NASA/TM—2009-215502 2008–01–2901

Lunar Regenerative Fuel Cell (RFC) Reliability Testing for Assured Mission Success

David J. Bents
Glenn Research Center, Cleveland, Ohio

February 2009

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David J. Bents
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Prepared for the
2008 Power Systems Conference
sponsored by the SAE International
Seattle, Washington, November 11–13, 2008

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

February 2009

Level of Review: This material has been technically reviewed by technical management.

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David J. Bents
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

NASA's Constellation program has selected the closed cycle hydrogen oxygen Polymer Electrolyte Membrane (PEM) Regenerative Fuel Cell (RFC) as its baseline solar energy storage system for the lunar outpost and manned rover vehicles. Since the outpost and manned rovers are "human-rated", these energy storage systems will have to be of proven reliability exceeding 99 percent over the length of the mission. Because of the low (TRL=5) development state of the closed cycle hydrogen oxygen PEM RFC at present, and because there is no equivalent technology base in the commercial sector from which to draw or infer reliability information from, NASA will have to spend significant resources developing this technology from TRL 5 to TRL 9, and will have to embark upon an ambitious reliability development program to make this technology ready for a manned mission. Because NASA would be the first user of this new technology, NASA will likely have to bear all the costs associated with its development.

When well-known reliability estimation techniques are applied to the hydrogen oxygen RFC to determine the amount of testing that will be required to assure RFC unit reliability over life of the mission, the analysis indicates the reliability testing phase by itself will take at least 2 yr, and could take up to 6 yr depending on the number of QA units that are built and tested and the individual unit reliability that is desired. The cost and schedule impacts of reliability development need to be considered in NASA's Exploration Technology Development Program (ETDP) plans, since life cycle testing to build meaningful reliability data is the only way to assure "return to the moon, this time to stay, then on to Mars" mission success.

Discussion

NASA's Constellation Program calls for establishment of a permanently manned lunar outpost on the moon by 2024. In the current mission scenario (Ref. 1), there is a habitat and eight lander modules (four solar array and four energy storage modules) that provide electrical power to the outpost. The outpost will be powered by photovoltaic (PV) arrays when there is sunlight, and by energy storage units when the base is shaded or there is no sunlight; each energy storage unit having been recharged by its PV array when there was sunlight (see Fig. 1). Under this mission scenario (Shackleton Crater location) an energy storage unit is expected to have a 5 yr calendar life (will operate 1000 hr per year for a 5000 hr operating life) with no replacement, repair or maintenance allowed. If a more equatorial mission location is chosen, a 10,000 hr operating life is required (Ref. 2).

Since viability of the outpost, and the astronaut's survival, depend on the constant availability of electric power, the PV arrays and energy storage units deployed on the Moon will have to be very reliable. While the reliability requirement has not been fully articulated, it is reasonable to expect that, for a high visibility, publicly financed endeavor such as a moon base where human lives are at stake, the reliability of electrical power delivery will have to be in the multiple nine digits range (i.e., exceeding 99 percent).

Some of this reliability will be achieved by interconnecting the PV array/energy storage units together in such a way that, if one unit fails, the remaining units will pick up the load (refer to Table 1). The rest will depend on the inherent reliability of the individual units themselves; that is, the probability that an individual unit will not fail (i.e., will continue to deliver power as required) during the length of its mission.

PV arrays have inherently high reliability since they are made up of redundant solar cell strings connected in parallel. For PV arrays the individual unit reliabilities are well established due to this technology's widespread application in satellites and spacecraft. However, that is not the case with the energy storage technology which was chosen. For lunar surface mission, the launch and transportation costs dominate; therefore the Constellation program has baselined the hydrogen oxygen RFC for its energy storage because it appears to be lowest mass of all the options considered (except for nuclear power). Although the hydrogen oxygen RFC is a largely undeveloped technology, the watt-hr per kilogram that could be delivered from an RFC unit versus other alternatives (1100 W-hr/kg for the RFC versus 200 W-hr/kg for a secondary battery) appear so much better that the technical risk (including its vulnerability to single point failures) is acceptable in view of the launch cost saving it affords (Ref. 2).

TABLE 1.—INTERCONNECTED PV ARRAY/ENERGY STORAGE UNITS
[Reliability of four interconnected units.]

Survival probability					
One individual unit (25 percent capacity)	0.800	0.900	0.950	0.990	0.995
4 out of 4 units (100 percent capacity)	0.410	0.656	0.814	0.961	0.980
At least 3 out of 4 units (75 percent capacity)	0.819	0.948	0.986	0.999	0.9998
At least 2 out of 4 units (50 percent capacity)	0.973	0.996	0.999	0.99999	~1
At least 1 out of 4 units (25 percent capacity)	0.998	0.9999	0.99999	~1	~1

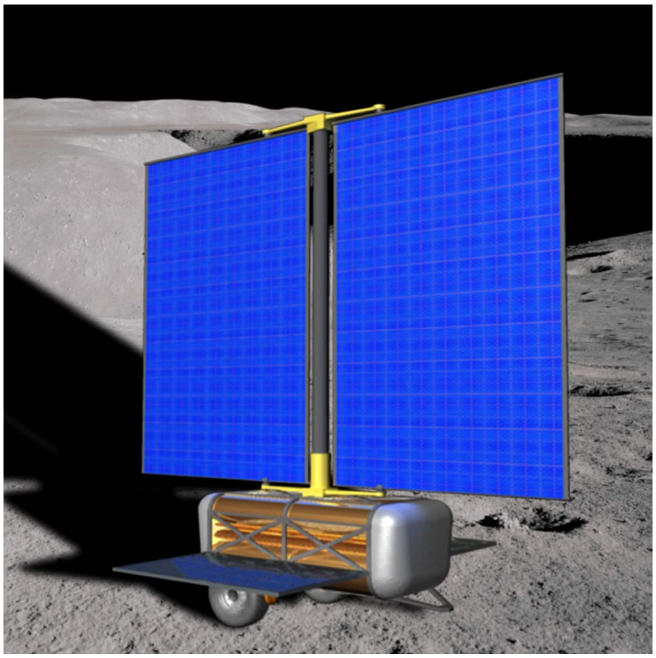

Figure 1.—PV array and energy storage unit on lunar surface.

Accordingly NASA has a project to develop the hydrogen oxygen RFC for its eventual lunar base. A major component of that project is developing the enabling technology to reduce technical risk, with intent to: (a) demonstrate operational feasibility for the lunar environment and (b) characterize life and reliability against the mission requirements.

It won't be easy establishing life and reliability of the hydrogen oxygen RFC. There is no existing fleet of units in service to draw failure data from. The few hydrogen oxygen RFCs which have been operated so far are not considered representative of units which might be deployed on the moon, and NASA’s development plans do not have a "fully representative" prototype appearing until 2016 (the due date for a TRL6 prototype). While there is a small population of terrestrial (hydrogen-air) RFCs operating sufficient to develop a failure database, their character is different enough from the hydrogen oxygen RFC to render invalid any correlations from the terrestrial unit's service history.

This presents a dilemma for mission planners. For other energy storage technologies (i.e., batteries) there are numerous examples of similar units serving in terrestrial applications, where there are populations large enough to empirically assess life and reliability, and infer similar life and reliability to the lunar base application. With the hydrogen oxygen RFC there is no terrestrial equivalent.

NASA cannot stake mission success on an untried technology. If the hydrogen oxygen RFC is to be deployed on the moon, it will have to undergo a reliability development program extensive enough to assure that an individual unit's operating life and reliability will meet or exceed the requirements. Lacking the experience base from a related terrestrial application, NASA will find it necessary to build, and life test, a representative number of identical RFC units, in order to positively establish life and reliability.

A "representative number" involves a production run of several identical RFC units (each unit is identical in design and construction to its sibling, built at the same location from the same manufacturing process) whose hardware design is as fully representative of the mission unit as possible. Life Test means each unit is operated under conditions as representative of the mission environment as possible; the same test regime is applied to all the units, and the test conditions must be applied for a duration that significantly exceeds the target operating lifetime.

This means setting up a production line, and a well-documented production process, to build the units. It also means life testing the individual units to failure, or at least a duration that significantly exceeds the target operating lifetime. Units which fail prematurely can be removed from test and examined for failure modes; as systemic failure modes are discovered in the hardware, incremental improvements can be made via changes to its design, and to the production process. The cycle of improvement, remanufacture and retest is repeated until eventually only wearout and random failures are occurring; at this point the hardware design and manufacturing process is "frozen" and a production run of identical quality assurance (QA) units can be built and put on test.

It is the life data from the QA units which positively establishes reliability. Mathematically, we can consider each unit's operating life as a random variable, and the operating life of all identical RFC units (each unit is identical in design and construction to its sibling, built at the same location from the same manufacturing process) as a population. To establish the life and reliability of the larger population (i.e., any and all RFC units built to that design and by the same process), we test a finite number of units—a sample—from that population and continue the test until there are a significant number of failures. The life test data, or more succinctly, the sample mean and sample variance obtained from that data, allow us to positively establish, within a predetermined level of confidence, the operating lifetime for the entire population by means of statistical analysis utilizing the T-distribution (Ref. 3). We do this by calculating a Confidence Interval about the sample mean, which is a function of the sample variance, the number of data points in the sample, and the level of confidence desired.

Refer to the example T-distribution probability density function (sample size = 4, = 3 degrees of freedom) shown in Figure 2. The confidence interval indicates a known percentage of the larger population which will always lie within designated Confidence Limits extending from either side of the sample mean. Considering a set of *n* life test data points taken from *n* identical units that were tested to failure, each data point is the elapsed time to failure for that unit:

The sample size is *n*

The sample mean is: $\overline{T} = \frac{1}{n}\sum_{j=1}^{n} t_j$

and the sample variance: $\delta^2 = \frac{1}{n-1}\sum_{j=1}^{n}\left(t_j - \overline{T}\right)^2$

and the sample deviation: $\delta = \sqrt{\delta^2}$.

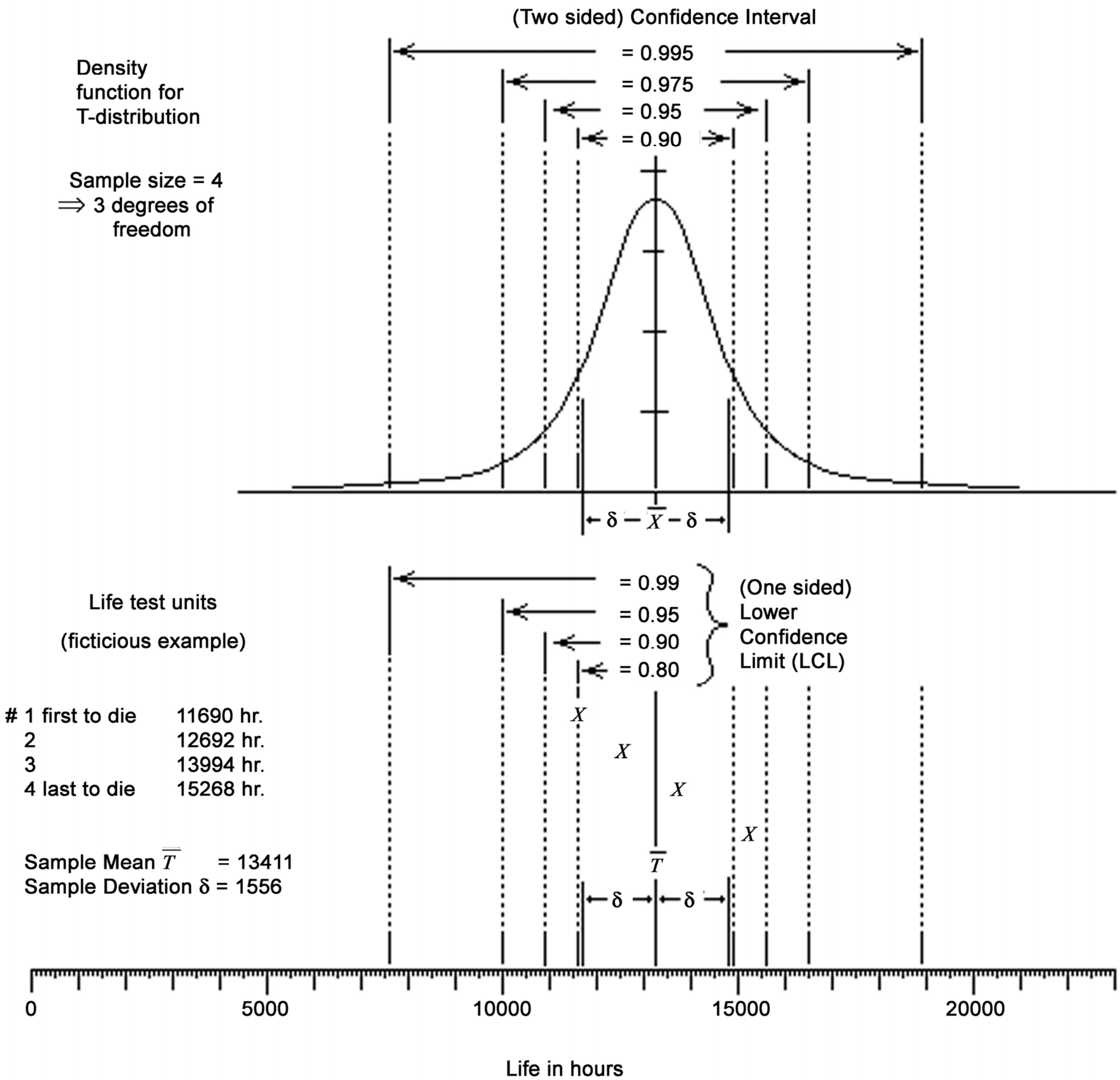

Figure 2.—Probability density function.

The sample mean would equate to the Mean Time To Failure for that sample of n units tested, the sample deviation would indicate the expected deviation of individual data points from the mean, and the Con-fidence Interval about the sample mean would indicate the time interval where a known percentage of the larger population of unit failures (based on data from the sample) must lie. For example, the two-sided 0.995 confidence interval shown in Figure 2 depicts the range of elapsed time where 99.5 percent of all failures are expected to occur, the 0.975 interval depicts where 97.5 percent of the failures will occur, the 0.95 interval shows where 95 percent of all the failures will occur and so on. The upper and lower bounds of the confidence interval are referred to as Confidence Limits which extend from either side of the sample mean. The amount they extend (i.e., width of the confidence interval) can be expressed as a multiple of the sample deviation δ. The numerical value of that multiple depends on: (a) the confidence level required, and (b) the number of data points in the sample, according to the T-distribution. The density function of Figure 2 is for a sample size n of four data points, or a T-distribution with 3 degrees of freedom.

The confidence interval can be used to estimate the larger population's reliability (i.e., probability of no failure) since the range of elapsed time values from zero to the Lower Confidence Limit happens to be the range where: a.) failures have not yet taken place, and b.) the known percentage of failures associated with that confidence interval <<cannot>> occur. Since we are only interested in this lower range (where failures may begin to occur), the probability of no failure during this time period (from zero to the lower confidence limit) actually corresponds to a "one-sided confidence limit" whose level of confidence is related to that of the two-sided interval by the relation:

$$P_{1\ \text{side}} = \frac{1}{2}\left(1 + P_{2\ \text{side}}\right)$$

Thus a "one-sided 0.95 confidence limit" (associated with 95 percent reliability) corresponds to a two-sided 0.975 confidence interval, a "one-sided 0.99 confidence limit" (associated with 99 percent reliability) corresponds to a two-sided 0.995 confidence interval, and so on. The example depicted in Figure 2 represents four units tested to failure, with the elapsed time to failure in hours. In this fictitious case, the sample mean exceeded 10000 hr by a considerable amount but, due to the limited number of data points and a sample deviation of only 12 percent, the 99 percent reliability level is considerably less than 10000 hr. If 10000 hr were a benchmark, we could say the data demonstrates 10000 hr with a reliability of about 95 percent.

We can also use the T-distribution to determine how long a unit must be tested and how many life tests (data points in the sample) are required to positively establish life and reliability of the units. For a given life and reliability requirement, it is the sample mean and variance (deviation from the mean) of the test data that will determine (a) whether or not the requirement can be met, and (b) how many life tests (data points in the sample) are required, and (c) how long each unit must be tested. This is of practical importance since the minimum acceptable unit life and reliability are specifications normally imposed on the unit's developer by a customer. The number of QA units that must be built and tested, together with the length of time each unit must be tested in order to demonstrate the specified life and reliability, directly impacts the developer's costs.

Table 2 displays the relevant parameters for a reliability estimate based on the T-distribution (using T-distribution function values from tables in Reference 4). Six examples are shown, corresponding to desired reliability levels of 90, 95 and 99 percent, and data deviations from the mean of 20 percent and 40 percent. The data show that when sample size n is small (few trials) the width of the confidence interval can be quite large, especially when there is appreciable deviation from the mean. For example, a developer who wants to demonstrate 95 percent reliability using only four life tests will face a "deviation multiplier" of 1.6. In the event the four trials produced $\pm$40 percent deviation from the sample mean, the 95 percent confidence limits about that mean (normalized to 1) would be 0.36 and 1.68, respectively. If those four trials deviated only 20 percent about the sample mean, however, the 95 percent confidence limits about the mean would narrow to 0.68 and 1.32, respectively. Increasing the sample size n also narrows the confidence limits. If the number of life tests were doubled from four trials to eight, the 1.6 "deviation multiplier" would be reduced to 0.84. Then, eight trials showing a deviation of 40 percent would narrow the 95 percent confidence limits to 0.67 and 1.33, respectively, and 20 percent deviation brings them in to 0.83 and 1.17, respectively.

To be assured of high reliability the confidence interval about the mean must be narrow enough to afford some operating time at low failure probability. In cases where variances (deviations) are too great and there are not enough trials in the sample (inadequate sample size n), the confidence interval can be so wide that it overlaps the entire time period (no confidence). If the variance is small it is possible to demonstrate reliability with only a few trials.

Table 3 recasts the six examples shown in Table 2 and normalizes them to the lower confidence limit not the sample mean. Here it is possible to see the implications on the amount of time each unit will have to remain under test (assuming no premature failures) based on the reliability level, the data deviation(s) and the number of units tested (sample size n).

TABLE 2.—RELIABILITY ESTIMATES BASED ON THE T-DISTRIBUTION
[Confidence limits from the T-distribution, normalized to the sample mean.]

Case 1A—90 percent reliability requirement, 40 percent deviation							
Sample size, *n* (no. of data points)	4	5	6	7	8	10	20
Degrees of freedom, *n*–1	3	4	5	6	7	9	19
Confidence level (1-sided interval)	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Corresponding 2-sided interval	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Parameter *c* from T-distribution	2.35	2.13	2.02	1.94	1.90	1.83	1.73
Deviation multiplier	1.18	0.953	0.82	0.73	0.673	0.58	0.39
Deviation form the sample mean (sample mean normalized to 1)	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Lower confidence limit (below sample mean)	0.53	0.62	0.67	0.71	0.73	0.77	0.85
Upper confidence limit (above sample mean)	1.47	1.38	1.33	1.29	1.27	1.23	1.15
Case 1B—90 percent reliability requirement, 20 percent deviation							
Sample size, *n* (no. of data points)	4	5	6	7	8	10	20
Degrees of freedom, *n*–1	3	4	5	6	7	9	19
Confidence level (1-sided interval)	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Corresponding 2-sided interval	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Parameter *c* from T-distribution	2.35	2.13	2.02	1.94	1.90	1.83	1.73
Deviation multiplier	1.17	0.95	0.82	0.73	0.67	0.58	0.39
Deviation form the sample mean (sample mean normalized to 1)	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Lower confidence limit (below sample mean)	0.77	0.81	0.84	0.85	0.86	0.88	0.92
Upper confidence limit (above sample mean)	1.23	1.19	1.16	1.15	1.13	1.11	1.08
Case 2A—95 percent reliability requirement, 40 percent deviation							
Sample size, *n* (no. of data points)	4	5	6	7	8	10	20
Degrees of freedom, *n*–1	3	4	5	6	7	9	19
Confidence level (1-sided interval)	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Corresponding 2-sided interval	0.975	0.975	0.975	0.975	0.975	0.975	0.975
Parameter *c* from T-distribution	3.18	2.78	2.57	2.45	2.37	2.26	2.09
Deviation multiplier	1.59	1.24	1.05	0.92	0.84	0.71	0.47
Deviation form the sample mean (sample mean normalized to 1)	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Lower confidence limit (below sample mean)	0.36	0.50	0.58	0.63	0.67	0.71	0.81
Upper confidence limit (above sample mean)	1.63	1.50	1.42	1.37	1.33	1.29	1.18
Case 2B—95 percent reliability requirement, 20 percent deviation							
Sample size, *n* (no. of data points)	4	5	6	7	8	10	20
Degrees of freedom, *n*–1	3	4	5	6	7	9	19
Confidence level (1-sided interval)	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Corresponding 2-sided interval	0.975	0.975	0.975	0.975	0.975	0.975	0.975
Parameter *c* from T-distribution	3.18	2.78	2.57	2.45	2.37	2.26	2.09
Deviation multiplier	1.59	1.24	1.05	0.93	0.84	0.71	0.47
Deviation form the sample mean (sample mean normalized to 1)	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Lower confidence limit (below sample mean)	0.68	0.75	0.79	0.81	0.83	0.86	0.91
Upper confidence limit (above sample mean)	1.32	1.25	1.21	1.19	1.17	1.14	1.09
Case 3A—90 percent reliability requirement, 40 percent deviation							
Sample size, *n* (no. of data points)	4	5	6	7	8	10	20
Degrees of freedom, *n*–1	3	4	5	6	7	9	19
Confidence level (1-sided interval)	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Corresponding 2-sided interval	0.995	0.995	0.995	0.995	0.995	0.995	0.995
Parameter *c* from T-distribution	5.84	4.60	4.03	3.71	3.50	3.25	2.86
Deviation multiplier	2.92	2.06	1.65	1.40	1.24	1.03	0.64
Deviation form the sample mean (sample mean normalized to 1)	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Lower confidence limit (below sample mean)	none	0.18	0.34	0.44	0.51	0.59	0.74
Upper confidence limit (above sample mean)	none	1.82	1.66	1.56	1.49	1.41	1.26
Case 3B—99 percent reliability requirement, 20 percent deviation							
Sample size, *n* (no. of data points)	4	5	6	7	8	10	20
Degrees of freedom, *n*–1	3	4	5	6	7	9	19
Confidence level (1-sided interval)	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Corresponding 2-sided interval	0.995	0.995	0.995	0.995	0.995	0.995	0.995
Parameter *c* from T-distribution	5.84	4.60	4.03	3.71	3.50	3.25	2.86
Deviation multiplier	2.92	2.06	1.65	1.40	1.24	1.03	0.64
Deviation form the sample mean (sample mean normalized to 1)	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Lower confidence limit (below sample mean)	0.42	0.59	0.67	0.72	0.75	0.79	0.87
Upper confidence limit (above sample mean)	1.58	1.41	1.33	1.28	1.25	1.21	1.12

TABLE 3.—RELIABILITY ESTIMATES BASED ON THE T-DISTRIBUTION
[Required life test period, normalized to lower confidence limit (LCL).]

Case 1A—90 percent reliability requirement, 40 percent deviation							
Number of QA units contemplated	4	5	6	7	8	10	20
Anticipated sample deviation, percent	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Desired confidence level, percent	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Sample mean extends beyond LCL (LCL normalized to 1.0)	0.88	0.62	0.49	0.42	0.37	0.30	0.18
Test time required beyond LCL	1.77	1.23	0.98	0.83	0.73	0.60	0.37
Case 1B—90 percent reliability requirement, 20 percent deviation							
Number of QA units contemplated	4	5	6	7	8	10	20
Anticipated sample deviation, percent	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Desired confidence level, percent	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Sample mean extends beyond LCL (LCL normalized to 1.0)	0.31	0.24	0.20	0.17	0.16	0.13	0.08
Test time required beyond LCL	0.61	0.47	0.40	0.34	0.31	0.26	0.17
Case 2A—95 percent reliability requirement, 40 percent deviation							
Number of QA units contemplated	4	5	6	7	8	10	20
Anticipated sample deviation, percent	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Desired confidence level, percent	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Sample mean extends beyond LCL (LCL normalized to 1.0)	1.75	0.99	0.72	0.59	0.50	0.40	0.23
Test time required beyond LCL	3.49	1.98	1.45	1.17	1.01	0.80	0.46
Case 2B—95 percent reliability requirement, 20 percent deviation							
Number of QA units contemplated	4	5	6	7	8	10	20
Anticipated sample deviation, percent	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Desired confidence level, percent	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Sample mean extends beyond LCL (LCL normalized to 1.0)	0.47	0.33	0.27	0.23	0.20	0.17	0.10
Test time required beyond LCL	0.93	0.66	0.53	0.45	0.40	0.33	0.21
Case 3A—99 percent reliability requirement, 40 percent deviation							
Number of QA units contemplated	4	5	6	7	8	10	20
Anticipated sample deviation, percent	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Desired confidence level, percent	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Sample mean extends beyond LCL (LCL normalized to 1.0)	void	4.64	1.92	1.27	0.98	0.70	0.34
Test time required beyond LCL	void	9.29	3.85	2.55	1.96	1.39	0.69
Case 3B—99 percent reliability requirement, 20 percent deviation							
Number of QA units contemplated	4	5	6	7	8	10	20
Anticipated sample deviation, percent	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Desired confidence level, percent	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Sample mean extends beyond LCL (LCL normalized to 1.0)	1.40	0.70	0.49	0.39	0.33	0.26	0.15
Test time required beyond LCL	2.81	1.40	0.98	0.78	0.66	0.52	0.29

For example, the developer who is trying to demonstrate 95 percent reliability using only four life tests (40 percent deviation) will have to contemplate an individual unit test period two or three times as long as the actual mission requirement. For a mission requirement of 10,000 hr, a deviation of 40 percent will necessitate a minimum test period of 34,900 hr, and 20 percent deviation will require 19,300 hr. If the number of life tests were doubled from 4 trials to 8, however, the minimum test period for 40 percent deviation would drop to 20,100 hr and for 20 percent deviation it would be 14,000 hr. If the number of life tests were raised to 20 trials, the minimum test period for 40 percent deviation would drop to 14,600 hr and for 20 percent deviation it would be 12,100 hr.

The developer of those four fictitious units shown in Figure 2 would be in full compliance if his customer had specified 10000 hr life with a reliability of 95 percent. If the customer requirement was for 10000 hr life with a reliability of 99 percent, however, the developer would not be able to demonstrate compliance unless he could show test results that either:

(a) Result in a higher sample mean and/or
(b) Produce less deviation from the sample mean, and/or
(c) More data points from more units tested (increase sample size *n*)

Fortunately the four fictitious data points in Figure 2 were far enough above the 10000 hr benchmark that they could support a 99 percent reliability demonstration. Figure 3 shows how the confidence limits may be changed by the insertion of two more data points into the sample of Figure 2. The new data fall below the previous sample mean and do not appreciably change the sample variance, yet causes the 99 percent confidence limit to cross just above 10000 hr, due to the T-distribution being narrowed by increasing the degrees of freedom from three to five. Our fictitious developer was fortunate that his relatively small sample variance allowed compliance to be demonstrated with only two more tests.

It is possible to demonstrate non-compliance also. Since sample mean and sample variance generally trace

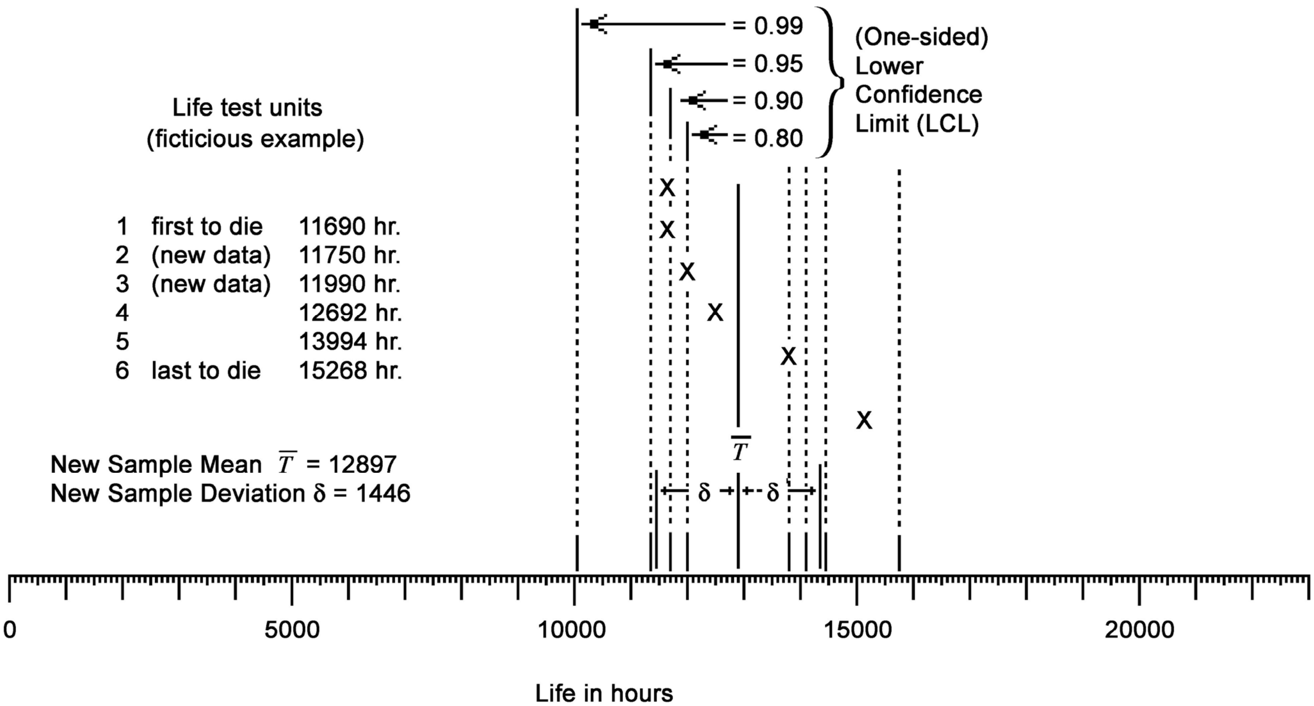

Figure 3.—Confidence limits changed with more data.

back to inherent physical characteristics of the thing being tested, it is normally impossible to improve these parameters without some sort of technological breakthrough (assuming the units under test were optimally designed for the life of the mission). If failures occur before the lower confidence limit is reached, or produce a sample mean that is too low, or a deviation that is too wide, no amount of additional testing will bring the sampled population up to compliance.

Implications for the Lunar Energy Storage Unit

Under the current mission scenario (Shackleton Crater location) an energy storage unit is expected to have a 5 year calendar life (will operate 1000 hr per year for a 5000 hr operating life) with no replacement, repair or maintenance allowed. A 10000 hr operating life, with no replacement, repair or maintenance allowed, was specified for other mission locations.

Table 1 shows the reliability of 4 energy storage modules when they are interconnected in such a way that if some individual units fail the remaining units pick up the load. If the outpost is able to survive some capacity loss, the ensemble reliability can approach 100 percent, using individual units of much lower reliability.

Suppose we specify the outpost cannot lose any more than 25 percent of its energy storage capacity (three out of four units remaining) at a survival probability of 99.0 percent, not more than 50 percent of its energy storage capacity (two out of four units remaining) at 99.9 percent, and must "never" lose all power capacity (survival probability exceeds 99.999 percent). An individual unit reliability of at least 95 percent will be required.

Or, we could be more sporting, and specify the outpost cannot lose any more than 25 percent of its energy storage capacity at a survival probability of 95 percent, and settle for a reasonable assurance (survival probability exceeds 99.99 percent) that power won't be completely lost. This still requires an individual unit reliability upwards of 90 percent.

For energy storage units not interconnected with the rest of the outpost (i.e., remote location) a reliability lower than 99.9 percent may be acceptable provided there is a failure mitigation strategy in place that ensures astronaut survival. Nevertheless it is reasonable to expect reliabilities of 99 percent or better for sake of the mission.

Can 10000 hr life and >90 percent reliability be ascribed to the hydrogen oxygen RFC? Not yet. Life and reliability of the hydrogen oxygen RFC unit is not yet characterized (the unit tests depicted in Figures 2 and 3 were entirely fictitious). But there is evidence that a system incorporating hydrogen oxygen PEM fuel cells may be capable of achieving operational lifetimes exceeding 10,000 hr. In the late 1990s the NASA Johnson Space Center tested an eight cell hydrogen oxygen PEM stack in an effort to evaluate its potential durability as a replacement for the Shuttle's alkaline fuel cell power plant. The stack demonstrated over 11,000 hr life before the test was arbitrarily terminated (Ref. 5). NASAs Next Generation Reusable Launch Vehicle (RLV) program carried out durability testing during 2004 through 2007 on a limited number of hydrogen oxygen PEM short (four cell) stacks. Most of the stacks demonstrated less than 5000 hr, but one specially constructed stack is reported by NASA to have achieved over 13,500 hr before the test was terminated (Ref. 6). A reliability estimate was made for the RLV primary fuel cell power generator based on known MTBFs for its ancillary components, and assuming a fuel cell stack reliability of 99 percent over its intended 10000 hr service life. A reliability of 86 percent was estimated, with suggested improvements for increasing reliability to 91 percent (Ref. 7).

Actual cell failure data for hydrogen-oxygen PEM fuel cells, based on measured degradation rates for identical cells which typically ranges from 2 to 6 μV per hour, suggests a deviation of about 40 to 45 percent for present day state-of-the-art.

Conclusion

Hydrogen oxygen PEM fuel cell technology could have the potential to meet life and reliability requirements associated with the lunar RFC, but this potential has not been demonstrated. Because of the more stressful internal operating environment inside hydrogen-oxygen fuel cells compared to hydrogen-air, the emerging life and reliability data from commercial hydrogen-air PEM fuel cells does not correlate closely enough to hydrogen-oxygen PEM technology to allow inferences to be drawn.

The life and reliability of hydrogen oxygen PEM fuel cell units are an "unknown population" statistically. A credible characterization of life and reliability will come only through testing a sample of that population. Cost and time considerations limit the amount of testing that can be performed, but statistical analysis allows us to positively establish life and reliability from a limited number of trials, and to estimate the number of trials and length of tests required to demonstrate.

Given the presently observed lifetime variation (40 percent deviation from the mean) for hydrogen oxygen PEM fuel cells of identical construction tested under uniform conditions, the analysis indicates:

NASA will need to build and test 10 to 12 identical units to positively demonstrate 10000 hr life and 99 percent individual unit reliability, with life tests for these units taking about 3 yr. The number of units under test can be reduced by half by approximately doubling the test period to 5-1/2 yr. The test period can be reduced to 2 yr by doubling the number of units tested to 20 identical units.

NASA will need to build and test seven to ten identical units to positively demonstrate 10000 hr life and 95 percent individual unit reliability, and the life tests for these units will take about 3 yr. If only 90 percent unit reliability is acceptable, NASA may build and test as few as four identical units and the life tests for these units will take at least 3 yr. This test period may be shortened 1 yr by increasing the number of identical units from four to seven units.

If more consistency is achieved in fuel cell stack construction, to the extent that only 20 percent deviation is demonstrated—NASA could positively demonstrate 10000 hr life and 95 percent individual unit reliability with five identical units and less than 2 yr of life tests. If only 90 percent unit reliability was acceptable, NASA could build and test as few as four identical units and the life tests for these units would take less than 2 yr.

The costs associated with the life tests, and the development costs leading up to the manufacture of life test units, will have to be shouldered by NASA since there are no earlier users of this technology. These costs and schedule impacts are not presently factored into NASAs energy storage development plans.

References

1. AIAA 90-STSA-20, "NASA's Lunar Architecture," SPACE 2007 Conference and Exposition, Long Beach, CA, Sept. 18–20, 2007.
2. Freeh, Joshua, and Nainiger, Joseph, "LAT-2 Study Outbrief," NASA Exploration Power Workshop held at Ohio Aerospace Institute, Cleveland, OH, August 28, 2007.
3. W.S. Gosset, "The Probable Error of a Mean," Biometrika, Vol. 6, (1908), pp. 1–25.
4. Erwin Kreyszig, *Advanced Engineering Mathematics*, John Wiley and Sons, Inc., 1967.
5. Contractor report, JSC Contract T634W, "Polymer Electrolyte Fuel Cell for the Space Shuttle, Ballard 8-Cell Mk513 Characteristics and Degradation Mechanisms," Ballard Power Systems, January 2000.
6. M. Manzo, M. Hoberecht, C. Reid, T. Miller and C. Mercer, "Fuel Cell and Battery Development for Lunar exploration Power Systems," Space Technology And Applications International Forum (STAIF) Conference, February 14, 2008.
7. Michael C. Kimble and Mark Hoberecht, "Performance Evaluation of ElectroChem's PEM Fuel Cell Power Plant for NASA's 2nd Generation Reusable Launch Vehicle," First International Energy Conversion Engineering Conference.

REPORT DOCUMENTATION PAGE					*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
01-02-2009

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Lunar Regenerative Fuel Cell (RFC) Reliability Testing for Assured Mission Success

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Bents, David, J.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 038957.04.06.01

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-16664-1

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORS ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2009-215502

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Categories: 20 and 44
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301-621-0390

13. SUPPLEMENTARY NOTES

14. ABSTRACT
NASA's Constellation program has selected the closed cycle hydrogen oxygen Polymer Electrolyte Membrane (PEM) Regenerative Fuel Cell (RFC) as its baseline solar energy storage system for the lunar outpost and manned rover vehicles. Since the outpost and manned rovers are "human-rated," these energy storage systems will have to be of proven reliability exceeding 99 percent over the length of the mission. Because of the low (TRL=5) development state of the closed cycle hydrogen oxygen PEM RFC at present, and because there is no equivalent technology base in the commercial sector from which to draw or infer reliability information from, NASA will have to spend significant resources developing this technology from TRL 5 to TRL 9, and will have to embark upon an ambitious reliability development program to make this technology ready for a manned mission. Because NASA would be the first user of this new technology, NASA will likely have to bear all the costs associated with its development.When well-known reliability estimation techniques are applied to the hydrogen oxygen RFC to determine the amount of testing that will be required to assure RFC unit reliability over life of the mission, the analysis indicates the reliability testing phase by itself will take at least 2 yr, and could take up to 6 yr depending on the number of QA units that are built and tested and the individual unit reliability that is desired. The cost and schedule impacts of reliability development need to be considered in NASA's Exploration Technology Development Program (ETDP) plans, since life cycle testing to build meaningful reliability data is the only way to assure "return to the moon, this time to stay, then on to Mars" mission success.

15. SUBJECT TERMS
Fuel cell power plants; Electric power supplies; Energy sources; Spacecraft power supplies; Electric power; Energy storage; Fuel cells

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					STI Help Desk (email:help@sti.nasa.gov)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
U	U	U	UU	14	301-621-0390