Large Satellite Bus Reliability

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Abstract: NASA is proposing to build a small space station in Cis-lunar orbit called Deep Space Gateway (DSG). At the heart of the DSG is the Power and Propulsion Element (PPE) which is conceptually similar to previously designed and operated satellite buses. A satellite bus is composed of the satellite spacecraft infrastructure minus the payload, and generally includes power, propulsion, avionics, and guidance, navigation and control. In November of 2017, five companies were awarded contracts by NASA to research PPE designs. In order to better understand the reliability of large satellite buses which may be the starting point of the PPE, NASA used Weibull analysis to evaluate spacecraft with similar masses and design life to the PPE. In addition, a subset of the large satellites which had satellite buses manufactured by any one of the five companies was also evaluated. This paper provides the results of the reliability analysis and compares the reliability of the general population of large satellites to the reliability associated with large satellite buses manufactured by the five companies currently studying PPE options.

Keywords: Reliability, Satellite, Spacecraft, Bus, Weibull

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1. INTRODUCTION

NASA is proposing to build a small space station in Cis-lunar orbit called Deep Space Gateway (DSG). At the heart of the DSG is the Power and Propulsion Element (PPE) which is conceptually similar to previously designed and operated satellite buses. A satellite bus is composed of the satellite spacecraft infrastructure minus the payload, and generally includes power, propulsion, avionics, and guidance, navigation and control. In November of 2017, five companies were awarded study contracts by NASA to research PPE designs [1].

In order to better understand the potential reliability of PPE over its intended operational life of 15 years and facilitate the development of reliability requirements data from large satellites with masses greater than 2500 kg and a design life of 15 years were evaluated.

The source of the data utilized in the analysis originates from Seradata SpaceTrak database [2]. The SpaceTrak database was initially developed to support insurance of satellite launches. Data is gathered from public and private sources and includes event histories and lifecycle for all spacecraft since Sputnik in 1957. For this analysis the subset of spacecraft evaluated included satellites launched from April 1990 to October 2017.

The Spacetrak database has been used in the past to calculate satellite reliability (e.g. “Satellite Reliability: Statistical Data Analysis and Modeling” [3]. However, the focus of this study is on large satellites with a design life of 15 years.

Calculated values are rounded to two significant figures, however, additional significant figures are provided for raw data.

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2. METHODOLOGY

A given satellite has either failed after a certain number of years, or it has operated without failure. That is, for each satellite there is either a failure time or a success time. Definition of what constitutes a failure in this analysis is provided in section 3. Success times are often described as being (right) censored. The Weibull distribution is a versatile model when given failure times and censored times. Two advantages of the Weibull distribution are that it can (1) identify trends in the occurrence of failure events and (2) take many shapes and therefore give a good fit to the data.

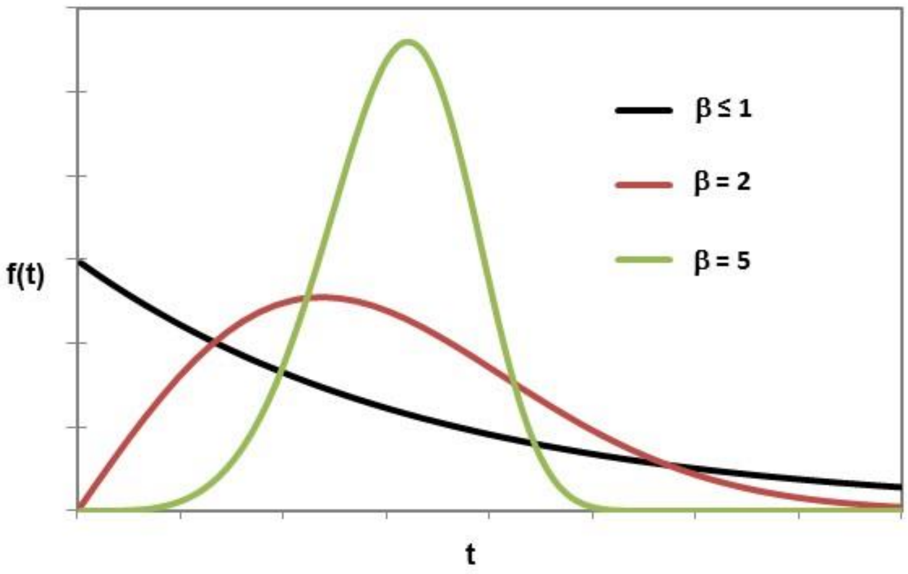
The Weibull density function is:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\alpha}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\alpha}{\eta}\right)^{\beta}}$$

where β is the shape parameter, η is the Weibull scale parameter, α is the location parameter, and t is time. In many cases the location parameter equals zero and is not shown.

Figure 1 shows the different shapes the Weibull density can have depending on the shape parameter β.

Figure 1: Weibull Density Plots



The shape parameter β determines whether the hazard rate (i.e., failure rate as a function of time) is increasing, decreasing, or constant as shown in Table 1.

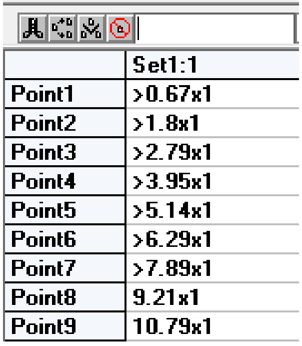
Table 1: Effect of β on the Hazard Rate

Value of β	**Hazard Rate**	**Description**
$\beta << 1.0$	Decreasing	Infant Mortality
$\beta \approx 1.0$	Constant	Random Failure
$\beta >> 1.0$	Increasing	Wear-out

The parameters β, η, and α are obtained using the software SuperSmith Weibull [4] and are calculated using maximum likelihood estimation.

When using SuperSmith Weibull, censored data (i.e., successes) are preceded by the greater-than sign (">"). Figure 2 shows a screen shot of SuperSmith Weibull where the first seven entries are censored and entries eight and nine are failures.

Figure 2: SuperSmith Weibull Data



	Set1:1
Point1	>0.67x1
Point2	>1.8x1
Point3	>2.79x1
Point4	>3.95x1
Point5	>5.14x1
Point6	>6.29x1
Point7	>7.89x1
Point8	9.21x1
Point9	10.79x1

Once the parameters are estimated the failure probability over a given time $\boldsymbol{t}$ can be calculated using the cumulative distribution function:

$$\boldsymbol{F(t) = 1 - e^{-\left(\frac{t-\alpha}{\eta}\right)^{\beta}}}$$

The reliability is simply the complement of the failure probability:

$$\boldsymbol{R(t) = e^{-\left(\frac{t-\alpha}{\eta}\right)^{\beta}}}$$

3. LARGE SATELLITE RELIABILITY

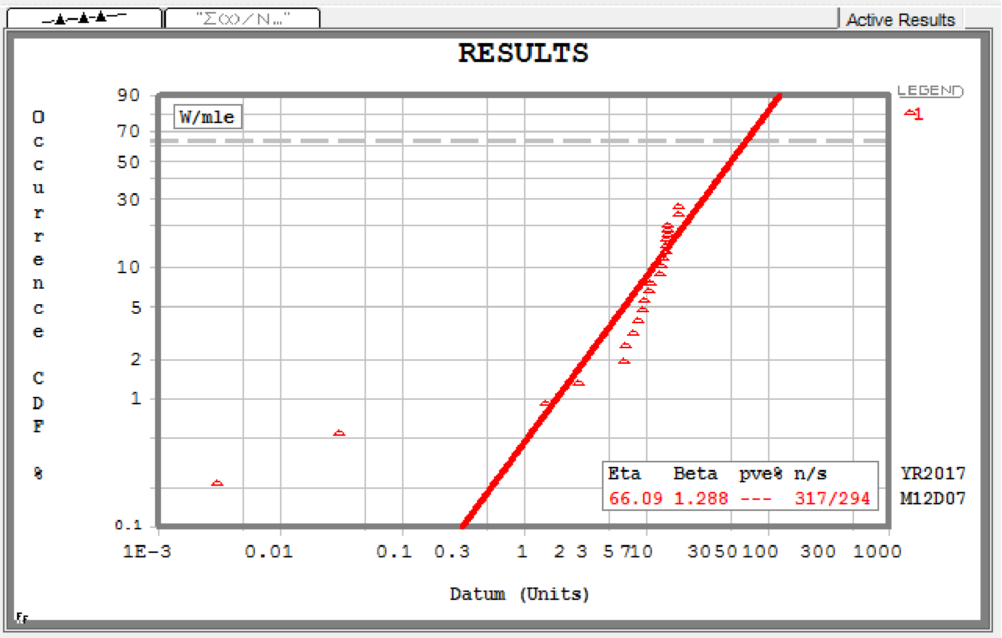
A query of the SpaceTrak database on both active and inactive large satellite buses with masses greater than 2500 kg and a design life of 15 years produced 319 spacecraft. Two of the 319 spacecraft terminated their mission early due to launch vehicle failures and therefore were removed from the dataset leaving 317 spacecraft. The operational time for each spacecraft, based upon current age as of November 17, 2017 [2] for those still active and age at retirement for inactive spacecraft are provided in Table 2 with failure times bolded. The spacecraft operating times ranged from 18 days to 28 years with a combined operating time of approximately 2500 years on-orbit. A spacecraft was assumed to be failed if it was retired prior to reaching its design life or if the spacecraft was retired due to failure after reaching its design life. Active spacecraft and spacecraft retired after reaching their design life for reasons other than failure were handled as right censored data. A total of 23 failures were included in the dataset with failure times varying from one day to 18 years. In many cases these satellite buses have continued to operate beyond their design life of 15 years as shown in Table 2.

Table 2: Operational Time of Large Satellites with Design Life of 15 Years

Operational Time (in years)												
0.00	0.67	1.80	2.79	3.95	5.14	6.29	7.89	**9.21**	**10.79**	13.55	15.98	18.67
0.03	0.76	1.81	2.82	3.96	5.25	6.35	7.99	9.27	10.94	**13.59**	16.01	19.07
0.05	0.76	1.84	2.89	4.07	5.30	6.42	7.99	9.35	11.03	14.14	16.43	19.23
0.10	0.80	1.90	2.93	4.14	5.36	6.50	8.06	9.37	11.06	14.29	16.52	19.48
0.11	0.81	1.94	2.95	4.22	5.37	6.50	8.06	9.37	11.10	**14.30**	16.53	19.96
0.13	0.87	1.98	3.08	4.32	5.47	**6.57**	8.13	**9.41**	11.25	14.45	16.62	19.97
0.13	0.91	1.99	3.09	4.33	5.48	6.58	8.17	9.44	11.28	**14.51**	16.84	20.22
0.14	0.91	2.02	3.09	4.46	5.51	6.58	8.20	9.44	11.30	14.53	17.01	20.24
0.18	0.92	2.04	3.12	4.52	5.51	**6.65**	8.22	9.45	11.42	**14.57**	17.06	20.47
0.25	0.99	2.09	3.14	4.55	5.51	6.89	8.25	9.50	11.48	14.61	17.08	20.50
0.25	1.04	2.09	3.17	4.59	5.57	6.89	8.25	9.59	11.59	**14.69**	17.13	20.81
0.25	1.12	2.13	3.19	4.65	5.64	6.90	8.27	9.59	11.70	**14.94**	17.14	21.20
0.37	1.12	2.13	3.19	4.78	5.65	6.98	8.39	9.60	11.70	**14.97**	17.19	21.21
0.39	1.23	2.13	3.20	4.78	5.76	7.01	8.39	9.68	11.76	15.05	17.32	21.62
0.39	1.26	2.18	3.29	4.80	5.92	7.10	8.51	10.01	12.20	15.18	17.34	23.06
0.40	1.40	2.21	3.48	4.92	5.98	7.21	**8.58**	10.02	12.28	15.23	17.36	23.54
0.42	1.42	2.22	3.66	4.92	6.08	7.29	8.63	10.02	12.41	15.34	17.36	27.59
0.44	1.42	2.25	3.66	4.95	6.12	7.29	8.73	10.13	12.50	15.38	17.44	blank
0.46	1.44	2.35	3.76	4.96	6.12	7.36	8.77	10.37	12.72	15.44	17.92	blank
0.46	1.44	2.48	3.78	4.98	6.14	7.40	8.92	10.38	12.77	15.54	18.02	blank
0.51	1.48	2.48	3.78	4.99	6.15	7.46	8.92	**10.50**	**12.89**	15.59	**18.05**	blank
0.54	**1.50**	2.56	3.82	5.02	6.16	7.50	8.94	10.55	12.93	15.60	**18.15**	blank
0.54	1.53	2.56	3.87	5.02	6.16	7.57	9.04	10.55	13.10	15.73	18.16	blank
0.60	1.69	2.67	3.90	5.10	6.17	7.67	9.06	10.62	13.34	15.75	18.22	blank
0.64	1.71	**2.77**	3.91	5.14	6.27	**7.85**	9.17	10.70	**13.35**	15.83	18.43	blank

Weibull analysis using software SuperSmith Weibull [4] of the data provided in Table 2 produced the results provided in Figure 3. Utilizing the calculated Weibull parameters $\beta = 1.3$, $\eta = 66$ the predicted reliability over 15 years is 0.86. Since β (the shape parameter) is close to 1.0, this population of satellites is experiencing a near constant failure or random failure rate. However, over a long period of time the effect of the beta being slightly greater than 1 is noticeable. The reliability for the first year is 0.995 and the reliability for the 15th year (i.e. after successful operation of 14 years) is 0.987. The failure probability for the 15th year is approximately 2.6 times the failure probability for the first year.

Figure 3: Large Satellite Weibull Analysis Results



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Eta   Beta  pve% n/s
66.09 1.288 ---  317/294
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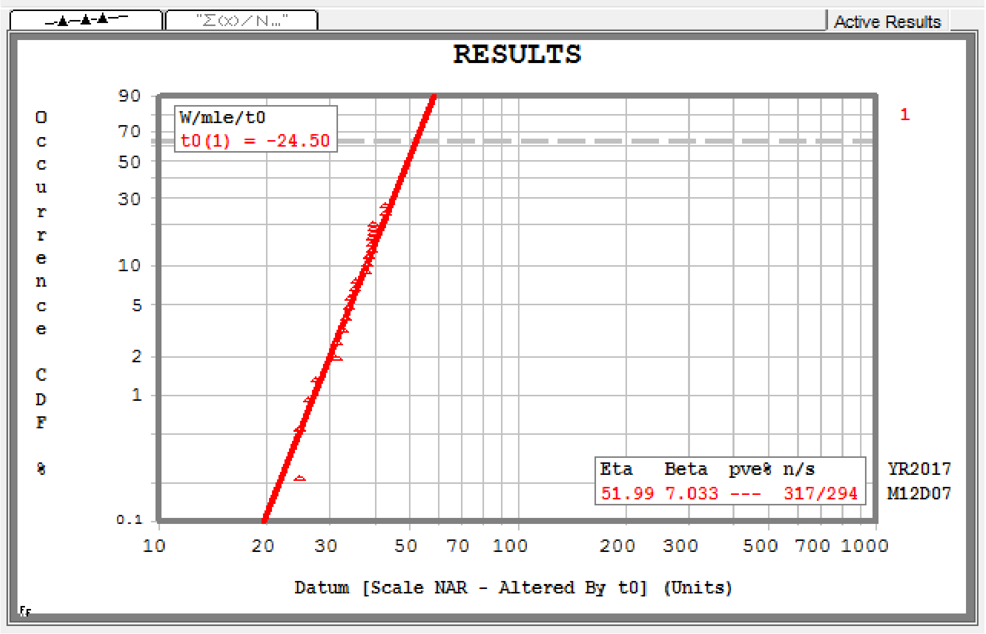
Upon further study of the graph in Figure 3, it appears as if the failure data does not match the Weibull prediction. Additional analysis was performed utilizing the location parameter which was previously assumed to be zero and is shown in Figure 4. The failure data appears to match the 3-parameter Weibull prediction more accurately. Utilizing the new Weibull parameters $\beta = 7.0$, $\eta = 52$ and $\alpha = -24$ the predicted reliability at 15 years is approximately 0.87 which is consistent with the original prediction. Therefore, the additional model fidelity utilized to fit the lower values appears to be unnecessary.

Figure 4: Large Satellite 3-Parameter Weibull Analysis Results



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Eta   Beta  pve% n/s
51.99 7.033 ---  317/294
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4. SPECIFIC LARGE SATELLITE RELIABILITY

In November 2017, study contracts were awarded to five satellite bus manufacturers to research PPE designs. A subset of the large satellite bus data evaluated in section 3, those manufactured by the five companies were evaluated to determine if the predicted reliability for the buses manufactured by these companies was different than the general population of large satellite buses.

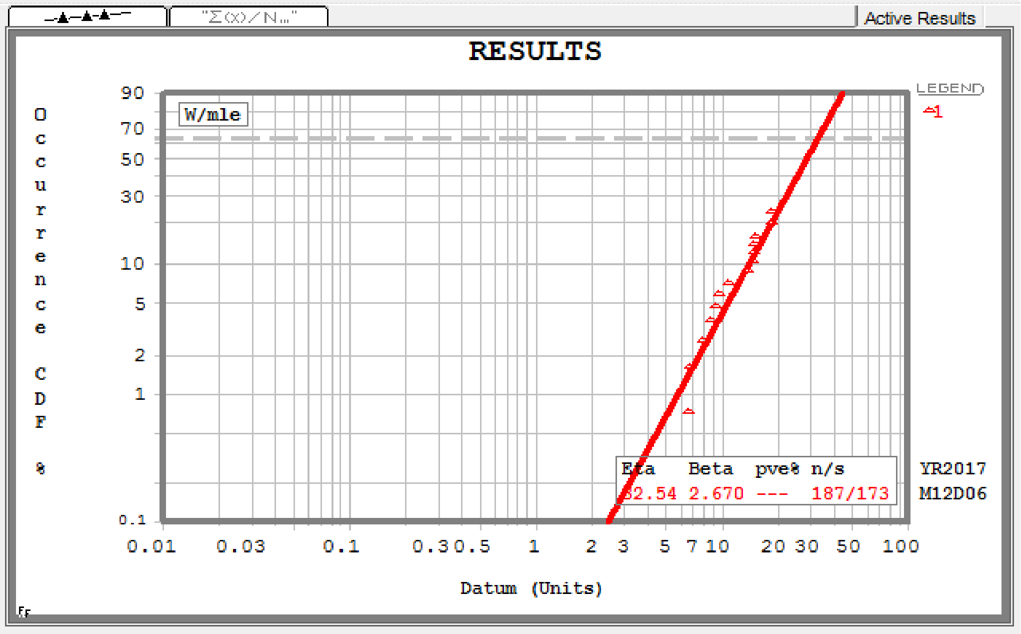
Filtering the original dataset produces 187 spacecraft with satellite buses manufactured by one of the five companies. The spacecraft operating times ranged from 49 days to 28 years with a combined operating time of approximately 1700 years on-orbit. The operational time for each spacecraft, based upon current age as of November 17, 2017 [2] for those still active and age at retirement for inactive spacecraft are provided in Table 3 with failure times bolded. There are a total of 14 failures in this dataset with failure times varying from 6.6 years to 18 years.

Weibull analysis using software SuperSmith Weibull [4] of the data provided in Table 3 produced the results provided in Figure 5. Utilizing the calculated Weibull parameters $\beta = 2.7, \eta = 33$ the predicted reliability over 15 years is 0.88. The beta or shape parameter is greater than 1.0 indicating that this population of satellites is experiencing an increasing failure or wear-out failure rate. The reliability for the first year is 0.99991 and the reliability for the 15th year (i.e. after successful operation of 14 years) is 0.979. The failure probability for the 15th year is approximately 230 times the failure probability for the first year.

Table 3: Operational Time of Specific Large Satellites with Design Life of 15 Years

Operational Time (in years)							
0.13	1.81	4.59	6.50	8.73	12.50	16.01	19.97
0.13	2.13	4.65	**6.57**	**9.21**	12.72	16.43	20.22
0.14	2.13	4.78	6.58	9.35	12.77	16.52	20.24
0.18	2.21	4.78	**6.65**	9.37	12.93	16.53	20.47
0.25	2.22	4.80	6.89	**9.41**	13.10	16.62	20.50
0.37	2.35	4.92	6.89	9.50	13.34	16.84	20.81
0.40	2.48	4.99	6.98	9.59	13.55	17.01	21.20
0.44	2.56	5.02	7.01	9.60	**13.59**	17.06	21.21
0.51	2.79	5.10	7.10	9.68	14.14	17.08	21.62
0.67	2.82	5.25	7.36	10.01	14.29	17.13	23.06
0.91	2.95	5.30	7.57	10.13	14.45	17.14	23.54
0.91	3.09	5.36	7.67	10.37	**14.51**	17.32	27.59
0.92	3.17	5.37	**7.85**	10.55	**14.57**	17.36	blank
0.99	3.19	5.47	7.89	**10.79**	14.61	17.44	blank
1.12	3.20	5.51	7.99	10.94	**14.69**	17.92	blank
1.23	3.29	5.51	8.06	11.06	**14.94**	18.02	blank
1.26	3.66	5.51	8.17	11.10	15.05	**18.05**	blank
1.40	3.78	5.65	8.20	11.28	15.34	**18.15**	blank
1.42	3.82	5.76	8.25	11.42	15.44	18.16	blank
1.42	3.87	5.98	8.25	11.48	15.54	18.22	blank
1.44	3.95	6.08	8.27	11.59	15.59	18.43	blank
1.48	3.96	6.12	8.39	11.70	15.60	18.67	blank
1.53	4.07	6.14	8.39	11.76	15.75	19.23	blank
1.69	4.22	6.16	8.51	12.28	15.83	19.48	blank
1.71	4.33	6.35	**8.58**	12.41	15.98	19.96	blank

Figure 5: Specific Large Satellite Weibull Analysis Results



5. LARGE SATELLITE RELIABILITY EXCLUDING SPECIFIC

In order to better compare the large satellite reliability of the specific bus manufacturers to the large satellite reliability, the satellite bus reliability of the other bus manufacturers was evaluated.

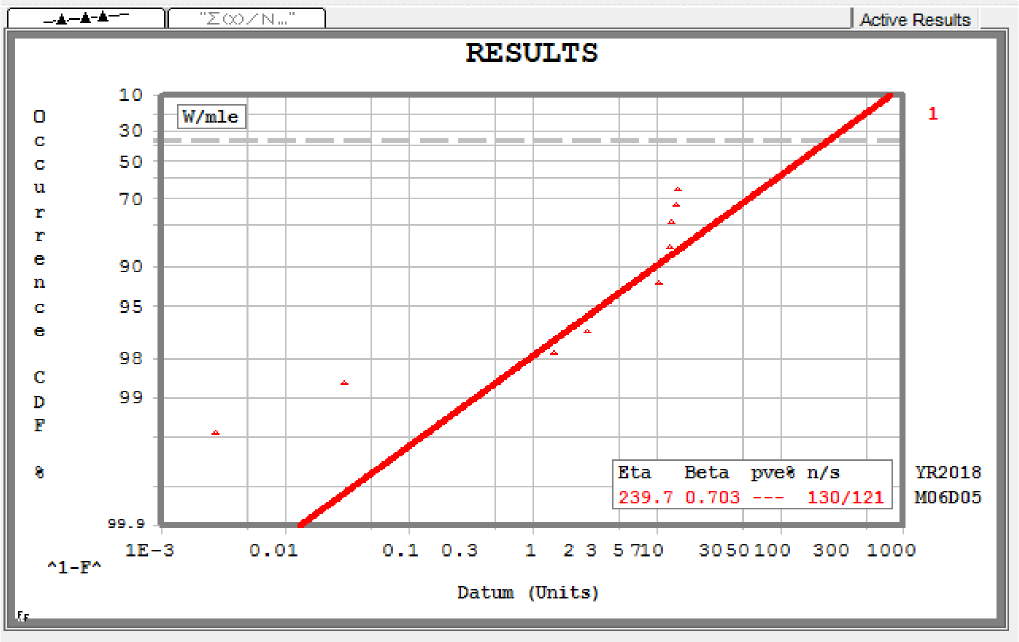
There are 130 spacecraft with satellite buses manufactured by companies other than the specific 5 in section 4. The spacecraft operating times ranged from 18 days to 19 years with a combined operating time of approximately 776 years on-orbit. The operational time for each spacecraft, based upon current age as of November 17, 2017 [2] for those still active and age at retirement for inactive spacecraft are provided in Table 4 with failure times bolded. There are a total of 9 failures in this dataset with failure times varying from one day to 15 years.

Table 4: Operational Time of Large Satellites with Design Life of 15 Years Excluding Specific

Operational Time (in years)					
0.00	1.12	3.09	5.58	8.63	11.30
0.03	1.44	3.12	5.64	8.77	11.70
0.05	**1.50**	3.14	5.92	8.92	12.20
0.10	1.80	3.19	6.12	8.92	**12.89**
0.17	1.84	3.48	6.15	8.94	**13.35**
0.25	1.90	3.66	6.16	9.04	**14.30**
0.25	1.94	3.76	6.17	9.06	14.53
0.39	1.98	3.78	6.27	9.17	**14.97**
0.39	1.99	3.90	6.29	9.27	15.18
0.42	2.02	3.91	6.42	9.37	15.23
0.46	2.04	4.14	6.50	9.44	15.38
0.46	2.09	4.32	6.58	9.44	15.73
0.54	2.09	4.46	6.90	9.45	17.19
0.54	2.13	4.52	7.21	9.59	17.34
0.60	2.18	4.55	7.29	10.02	17.36
0.64	2.25	4.92	7.29	10.02	19.07
0.76	2.48	4.95	7.40	10.38	blank
0.76	2.56	4.96	7.46	**10.50**	blank
0.80	2.67	4.98	7.50	10.55	blank
0.81	**2.77**	5.02	7.99	10.62	blank
0.87	2.89	5.14	8.06	10.70	blank
1.04	2.93	5.14	8.13	11.03	blank

Weibull analysis using software SuperSmith Weibull [4] of the data provided in Table 4 produced the results provided in Figure 6. Utilizing the calculated Weibull parameters $\beta = 0.70$, $\eta = 240$ the predicted reliability over 15 years is 0.87. The beta or shape parameter is less than 1.0 indicating that this population of satellites is experiencing a decreasing failure or infant mortality failure rate. The reliability for the first year is 0.98 and the reliability for the 15th year (i.e. after successful operation of 14 years) is 0.993. The failure probability for the 15th year is approximately 3 times lower than the failure probability for the first year.

Figure 6: Large Satellite Excluding Specific Weibull Analysis Results



6. CONCLUSION

There is a difference in the reliability of large satellite buses with design life of 15 years compared to the reliability of the subset manufactured by the five companies researching PPE designs. The predicted reliability is slightly higher over 15 years, 0.88 vs. 0.86 for the general population or 0.87 for the population excluding the specific bus manufacturers. However, the general population has a failure rate that is nearly constant (factor of 2.6 between first year and 15th year failure probabilities) and the population excluding the specific bus manufacturers has a decreasing failure rate (factor of 3 higher for between the first year and 15th year failure probabilities) compared to increasing failure rate (factor of 230 higher between the first year and 15th year failure probabilities) for those manufactured by the specific group of companies.

Acknowledgements

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