"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

Reliability-Driven Design of a Nuclear Thermal Rocket Engine

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THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

CSIL Complex Systems Integration Laboratory

Nuclear Engine for Rocket Vehicle Application (NERVA)

NASA/DOE/DOD Project from 1961-1972

- Subproject within the Rover Program (started in 1955)
- Originally proposed for Apollo (third stage of the Saturn V rocket)
- Canceled in 1972 due to loss of mission

22 full-scale ground engine/reactor tests

- No (unintentional) catastrophic failures
- Final test was flight configuration (TRL 6); however, program canceled before reaching flight certification

> *"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

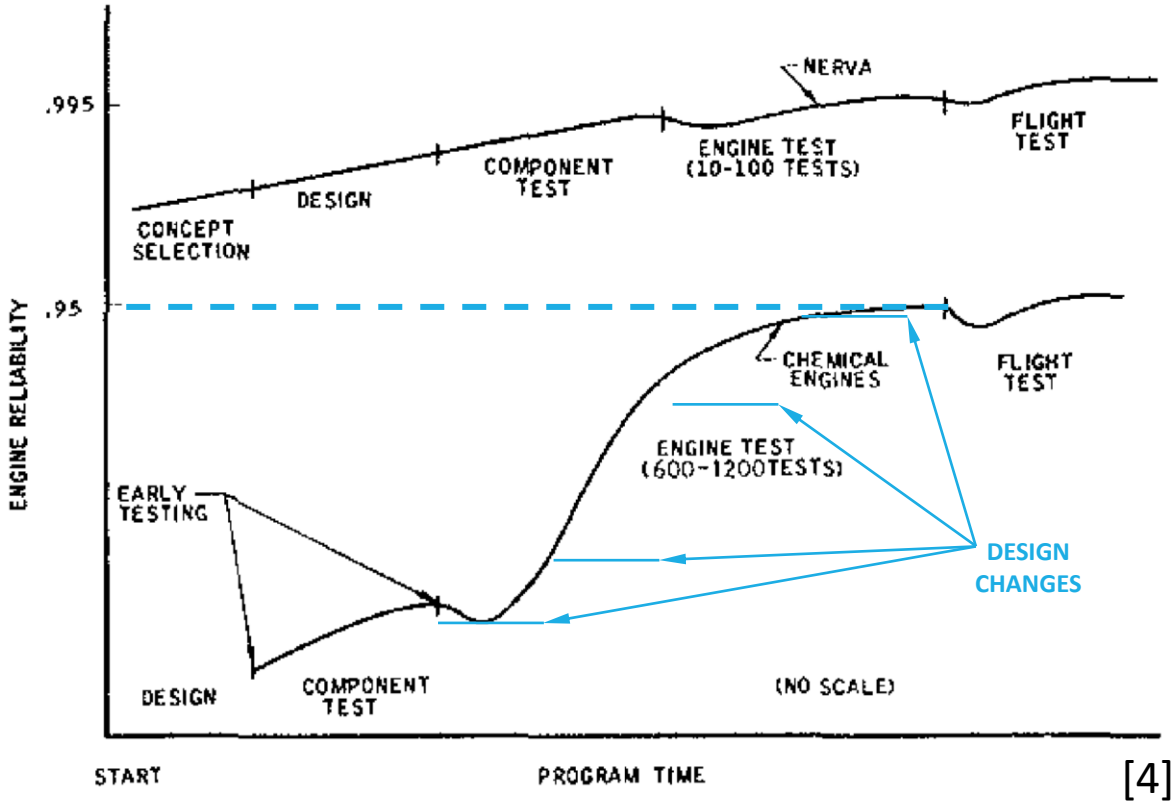
NERVA Engine Reliability Methodology

"Test-Fail-Fix" does not work with space nuclear systems
- Testing costs more than for a non-nuclear alternative
- Lower programmatic and societal tolerance for failure

NERVA created early version of "Design for Reliability"

> *"The basic theory of probabilistic design technology is many years old; however, the development and application of the technique is new.* ***NERVA was the first program to incorporate this philosophy into the design and development effort as a requirement."***
>
> – NERVA Probabilistic Design Training Course, June 1972

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



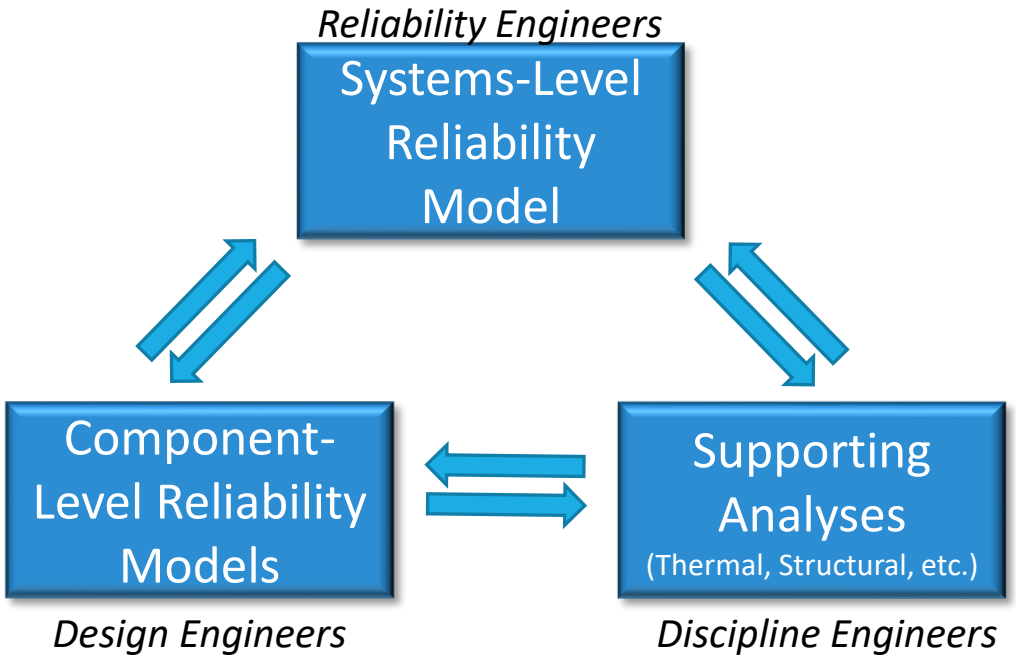
[4]

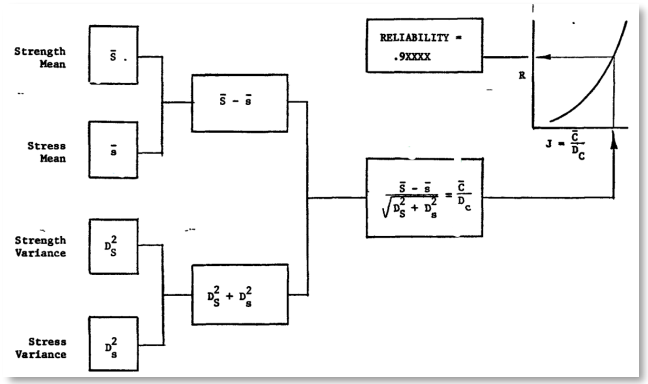
FIGURE 1 - RELIABILITY GROWTH COMPARISON ACTUAL CHEMICALS AND REQUIRED NERVA

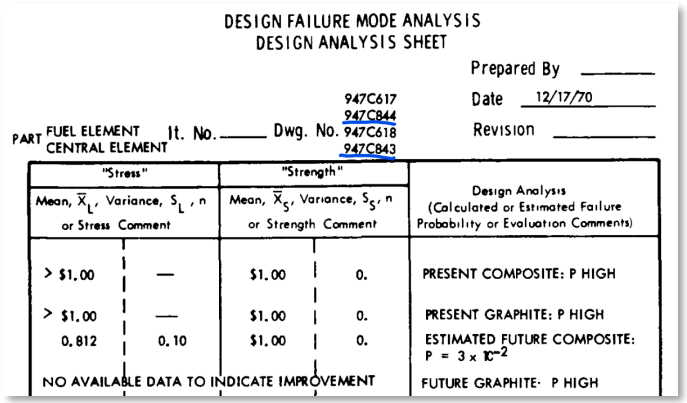
NERVA Reliability Methodology Overview

"A separate group working alone to achieve reliability will not attain the high reliability requirements of the NERVA program. ***All management, design, manufacturing, and test personnel must be responsibly involved to see that the desired reliability is achieved."***

- NERVA Reliability Plan, 1970






DESIGN FAILURE MODE ANALYSIS
DESIGN ANALYSIS SHEET

Prepared By
Date 12/17/70
Revision

PART FUEL ELEMENT / CENTRAL ELEMENT It. No. ____ Dwg. No. 947C617 / 947C844 / 947C618 / 947C843

"Stress" Mean, $\bar{X}_L$, Variance, S_L, n or Stress Comment		"Strength" Mean, $\bar{X}_S$, Variance, S_S, n or Strength Comment		Design Analysis (Calculated or Estimated Failure Probability or Evaluation Comments)
> $1.00	—	$1.00	0.	PRESENT COMPOSITE: P HIGH
> $1.00	—	$1.00	0.	PRESENT GRAPHITE: P HIGH
0.812	0.10	$1.00	0.	ESTIMATED FUTURE COMPOSITE: $P = 3 \times 10^{-2}$
NO AVAILABLE DATA TO INDICATE IMPROVEMENT				FUTURE GRAPHITE· P HIGH

[6,7]

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%**

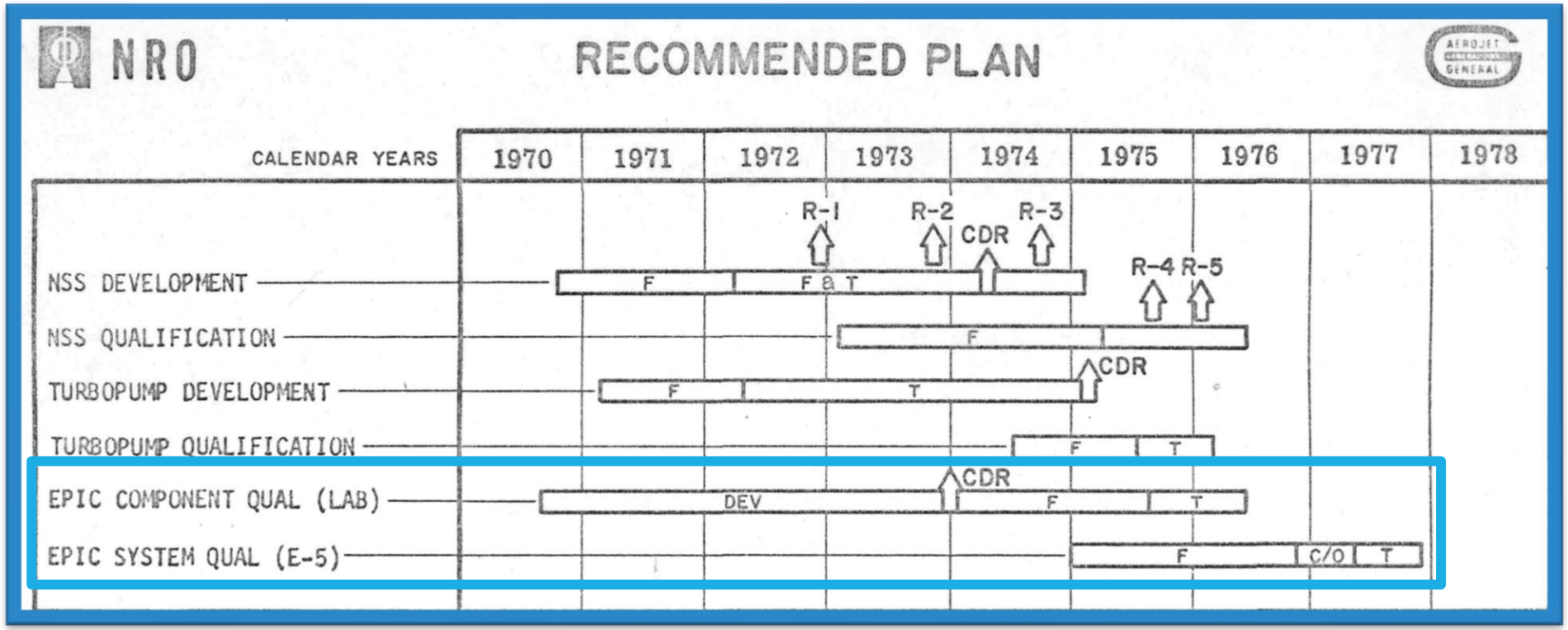
**Subscript represents number of times preceding number is repeated. E.g. $0.9_30 = 0.9990$*

[9]

Resultant Proposed Test Plan

Future plans prioritized additional testing of the nuclear subsystem, turbopumps, and EPIC

EPIC (Electronics, Power, Instrumentation, and Control) required >3 more years of development



[10]

Reliability-Driven Design & Development

1. Design – maximize reliability
   - Propellant Feed System (PFS) Configuration – 2 vs 1 turbopumps
   - Primarily aleatory uncertainty – Fault Prevention & Fault Tolerance

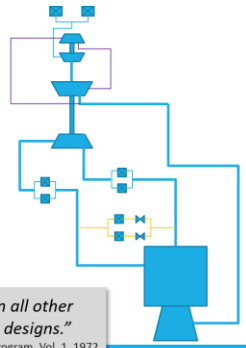
2. Development / Test – minimize technical uncertainty

PFS Reliability Analysis Conclusion:
Some form of redundancy **is** required

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	-

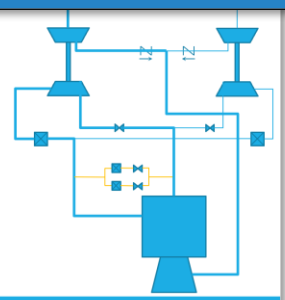


"No. 4 is not actually a serious contender. It is a single TPA configuration with redundancy in all other components and is included merely to permit an assessment of the benefits of the dual TPA designs."
– Technical Summary Report of NERVA Program, Vol. 1, 1972

17

NERVA

Component	Failure Mode	Chilldown							
PSOV (2)	Open	I							
	Closed	I							
TBV (2)	Open	-							
	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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Fault Prevention Techniques

NERVA:
- Design for Reliability
- Test for Uncertainty Reduction
- Custom Components
- Reduced Operational Requirements

Liquid Rocket Engines:
- 60+ years of flight heritage
- Extensive Testing

	NERVA	RL-10
Burn Time	600s	482s
Total # Flights (by 1/2022)	--	261

Terrestrial Nuclear Power Plants:
- Defence-in-Dep
- Conservative De
  - Earthquakes, torn
  - Safety factor of 4
- Operational lim
- Preventative Ma

Fault Tolerance Techniques

3 Types of Responses:
- Full Fault Tolerance
- Graceful Degradation
- Fail Safe (e.g. safe shutdown)

NERVA:
- 100% Component Redundancy
- Preliminary Trend Monitoring System

Liquid Rocket Engines:
- Minimal Hardware Redundancy
- Advanced Health Monitoring Systems

Terrestrial Nuclear Power Plants:
- n+2 redundancy; diverse & separable

Defence-in-Depth	Description	Events / Yr
Level 1: Prevention of Malfunctions	Fault Prevention, Redundancy	Normal Operation
Level 2: Control of Abnormal Operation	Autonomous Fault Detection & Diagnosis for Minor Faults	10^{-2}
Level 3: Accident Management	Rapid Shutdown, Redundant Systems, & Physical Barriers	$10^{-2} – 10^{-6}$
Level 4: Management of Severe Conditions	Minimize Damage, Physical Barriers	$10^{-2} – 10^{-6}$
Level 5: Emergency Response Planning	Off-Site Solutions, Protect Public	$<10^{-6}$ (1 in 1,000,000 yrs)

9

[11]

Reliability-Driven Design & Development

1. Design – maximize reliability
   - Propellant Feed System (PFS) Configuration – 2 vs 1 turbopumps
   - Primarily aleatory uncertainty – Fault Prevention & Fault Tolerance

2. Development / Test – minimize technical uncertainty
   - Reactor Fuel Test Program – New fuel design & unique operating conditions
   - Primarily epistemic uncertainty – Physics models don't exist yet

> *"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

Proposed Fuel Test Program Methodology

Step 1: Identify & characterize the key **system-level** areas of uncertainty

- ***Assumption:*** no entirely new field of physics will be discovered during fuel testing

Step 2: Generate 2-4 test alternatives for each parameter

- Focus on variables measurements (e.g. test to failure) rather than attributes measurements (go/no-go)

Step 3: Quantify the predicted uncertainty reduction for each test alternative

- Bjorkman's "Uncertainty as Test Value" & Shannon's Information Entropy

Step 4: Generate initial "optimal" testing program

[5,13]

Step 1:
Define Uncertainty Parameters

Nuclear fuel generally has two functions:
- Get hot
- Don't break

Primary failure modes then are:
- Can't get hot (reactivity loss)
- Breaks

Both are a function of:
- Temperature
- Hydrogen flow
- Duration

DESIGN FAILURE MODE ANALYSIS
MODE-MECHANISM SHEET

Prepared By _____
Date 12/17/70
Revision _____

Part FUEL ELEMENT CENTRAL ELEMENT It. No. _____ Dwg. No. 947C617 947C844 947C618 947C843

Mode Ident No.	Modes and Mechanisms of Failure		Mission Phase	Environmental Factors
1.	FUEL ELEMENT REACTIVITY LOSS - 60 CYCLES	Hot end diffusion, cyclic degradation effects, external surface corrosion	Thrust Buildup ↓ Temp. Retreat	Temp., GH_2 Flow, Creep Bulging of Central Elements
2.	ELEMENT BREAKS	Combined Stresses	" "	Temperature Gradient, etc.
3.	COATING LOSS/MATRIX MICROSTRUCTURE CHANGES	Melting/Eutectic	" "	Temperature, Nuclear Radiation
4.	INCREMENTAL WEIGHT LOSS* >1.5 GM/INCH	CORROSION (ALL ELEMENTS)	" "	Temperature, GH_2 Flow

[7]

Step 2:
Identify Test Alternatives

Unprioritized List of Environmental Conditions

Temperature

Duration

Hydrogen Flow

Table 5. Comparison of a subset of SMART and existing test facilities and capabilities.

NTP Parameter	Goal	SMART 14-MW TRIGA	SMART ATR-Fuel Driver Core	TREAT	NTREES	MITR	MURR	ATR Reactor Loop	HFIR
Average Power Density (MW/L)	5	0.1	5		>2MW/L (by induction heating only)	< 1	0.303	1	1.7
Thermal Neutron Flux (n-cm^2-s)	1E15	1E14	1E15	~7E12 per MW	No nuclear heating	6E14	6E14	1E15	2.5E15
Fuel Region or Test Article Length	1 m	0.5 m	1 m	1.2 m active core length, 0.61 m for best flux profile	2.5 m test article length	0.61 m	0.61 m	1 m	0.51 m
Room for 3-Unit Cells or a Fuel/Moderator Bundle	7–13 cm	18 cm	13 cm	<6 cm	30 cm	4.572 cm	13.6 cm	16 cm	<6 cm
Peak Test Article Fuel Temperature	3000 K+			2700 K	3800 K achieved to date	2500 K		3000 K	2500 K
Fuel Temperature Ramp Rate in Test Article	20–100 k/sec			100 K/s is in use for current experiments	>100 K/s				
Lifetime	240 minutes							>24 hours	>24 hours
Operation Time	20 min. operation with cooldown. Repeat five times			< 40 Sec			Main function is isotope production so not run for short durations	>24 hours	>24 hours
Hydrogen Pressure through Core	7–11 Mpa			Peak pressure of 1000 psig (~7 Mpa)	Peak pressure of 1000 psig (~7 Mpa)	Static Pressure (has used GH_2 in rabbits)	Static pressure (has not used GH_2)		Has flow capabilities but has not used GH_2
Hydrogen Mass-Flow Rate	~2 g/s per channel			Up to 200 g/s total (in progress for 2023)	Max of 250 g/s (by regulation)				

LEGEND:
Green: Goal achievable
Yellow: Can obtain useful data or modify to achieve goal
Red: Goal not likely

[12]

Steps 3 & 4:
Quantify Uncertainty Reduction & Test Program

Currently identifying “most useful” quantification technique

Duration	Hydrogen Pressure	Temperature
Operation Time (20 min)	Max (7 Mpa)	Min (298K)
		Avg (1200K)
		Max (3000K)
	Min (11 Mpa)	Min (298K)
		Avg (1200K)
		Max (3000K)
Lifetime (240 min)	Max (7 Mpa)	Min (298K)
		Avg (1200K)
		Max (3000K)
	Min (11 Mpa)	Min (298K)
		Avg (1200K)
		Max (3000K)

Bjorkman “Test and Evaluation Resource Allocation Using Uncertainty Reduction”

- Shannon’s Information Entropy for Uncertainty Quantification
- Heavily relies on SME input for initial variance estimates
- Design of Experiments, Full Factorial Design (3 factors, 2x2x3 levels)

Stress-Strain Interference Theory

- Using historical NERVA data for estimates of initial stress variance, strength mean, and strength variance
- For an assumed stress mean, estimate the required variance reduction

Stress Mean	Stress Variance	Predicted Reliability
0.09	0.03	0.610580882
Strength Mean	0.02	0.663213732
0.098425	0.01	0.80024593
Strength variance	0.005	0.954005714
0		

**Both methods assume normal distributions*

Conclusions & Next Steps

The NERVA program was perhaps the first to truly embrace "design for reliability"

- Highly credits their program success to this approach

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

- E.g. redundant pump system required

Future work involves implementation of uncertainty reduction techniques

- Only model as necessary

"It should be noted that no one has ever developed a complete model which rigorously relates all identified parameters to the top reliability requirement. Many reliability programs, however, have been made useless by people who attempted to develop the ultimate reliability model…The cardinal rule for modeling based on NERVA experience is 'KEEP IT SIMPLE'."

- NERVA Probabilistic Design Training Course, 1972

Acknowledgements

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TABLE A-15

NSS FAILURE RATE SUMMARY FOR FAILURE EFFECT

CATEGORIES II I & IV

FAILURE MODE	FAILURE PROBABILITY OF MODE	FAILURE GOVERNING PART/PART FAILURE MODE-MECHANISM/FAILURE PROBABILITY	PART FAILURE PROBABILITY DATA SOURCE
FUEL ELEMENTS			
1. Reactivity loss exceeds one dollar (NF 0001)	.03 ✓	Fuel Element/Bore corrosion/.03	WANL DRM No. 53041
2. Loss of structural integrity due to structural collapse (NF 0004)	10^{-5} ✓	Fuel Element/Severe corrosion/10^{-5}	WANL DRM No. 53041
3. Pieces of fuel element ejected (NF 5203)	10^{-10} ✓	Fuel Element/Cracking/10^{-10}	WANL DRM No. 53041

Failure Mode	Contribution to Single Cycle Failure Probability		Failure Effects Category (Criticality)	Factors To Be Evaluated For Reliability Growth During Detail Design and Assessment Phase
	Failures	% of Total		
Fuel Elements				
1. Corrosion due to hot end coating degradation	See Footnote Below	100%	III-B	Further evaluation of coating/matrix interaction. Electrical and reactor test data correlation. Development of NDT for coating bond quality.
2. Structural failure allowing bore to interstitial flow				
Central Support Element				
1. Structural cracking of CSE allowing interstitial flow to attack insulation tube and/or CHESH insulation.	2×10^{-5}	Negligible	I	Analyses and tests to verify adequacy of these evaluation.

NOTE:

Composite, 60 cycle 10 hour value. Assumes that best 10 hr/60 cycle corrosion test performance so far demonstrated for 4000°R will extrapolate to 4250°R and a structural reliability for fuel element cracking of ~0.996. If this were 0.999, fuel reliability = 0.999910 which would meet goal. A slight increase in reactivity limit >$1.00 has a large effect on the reliability. Uncertainty in cracking and resulting corrosion must be better understood to confidently assess reliability.

Supporting Analyses

DESIGN FAILURE MODE ANALYSIS
MODE-MECHANISM SHEET

Part FUEL ELEMENT CENTRAL ELEMENT It. No. ____ Dwg. No. 947C617 947C844 947C618 947C843 Prepared By ____ Date 12/17/70 Revision ____

Mode Ident No.	Modes and Mechanisms of Failure		Mission Phase	Environmental Factors
	FUEL ELEMENT			
1.	REACTIVITY LOSS - 60 CYCLES	Hot end diffusion, cyclic degradation effects, external surface corrosion	Thrust Buildup ↑ Temp. Retreat	Temp., GH_2 Flow, Creep Bulging of Central Elements
2.	ELEMENT BREAKS	Combined Stresses	" "	Temperature Gradient, etc.
3.	COATING LOSS/MATRIX MICROSTRUCTURE CHANGES	Melting/Eutectic	" "	Temperature, Nuclear Radiation
4.	INCREMENTAL WEIGHT LOSS* >1.5 GM/INCH	CORROSION (ALL ELEMENTS)	" "	Temperature, GH_2 Flow
	CENTRAL ELEMENT			
1.	ELEMENT BREAKS	Combined stresses	" "	Temperature Gradient, etc.

*LOSS OF PHYSICAL INTEGRITY - INCLUDES ELEMENT BREAKAGE, LOSS OF COATING, BRAZE JOINT FAILURE, AND BYPASS OF FLOW CHANNELS, ALL CAUSED BY EXCESSIVE INCREMENTAL WEIGHT LOSS.

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DESIGN FAILURE MODE ANALYSIS
DESIGN ANALYSIS SHEET

Part FUEL ELEMENT CENTRAL ELEMENT It. No. ____ Dwg. No. 947C617 947C844 947C618 947C843 Prepared By ____ Date 12/17/70 Revision ____

"Stress" Mean, $\bar{X}_L$, or Stress	"Stress" Variance, S_L, n Comment	"Strength" Mean, $\bar{X}_S$, or Strength	"Strength" Variance, S_S, n Comment	Design Analysis (Calculated or Estimated Failure Probability or Evaluation Comments)
> $1.00	—	$1.00	0.	PRESENT COMPOSITE: P HIGH
> $1.00	—	$1.00	0.	PRESENT GRAPHITE: P HIGH
0.812	0.10	$1.00	0.	ESTIMATED FUTURE COMPOSITE: $P = 3 \times 10^{-2}$
NO AVAILABLE DATA TO INDICATE IMPROVEMENT				FUTURE GRAPHITE: P HIGH
10,000 psi	8700 psi	7800 psi	800 psi	COMPOSITE: P = 0.6
1,850 psi	1600 psi	3650 psi	500 psi	GRAPHITE: P = 0.15
4,433°R	Function of Location	Function of Loading	45°R	COMPOSITE: $P = 10^{-5}$
4,387°R	Function of Location	4990°R	45°R	GRAPHITE: $P = 10^{-10}$
1.29 gm/in	0.15 gm/in	1.5 gm/in	0.	Future COMPOSITE at 60 cycles: $P = 8 \times 10^{-2}$
0.83 gm/in	0.10 gm/in	1.5 gm/in	0.	Present GRAPHITE after $1.00: $P = 10^{-6}$
4,120 psi	1440 psi	5500 psi	600 psi	COMPOSITE: P = 0.2
1,800 psi	1000 psi	4825 psi	800 psi	GRAPHITE: $P = 1.5 \times 10^{-2}$

W59110-1B

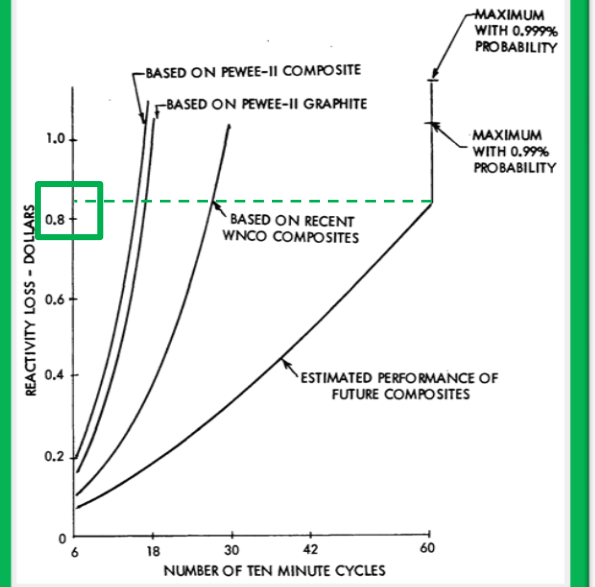
1

THERMAL ANALYSIS

- VALIDITY OF ANALYSIS AND MODEL CHECKS
- STEADY STATE TEMPERATURE EVALUATION (PROBABALISTIC AND NOMINAL)
  - INPUT TO CORROSION ANALYSIS
  - LIFETIME EFFECTS
  - PROBABILITY OF EXCEEDING MATERIAL TEMPERATURE LIMITS

	COMPOSITE	GRAPHITE
R-1	10^{-2}	$\sim 10^{-8}$
NERVA	10^{-5}	10^{-10}

2



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STRUCTURAL PROBABILITY MATRIX

P = Probability : (Strength < Stress)

	Stress (psi)	Strength (psi)	P	Stress (psi)	Strength (psi)	P
RATED STEADY STATE				DESIGN APPROACH NO. 1 COMPOSITE		
FUEL ELEMENT						
AXIAL THERMAL STRESS	(4300, 2900)*	(7800,800)	7×10^{-2}	(850,1		
TRANSVERSE THERMAL STRESS	(2900,580)	(6000,600)	10^{-4}	(1000,		
COLD END SUPPORT STRESS	(506,100)	(4500,675)	2×10^{-9}	(506,		
PERIPHERAL FUEL ELEMENT						
AXIAL THERMAL STRESS	(4800,4000)	(7800,800)	.26	(1000,		
SUPPORT ELEMENT						
COLD END SUPPORT STRESS	(584,43)	(8150,1230)	4×10^{-10}	(583,4		
RAMP UP TRANSIENT						
FUEL ELEMENT						
AXIAL THERMAL STRESS	(5470,3370)	(7800,800)	.25	(1360,1290)	(3650,500)	4.5×10^{-2}
PERIPHERAL FUEL ELEMENT						
AXIAL THERMAL STRESS	(10000,8700)	(7800,800)	.6	(1850,1600)	(3650,500)	.15
SUPPORT ELEMENT						
[illegible]	[illegible]	[illegible]	10^{-3}	[illegible]	[illegible]	10^{-6}
TRANSVERSE THERMAL STRESS	(4120,1440)	(5500,600)	.2	(1800, 1000)	(4825,800)	1.5×10^{-2}

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

Stress-Strength Interference Theory

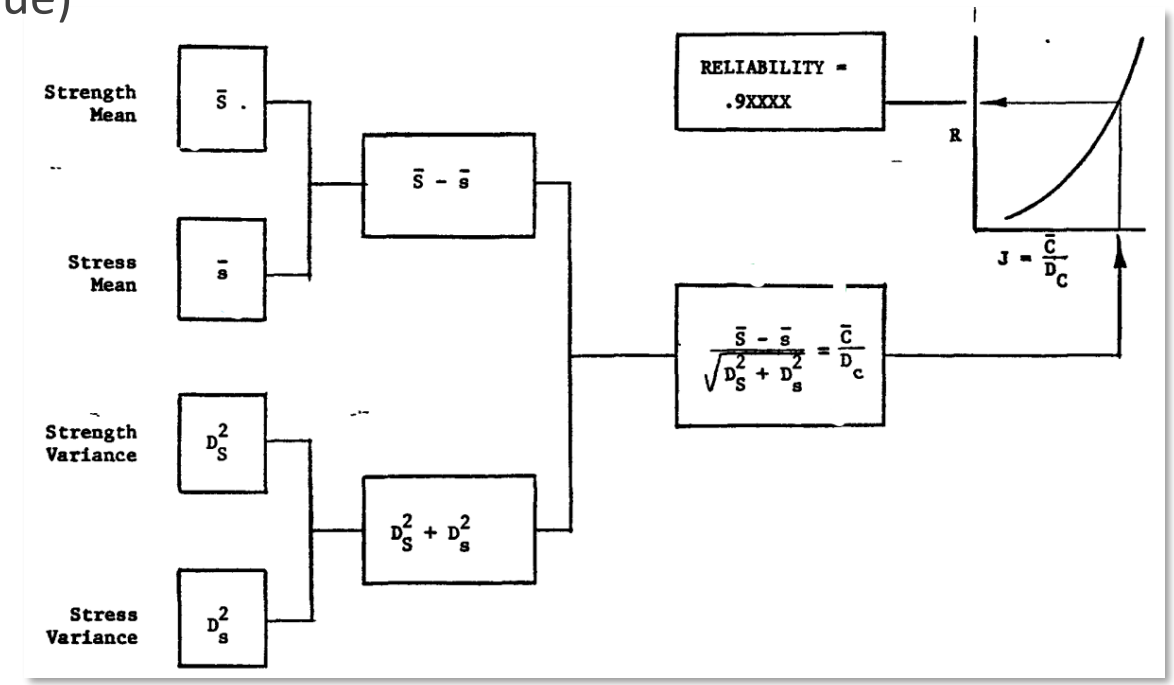
1. Determine the “stress” function
2. Determine the “strength” function
3. Calculate the combination function (C/D_c or z-value)
4. Find the value of reliability (from tables or MC)

DESIGN FAILURE MODE ANALYSIS
DESIGN ANALYSIS SHEET

Prepared By _____
Date 12/17/70
Revision _____

PART FUEL ELEMENT CENTRAL ELEMENT lt. No. _____ Dwg. No. 947C617 947C844 947C618 947C843

"Stress"		"Strength"		Design Analysis (Calculated or Estimated Failure Probability or Evaluation Comments)
Mean, $\bar{X}_L$, or Stress	Variance, S_L, n Comment	Mean, $\bar{X}_S$, or Strength	Variance, S_S, n Comment	
> $1.00	—	$1.00	0.	PRESENT COMPOSITE: P HIGH
> $1.00	—	$1.00	0.	PRESENT GRAPHITE: P HIGH
0.812	0.10	$1.00	0.	ESTIMATED FUTURE COMPOSITE: P = 3 x 10^{-2}
NO AVAILABLE DATA TO INDICATE IMPROVEMENT				FUTURE GRAPHITE· P HIGH



Fuel Element Stresses & Example

Transverse Stresses:

- Internal Heat Generation Stress
- Coating-Matrix Interaction Stress
- Fuel Bead-Matrix Interaction Stress
- Compressive Bundling Load (negligible)

Axial Stresses:

- Internal Heat Generation
- Coating-Matrix
- Bead-Matrix
- Axial Friction Stress
- Transverse Temperature Gradient
- Core Pressure Drop (neglected)

Heat Generation Stress Example:

1. $\sigma_q''' \propto \frac{E\alpha q'''}{k}$

2. Calculate standard deviation of $(E\alpha q'''/k)$ from known standard deviations of all parameters by algebra of normal functions.

3. Calculate standard deviation of σ_q''' at point of maximum combined stress by assuming:

$$\frac{\text{standard deviation } (\sigma_q''')}{\text{mean } (\sigma_q''')} = \frac{\text{standard deviation } (E\alpha q'''/k)}{\text{mean } (E\alpha q'''/k)}$$

4. Similarly treat all components of stress and combine standard deviations statistically to determine standard deviation of maximum combined stress.