Galileo Probe Battery Lifetime Estimation

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SUMMARY

The Galileo spacecraft deployed a probe, during 1995, to investigate the atmosphere of Jupiter. It was powered by Li/SO_2 batteries that could not be tested during the 6 years of travel from Earth to Jupiter. The fundamental problem for the decision-makers during the mission was the uncertainty in knowing whether the batteries had sufficient capacity left to perform the planned mission. Battery tests performed at Ames Research Center dating back to 1984 indicated that sufficient capacity should be available. However, the statistical uncertainties associated with the data set and the inherent applicability of the data set to the in-flight set of batteries had not been considered. Accounting for all identified uncertainties, a Bayesian Weibull analysis using a Monte Carlo solution technique, determined the confidence that the battery set on-board the Galileo probe would perform adequately.

1. *INTRODUCTION*

The Galileo spacecraft was launched in late 1989 on the Space Shuttle. The mission used an Inertial Upper Stage to propel the spacecraft from an Earth parking orbit into an escape trajectory toward Jupiter. Transit time to Jupiter was approximately 6 years and 4 months. A probe was deployed from the spacecraft, during 1995, 150 days before arrival at Jupiter. The probe descended into the Jovian atmosphere to make measurements and transmit data back to the orbiting Galileo spacecraft, which, in turn, relayed the information back to Earth. The electrical instrumentation, control and communication power was provided by three parallel but not redundant modules of Li/SO2 batteries. These batteries were designed to provide approximately 51 minutes of dc power (approximately 15 Amp-hours) before the voltage drops below 27 Vdc against the anticipated load while transiting the Jovian atmosphere. It was possible that variation in mission parameters might have required as much as 75 minutes (approximately 19 Amp-hours) for a successful mission.

This analysis was performed as the Galileo spacecraft was approaching Jupiter. Its objective was to assess the confidence in the ability of the on-board set of batteries to power the probe, during the planned set of experiments. If the result showed low confidence in the ability of the batteries to complete the mission, the mission objectives would have been modified.

2. *UNCERTAINTY WAS THE PROBLEM*

The probe and its electrical power supply performed well during its journey through the Jovian atmosphere. However, before arrival, the fundamental problem was the uncertainty that arose because the Galileo probe flight battery capacity is not testable in flight. It is well known that capacity loss occurs owing to slow discharges during storage or in-flight. The remaining useful capacity (in amp-hours) for the mission of the probe could not be precisely known. In an attempt to gain confidence that the flight batteries would perform as needed, a dozen sets of battery modules, which were similar to the flight lot, had been tested since 1984 at NASA Ames Research Center (Exhibit 1). These test simulations were conducted under conditions more or less similar to flight conditions and load profile. Simulated flight conditions for these tests included 1) the storage loss of more than 6 years of flight, 2) 150 day coast of the probe before reaching the Jovian atmosphere, and 3) the final high load demand required during the transit through the Jovian atmosphere. Nominal temperature of the probe and batteries is approximately 0^{o}C. Ames Research Center provided us with these test results. Having already used simple statistical and linear regression methods to estimate in-flight battery life, they asked us to provide an independent analysis that accounted for the uncertainty.

Two categories of uncertainties associated with the Galileo probe battery lifetime estimation were identified: aleatory and epistemic. Aleatory uncertainty arose from stochastic processes and is generally represented by scatter in the data. Epistemic uncertainty arose from imprecise knowledge of the physical processes, models, and parameters of the model.

Our objective was to assess the capacity of the Galileo battery modules to a discharge level of 27 Vdc output using the planned mission loading profile. The results were presented as a probability density function depicting the confidence of obtaining a level of battery capacity.

We used the normalized test simulation results from Ames Research Center as the database. Because not all tests were run the same way, the data provided had been normalized to the same estimated storage loss. The likelihood that the probe contains an out-of-population ("bad") battery was treated as a multiplicative constant on the probability that the desired capacity was reached. An effective quality control program was in place as indicated by the data in Exhibit 1. Therefore, a high probability of a good battery set on the probe was assumed and the multiplicative constant was set to unity.

3. TREATMENT OF ALEATORY UNCERTAINTY

The data of Exhibit 1 coupled with the battery failure mode of interest for this study (i.e. discharge) indicated an end-of-life (or wearout) type of analysis rather than an analysis of the constant hazard failure regime. We tested this hypothesis by plotting the data on Weibull probability paper. Consistent with traditional Weibull analysis[1], the shape factor (β) is the slope of the data plotted on Weibull probability paper. Because the data itself reflects natural stochastic variability of the underlying process, different slopes can fit the data. This is particularly the case if the data is sparse. Therefore, the shape factor can be viewed as an uncertain quantity. Traditional Weibull analysis fits the data by use of either the method of least squares or the maximum likelihood method. The former was used in this study. An underlying assumption of the use of a least squares fit is that the random variable, in this case β, is normally distributed. Traditional Weibull plots produce the median β, which has a value of 17.1, as shown in Exhibit 2. The standard deviation of the underlying distribution of β is 1.2. Exhibit 2 shows the data plotted with a least squares fit. Note that the median Weibull shape factor (β) is much greater than unity confirming that an aging phenomenon was observed.

The above traditional Weibull analysis is unable to treat the aleatory uncertainty associated with the Weibull scale factor (λ). This scale factor is proportional to the inverse of a characteristic discharge time. We are interested in estimating the aleatory uncertainty associated with achieving particular values of discharge capacity, Ah. A Bayesian Weibull approach was used for this. The approach assumes that the Weibull scale factor, λ, is not known but the Weibull shape factor, β, is known exactly[2]. A Gamma distribution over the scale factor results. There obtains,

$$g(\lambda) = \frac{\omega^n}{\Gamma(n)} \lambda^{n-1} e^{-\omega\lambda} \qquad \text{Equation 1}$$

$$\omega = \Sigma\, \tau_i^{\beta} \qquad \text{Equation 2}$$

In these equations, n is the shape parameter of a gamma distribution, $g(\lambda)$, and equals the number of tests; ω is a gamma distribution scale parameter; summation, Σ, is over the 12 tests noted in Exhibit 1, in which τ_i of each test is the discharge time; and β was defined above.

Finally, the discharge capacity may be expressed as follows:

$$Ah = (-\ln(r)/\lambda)^{(1/\beta)} \qquad \text{Equation 3}$$

In equation 3, r is the reliability that the discharge capacity, Ah, is achieved or exceeded.

The resultant probability distribution for Ah was obtained by solving the above set of three equations using Monte Carlo simulation. The Weibull shape factor, β, is sampled from the normal distribution defined above. The Weibull parameter, λ, is sampled from the gamma distribution, using the sampled value of β and r is sampled from a uniform distribution between zero and one. Sampling r in this manner is equivalent to repeated solutions of the above equation each for a selected value of reliability.

4. TREATMENT OF EPISTEMIC UNCERTAINTY

It remains to modify this methodology to treat epistemic uncertainty as well. Such uncertainty arises because the data is not directly applicable to the actual in-flight Galileo probe batteries. Limitations in data applicability stem from four factors:

- Differences in storage and test environments
- Differences in loading profiles
- Differences in battery composition owing to different production lots
- Differences in battery age

To account for the possible limitation in applicability of the data set to the in-flight batteries, an applicability factor was introduced. This is a number between zero and unity which is a judgmental probability that a test faithfully replicates the conditions experienced by the in-flight batteries. A factor was developed for each test in Exhibit 1. In effect, the factor reduces the population of tests from n to a smaller number and, thereby, increases the statistical uncertainty in the estimated battery capacity. The applicability weight is introduced into Equations 1 and 2. With the assistance of NASA Ames Research Center each test was evaluated with respect to the above four differences and a weight estimated. Applicability weights varied between 45% and 86% over the twelve tests.

Performing the Monte Carlo simulation described above, with the weighting factor introduced into Equations 1, 2 and 3 produced the desired result.

5. ESTIMATION OF BATTERY LIFE WITH UNCERTAINTY

The solution, which represents the epistemic and aleatory uncertainty in the discharge capacity of the in-flight set of Galileo probe batteries, is given in Exhibit 3. This is a probability density function of the estimated Galileo probe discharge capacity (in amp-hours) based on ground test results. The area under the curve, measured from right to left, is the probability of meeting or exceeding each value of capacity (in amp-hours) shown on the x-axis. The mission of the Galileo probe battery was nominally expected to be about 51.3 minutes. This analysis indicated that this level of performance or greater will be achieved with a probability of 98.5%. An extremely demanding mission may have required 75 minutes of battery operation. The results show a 60% chance that 75 or more minutes will be achievable.

Three sensitivity calculations were also performed to estimate the contribution of each type of uncertainty on the dispersion of the probability density function. The approach used below is to remove successive epistemic uncertainties in order to visualize the relative impact of aleatory verses epistemic uncertainty.

1. The first set all applicability factors to 1.0
2. The second set all applicability factors to 1.0 and used the median Weibull shape factor (β) instead of allowing it to vary within a Monte Carlo simulation
3. The third eliminated all sources of uncertainty by setting all applicability factors to 1.0, using the median β and using the mean Weibull scale factor (λ) instead of allowing it to vary within a Monte Carlo simulation

As shown in Exhibit 4, the results are not significantly affected by removing the epistemic uncertainty that is embodied in applicability weights, Weibull scale factor and Weibull shape factor. That is, the stochastic variability of the data itself (i.e. aleatory uncertainty), as provided by NASA Ames Research Center, dominates the dispersion shown in Exhibit 3. Using mean values for the scale and shape factors and no applicability weights produces nearly the same results as the full treatment of uncertainties.

This analysis of the estimated Galileo probe battery lifetime gave NASA engineers high confidence that sufficient battery capacity would be available to complete the planned mission. Modifications to the planned set of experiments were not necessary and the Galileo probe performed as expected.

REFERENCES

1. Abernathy, R.B. et.al, "Weibull Analysis Handbook", AFWAL-TR-83-2079, Pratt & Whitney Aircraft, 1983.
2. Martz, H.F. and Waller, R.A., "Bayesian Reliability Analysis", Krieger Publishing Co., Florida, 1991.

BIOGRAPHIES

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Dr. Michael V. Frank is founder and President of Safety Factor Associates, Inc. He is an active technical participant in the company's projects. During 27 years of experience, he has authored over 60 technical publications and has made numerous presentations in national and international forums. Subjects include risk and reliability of aerospace systems, cost and safety decision-making in the face of uncertainties, risk of plutonium release from launch vehicles, risk of nuclear power production systems/facilities, root cause analysis, reliability, availability, maintainability, artificial intelligence, and value-impact analysis. He currently serves as risk assessment consultant to the Interagency Nuclear Safety Review Panel which is chartered to evaluate the safety of nuclear payload space launches for the President of the United States.

His particular expertise is the assessment and management of all risks associated with engineered systems and the decision-making that accompanies risk management. He is at ease and is skilled in teaching as well as performing studies. Dr. Frank is a Professional Engineer with a strong background in mechanical (heat transfer, fluid flow, and thermal-hydraulics) as well as reliability and risk analysis. He has made contributions to the theory and practice of risk assessment in three industries: Defense, Aerospace, and Nuclear.

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Kevin Silke is an engineer in the Atlas program at Lockheed Martin. This work was performed while he was with Safety Factor Associates, Inc. He has degrees in Electrical Engineering and Business Management. He has spent his entire professional career in reliability and risk assessment of spacecraft, launch vehicles, and NASA operated high energy ground research facilities. His technical skills include creation of software (in a variety of languages) for specialized solutions to reliability and statistical problems. His risk assessment talents include reliability modeling and reliability data analysis, fault tree analysis, event sequence diagram development, event tree analysis, failure/success database development, common cause failure analysis using the Multiple Greek Letter Method, Bayesian data analysis, Failure Mode and Effects Analysis, uncertainty analysis, and Monte Carlo analysis.

Lot Number & Test	Capacity Loss While in Storage in Amp-hours	Simulated Coast Load	Total Adjusted Discharge (τi) in Amp-hours	Notes
4 – Battery Test #2 (18 July 1984)	3.3 Amp-hours	Real Time (150 days)	18.33 Amp-hours	
6 – Qualification Test (3 Dec. 1985)	3.3	Real Time (150 days)	16.78	Anomalous test loads
6 – Qualification Test (4 Dec. 1985)	3.3	Real Time (150 days)	17.40	
10 – Qualification Test (29 Aug. 1989)	3.3	Real Time (150 days)	19.24	
6 – 180-day Coast Test (17 July 1986)	3.3	Real Time (180 days)	19.12	
3 – Aged Module Test (8 Dec. 1987)	---	Real Time (150 days)	19.67	6.7 year old battery
7 – Texas Carbon Modules (10 Dec. 1987)	3.3	Real Time (150 days)	17.76	Texas v Canadian Manufacturer
4 – Battery Test #3 (19 July 1984)	3.3	Accelerated (150 day equivalent)	20.59	
6 – Qualification Test (17 July 1985)	3.3	Accelerated (150 day equivalent)	20.00	
9 – Qualification Test (21 March 1989)	3.3	Accelerated (150 day equivalent)	19.88	
10 – Qualification Test (23 March 1989)	3.3	Accelerated (150 day equivalent)	20.28	
10 – FDAT (21 Feb. 1995)	---	Real Time (155 days)	19.50	6.1 year old battery

Exhibit 1. Summary of Input Data for Galileo Probe Lifetime Estimation

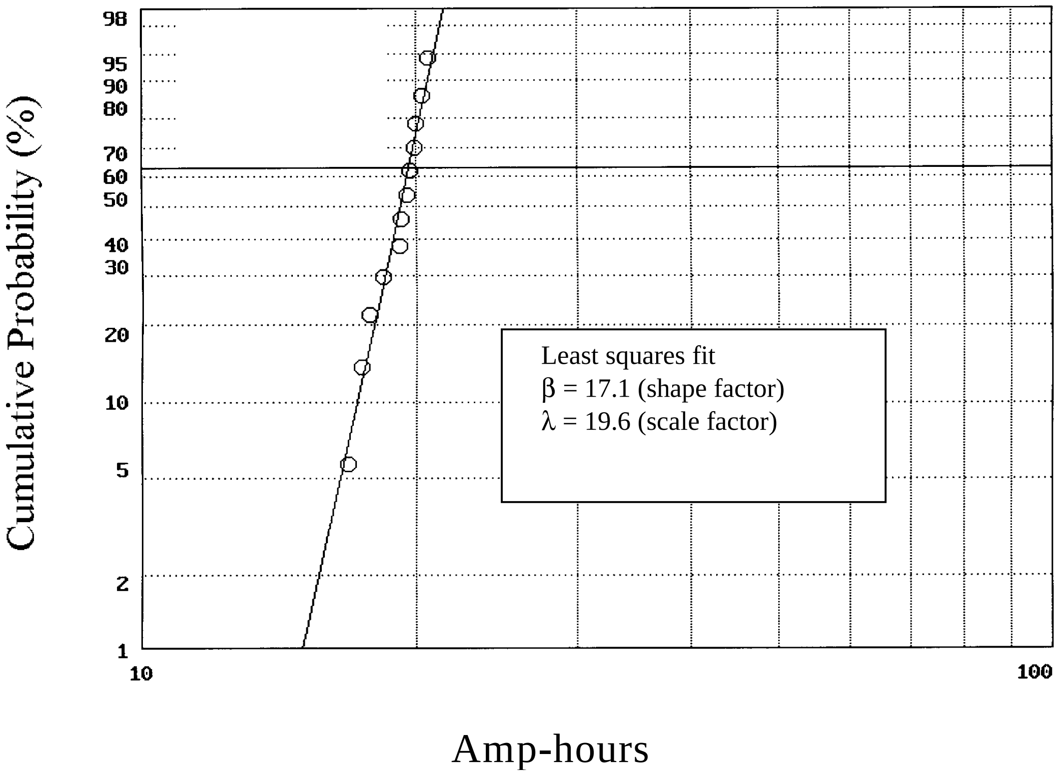

Exhibit 2: Weibull Plot of Galileo Battery Probe Test Simulation Data

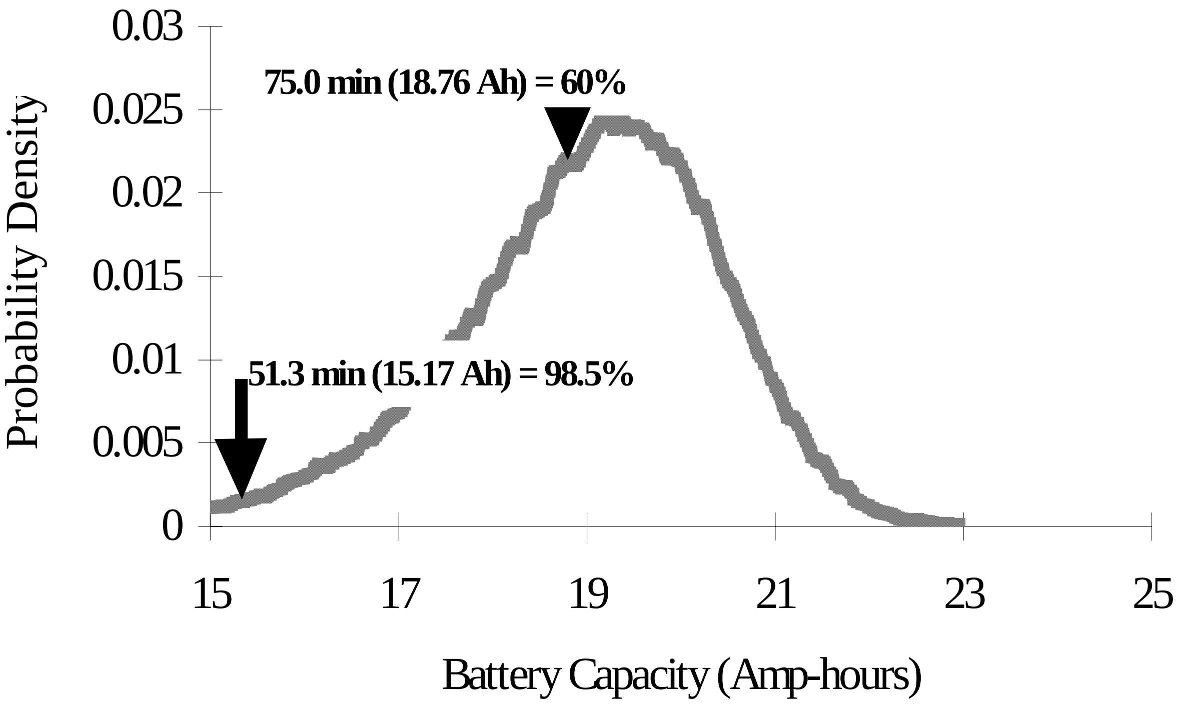

Exhibit 3. Predictive Uncertainty in Galileo Probe Battery Capacity

Exhibit 4. Investigation in Sensitivity of Results to Treatment of Uncertainties