MECHANICAL RELIABILITY PREDICTION METHODS FOR SOLID ROCKET MOTORS AND OTHER ORDNANCE

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What is a Reliability Prediction?
(and what it is not)

A reliability prediction is a <u>relative</u> measure of the <u>inherent</u> reliability of the system design

A reliability prediction is NOT an estimate of the expected reliability of the system

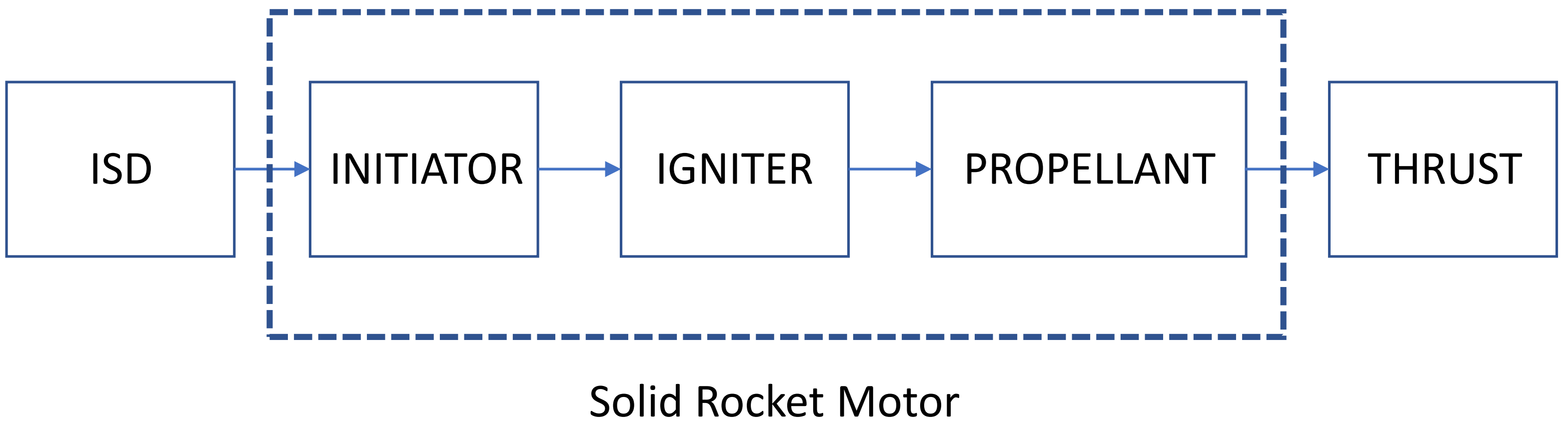
BASIC PREDICTION METHODS FOR MECHANICAL* COMPONENTS

Method I   - Parts Count (NPRD-16)
Method II - Parts Stress (NSWC -11)
Method III - Physics of Failure

*MIL-HDBK-217FN2 is used for electrical components

Typical Solid Rocket Motor Design has ~ 50-100 parts

- Includes Propellant(s) and BKNO3 “chemical” parts
- Does not include Ignition Safety Device “electrical” parts
- Usually there are no redundant mechanical parts

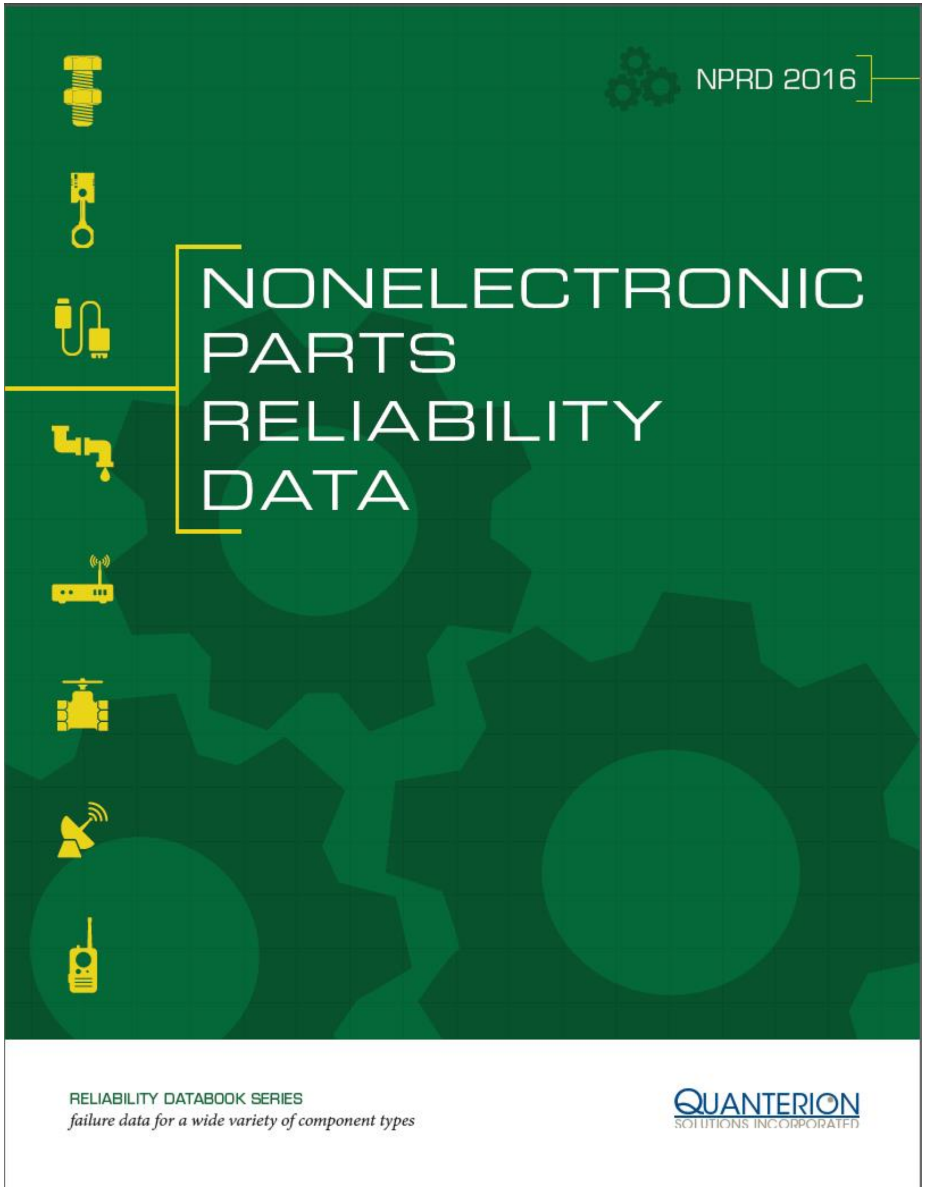


Typical Solid Rocket Motor Operation Environments

- Ground Benign (GB) / Ground Fixed (GF)
- Ground Mobile (GM)
- Missile Launch (ML)
- Missile Free Flight (MF)
- Canon Launch (CL)

  (for other ordnance)

Method I – Parts Count



Method I

Approach

- Identify Parts from Current Design
- Obtain Failure Rate for Each Part (or Part Type)
- Adjust Failure Rates for Operational Environment
- Sum Adjusted Failure Rates (by Operational Environment)
- Use Exponential Distribution to get Predicted Reliabilities for Each Mission Phase

<u>Example Mission Profile</u>

Operations (GM) -> 15 minutes
Launch (ML) -> 5 seconds
Free Flight (MF) -> 180 seconds

$$R(t) = R_{opns} \times R_{ML} \times R_{MF}$$

Sample O-Ring Failure Rate Data from NPRD-16

Part Description	Quality Level	App. Env.	Data Source	Fail Per E6 Units	Total Failed	Op. Hours/ Miles(M)/ Cycles(C)(E6)	Detail Page
O-Ring (continued)	Military	ARW	221011-000	< 0.116104	0	8.612982	10453
O-Ring			221012-000	< 0.123432	0	8.101656	10458
			221013-000	< 0.133012	0	7.518114	10462
			221014-000	< 0.154961	0	6.453234	10466
		AUA		4.376886			
			221001-000	10.361878	5	0.482538	10470
			221002-000	2.165149	1	0.461862	10470
			221003-000	2.196769	1	0.455214	10470
			221004-000	10.898232	5	0.458790	10470
			221005-000	2.990609	1	0.334380	10471
		N		19.254755			
			221015-000	< 0.138150	0	7.238532	10471
			221016-000	< 0.194832	0	5.132640	10487
			221017-000	< 0.234903	0	4.257072	10503
			221018-000	< 0.164783	0	6.068592	10519
			221019-000	< 0.273730	0	3.653232	10535
			221020-000	< 1.743229	0	0.573648	10551
			800105-000	5.856594	2528	431.650198	10567
			800106-000	30.705882	71699	2335.024896	10629
			800107-000	33.243521	127592	3838.101302	10700
			800108-000	23.187082	142219	6133.544484	10770
	Unknown			2.272727			
				0.261298M			
		GM		2.272727			
				0.261298M			
			27024-000	2.272727	1	0.440000	10841
			27030-000	0.261298M	473	1810.191368M	10841
O-Ring,Case Sealing	Military	AC		< 0.087070			
			800119-000	< 0.935097	0	1.069408	10841
			800120-000	< 0.869789	0	1.149704	10841
			800121-000	< 0.788268	0	1.268604	10842
			800122-000	< 0.722637	0	1.383820	10842
			800123-000	< 0.783404	0	1.276480	10842
			800124-000	< 0.830096	0	1.204680	10842
			800125-000	< 0.915808	0	1.091932	10842
			800126-000	< 0.943881	0	1.059456	10842
			800127-000	< 0.997725	0	1.002280	10842
			800128-000	< 1.021860	0	0.978608	10842
O-Ring,Common	Military	ARW		< 4.289581			
			221006-000	< 37.782899	0	0.026467	10842
			221007-000	< 37.194079	0	0.026886	10842
			221008-000	< 37.170576	0	0.026903	10842
			221009-000	< 39.215686	0	0.025500	10842
			221010-000	< 36.919442	0	0.027086	10842
			221011-000	< 35.527765	0	0.028147	10842
			221012-000	< 37.770056	0	0.026476	10842
			221013-000	< 40.701697	0	0.024569	10842
			221014-000	< 47.418085	0	0.021089	10842

What's Missing?

Table 1 is an update to Table 6.3.3-2 "Environmental Conversion Factors" in the RAC publication "Reliability Toolkit: Commercial Practices Edition".

Table 1. Environmental Conversion Factors

To / From	217 ⇒	GB	GF	GM	NS	NU	AIC	AIF	AUC	AUF	ARW	SF
217 ⇓	SD-18 ⇓⇒	Protected	-	-	Normal	Severe	Normal	-	Severe	Severe	Severe	-
GB	Protected	X	0.5	0.2	0.3	0.1	0.3	0.2	0.1	0.1	0.1	1.1
GF	-	2.0	X	0.4	0.6	0.3	0.6	0.4	0.2	0.1	0.2	2.0
GM	-	5.0	2.5	X	1.4	0.7	1.4	0.9	0.6	0.3	0.5	5.0
NS	Normal	3.3	1.7	0.7	X	0.5	1.0	0.7	0.4	0.2	0.3	3.3
NU	Severe	10.0	3.3	1.4	2.0	X	2.0	1.4	0.9	0.5	0.7	10.0
AIC	Normal	3.3	1.7	0.7	1.0	0.5	X	0.7	0.4	0.2	0.3	3.3
AIF	-	5.0	2.5	1.1	1.4	0.7	1.4	X	0.6	0.4	0.5	5.0
AUC	Severe	10.0	5.0	1.7	2.5	1.1	2.5	1.7	X	0.6	0.8	10.0
AUF	Severe	10.0	10.0	3.3	5.0	2.0	5.0	2.5	1.7	X	1.4	10.0
ARW	Severe	10.0	5.0	2.0	3.3	1.4	3.3	2.0	1.3	0.7	X	10.0
SF	-	0.9	0.5	0.2	0.3	0.1	0.3	0.2	0.1	0.1	0.1	X

CAUTION: It is not valid to apply to these conversions to Mean Time Between Critical Failures (MTBCF) as reliability modeling must be performed.

The primary environmental symbols used in Table 1 represent the environments defined in MIL-HDBK-217F and they are shown in Table 2. The secondary terms in Table 1 represent the environments in the Navy document SD-18 "Part Requirement and Application Guide" these environments are described in Table 3.

No ML or MF or CL

Conversion FR Factors for SRM and Ordnance

GF (Baseline) = 1.0
GM = 2.5
ML = 50
MF = 25
CL = 200

Failure Rate for O-Ring from NPRD-16 = 4.289581 (ARW)

Using Conversion Table from Previous Slide and above factors

O-Ring Failure Rate = 0.8579162 (GF) *ARWx0.2*
= 2.1447905 (GM)
= 42.89581 (ML)
= 21.447905 (MF)

Method I – Parts Count

Pros: Ease of use
Can be performed relatively quickly
Short mission times for SRM make predictions robust to individual part changes
Doesn't require detailed knowledge of operating conditions

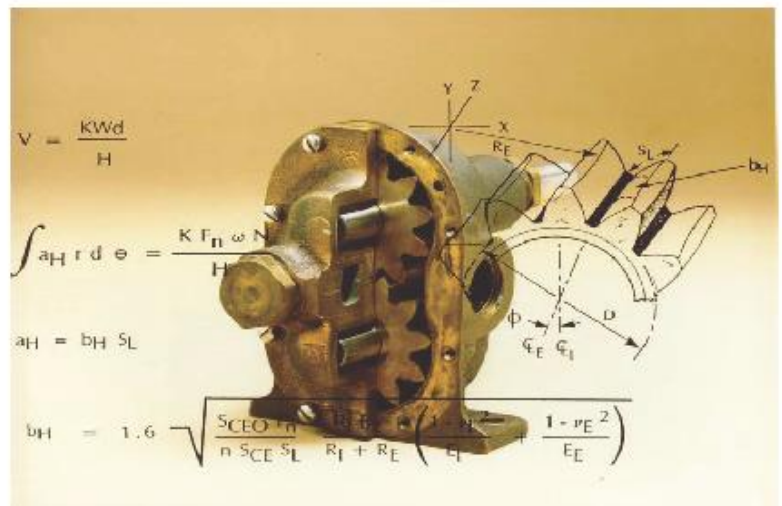
Cons: High variability in NPRD-16 Failure Data for same part description
Custom parts not in NPRD-16

Method II – Parts Stress

NSWC
Naval Surface Warfare Center
CARDEROCK DIVISION

Naval Surface Warfare Center
Carderock Division
West Bethesda, Maryland 20817-5700

Handbook of Reliability Prediction Procedures for Mechanical Equipment



Logistics Technology Support

CARDEROCKDIV, NSWC-11
May 2011

Method II

Approach

- Identify Parts from Current Design
- Obtain Material Characteristics and Operating Conditions for Each Part (or Part Type)
- Calculate Failure Rate for Most Extreme Condition (i.e., ML) using NSWC-11 for Each Part
- Calculate or Adjust Failure Rates for Lesser Operational Environments
- Sum Adjusted Failure Rates (by Operational Environment)
- Use Exponential Distribution to get Predicted Reliabilities

Sample O-Ring Failure Rate Model from NSWC-11

3.2.3 Failure Rate Model for Gaskets and Static Seals

By normalizing the equation to those values for which historical failure rate data from the Navy Maintenance and Material Management (3-M) system are available, the following model can be derived:

$$\lambda_{SE} = \lambda_{SE,B} \bullet C_P \bullet C_Q \bullet C_{DL} \bullet C_H \bullet C_F \bullet C_V \bullet C_T \bullet C_N \quad \text{(3-7)}$$

Where: λ_{SE} = Failure rate of a seal in failures/million hours

$\lambda_{SE,B}$ = Base failure rate of seal, 2.4 failures/million hours

C_P = Multiplying factor which considers the effect of fluid pressure on the base failure rate (Figure 3.10)

C_Q = Multiplying factor which considers the effect of allowable leakage on the base failure rate (See Figure 3.11)

C_{DL} = Multiplying factor which considers the effect of seal size on the base failure rate (See Figure 3.12 for seals or Figure 3.13 for gaskets)

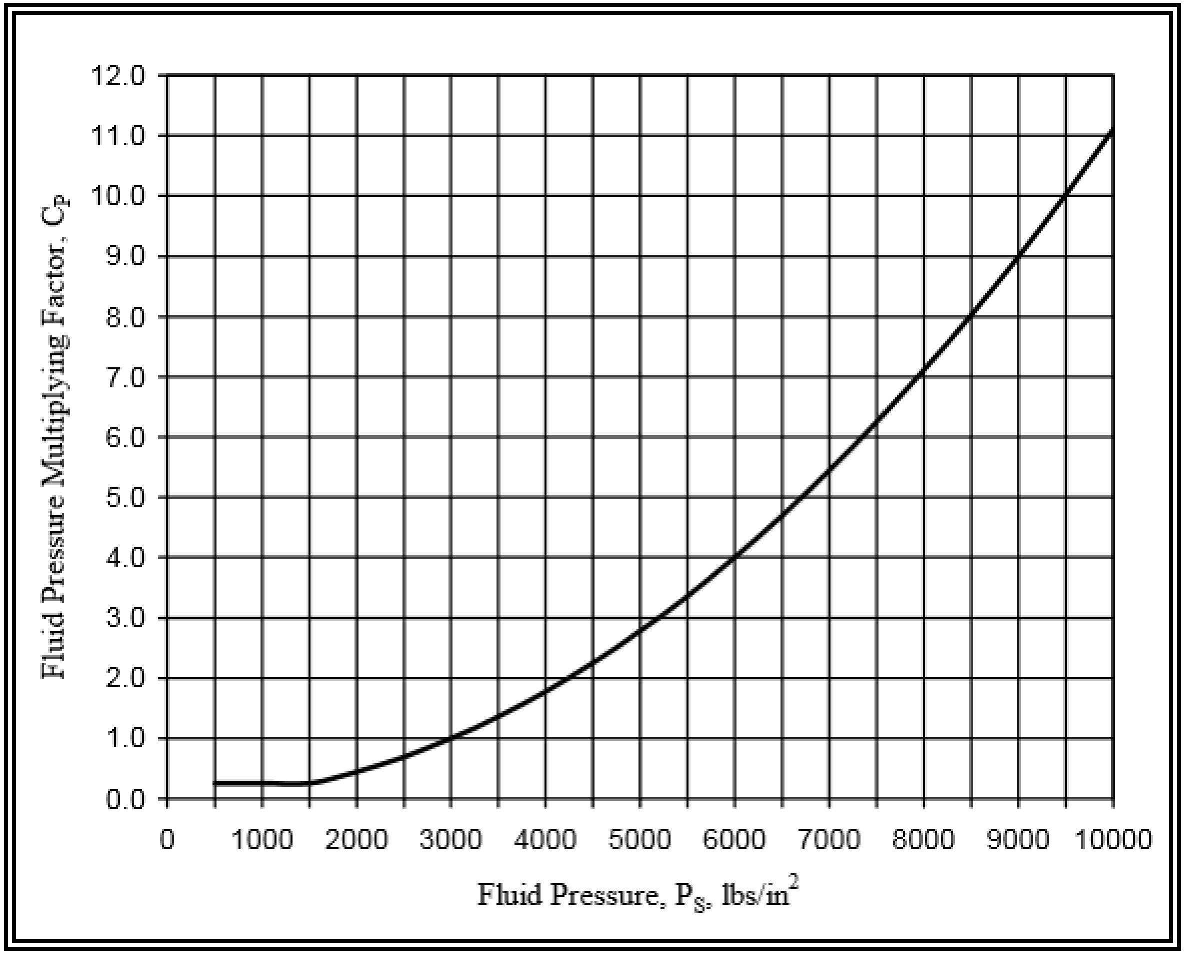
C_H = Multiplying factor which considers the effect of contact stress and seal hardness on the base failure rate (See Figure 3.14)

C_F = Multiplying factor which considers the effect of seat smoothness on the base failure rate (See Figure 3.15)

C_V = Multiplying factor which considers the effect of fluid viscosity on the base failure rate (See Table 3-3)

C_T = Multiplying factor which considers the effect of temperature on the base failure rate (See Figure 3.16)

C_N = Multiplying factor which considers the effect of contaminants on the base failure rate (See Table 3-4)

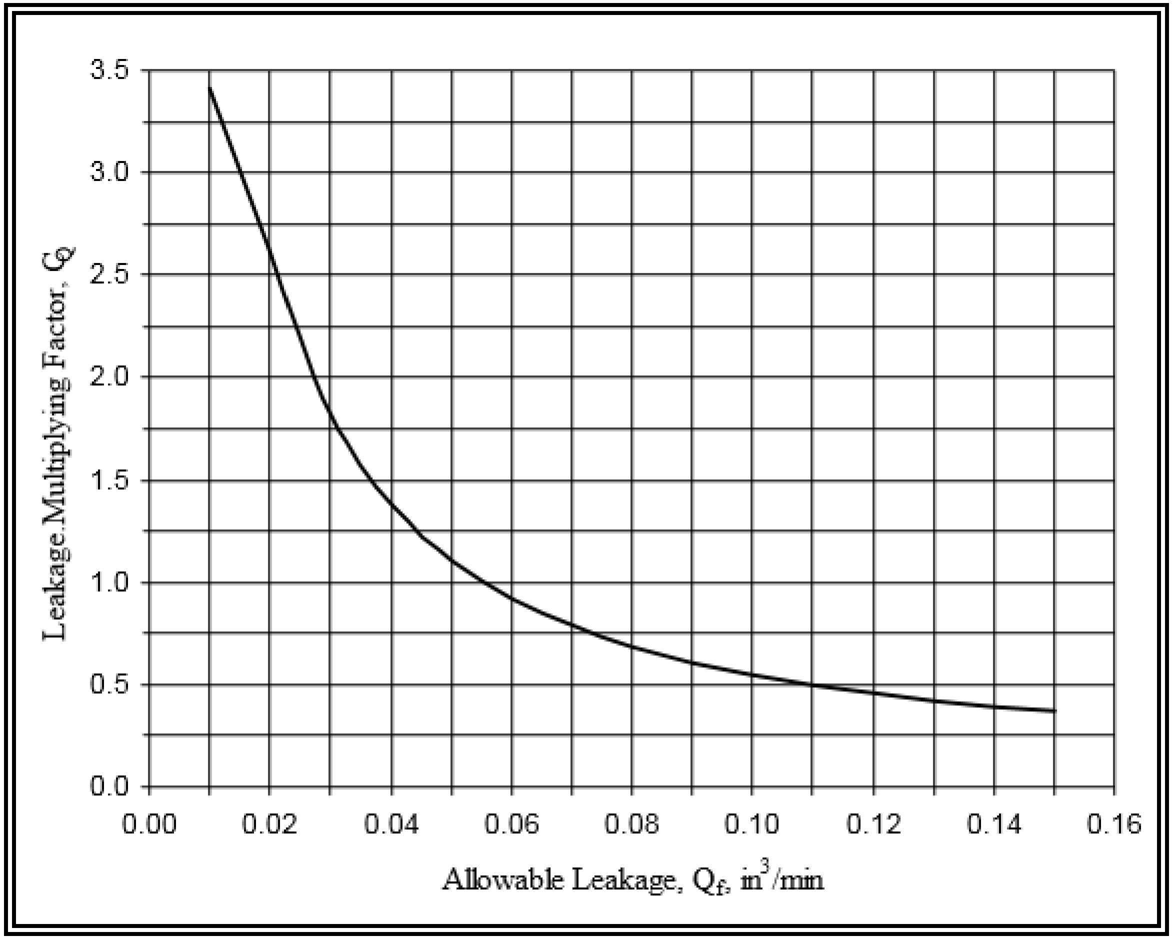


For $P_S \leq 1500$ lbs/in^2, $C_P = 0.25$

For $P_S > 1500$ lbs/in^2, $C_P = \left(\frac{P_S}{3000}\right)^2$

Ps ~ 1500 psi
$C_p = 0.25$

Where $P_S = P_1 - P_2$ (upstream – downstream pressure)

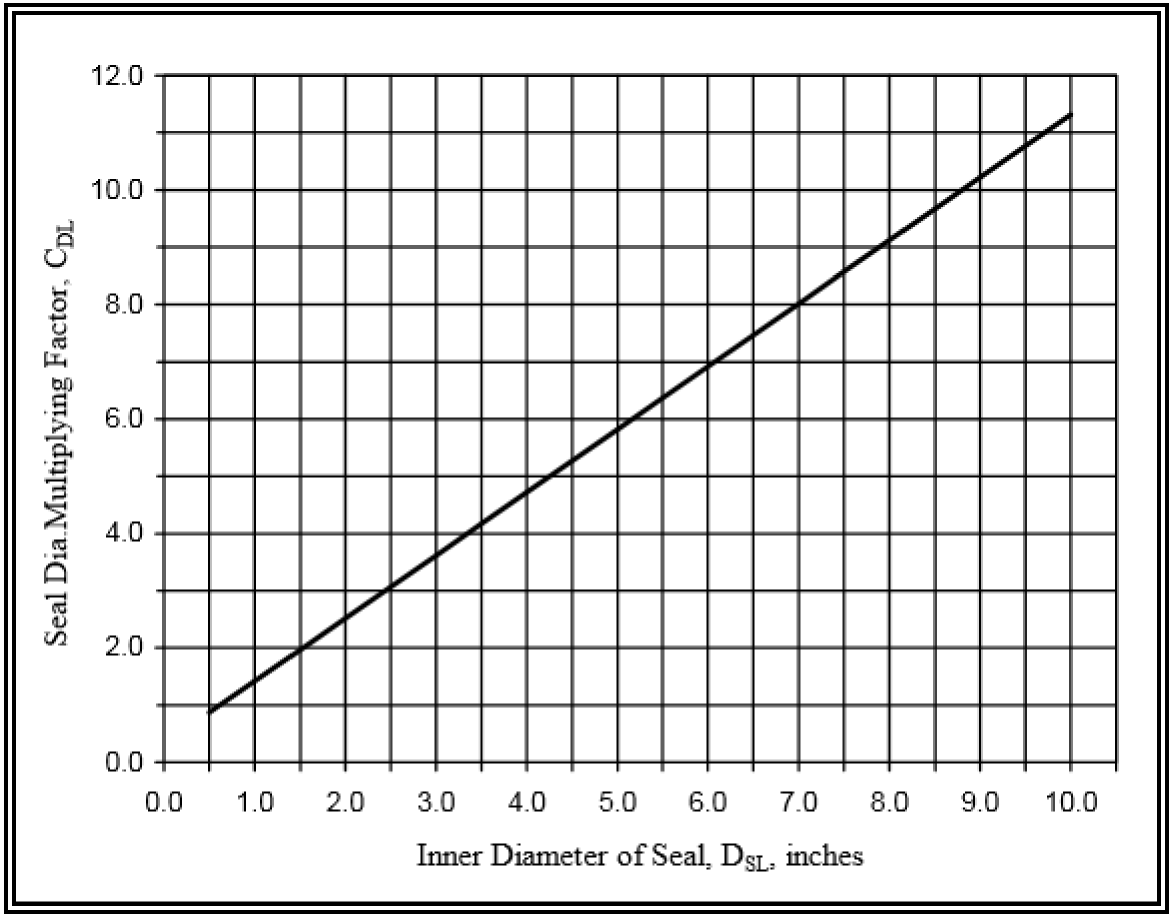


For Leakage $>$ 0.03 in^3/min, $C_Q = 0.055/Q_f$

Leakage = 0

For Leakage $\leq$ 0.03 in^3/min, $C_Q = 4.2 - (79\ Q_f)$

$C_Q = 4.2$

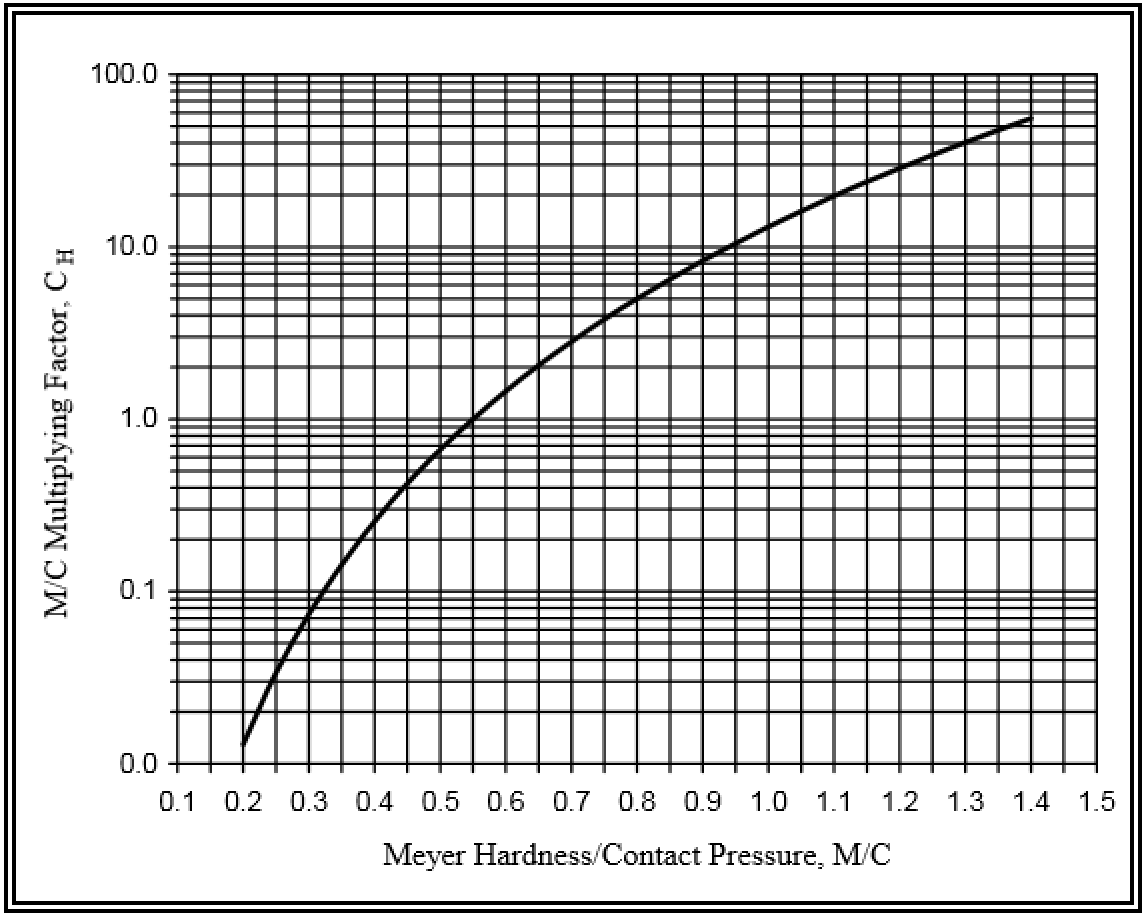


$C_{DL} = 1.1\, D_{SL} + 0.32$

Where: D_{SL} = Inner diameter of seal

Assume 4 in. I.D.

$C_{DL} = 4.72$



$$C_H = \left(\frac{M/C}{0.55}\right)^{4.3}$$

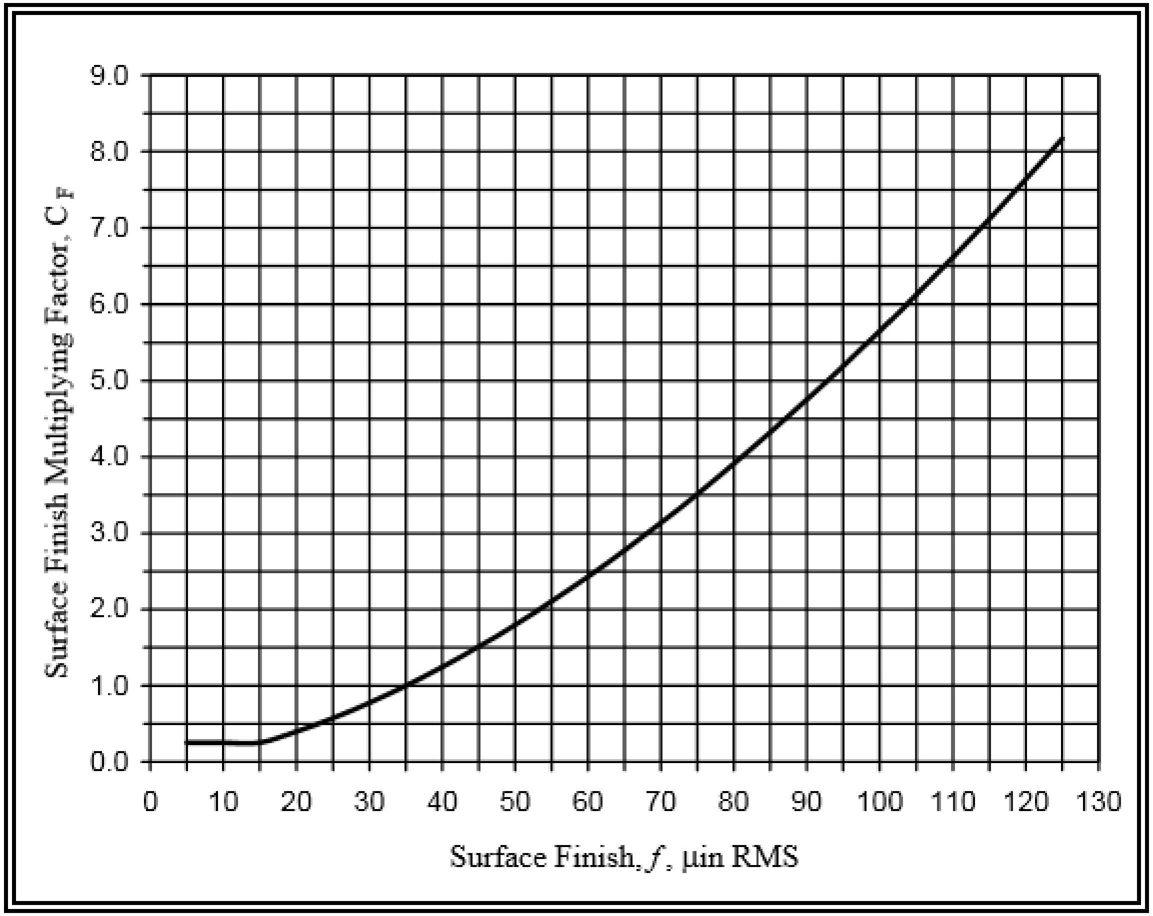
Where: M = Meyer Hardness, lbs/in^2

C = Contact Pressure, lbs/in^2

M = 870 psi

C = 1800 psi

C_H = 0.574



For $f \leq 15$ μin, $C_f = 0.25$

For $f > 15$ μin, $C_f = \dfrac{f^{1.65}}{353}$

Where: f = Surface Finish, μin RMS

$f = 32\mu in$
$C_f = 0.862$

FLUID	C_V								
	Fluid Temperature, °F								
	-50	0	50	100	150	200	250	300	350
Air	554.0	503.4	462.9	430.1	402.6	379.4	359.5	---	---
Oxygen	504.6	457.8	420.6	390.2	365.9	343.6	325.3	---	---
Nitrogen	580.0	528.0	486.5	452.6	424.3	400.0	379.6	---	---
Carbon Dioxide	---	599.9	510.7	449.7	395.9	352.1	---	---	---
Water	---	---	6.309	12.15	19.43	27.30	---	---	---
SAE 10 Oil	---	---	0.060	0.250	0.750	1.690	2.650	---	---
SAE 20 Oil	---	---	0.0314	0.167	0.492	1.183	2.213	2.861	5.204
SAE 30 Oil	---	---	0.0297	0.1129	0.3519	0.8511	1.768	2.861	4.309
SAE 40 Oil	---	---	0.0122	0.0534	0.2462	0.6718	1.325	2.221	3.387
SAE 50 Oil	---	---	0.0037	0.0326	0.1251	0.3986	0.8509	1.657	2.654
SAE 90 Oil	---	---	0.0012	0.0189	0.0973	0.3322	0.7855	1.515	2.591
Diesel Fuel	0.1617	0.7492	2.089	3.847	6.228	9.169	12.78	16.31	---
MIL-H-83282	0.0031	0.0432	0.2137	0.6643	1.421	2.585	4.063	0.6114	0.7766
MIL-H-5606	0.0188	0.0951	0.2829	0.6228	1.108	1.783	2.719	3.628	4.880

--- Data for these temperatures determined to be unreliable

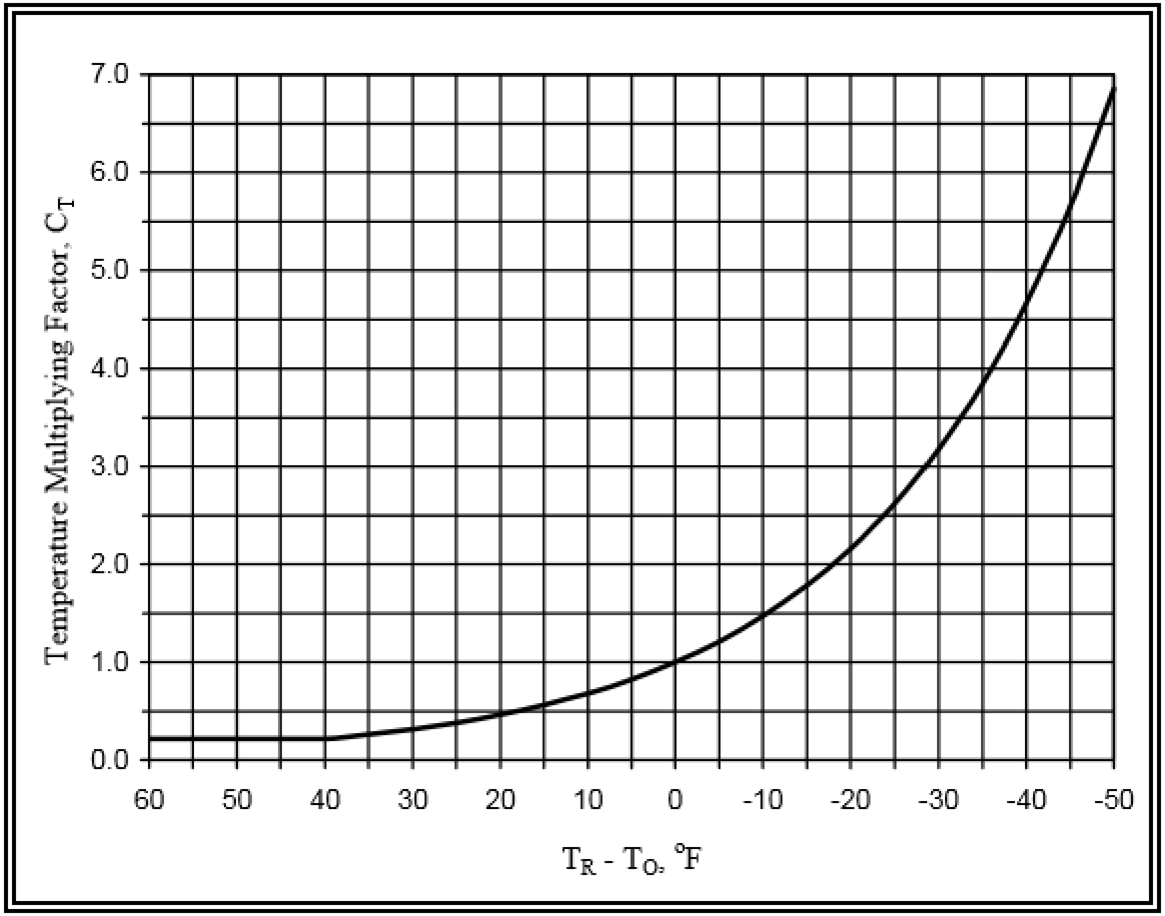
$$C_V = \left(\frac{\nu_o}{\nu}\right)$$

V = 2.28E-10

C_V = 87.72

Where: ν_o = 2 x 10^{-8} lbf-min/in^2

ν = Dynamic viscosity of fluid being used, lbf-min/in^2



$$C_T = \frac{1}{2^t}$$

Where: $t = \frac{(T_R - T_O)}{18}$ for $(T_R - T_O) \le 40\ ^oF$

and: $C_T = 0.21$ for $(T_R - T_O) > 40\ ^oF$

T_R = Rated Temperature of Seal, °F (See Table 3-6)

T_O = Operating Temperature of Seal, °F

T_R = 250F

T_O = 150F

C_T = 0.21

TYPICAL QUANTITIES OF PARTICLES PRODUCED BY HYDRAULIC COMPONENTS	PARTICLE MATERIAL	NUMBER PARTICLES UNDER 10 MICRON PER HOUR PER RATED GPM (N10)
Piston Pump	steel	0.017
Gear Pump	steel	0.019
Vane Pump	steel	0.006
Cylinder	steel	0.008
Sliding action valve	steel	0.0004
Hose	rubber	0.0013

$$C_N = \left(\frac{C_O}{C_{10}}\right)^3 \bullet FR \bullet N_{10}$$

N/A

Assume $C_N = 1.0$

Where: C_o = System filter size in microns

C_{10} = Standard system filter size = 10 micron

FR = Rated flow rate, GPM

N_{10} = Particle size factor

Table 3-5. T_R Values for Typical Seal Materials (Reference 27)

SEAL MATERIAL	T_R (^oF)
Natural rubber	160
Ethylene propylene	250
Neoprene	250
Nitrile	250
Polyacrylate	300
Fluorosilicon	450
Fluorocarbon	475
Silicon rubbers	450
Butyl rubber	250
Urethane	210
Fluroelastomers	500
Fluroplastics	500
Leather	200
Impregnated poromeric material	250

$$\lambda_{SE} = \lambda_{SE,B} \times C_P \times C_Q \times C_{DL} \times C_H \times C_F \times C_V \times C_T = \mathbf{108.413}\,\text{FPMH}$$

For ML environment (4in. O-ring made of EDPM)

Either repeat process for conditions of GF,GM and MF

or

Use conversion factors for Parts Count Method.

RELIABILITY PREDICTION PROCEDURES FOR MECHANICAL EQUIPMENT

CARDEROCKDIV, NSWC-11

Method II – Parts Stress Method

Pros:

More realistic prediction than parts count method

Considers environmental stresses on individual parts

Cons:

Requires detail knowledge of operational stresses

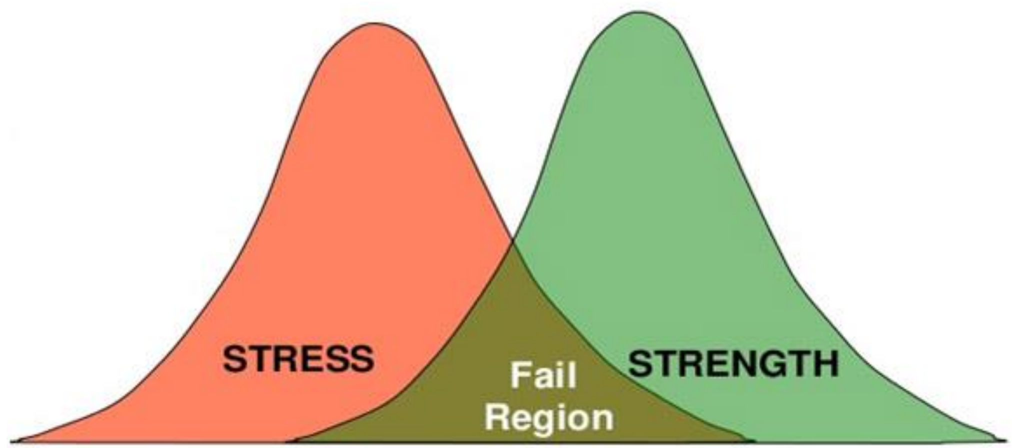
Requires detail knowledge of part/process characteristics

Can be time consuming

Limited number of part categories in NSWC-11 compared to NPRD-16

Method III – Physics of Failure

- Need detailed knowledge of environmental stresses on each part
- Need detailed technical data for each part (strength, etc)



Pro: Usually provides the most realistic reliability prediction for mechanical parts

Cons: Difficult to obtain the necessary information / data
Time consuming

What about Chemical “Parts”?

NPRD-16 contains failure rate data for initiators and igniters

Approach

Failure rate for exploding foil = FR(initiator) – ΣFR(hardware)

Failure rate for igniter pellets (BKNO3) = FR(igniter) – ΣFR(hardware)

Failure rate for main propellant more difficult

Part Description	Quality Level	App. Env.	Data Source	Fail Per E6 Units	Total Failed	Op. Hours/ Miles (M)/ Cycles (C) (E6)	Detail Page
Initiator,Cartridge Actuated (continued)	Military	AA	800102-000	173.418887	26	0.149926	9440
Initiator,Cartridge Actuated			800103-000	348.615405	53	0.152030	9440
			800104-000	50.464271	8	0.158528	9440
		AIA		27.362476			
			221001-000	124.342539	10	0.080423	9440
			221002-000	< 12.990893	0	0.076977	9440
			221003-000	< 13.180614	0	0.075869	9440
			221004-000	< 13.077879	0	0.076465	9440
			221005-000	< 17.943657	0	0.055730	9440
Initiator,Propellant	Military			39.411872			
		AA		85.813194			
			800101-000	1884.061928	138	0.073246	9440
			800102-000	13.339914	1	0.074963	9441
			800103-000	171.018878	13	0.076015	9441
			800104-000	12.616068	1	0.079264	9441
		AIA		10.949640			
			221001-000	12.434254	1	0.080423	9441
			221002-000	< 12.990893	0	0.076977	9441
			221003-000	52.722456	4	0.075869	9441
			221004-000	< 13.077879	0	0.076465	9441
			221005-000	< 17.943657	0	0.055730	9441
Initiator Assembly,Canopy Ground Emergency Release	Military	AA		< [illegible]			

Part Description	Quality Level	App. Env.	Data Source	Fail Per E6 Units	Total Failed	Op. Hours/ Miles (M)/ Cycles (C) (E6)	Detail Page
Igniter,Explosive,Solid Propellant (continued)	Military	DOR	NPRD-116	< 0.583431	0	1.714000	9327
Igniter,Explosive,Solid Propellant	Unknown	GF	14182-001	0.534000	-	--------	9327
Igniter,Explosive,Squib				0.192003			
	Military	DOR	NPRD-110	< 0.581734	0	1.719000	9327
	Unknown	GF		0.504257			
			14182-001	0.533000	-	--------	9327
			18354-000	< 17.543860	0	0.057000	9327
Igniter,Friction	Military	N		2.583545			
			221015-000	< 173.792145	0	0.005754	9327
			221016-000	< 245.098039	0	0.004080	9327
			221017-000	< 295.508274	0	0.003384	9327
			221018-000	< 207.296849	0	0.004824	9327
			221019-000	< 344.352617	0	0.002904	9327
			221020-000	< 2192.982456	0	0.000456	9327
			800105-000	< 12.477696	0	0.080143	9327
			800106-000	< 2.306614	0	0.433536	9327
			800107-000	4.209894	3	0.712607	9327
			800108-000	2.634366	3	1.138794	9327
Igniter,Ignition Plug				47.447881			
	Military			35.800260			
		AU	NPRD-051	112.736274	501	4.444000	9327
		AUF	16953-000	8.547009	1	0.117000	9327
		GM	NPRD-095	47.619048	1	0.021000	9327
	Unknown			72.395702			
		A	14182-001	110.064000	-	--------	9327

What about Storage Reliability?

AD A122054

ADE 950 319

5

STORAGE RELIABILITY OF MISSILE MATERIEL PROGRAM

STORAGE RELIABILITY ANALYSIS SUMMARY REPORT VOLUME IV ORDNANCE DEVICES

LC 82-2 SEPTMBER 1982

U.S. ARMY MISSILE COMMAND
Redstone Arsenal, Alabama 35898

PRODUCT ASSURANCE DIRECTORATE

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2.5 Conclusions and Recommendations

The data analyzed for solid propellant motors indicated no motor failures which would have failed the mission requirements. Until more data is collected, it is recommended that the following reliability prediction be used for solid propellant units:

5 Year Reliability:	**.994 at 50% confidence**
	.981 at 90% confidence
10 Year Reliability:	**.964 at 50% confidence**
	.890 at 90% confidence

Igniters are not included in this prediction. See Section 3 for analysis of igniters.

FIGURE 3.3-1. IGNITER RELIABILITY PREDICTION MODEL

$$R(t)_{igniter} = [R(t)_{aging}] \times [R(t)_{random}]$$

$$R(t)_{random} = \exp(-\lambda t)$$

	R(t) Aging				λ	
	50% confidence		90% confidence		50% Confidence	90% Confidence
Classification	5 yrs.	10 yrs.	5 yrs.	10 yrs.		
Solid Rocket Motor Pyrogen Igniters	.998	.986	.994	.954	65×10^{-9}	129×10^{-9}
Solid Rocket Motor Pyrotechnic Igniters	.995	.991	.984	.969	65×10^{-9}	129×10^{-9}
Gas Generator Igniters	.997	.979	.991	.934	65×10^{-9}	129×10^{-9}

Conclusions

Reliability Predictions for Solid Rocket Motors and Ordnance

<u>Historical failure data on similar systems (adjusted for new design) is optimal</u>

- *Can be difficult to obtain for contractors due to being OEM proprietary data*
- *Common for SRM manufacturers to use engineering judgement for reliability*

<u>Parts Count Method is simple and relatively fast</u>

- *NPRD-16 contains 10,000+ parts (categories and subcategories)*
- *Failure Rates vary widely across same part, so care must be used in selection*

<u>Parts Stress Method usually gives better estimates of failure rates</u>

- *Requires knowledge of part and detailed operating environments*
- *NSWC-11 does not contain most parts related to SRMs*

<u>Physics of Failure Method most accurate for mechanical parts</u>

- *Requires much time and detailed knowledge*

When no historical data exists – we use combination of Parts Count and Parts Stress

Free Mechanical Failure Rate Data Sources

https://aldservice.com/Reliability-Software/free-mtbf-calculator.html

https://reliabilityanalyticstoolkit.appspot.com/

(29. Mechanical reliability data)

http://everyspec.com/USN/NSWC/NSWC-11_RELIABILITY_HDBK_MAY2011_55322/

Not Free

https://www.quanterion.com/product/publications/nonelectronic-parts-reliability-data-publication-nprd-2016/ $275+