

Lunar RFC Reliability Testing for Assured Mission Success

D. J. Bents

NASA Glenn Research Center

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 regenerative fuel cell (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

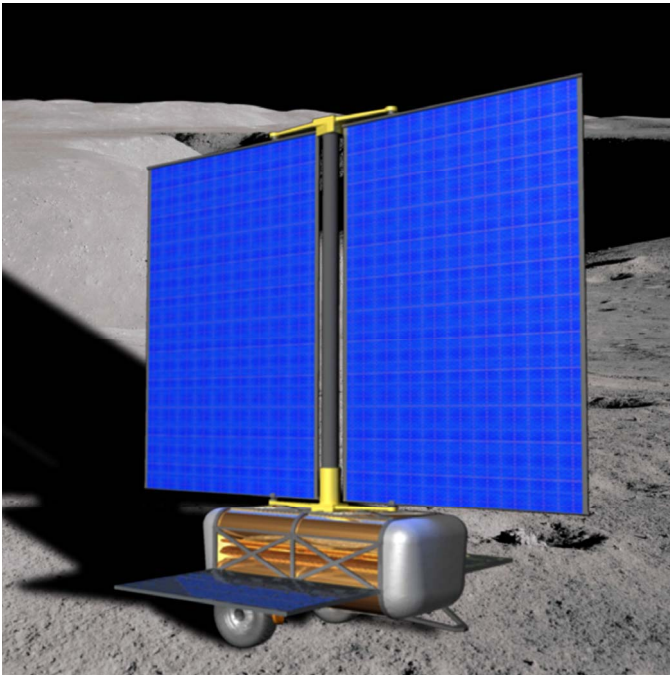


Figure 1. PV array and energy storage unit on lunar surface.

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 NASAs 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: $\bar{T} = \frac{1}{n} \sum_{j=1}^n t_j$

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

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

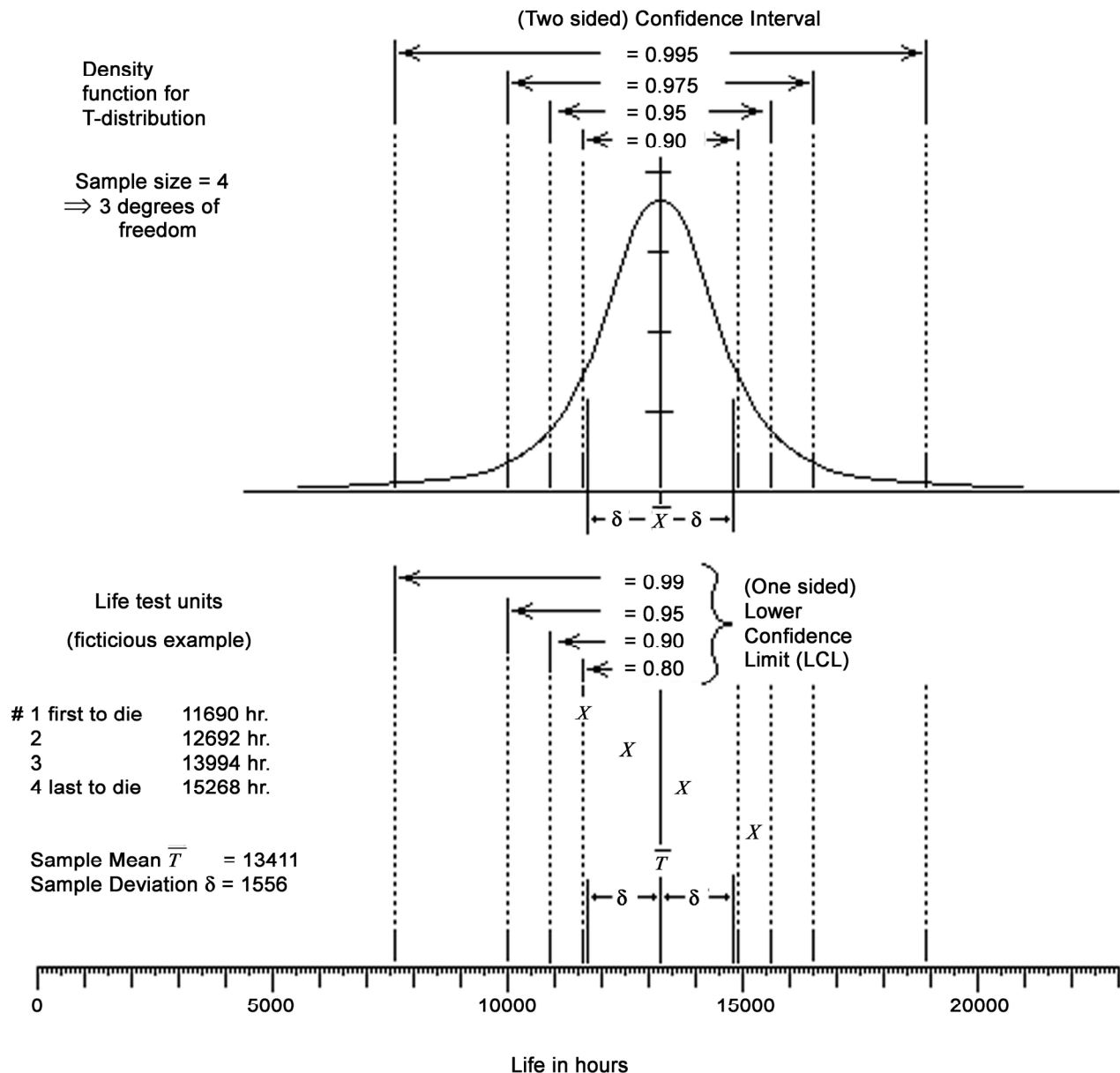


Figure 2. Probability density function.