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Advanced Stirling Radioisotope Generator Life Certification Plan

Jeffrey J. Rusick[1], Edward J. Zampino[1]

[1]*Reliability and Systems Safety Branch, NASA Glenn Research Center, Cleveland, OH 44135*

Abstract. An Advanced Stirling Radioisotope Generator (ASRG) power supply is being developed by the Department of Energy (DOE) in partnership with NASA for potential future deep space science missions. Unlike previous radioisotope power supplies for space exploration, such as the passive MMRTG used recently on the Mars Curiosity rover, the ASRG is an active dynamic power supply with moving Stirling engine mechanical components. Due to the long life requirement of 17 years and the dynamic nature of the Stirling engine, the ASRG project faced some unique challenges trying to establish full confidence that the power supply will function reliably over the mission life. These unique challenges resulted in the development of an overall life certification plan that emphasizes long-term Stirling engine test and inspection when analysis is not practical. The ASRG life certification plan developed is described.

Keywords: ASRG, Radioisotope, Stirling, Generator

1. INTRODUCTION

The purpose of the Advanced Stirling Radioisotope Generator (ASRG) is to serve as a highly efficient and reliable power source to provide electricity for spacecraft or planetary surface operations on future space exploration missions. The great challenge has been to design, build, test, and verify that the ASRG can provide power for a period of 17 years with a probability of success (reliability) of at least 0.90. The required design life consists of 14 years of *continuous* operation in space following a potential storage period of 3 years in controlled environments after fueling. Once the ASRG is fueled, it must operate continuously and therefore it operates throughout the storage duration as well as in-space. [1] The ASRG (see Figure 1) incorporates four major subsystems: two General Purpose Heat Source (GPHS) modules that contain the radioisotope fuel, two Advanced Stirling Convertors (ASCs), one Generator Housing Assembly (GHA) that integrates the ASRG, and a remote Advanced Controller Unit (ACU) that controls and synchronizes the ASCs.

The ASC unit (see Figure 2) is a free-piston, Stirling engine-driven linear alternator design that converts heat from a GPHS into AC electrical power. The working fluid, helium gas, is hermetically sealed within the ASC pressure vessel. At a frequency of 102 Hz, the displacer and piston reciprocate between the expansion and compression spaces inside a cylinder within the helium pressure vessel. Electrical power is produced by the linear alternator, which has a permanent magnet assembly attached to the moving piston. The regenerator, a high-porosity matrix made of corrosion-resistant alloy, allows heat recovery of the working gas between expansion and compression cycles.

The Cold-Side Adapter Flange (CSAF) provides a structural connection to the General Housing Assembly (GHA) and a heat rejection path to the generator radiator. The AC electrical power is sent to the ACU from the ASCs via hermetic feed-through assemblies. Designed to be mounted remotely from the GHA, the ACU must rectify the AC power to DC power and provide the capability for output power control. It must also synchronize the operating frequencies of two ASCs within the ASRG to obtain a momentum-balanced system. Finally, the ACU must safeguard the ASC by controlling them within allowable hot-end temperatures and piston displacement limits.

The ACU is required to provide for fully autonomous operation, requiring no intervention during nominal performance. The unit extracts power from the ASC with an open-loop voltage control algorithm, adjusting continuously for the optimum interface AC voltage. This control process, named “feed-forward” compensation, also indirectly controls the ASC piston amplitude. When configured for redundant application, the controller is required to be single fault tolerant. In this case, a configuration of two out of three cards is used, i.e. with two main cards in operation and a backup card capable of replacing either one if a fault is detected. [2]

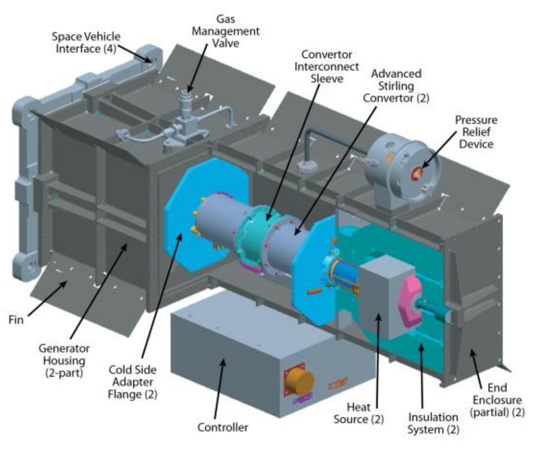

FIGURE 1 ASRG and its major subsystems.

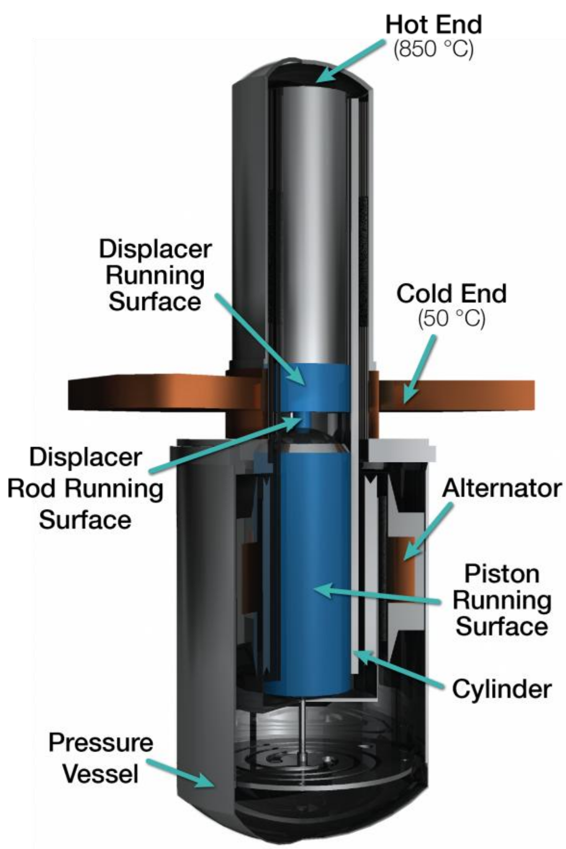

FIGURE 2 ASC and its major components.

2. ASRG LIFE CERTIFICATION CHALLENGES

The plan to develop ASRG units for space flight included the assembly of three engineering model ASCs with fidelities designated as ASC-E, ASC-E2, and ASC-E3 (as shown in Figure 3), before the ASRG Qualification Unit (QU) and Flight Unit (FU) builds. The concept was developed to take advantage of design and manufacturing lessons learned on the engineering models, and reduce the risk associated with the unique ASC design.

FIGURE 3 Progression of ASC Maturity

The unique design features of the ASC are shown in Figure 2, and include:

a. Free-piston Stirling engine.
b. "Non-contacting" piston/displacer designs supported within a cylinder by gas bearings.
c. Xylan lubrication on piston/displacer running surfaces.
d. Extremely tight running surface clearances (~20 microns).
e. Large operating temperature gradients (850 C to 50 C).

The "non-contacting" design, where the free piston and displacer are supported by piston gas bearings that prevent running surface rubbing during operation, turned out to be a major challenge in planning life certification. The pistons outside diameter gas bearings prevent rubbing between the piston running surface and the cylinder. The displacer rod passes through a hole in the center of the piston, and the pistons inside diameter gas bearings prevent rubbing between the displacer rod running surface and the piston. Both sets of piston gas bearings also center the displacer running surface within the cylinder to prevent rubbing. As a result of this "non-contacting" design, accelerated tests of Xylan running surface wear during normal operation for extended periods of time were not possible. However, for certain operations and events, such as start-up/shutdown operations, and dynamic loading events such as launch, running surface rubbing is expected, and therefore, this became one of the elements of the life certification plan.

Before the engine is started-up and the gas bearings are operational, the piston/displacer running surfaces coated with Xylan are in contact with the surfaces they can rub against, and some Xylan wear is expected. The same is true for shutdown operations. Since Xylan lubrication is essential for successful engine operation, a plan to characterize Xylan wear during these operations was developed. Specifically, multiple cycle start-up/shutdown durability tests (DTs) and running surface inspections to assess the Xylan wear and potential impact to the 17-year life were implemented in the life certification plan. Since running surface contact and Xylan wear is also expected during dynamic loading events, such as launch, ground handling, entry, descent, and landing, where the gas bearings are not capable of preventing it, more DTs and similar inspections were planned to assess running surface wear under this set of conditions.

The large Stirling engine temperature gradients (850 C to 50 C) needed for high efficiency, combined with tight running surface clearances (~20 microns) and materials with high coefficients of thermal expansion (CTE), presented another challenge, but it was fairly straight forward to address via design, testing, and inspection. First, materials were chosen to match CTEs as much as possible between the cylinder, piston, and displacer. Second, a range of cold-end operating test conditions was defined that enveloped the normal operating point with temperature margins (~30 C). Data from ASC testing over the conservative cold-end temperature envelope became part of the life certification plan, as it demonstrates clearances will be maintained during normal operation with margin, by showing no significant running surface wear during these limiting thermal operational conditions.

During integrated tests of the ASC with the ACU, smooth control of the free piston and displacer body motions is critical in assuring that the piston and displacer are synchronized, and do not make contact with each other or the hard stops at high amplitudes, which can cause piston/displacer running surface rubbing . Piston, displacer, and hard stop contacts can cause running surface rubbing due to the unbalance forces that result on the piston and displacer during the events. To evaluate the impact of integrated controlled operation on ASC running surface wear, a series of integrated tests (ITs) were planned over the full range of operation, to assess whether or not the piston/displacer are controlled well enough to preclude running surface rubbing. These ITs are part of the life certification plan.

During the ASC engineering model development phase, a significant challenge arose during extended steady state operational tests. Specifically, significant power losses and fluctuations (~1-20 Watts) were experienced with a number of E and E2 ASC units that were difficult to explain. After a six-month Red Team review, it was decided that corrective actions on workmanship, clearances, and gas bearing flows were required to minimize the power losses and fluctuations, because they were indicative of unacceptable wear on the piston and displacer running surfaces.

Workmanship/cleanliness turned out to be important in that any small debris (>20 microns) left in the ASC during manufacturing was getting into the tight running surface clearances, causing rubbing, and wearing away the Xylan on the running surfaces, which in turn caused the power losses and fluctuations. In addition, workmanship issues on internal electrical components resulted in liberated epoxy debris during operation, and this debris also caused similar changes in power.

The tight running surface clearances (~20 microns) within the ASC, which are at the limits of state-of-the-art inspection, proved to be very important during the review. It was decided that clearances needed to be increased, to improve manufacturing and workmanship repeatability, and reduce sensitivity to large temperature gradients. Improved state-of-the-art inspection techniques were also implemented to assure repeatability.

Finally, the strengths of the piston gas bearings were evaluated, and it was determined that the integrated running surface clearances plus gas bearing flows required improved controls to increase bearing capacity, and reduce the likelihood and extent of rubbing/wear during dynamic loading events.

As a result of the review findings, it was decided that the Red Team's recommended corrective actions must be verified in the next engineering model build, the E3s, and Extended Operational Testing (EOT) of E3s became part of the life certification plan. To enable this verification, Red Team acceptance limits on power fluctuations were developed to verify the effectiveness of the corrective actions implemented for the E3s, which should assure long term piston and displacer running surface life for the ASRG flight units.

The ASRG life requirement of 17 years is a challenge, because it is not practical to test one ASC to 1.5 times service life as typically required by an aerospace mechanism standard [6]. As a result, an approach consisting of EOTs of multiple ASC E3s for shorter times followed by disassembly and inspection was developed to increase confidence, thereby building a database of long-term ASC piston and displacer running surface wear characteristics. The approach taken does not produce maximum confidence, since the number of ASCs available to test is unavoidably limited, but it was determined to be the best and most practical option. These multiple ASC EOTs are part of the ASRG life certification plan.

Finally, the ASC was found to be extremely challenging to analyze as a system in regards to reliability, due to the complex multibody dynamics, tight clearances, and the potential effects of random debris. Certain features, such as the gas bearings, alternator, thermo-dynamics, and other components, were modeled successfully, but an integrated model of the whole system to assess reliability was found to be impractical. The inability to model long term ASC wear out reinforced the need to include long-term EOTs of multiple ASCs in the life certification plan.

3. ASRG LIFE CERTIFCATION PLAN

The overall plan to certify the life of the ASRG includes extensive Component Testing and Analysis (CTA), Extended Operational Testing (EOT) of ASCs, Durability Testing (DT) of ASCs, Integrated Testing (IT) of ASCs and an ACU, and full fidelity ASRG QU and FU Testing. The plan addresses the unique ASC life certification challenges as previously discussed and typical life certification analysis, inspection, and tests for the rest of the ASRG components.

3.1 Component Testing and Analysis

A body-of-evidence approach [5] was defined as taking the results from analysis, inspection, system testing, component level testing, and simulation models, and using them collectively to provide a consistent indication that the ASRG design will perform its intended function over the duration of the 17-year reference mission. Figure 4 shows the various types of testing, analysis, simulation, and inspection that are planned to support ASRG life certification.

The Failure Modes, Effects, and Criticality Analysis (FMECA) and Reliability Analysis [2], which contains the Single-Point Failure (SPF) list of components that, if failed, can cause the ASRG to fail, provides the analytical basis for the overall ASRG life certification plan. Each SPF was addressed in terms of criticality, and analysis, inspection, and test mitigations were developed for component risk reduction. The reliability analysis included a fault tree analysis for the entire ASRG. The basic events (hardware failures) were assigned probabilities or event frequencies obtained from analysis of the electronic controller (reliability block diagram models) and from physics-based analysis of ASC internal components, which is a stress-strength interference technique involving limit-states and material properties of components. Nearly all of the ASC component reliability models were developed with finite-element analysis involving stress and strength distributions.

Other important analytical tasks completed were the ASC-ACU interface simulation; the physics-based structural reliability analysis of the ASC subject to random launch vibration; Worst-Case Circuit Analysis (WCA) for the ACU; and a space environment radiation analysis for the ACU.

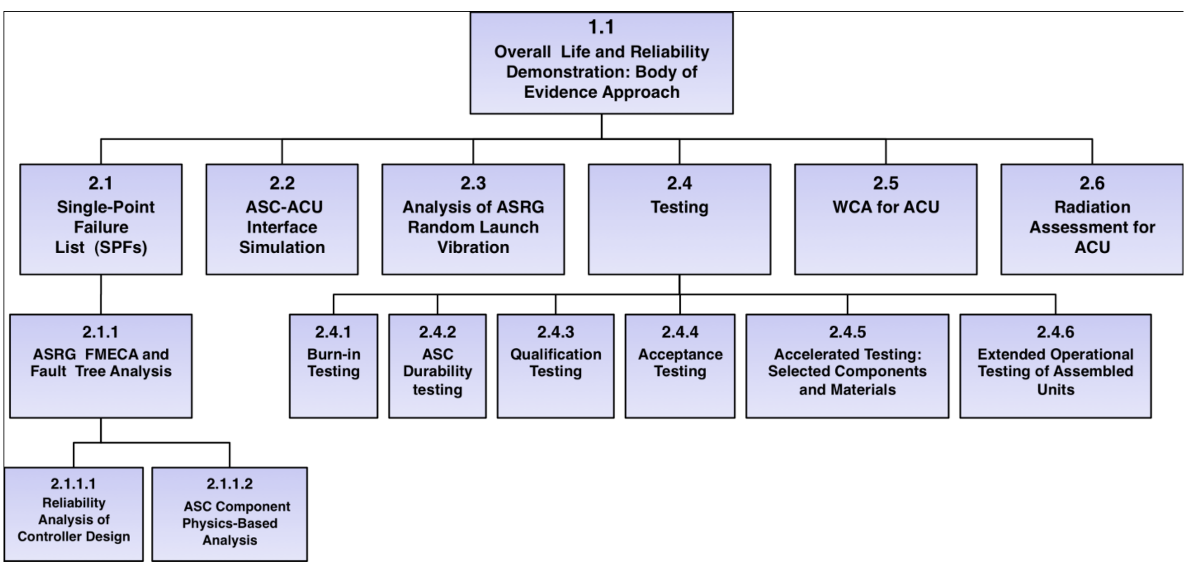

FIGURE 4 Body of Evidence Approach

3.2 Extended Operational Test (EOT)

One of the important lessons learned from our testing experience with the ASC-E and ASC-E2 engineering models was that the convertors were vulnerable to the effects of particulate contamination and variations in the shape of component parts that had extremely tight clearances. Further, it was learned that these two aspects had an interactive effect. Contamination could, over time, lodge itself in small gaps inside the convertor, causing rubbing (contact) between moving and stationary parts. On the other hand, the unpredictable phenomenon of contact between moving and stationary parts could generate debris. Even if Stirling Convertors could operate for extended periods of time without showing power output fluctuations (providing some confidence in their operation), we could not be certain that these failure mechanisms were eliminated. In addition, due to the fact that we were not able to simulate or predict the onset of the wear-out mechanisms, it became apparent that a specific inspection and measurement requirement would have to accompany the extended operational testing of the E3 model ASCs. Thus, the extended operational testing of the E3 models was planned to include the following aspects and tasks:

- Infant mortality EOT of 2,000 hours on all ASC E3s.
- Measure level of power fluctuations, and assess acceptability per Red Team criteria.
- Disassemble, measure/inspect running surface wear on piston/displacer, and demonstrate minimal wear.
- Inspect for internal debris generation, and demonstrate minimal debris generated.

Along with the 2,000-hour EOT, the plan is to test E3s over a set of parametric conditions that simulate the widest range of expected ASC thermal operating conditions, including:

(a) Beginning Of Mission (BOM) performance
(b) End Of Mission (EOM) performance
(c) ASC Cold-End Thermal cycling
(d) Increased piston amplitude
(e) Thermal vacuum operation

In addition to the parametric testing and the 2,000-hour EOT, additional EOT of eight ASC E3s is planned. Commencing test in June 2013 and ending testing in December 2015, a total accumulated test time of 18.3 years will be realized. This additional EOT time, although limited in sample size, should provide additional confidence that significant randomly occurring failure mechanisms (that can induce wear-out) have been controlled. The plan is to document the results from this additional EOT to assure that wear-out mechanisms have been controlled effectively by the corrective actions implemented as a result of the Red Team activity. The criteria used for judging effectiveness will be the same criteria as used for the initial 2,000-hour EOT as described earlier.

3.3 Durability Testing (DT)

In order to evaluate ASC wear-out mechanisms during ground operation and flight dynamic loading, start/stop, centrifuge acceleration and vibration durability tests are planned. The DT will be based on the dynamic launch and landing load requirements for the ASRG. The planned success criterion for the DT includes these tasks:

- Inspect post testing, and demonstrate minimal internal debris generation.
- Inspect post testing, and demonstrate minimal piston/displacer running surface wear.

3.4 Integrated Testing (IT)

In order to evaluate the impact of ACU control on ASC wear-out mechanisms, the plan is to run two paired E3 ASCs under ACU control, including startup and shutdown cycles. During integrated testing, the level of power fluctuations will be measured, similarly to the EOT, and compared to the same Red Team acceptance criteria. After integrated testing, the E3s units will see long-term EOT. The plan is to disassemble the unit(s), and inspect, as described previously for EOT and DT, using the same criterion for success. The results of the integrated ASC/ACU testing and long-term EOT testing and inspections will be documented in support of the life certification process.

3.5 Qualification and Flight Acceptance Testing

During the qualification and flight acceptance testing planned for the ASRG, the level of power fluctuations will be measured and acceptability will be judged using the Red Team criteria. The acceptability of the QU and FU fluctuations will provide the basis and confidence to certify the ASRG life for flight. That is, the power fluctuations seen during E3 testing, and the QU and FU testing, should enable life certification via similarity.

CONCLUSION

The plan to certify the life of the ASRG includes Component Testing and Analyses, Extended Operational Testing, Durability Testing, Integrated Testing of paired ASCs and an ACU, and QU and FU Testing. Testing of E3 units is expected to start in 2013, and QU testing is expected to start in 2014. The analyses, inspections, and test results, as summarized in this paper should enable ASRG Flight Unit (FU) certification in 2016.

NOMENCLATURE

ASC	=	Advanced Stirling Converter
ASRG	=	Advanced Stirling Radioisotope Generator
EOT	=	Extended Operational Test
BOM	=	Beginning of Mission
EOM	=	End of Mission
E, E2, E3	=	Engineering model units 1, 2, and 3
CSAF	=	Cold Side Adapter Flange
GPHS	=	General Purpose Heat Source
ACU	=	Advanced Controller Unit
GHA	=	General Housing Assembly
APS	=	ASC Piston Sensor
ALT	=	Accelerated Life Test
FMECA	=	Failure Modes and Effects Criticality Analysis
SPF	=	Single Point Failure
WCA	=	Worst Case Analysis
QU	=	Qualification Unit
FU	=	Flight Unit

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