provide a specific impulse of atleast 450 seconds in vacuum"

«requirement» Combustion Devices
Id = "Req.1"
Text = "The combustion devices shall collectively achieve the capability to burn fuel efficiently to produce required power"

«requirement» Turbopumps
Id = "Req.2"
Text = "The turbopump shall have the capability to accept and discahrge fluid at a pre-determined pressure and efficiency"

«requirement» Oxidiser Pre-burner
Id = "Req.1.5"
Text = "The oxidiser pre-burner shall enable combustion of hydrogen and oxygen at a required fuel rich mixture ratio and supply hot gases to drive HPOTP at variable rates"

«requirement» Fuel Pre-Burner
Id = "Req.1.1"
Text = "The fuel pre-burner shall enable combustion of hydrogen and oxygen at a required fuel rich mixture ratio and supply hot gases to drive HPFTP at variable rates"

«requirement» Hot Gas Manifold
Id = "Req.1.2"
Text = "The hot gas manifold shall facilitate flow of hot gases from the high pressure turbopump turbines to the main injector"

«requirement» Main Injector
Id = "Req.1.3"
Text = "The main injector shall be capable to inject a combination of hot and cold hydrogen gas and liquid oxygen to the Main combustion Chamber"

«requirement» LPFTP
Id = "Req.2.1"
Text = "The LPFTP shall raise the pressure of liquid hydrogen to x psi and y % efficiency that can keep fuel tank ullage pressure low enough for HPFTP to run at faster speeds"

«requirement» HPFTP
Id = "Req.2.2"
Text = "The HPFTP shall raise the pressure of hydrogen flowing through the combustion chamber sufficiently to ensure positive injection of hydrogen at all thrust levels"

«requirement» Nozzle
Id = "Req.1.4"
Text = "The nozzle shall have the required area ratio to increase the velocity of exhaust gas stream to produce required thrust for the engine"

«requirement» Main Combustion Chamber
Id = "Req.1.6"
Text = "The Main Combustion Chamber shall contain the combustion process, accelerate gas flow at a required temperature and inititiate expansion of gases through its diverging section"

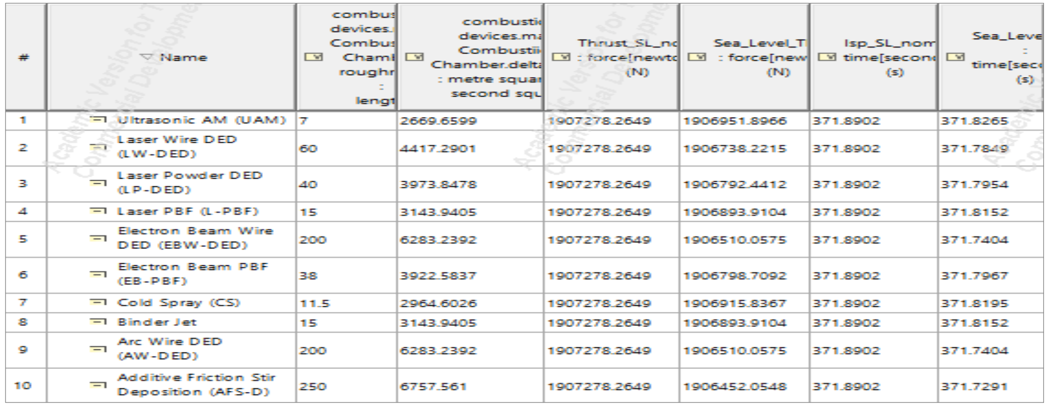
«requirement» Heat Exchanger
Id = "Req.1.7"
Text = "The heat exchanger shall be capable to convert liquid oxygen to gaseous oxygen and maintain temperature and pressure of hot gas against thrust changes"

«requirement» LPOTP
Id = "Req.2.3"
Text = "The LPOTP shall raise the pressure of liquid oxygen to x psi and y % efficiency that can keep oxidiser tank ullage pressure low enough for HPTOP to run at faster speeds"

«requirement» HPOTP
Id = "Req.2.4"
Text = "The LPFTP shall raise the pressure of liquid oxygen flowing through the main and preburner injectors sufficiently to ensure positive injection of oxidizer at all thrust levels"

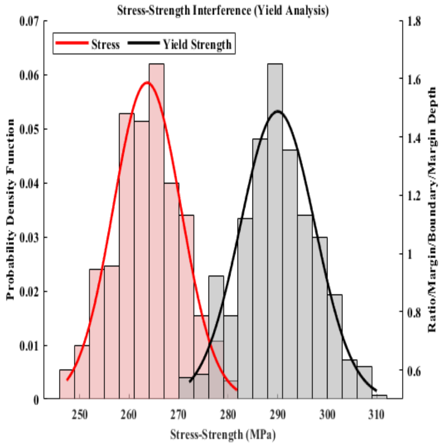
ReDDT

Test

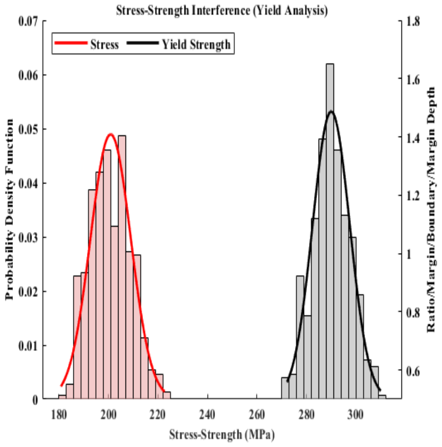


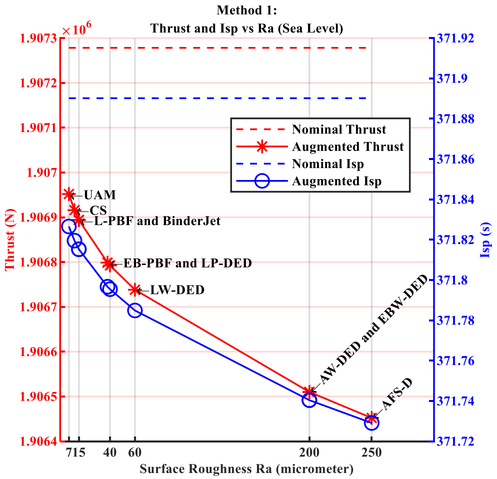
#	Name	combus devices. Combus Chaml roughr : lengt	combustic devices.ma Combustic Chamber.delta : metre squar second squ	Thrust_SL_nc : force[newtc (N)	Sea_Level_T : force[new (N)	Isp_SL_nom time[secon (s)	Sea_Leve : time[sec (s)
1	Ultrasonic AM (UAM)	7	2669.6599	1907278.2649	1906951.8966	371.8902	371.8265
2	Laser Wire DED (LW-DED)	60	4417.2901	1907278.2649	1906738.2215	371.8902	371.7849
3	Laser Powder DED (LP-DED)	40	3973.8478	1907278.2649	1906792.4412	371.8902	371.7954
4	Laser PBF (L-PBF)	15	3143.9405	1907278.2649	1906893.9104	371.8902	371.8152
5	Electron Beam Wire DED (EBW-DED)	200	6283.2392	1907278.2649	1906510.0575	371.8902	371.7404
6	Electron Beam PBF (EB-PBF)	38	3922.5837	1907278.2649	1906798.7092	371.8902	371.7967
7	Cold Spray (CS)	11.5	2964.6026	1907278.2649	1906915.8367	371.8902	371.8195
8	Binder Jet	15	3143.9405	1907278.2649	1906893.9104	371.8902	371.8152
9	Arc Wire DED (AW-DED)	200	6283.2392	1907278.2649	1906510.0575	371.8902	371.7404
10	Additive Friction Stir Deposition (AFS-D)	250	6757.561	1907278.2649	1906452.0548	371.8902	371.7291

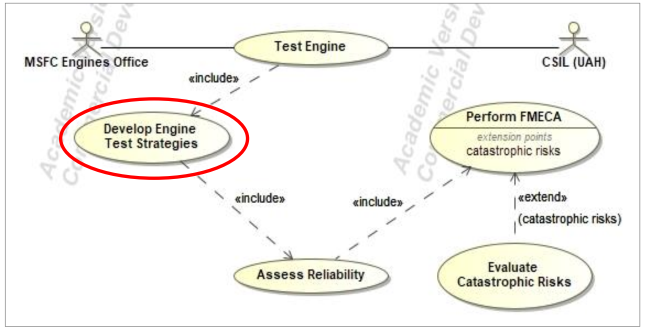
Overlaps (FoS-Based)



No Overlaps (Margin-Based Design)




Method 1:
Thrust and Isp vs Ra (Sea Level)

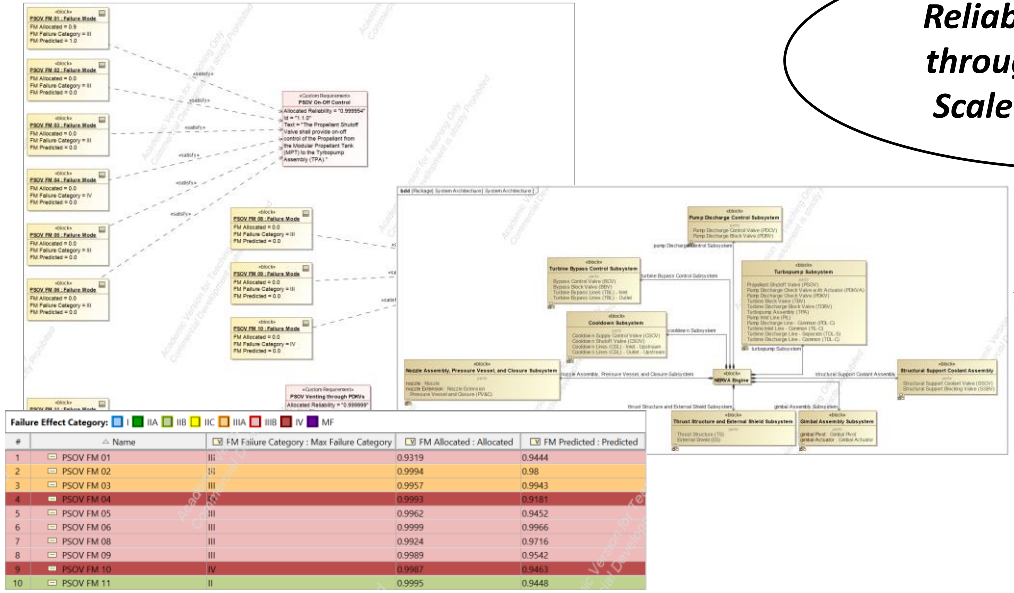


Case Study 2: Nuclear Thermal Propulsion

Systems Engineering

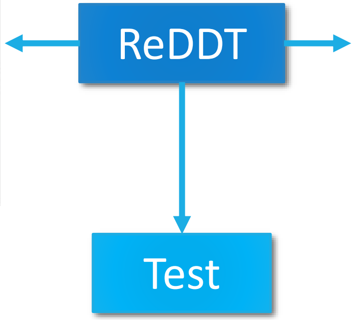
Design Engineering

Reliability Verification through Minimal Full-Scale Ground Testing



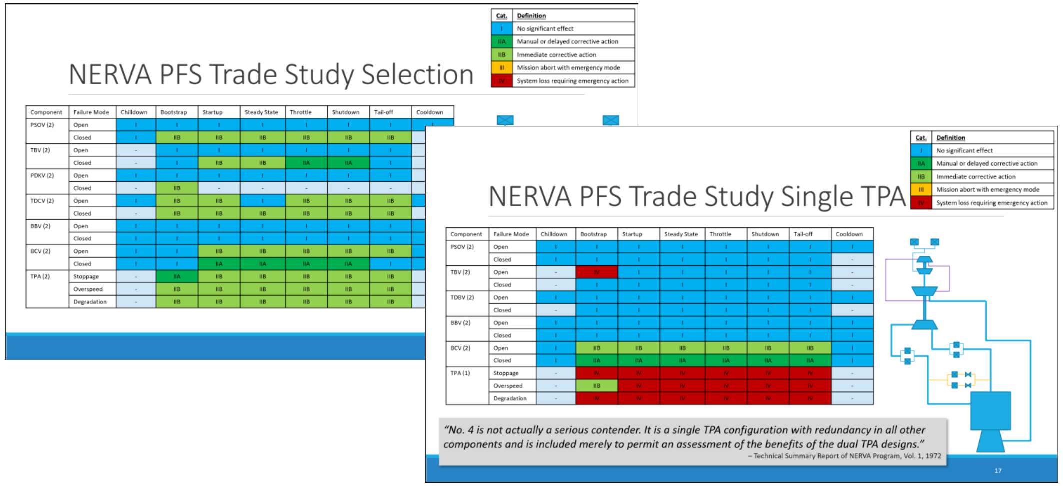
Failure Effect Category: 🟦 I 🟩 IIA 🟩 IIB 🟨 IIC 🟧 IIIA 🟥 IIIB 🟥 IV 🟪 MF

#	Name	FM Failure Category : Max Failure Category	FM Allocated : Allocated	FM Predicted : Predicted
1	PSOV FM 01	III	0.9319	0.9444
2	PSOV FM 02	III	0.9994	0.98
3	PSOV FM 03	III	0.9957	0.9943
4	PSOV FM 04	IV	0.9993	0.9181
5	PSOV FM 05	III	0.9962	0.9452
6	PSOV FM 06	III	0.9999	0.9966
7	PSOV FM 08	III	0.9924	0.9716
8	PSOV FM 09	III	0.9989	0.9542
9	PSOV FM 10	IV	0.9987	0.9463
10	PSOV FM 11	II	0.9995	0.9448



ReDDT

Test



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PSOV (2)	Open	I	I	I	I	I	I	I	I
	Closed	I	IIB	IIB	IIB	IIB	IIB	IIB	
TBV (2)	Open	-	I	I	I	I	I	I	
	Closed	-	I	IIB	IIB	IIA	IIA	I	
PDKV (2)	Open	I	I	I	I	I	I	I	
	Closed	-	IIB	-	-	-	-	-	
TDCV (2)	Open	I	IIB	IIB	I	IIB	IIB	IIB	
	Closed	-	IIB	IIB	IIB	IIB	IIB	IIB	
BBV (2)	Open	I	I	I	I	I	I	I	
	Closed	I	I	I	I	I	I	I	
BCV (2)	Open	I	I	IIB	IIB	IIB	IIB	IIB	
	Closed	I	I	IIA	IIA	IIA	IIA	I	
TPA (2)	Stoppage	-	IIA	IIB	IIB	IIB	IIB	IIB	
	Overspeed	-	IIB	IIB	IIB	IIB	IIB	IIB	
	Degradation	-	IIB	IIB	IIB	IIB	IIB	IIB	

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PSOV (2)	Open	I	I	I	I	I	I	I	I
	Closed	I	I	I	I	I	I	I	-
TBV (2)	Open	-	IV	I	I	I	I	I	-
	Closed	-	I	I	I	I	I	I	-
TDBV (2)	Open	I	I	I	I	I	I	I	I
	Closed	-	I	I	I	I	I	I	-
BBV (2)	Open	I	I	I	I	I	I	I	I
	Closed	I	I	I	I	I	I	I	I
BCV (2)	Open	I	IIB	IIB	IIB	IIB	IIB	IIB	I
	Closed	I	IIA	IIA	IIA	IIA	IIA	IIA	I
TPA (1)	Stoppage	-	IV	IV	IV	IV	IV	IV	-
	Overspeed	-	IIB	IV	IV	IV	IV	IV	-
	Degradation	-	IV	IV	IV	IV	IV	IV	-

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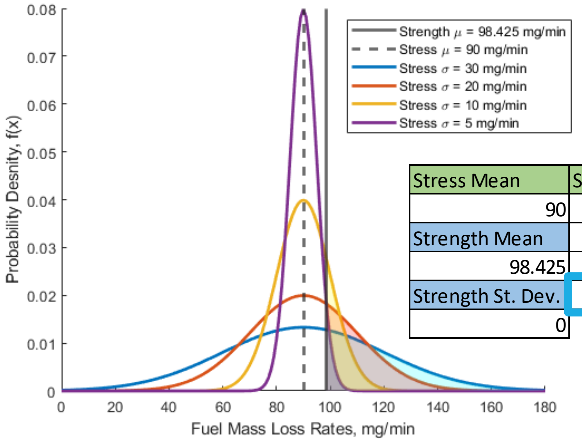
ID #	COMPONENT NAME	FUNCTION	FAILURE MODES	FAILURE MECHANISMS	MISSION PHASE	ENVIRONMENTAL FACTORS
8.1	Fuel Elements - Reactor Core	Heat the propellant	Excessive Reactivity Loss	Hot end diffusion	Thrust Buildup --> Temperature Retreat	Temperature, Hydrogen propellant flow, Creep, Bulging of Central Elements
				Cyclic Degradation Effects		
				External Surface Corrosion		
		Structurally support the reactor	Element Breaks	Combined stresses	"" ""	Temperature Gradient, etc.
			Coating Loss/Matrix Microstructure Changes	Melting/Eutectic	"" ""	Temperature, Nuclear Radiation
			Loss of Physical Integrity / Incremental Weight Loss	Corrosion (All elements)	"" ""	Temperature, Hydrogen flow, Duration



Stress Mean	Stress St. Dev.	Predicted Reliability
90	30	0.610581
Strength Mean	20	0.663214
98.425	10	0.800246
Strength St. Dev.	5	0.954006
0		

Conclusions

- ReDDT helps bridge the disconnect between reliability, design & development, and integration & test artifacts
- This approach was demonstrated on two rocket engine cases (RS-25 Engines and NTP)
- The methodology can be suited generally for any complex system architecture
- Pursuance of ReDDT in a model-based environment (Model Based Systems Engineering) helps transform the document-based SE practices.
    - Enables Perform SE based activities such as Requirements Verification efficiently.

Current/Future Investigations:

- Full implementation of ReDDT in *SysML*
- Design based improvements to RS-25 and NTP architectures, and its impact using ReDDT process flow

Acknowledgements

(Courtesy: NASA)

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THANK YOU!

PRESENTER: SAMANTHA B. RAWLINS
CO-AUTHORS: SHREYAS L. RAGHU | MICHAEL C. HALVORSON | TAMIA NEAL

ADVISOR: DR. DALE THOMAS

EMAIL: SR0134@UAH.EDU

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Complex Systems Integration Laboratory

BACK-UP SLIDES

PRESENTER: SAMANTHA B. RAWLINS
CO-AUTHORS: SHREYAS L. RAGHU | MICHAEL C. HALVORSON | TAMIA NEAL

ADVISOR: DR. DALE THOMAS

EMAIL: SR0134@UAH.EDU

Systems Engineering & Reliability

Currently:

- SE often an underappreciated specialty
- Highly subjective → Cultural shift towards Model-Based Systems Engineering (MBSE) to provide objectivity
- Reliability consistently undervalued as a “number-crunching exercise”

> *“[Reliability] is one of the most vital SE Decision Support activities…‘The single most important factor that differentiates between effective and ineffective implementation of a reliability program is timing of the reliability effort.’”*
>
> – 2015, Wasson, *System Engineering Analysis, Design and Development*
> **Chapter 34 of 34**

Opportunities from RE:

- Improved traceability between SE & RE artifacts offers a means of quantifying SE & supporting program-level decision making

RE Products:		SE Products:
Failure Modes	↔	Requirements Diagrams
Failure Mechanisms		Composition Diagrams
Predicted Reliabilities		Functional Diagrams

If functional requirement is: “generate thrust”
…*then* failure mode is “fails to generate thrust”

…and vice versa

Systems Engineering & Reliability

Currently:

- Also an often underappreciated discipline
- Highly subjective → Cultural shift towards Model-Based Systems Engineering (MBSE)
- Reliability is recognized as a crucial part of program success, but is consistently under-valued as a "number crunching exercise"
  - e.g. classified as a "non-functional" requirement or a "specialty discipline"

> *"[Reliability] is one of the most vital SE Decision Support activities…'The single most important factor that differentiates between effective and ineffective implementation of a reliability program is timing of the reliability effort.'"*
>
> – 2015, Wasson, *System Engineering Analysis, Design and Development*
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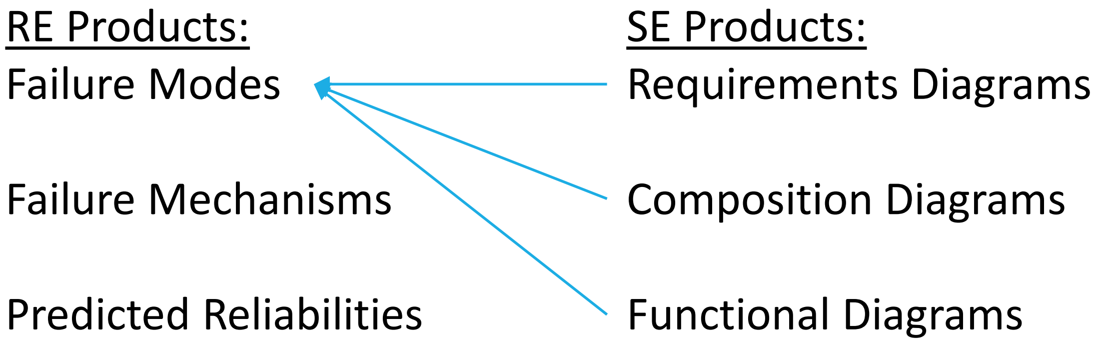
- Improved traceability between SE & RE artifacts offers a means of quantifying SE & supporting program-level decision making



RE Products:

Failure Modes

Failure Mechanisms

Predicted Reliabilities

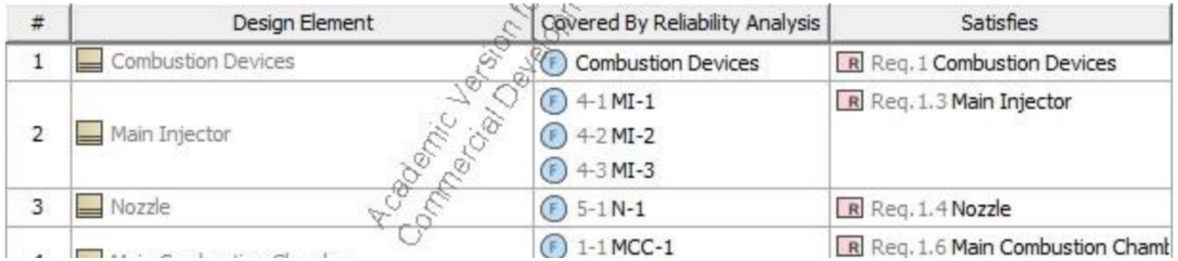
SE Products:

Requirements Diagrams

Composition Diagrams

Functional Diagrams

Initial FMECA can be automatically generated from first SE artifacts (requirements, structure, and behavior)

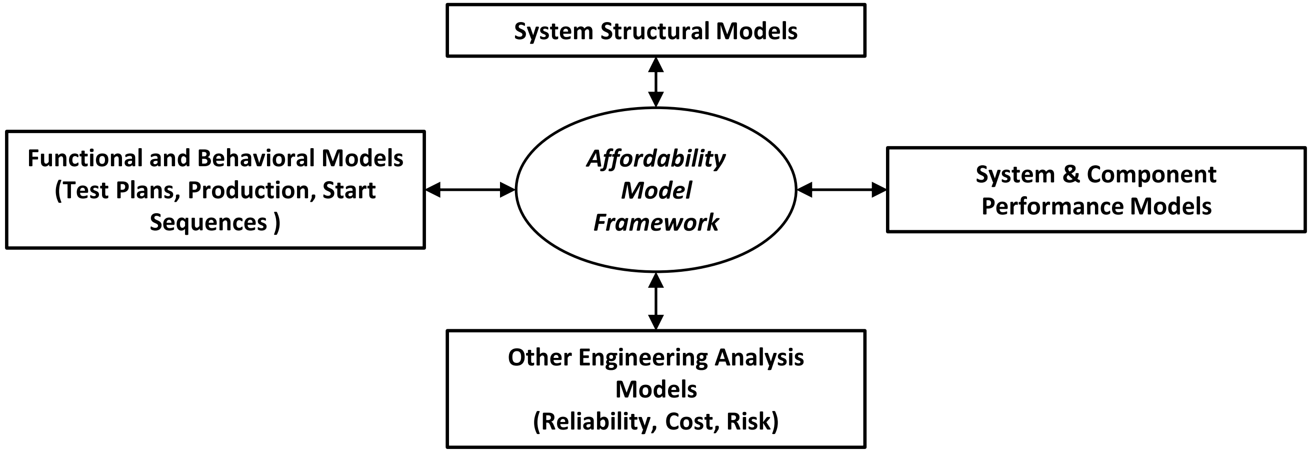


#	Design Element	Covered By Reliability Analysis	Satisfies
1	Combustion Devices	Ⓕ Combustion Devices	R Req. 1 Combustion Devices
2	Main Injector	Ⓕ 4-1 MI-1 Ⓕ 4-2 MI-2 Ⓕ 4-3 MI-3	R Req. 1.3 Main Injector
3	Nozzle	Ⓕ 5-1 N-1	R Req. 1.4 Nozzle
		Ⓕ 1-1 MCC-1	R Req. 1.6 Main Combustion Chaml

Case Study 2: RS-25 (SLS Core Stage Engines)

- High Performance, Reliability, and Versatility
- 16 engines to be upgraded and reused for immediate missions (Artemis I-IV)
- Highly Expensive, Requires Rigorous Test-Fail-Fix (TFF) Cycles [3]
- Future variants of the engine will inevitably involve design changes [3-8]
    - Engine needs to be recertified (provides an opportunity to pursue ReDDT to drive down number of tests)

Systems Engineering



Aspects of Affordability Modeling Framework in Development in *SysML (Systems Modeling Language) [3-8]*

Design Engineering

Structural Failures Dominate the TFF cycle. [9]

- Insufficient Safety Factors

Test

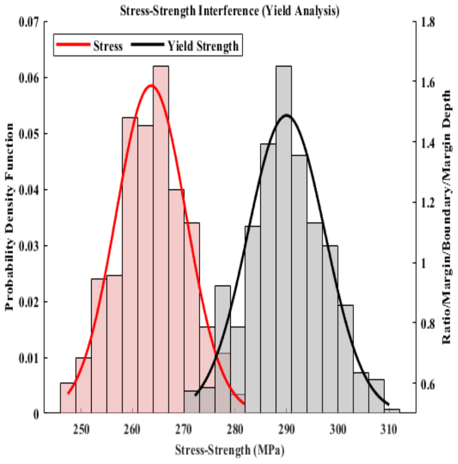
How to inform a test plan if design changes are made? (For instance: Additive Manufacturing (AM) utilization)

Case Study 2: RS-25 (SLS Core Stage)

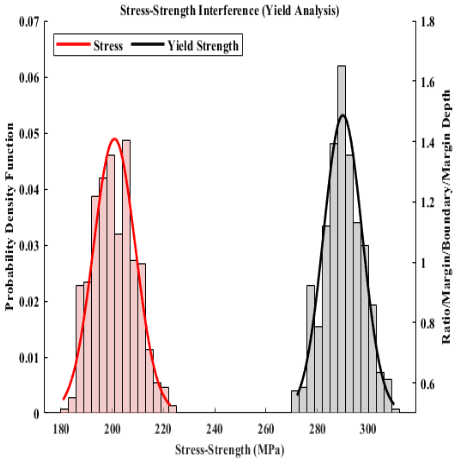
Design Engineering

Test

Overlaps (FoS Based)



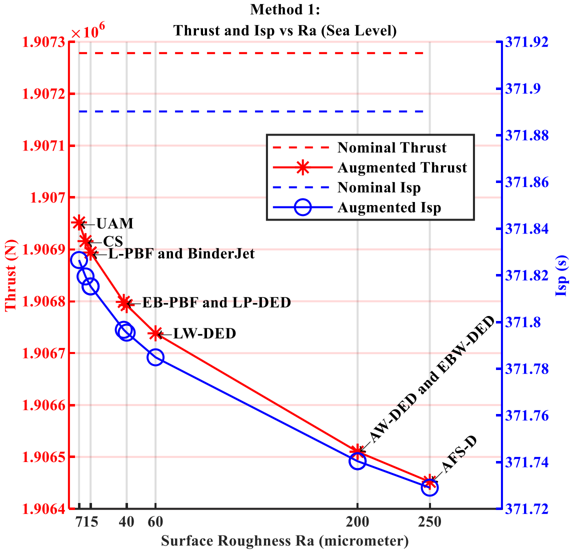
No Overlaps (Margin based Design)



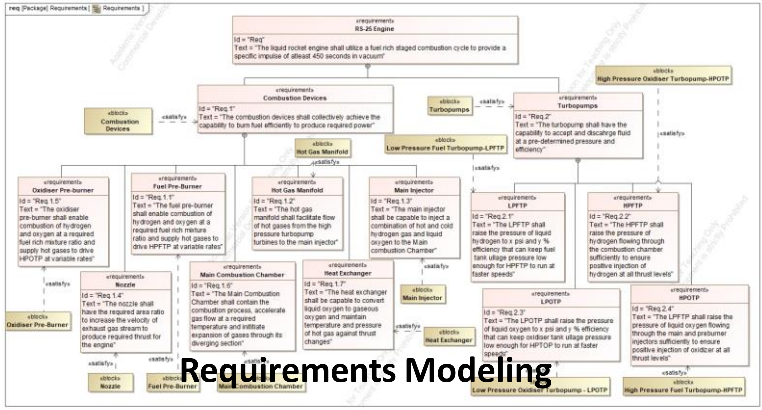
Using Structural Margin in Design to Enable Affordability in RS-25 Upgrades [10]

ReDDT

Surface Roughness in AM can be detrimental to RS-25 performance [7]



- *Surface roughness effects needs to be incorporated into Reliability – Currently being investigated*
- *Helps in informed decision making for test planning/strategy*



«requirement»
RS-25 Engine
Id = "Req"
Text = "The liquid rocket engine shall utilize a fuel rich staged combustion cycle to provide a specific impulse of atleast 450 seconds in vacuum"

«requirement»
Combustion Devices
Id = "Req.1"
Text = "The combustion devices shall collectively achieve the capability to burn fuel efficiently to produce required power"

«requirement»
Oxidiser Pre-burner
Id = "Req.1.5"
Text = "The oxidiser pre-burner shall enable combustion of hydrogen and oxygen at a required fuel rich mixture ratio and supply hot gases to drive HPOTP at variable rates"

«requirement»
Fuel Pre-Burner
Id = "Req.1.1"
Text = "The fuel pre-burner shall enable combustion of hydrogen and oxygen at a required fuel rich mixture ratio and supply hot gases to drive HPFTP at variable rates"

«requirement»
Hot Gas Manifold
Id = "Req.1.2"
Text = "The hot gas manifold shall facilitate flow of hot gases from the high pressure turbopump turbines to the main injector"

«requirement»
Main Injector
Id = "Req.1.3"
Text = "The main injector shall be capable to inject a combination of hot and cold hydrogen gas and liquid oxygen to the Main combustion Chamber"

«requirement»
Nozzle
Id = "Req.1.4"
Text = "The nozzle shall have the required area ratio to increase the velocity of exhaust gas stream to produce required thrust for the engine"

«requirement»
Main Combustion Chamber
Id = "Req.1.6"
Text = "The Main Combustion Chamber shall contain the combustion process, accelerate gas flow at a required temperature and inititate expansion of gases through its diverging section"

«requirement»
Heat Exchanger
Id = "Req.1.7"
Text = "The heat exchanger shall be capable to convert liquid oxygen to gaseous oxygen and maintain temperature and pressure of hot gas against thrust changes"

«requirement»
Turbopumps
Id = "Req.2"
Text = "The turbopump shall have the capability to accept and discahrge fluid at a pre-determined pressure and efficiency"

«requirement»
LPFTP
Id = "Req.2.1"
Text = "The LPFTP shall raise the pressure of liquid hydrogen to x psi and y % efficiency that can keep fuel tank ullage pressure low enough for HPFTP to run at faster speeds"

«requirement»
HPFTP
Id = "Req.2.2"
Text = "The HPFTP shall raise the pressure of hydrogen flowing through the combustion chamber sufficiently to ensure positive injection of hydrogen at all thrust levels"

«requirement»
LPOTP
Id = "Req.2.3"
Text = "The LPOTP shall raise the pressure of liquid oxygen to x psi and y % efficiency that can keep oxidiser tank ullage pressure low enough for HPTOP to run at faster speeds"

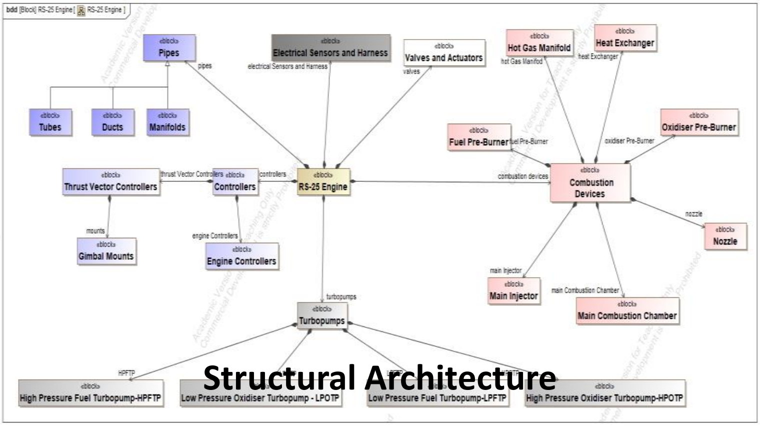
«requirement»
HPOTP
Id = "Req.2.4"
Text = "The LPFTP shall raise the pressure of liquid oxygen flowing through the main and preburner injectors sufficiently to ensure positive injection of oxidizer at all thrust levels"

Requirements Modeling

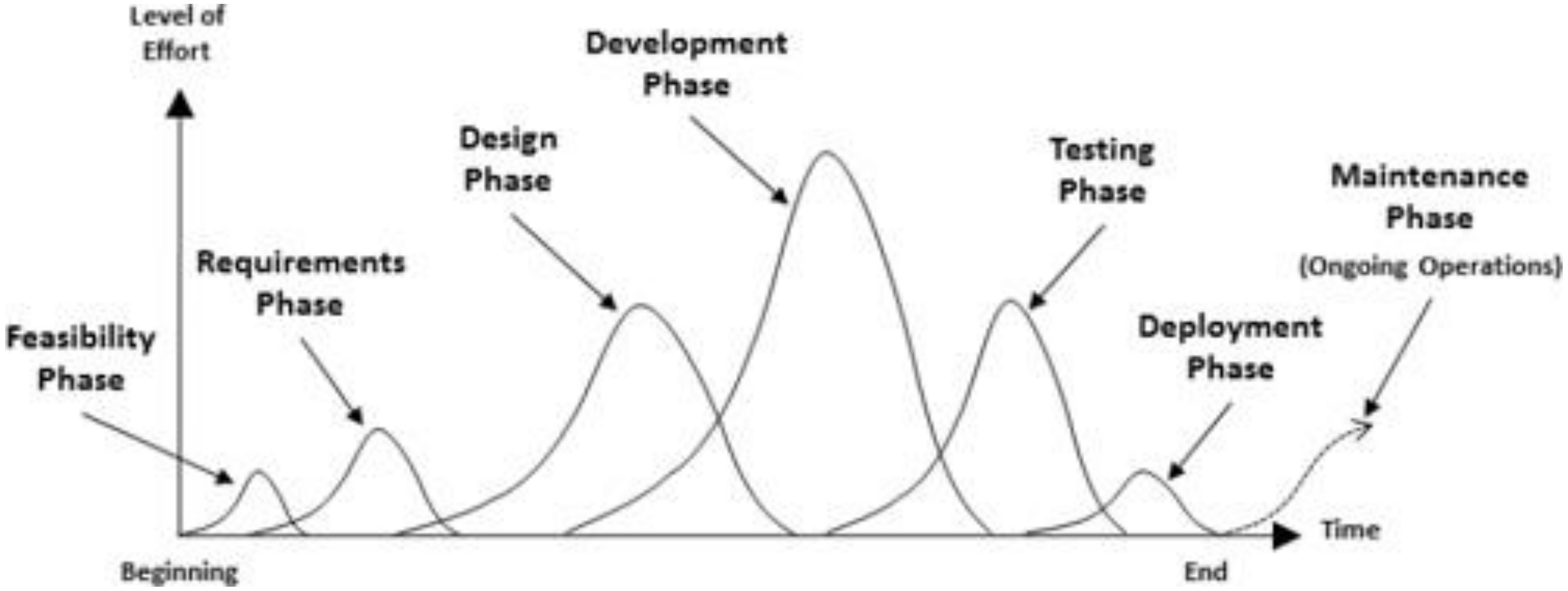
Affordability Modelling Framework for RS-25 Engine in SysML

[3-8]

Systems Engineering



Structural Architecture


Level of Effort
Development Phase
Design Phase
Testing Phase
Maintenance Phase
(Ongoing Operations)
Requirements Phase
Feasibility Phase
Deployment Phase
Time
Beginning
End

Risk, Safety, Reliability: *The Fluffy Analogy*

Risk

Fluffy is caught in the tree *and there's a* ***chance Fluffy could fall*** *and* ***get hurt.***

Safety

Prevent Fluffy from getting hurt.

Reliability

Prevent the branch from breaking.

Risk, Safety, Reliability: Premise

Risk

Fluffy is caught in the tree *and there's a* ***chance Fluffy could fall*** *and* ***get hurt.***

Defined by the triplets (Scenario, Likelihood, Consequence)

Safety

Prevent Fluffy from getting hurt.

Freedom from accident and loss

Reliability

Prevent the branch from breaking.

Probability of performing the intended function (no failures), given a period of time, and conditions

Some NTP Reliability Perspectives

The reactor ***is not*** the least reliable subsystem[1,2]

The engine ***will require*** a secondary turbopump[2-6]

“Test-Fail-Fix” ***will not work*** for space nuclear systems[7-8]

[1]

NERVA Engine Component	Predicted Reliability
Turbopump Assembly	55.6%
Instrumentation & Control	68.5%
Cooldown	88.1%
Fuel & Central Support Elements	97.0%

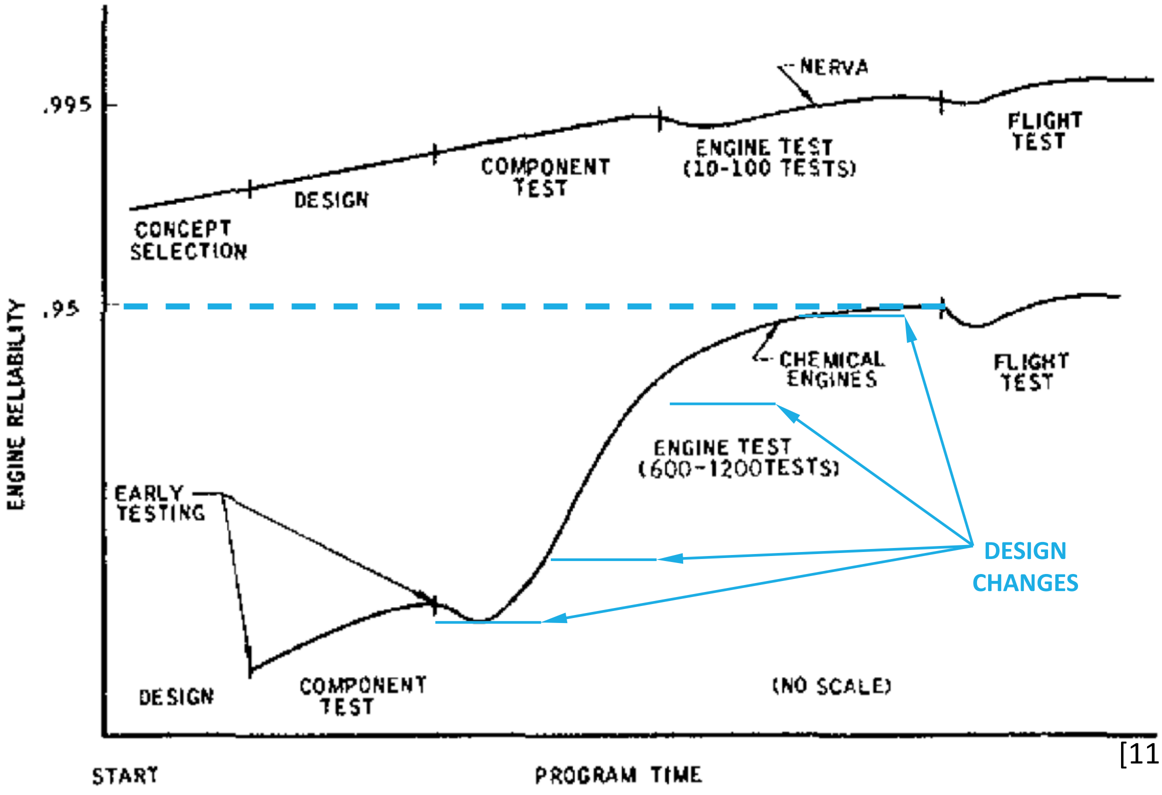
NERVA Prioritized Reliability – It worked.

> *“We realized early in the nuclear propulsion program that the basic build/break mode was neither practical nor desirable.”*
>
> – W. W. Madsen, Nuclear Propulsion Systems Engineering, 1991

NERVA created a new methodology rooted in reliability

- Start with highly reliable concept and improve from there
- Willing to lower engine performance to meet reliability requirements

Estimated only **8 additional full-scale tests** (30 total) to reach flight readiness with 99.5% reliability[10]



[11]

FIGURE 1 - RELIABILITY GROWTH COMPARISON ACTUAL CHEMICALS AND REQUIRED NERVA

Nuclear Thermal Propulsion (NTP) Programs Seek to Minimize Full-Scale Ground Testing

Testing costs more

Lower tolerance for failure

How can we decrease the need for full-scale ground testing?

“Test-Fail-Fix” will not work for space nuclear systems

No rocket engine has been flown without extensive ground testing

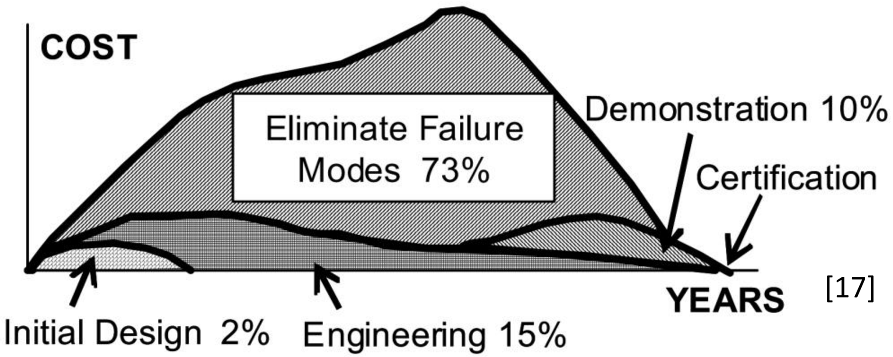
- SSME required 37 attempts and 13 turbopump replacements to achieve 50% power level[12, 13]
- Test-Fail-Fix is a key driver of program cost[14-19]

Largest contributor to Test-Fail-Fix is redesign/eliminating failure modes[17]

- <u>Reason 1:</u> Reliability not considered until testing, then most testing is about improving reliability[11, 20-22]
- <u>Reason 2:</u> Physics-based modeling mostly neglects reliability[22,23]
- <u>Reason 3:</u> Safety margins are known to be an inaccurate substitute for reliability[8,17,24-27]

Space nuclear systems do not have the luxury of undergoing the extensive Test-Fail-Fix process

- Consequences of failure too severe – including loss of test stand



[17]

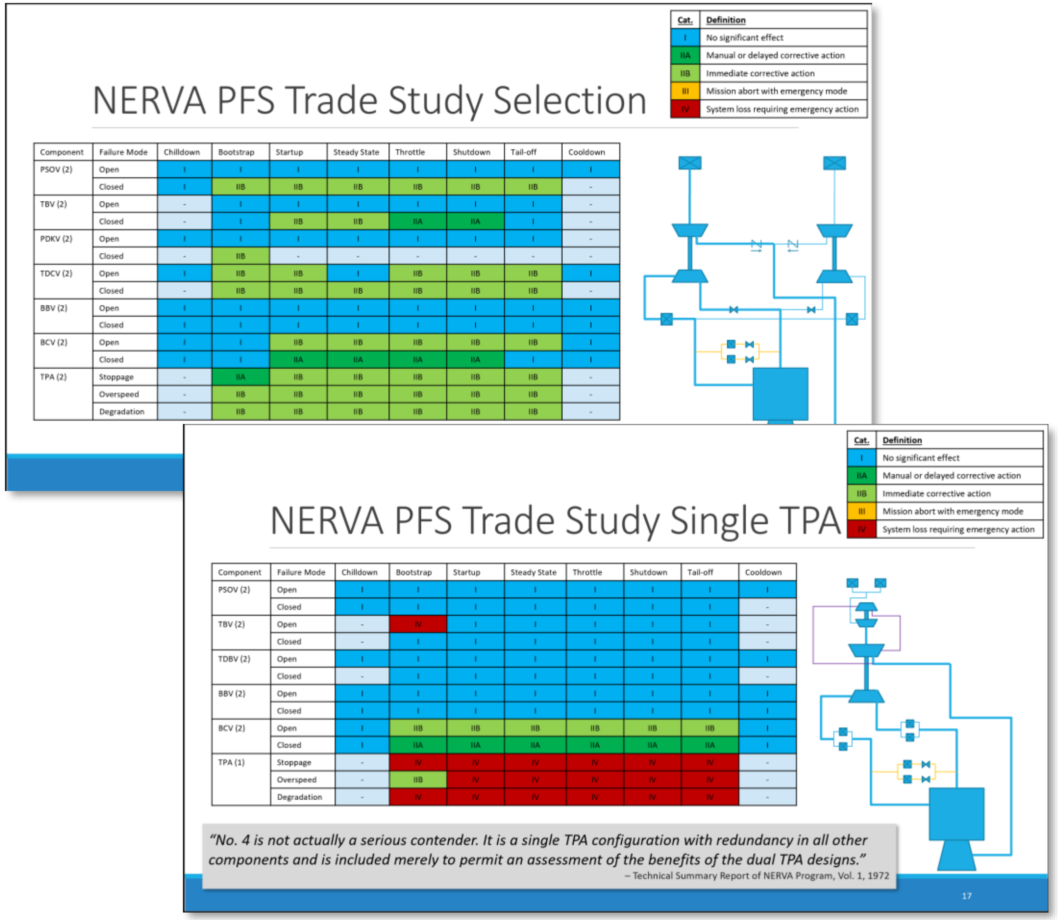
Adjusting the Means

$J = \frac{\bar{S} - \bar{s}}{\sqrt{D_S^2 + D_s^2}}$	**Increase Mean Strength, $\bar{S}$**	**Decrease Mean Stress, $\bar{s}$**	**Decrease Strength Var., D_S^2**	**Decrease Stress Var., D_s^2**
Redesign	X	X	X	X
Testing			X	X
Quality/ Manufacturing	X		X	X
De-rate/Modify Requirements	X	X		

Redesign:
- Fault Prevention & Tolerance
- Select higher TRL components
- Physics of Failure Modeling

De-rate/Modify Requirements:
- Select over-sized components
- Lower performance requirements (Isp, duration, etc.)

Quality/Manufacturing:
- Material selection
- Manufacturing technique (AM, casting, machining, etc.)



NERVA PFS Trade Study Selection

Cat.	Definition
I	No significant effect
IIA	Manual or delayed corrective action
IIB	Immediate corrective action
III	Mission abort with emergency mode
IV	System loss requiring emergency action

Component	Failure Mode	Chilldown	Bootstrap	Startup	Steady State	Throttle	Shutdown	Tail-off	Cooldown
PSOV (2)	Open	I	I	I	I	I	I	I	I
	Closed	I	IIB	IIB	IIB	IIB	IIB	IIB	-
TBV (2)	Open	-	I	I	I	I	I	I	-
	Closed	-	I	IIB	IIB	IIA	IIA	I	-
PDKV (2)	Open	I	I	I	I	I	I	I	-
	Closed	-	IIB	-	-	-	-	-	-
TDCV (2)	Open	I	IIB	IIB	I	IIB	IIB	IIB	I
	Closed	-	IIB	IIB	IIB	IIB	IIB	IIB	-
BBV (2)	Open	I	I	I	I	I	I	I	I
	Closed	I	I	I	I	I	I	I	I
BCV (2)	Open	I	I	IIB	IIB	IIB	IIB	IIB	I
	Closed	I	I	IIA	IIA	IIA	IIA	I	I
TPA (2)	Stoppage	-	IIA	IIB	IIB	IIB	IIB	IIB	-
	Overspeed	-	IIB	IIB	IIB	IIB	IIB	IIB	-
	Degradation	-	IIB	IIB	IIB	IIB	IIB	IIB	-

NERVA PFS Trade Study Single TPA

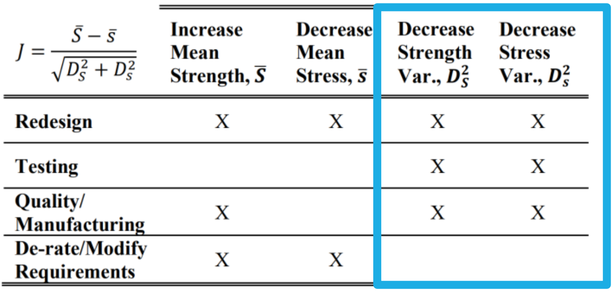
Cat.	Definition
I	No significant effect
IIA	Manual or delayed corrective action
IIB	Immediate corrective action
III	Mission abort with emergency mode
IV	System loss requiring emergency action

Component	Failure Mode	Chilldown	Bootstrap	Startup	Steady State	Throttle	Shutdown	Tail-off	Cooldown
PSOV (2)	Open	I	I	I	I	I	I	I	I
	Closed	I	I	I	I	I	I	I	-
TBV (2)	Open	-	IV	I	I	I	I	I	-
	Closed	-	I	I	I	I	I	I	-
TDBV (2)	Open	I	I	I	I	I	I	I	I
	Closed	-	I	I	I	I	I	I	-
BBV (2)	Open	I	I	I	I	I	I	I	I
	Closed	I	I	I	I	I	I	I	I
BCV (2)	Open	I	IIB	IIB	IIB	IIB	IIB	IIB	I
	Closed	I	IIA	IIA	IIA	IIA	IIA	IIA	I
TPA (1)	Stoppage	-	IV	IV	IV	IV	IV	IV	-
	Overspeed	-	IIB	IV	IV	IV	IV	IV	-
	Degradation	-	IV	IV	IV	IV	IV	IV	-

> *"No. 4 is not actually a serious contender. It is a single TPA configuration with redundancy in all other components and is included merely to permit an assessment of the benefits of the dual TPA designs."*
> – Technical Summary Report of NERVA Program, Vol. 1, 1972

17

Decreasing the Variances



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Redesign	X	X	X	X
Testing			X	X
Quality/ Manufacturing	X		X	X
De-rate/Modify Requirements	X	X		

Redesign:

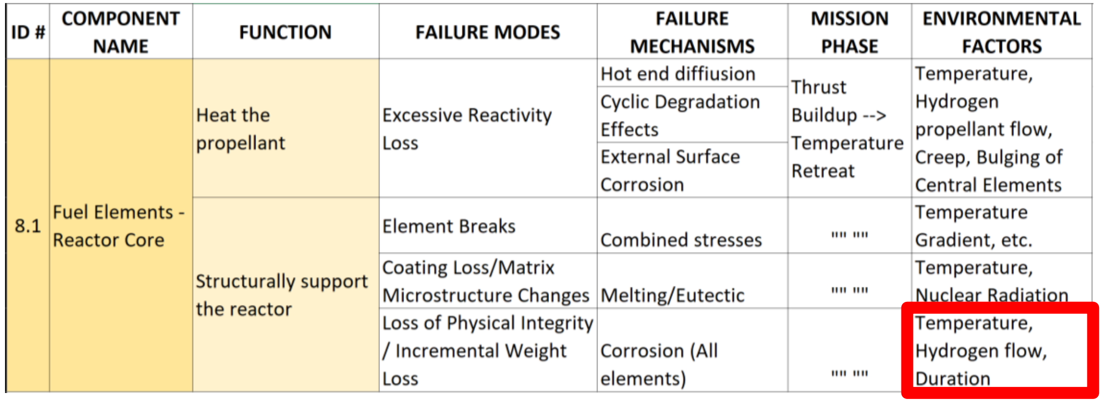
- Fault Prevention & Tolerance
- Select higher TRL/flight proven components

Testing:

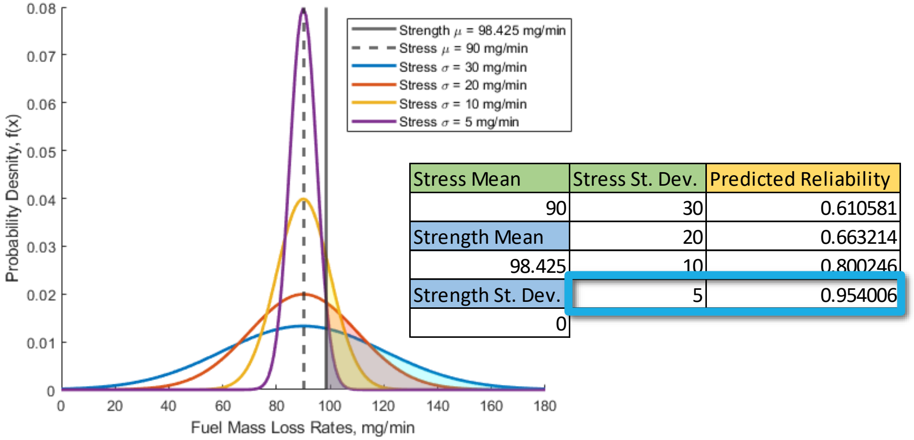
- Accelerated Life Testing
- Component testing to support models
- Design test plan around uncertainty reduction

Quality/Manufacturing:

- Tolerances
- Quality Assurance



ID #	COMPONENT NAME	FUNCTION	FAILURE MODES	FAILURE MECHANISMS	MISSION PHASE	ENVIRONMENTAL FACTORS
8.1	Fuel Elements - Reactor Core	Heat the propellant	Excessive Reactivity Loss	Hot end diffusion Cyclic Degradation Effects External Surface Corrosion	Thrust Buildup --> Temperature Retreat	Temperature, Hydrogen propellant flow, Creep, Bulging of Central Elements
		Structurally support the reactor	Element Breaks	Combined stresses	"" ""	Temperature Gradient, etc.
			Coating Loss/Matrix Microstructure Changes	Melting/Eutectic	"" ""	Temperature, Nuclear Radiation
			Loss of Physical Integrity / Incremental Weight Loss	Corrosion (All elements)	"" ""	Temperature, Hydrogen flow, Duration



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90	30	0.610581
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98.425	10	0.800246
Strength St. Dev.	5	0.954006
0		

Conclusions & Next Steps

Test-Fail-Fix is incompatible with space nuclear systems

- Test/Development costs are too high
- Lower tolerance for failure

An updated reliability-driven design and test approach can already have significant impacts to current NTP programs

- E.g. some form of redundant pump system required

Future work involves quantifying impact of design changes on test plan

Acknowledgements

This work was supported by NASA’s Space Technology Mission Directorate (STMD) through the Space Nuclear Propulsion (SNP) project. The contract grant number is MSFC-UAH 2D0QA.

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Test Planning and Uncertainty Reduction

How can we decrease the need for full-scale ground testing?

Fundamentally, only ***two*** reasons full-scale ground testing is necessary and irreplaceable:

1. Integration testing
2. Model validation

Both forms of uncertainty/variance reduction

Thus, to reduce full-scale ground testing, prioritize uncertainty reduction by other means:

1. Redesign – Fault Prevention & Tolerance
2. Derate/Modify Requirements – Lower mission

Predicted Reliabilities by End of Program

	Predicted Reliability
Nuclear Subsystem (NSS)	**92.1%**
Fuel & Central Support Elements	97.0%
Cluster Hardware	97.7%
Core Periphery	99.95%
Support Plate & Plena	99.996%
Internal Shield	$99.9_{10}8$%*
Reflector Assembly	99.5%
Control Drum Drive Actuators	99.996%
Structural Support Coolant Assembly	97.7%

	Predicted Reliability
Non-Nuclear Subsystem (NNSS)	**32.3%**
Turbopump Assembly	**55.6%**
Pump Discharge Control	99.2%
Turbine Bypass Control	99.90%
Cooldown	88.1%
Nozzle Assembly & Pressure Vessel	99.91%
Thrust Structure & External Shield	99.996%
Gimbal Assembly	96.9%
Instrumentation & Control	**68.5%**

**Subscript represents number of times preceding number is repeated. E.g.* $0.9_{3}0 = 0.9990$

[9]

Shannon's Information Entropy Example

Entropy (H): a measure of the average uncertainty

- Maximum when all outcomes are equally likely
- Entropy is reduced through predictability (e.g. variance reduction)

Example Bjorkman Case Study: Component EMI Effects

- Test Objective: determine if newly added component is free of EMI from other components/factors
- Test Goal: reduce the uncertainty involved in knowing if one or more of the systems causes EMI effects

	A	B	C	D	E	F	Replicates
Test A	2	2	2	2	3		2
Test B	2	2	2	2	3		3
Test C	2	2	2	3	3	3	2

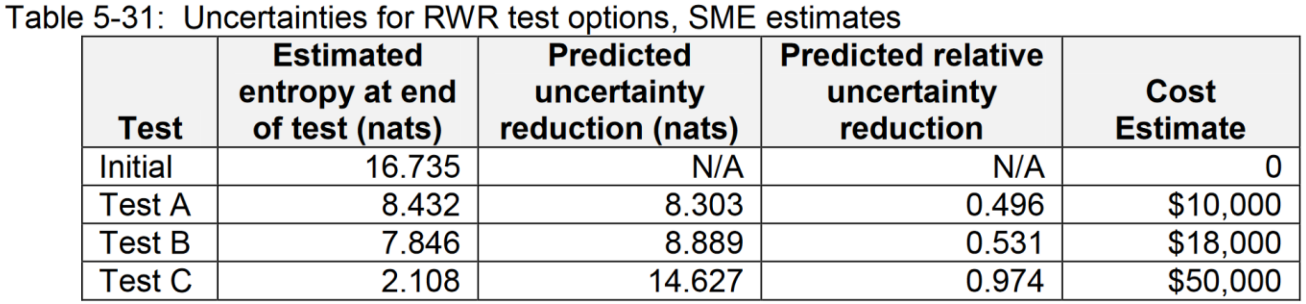


Table 5-31: Uncertainties for RWR test options, SME estimates

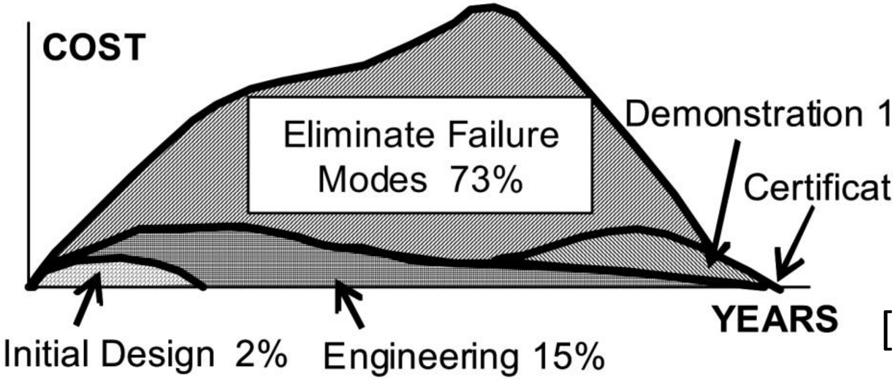
Test	Estimated entropy at end of test (nats)	Predicted uncertainty reduction (nats)	Predicted relative uncertainty reduction	Cost Estimate
Initial	16.735	N/A	N/A	0
Test A	8.432	8.303	0.496	$10,000
Test B	7.846	8.889	0.531	$18,000
Test C	2.108	14.627	0.974	$50,000

$$H(x) = -p \cdot \log(p) - (1-p) \cdot \log(1-p)$$

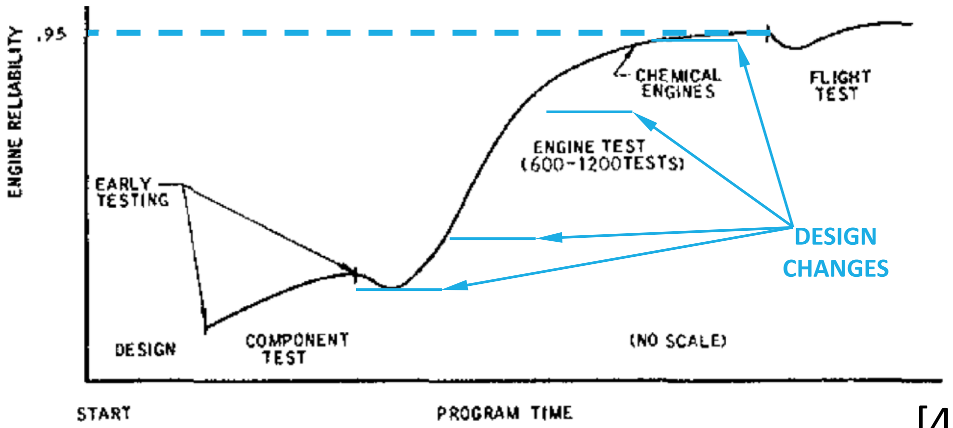
“Confidence” and the Purpose of Testing

> *“**<u>Confidence</u>** is a statistical term associated with the **uncertainties involved in estimating reliability** from a given sample of test data.”*
>
> – NERVA Probabilistic Design Training Course, 1972

> *“It is a long-standing challenge…to quantify the value of testing….Changing [it] to **<u>the quantification and planned mitigation of technical uncertainty</u>** eliminates this issue.”*
>
> – Transforming Ground and Flight Testing through Digital Engineering, 2020



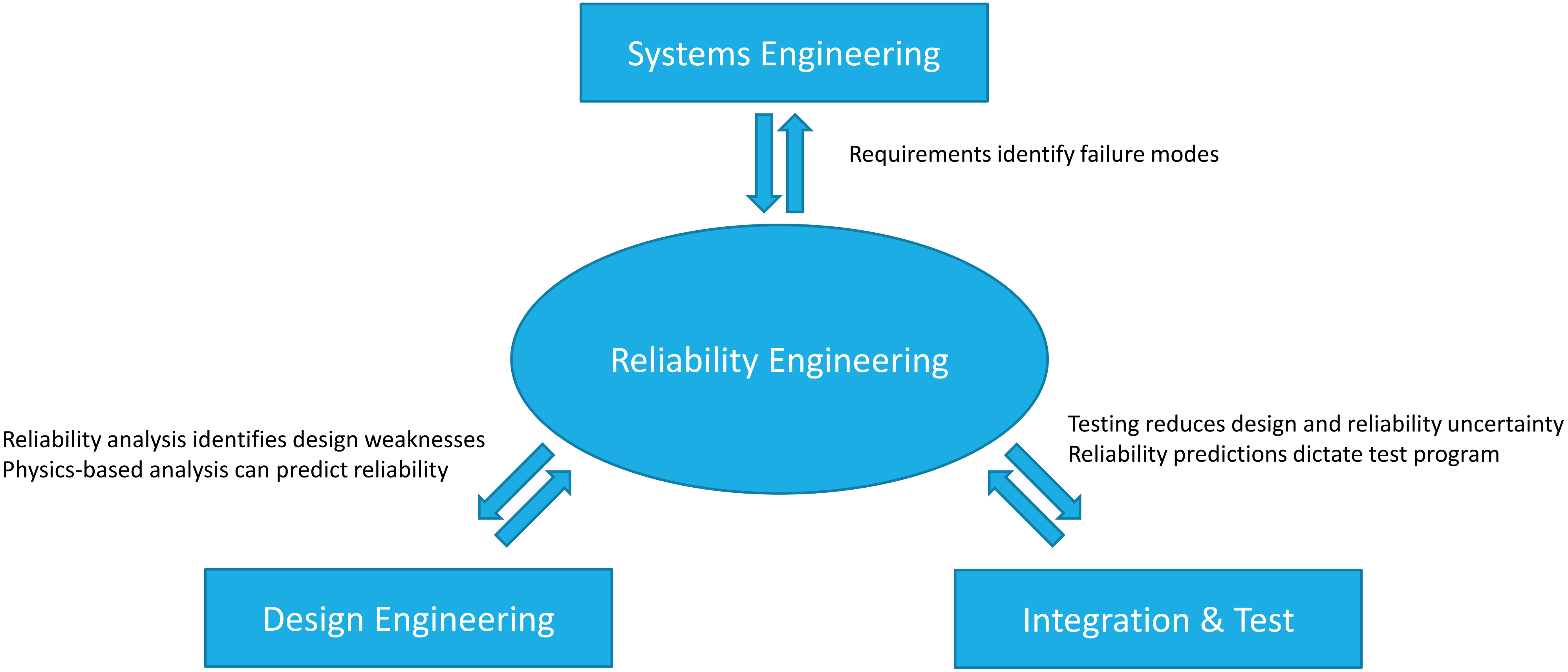
[3]



[4]

> *“The prime **purpose of the test program** is to **<u>investigate these critical modes of failure</u>** as they affect the ability of the design to perform its required functions.”*
>
> - NERVA Reliability Plan, 1970

Summary of the Relationship Between Disciplines



Systems Engineering

Requirements identify failure modes

Reliability Engineering

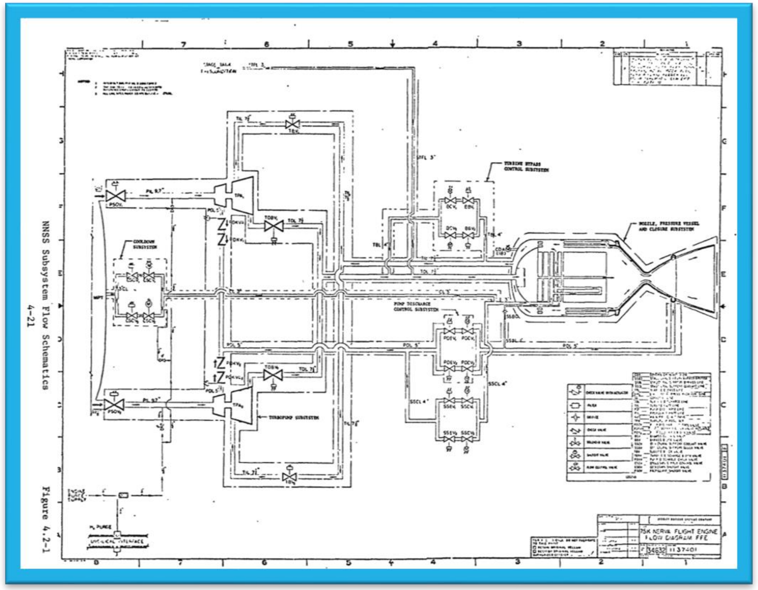
Reliability analysis identifies design weaknesses
Physics-based analysis can predict reliability

Testing reduces design and reliability uncertainty
Reliability predictions dictate test program

Design Engineering

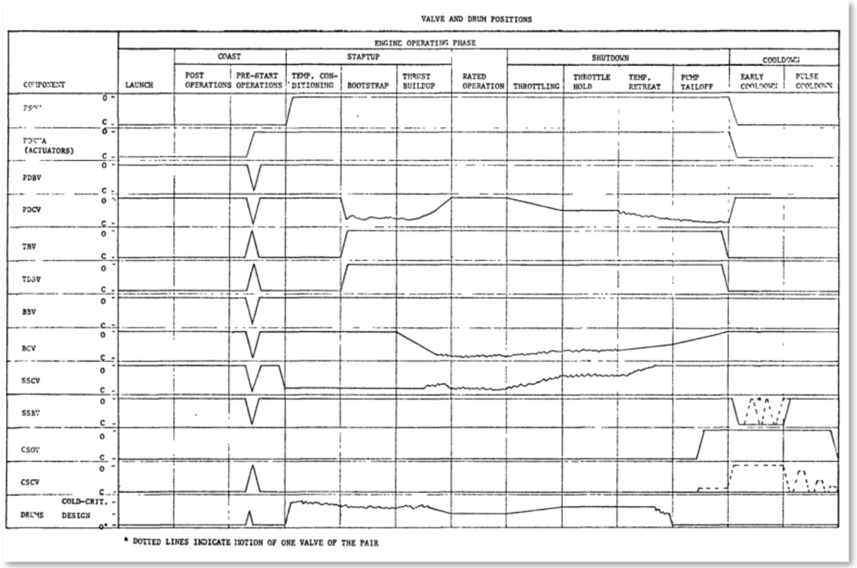
Integration & Test

Steps 1 & 2: Collect Inputs & Compare



System-Level Conceptual Design & Functional Requirements

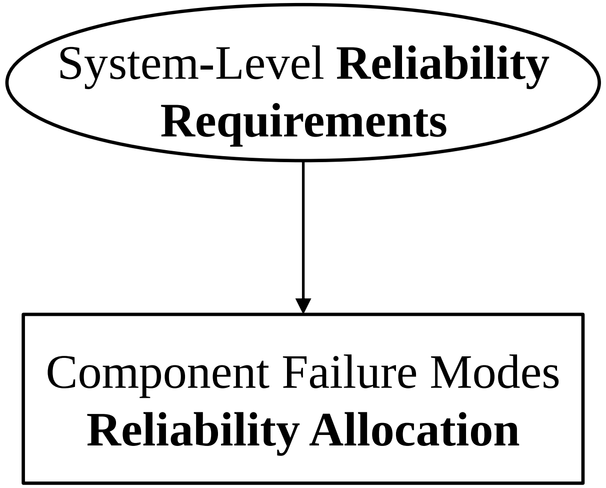
System-Level FMECA



* DOTTED LINES INDICATE MOTION OF ONE VALVE OF THE PAIR

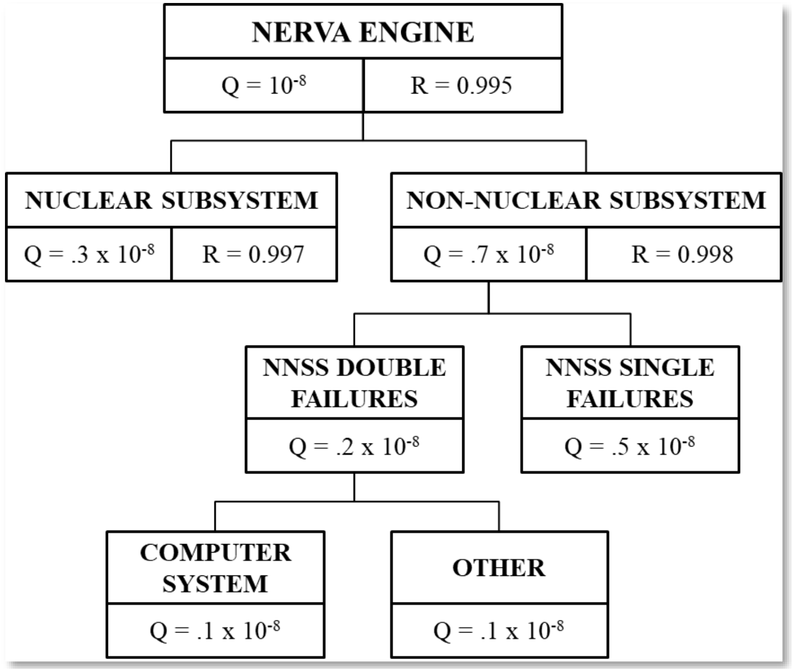
ID #	COMPONENT NAME	QTY	FAILURE MODES	OPERATIONAL PHASES													OPERATING PHASE-FAILURE EVENTS BY FAILURE EFFECT CATEGORY								EFFECT ON SYSTEM OPERATION	MAX. CAT.
				L.	Coast		Startup			Op.	Shutdown				Cool.		I	IIA	IIB	IIC	IIIA	IIIB	IV	MF		
SYS	Non-Nuclear Subsystem	44	155	A	B	C	D	E	F	G	H	I	J	K	L	M	22	531	214	119	236	359	551	165		IV
1	TURBOPUMP SUBSYSTEM	19	58														0	314	4	0	236	140	192	84		IV
1.1	Propellant Shutoff Valve (PSOV)	2	10														0	36	4	0	26	50	36	22		IV
	Valve FM 01		001	--	--	--	IIA	IIA	IIA	IIA	IIA	IIA	IIA	IIIB	--	--	0	7	0	0	0	1	0	0	Emergency mode operating capability only.	IIIB
	Effect 1			--	--	--									--	--									Not applicable. Valve is closed	
	Effect 2						IIA	IIA	IIA	IIA	IIA	IIA	IIA												Loss of the capability of the valve to close degrades s	
	Effect 3													IIIB											Failure of a PSOV to close on demand results in exces	

Steps 1 & 2: Collect Inputs & Compare



System-Level **Reliability Requirements**

Component Failure Modes **Reliability Allocation**



NERVA ENGINE
$Q = 10^{-8}$ | $R = 0.995$

NUCLEAR SUBSYSTEM
$Q = .3 \times 10^{-8}$ | $R = 0.997$

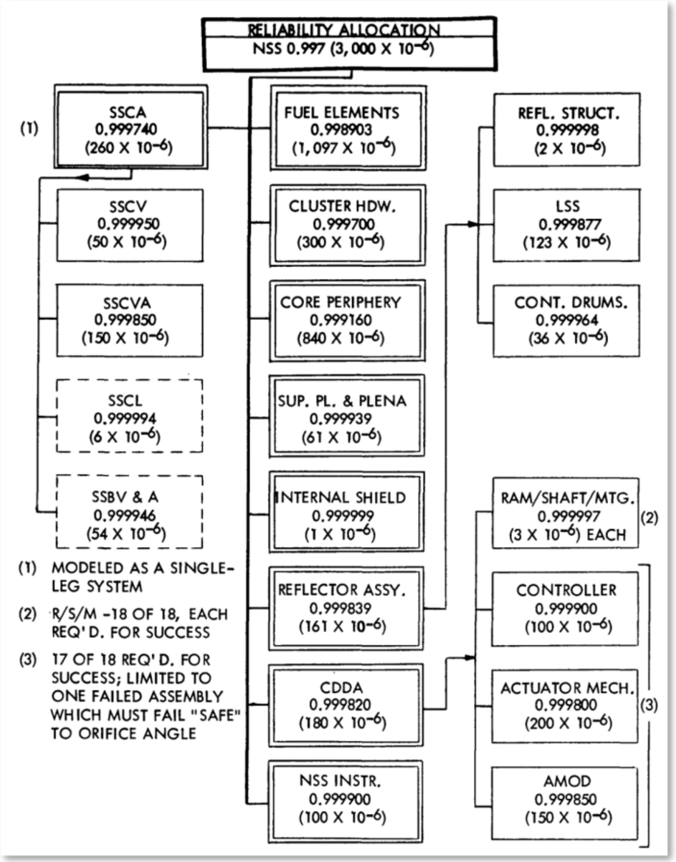
NON-NUCLEAR SUBSYSTEM
$Q = .7 \times 10^{-8}$ | $R = 0.998$

NNSS DOUBLE FAILURES
$Q = .2 \times 10^{-8}$

NNSS SINGLE FAILURES
$Q = .5 \times 10^{-8}$

COMPUTER SYSTEM
$Q = .1 \times 10^{-8}$

OTHER
$Q = .1 \times 10^{-8}$

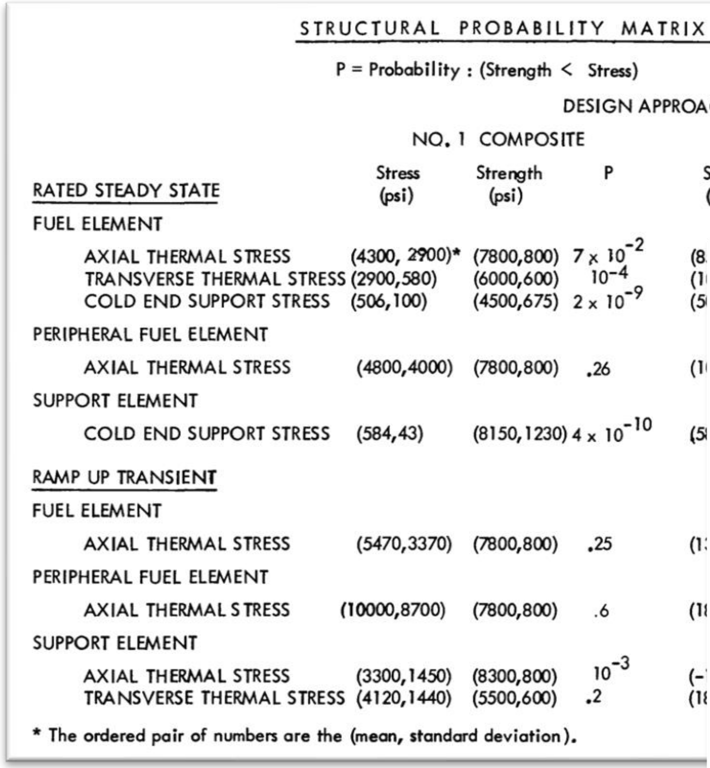


(1) MODELED AS A SINGLE-LEG SYSTEM

(2) R/S/M -18 OF 18, EACH REQ'D. FOR SUCCESS

(3) 17 OF 18 REQ'D. FOR SUCCESS; LIMITED TO ONE FAILED ASSEMBLY WHICH MUST FAIL "SAFE" TO ORIFICE ANGLE

Steps 1 & 2: Collect Inputs & Compare

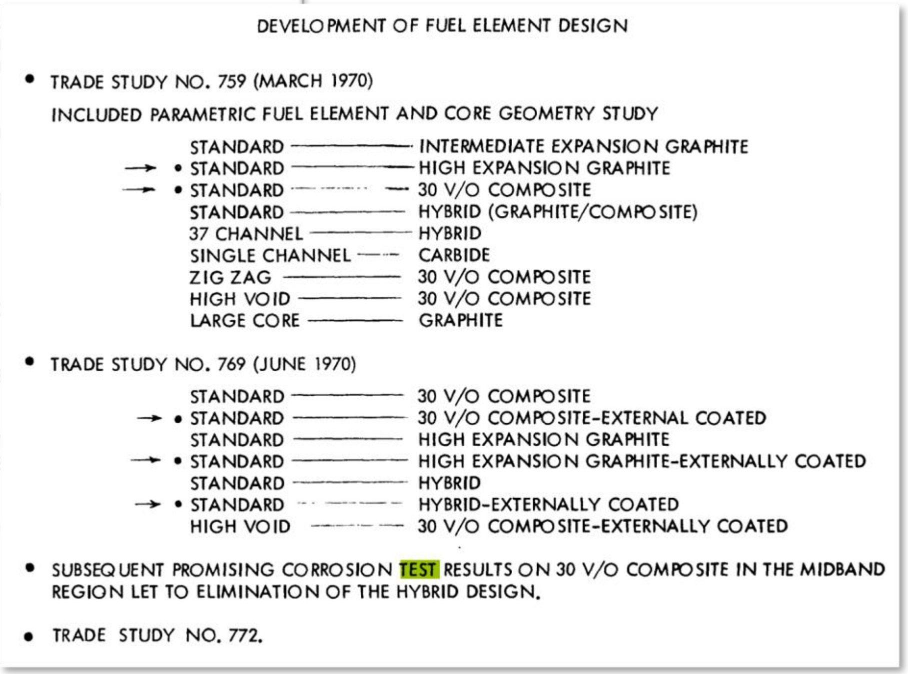


STRUCTURAL PROBABILITY MATRIX

P = Probability : (Strength < Stress)

	DESIGN APPROACHES					
	NO. 1 COMPOSITE			NO. 2 GRAPHITE		
RATED STEADY STATE	Stress (psi)	Strength (psi)	P	Stress (psi)	Strength (psi)	P
FUEL ELEMENT						
AXIAL THERMAL STRESS	(4300, 2900)*	(7800,800)	7×10^{-2}	(8		
TRANSVERSE THERMAL STRESS	(2900,580)	(6000,600)	10^{-4}	(1		
COLD END SUPPORT STRESS	(506,100)	(4500,675)	2×10^{-9}	(5		
PERIPHERAL FUEL ELEMENT						
AXIAL THERMAL STRESS	(4800,4000)	(7800,800)	.26	(1		
SUPPORT ELEMENT						
COLD END SUPPORT STRESS	(584,43)	(8150,1230)	4×10^{-10}	(5		
RAMP UP TRANSIENT						
FUEL ELEMENT						
AXIAL THERMAL STRESS	(5470,3370)	(7800,800)	.25	(1		
PERIPHERAL FUEL ELEMENT						
AXIAL THERMAL STRESS	(10000,8700)	(7800,800)	.6	(1		
SUPPORT ELEMENT						
AXIAL THERMAL STRESS	(3300,1450)	(8300,800)	10^{-3}	(-		
TRANSVERSE THERMAL STRESS	(4120,1440)	(5500,600)	.2	(1		

* The ordered pair of numbers are the (mean, standard deviation).



DEVELOPMENT OF FUEL ELEMENT DESIGN

- TRADE STUDY NO. 759 (MARCH 1970)

  INCLUDED PARAMETRIC FUEL ELEMENT AND CORE GEOMETRY STUDY

  STANDARD —— INTERMEDIATE EXPANSION GRAPHITE
  → • STANDARD —— HIGH EXPANSION GRAPHITE
  → • STANDARD —— 30 V/O COMPOSITE
  STANDARD —— HYBRID (GRAPHITE/COMPOSITE)
  37 CHANNEL —— HYBRID
  SINGLE CHANNEL —— CARBIDE
  ZIG ZAG —— 30 V/O COMPOSITE
  HIGH VOID —— 30 V/O COMPOSITE
  LARGE CORE —— GRAPHITE

- TRADE STUDY NO. 769 (JUNE 1970)

  STANDARD —— 30 V/O COMPOSITE
  → • STANDARD —— 30 V/O COMPOSITE-EXTERNAL COATED
  STANDARD —— HIGH EXPANSION GRAPHITE
  → • STANDARD —— HIGH EXPANSION GRAPHITE-EXTERNALLY COATED
  STANDARD —— HYBRID
  → • STANDARD —— HYBRID-EXTERNALLY COATED
  HIGH VOID —— 30 V/O COMPOSITE-EXTERNALLY COATED

- SUBSEQUENT PROMISING CORROSION TEST RESULTS ON 30 V/O COMPOSITE IN THE MIDBAND REGION LET TO ELIMINATION OF THE HYBRID DESIGN.

- TRADE STUDY NO. 772.

Component **Failure Mode Analyses**

- Historical Data
- Existing Test Data
- Subject Matter Expert Data
- Physics-Based Models

Component Failure Modes
Reliability Prediction