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Rotorcraft Spectrum Reliability Comparisons by Endurance Limit Adjustments

March 2016

Final Report

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16. Abstract The purpose of this study was to develop and demonstrate methods for comparing the relative aircraft system reliability of different spectra. Three methods were demonstrated: Method 1, Constant Component Reliability; Method 2, Relative Endurance Limit (EL); and Method 3, the Structural Usage Monitoring System (SUMS) Reference. All three methods use the distribution of strength available from coupon and component fatigue tests as a measurement of reliability. Two different spectra will generate different lives for a given part. Given a candidate spectrum, the EL is changed until the part life matches the life of the reference spectrum. The change in EL, along with the distribution, provides a measurement of the change in reliability for each part, which is combined to compare relative system reliabilities between the two spectra. The Constant Component Reliability method assumes that all parts start at fixed reliability with the Composite Worst Case—and the reliability changes determined by changing the EL are added to that. This method for comparing relative spectra reliabilities was found to be invalid by comparison with the other methods because the assumption of constant reliability was not a good fit. This method should not be used. The Relative EL method changes the EL for parts with the candidate spectrum until they match the reference spectrum, generating a relative reliability difference due to usage changes only. This method was found to be effective. Because it is a relative comparison between any two spectra, it is most useful when there are no SUMS data available. The SUMS Reference method compares any spectrum against the SUMS average, which contributes 50% reliability to each part. Each spectrum is analyzed independently and then compared against the SUMS average. This method provides an actual reliability value based on strength and usage. Because it compares the average to a set of lives, it becomes possible to assign lives by other methods, such as operational field data. This method was found to be effective.					
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LIST OF ACRONYMS

9 _x	Reliability notation where x is the number of 9s
AED	Aviation Engineering Directorate
CWC	Composite Worst Case
CWC*	Adjusted CWC spectrum
EL	Endurance Limit
FAA	Federal Aviation Administration
FLM	Fatigue Life Management
FSR	Fatigue Substantiation Report
GAG	Ground-Air-Ground
IVHMS	Integrated Vehicle Health Management System
M	SUMS Average (Mean) spectrum
M+1	SUMS Mean+1*Standard Deviation spectrum
M+2	SUMS Mean+2*Standard Deviation spectrum
SN	Load, S, vs. Cycles, N, fatigue curve
SUMS	Structural Usage Monitoring System

EXECUTIVE SUMMARY

The purpose of this study was to develop and demonstrate methods for comparing the relative aircraft system reliability of different spectra. Three methods were demonstrated: Method 1, Constant Component Reliability; Method 2, Relative Endurance Limit (EL); and Method 3, Structural Usage and Monitoring System (SUMS) Reference.

All three methods use the distribution of strength available from coupon and component fatigue tests as a measurement of reliability. Two different spectra will generate different lives for a given part. Given a candidate spectrum, the EL is changed until the part life matches the life of the reference spectrum. The change in EL, along with the distribution, provides a measurement of the change in reliability for each part. All of the part reliabilities are combined to provide a system level change in reliability, which allows a comparison between the candidate and reference spectrum. In most cases, the reference spectrum will be the Composite Worst Case (CWC).

The Constant Component Reliability method assumes that all parts start at a fixed reliability with the CWC. The change in reliability for each part is added to the fixed baseline to give a new reliability for each part. The product of all the part reliabilities is taken for the system reliability and compared to the product of the fixed reliability for all of the parts. The advantage to this method is that because it starts from a point which includes reliability contributions from strength, usage, and loads, it calculates the total reliability for the system of fatigue critical parts. This method for comparing spectra reliability was found to be invalid by comparison with the other methods. The constant reliability for all parts is not true, but if it were close, the method would still be useful for comparisons. However, because this method behaved significantly differently than the other methods, the assumption is shown to be invalid. This method should not be used.

The Relative EL method changes the EL for parts with the candidate spectrum until they match the reference spectrum. After determining the new strength reliability for each part, the product is taken and compared to the product of the baseline with all parts at the reference EL reliability. This generates a relative reliability difference, which is due to usage changes only, so it cannot be taken as a true system reliability. This method was still found to be effective. Because it is a relative comparison between any two spectra, it is most useful when there are no SUMS data available.

The SUMS Reference method compares any spectrum against the SUMS average. Because the SUMS average is used, it contributes 50% reliability, which is added to the change in reliability for each part. First, the baseline spectrum would be compared against the SUMS average and then the candidate spectrum. The results from the two analyses are compared against each other to determine which is more reliable. Strength is incorporated by including the baseline strength reliability contribution, but loads are not included. This method has the advantage of providing an actual value for strength and usage reliability contributions because it is anchored to the SUMS average. It is also useful because it compares the average to a set of lives which may or may not be derived from a fully defined spectrum. This allows the possibility to assign lives by other methods, such as operational field data. This method was found to be effective. It does require the availability of SUMS data but allows the lives to be assigned by methods other than

fatigue calculations. A likely approach would be assigning upper-bound lives based on biased SUMS usage and then reducing the lives of long-life parts based on information from the field. Reliability gained by reducing lives based on operational data could be redistributed to increase the life of parts that consistently reach their life limits.

Useful follow-on work could include setting up the calculations to use an optimization engine that would use the Relative EL method to maximize the increase of short-life parts while maintaining the same level of system reliability as the CWC. Another possibility would be to review operational data for when parts are removed in the field and then using that information with the SUMS Reference method to gain the most benefit for short-life parts.

1. INTRODUCTION

1.1 PURPOSE

This research was conducted under a partnership between the Federal Aviation Administration (FAA) and Army Aviation Engineering Directorate (AED) to support the enhancement of FAA Advisory Circular AC-29-2C, MG-15 for the use of structural usage monitoring system (SUMS) based data. As part of this partnership, AED was given the task to evaluate methods of comparing the reliability between two spectra to evaluate whether a proposed new spectrum is more, or less, reliable than the spectrum being replaced.

1.2 BACKGROUND

According to ADS-79 [1], there are three ways to maintain the reliability of U.S. Army aircraft systems when applying Condition Based Maintenance approaches.

The most commonly used method in structural Fatigue Life Management (FLM) is to hold each individual component to a reliability of 0.999999 (six nines, or 9_6). Because of a general lack of sufficient data to apply a model for loads to the reliability calculations, ADS-79 makes several allowances. When usage is monitored and part damage is tracked by serial number using legacy load and part strengths, reliability is assumed to be maintained when the part is removed at a damage fraction of 0.5. When SUMS data are used to update the spectrum for part number tracking by the legacy method, reliability is assumed to be maintained when the damaging regime time is the mean plus two sigma level, based on data from multiple aircraft.

Another allowable approach for maintaining the reliability of U.S. Army aircraft systems, not addressed here, is to substantiate that the risk of a failure is less than 0.01 in 100,000 flight hours.

The final approach, according to ADS-79, is to “substantiate that the incorporation of FLM has not increased the aircraft system level risk.” This is the approach addressed in this report. Specifically, processes are demonstrated for comparing the relative reliability of two different spectra. The objective is to show that the overall reliability of the system is not degraded by application of a new spectrum. The two spectra to be compared would be the existing Composite Worst Case (CWC) spectrum and the new proposed spectrum.

There is no definition of how the proposed spectrum should be derived because the system level risk requirement is independent of the 9_6 requirement for components. However, this report will make use of SUMS usage data in two ways. The first is to use the mean plus two sigma and mean plus one sigma spectra for comparison against the CWC because this use is well-known within the discipline because of its inclusion in ADS-79. The second is to provide a lower bound for time spent in regimes when developing an adjusted spectrum through engineering judgment. No damaging regime will be allowed less time than the mean plus one sigma.

Three methods are demonstrated. All three use the same basic approach for which the endurance limit (EL), already modeled statistically, is used to measure reliability. A reference spectrum is applied to each failure mode and the EL is adjusted until the new spectrum life matches the reference spectrum life. The difference in EL, in standard deviations, provides a part-by-part

measurement of the change in reliability. The reliability for each failure mode is determined and the product of the individual reliabilities provides the overall system reliability.

The three methods differ in what is used as a reference point for reliability. Method 1, or the Constant Component Reliability method, assumes that every part starts at a fixed reliability with the initial spectrum. Method 2, or the Relative EL method, looks at the relationships between the two spectra without determining any independent reliability value. Method 3, the SUMS Reference method, relates a spectrum back to the SUMS average (with a known reliability) to provide a true reliability contribution from usage monitoring to be compared against another spectrum.

1.3 LEGACY SAFE-LIFE FATIGUE METHOD

The legacy method of determining the safe-life of fatigue critical parts has three inputs: the Load, S, vs. Cycles, N, fatigue curve (SN); the flight loads; and the usage spectrum. The spectrum and the flight loads define the number of cycles at each load. Each load cycle is compared to the SN to determine the amount of damage—and the damage from all cycles is combined via Miner's Rule. The life of the part is the inverse of the accumulated damage rate.

The shape of the SN curve is typically determined by numerous coupon tests of the specific material. The magnitude of the curve is then adjusted based on a limited number of tests of the actual component.

The flight loads are determined for each regime from flight load surveys of a heavily instrumented aircraft. Steady state maneuvers typically use the top-of-scatter load or the highest load observed during that maneuver. Transient maneuvers often use the cycle-counted damage of the most damaging instance of that particular regime.

The spectrum defines how many times a transient regime occurs or how long the aircraft is in each steady state regime. There is also a definition of how many Ground-Air-Ground (GAG) cycles the aircraft will see during flight.

The amount of damage for time/occurrences of each regime in the spectrum time frame is added to the damage calculated, based on GAG cycles, to determine the life of the part.

2. DISCUSSION

The results of the three methods for determining relative total aircraft reliability are shown in sections 2.1 through 2.5.. The procedures for implementing the three methods are shown in section 3.

Five usage spectra were used in the system reliability analyses. These spectra, which are shown in figure 1, consist of the following:

- Fatigue Substantiation Report (FSR) CWC
- Adjusted CWC Spectrum (CWC*)
- SUMS Mean (M)

- SUMS Mean + 1σ (M+1)
- SUMS Mean + 2σ (M+2)

A total of 84 parts/failure modes were included in the analysis. The parts are listed in figure 2, with the fatigue lives associated with each spectrum listed in figure 3. Failure modes with very long or infinite fatigue lives were neglected, with the assumption that their reliability was essentially 1.0 and would not change significantly with adjustments to the spectrum.

The method for developing the SUMS-based spectra is discussed in section 3.2. Inspection of the SUMS spectra in relation to the CWC could raise some questions that would need to be addressed. In particular, the SUMS mean spectrum time in hover is much lower, times in sideward flight (as well as entries/recoveries) are much higher, and GAG and Min-Max occurrences are higher. Because the data were drawn primarily from training flights, a high occurrence of take-offs and landings is logical. However, the sideward flight numbers appear abnormal. This probably results from the fact that the difference between hover and sideward flight is a single SUMS parameter set at a fairly low value. It is suspected that much of the sideward flight time should be classified as hover and that the large number of entries/recoveries is because of flight conditions shifting slightly around the key parameter. The SUMS software for this aircraft has not yet been validated. However, for purposes of demonstrating the methods and comparing spectra, these issues are not relevant.

The CWC* spectra were derived by manually adjusting times in various regimes. The goal was to increase the life of short-life parts by reducing time in regimes that cause the most damage, not to be less than the M+1 value for those regimes. Because leaving these parts on longer reduces the overall reliability of the system, time had to be added to regimes that damaged only higher-life parts. This adjusted spectrum was developed by reducing many of the regimes that damaged the short-life parts to the M+1 spectrum time, then choosing regimes by inspection that would add damage to high-life parts.

In figure 4, the lives of the CWC and CWC* spectra are plotted in ascending CWC order. It is evident that virtually all of the lives for short-lived parts increase. The lowest part life is 1019 hours in the CWC for failure mode 74, which increased 37% to 1401 hours. To balance the loss in reliability, other parts have their lives reduced, most notably failure modes 5 and 65—which are strongly affected by regimes 35 and 36. These two parts drop from lives in excess of 20,000 hours to approximately 10,000 hours. Although that is a large drop in life, 10,000 hours is still operationally a very long time.

Reg. No.	Description	CWC			SUMS M			SUMS M+1			SUMS M+2			CWC*		
		PCT Time	Occs /100	Secs /Occ	PCT Time	Occs /100	Secs /Occ	PCT Time	Occs /100	Secs /Occ	PCT Time	Occs /100	Secs /Occ	PCT Time	Occs /100	Secs /Occ
1	Hover	1.058			0.003			0.004			0.006			1.058		
2	Left Sideward Flight	0.300			2.972			3.251			3.530			0.300		
3	Right Sideward Flight	0.300			12.463			13.452			14.440			0.300		
4	Rearward Flight	0.300			3.425			3.798			4.171			0.300		
5	Climb	2.520			1.269			1.372			1.474			1.372		
6	Level Flight @ 0.1VH	1.376			0.000			0.000			0.000			1.376		
7	Level Flight @ 0.2VH	0.920			19.970			21.317			22.664			0.920		
8	Level Flight @ 0.4VH	1.836			0.426			0.482			0.538			1.836		
9	Level Flight @ 0.5VH	1.836			0.658			0.749			0.840			1.836		
10	Level Flight @ 0.6VH	2.526			2.258			2.553			2.849			2.526		
11	Level Flight @ 0.7VH	2.755			4.822			5.249			5.677			2.755		
12	Level Flight @ 0.8VH	9.187			3.480			4.204			4.929			9.187		
13	Level Flight @ 0.9VH	13.782			0.995			1.470			1.945			13.782		
14	Level Flight @ 1.0VH	6.891			0.190			0.326			0.461			0.326		
15	Sideslip	0.600			1.002			1.087			1.172			0.687		
16	Autorotation	0.801			0.009			0.013			0.017			0.801		
17	Partial Power Descent	1.200			1.156			1.293			1.431			1.293		
18	Dive	1.394			0.453			0.626			0.799			1.394		
19	Turn 30 Degrees Left	2.125			1.338			1.487			1.635			2.125		
20	Turn 30 Degrees Right	2.125			1.029			1.144			1.259			2.125		
21	Turn 45 Degrees Left	0.312			0.008			0.011			0.014			0.312		
22	Turn 45 Degrees Right	0.312			0.008			0.010			0.012			0.312		
23	Turn 60 Degrees Left	0.025			0.000			0.002			0.003			0.025		
24	Turn 60 Degrees Right	0.025			0.001			0.003			0.005			0.025		
25	Take Off	0.600	360	6	1.106	663	6	1.166	700	6	1.227	736	6	1.166	700	6
26	Left Hover Turn	0.500	150	12	9.206	2762	12	10.741	3222	12	12.275	3683	12	0.500	150	12
27	Right Hover Turn	0.500	150	12	8.009	2403	12	9.343	2803	12	10.677	3203	12	0.500	150	12
28	E/R Partial Power Descent	0.300	720	1.5	0.289	693	1.5	0.323	776	1.5	0.358	858	1.5	0.323	775	1.5
29	E/R Turn 30 Degrees Left	0.375	900	1.5	0.236	567	1.5	0.262	630	1.5	0.289	693	1.5	0.262	629	1.5
30	E/R Turn 30 Degrees Right	0.375	900	1.5	0.182	436	1.5	0.202	485	1.5	0.222	533	1.5	0.202	485	1.5
31	E/R Turn 45 Degrees Left	0.113	203	2	0.003	5	2	0.004	7	2	0.005	9	2	0.004	7	2
32	E/R Turn 45 Degrees Right	0.113	203	2	0.003	5	2	0.004	7	2	0.004	8	2	0.004	7	2
33	E/R Turn 60 Degrees Left	0.064	92	2.5	0.001	2	2.5	0.005	7	2.5	0.009	13	2.5	0.005	7	2.5
34	E/R Turn 60 Degrees Right	0.064	92	2.5	0.002	3	2.5	0.008	11	2.5	0.014	20	2.5	0.008	12	2.5
35	Auto Turn Left	0.138	33	15	0.013	3	15	0.024	6	15	0.034	8	15	4.338	1041	15
36	Auto Turn Right	0.138	33	15	0.013	3	15	0.024	6	15	0.034	8	15	1.938	465	15
37	Hover Approach	0.333	300	4	0.194	174	4	0.238	215	4	0.283	255	4	0.333	300	4
38	Taxi	0.270			32.046			33.187			34.328			0.270		
39	Taxi Turn	0.333	480	2.5	0.464	669	2.5	0.551	793	2.5	0.637	917	2.5	0.551	793	2.5

Figure 1. FSR CWC and SUMS usage spectra

Reg. No.	Description	CWC			SUMS M			SUMS M+1			SUMS M+2			CWC*		
		PCT Time	Occs /100	Secs /Occ	PCT Time	Occs /100	Secs /Occ	PCT Time	Occs /100	Secs /Occ	PCT Time	Occs /100	Secs /Occ	PCT Time	Occs /100	Secs /Occ
40	Hover	0.705			0.000			0.000			0.000			0.705		
41	Left Sideward Flight	0.200			0.061			0.066			0.072			0.200		
42	Right Sideward Flight	0.200			0.254			0.275			0.295			0.200		
43	Rearward Flight	0.200			0.070			0.078			0.085			0.200		
44	Climb	1.680			0.026			0.028			0.030			0.028		
45	Level Flight @ 0.1VH	0.918			0.000			0.000			0.000			0.918		
46	Level Flight @ 0.2VH	0.613			0.408			0.435			0.463			0.613		
47	Level Flight @ 0.4VH	1.224			0.009			0.010			0.011			1.224		
48	Level Flight @ 0.5VH	1.224			0.013			0.015			0.017			1.224		
49	Level Flight @ 0.6VH	1.684			0.046			0.052			0.058			1.684		
50	Level Flight @ 0.7VH	1.837			0.098			0.107			0.116			1.837		
51	Level Flight @ 0.8VH	6.125			0.071			0.086			0.101			6.125		
52	Level Flight @ 0.9VH	9.188			0.020			0.030			0.040			9.188		
53	Level Flight @ 1.0VH	4.594			0.004			0.007			0.009			0.094		
54	Sideslip	0.400			0.020			0.022			0.024			0.400		
55	Autoration	0.534			0.000			0.000			0.000			0.534		
56	Partial Power Descent	0.800			0.024			0.026			0.029			0.800		
57	Dive	0.930			0.009			0.013			0.016			0.830		
58	Turn 30 Degrees Left	1.417			0.027			0.030			0.033			1.417		
59	Turn 30 Degrees Right	1.417			0.021			0.023			0.026			1.417		
60	Turn 45 Degrees Left	0.207			0.000			0.000			0.000			0.207		
61	Turn 45 Degrees Right	0.207			0.000			0.000			0.000			0.207		
62	Turn 60 Degrees Left	0.017			0.000			0.000			0.000			0.017		
63	Turn 60 Degrees Right	0.017			0.000			0.000			0.000			0.017		
64	Take Off	0.400	240	6	0.023	14	6	0.024	14	6	0.025	15	6	0.400	240	6
65	Left Hover Turn	0.333	100	12	0.188	56	12	0.219	66	12	0.251	75	12	0.333	100	12
66	Right Hover Turn	0.333	100	12	0.163	49	12	0.191	57	12	0.218	65	12	6.277	1883	12
67	E/R Partial Power Descent	0.200	480	1.5	0.006	14	1.5	0.007	16	1.5	0.007	18	1.5	0.200	480	1.5
68	E/R Turn 30 Degrees Left	0.250	600	1.5	0.005	12	1.5	0.005	13	1.5	0.006	14	1.5	0.250	600	1.5
69	E/R Turn 30 Degrees Right	0.250	600	1.5	0.004	9	1.5	0.004	10	1.5	0.005	11	1.5	0.250	600	1.5
70	E/R Turn 45 Degrees Left	0.076	137	2	0.000	0	2	0.000	0	2	0.000	0	2	0.076	137	2
71	E/R Turn 45 Degrees Right	0.076	137	2	0.000	0	2	0.000	0	2	0.000	0	2	0.076	137	2
72	E/R Turn 60 Degrees Left	0.043	62	2.5	0.000	0	2.5	0.000	0	2.5	0.000	0	2.5	0.043	62	2.5
73	E/R Turn 60 Degrees Right	0.043	62	2.5	0.000	0	2.5	0.000	0	2.5	0.000	0	2.5	0.043	62	2.5
74	Auto Turn Left	0.061	22	10	0.000	0	10	0.000	0	10	0.001	0	10	0.061	22	10
75	Auto Turn Right	0.061	22	10	0.000	0	10	0.000	0	10	0.001	0	10	1.661	598	10
76	Hover Approach	0.222	200	4	0.004	4	4	0.005	4	4	0.006	5	4	0.222	200	4
77	Taxi	0.180			0.654			0.677			0.701			0.180		
78	Taxi Turn	0.222	320	2.5	0.009	14	2.5	0.011	16	2.5	0.013	19	2.5	0.222	320	2.5

Figure 1. FSR CWC and SUMS usage spectra (continued)

Reg. No.	Description	CWC			SUMS M			SUMS M+1			SUMS M+2			CWC*		
		PCT Time	Occs /100	Secs /Occ	PCT Time	Occs /100	Secs /Occ	PCT Time	Occs /100	Secs /Occ	PCT Time	Occs /100	Secs /Occ	PCT Time	Occs /100	Secs /Occ
79	Normal Landing	0.458	550	3	0.524	629	3	0.577	692	3	0.629	755	3	0.458	550	3
80	Run-on Landing	0.097	50	7	0.000	0	7	0.000	0	7	0.000	0	7	0.097	50	7
81	Hover Rudder Reversal	0.046	110	1.5	0.000	0	1.5	0.000	0	1.5	0.000	1	1.5	0.046	110	1.5
82	Level Flight Rudder Reversal	0.123	295	1.5	0.000	1	1.5	0.001	3	1.5	0.002	4	1.5	0.173	415	1.5
83	Hover Longitudinal Reversal	0.046	110	1.5	0.018	43	1.5	0.024	58	1.5	0.030	72	1.5	0.024	58	1.5
84	Level Flight Longitudinal Reversal	0.123	295	1.5	0.066	158	1.5	0.131	315	1.5	0.197	473	1.5	0.131	314	1.5
85	Hover Lateral Reversal	0.046	110	1.5	0.026	62	1.5	0.037	89	1.5	0.049	117	1.5	0.046	110	1.5
86	Level Flight Lateral Reversal	0.123	295	1.5	0.028	68	1.5	0.041	97	1.5	0.053	127	1.5	0.123	295	1.5
87	Moderate Pullout	0.222	80	10	0.256	92	10	0.277	100	10	0.298	107	10	0.277	100	10
88	Severe Pullout	0.056	40	5	0.000	0	5	0.000	0	5	0.000	0	5	0.059	42	5
89	Entry Autorotation	0.053	95	2	0.012	22	2	0.012	22	2	0.012	22	2	0.053	95	2
90	Recover from Autorotation	0.053	95	2	0.012	22	2	0.012	22	2	0.012	22	2	0.012	22	2
91	Entry Left Sideward	0.125	180	2.5	0.758	1092	2.5	0.829	1194	2.5	0.900	1297	2.5	0.125	180	2.5
92	Recovery Left Sideward	0.125	180	2.5	0.758	1092	2.5	0.829	1194	2.5	0.900	1297	2.5	0.125	180	2.5
93	Entry Right Sideward	0.125	180	2.5	3.179	4578	2.5	3.432	4941	2.5	3.684	5305	2.5	0.125	180	2.5
94	Recovery Right Sideward	0.125	180	2.5	3.179	4578	2.5	3.432	4941	2.5	3.684	5305	2.5	0.125	180	2.5
95	Entry Rearward	0.125	180	2.5	0.874	1258	2.5	0.969	1395	2.5	1.064	1532	2.5	0.125	180	2.5
96	Recovery Rearward	0.125	180	2.5	0.874	1258	2.5	0.969	1395	2.5	1.064	1532	2.5	0.125	180	2.5
97	Droop Stop Pounding		500	1		50	1		75	1		100	1	0.000	500	1
98	Extreme Maneuver		0.1	5		0.0	5		0.0	5		0.0	5	0.000	0.1	5
99	3.3G Pullout (Structural Design)	0.003	2	5	0.000	0	5	0.000	0	5	0.000	0	5	0.003	2	5
100	Single Engine Failure in Hover		50			0			0			0		0.000	50	
101	Single Engine Failure at Altitude		100			0			0			0		0.000	100	
102	GAG/Flight		400			478			503			527		0.000	400	
103	Min-Max (a.k.a. Full-Stop Landing)		200			218			587			955		0.000	200	

Figure 1. FSR CWC and SUMS usage spectra (continued)

Failure Mode	Description
1	MR Cuff no Chafing
2	MR Cuff-to-Blade Bolts
3	MR Expandable Pin Steel with Chafing
4	MR Expandable Pin Steel No Chafing
5	IDGB MR Shaft Assembly Chafing in Upper Bearing
6	IDGB MR Shaft Assembly Potential No Chafing
7	IDGB MR Shaft Extender Attach Shoulder Chafing
8	IDGB MR Shaft Ext Attach Shoulder Potential No Chafing
9	MR Hub Assembly Arm Observation Hole No Chafing
10	MR Elastomer Bearing End Plate Potential No Chafing
11	MR Bifilar Assembly Potential Chafing
12	MR Bifilar Assembly Potential No Chafing
13	MR Growth Spindle Droop Stop Shank No Chafing
14	MR Growth Spindle Axial Thread No Chafing
15	MR Growth Spindle Horn Attachment Flange Chafing
16	MR Growth Spindle Horn Attachment Flange Potential No Chafing
17	MR Spindle Retention Nut Potential Chafing
18	MR Pitch Horn Radius No Chafing
19	MR Pitch Horn Potential No Chafing
20	MR Pitch Horn Attach Bolts Potential No Chafing
21	MR Pushrod to Swashplate Attach Bolts Potential Chafing
22	MR Pushrod to Swashplate Attach Bolts Potential No Chafing
23	MR Rotating Swashplate Chafing
24	MR Rotating Swashplate Potential No Chafing
25	Main Gearbox Housing Vertical Aft Support Bridge Potential No Chafing
26	Main Gearbox Housing Vertical Aft Support Bridge Attach Potential Chafing
27	Main Gearbox Housing Horiz Aft Support Bridge Attachment Potential No Chafing
28	Main Gearbox Housing Horiz Aft Support Bridge Attachment Potential Chafing
29	Main Gearbox Housing Support Bridge Tongue Pad Potential No Chafing
30	Main Gearbox Housing Support Bridge Tongue Pad Potential Chafing
31	Main Gearbox Housing Left Tie Rod Attach Pad Potential No Chafing
32	Main Gearbox Housing Left Tie Rod Attach Pad Potential Chafing
33	Aft Support Bridge Dowel Pin Potential No Chafing
34	Aft Tie Rod Dowel Pin Potential No Chafing
35	Left Tie Rod Dowel Pin Potential No Chafing
36	Left Tie Rod Dowel Pin Potential Chafing
37	Aft Support Bridge Bellcrank Pivot Lug No Chafing
38	Main Support Bridge Potential No Chafing
39	Main Support Bridge Potential Chafing
40	Aft Walking Beam Potential No Chafing
41	Aft Bellcrank Potential No Chafing
42	Forward Bellcrank Potential No Chafing

Failure Mode	Description
43	Lateral Bellcrank Potential No Chafing
44	MR Aft Tie Rod Potential No Chafing
45	Left Tie Rod No Chafing
46	Left Tie Rod with Chafing
47	Right Tie Rod Attachment Bolt No Chafing
48	Aft Walking Beam Pivot Bolt No Chafing
49	Lateral Swashplate Link to Bellcrank Pivot Bolt Potential No Chafing
50	Lateral Bellcrank Pivot Bolt Potential No Chafing
51	Aft Bellcrank Pivot Bolt Potential No Chafing
52	Aft Support Strut and Base Potential No Chafing
53	Aft-Forward Servo Beam Rail Potential No Chafing
54	Aft-Forward Servo Beam Rail Potential Chafing
55	Forward Servo Beam Rail Aft Lug No Chafing
56	Lateral Servo Beam Rail Potential No Chafing
57	Lateral Servo Beam Rail Potential Chafing
58	Aft-Lateral Servo Beam Rail Lug No Chafing
59	Aft-Lateral Servo Beam Rail Lug Potential Chafing
60	Swashplate Bearing Retainer Ring No Chafing
61	Swashplate Bearing Retainer Ring Link Lug No Chafing
62	Swashplate Bearing Retainer Potential Chafing
63	TR Shaft Nut Under Split Cone Chafing
64	TR Blade Spar Potential Fiber Mode
65	TR Pitch Horn Trailing Edge No Chafing
66	TR Pitch Servo Assembly No Chafing
67	TR Servo Assembly Rod End Lug Chafing
68	TR Servo Assembly Rod End Lug No Chafing
69	TR Servo Fitting and Sleeve Assembly Potential No Chafing
70	Composite Horizontal Stabilator Wing Panel Matrix
71	Composite Stabilator Wing-to-Pylon Lugs Chafing
72	Composite Stabilator Wing-to-Pylon Lugs Potential No Chafing
73	Horizontal Stabilator Clevis Assembly Potential No Chafing
74	Composite Stabilator Center Box Chafing
75	Composite Stabilator Center Box Potential No Chafing
76	Transfer Module Common Manifold No Chafing
77	Hydraulic Pump Module Manifold No Chafing
78	SAS Actuator Assembly No Chafing
79	Pilot Assist Hydraulic Manifold No Chafing
80	Self Sealing Coupling Steel No Chafing
81	Self Sealing Coupling Aluminum No Chafing
82	Self Sealing Coupling 2 Aluminum No Chafing
83	MR Primary Servo Housing No Chafing
84	TR Servo Housing No Chafing

Figure 2. 84 failure modes

Failure Mode	CWC	SUMS M	SUMS M+1	SUMS M+2	CWC*	Failure Mode	CWC	SUMS M	SUMS M+1	SUMS M+2	CWC*
1	8513	7370	4710	3460	8513	43	11045	93016	59437	43671	10563
2	24008	33762	17172	11514	23104	44	23650	20390	13029	9573	23650
3	13012	22646	14465	10626	13218	45	10370	11114	7099	5214	10366
4	8465	7298	4664	3427	8465	46	5241	12882	8472	6311	5877
5	21462	27622	21761	17952	10275	47	13224	29330	18740	13768	12848
6	14903	33773	21650	15932	14661	48	12191	10565	6751	4960	12187
7	18449	40526	26475	19659	19746	49	12845	99852	63805	46881	12290
8	6644	19080	12282	9055	6561	50	11045	93016	59437	43671	10563
9	8936	17296	11965	9146	8907	51	12898	11157	7129	5238	12896
10	21182	49349	31809	23468	21180	52	23874	25645	16391	12045	23744
11	16068	28422	22024	17978	15211	53	24465	95805	62655	46548	23925
12	17178	32129	24141	19334	16508	54	15687	89580	61066	46322	15654
13	10158	48513	40781	35175	9832	55	4281	24919	17005	12906	4280
14	8795	8691	4600	3127	8795	56	12105	37835	25432	19154	12147
15	17779	45413	29148	21462	17426	57	7275	50268	34460	26216	9533
16	23122	56251	36769	27311	22472	58	4143	20973	14264	10807	4614
17	18500	24415	15633	11498	18500	59	6501	47191	32396	24664	8757
18	9961	28101	19445	14866	10442	60	21685	86807	56980	42408	21204
19	12670	47800	33867	26223	15141	61	10408	34792	23431	17663	10501
20	11034	24201	15454	11351	10831	62	9000	56473	38612	29334	11186
21	24321	68572	48020	36947	23484	63	1817	4400	3850	3423	2383
22	8937	20361	13513	10111	8688	64	17830	71801	55439	45151	18213
23	5169	18248	13026	10128	5628	65	21194	35544	23314	17346	10019
24	7428	20809	14511	11139	7512	66	16087	13870	8863	6512	16087
25	16124	19437	12478	9188	15977	67	22746	19675	12732	9411	22515
26	9801	19570	13128	9877	9692	68	23509	20269	12952	9516	23509
27	12013	15836	10205	7528	11873	69	10971	9459	6044	4441	10971
28	22836	35641	23234	17234	22448	70	1659	1430	914	671	1659
29	11637	37013	24894	18753	11689	71	2992	7451	5128	3909	3082
30	8828	55887	38221	29041	11025	72	9443	8142	5202	3823	9443
31	5159	7537	4830	3553	5309	73	20859	18218	11641	8553	20845
32	4696	9799	6841	5255	5277	74	1030	3089	2321	1859	1421
33	12616	10935	6987	5134	12613	75	2410	4075	2735	2058	2462
34	23650	20390	13029	9573	23650	76	12981	11191	7151	5254	12981
35	6638	6450	4122	3028	6600	77	9028	7784	4974	3654	9028
36	34173	36583	23376	17176	33831	78	13261	11433	7306	5368	13261
37	21625	23910	15303	11253	21481	79	12402	10692	6832	5020	12402
38	19067	48321	32264	24217	18925	80	21406	18455	11793	8665	21406
39	14893	70912	48192	36498	15432	81	24444	21074	13466	9894	24444
40	11088	9638	6159	4525	11083	82	24444	21074	13466	9894	24444
41	12898	11157	7129	5238	12896	83	20127	17352	11088	8147	20127
42	14840	44540	28446	20895	14455	84	23498	20259	12945	9512	23498

Figure 3. Component fatigue life for each of the usage spectra

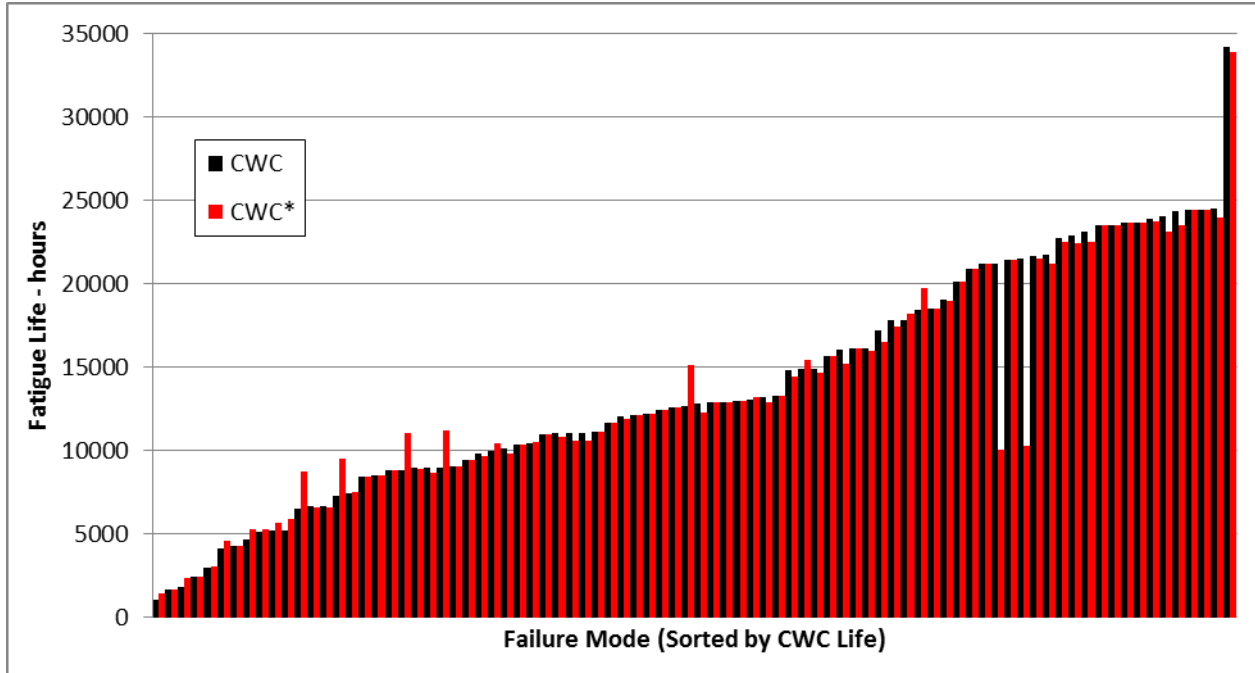


Figure 4. Comparison of CWC and CWC* fatigue lives

2.1 METHOD 1 RESULTS, CONSTANT COMPONENT RELIABILITY

As explained in section 3.3, Method 1 assumes that each of the 84 failure modes start with a fixed reliability. A constant reliability of 9_6 is chosen for consistency with ADS-79 and previous work. The EL for each part is adjusted to find the change in reliability between spectra, which is added to the fixed reliability baseline. The product of all the failure modes provides a system reliability. The new reliability is compared to the baseline reliability of $0.999999^{84} = 0.999916$.

The results of the reliability calculations for the M+1, M+2, and CWC* spectra are shown in table 1, with the individual reliability calculations shown in figures 5–7. For the Constant Component Reliability method, it can be seen that none of the spectra being compared to the CWC are more reliable because they all have fewer than $9_{4.08}$.

Table 1. Method 1 spectra reliability comparisons

	Reliability	9s
CWC	0.999916	4.08
SUMS M+1	0.997530	2.61
SUMS M+2	0.999039	3.02
CWC*	0.999911	4.05

Failure Mode	M+1	CWC	Adj. ELZ	Δ Reliability (9s)	Part Reliability	Failure Mode	M+1	CWC	Adj. ELZ	Δ Reliability (9s)	Part Reliability
1	8513	8513	-2.20	1.02	1.000000	43	59437	11045	-4.49	-2.58	0.999617
2	24008	24008	-3.04	-0.06	0.999999	44	13029	23650	-2.36	0.83	1.000000
3	13012	13012	-3.30	-0.45	0.999997	45	7099	10370	-2.42	0.76	1.000000
4	8465	8465	-1.52	1.68	1.000000	46	8472	5241	-3.22	-0.32	0.999998
5	21462	21462	-3.01	-0.01	0.999999	47	18740	13224	-3.38	-0.56	0.999996
6	14903	14903	-3.29	-0.43	0.999997	48	6751	12191	-1.90	1.33	1.000000
7	18449	18449	-3.44	-0.67	0.999995	49	63805	12845	-4.49	-2.57	0.999629
8	6644	6644	-3.38	-0.57	0.999996	50	59437	11045	-4.49	-2.58	0.999617
9	8936	8936	-3.19	-0.28	0.999998	51	7129	12898	-1.94	1.29	1.000000
10	21182	21182	-3.35	-0.53	0.999997	52	16391	23874	-2.53	0.63	1.000000
11	16068	16068	-3.29	-0.43	0.999997	53	62655	24465	-3.74	-1.17	0.999985
12	17178	17178	-3.18	-0.27	0.999998	54	61066	15687	-4.27	-2.13	0.999864
13	10158	10158	-3.72	-1.12	0.999987	55	17005	4281	-4.29	-2.18	0.999849
14	8795	8795	-1.74	1.49	1.000000	56	25432	12105	-3.66	-1.03	0.999989
15	17779	17779	-3.56	-0.85	0.999993	57	34460	7275	-4.29	-2.18	0.999850
16	23122	23122	-3.44	-0.67	0.999995	58	14264	4143	-4.19	-1.99	0.999903
17	18500	18500	-2.78	0.30	0.999999	59	32396	6501	-4.29	-2.18	0.999848
18	9961	9961	-3.50	-0.77	0.999994	60	56980	21685	-3.77	-1.22	0.999983
19	12670	12670	-3.83	-1.32	0.999979	61	23431	10408	-3.73	-1.15	0.999986
20	11034	11034	-3.42	-0.64	0.999996	62	38612	9000	-4.30	-2.21	0.999839
21	24321	24321	-3.77	-1.22	0.999984	63	3850	1817	-3.41	-0.61	0.999996
22	8937	8937	-3.43	-0.65	0.999996	64	55439	17830	-3.65	-1.01	0.999990
23	5169	5169	-3.83	-1.33	0.999979	65	23314	21194	-3.04	-0.06	0.999999
24	7428	7428	-3.56	-0.85	0.999993	66	8863	16087	-2.11	1.11	1.000000
25	16124	16124	-2.67	0.45	1.000000	67	12732	22746	-1.22	1.92	1.000000
26	9801	9801	-3.30	-0.45	0.999997	68	12952	23509	-2.36	0.83	1.000000
27	12013	12013	-2.78	0.30	0.999999	69	6044	10971	-1.79	1.44	1.000000
28	22836	22836	-3.02	-0.03	0.999999	70	914	1659	-2.67	0.45	1.000000
29	11637	11637	-3.68	-1.06	0.999989	71	5128	2992	-3.60	-0.92	0.999992
30	8828	8828	-4.30	-2.19	0.999845	72	5202	9443	-1.51	1.69	1.000000
31	5159	5159	-2.94	0.09	0.999999	73	11641	20859	-2.31	0.89	1.000000
32	4696	4696	-3.23	-0.34	0.999998	74	2321	1030	-3.54	-0.82	0.999993
33	12616	12616	-1.93	1.30	1.000000	75	2735	2410	-3.10	-0.15	0.999999
34	23650	23650	-2.36	0.83	1.000000	76	7151	12981	-2.08	1.14	1.000000
35	6638	6638	-1.68	1.54	1.000000	77	4974	9028	-2.01	1.21	1.000000
36	34173	34173	-1.98	1.25	1.000000	78	7306	13261	-2.09	1.13	1.000000
37	21625	21625	-2.56	0.58	1.000000	79	6832	12402	-2.07	1.15	1.000000
38	19067	19067	-3.46	-0.70	0.999995	80	11793	21406	-2.31	0.89	1.000000
39	14893	14893	-4.12	-1.86	0.999928	81	13466	24444	-2.21	1.00	1.000000
40	11088	11088	-1.82	1.41	1.000000	82	13466	24444	-2.21	1.00	1.000000
41	12898	12898	-1.94	1.29	1.000000	83	11088	20127	-2.27	0.94	1.000000
42	14840	14840	-3.56	-0.86	0.999993	84	12945	23498	-2.36	0.83	1.000000
										R_{sys}	0.997530

Figure 5. Method 1 M+1 reliability

Failure Mode	M+2	CWC	Adj. EL Z	Δ Reliability (9s)	Part Reliability	Failure Mode	M+2	CWC	Adj. EL Z	Δ Reliability (9s)	Part Reliability
1	3460	8513	-1.78	1.45	1.000000	43	43671	11045	-4.16	-1.94	0.999913
2	11514	24008	-2.41	0.77	1.000000	44	9573	23650	-2.13	1.09	1.000000
3	10626	13012	-2.40	0.78	1.000000	45	5214	10370	-1.93	1.30	1.000000
4	3427	8465	-0.89	2.14	1.000000	46	6311	5241	-3.06	-0.09	0.999999
5	17952	21462	-2.86	0.19	0.999999	47	13768	13224	-3.04	-0.06	0.999999
6	15932	14903	-3.05	-0.07	0.999999	48	4960	12191	-1.45	1.73	1.000000
7	19659	18449	-3.08	-0.11	0.999999	49	46881	12845	-4.20	-2.00	0.999900
8	9055	6644	-3.20	-0.30	0.999998	50	43671	11045	-4.16	-1.94	0.999913
9	9146	8936	-3.02	-0.03	0.999999	51	5238	12898	-1.52	1.68	1.000000
10	23468	21182	-3.10	-0.14	0.999999	52	12045	23874	-2.14	1.08	1.000000
11	17978	16068	-3.10	-0.15	0.999999	53	46548	24465	-3.52	-0.79	0.999994
12	19334	17178	-3.06	-0.09	0.999999	54	46322	15687	-4.04	-1.71	0.999949
13	35175	10158	-3.64	-0.99	0.999990	55	12906	4281	-4.06	-1.75	0.999944
14	3127	8795	-1.00	2.07	1.000000	56	19154	12105	-3.42	-0.63	0.999996
15	21462	17779	-3.26	-0.38	0.999998	57	26216	7275	-4.22	-2.04	0.999891
16	27311	23122	-3.16	-0.23	0.999998	58	10807	4143	-3.94	-1.52	0.999967
17	11498	18500	-2.41	0.77	1.000000	59	24664	6501	-4.19	-1.98	0.999904
18	14866	9961	-3.31	-0.46	0.999997	60	42408	21685	-3.55	-0.84	0.999993
19	26223	12670	-3.62	-0.96	0.999991	61	17663	10408	-3.49	-0.74	0.999994
20	11351	11034	-3.03	-0.05	0.999999	62	29334	9000	-4.19	-1.99	0.999902
21	36947	24321	-3.52	-0.80	0.999994	63	3423	1817	-3.33	-0.50	0.999997
22	10111	8937	-3.14	-0.20	0.999998	64	45151	17830	-3.53	-0.81	0.999993
23	10128	5169	-3.65	-1.01	0.999990	65	17346	21194	-2.93	0.10	0.999999
24	11139	7428	-3.34	-0.51	0.999997	66	6512	16087	-1.77	1.45	1.000000
25	9188	16124	-2.26	0.95	1.000000	67	9411	22746	-0.18	2.50	1.000000
26	9877	9801	-3.01	-0.01	0.999999	68	9516	23509	-2.13	1.09	1.000000
27	7528	12013	-2.36	0.83	1.000000	69	4441	10971	-1.29	1.86	1.000000
28	17234	22836	-2.60	0.54	1.000000	70	671	1659	-2.49	0.67	1.000000
29	18753	11637	-3.44	-0.66	0.999995	71	3909	2992	-3.33	-0.49	0.999997
30	29041	8828	-4.20	-2.01	0.999897	72	3823	9443	-0.87	2.15	1.000000
31	3553	5159	-2.44	0.74	1.000000	73	8553	20859	-2.05	1.18	1.000000
32	5255	4696	-3.08	-0.11	0.999999	74	1859	1030	-3.41	-0.61	0.999996
33	5134	12616	-1.50	1.70	1.000000	75	2058	2410	-2.86	0.19	0.999999
34	9573	23650	-2.13	1.09	1.000000	76	5254	12981	-1.59	1.61	1.000000
35	3028	6638	-0.94	2.11	1.000000	77	3654	9028	-1.47	1.72	1.000000
36	17176	34173	-1.14	1.97	1.000000	78	5368	13261	-1.60	1.61	1.000000
37	11253	21625	-2.17	1.05	1.000000	79	5020	12402	-1.58	1.63	1.000000
38	24217	19067	-3.22	-0.32	0.999998	80	8665	21406	-2.05	1.18	1.000000
39	36498	14893	-3.88	-1.41	0.999974	81	9894	24444	-1.81	1.42	1.000000
40	4525	11088	-1.33	1.83	1.000000	82	9894	24444	-1.81	1.42	1.000000
41	5238	12898	-1.52	1.68	1.000000	83	8147	20127	-1.99	1.23	1.000000
42	20895	14840	-3.26	-0.38	0.999998	84	9512	23498	-2.13	1.09	1.000000
										R_{sys}	0.999039

Figure 6. Method 1 M+2 Reliability

Failure Mode	CWC*	CWC	Adj. ELZ	Δ Reliability (9s)	Part Reliability	Failure Mode	CWC*	CWC	Adj. ELZ	Δ Reliability (9s)	Part Reliability
1	8513	8513	-3.00	0.00	0.999999	43	10563	11045	-2.94	0.09	0.999999
2	23104	24008	-3.05	-0.07	0.999999	44	23650	23650	-3.00	0.00	0.999999
3	13218	13012	-3.02	-0.03	0.999999	45	10366	10370	-3.00	0.00	0.999999
4	8465	8465	-3.00	0.00	0.999999	46	5877	5241	-3.06	-0.09	0.999999
5	10275	21462	-2.49	0.67	1.000000	47	12848	13224	-2.98	0.03	0.999999
6	14661	14903	-2.98	0.02	0.999999	48	12187	12191	-3.00	0.00	0.999999
7	19746	18449	-3.09	-0.13	0.999999	49	12290	12845	-2.95	0.08	0.999999
8	6561	6644	-2.99	0.01	0.999999	50	10563	11045	-2.94	0.09	0.999999
9	8907	8936	-3.00	0.00	0.999999	51	12896	12898	-3.00	0.00	0.999999
10	21180	21182	-3.00	0.00	0.999999	52	23744	23874	-3.00	0.01	0.999999
11	15211	16068	-2.95	0.07	0.999999	53	23925	24465	-2.99	0.02	0.999999
12	16508	17178	-2.98	0.03	0.999999	54	15654	15687	-3.00	0.00	0.999999
13	9832	10158	-2.98	0.02	0.999999	55	4280	4281	-3.00	0.00	0.999999
14	8795	8795	-3.00	0.00	0.999999	56	12147	12105	-3.00	0.00	0.999999
15	17426	17779	-2.98	0.03	0.999999	57	9533	7275	-3.21	-0.31	0.999998
16	22472	23122	-2.97	0.04	0.999999	58	4614	4143	-3.07	-0.10	0.999999
17	18500	18500	-3.00	0.00	0.999999	59	8757	6501	-3.24	-0.35	0.999998
18	10442	9961	-3.03	-0.04	0.999999	60	21204	21685	-2.99	0.02	0.999999
19	15141	12670	-3.13	-0.19	0.999998	61	10501	10408	-3.00	-0.01	0.999999
20	10831	11034	-2.98	0.02	0.999999	62	11186	9000	-3.16	-0.23	0.999998
21	23484	24321	-2.94	0.08	0.999999	63	2383	1817	-3.12	-0.18	0.999998
22	8688	8937	-2.97	0.04	0.999999	64	18213	17830	-3.01	-0.01	0.999999
23	5628	5169	-3.08	-0.12	0.999999	65	10019	21194	-2.92	0.11	0.999999
24	7512	7428	-3.01	-0.01	0.999999	66	16087	16087	-3.00	0.00	0.999999
25	15977	16124	-2.99	0.01	0.999999	67	22515	22746	-2.97	0.04	0.999999
26	9692	9801	-2.99	0.01	0.999999	68	23509	23509	-3.00	0.00	0.999999
27	11873	12013	-2.99	0.01	0.999999	69	10971	10971	-3.00	0.00	0.999999
28	22448	22836	-2.98	0.02	0.999999	70	1659	1659	-3.00	0.00	0.999999
29	11689	11637	-3.00	0.00	0.999999	71	3082	2992	-3.03	-0.05	0.999999
30	11025	8828	-3.17	-0.24	0.999998	72	9443	9443	-3.00	0.00	0.999999
31	5309	5159	-3.02	-0.03	0.999999	73	20845	20859	-3.00	0.00	0.999999
32	5277	4696	-3.07	-0.10	0.999999	74	1421	1030	-3.18	-0.27	0.999998
33	12613	12616	-3.00	0.00	0.999999	75	2462	2410	-3.01	-0.02	0.999999
34	23650	23650	-3.00	0.00	0.999999	76	12981	12981	-3.00	0.00	0.999999
35	6600	6638	-2.99	0.02	0.999999	77	9028	9028	-3.00	0.00	0.999999
36	33831	34173	-2.98	0.03	0.999999	78	13261	13261	-3.00	0.00	0.999999
37	21481	21625	-2.99	0.01	0.999999	79	12402	12402	-3.00	0.00	0.999999
38	18925	19067	-3.00	0.00	0.999999	80	21406	21406	-3.00	0.00	0.999999
39	15432	14893	-3.02	-0.03	0.999999	81	24444	24444	-3.00	0.00	0.999999
40	11083	11088	-3.00	0.00	0.999999	82	24444	24444	-3.00	0.00	0.999999
41	12896	12898	-3.00	0.00	0.999999	83	20127	20127	-3.00	0.00	0.999999
42	14455	14840	-2.98	0.03	0.999999	84	23498	23498	-3.00	0.00	0.999999
										R_{sys}	0.999911

Figure 7. Method 1 CWC* reliability

2.2 METHOD 2 RESULTS, RELATIVE EL

As explained in section 3.4, Method 2 is a relative comparison between the adjusted and the baseline EL. For each part, the EL is adjusted so that the new spectrum life matches the baseline spectrum life to determine the strength reliability of each part. The product of all the new strength reliabilities is compared to 84 parts, with a reliability determined from -3 standard deviations.

The results of the reliability calculations for the M+1, M+2, and CWC* spectra are shown in table 2, with the individual reliability calculations shown in figures 8–10. In this case, it can be seen by examining the delta reliability that both the M+1 and M+2 spectra are more reliable than the CWC and that the more severe M+2 is more reliable than M+1. For this method, a smaller R_{sys} indicates that a spectrum is more reliable. The CWC* spectrum is shown to be slightly more reliable than the CWC.

Table 2. Method 2 spectra reliability comparisons

	R_{sys}	Δ Reliability
CWC	0.892733	
SUMS M+1	0.447009	0.445724
SUMS M+2	0.071994	0.820739
CWC*	0.891117	0.001615

Failure Mode	M+1	CWC	Adj. EL Z	Reliability Usage
1	4710	8513	-2.20	0.986016
2	17172	24008	-3.04	0.998821
3	14465	13012	-3.30	0.999522
4	4664	8465	-1.52	0.935686
5	21761	21462	-3.01	0.998696
6	21650	14903	-3.29	0.999502
7	26475	18449	-3.44	0.999713
8	12282	6644	-3.38	0.999633
9	11965	8936	-3.19	0.999288
10	31809	21182	-3.35	0.999603
11	22024	16068	-3.29	0.999494
12	24141	17178	-3.18	0.999270
13	40781	10158	-3.72	0.999899
14	4600	8795	-1.74	0.958699
15	29148	17779	-3.56	0.999811
16	36769	23122	-3.44	0.999713
17	15633	18500	-2.78	0.997314
18	19445	9961	-3.50	0.999771
19	33867	12670	-3.83	0.999936
20	15454	11034	-3.42	0.999690
21	48020	24321	-3.77	0.999918
22	13513	8937	-3.43	0.999697
23	13026	5169	-3.83	0.999937
24	14511	7428	-3.56	0.999811
25	12478	16124	-2.67	0.996186
26	13128	9801	-3.30	0.999516
27	10205	12013	-2.78	0.997310
28	23234	22836	-3.02	0.998750
29	24894	11637	-3.68	0.999882
30	38221	8828	-4.30	0.999991
31	4830	5159	-2.94	0.998336
32	6841	4696	-3.23	0.999379
33	6987	12616	-1.93	0.972994
34	13029	23650	-2.36	0.990965
35	4122	6638	-1.68	0.953437
36	23376	34173	-1.98	0.976038
37	15303	21625	-2.56	0.994816
38	32264	19067	-3.46	0.999731
39	48192	14893	-4.12	0.999981
40	6159	11088	-1.82	0.965439
41	7129	12898	-1.94	0.973879
42	28446	14840	-3.56	0.999812

Failure Mode	M+1	CWC	Adj. EL Z	Reliability Usage
43	59437	11045	-4.49	0.999996
44	13029	23650	-2.36	0.990965
45	7099	10370	-2.42	0.992251
46	8472	5241	-3.22	0.999359
47	18740	13224	-3.38	0.999632
48	6751	12191	-1.90	0.971045
49	63805	12845	-4.49	0.999996
50	59437	11045	-4.49	0.999996
51	7129	12898	-1.94	0.973879
52	16391	23874	-2.53	0.994275
53	62655	24465	-3.74	0.999909
54	61066	15687	-4.27	0.999990
55	17005	4281	-4.29	0.999991
56	25432	12105	-3.66	0.999874
57	34460	7275	-4.29	0.999991
58	14264	4143	-4.19	0.999986
59	32396	6501	-4.29	0.999991
60	56980	21685	-3.77	0.999919
61	23431	10408	-3.73	0.999904
62	38612	9000	-4.30	0.999992
63	3850	1817	-3.41	0.999672
64	55439	17830	-3.65	0.999868
65	23314	21194	-3.04	0.998833
66	8863	16087	-2.11	0.982648
67	12732	22746	-1.22	0.888897
68	12952	23509	-2.36	0.990882
69	6044	10971	-1.79	0.962930
70	914	1659	-2.67	0.996169
71	5128	2992	-3.60	0.999839
72	5202	9443	-1.51	0.934166
73	11641	20859	-2.31	0.989557
74	2321	1030	-3.54	0.999797
75	2735	2410	-3.10	0.999040
76	7151	12981	-2.08	0.981408
77	4974	9028	-2.01	0.977886
78	7306	13261	-2.09	0.981602
79	6832	12402	-2.07	0.980988
80	11793	21406	-2.31	0.989434
81	13466	24444	-2.21	0.986520
82	13466	24444	-2.21	0.986520
83	11088	20127	-2.27	0.988310
84	12945	23498	-2.36	0.990875
			$R_{Sys,CWC}$	0.447009
			$R_{Sys,\mu-3\sigma}$	0.892733
			ΔR_{Sys}	0.445724

Figure 8. Method 2 M+1 Δ reliability

Failure Mode	M+2	CWC	Adj. EL Z	Reliability Usage
1	3460	8513	-1.78	0.962086
2	11514	24008	-2.41	0.992056
3	10626	13012	-2.40	0.991873
4	3427	8465	-0.89	0.814014
5	17952	21462	-2.86	0.997905
6	15932	14903	-3.05	0.998863
7	19659	18449	-3.08	0.998961
8	9055	6644	-3.20	0.999319
9	9146	8936	-3.02	0.998733
10	23468	21182	-3.10	0.999028
11	17978	16068	-3.10	0.999040
12	19334	17178	-3.06	0.998902
13	35175	10158	-3.64	0.999862
14	3127	8795	-1.00	0.841561
15	21462	17779	-3.26	0.999434
16	27311	23122	-3.16	0.999213
17	11498	18500	-2.41	0.992004
18	14866	9961	-3.31	0.999531
19	26223	12670	-3.62	0.999851
20	11351	11034	-3.03	0.998786
21	36947	24321	-3.52	0.999784
22	10111	8937	-3.14	0.999148
23	10128	5169	-3.65	0.999867
24	11139	7428	-3.34	0.999582
25	9188	16124	-2.26	0.987956
26	9877	9801	-3.01	0.998686
27	7528	12013	-2.36	0.990977
28	17234	22836	-2.60	0.995346
29	18753	11637	-3.44	0.999706
30	29041	8828	-4.20	0.999987
31	3553	5159	-2.44	0.992598
32	5255	4696	-3.08	0.998951
33	5134	12616	-1.50	0.932865
34	9573	23650	-2.13	0.983480
35	3028	6638	-0.94	0.825416
36	17176	34173	-1.14	0.873610
37	11253	21625	-2.17	0.984980
38	24217	19067	-3.22	0.999348
39	36498	14893	-3.88	0.999947
40	4525	11088	-1.33	0.908645
41	5238	12898	-1.52	0.935826
42	20895	14840	-3.26	0.999442

Failure Mode	M+2	CWC	Adj. EL Z	Reliability Usage
43	43671	11045	-4.16	0.999984
44	9573	23650	-2.13	0.983480
45	5214	10370	-1.93	0.973324
46	6311	5241	-3.06	0.998892
47	13768	13224	-3.04	0.998813
48	4960	12191	-1.45	0.926854
49	46881	12845	-4.20	0.999986
50	43671	11045	-4.16	0.999984
51	5238	12898	-1.52	0.935826
52	12045	23874	-2.14	0.983923
53	46548	24465	-3.52	0.999783
54	46322	15687	-4.04	0.999974
55	12906	4281	-4.06	0.999976
56	19154	12105	-3.42	0.999687
57	26216	7275	-4.22	0.999988
58	10807	4143	-3.94	0.999960
59	24664	6501	-4.19	0.999986
60	42408	21685	-3.55	0.999806
61	17663	10408	-3.49	0.999757
62	29334	9000	-4.19	0.999986
63	3423	1817	-3.33	0.999571
64	45151	17830	-3.53	0.999793
65	17346	21194	-2.93	0.998288
66	6512	16087	-1.77	0.961808
67	9411	22746	-0.18	0.570088
68	9516	23509	-2.13	0.983284
69	4441	10971	-1.29	0.902229
70	671	1659	-2.49	0.993659
71	3909	2992	-3.33	0.999567
72	3823	9443	-0.87	0.809068
73	8553	20859	-2.05	0.979694
74	1859	1030	-3.41	0.999671
75	2058	2410	-2.86	0.997889
76	5254	12981	-1.59	0.944531
77	3654	9028	-1.47	0.929672
78	5368	13261	-1.60	0.945327
79	5020	12402	-1.58	0.942802
80	8665	21406	-2.05	0.979768
81	9894	24444	-1.81	0.964509
82	9894	24444	-1.81	0.964509
83	8147	20127	-1.99	0.976948
84	9512	23498	-2.13	0.983268
			$R_{Sys,CWC}$	0.071994
			$R_{Sys,\mu-3\sigma}$	0.892733
			ΔR_{Sys}	0.820739

Figure 9. Method 2 M+2 Δ reliability

Failure Mode	CWC*	CWC	Adj. EL Z	Reliability Usage
1	8513	8513	-3.00	0.998650
2	23104	24008	-3.05	0.998862
3	13218	13012	-3.02	0.998737
4	8465	8465	-3.00	0.998650
5	10275	21462	-2.49	0.993639
6	14661	14903	-2.98	0.998582
7	19746	18449	-3.09	0.999004
8	6561	6644	-2.99	0.998605
9	8907	8936	-3.00	0.998636
10	21180	21182	-3.00	0.998650
11	15211	16068	-2.95	0.998429
12	16508	17178	-2.98	0.998568
13	9832	10158	-2.98	0.998574
14	8795	8795	-3.00	0.998650
15	17426	17779	-2.98	0.998565
16	22472	23122	-2.97	0.998531
17	18500	18500	-3.00	0.998650
18	10442	9961	-3.03	0.998780
19	15141	12670	-3.13	0.999137
20	10831	11034	-2.98	0.998580
21	23484	24321	-2.94	0.998382
22	8688	8937	-2.97	0.998517
23	5628	5169	-3.08	0.998979
24	7512	7428	-3.01	0.998685
25	15977	16124	-2.99	0.998621
26	9692	9801	-2.99	0.998611
27	11873	12013	-2.99	0.998603
28	22448	22836	-2.98	0.998576
29	11689	11637	-3.00	0.998660
30	11025	8828	-3.17	0.999225
31	5309	5159	-3.02	0.998736
32	5277	4696	-3.07	0.998931
33	12613	12616	-3.00	0.998648
34	23650	23650	-3.00	0.998650
35	6600	6638	-2.99	0.998590
36	33831	34173	-2.98	0.998549
37	21481	21625	-2.99	0.998624
38	18925	19067	-3.00	0.998635
39	15432	14893	-3.02	0.998752
40	11083	11088	-3.00	0.998646
41	12896	12898	-3.00	0.998649
42	14455	14840	-2.98	0.998560

Failure Mode	CWC*	CWC	Adj. EL Z	Reliability Usage
43	10563	11045	-2.94	0.998346
44	23650	23650	-3.00	0.998650
45	10366	10370	-3.00	0.998648
46	5877	5241	-3.06	0.998901
47	12848	13224	-2.98	0.998568
48	12187	12191	-3.00	0.998648
49	12290	12845	-2.95	0.998387
50	10563	11045	-2.94	0.998346
51	12896	12898	-3.00	0.998649
52	23744	23874	-3.00	0.998628
53	23925	24465	-2.99	0.998587
54	15654	15687	-3.00	0.998643
55	4280	4281	-3.00	0.998650
56	12147	12105	-3.00	0.998658
57	9533	7275	-3.21	0.999336
58	4614	4143	-3.07	0.998935
59	8757	6501	-3.24	0.999397
60	21204	21685	-2.99	0.998585
61	10501	10408	-3.00	0.998671
62	11186	9000	-3.16	0.999213
63	2383	1817	-3.12	0.999100
64	18213	17830	-3.01	0.998680
65	10019	21194	-2.92	0.998255
66	16087	16087	-3.00	0.998650
67	22515	22746	-2.97	0.998524
68	23509	23509	-3.00	0.998650
69	10971	10971	-3.00	0.998650
70	1659	1659	-3.00	0.998650
71	3082	2992	-3.03	0.998786
72	9443	9443	-3.00	0.998650
73	20845	20859	-3.00	0.998646
74	1421	1030	-3.18	0.999268
75	2462	2410	-3.01	0.998703
76	12981	12981	-3.00	0.998650
77	9028	9028	-3.00	0.998650
78	13261	13261	-3.00	0.998650
79	12402	12402	-3.00	0.998650
80	21406	21406	-3.00	0.998650
81	24444	24444	-3.00	0.998650
82	24444	24444	-3.00	0.998650
83	20127	20127	-3.00	0.998650
84	23498	23498	-3.00	0.998650
			$R_{Sys,CWC}$	0.891117
			$R_{Sys,\mu-3\sigma}$	0.892733
			ΔR_{Sys}	0.001615

Figure 10. Method 2 CWC* Δ reliability

2.3 METHOD 3 RESULTS, SUMS REFERENCE

As explained in section 3.5, Method 3 determines an absolute strength and usage reliability value for a given spectrum by referencing it to the SUMS average spectrum, or SUMS M. For this method, each spectrum is compared individually against the SUMS average and then the reliability results can be compared to each other.

The results of the reliability calculations for the M+1, M+2, and CWC* spectra are shown in table 3, with the individual reliability calculations shown in figures 11–14. For the SUMS Reference method, all of the candidate spectra are more reliable than the CWC, with the more severe M+2 being more reliable than M+1. CWC* is shown to be more reliable than the CWC, but only by a very small amount.

Table 3. Method 3 spectra reliability comparisons

	Reliability	9s
CWC	0.955630	1.35
M+1	0.986219	1.86
M+2	0.993018	2.16
CWC*	0.956163	1.36

Failure Mode	M	CWC	Adj. ELZ	Δ Reliability (9's)	Δ Rel. EL+Usage (9's)	Reliability EL+Usage	Failure Mode	M	CWC	Adj. ELZ	Δ Reliability (9's)	Δ Rel. EL+Usage (9's)	Reliability EL+Usage
1	7370	8513	-2.81	0.03	2.90	0.998747	43	93016	11045	-5.08	4.15	7.02	1.000000
2	33762	24008	-3.58	1.19	4.06	0.999913	44	20390	23650	-2.82	0.05	2.92	0.998786
3	22646	13012	-4.49	2.87	5.74	0.999998	45	11114	10370	-3.10	0.45	3.32	0.999521
4	7298	8465	-2.60	-0.23	2.64	0.997694	46	12882	5241	-3.37	0.86	3.73	0.999814
5	27622	21462	-3.14	0.51	3.38	0.999579	47	29330	13224	-3.82	1.60	4.47	0.999966
6	33773	14903	-3.67	1.35	4.22	0.999940	48	10565	12191	-2.70	-0.10	2.77	0.998282
7	40526	18449	-3.59	1.22	4.09	0.999919	49	99852	12845	-5.01	4.00	6.87	1.000000
8	19080	6644	-3.58	1.19	4.06	0.999913	50	93016	11045	-5.08	4.15	7.02	1.000000
9	17296	8936	-3.39	0.88	3.75	0.999824	51	11157	12898	-2.71	-0.09	2.78	0.998323
10	49349	21182	-3.55	1.14	4.01	0.999903	52	25645	23874	-3.08	0.42	3.29	0.999489
11	28422	16068	-3.52	1.10	3.97	0.999892	53	95805	24465	-4.05	2.02	4.89	0.999987
12	32129	17178	-3.34	0.81	3.68	0.999792	54	89580	15687	-4.53	2.96	5.83	0.999999
13	48513	10158	-3.81	1.59	4.46	0.999965	55	24919	4281	-4.48	2.86	5.73	0.999998
14	8691	8795	-2.98	0.27	3.14	0.999273	56	37835	12105	-3.97	1.88	4.75	0.999982
15	45413	17779	-4.03	1.98	4.85	0.999986	57	50268	7275	-4.40	2.70	5.56	0.999997
16	56251	23122	-3.83	1.63	4.50	0.999968	58	20973	4143	-4.39	2.67	5.54	0.999997
17	24415	18500	-3.37	0.85	3.72	0.999811	59	47191	6501	-4.39	2.68	5.55	0.999997
18	28101	9961	-3.76	1.50	4.37	0.999958	60	86807	21685	-4.08	2.08	4.95	0.999989
19	47800	12670	-4.08	2.07	4.94	0.999989	61	34792	10408	-4.04	2.00	4.87	0.999987
20	24201	11034	-4.13	2.17	5.04	0.999991	62	56473	9000	-4.40	2.70	5.57	0.999997
21	68572	24321	-4.10	2.12	4.99	0.999990	63	4400	1817	-3.49	1.05	3.92	0.999879
22	20361	8937	-3.82	1.61	4.48	0.999967	64	71801	17830	-3.73	1.44	4.31	0.999951
23	18248	5169	-4.05	2.02	4.89	0.999987	65	35544	21194	-3.18	0.56	3.43	0.999626
24	20809	7428	-3.84	1.64	4.51	0.999969	66	13870	16087	-2.75	-0.04	2.83	0.998507
25	19437	16124	-3.23	0.64	3.51	0.999692	67	19675	22746	-2.59	-0.25	2.62	0.997604
26	19570	9801	-3.66	1.34	4.20	0.999938	68	20269	23509	-2.82	0.04	2.91	0.998782
27	15836	12013	-3.35	0.82	3.69	0.999795	69	9459	10971	-2.67	-0.15	2.72	0.998088
28	35641	22836	-3.33	0.80	3.67	0.999785	70	1430	1659	-2.92	0.18	3.05	0.999118
29	37013	11637	-3.99	1.91	4.78	0.999984	71	7451	2992	-3.79	1.56	4.43	0.999962
30	55887	8828	-4.40	2.70	5.57	0.999997	72	8142	9443	-2.60	-0.24	2.63	0.997675
31	7537	5159	-3.40	0.90	3.77	0.999831	73	18218	20859	-2.82	0.04	2.91	0.998782
32	9799	4696	-3.38	0.87	3.73	0.999816	74	3089	1030	-3.70	1.39	4.26	0.999945
33	10935	12616	-2.71	-0.09	2.77	0.998321	75	4075	2410	-3.35	0.83	3.70	0.999799
34	20390	23650	-2.82	0.05	2.92	0.998786	76	11191	12981	-2.78	-0.01	2.86	0.998630
35	6450	6638	-2.92	0.18	3.05	0.999113	77	7784	9028	-2.76	-0.03	2.84	0.998565
36	36583	34173	-3.18	0.56	3.43	0.999632	78	11433	13261	-2.78	-0.01	2.86	0.998634
37	23910	21625	-3.12	0.48	3.35	0.999551	79	10692	12402	-2.78	-0.01	2.86	0.998622
38	48321	19067	-3.78	1.54	4.41	0.999961	80	18455	21406	-2.80	0.02	2.89	0.998725
39	70912	14893	-4.44	2.77	5.64	0.999998	81	21074	24444	-2.81	0.03	2.90	0.998743
40	9638	11088	-2.69	-0.12	2.75	0.998210	82	21074	24444	-2.81	0.03	2.90	0.998743
41	11157	12898	-2.71	-0.09	2.78	0.998323	83	17352	20127	-2.79	0.01	2.88	0.998683
42	44540	14840	-4.11	2.13	5.00	0.999990	84	20259	23498	-2.82	0.04	2.91	0.998782
												R_{sys}	0.955630

Figure 11. Method 3 CWC reliability

Failure Mode	M	M+1	Adj. EL Z	Δ Reliability (9's)	Δ Rel. EL+Usage (9's)	Reliability EL+Usage	Failure Mode	M	M+1	Adj. EL Z	Δ Reliability (9's)	Δ Rel. EL+Usage (9's)	Reliability EL+Usage
1	7370	4710	-3.59	1.22	4.09	0.999918	43	93016	59437	-3.52	1.10	3.97	0.999892
2	33762	17172	-3.93	1.80	4.67	0.999978	44	20390	13029	-3.66	1.34	4.21	0.999938
3	22646	14465	-4.24	2.38	5.25	0.999994	45	11114	7099	-3.57	1.17	4.04	0.999910
4	7298	4664	-4.26	2.42	5.29	0.999995	46	12882	8472	-3.14	0.50	3.37	0.999572
5	27622	21761	-3.13	0.49	3.36	0.999567	47	29330	18740	-3.50	1.07	3.94	0.999884
6	33773	21650	-3.34	0.80	3.67	0.999787	48	10565	6751	-4.03	1.99	4.85	0.999986
7	40526	26475	-3.48	1.02	3.89	0.999872	49	99852	63805	-3.67	1.35	4.22	0.999940
8	19080	12282	-3.27	0.70	3.57	0.999730	50	93016	59437	-3.52	1.10	3.97	0.999892
9	17296	11965	-3.22	0.62	3.49	0.999675	51	11157	7129	-4.00	1.92	4.79	0.999984
10	49349	31809	-3.35	0.83	3.70	0.999801	52	25645	16391	-3.52	1.10	3.97	0.999893
11	28422	22024	-3.23	0.64	3.51	0.999691	53	95805	62655	-3.33	0.79	3.66	0.999780
12	32129	24141	-3.15	0.52	3.39	0.999593	54	89580	61066	-3.37	0.86	3.73	0.999814
13	48513	40781	-3.09	0.43	3.30	0.999504	55	24919	17005	-3.38	0.87	3.74	0.999816
14	8691	4600	-4.28	2.46	5.33	0.999995	56	37835	25432	-3.35	0.83	3.70	0.999801
15	45413	29148	-3.46	0.99	3.86	0.999863	57	50268	34460	-3.39	0.88	3.75	0.999823
16	56251	36769	-3.40	0.90	3.77	0.999830	58	20973	14264	-3.37	0.86	3.73	0.999814
17	24415	15633	-3.62	1.27	4.14	0.999927	59	47191	32396	-3.39	0.88	3.75	0.999824
18	28101	19445	-3.27	0.70	3.57	0.999733	60	86807	56980	-3.33	0.79	3.66	0.999782
19	47800	33867	-3.28	0.72	3.59	0.999744	61	34792	23431	-3.36	0.83	3.70	0.999803
20	24201	15454	-3.58	1.20	4.07	0.999915	62	56473	38612	-3.38	0.88	3.75	0.999820
21	68572	48020	-3.44	0.97	3.84	0.999855	63	4400	3850	-3.08	0.41	3.28	0.999475
22	20361	13513	-3.42	0.93	3.80	0.999841	64	71801	55439	-3.16	0.53	3.40	0.999600
23	18248	13026	-3.30	0.75	3.62	0.999762	65	35544	23314	-3.14	0.51	3.38	0.999578
24	20809	14511	-3.29	0.74	3.61	0.999752	66	13870	8863	-3.87	1.69	4.56	0.999973
25	19437	12478	-3.54	1.13	4.00	0.999900	67	19675	12732	-3.42	0.93	3.80	0.999841
26	19570	13128	-3.39	0.89	3.76	0.999825	68	20269	12952	-3.67	1.34	4.21	0.999939
27	15836	10205	-3.49	1.05	3.92	0.999879	69	9459	6044	-4.10	2.11	4.98	0.999990
28	35641	23234	-3.32	0.78	3.65	0.999774	70	1430	914	-3.25	0.67	3.54	0.999709
29	37013	24894	-3.35	0.83	3.70	0.999801	71	7451	5128	-3.45	0.98	3.85	0.999858
30	55887	38221	-3.38	0.88	3.75	0.999821	72	8142	5202	-3.91	1.77	4.64	0.999977
31	7537	4830	-3.46	1.00	3.87	0.999866	73	18218	11641	-3.08	0.41	3.28	0.999475
32	9799	6841	-3.19	0.59	3.45	0.999649	74	3089	2321	-3.17	0.55	3.42	0.999623
33	10935	6987	-4.01	1.95	4.82	0.999985	75	4075	2735	-3.27	0.70	3.57	0.999732
34	20390	13029	-3.66	1.34	4.21	0.999938	76	11191	7151	-3.64	1.30	4.17	0.999933
35	6450	4122	-4.34	2.58	5.45	0.999996	77	7784	4974	-3.68	1.36	4.23	0.999942
36	36583	23376	-3.71	1.42	4.29	0.999948	78	11433	7306	-3.64	1.30	4.17	0.999932
37	23910	15303	-3.53	1.11	3.98	0.999895	79	10692	6832	-3.65	1.31	4.18	0.999934
38	48321	32264	-3.35	0.82	3.69	0.999796	80	18455	11793	-3.71	1.42	4.29	0.999949
39	70912	48192	-3.37	0.85	3.72	0.999810	81	21074	13466	-3.58	1.19	4.06	0.999913
40	9638	6159	-4.09	2.09	4.96	0.999989	82	21074	13466	-3.58	1.19	4.06	0.999913
41	11157	7129	-4.00	1.92	4.79	0.999984	83	17352	11088	-3.75	1.48	4.35	0.999955
42	44540	28446	-3.35	0.83	3.70	0.999801	84	20259	12945	-3.67	1.34	4.21	0.999939
												R_{sys}	0.986219

Figure 12. Method 3 M+1 reliability

Failure Mode	M	M+2	Adj. ELZ	Δ Reliability (9's)	Δ Rel. EL+Usage (9's)	Reliability EL+Usage	Failure Mode	M	M+2	Adj. ELZ	Δ Reliability (9's)	Δ Rel. EL+Usage (9's)	Reliability EL+Usage
1	7370	3460	-3.99	1.91	4.78	0.999983	43	93016	43671	-3.68	1.37	4.24	0.999943
2	33762	11514	-4.32	2.54	5.41	0.999996	44	20390	9573	-4.21	2.33	5.20	0.999994
3	22646	10626	-4.89	3.74	6.61	1.000000	45	11114	5214	-3.83	1.63	4.50	0.999968
4	7298	3427	-5.14	4.28	7.15	1.000000	46	12882	6311	-3.29	0.73	3.60	0.999751
5	27622	17952	-3.21	0.60	3.47	0.999663	47	29330	13768	-3.81	1.60	4.47	0.999966
6	33773	15932	-3.61	1.24	4.11	0.999923	48	10565	4960	-4.70	3.31	6.18	0.999999
7	40526	19659	-3.59	1.21	4.08	0.999918	49	99852	46881	-3.82	1.61	4.48	0.999967
8	19080	9055	-3.43	0.95	3.82	0.999847	50	93016	43671	-3.68	1.37	4.24	0.999943
9	17296	9146	-3.37	0.86	3.73	0.999815	51	11157	5238	-4.74	3.41	6.28	0.999999
10	49349	23468	-3.49	1.04	3.91	0.999878	52	25645	12045	-3.86	1.68	4.55	0.999972
11	28422	17978	-3.42	0.93	3.80	0.999841	53	95805	46548	-3.56	1.16	4.03	0.999906
12	32129	19334	-3.27	0.71	3.58	0.999735	54	89580	46322	-3.64	1.30	4.17	0.999932
13	48513	35175	-3.17	0.55	3.42	0.999621	55	24919	12906	-3.64	1.30	4.17	0.999932
14	8691	3127	-5.14	4.29	7.16	1.000000	56	37835	19154	-3.59	1.22	4.09	0.999919
15	45413	21462	-3.78	1.54	4.41	0.999961	57	50268	26216	-3.66	1.33	4.20	0.999937
16	56251	27311	-3.68	1.36	4.23	0.999941	58	20973	10807	-3.64	1.29	4.16	0.999931
17	24415	11498	-4.10	2.11	4.98	0.999990	59	47191	24664	-3.66	1.34	4.21	0.999938
18	28101	14866	-3.47	1.01	3.88	0.999869	60	86807	42408	-3.56	1.17	4.04	0.999908
19	47800	26223	-3.50	1.06	3.93	0.999882	61	34792	17663	-3.60	1.23	4.10	0.999920
20	24201	11351	-4.08	2.07	4.94	0.999989	62	56473	29334	-3.65	1.32	4.19	0.999935
21	68572	36947	-3.69	1.38	4.25	0.999944	63	4400	3423	-3.13	0.48	3.35	0.999556
22	20361	10111	-3.70	1.40	4.27	0.999946	64	71801	45151	-3.28	0.72	3.59	0.999740
23	18248	10128	-3.53	1.12	3.99	0.999897	65	35544	17346	-3.25	0.67	3.54	0.999710
24	20809	11139	-3.51	1.08	3.95	0.999887	66	13870	6512	-4.55	2.99	5.86	0.999999
25	19437	9188	-3.80	1.57	4.44	0.999964	67	19675	9411	-3.56	1.16	4.03	0.999907
26	19570	9877	-3.66	1.32	4.19	0.999936	68	20269	9516	-4.22	2.34	5.21	0.999994
27	15836	7528	-3.72	1.44	4.31	0.999951	69	9459	4441	-4.90	3.75	6.62	1.000000
28	35641	17234	-3.55	1.14	4.01	0.999902	70	1430	671	-3.42	0.93	3.80	0.999841
29	37013	18753	-3.60	1.22	4.09	0.999919	71	7451	3909	-3.63	1.28	4.15	0.999930
30	55887	29041	-3.65	1.32	4.19	0.999935	72	8142	3823	-3.99	1.92	4.79	0.999984
31	7537	3553	-3.63	1.27	4.14	0.999928	73	18218	8553	-3.08	0.42	3.29	0.999484
32	9799	5255	-3.32	0.78	3.64	0.999773	74	3089	1859	-3.31	0.77	3.64	0.999771
33	10935	5134	-4.75	3.42	6.29	0.999999	75	4075	2058	-3.43	0.95	3.82	0.999850
34	20390	9573	-4.21	2.33	5.20	0.999994	76	11191	5254	-4.06	2.04	4.91	0.999988
35	6450	3028	-5.02	4.01	6.88	1.000000	77	7784	3654	-4.11	2.14	5.01	0.999990
36	36583	17176	-4.03	1.98	4.85	0.999986	78	11433	5368	-4.05	2.03	4.90	0.999987
37	23910	11253	-3.87	1.69	4.56	0.999973	79	10692	5020	-4.06	2.05	4.92	0.999988
38	48321	24217	-3.59	1.21	4.08	0.999917	80	18455	8665	-4.30	2.49	5.36	0.999996
39	70912	36498	-3.63	1.28	4.15	0.999929	81	21074	9894	-3.96	1.85	4.72	0.999981
40	9638	4525	-4.56	3.03	5.90	0.999999	82	21074	9894	-3.96	1.85	4.72	0.999981
41	11157	5238	-4.74	3.41	6.28	0.999999	83	17352	8147	-4.35	2.59	5.46	0.999997
42	44540	20895	-3.67	1.36	4.23	0.999940	84	20259	9512	-4.22	2.34	5.21	0.999994
												R_{sys}	0.993018

Figure 13. Method 3 M+2 reliability

Failure Mode	M	CWC*	Adj. ELZ	Δ Reliability (9's)	Δ Rel. EL+Usage (9's)	Reliability EL+Usage	Failure Mode	M	CWC*	Adj. ELZ	Δ Reliability (9's)	Δ Rel. EL+Usage (9's)	Reliability EL+Usage
1	7370	8513	-2.81	0.03	2.90	0.998747	43	93016	10563	-5.14	4.30	7.17	1.000000
2	33762	23104	-3.62	1.26	4.13	0.999925	44	20390	23650	-2.82	0.05	2.92	0.998786
3	22646	13218	-4.45	2.80	5.67	0.999998	45	11114	10366	-3.10	0.45	3.32	0.999522
4	7298	8465	-2.60	-0.23	2.64	0.997694	46	12882	5877	-3.33	0.79	3.66	0.999782
5	27622	10275	-3.32	0.78	3.65	0.999775	47	29330	12848	-3.82	1.61	4.48	0.999967
6	33773	14661	-3.69	1.38	4.25	0.999944	48	10565	12187	-2.70	-0.10	2.77	0.998285
7	40526	19746	-3.59	1.21	4.08	0.999918	49	99852	12290	-5.07	4.14	7.01	1.000000
8	19080	6561	-3.58	1.20	4.07	0.999915	50	93016	10563	-5.14	4.30	7.17	1.000000
9	17296	8907	-3.39	0.89	3.76	0.999825	51	11157	12896	-2.71	-0.09	2.78	0.998325
10	49349	21180	-3.55	1.14	4.01	0.999903	52	25645	23744	-3.09	0.43	3.30	0.999500
11	28422	15211	-3.57	1.18	4.05	0.999911	53	95805	23925	-4.07	2.05	4.92	0.999988
12	32129	16508	-3.37	0.85	3.72	0.999809	54	89580	15654	-4.53	2.96	5.83	0.999999
13	48513	9832	-3.83	1.62	4.49	0.999968	55	24919	4280	-4.48	2.86	5.73	0.999998
14	8691	8795	-2.98	0.27	3.14	0.999273	56	37835	12147	-3.97	1.88	4.75	0.999982
15	45413	17426	-4.06	2.04	4.91	0.999988	57	50268	9533	-4.29	2.48	5.35	0.999996
16	56251	22472	-3.86	1.67	4.54	0.999971	58	20973	4614	-4.34	2.59	5.46	0.999997
17	24415	18500	-3.37	0.85	3.72	0.999811	59	47191	8757	-4.28	2.46	5.33	0.999995
18	28101	10442	-3.73	1.44	4.31	0.999951	60	86807	21204	-4.10	2.11	4.98	0.999990
19	47800	15141	-3.94	1.82	4.69	0.999980	61	34792	10501	-4.03	1.99	4.86	0.999986
20	24201	10831	-4.16	2.23	5.10	0.999992	62	56473	11186	-4.31	2.52	5.39	0.999996
21	68572	23484	-4.14	2.18	5.05	0.999991	63	4400	2383	-3.33	0.79	3.66	0.999780
22	20361	8688	-3.85	1.66	4.53	0.999970	64	71801	18213	-3.73	1.44	4.31	0.999951
23	18248	5628	-3.99	1.91	4.78	0.999983	65	35544	10019	-3.46	1.00	3.87	0.999866
24	20809	7512	-3.83	1.62	4.49	0.999968	66	13870	16087	-2.75	-0.04	2.83	0.998507
25	19437	15977	-3.24	0.66	3.53	0.999704	67	19675	22515	-2.62	-0.21	2.66	0.997800
26	19570	9692	-3.67	1.35	4.22	0.999940	68	20269	23509	-2.82	0.04	2.91	0.998782
27	15836	11873	-3.36	0.84	3.71	0.999805	69	9459	10971	-2.67	-0.15	2.72	0.998088
28	35641	22448	-3.35	0.82	3.69	0.999795	70	1430	1659	-2.92	0.18	3.05	0.999118
29	37013	11689	-3.99	1.91	4.78	0.999983	71	7451	3082	-3.77	1.52	4.39	0.999960
30	55887	11025	-4.31	2.52	5.39	0.999996	72	8142	9443	-2.60	-0.24	2.63	0.997675
31	7537	5309	-3.37	0.86	3.73	0.999813	73	18218	20845	-2.82	0.05	2.92	0.998785
32	9799	5277	-3.32	0.77	3.64	0.999772	74	3089	1421	-3.49	1.05	3.92	0.999879
33	10935	12613	-2.71	-0.09	2.78	0.998324	75	4075	2462	-3.34	0.81	3.68	0.999789
34	20390	23650	-2.82	0.05	2.92	0.998786	76	11191	12981	-2.78	-0.01	2.86	0.998630
35	6450	6600	-2.93	0.21	3.08	0.999160	77	7784	9028	-2.76	-0.03	2.84	0.998565
36	36583	33831	-3.21	0.60	3.47	0.999665	78	11433	13261	-2.78	-0.01	2.86	0.998634
37	23910	21481	-3.13	0.49	3.36	0.999563	79	10692	12402	-2.78	-0.01	2.86	0.998622
38	48321	18925	-3.79	1.55	4.42	0.999962	80	18455	21406	-2.80	0.02	2.89	0.998725
39	70912	15432	-4.40	2.71	5.58	0.999997	81	21074	24444	-2.81	0.03	2.90	0.998743
40	9638	11083	-2.69	-0.12	2.75	0.998215	82	21074	24444	-2.81	0.03	2.90	0.998743
41	11157	12896	-2.71	-0.09	2.78	0.998325	83	17352	20127	-2.79	0.01	2.88	0.998683
42	44540	14455	-4.15	2.20	5.07	0.999992	84	20259	23498	-2.82	0.04	2.91	0.998782
												R_{sys}	0.956163

Figure 14. Method 3 CWC* reliability

2.4 METHOD 3 RESULTS, SUMS REFERENCE—TRUNCATED

Methods 1 and 2 compare two different spectra to generate a relative reliability difference. In doing that, both spectra are inherently tied to the life of each failure mode. Method 3 differs in that each candidate spectrum is used to generate a life, and the SUMS average spectrum is manipulated to match that life. This means that Method 3 is actually comparing the SUMS average to a set of lives rather than to a different spectrum. This opens the possibility of assigning part lives by methods other than by a spectrum.

In the following reliability calculations, referred to as Truncated, failure modes with lives less than 10,000 hrs are based on the identified spectrum. Lives that are higher are truncated at exactly 10,000 hrs. By removing the long-life parts sooner, the system reliability goes up—and that increased reliability could be redistributed to the lower-life parts. This suggests the possibility of lifing critical parts with a hybrid approach in which the life could be no higher than a life based on the M+1 spectrum, but which is otherwise determined by operational usage. That is, if a 15,000-hr part is consistently removed before 9000 hours for other reasons, then the 9000-hour life could be assigned.

A comparison of the M+1 Truncated and CWC lives is shown in figure 15. The results of the reliability calculations for the M+1, M+2, and CWC* spectra are shown in table 4, with the individual reliability calculations shown in figures 16–19.

In each case, when the spectrum is truncated, the reliability increases. Many of the low-life parts have their lives increased using the M+1 truncated life over the CWC and there is still a significant amount of reliability (i.e., $9_{0.557}$) that could be redistributed.

Table 4. Method 3 truncated spectra reliabilities

	Reliability	9s
CWC	0.955630	1.35
CWC Truncated	0.982275	1.75
M+1	0.986219	1.86
M+1 Truncated	0.994455	2.26
M+2	0.993018	2.16
M+2 Truncated	0.996024	2.40
CWC*	0.956163	1.36
CWC* Truncated	0.982053	1.75

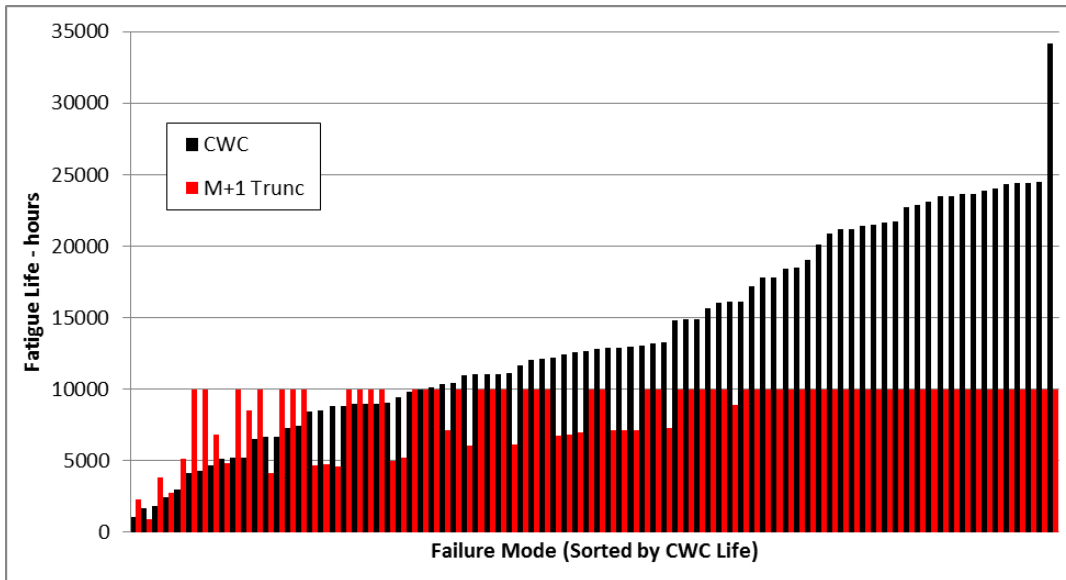


Figure 15. Comparison of CWC and SUMS M+1 truncated fatigue lives

Failure Mode	M	CWC Trunc	Adj. ELZ	Δ Reliability (9's)	Δ Rel. EL+Usage (9's)	Reliability EL+Usage	Failure Mode	M	CWC Trunc	Adj. ELZ	Δ Reliability (9's)	Δ Rel. EL+Usage (9's)	Reliability EL+Usage
1	7370	8513	-2.81	0.03	2.90	0.998747	43	93016	10000	-5.17	4.37	7.24	1.000000
2	33762	10000	-4.38	2.66	5.53	0.999997	44	20390	10000	-4.13	2.17	5.04	0.999991
3	22646	10000	-5.01	3.99	6.86	1.000000	45	11114	10000	-3.16	0.53	3.40	0.999601
4	7298	8465	-2.60	-0.23	2.64	0.997694	46	12882	5241	-3.37	0.86	3.73	0.999814
5	27622	10000	-3.33	0.79	3.66	0.999782	47	29330	10000	-3.85	1.65	4.52	0.999970
6	33773	10000	-3.95	1.85	4.72	0.999981	48	10565	10000	-3.12	0.47	3.34	0.999546
7	40526	10000	-3.66	1.33	4.20	0.999937	49	99852	10000	-5.31	4.69	7.56	1.000000
8	19080	6644	-3.58	1.19	4.06	0.999913	50	93016	10000	-5.17	4.37	7.24	1.000000
9	17296	8936	-3.39	0.88	3.75	0.999824	51	11157	10000	-3.23	0.64	3.51	0.999691
10	49349	10000	-3.93	1.80	4.67	0.999979	52	25645	10000	-4.01	1.95	4.82	0.999985
11	28422	10000	-3.96	1.86	4.73	0.999981	53	95805	10000	-4.71	3.34	6.21	0.999999
12	32129	10000	-3.67	1.35	4.22	0.999940	54	89580	10000	-4.70	3.31	6.18	0.999999
13	48513	10000	-3.82	1.60	4.47	0.999966	55	24919	4281	-4.48	2.86	5.73	0.999998
14	8691	8795	-2.98	0.27	3.14	0.999273	56	37835	10000	-4.13	2.17	5.04	0.999991
15	45413	10000	-4.93	3.82	6.69	1.000000	57	50268	7275	-4.40	2.70	5.56	0.999997
16	56251	10000	-4.56	3.03	5.90	0.999999	58	20973	4143	-4.39	2.67	5.54	0.999997
17	24415	10000	-4.24	2.38	5.25	0.999994	59	47191	6501	-4.39	2.68	5.55	0.999997
18	28101	9961	-3.76	1.50	4.37	0.999958	60	86807	10000	-4.66	3.23	6.10	0.999999
19	47800	10000	-4.26	2.41	5.28	0.999995	61	34792	10000	-4.07	2.07	4.94	0.999988
20	24201	10000	-4.30	2.50	5.37	0.999996	62	56473	9000	-4.40	2.70	5.57	0.999997
21	68572	10000	-5.08	4.17	7.03	1.000000	63	4400	1817	-3.49	1.05	3.92	0.999879
22	20361	8937	-3.82	1.61	4.48	0.999967	64	71801	10000	-3.99	1.91	4.78	0.999983
23	18248	5169	-4.05	2.02	4.89	0.999987	65	35544	10000	-3.46	1.00	3.87	0.999866
24	20809	7428	-3.84	1.64	4.51	0.999969	66	13870	10000	-3.62	1.26	4.13	0.999926
25	19437	10000	-3.73	1.46	4.33	0.999953	67	19675	10000	-3.53	1.11	3.98	0.999896
26	19570	9801	-3.66	1.34	4.20	0.999938	68	20269	10000	-4.12	2.16	5.03	0.999991
27	15836	10000	-3.51	1.08	3.95	0.999887	69	9459	10000	-2.87	0.12	2.99	0.999894
28	35641	10000	-3.94	1.83	4.70	0.999980	70	1430	1659	-2.92	0.18	3.05	0.999118
29	37013	10000	-4.11	2.14	5.01	0.999990	71	7451	2992	-3.79	1.56	4.43	0.999962
30	55887	8828	-4.40	2.70	5.57	0.999997	72	8142	9443	-2.60	-0.24	2.63	0.997675
31	7537	5159	-3.40	0.90	3.77	0.999831	73	18218	10000	-3.08	0.41	3.28	0.999479
32	9799	4696	-3.38	0.87	3.73	0.999816	74	3089	1030	-3.70	1.39	4.26	0.999945
33	10935	10000	-3.19	0.58	3.45	0.999644	75	4075	2410	-3.35	0.83	3.70	0.999799
34	20390	10000	-4.13	2.17	5.04	0.999991	76	11191	10000	-3.17	0.54	3.41	0.999614
35	6450	6638	-2.92	0.18	3.05	0.999113	77	7784	9028	-2.76	-0.03	2.84	0.998565
36	36583	10000	-4.55	3.00	5.87	0.999999	78	11433	10000	-3.20	0.59	3.46	0.999652
37	23910	10000	-3.94	1.83	4.70	0.999980	79	10692	10000	-3.10	0.45	3.32	0.999516
38	48321	10000	-4.29	2.48	5.35	0.999996	80	18455	10000	-4.02	1.96	4.83	0.999985
39	70912	10000	-4.51	2.91	5.78	0.999998	81	21074	10000	-3.94	1.83	4.70	0.999980
40	9638	10000	-2.92	0.18	3.05	0.999115	82	21074	10000	-3.94	1.83	4.70	0.999980
41	11157	10000	-3.23	0.64	3.51	0.999691	83	17352	10000	-3.94	1.82	4.69	0.999980
42	44540	10000	-4.72	3.35	6.22	0.999999	84	20259	10000	-4.12	2.16	5.03	0.999991
												R_{sys}	0.982275

Figure 16. Method 3 CWC truncated reliability

Failure Mode	M	M+1 Trunc	Adj. ELZ	Δ Reliability (9's)	Δ Rel. EL+Usage (9's)	Reliability EL+Usage	Failure Mode	M	M+1 Trunc	Adj. ELZ	Δ Reliability (9's)	Δ Rel. EL+Usage (9's)	Reliability EL+Usage
1	7370	4710	-3.59	1.22	4.09	0.999918	43	93016	10000	-5.17	4.37	7.24	1.000000
2	33762	10000	-4.38	2.66	5.53	0.999997	44	20390	10000	-4.13	2.17	5.04	0.999991
3	22646	10000	-5.01	3.99	6.86	1.000000	45	11114	7099	-3.57	1.17	4.04	0.999910
4	7298	4664	-4.26	2.42	5.29	0.999995	46	12882	8472	-3.14	0.50	3.37	0.999572
5	27622	10000	-3.33	0.79	3.66	0.999782	47	29330	10000	-3.85	1.65	4.52	0.999970
6	33773	10000	-3.95	1.85	4.72	0.999981	48	10565	6751	-4.03	1.99	4.85	0.999986
7	40526	10000	-3.66	1.33	4.20	0.999937	49	99852	10000	-5.31	4.69	7.56	1.000000
8	19080	10000	-3.38	0.87	3.74	0.999817	50	93016	10000	-5.17	4.37	7.24	1.000000
9	17296	10000	-3.33	0.79	3.66	0.999780	51	11157	7129	-4.00	1.92	4.79	0.999984
10	49349	10000	-3.93	1.80	4.67	0.999979	52	25645	10000	-4.01	1.95	4.82	0.999985
11	28422	10000	-3.96	1.86	4.73	0.999981	53	95805	10000	-4.71	3.34	6.21	0.999999
12	32129	10000	-3.67	1.35	4.22	0.999940	54	89580	10000	-4.70	3.31	6.18	0.999999
13	48513	10000	-3.82	1.60	4.47	0.999966	55	24919	10000	-3.87	1.69	4.56	0.999973
14	8691	4600	-4.28	2.46	5.33	0.999995	56	37835	10000	-4.13	2.17	5.04	0.999991
15	45413	10000	-4.93	3.82	6.69	1.000000	57	50268	10000	-4.27	2.44	5.31	0.999995
16	56251	10000	-4.56	3.03	5.90	0.999999	58	20973	10000	-3.71	1.41	4.28	0.999948
17	24415	10000	-4.24	2.38	5.25	0.999994	59	47191	10000	-4.22	2.35	5.22	0.999994
18	28101	10000	-3.76	1.50	4.37	0.999957	60	86807	10000	-4.66	3.23	6.10	0.999999
19	47800	10000	-4.26	2.41	5.28	0.999995	61	34792	10000	-4.07	2.07	4.94	0.999988
20	24201	10000	-4.30	2.50	5.37	0.999996	62	56473	10000	-4.36	2.61	5.48	0.999997
21	68572	10000	-5.08	4.17	7.03	1.000000	63	4400	3850	-3.08	0.41	3.28	0.999475
22	20361	10000	-3.71	1.42	4.29	0.999949	64	71801	10000	-3.99	1.91	4.78	0.999983
23	18248	10000	-3.54	1.14	4.01	0.999902	65	35544	10000	-3.46	1.00	3.87	0.999866
24	20809	10000	-3.60	1.22	4.09	0.999919	66	13870	8863	-3.87	1.69	4.56	0.999973
25	19437	10000	-3.73	1.46	4.33	0.999953	67	19675	10000	-3.53	1.11	3.98	0.999896
26	19570	10000	-3.64	1.30	4.17	0.999933	68	20269	10000	-4.12	2.16	5.03	0.999991
27	15836	10000	-3.51	1.08	3.95	0.999887	69	9459	6044	-4.10	2.11	4.98	0.999990
28	35641	10000	-3.94	1.83	4.70	0.999980	70	1430	914	-3.25	0.67	3.54	0.999709
29	37013	10000	-4.11	2.14	5.01	0.999990	71	7451	5128	-3.45	0.98	3.85	0.999858
30	55887	10000	-4.35	2.60	5.47	0.999997	72	8142	5202	-3.91	1.77	4.64	0.999977
31	7537	4830	-3.46	1.00	3.87	0.999866	73	18218	10000	-3.08	0.41	3.28	0.999479
32	9799	6841	-3.19	0.59	3.45	0.999649	74	3089	2321	-3.17	0.55	3.42	0.999623
33	10935	6987	-4.01	1.95	4.82	0.999985	75	4075	2735	-3.27	0.70	3.57	0.999732
34	20390	10000	-4.13	2.17	5.04	0.999991	76	11191	7151	-3.64	1.30	4.17	0.999933
35	6450	4122	-4.34	2.58	5.45	0.999996	77	7784	4974	-3.68	1.36	4.23	0.999942
36	36583	10000	-4.55	3.00	5.87	0.999999	78	11433	7306	-3.64	1.30	4.17	0.999932
37	23910	10000	-3.94	1.83	4.70	0.999980	79	10692	6832	-3.65	1.31	4.18	0.999934
38	48321	10000	-4.29	2.48	5.35	0.999996	80	18455	10000	-4.02	1.96	4.83	0.999985
39	70912	10000	-4.51	2.91	5.78	0.999998	81	21074	10000	-3.94	1.83	4.70	0.999980
40	9638	6159	-4.09	2.09	4.96	0.999989	82	21074	10000	-3.94	1.83	4.70	0.999980
41	11157	7129	-4.00	1.92	4.79	0.999984	83	17352	10000	-3.94	1.82	4.69	0.999980
42	44540	10000	-4.72	3.35	6.22	0.999999	84	20259	10000	-4.12	2.16	5.03	0.999991
												R_{sys}	0.994455

Figure 17. Method 3 M+1 truncated reliability

Failure Mode	M	M+2 Trunc	Adj. ELZ	Δ Reliability (9's)	Δ Rel. EL+Usage (9's)	Reliability EL+Usage	Failure Mode	M	M+2 Trunc	Adj. ELZ	Δ Reliability (9's)	Δ Rel. EL+Usage (9's)	Reliability EL+Usage
1	7370	3460	-3.99	1.91	4.78	0.999983	43	93016	10000	-5.17	4.37	7.24	1.000000
2	33762	10000	-4.38	2.66	5.53	0.999997	44	20390	9573	-4.21	2.33	5.20	0.999994
3	22646	10000	-5.01	3.99	6.86	1.000000	45	11114	5214	-3.83	1.63	4.50	0.999968
4	7298	3427	-5.14	4.28	7.15	1.000000	46	12882	6311	-3.29	0.73	3.60	0.999751
5	27622	10000	-3.33	0.79	3.66	0.999782	47	29330	10000	-3.85	1.65	4.52	0.999970
6	33773	10000	-3.95	1.85	4.72	0.999981	48	10565	4960	-4.70	3.31	6.18	0.999999
7	40526	10000	-3.66	1.33	4.20	0.999937	49	99852	10000	-5.31	4.69	7.56	1.000000
8	19080	9055	-3.43	0.95	3.82	0.999847	50	93016	10000	-5.17	4.37	7.24	1.000000
9	17296	9146	-3.37	0.86	3.73	0.999815	51	11157	5238	-4.74	3.41	6.28	0.999999
10	49349	10000	-3.93	1.80	4.67	0.999979	52	25645	10000	-4.01	1.95	4.82	0.999985
11	28422	10000	-3.96	1.86	4.73	0.999981	53	95805	10000	-4.71	3.34	6.21	0.999999
12	32129	10000	-3.67	1.35	4.22	0.999940	54	89580	10000	-4.70	3.31	6.18	0.999999
13	48513	10000	-3.82	1.60	4.47	0.999966	55	24919	10000	-3.87	1.69	4.56	0.999973
14	8691	3127	-5.14	4.29	7.16	1.000000	56	37835	10000	-4.13	2.17	5.04	0.999991
15	45413	10000	-4.93	3.82	6.69	1.000000	57	50268	10000	-4.27	2.44	5.31	0.999995
16	56251	10000	-4.56	3.03	5.90	0.999999	58	20973	10000	-3.71	1.41	4.28	0.999948
17	24415	10000	-4.24	2.38	5.25	0.999994	59	47191	10000	-4.22	2.35	5.22	0.999994
18	28101	10000	-3.76	1.50	4.37	0.999957	60	86807	10000	-4.66	3.23	6.10	0.999999
19	47800	10000	-4.26	2.41	5.28	0.999995	61	34792	10000	-4.07	2.07	4.94	0.999988
20	24201	10000	-4.30	2.50	5.37	0.999996	62	56473	10000	-4.36	2.61	5.48	0.999997
21	68572	10000	-5.08	4.17	7.03	1.000000	63	4400	3423	-3.13	0.48	3.35	0.999556
22	20361	10000	-3.71	1.42	4.29	0.999949	64	71801	10000	-3.99	1.91	4.78	0.999983
23	18248	10000	-3.54	1.14	4.01	0.999902	65	35544	10000	-3.46	1.00	3.87	0.999866
24	20809	10000	-3.60	1.22	4.09	0.999919	66	13870	6512	-4.55	2.99	5.86	0.999999
25	19437	9188	-3.80	1.57	4.44	0.999964	67	19675	9411	-3.56	1.16	4.03	0.999907
26	19570	9877	-3.66	1.32	4.19	0.999936	68	20269	9516	-4.22	2.34	5.21	0.999994
27	15836	7528	-3.72	1.44	4.31	0.999951	69	9459	4441	-4.90	3.75	6.62	1.000000
28	35641	10000	-3.94	1.83	4.70	0.999980	70	1430	671	-3.42	0.93	3.80	0.999841
29	37013	10000	-4.11	2.14	5.01	0.999990	71	7451	3909	-3.63	1.28	4.15	0.999930
30	55887	10000	-4.35	2.60	5.47	0.999997	72	8142	3823	-3.99	1.92	4.79	0.999984
31	7537	3553	-3.63	1.27	4.14	0.999928	73	18218	8553	-3.08	0.42	3.29	0.999484
32	9799	5255	-3.32	0.78	3.64	0.999773	74	3089	1859	-3.31	0.77	3.64	0.999771
33	10935	5134	-4.75	3.42	6.29	0.999999	75	4075	2058	-3.43	0.95	3.82	0.999850
34	20390	9573	-4.21	2.33	5.20	0.999994	76	11191	5254	-4.06	2.04	4.91	0.999988
35	6450	3028	-5.02	4.01	6.88	1.000000	77	7784	3654	-4.11	2.14	5.01	0.999990
36	36583	10000	-4.55	3.00	5.87	0.999999	78	11433	5368	-4.05	2.03	4.90	0.999987
37	23910	10000	-3.94	1.83	4.70	0.999980	79	10692	5020	-4.06	2.05	4.92	0.999988
38	48321	10000	-4.29	2.48	5.35	0.999996	80	18455	8665	-4.30	2.49	5.36	0.999996
39	70912	10000	-4.51	2.91	5.78	0.999998	81	21074	9894	-3.96	1.85	4.72	0.999981
40	9638	4525	-4.56	3.03	5.90	0.999999	82	21074	9894	-3.96	1.85	4.72	0.999981
41	11157	5238	-4.74	3.41	6.28	0.999999	83	17352	8147	-4.35	2.59	5.46	0.999997
42	44540	10000	-4.72	3.35	6.22	0.999999	84	20259	9512	-4.22	2.34	5.21	0.999994
												R_{sys}	0.996024

Figure 18. Method 3 M+2 truncated reliability

Failure Mode	M	CWC* Trunc	Adj. ELZ	Δ Reliability (9's)	Δ Rel. EL+Usage (9's)	Reliability EL+Usage	Failure Mode	M	CWC* Trunc	Adj. ELZ	Δ Reliability (9's)	Δ Rel. EL+Usage (9's)	Reliability EL+Usage
1	7370	8513	-2.81	0.03	2.90	0.998747	43	93016	10000	-5.17	4.37	7.24	1.000000
2	33762	10000	-4.38	2.66	5.53	0.999997	44	20390	10000	-4.13	2.17	5.04	0.999991
3	22646	10000	-5.01	3.99	6.86	1.000000	45	11114	10000	-3.16	0.53	3.40	0.999601
4	7298	8465	-2.60	-0.23	2.64	0.997694	46	12882	5877	-3.33	0.79	3.66	0.999782
5	27622	10000	-3.33	0.79	3.66	0.999782	47	29330	10000	-3.85	1.65	4.52	0.999970
6	33773	10000	-3.95	1.85	4.72	0.999981	48	10565	10000	-3.12	0.47	3.34	0.999546
7	40526	10000	-3.66	1.33	4.20	0.999937	49	99852	10000	-5.31	4.69	7.56	1.000000
8	19080	6561	-3.58	1.20	4.07	0.999915	50	93016	10000	-5.17	4.37	7.24	1.000000
9	17296	8907	-3.39	0.89	3.76	0.999825	51	11157	10000	-3.23	0.64	3.51	0.999691
10	49349	10000	-3.93	1.80	4.67	0.999979	52	25645	10000	-4.01	1.95	4.82	0.999985
11	28422	10000	-3.96	1.86	4.73	0.999981	53	95805	10000	-4.71	3.34	6.21	0.999999
12	32129	10000	-3.67	1.35	4.22	0.999940	54	89580	10000	-4.70	3.31	6.18	0.999999
13	48513	9832	-3.83	1.62	4.49	0.999968	55	24919	4280	-4.48	2.86	5.73	0.999998
14	8691	8795	-2.98	0.27	3.14	0.999273	56	37835	10000	-4.13	2.17	5.04	0.999991
15	45413	10000	-4.93	3.82	6.69	1.000000	57	50268	9533	-4.29	2.48	5.35	0.999996
16	56251	10000	-4.56	3.03	5.90	0.999999	58	20973	4614	-4.34	2.59	5.46	0.999997
17	24415	10000	-4.24	2.38	5.25	0.999994	59	47191	8757	-4.28	2.46	5.33	0.999995
18	28101	10000	-3.76	1.50	4.37	0.999957	60	86807	10000	-4.66	3.23	6.10	0.999999
19	47800	10000	-4.26	2.41	5.28	0.999995	61	34792	10000	-4.07	2.07	4.94	0.999988
20	24201	10000	-4.30	2.50	5.37	0.999996	62	56473	10000	-4.36	2.61	5.48	0.999997
21	68572	10000	-5.08	4.17	7.03	1.000000	63	4400	2383	-3.33	0.79	3.66	0.999780
22	20361	8688	-3.85	1.66	4.53	0.999970	64	71801	10000	-3.99	1.91	4.78	0.999983
23	18248	5628	-3.99	1.91	4.78	0.999983	65	35544	10000	-3.46	1.00	3.87	0.999866
24	20809	7512	-3.83	1.62	4.49	0.999968	66	13870	10000	-3.62	1.26	4.13	0.999926
25	19437	10000	-3.73	1.46	4.33	0.999953	67	19675	10000	-3.53	1.11	3.98	0.999896
26	19570	9692	-3.67	1.35	4.22	0.999940	68	20269	10000	-4.12	2.16	5.03	0.999991
27	15836	10000	-3.51	1.08	3.95	0.999887	69	9459	10000	-2.87	0.12	2.99	0.999894
28	35641	10000	-3.94	1.83	4.70	0.999980	70	1430	1659	-2.92	0.18	3.05	0.999118
29	37013	10000	-4.11	2.14	5.01	0.999990	71	7451	3082	-3.77	1.52	4.39	0.999960
30	55887	10000	-4.35	2.60	5.47	0.999997	72	8142	9443	-2.60	-0.24	2.63	0.997675
31	7537	5309	-3.37	0.86	3.73	0.999813	73	18218	10000	-3.08	0.41	3.28	0.999479
32	9799	5277	-3.32	0.77	3.64	0.999772	74	3089	1421	-3.49	1.05	3.92	0.999879
33	10935	10000	-3.19	0.58	3.45	0.999644	75	4075	2462	-3.34	0.81	3.68	0.999789
34	20390	10000	-4.13	2.17	5.04	0.999991	76	11191	10000	-3.17	0.54	3.41	0.999614
35	6450	6600	-2.93	0.21	3.08	0.999160	77	7784	9028	-2.76	-0.03	2.84	0.998565
36	36583	10000	-4.55	3.00	5.87	0.999999	78	11433	10000	-3.20	0.59	3.46	0.999652
37	23910	10000	-3.94	1.83	4.70	0.999980	79	10692	10000	-3.10	0.45	3.32	0.999516
38	48321	10000	-4.29	2.48	5.35	0.999996	80	18455	10000	-4.02	1.96	4.83	0.999985
39	70912	10000	-4.51	2.91	5.78	0.999998	81	21074	10000	-3.94	1.83	4.70	0.999980
40	9638	10000	-2.92	0.18	3.05	0.999115	82	21074	10000	-3.94	1.83	4.70	0.999980
41	11157	10000	-3.23	0.64	3.51	0.999691	83	17352	10000	-3.94	1.82	4.69	0.999980
42	44540	10000	-4.72	3.35	6.22	0.999999	84	20259	10000	-4.12	2.16	5.03	0.999991
												R_{sys}	0.982053

Figure 19. Method 3 CWC* truncated reliability

2.5 SUMMARY OF METHOD RESULTS

The reliability results from all of the methods are shown in table 5. A direct comparison of reliability values between methods is not possible because of the different contributors that are included in each. However, some useful observations are possible.

First, Method 1 showed that all of the candidate spectra were less reliable than the CWC and that the CWC* spectrum was more reliable than M+2. This is in stark contrast with the other methods. The Method 1 assumption that each part starts at a constant reliability is clearly shown to be invalid because of these inconsistencies. This method is not recommended.

Second, Methods 2 and 3 showed similar results, with the M+2 spectrum being more reliable than the M+1 spectrum—and both being more reliable than the CWC. In both cases, the CWC* spectrum is slightly more conservative than the CWC. The agreement in the results of these approaches indicates that both are valid.

Truncating of lives at a maximum of 10,000 for Method 3 showed a significant increase in reliability over each non-truncated spectrum. That additional reliability may be redistributed among the remaining parts to increase their lives.

Method 1 should not be used. Method 2 is most applicable for comparing any two spectra when SUMS data are not available. Method 3 is most applicable when the SUMS spectrum is available and there might be a desire to assign lives directly rather than indirectly through a spectrum.

Table 5. Summary of system reliabilities

Spectrum	Reliability Calculation	9s	Δ Reliability
Method 1—Constant Component Reliability—Strength, Usage, Loads			
CWC	0.999916	4.08	
SUMS M+1	0.997530	2.61	-0.002386
SUMS M+2	0.999039	3.02	-0.000877
CWC*	0.999911	4.05	-0.000005
Method 2—Relative EL—Usage			
CWC	0.892733		
SUMS M+1	0.447009		0.445724
SUMS M+2	0.071994		0.820739
CWC*	0.891117		0.001615
Method 3—SUMS Reference—Strength, Usage			
CWC	0.955630	1.35	
CWC Truncated	0.982275	1.75	0.026645
M+1	0.986219	1.86	0.030589
M+1 Truncated	0.994455	2.26	0.038825
M+2	0.993018	2.16	0.037388
M+2 Truncated	0.996024	2.40	0.040394
CWC*	0.956163	1.36	0.000533
CWC* Truncated	0.982053	1.75	0.026423

3. EVALUATION APPROACH

3.1 COMPONENT RELIABILITY MEASURE BY EL

3.1.1 Relevant Probability/Reliability Concepts

3.1.1.1 Nines Notation and Reliability

U.S. Army guidelines dictate that dynamic aircraft components should have six 9s of reliability [1]. This is based on having a fleet of roughly 8,000 helicopters, each with more than 100 flight critical components—totaling almost one million components in service at any one time [2]. The case has been made that the safe-life method provides reliability on the order of six 9s and, furthermore, that the relative contributions are one 9 from usage bias, two 9s from loads bias, and three 9s from strength bias [3]. Although the distribution of 9s is too general an observation to be useful on specific parts, it is a fair representation of the overall sensitivity of reliability to the safe-life method inputs.

A shorthand notation for 9s of reliability used in this document is 9_x , where “x” is the number of 9s of reliability. That is, 9_6 represents 0.999999.

The numerical relationships for x 9s and reliability, r , are (with 9_3 being used as an example):

$$r = 1 - 10^{-X} \quad = 1 - 10^{-3} \quad = 0.999 \quad (1)$$

$$X = -\text{LOG}(1 - r) \quad = -\text{LOG}(1 - 0.999) \quad = 3.0 \quad (2)$$

The number of 9s is additive, in that one 9 from usage, two 9s from loads, and three 9s from strength can be summed to 9_6 .

It is also relevant to note that for a normal distribution, the average value has a 50% reliability. Letting $r = 0.5$ in equation 2 results in 0.301 9s, or $9_{0.301}$.

3.1.1.2 Normal Distribution and the Z Score

Reliability is the integral of a probability curve between specified, often one-sided, bounds. In this document, the normal distribution is used, which is defined by the mean, μ , and the standard deviation, σ . The bound on the reliability integration is defined by the number of standard deviations, Z .

When the working EL is defined as the mean EL minus three standard deviations, then $EL = \mu - Z*\sigma$, with $Z = -3$. The reliability that comes from $Z = -3$ is the integral of the normal probability curve above -3 , to the right of the red line in figure 20. For usage, which will be biased upwards as in the case of the $\mu + 2\sigma$ spectrum, reliability comes from the integral below $Z = 2$, to the left of the green line in figure 20.

In Microsoft Excel 2010, the function to calculate this is `NORM.S.DIST(Z,TRUE)`, where `TRUE` is the flag indicating integration from negative infinity up to the Z value (as opposed to simply providing the function value at that point). In older versions of Microsoft Excel, `NORMSDIST(Z)` performed the same calculation. If $Z = -3$ is the input for strength, then the reliability is the area to the right of Z , which would be $1-\text{NORM.S.DIST}(-3,\text{TRUE}) = 0.998650$. This is also equal to `NORM.S.DIST(3,TRUE)` because the standard normal probability curve is symmetric.

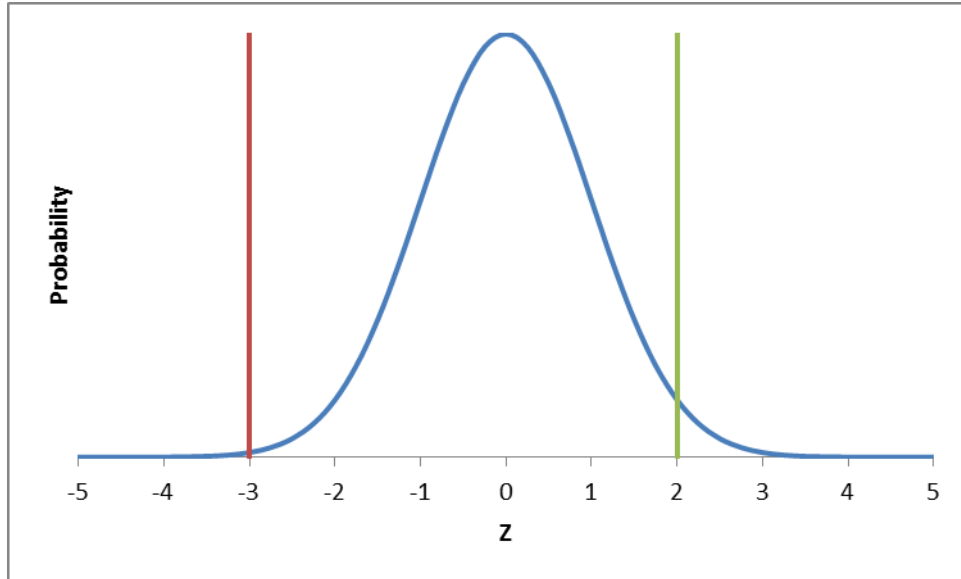


Figure 20. Normal probability curve

3.1.2 Typical EL Development

SN curves for rotorcraft components usually have their shape derived by numerous tests of material coupons. One representation of the resulting curve shape that can be used is:

$$\frac{S}{EL} = 1 + \beta * N^{-\gamma} \quad (3)$$

Where N is expressed in millions of cycles, S is the oscillatory load, β and γ are material shape constants, and EL stands for the EL.

A small number of tests (typically ~6) of the actual component are then performed. The results of these tests are combined with the curve shape to provide a mean and standard deviation for the EL of the part.

The legacy safe-life approach reduces the mean EL by a certain amount to provide the working EL. Some original equipment manufacturers determine the reduction based on the material coupons while others base it on the number of component tests; however, the working EL is typically taken to be the mean minus three standard deviations (or $\mu - 3\sigma$). A normalized example is shown in figure 21. The shape of the SN curve has been defined and six component tests (including three run outs) are plotted. The EL, S_e in this figure, is determined for each component and the valid results are used to determine a mean value. The distribution of the EL is used to reduce the value by three standard deviations to generate the working SN curve.

The FSR for each platform includes the mean and the working ELs for every part. For the purposes of the methods in this document, it is assumed that the difference between these two ELs is 3σ .

Specimen Number	Vibratory Load	Cycles x 10 ⁶	Result	S _e
1	1.653	7.900	Failure	1.478
2	1.923	12.100	Failure	1.770
3	1.788	15.550	Failure	1.670
4	2.261	0.800	Insignificant Runout	1.539
5	2.015	3.000	Insignificant Runout	1.652
6	2.310	0.367	Insignificant Runout	1.347

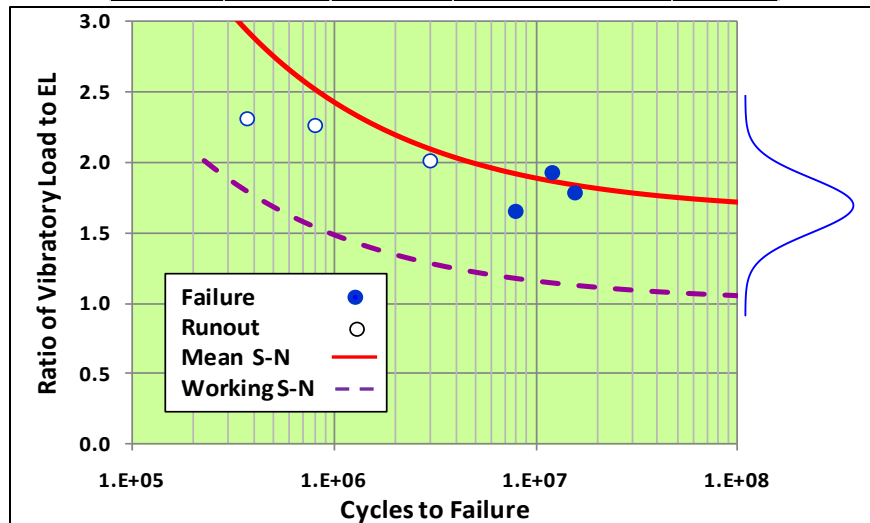


Figure 21. Mean and working EL

3.1.3 Adjusted EL Reliability Measure for a Single Part and Load

To demonstrate the application of adjusting the EL to measure reliability, assume a part as follows:

Mean, EL = 3699

Standard Deviation, EL = 370

$\beta = .526$

$\gamma = .667$

Assume that the usage for the part is 200,000 cycles. With a Mean-3 working EL of $3699 - 3 \times 370 = 2,589$ and using the SN curve as defined in equation 3, the equivalent load is 6573.

Now consider a revised usage to be 150,000 cycles. Using the same load, equation 3 can be back-solved to provide an adjusted EL of 2,295. Using the mean EL, the adjusted EL, and the standard deviation, the new Z score, or number of standard deviations, is $(3699 - 2295)/370 = 3.795$.

Finding the cumulative normal distribution (by NORM.S.DIST in Excel) for $Z = 3$ and $Z = 3.795$ gives probabilities of 0.998650 and 0.999926, respectively.

Figure 22 shows the SN curves for the mean EL, the working Mean-3, and the Adjusted Mean-3.795 with the load of 6,573 shown. Figure 23 shows the probability distribution of the EL based on the given mean and standard deviation values, with the relative positions of the Mean-3 and adjusted ELs shown. Table 6 shows the baseline and adjusted cases, where N , S , and EL are related by equation 1 and $Z = (\text{mean EL} - \text{EL})/\sigma$. The middle of the three rows is the baseline case, with a final reliability of $9_{2.870}$. Below that is the case in which the usage is adjusted down to 150,000 cycles and the reliability increases to $9_{4.132}$ because fewer cycles at the same load are less likely to fail. The top row is a reference case using the mean EL, for which a 50% reliability, $9_{.301}$, would allow 557,158 cycles.

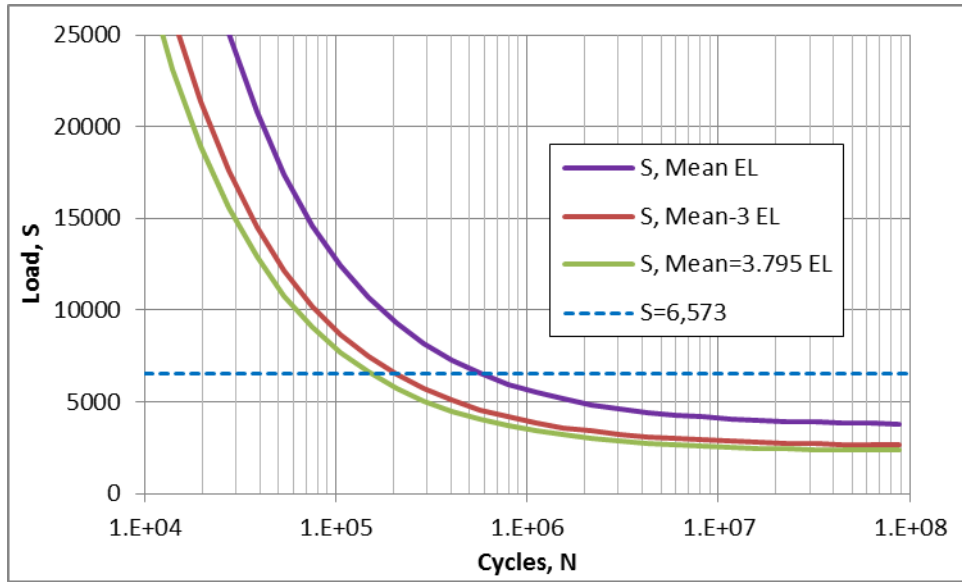


Figure 22. Example SN curve

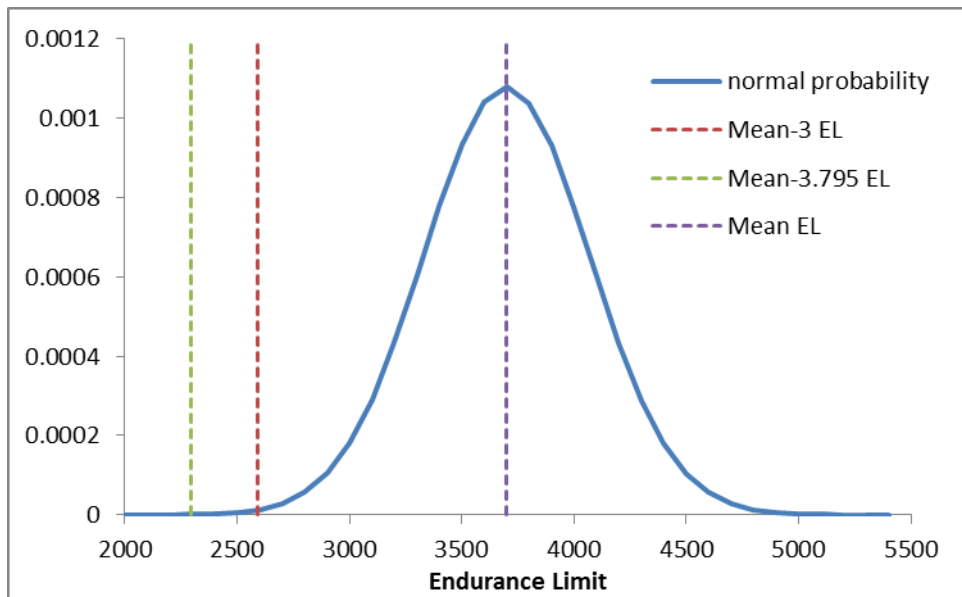


Figure 23. Example EL normal curve

Table 6. Example part reliability comparison

Cycles, N	Load, S	Z	EL, μ -Z σ	Normal Distribution, p	9s
557,158	6573	0	3699	0.500000	0.301
200,000	6573	3.000	2589	0.998650	2.870
150,000	6573	3.795	2295	0.999926	4.132

3.1.4 Adjusted EL for a Target Life

In the example shown in section 3.1.3, usage is a given number of cycles at a specific load. In the legacy safe-life method, the load is determined by Flight Load Survey testing and the usage (or number of cycles) is defined by the spectrum. Because loading of most fatigue critical parts occurs at a known frequency (1/rev for parts in the rotating system, 1/blade pass for parts in the fixed system), time in regime translates directly to number of cycles.

Figure 24 shows how the EL is adjusted based on an entire spectrum for a single part. Under the Description column are all of the regimes that are in the spectrum (not all regimes are shown). PCT Time is the amount of time for each regime in the proposed spectrum. Occ and Secs/Occ are used to determine the number of cycles experienced. Load is the maximum load for each regime. SS Freq is the frequency of loading for that part. $N_{allowable}$ is the allowable number of cycles, in millions, at the given load from the SN curve. The n/N is the damage determined from the number of cycles experienced in the spectrum, n , over the allowed number of cycles at that load, N . Some regimes are transient and are more difficult to calculate because loads are varying. In those cases, the time history from the flight load survey will be cycle-counted and an equivalent damage applied, as shown in box Cycle Count 1. Other regimes may give distinctly different loads based on some change in configuration, and these are accounted for by prorating to time spent in each configuration, as shown in boxes Prorate 1 and Prorate 2.

Damage is summed for this platform within three groupings: Low, High, and any Gross Weight, shown in the top right box. Life is $1/(\text{total damage}) * 100$, because the spectrum in this case is based on 100 hours of flight time.

The baseline life of this part is 8961 hours from the FSR, based on the Mean-3 EL. The EL is adjusted iteratively and all of the damage recalculated until the life using the revised spectrum matches the life of the baseline spectrum. In this case, the adjusted EL has a Z score of -3.5. There is some nonlinearity in the solution because changes in the adjusted EL can cause regimes to change between damaging and non-damaging. Because of this, occasionally the solver cannot find a precise solution and the adjusted EL must be determined as closely as possible.

Therefore, with a life of 8961, the adjusted EL has a reliability of $NORM.S.DIST(3.5,TRUE) = 0.999767$ (or $9_{3.633}$). The original working EL contributed $9_{2.870}$. Because the EL for the proposed spectrum has to contribute more reliability to achieve the same life, that means the revised spectrum has lost $3.633 - 2.870 = 0.763$ 9s of reliability in relation to the baseline. Assuming the part initially had 9_6 reliability, with the new spectrum it only had $9_{6.763}$ (or $1 - 10^{-5.237} = 0.999994$).

	Description	PCT Time	Occs	Secs/ Occ	Load (lbs)	SS Freq	N _{allowable}	n/N					
									Low GW	High GW	Any GW	Total	Life
GW=0 to 17,000 lbs; 60% of Usage	Hover	0.006			1200	4.3	0.00	0.00000	0.00000	0.00001	0.01115	0.01116	8961
	Left Sideward Flight	3.530			1280	4.3	0.00	0.00000					
	Right Sideward Flight	14.440			1200	4.3	0.00	0.00000					
	Rearward Flight	4.171			1210	4.3	0.00	0.00000	Cycle Count 1				
	Climb	1.474			1370	4.3	0.00	0.00000	Occs/100 0				
	Level Flight @ 0.1VH	0.000			627	4.3	0.00	0.00000	Cycles Load (lbs) N n/N				
	Level Flight @ 0.2VH	22.664			1100	4.3	0.00	0.00000	13.0	2830	4.18	0.000039	
	Level Flight @ 0.4VH	0.538			1100	4.3	0.00	0.00000	0.000039				
	Level Flight @ 0.5VH	0.840			1200	4.3	0.00	0.00000					
	Level Flight @ 0.6VH	2.849			1250	4.3	0.00	0.00000	Prorate 1				
	Level Flight @ 0.7VH	5.677			1200	4.3	0.00	0.00000	Occs/100 430				
	Level Flight @ 0.8VH	4.929			1230	4.3	0.00	0.00000	Prorate Load (lbs) N n/N				
	Level Flight @ 0.9VH	1.945			1300	4.3	0.00	0.00000	0.03	4300	0.51	0.000025	
	Level Flight @ 1.0VH	0.461			1540	4.3	0.00	0.00000	0.20	3500	1.12	0.000077	
	Sideslip	1.172			1370	4.3	0.00	0.00000	0.77	2800	4.61	0.000072	
	Autorotation	0.017			1890	4.3	0.00	0.00000	0.000174				
	Partial Power Descent	1.431			1460	4.3	0.00	0.00000					
	Dive	0.799			1800	4.3	0.00	0.00000	Prorate 2				
	Turn 30 Degrees Left	1.635			1410	4.3	0.00	0.00000	Occs/100 1482.3				
	Turn 30 Degrees Right	1.259			1430	4.3	0.00	0.00000	Prorate Load (lbs) N n/N				
	Turn 45 Degrees Left	0.014			1410	4.3	0.00	0.00000	0.1583	7670	0.11	0.002087	
	Turn 45 Degrees Right	0.012			1440	4.3	0.00	0.00000	0.0117	7660	0.11	0.000154	
	Turn 60 Degrees Left	0.003			1530	4.3	0.00	0.00000	0.0667	7190	0.13	0.000763	
	Turn 60 Degrees Right	0.005			1870	4.3	0.00	0.00000	0.0550	7020	0.14	0.000596	
	Take Off	1.227	736.1	6	1310	4.3	0.00	0.00000	0.1033	7010	0.14	0.001116	
Left Hover Turn	12.275	3683	12	1040	4.3	0.00	0.00000	0.6050	6860	0.14	0.006225		
Right Hover Turn	10.677	3203	12	1180	4.3	0.00	0.00000	0.010941					
Recovery Right Sideward	3.683708	5305	2.5	1740	4.30	0.00000	0.00000						
Entry Rearward	1.063917	1532	2.5	1440	4.3	0.00	0.00000	Sample Statistics					
Recovery Rearward	1.063917	1532	2.5	1700	4.3	0.00	0.00000	Mean 3699					
Droop Stop Pounding		100	1	4300	4.3	PR#1	0.00017	StDev 370					
Extreme Maneuver		2.43	5	2530	4.3	18.48	0.00000	CV-hat 10.0%					
3.3G Pullout (Structural Design)	0	0	5	2410	4.3	0.00	0.00000	n 1					
Single Engine Failure in Hover		0		0	4.3	0.00	0.00000	Z -3.5					
Single Engine Failure at Altitude		0		0	4.3	0.00	0.00000	2000 Adj EL					
GAG/Flight	GAG +	527.2		7670	4.3	PR#2	0.010941	2353					
Min-Max (a.k.a. Full-Stop Landing)	Max-Min	955.1		0	4.3	0.00	0.00000						
								with	β	0.526			
								Chafing	γ	0.667			
								Life	8961				

Figure 24. Adjusted EL by spectrum

3.2 SPECTRUM DEVELOPMENT

AED Structures requested 10,000 flight hours from a single operational environment for this analysis. Integrated Vehicle Health Management System (IVHMS) training data for the specified platform were selected because they were available in the quantities needed and the parameters could be processed with regime recognition algorithms that mapped to the FSR flight regimes.

The collected operational data originally consisted of more than 6200 potential flights from 32 aircraft. The bus parameters for each of the flights were converted into a .csv format and run through the IVHMS regime recognition algorithms. The regime recognition algorithms produced a text file for each flight, with the flight regimes flown in sequence. IVHMS regime definitions were determined for 94 regimes. These IVHMS regimes were then mapped to FSR regimes, as shown in figures 25 and 26.

HUMS Regimes		FSR Regimes			
		Low-Mid GW	Mid-High GW	Any GW	Alt. Config.
1	Power On Aircraft, Rotors Not Turning				
2	Power On Aircraft, Rotors Turning, Taxi or Stationary	38	77		TAXI
3	Left Taxi Turn				
4	Right Taxi Turn	39	78		TAXI TURN
5	Takeoff	25	64		TAKE OFF
6	Landing			79	NML LAND
				80	RUN LAND
↓	Approach	37	76	37	HOV APP
7	IGE Hover				
8	OGE Hover	1	40		HOVER
9	Forward Flight to 0.3 VH	6	45		LF 0.1VH
↓	Entry			93	ENT R.S.
10	Right Sideward Flight	3	42		RT S FLT
↑	Recovery			94	REC R.S.
↓	Entry			91	ENT L.S.
11	Left Sideward Flight	2	41		LT S FLT
↑	Recovery			92	REC L.S.
↓	Entry			95	ENT RR
12	Rearward Flight	4	43		REAR FLT
↑	Recovery			96	REC RR
13	Left Hover Turn	26	65		L HOV TN
14	Right Hover Turn	27	66		R HOV TN
15	Rudder Reversal in Hover			81	HVRD REV
16	Longitudinal Reversal in Hover			83	HVLO REV
17	Lateral Reversal in Hover			85	HVLA REV
18	Level Flight up to 0.3 VH	7	46		LF 0.1VH
19	Level Flight between 0.3 VH and 0.4 VH	8	47		LF 0.4VH
20	Level flight between 0.4 VH and 0.5 VH	9	48		LF 0.5VH
21	Level Flight between 0.5 VH and 0.6 VH	10	49		LF 0.6VH
22	Level Flight between 0.6 VH and 0.7 VH	11	50		LF 0.7VH
23	Level Flight between 0.7 VH and 0.8 VH	12	51		LF 0.8VH
24	Level Flight between 0.8 VH and 0.9 VH	13	52		LF 0.9VH
25	Level Flight between 0.9 VH and 1.0 VH	14	53		LF 1.0VH
26	Rudder Reversal in Level Flight to 1.0 VH			82	LFRD REV
27	Lateral Reversal in Level Flight to 1.0 VH			86	LFLA REV
28	Longitudinal Reversal in Level Flight to 1.0 VH			84	LFLO REV
29	Left Sideslip in Level Flight				
30	Right Sideslip in Level Flight	15	54		SIDESLIP
31	Best Rate of Climb				
32	Intermediate Power Climb	5	44		CLIMB
33	Takeoff Power Climb				CLIMB
34	Left Sideslip in Climb				
35	Right Sideslip in Climb	15	54		SIDESLIP
36	Left Climbing Turn	5	44		CLIMB
37	Right Climbing Turn	5	44		CLIMB
38	Approach				
39	Rough Approach	38	39		HOV APP
↓	Entry			89	ENT AUTO
40	Autorotation	16	55		AUTO
↑	Recovery			90	REC AUTO
41	Autorotation with Left Sideslip				
42	Autorotation with Right Sideslip	16	55		AUTO
43	Rudder Reversal in Autorotation			82	LFRD REV
44	Longitudinal Reversal in Autorotation			84	LFLO REV
45	Lateral Reversal in Autorotation			86	LFLA REV
46	Collective Reversal in Autorotation	16	55		AUTO
47	Partial Power Descent	17	56		PART PWR
↑	Entry & Recovery	28	67		E&R PART PWR

Figure 25. Regime mapping, regimes 1–47

HUMS Regimes		FSR Regimes			
		Low-Mid GW	Mid-High GW	Any GW	Alt. Config.
48	Rudder Reversal in Partial Power Descent			82	LFRD REV
49	Longitudinal Reversal in Partial Power Descent			84	LFLO REV
50	Lateral Reversal in Partial Power Descent			86	LFLA REV
51	Dive	18	57		DIVE
52	Rudder Reversal in Dive			82	LFRD REV
53	Longitudinal Reversal in Dive			84	LFLO REV
54	Lateral Reversal in Dive			86	LFLA REV
55	Level Left Turns - 30° AOB Level Left Turn, 10° to 35° AOB	19	58		TURN 30L
56	Level Left Turns - 45° AOB Level Left Turn, 35° to 50° AOB	21	60		TURN 45L
57	Level Left Turns - 60° AOB Level Left Turn, 50° to 65° AOB				TURN 60L
58	Level Left Turns - > 60° AOB Level Left Turn, > 65° AOB	23	62		TURN 60L
59	Level Right Turns - 30° AOB Level Right Turn, 10° to 35° AOB	20	59		TURN 30R
60	Level Right Turns - 45° AOB Level Right Turn, 35° to 50° AOB	22	61		TURN 45R
61	Level Right Turns - 60° AOB Level Right Turn, 50° to 65° AOB				TURN 60R
62	Level Right Turns - > 60° AOB Level Right Turn, > 65° AOB	24	63		TURN 60R
63	Descending Left Turns - 30° AOB, 10° to 35° AOB	19	58		TURN 30L
64	Descending Left Turns - 45° AOB, 35° to 50° AOB	21	60		TURN 45L
65	Descending Left Turns - 60° AOB, 50° to 65° AOB				TURN 60L
66	Descending Left Turns - > 60° AOB, > 65° AOB	23	62		TURN 60L
67	Descending Right Turns - 30° AOB, 10° to 35° AOB	20	59		TURN 30R
68	Descending Right Turns - 45° AOB, 35° to 50° AOB	22	61		TURN 45R
69	Descending Right Turns - 60° AOB, 50° to 65° AOB				TURN 60R
70	Descending Right Turns - > 60° AOB, > 65° AOB	24	63		TURN 60R
71	Autorotation Left Turns	35	74		AUT TN L
72	Autorotation Right Turns	36	75		AUT TN R
73	Symmetrical Pullouts - to 1.2 VH , Up to 1.8 G's			87	MOD P.O.
74	Symmetrical Pullouts - to 1.2 VH , 1.9 to 3.0 G's			88	SEV P.O.
75	Symmetrical Pullouts - to 1.2 VH , 3.1 to 4.0 G's			99	PO 3.3G-SD
76	Left Rolling Pullouts - to 1.2 VH , Up to 1.8 G's			87	MOD P.O.
77	Left Rolling Pullouts - to 1.2 VH , 1.9 to 3.0 G's			88	SEV P.O.
78	Left Rolling Pullouts - to 1.2 VH , 3.1 to 4.0 G's			99	PO 3.3G-SD
79	Right Rolling Pullouts - to 1.2 VH , Up to 1.8 G's			87	MOD P.O.
80	Right Rolling Pullouts - to 1.2 VH , 1.9 to 3.0 G's			88	SEV P.O.
81	Right Rolling Pullouts - to 1.2 VH , 3.1 to 4.0 G's			99	PO 3.3G-SD
82	Pushovers - to 1.2 VH , 0.3 to 0.8 G's				DIVE
83	Pushovers - to 1.2 VH , 0.0 to 0.3 G's	18	57		DIVE
84	Pushovers - to 1.2 VH , -0.5 to -0.0 G's				DIVE
85	Dynamic Yaw			98	EXTR MAN
86	Other Maneuver 1, Left Climbing Turn Exceeding AOB Limits			98	EXTR MAN
87	Other Maneuver 2, Right Climbing Turn Exceeding AOB Limits			98	EXTR MAN
88	Other Maneuver 3, Level Flight exceeding 1.0 VH	14	53		LF 1.0VH
89	Other Maneuver 4, Dive exceeding 1.2 VH	18	57		DIVE
90	Other Maneuver 5, Symmetrical Pullout exceeding 1.2 VH			98	EXTR MAN
91	Right Turn Entry	30	69		E&R TURN 30R
		32	71		E&R TURN 45R
		34	73		E&R TURN 60R
92	Left Turn Entry	29	68		E&R TURN 30L
		31	70		E&R TURN 45L
		33	72		E&R TURN 60L
93	Right Turn Recovery	30	69		E&R TURN 30R
		32	71		E&R TURN 45R
		34	73		E&R TURN 60R
94	Left Turn Recovery	29	68		E&R TURN 30L
		31	70		E&R TURN 45L
		33	72		E&R TURN 60L
				97	DRP STOP
				102	GAG/FLT
				103	MIN-MAX

Figure 26. Regime mapping, regimes 48–94

Any time in the flight that was identified as “Unrecognized” was assigned to the time of the damaging regime that occurred before or after the unrecognized regime.

Entry and recovery regimes were assumed to take place immediately before and after the associated steady state regime. The time for these entry and recovery regimes was added to the

total time for the flight. Because of the way the flights were processed, gross weight for each flight could not be easily calculated. Based on previous studies of training data, the gross weight was prorated to 90% low gross weight and 10% high gross weight. Any potential flight that did not contain a GAG cycle or did not exceed 0.05 hours was eliminated from the data set. After all of the processing was completed, the data set consisted of 8289 hours from 32 aircraft.

Three usage spectra were calculated for this analysis. Using the time in each regime for each tail number, the average time in each regime and the standard deviation were calculated. These were used to calculate a mean spectrum, $\mu + \sigma$ spectrum, and $\mu + 2\sigma$ spectrum, listed in figure 1.

3.3 METHOD 1 PROCEDURE, CONSTANT COMPONENT RELIABILITY

Method 1 assumes that every part is starting at a constant reliability, taken to be 9_6 , and measures the differences from that point. The steps in the calculation, given a revised spectrum, are shown in figure 27. The first column is the identification of the failure mode for all of the parts being included in the analysis. M+2 is the life calculated, as discussed in section 3.1.4, using the new spectrum (in this case M+2) and the typical Mean-3 EL. CWC is the target life from the CWC. Adj. EL Z is the Z score, the number of standard deviations that the EL must change to for the revised spectrum life to match the CWC life. This is found iteratively for each part using Goal Seek within Excel.

Δ Reliability (9s) is the change in number of 9s reliability from the assumed reference of 6. This makes the Part Reliability 6 plus the Δ 9s converted into a reliability value. These are found with the Microsoft Excel functions:

$$\Delta \text{ Reliability (9s)} = \text{LOG}(\text{NORM.S.DIST}(Z, \text{TRUE})) - \text{LOG}(\text{NORM.S.DIST}(-3, \text{TRUE}))$$

$$\text{Postulated Overall Reliability} = 1 - 10^{-(6+\Delta)}$$

Once the overall reliability for every failure mode is determined, they are multiplied to provide the product, which is the system reliability with the assumption that each failure mode is independent. In the example shown, the system reliability is 0.999039 (or $9_{3.02}$). This is compared against a system reliability in which all 84 failure modes are at 9_6 . 0.999999^{84} is 0.999916 (or $9_{4.08}$). Because the system reliability of $9_{3.02}$ is lower than $9_{4.08}$, it fails to meet the ADS-79 system reliability criterion.

The advantage of this method is that by basing it on the individual part reliabilities, the final reliability is a true system reliability, which incorporates contributions from strength, usage, and loads. The drawback is that the assumption that each part starts at the same reliability is not true. Because the differences are relative, the method would remain valid if the reliabilities were close to the assumption. However, parts starting with excessively high or low reliabilities distort the final results.

Failure Mode	M+2	CWC	Adj. EL Z	Δ Reliability (9's)	Part Reliability
1	3460	8513	-1.78	1.45	1.000000
2	11514	24008	-2.41	0.77	1.000000
3	10626	13012	-2.40	0.78	1.000000
4	3427	8465	-0.89	2.14	1.000000
5	17952	21462	-2.86	0.19	0.999999
6	15932	14903	-3.05	-0.07	0.999999
7	19659	18449	-3.08	-0.11	0.999999
80	8665	21406	-2.05	1.18	1.000000
81	9894	24444	-1.81	1.42	1.000000
82	9894	24444	-1.81	1.42	1.000000
83	8147	20127	-1.99	1.23	1.000000
84	9512	23498	-2.13	1.09	1.000000
				R_{sys}	0.999039

Figure 27. Method 1 calculations

3.4 METHOD 2 PROCEDURE, RELATIVE EL

Method 2 is a relative comparison of the reliability between the adjusted and the baseline EL. The Z score of the adjusted EL provides the strength contribution to reliability. The product of all of the EL-based reliabilities provides a system level reliability contribution. That contribution is compared to the case in which every part has a Z of -3 from $\mu-3\sigma$ EL. The steps of the calculation are shown in figure 28. The first four columns are the same as for Method 1: failure mode, life calculation based on the revised spectrum, life based on the baseline spectrum, and the number of standard deviations of the adjusted EL to make the revised life match the baseline life.

The last column, Reliability Usage, is the probability based on the adjusted EL Z score, calculated by (1-NORM.S.DIST(Z,TRUE)).

The results are shown in the bottom right of the figure. $R_{sys,CWC}$ is the product of the 84 adjusted EL reliabilities. $R_{sys,\mu-3\sigma}$ is the product of 84 parts with a baseline Z score of 3. ΔR_{sys} is the difference between the two. In this instance, because the Mean-3 product is the greater value, the M+2 spectrum is more conservative and this spectrum would meet the ADS-79 criterion. The sign convention is a product of which spectrum is getting changed to match the other.

This approach avoids the problem with Method 1 because there are no assumptions made about the initial reliability of the part. The reliability values also include only relative contributions from changes in usage and are therefore only useful as a comparison to each other.

Failure Mode	M+2	CWC	Adj. EL Z	Reliability Usage
1	3460	8513	-1.78	0.962086
2	11514	24008	-2.41	0.992056
3	10626	13012	-2.40	0.991873
4	3427	8465	-0.89	0.814014
5	17952	21462	-2.86	0.997905
6	15932	14903	-3.05	0.998863
7	19659	18449	-3.08	0.998961
80	8665	21406	-2.05	0.979768
81	9894	24444	-1.81	0.964509
82	9894	24444	-1.81	0.964509
83	8147	20127	-1.99	0.976948
84	9512	23498	-2.13	0.983268
			$R_{Sys,CWC}$	0.071994
			$R_{Sys,\mu-3\sigma}$	0.892733
			ΔR_{Sys}	0.820739

Figure 28. Method 2 calculations

3.5 METHOD 3 PROCEDURE, SUMS REFERENCE

Method 3 determines a true value for a given spectrum by referencing it to the SUMS average spectrum. A spectrum of interest can be compared to the SUMS average by adjusting the EL in the same way as the previous methods. An average provides $9_{0.301}$ because $1-10^{-0.301} = 50\%$, so that can be added to the total to give a true reliability contribution. The process would be performed for both the CWC and the proposed spectrum, with the final values compared. The calculation steps are shown in figure 29. The first column identifies the failure mode. The M is the life calculated for each part by using the SUMS average spectrum. Note that the lives are quite a bit higher as there is no bias included in this spectrum. M+2 is the life calculated using the spectrum of interest, in this case M+2. Adj. EL Z is the Z score of the adjusted EL. Δ Reliability (9s) is the difference between the adjusted EL and the baseline EL, plus the reliability contribution from the SUMS average. That is:

$$9_s = -\text{LOG}_{10}(\text{NORM.S.DIST}(Z, \text{True}))$$

$$\begin{aligned} \Delta 9_s &= 9_{\text{adjusted EL}} - 9_{\text{baseline EL}} + 9_{\text{SUMS Average}} \\ &= -\text{LOG}(\text{NORM.S.DIST}(Z, \text{True})) + \text{LOG}(\text{NORM.S.DIST}(3, \text{True})) - \text{LOG}(\text{NORM.S.DIST}(0, \text{True})) \end{aligned}$$

Δ Reliability EL+Usage (9s) includes the strength contribution by adding $-\text{LOG}_{10}(\text{NORM.S.DIST}(-3, \text{TRUE})) = 2.8697$ to Δ Reliability. Reliability EL+Usage is calculated from the Δ Reliability EL+Usage (9s) by $1-10^{-X}$. The product of the part reliabilities is calculated and, in this example, is 0.993018. If you assumed 9_1 from usage and 9_3 from strength [2], then the comparative value would be $0.9999^{84} = 0.99163$.

To finish the example, repeating the same procedure with the CWC as the spectrum of interest results in a spectrum+strength contribution of 0.955630. Because the M+2 reliability is greater than the CWC reliability, the revised spectrum would meet the ADS-79 system reliability criterion.

Failure Mode	M	M+2	Adj. ELZ	Δ Reliability (9's)	Δ Rel. EL+Usage (9's)	Reliability EL+Usage
1	7370	3460	-3.99	1.91	4.78	0.999983
2	33762	11514	-4.32	2.54	5.41	0.999996
3	22646	10626	-4.89	3.74	6.61	1.000000
4	7298	3427	-5.14	4.28	7.15	1.000000
5	27622	17952	-3.21	0.60	3.47	0.999663
6	33773	15932	-3.61	1.24	4.11	0.999923
7	40526	19659	-3.59	1.21	4.08	0.999918
80	18455	8665	-4.30	2.49	5.36	0.999996
81	21074	9894	-3.96	1.85	4.72	0.999981
82	21074	9894	-3.96	1.85	4.72	0.999981
83	17352	8147	-4.35	2.59	5.46	0.999997
84	20259	9512	-4.22	2.34	5.21	0.999994
					R_{sys}	0.993018

Figure 29. Method 3 calculations

4. CONCLUSIONS

The purpose of this study was to develop and demonstrate methods for comparing the relative aircraft system reliability of different spectra, which is one of three independent approaches in ADS-79 for maintaining reliability of U.S. Army aircraft. The goal was to show that a revised spectrum is more reliable than the spectrum it is replacing. Three methods were demonstrated: Method 1, Constant Component Reliability; Method 2, Relative Endurance Limit (EL); and Method 3, Structural Usage Monitoring System (SUMS) Reference.

All three methods use the distribution of strength available from coupon and component fatigue tests as a measurement of reliability for individual components. All of the part reliabilities are combined to provide a system level change in reliability, which allows a comparison between the candidate and reference spectrum. The three methods are differentiated regarding what they use as a reference point and elements of the safe life calculations (usage, loads, and strength) they incorporate.

The Constant Component Reliability method assumes every part has the same reliability when using the reference spectrum. Because its reference reliability includes contributions from usage, loads, and strength, they are a part of the comparison. This was found to be invalid because of inconsistent results and significant deviations when compared to the other methods. The

assumption of constant component reliability is not accurate, but if it was, this method would have been viable for comparisons among spectra.

The Relative EL method is strictly a relative comparison between two spectra, changing the EL with one spectrum so that the lives match the other. This addresses only the reliability changes due to usage. This method was found to be effective and is most useful when there are no SUMS data available. ADS-79 does not specify how a new spectrum will be developed, only that it must be demonstrated to be more reliable than the old spectrum. Input data for developing and accepting a new spectrum using this method could come from any source or a combination of sources—ranging from traditional pilot surveys to SUMS data.

The SUMS Reference method independently compares two different spectra to the SUMS Mean and compares the final result. Because the strength contribution is added in, the calculated reliabilities are an absolute value for the contributions from strength and usage but not loads. This method was found to be effective. Because the SUMS Mean is the reference point, SUMS data are obviously a prerequisite. This method, rather than comparing spectra, compares a set of lives to the SUMS Mean lives. Because the lives are not dependent on a spectrum, it is possible to assign lives by other methods, such as from operational field data.

Useful follow-on work would include linking to a numerical optimization engine which would use the Relative EL method to maintain the same level of system reliability. The optimization engine could either maximize the increase in life for short-life parts or minimize the costs of replacement parts and associated labor costs. Other potential work would entail reviewing operational data for when parts are removed in the field for either reaching their fatigue life or other reasons, such as damage. Parts removed earlier would have a higher fatigue reliability, which could be transferred to the short-life parts to increase their lives.

5. REFERENCES

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2. Everett, R.A., Jr., Bartlett, F.D., Jr., and Elber, W., “Probabilistic Fatigue Methodology for Six Nines Reliability,” NASA Technical Memorandum 102757, AVSCOM Technical Report 90-B-009, December 1990.
3. Thompson, A.E. and Adams, D.O., “A Computational Method for the Determination of Structural Reliability of Helicopter Dynamic Components,” *American Helicopter Society Annual Forum*, Washington, D.C., May 1990.

Note: a variety of proprietary sources were used for this report, including resources that were used for FSRs, flight load survey reports and data, and fatigue methodology reports from multiple original equipment manufacturers. Because this material is not publically available, the sources are not included as references herein.