# Development of the European Radioisotope Stirling Generator (ERSG)

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## ABSTRACT

Thales Alenia Space, The Rutherford Appleton Laboratory, Oxford University, Centre Spatial de Liege, and Qinetiq Space are developing the first European Radioisotope Stirling Generator (ERSG). The ERSG will be a key enabling technology for ESA's ambition to operate long-duration, deep space and planetary missions, that have a requirement to be independent of solar energy.

This program brings together expertise in: long-life space cryocooler engineering; Stirling cycle modelling; high temperature materials; systems & control engineering; and power conditioning. The goal is to provide 100 $W_e$ DC at 28 V from 435 $W_{th}$ harvested from the decay heat of Americium-241. Initial breadboard testing is about to take place with a resistive heater simulating the radioisotope fuel cells. This paper summarises the ERSG development and progress to date.

## INTRODUCTION

Nuclear power sources (NPS) and photovoltaics (PV) are the only known systems capable of providing both sufficient power and lifetime for space exploration.[1,2] These two technologies are complimentary and enable a wide variety of mission classes. PV power systems are the primary power supply for the majority of space exploration. For some mission classes, however, (such as long-duration deep-space voyages and exploration of permanently-shadowed regions of planets, moons, or other celestial objects) it is either not possible to rely on harvesting solar energy or not practical due to insufficient energy density. In these situations, NPS are required since their performance is independent of the mission orbit, orientation, or distance from the sun.

A sub-class of NPS is the radioactive power sources (RPS) which are distinct from other categories (fission reactors) in that they directly utilize decay from a radioactive source. Radioisotope thermoelectric generators (RTG) are the most successful incarnation of this philosophy having been present on all past interplanetary missions beyond Jupiter, and on-board most planetary landers. ESA has previously collaborated on scientific missions involving RTGs provided

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by NASA. ESA is currently pursuing active research into the development of its own RPS programs.

In order to independently meet the needs of future deep-space missions, whilst being constrained by both the lack of $^{238}$Pu in European civil nuclear stockpiles and advanced RTGs having conversion efficiencies <7%,[3] ESA is interested in developing a high efficiency dynamic-conversion technology. Stirling cycle technology for space is mature within the cryogenics community of Europe and could meet ESA's requirements. To this end, the first breadboard European Radioisotope Stirling Generator (ERSG) has been manufactured by a consortium selected for their ability to leverage ESA's cryocooler heritage.

There has been over 30 years of cryocooler mechanism development, Stirling cycle modelling, and thermal modelling for space at RAL. The other members of the consortium and the consortium's expertise are listed here:

- Thales Alenia Space in the UK provide expertise in systems-control and electronics;
- Centre Spatial de Liege supply knowledge and manufacturing of high temperature vacuum components;
- Oxford University also has heritage developing long life linear mechanisms.

A design description of the ERSG has been previously reported elsewhere.[3] This paper will provide an update and overview of the ERSG system; however, the technical discussion will focus on aspects directly comparable with cryocooler technology.

## CURRENT STATUS AND PERFORMANCE PREDICTIONS

The breadboard ERSG has been manufactured and the characterization and workmanship trials have been completed for each of the major subsystems. The breadboard ERSG is ready to begin initial performance testing. Performance mapping will aim to validate the system-level and thermodynamic modeling used to size the ERSG. It will also be the first time the system is exposed to high temperatures and thermal gradients. The test hardware is shown in Figure 1, excluding the support structure and electronics.

Under nominal operating conditions, the breadboard ERSG has been sized to produce 100 $W_e$ DC power supplied at 28 V (in order to be compatible with a spacecraft bus). Predicted and measured system-level performance metrics for the ERSG are listed in Table 1. The most significant differences between the breadboard ERSG and a flight design are:

- The heat source is a resistive heater instead of a radioisotope;
- The electronics are housed in a laboratory grade chassis;
- There is additional telemetry;
- A laboratory chiller maintains an isothermal interface where the spacecraft radiator would attach.

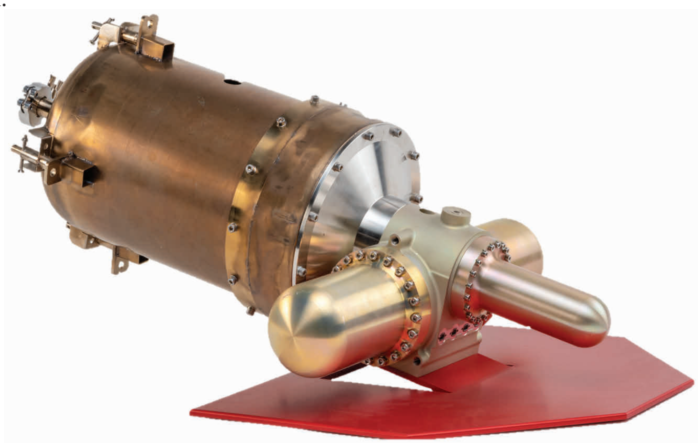

**Figure 1.** The breadboard ERSG displayed without the support structure and PCE.

**Table 1.** System performance predictions (left). Measured mass of the breadboard ERSG compared with a flight configuration (right).

| Specification | Value | Unit |
|---|---|---|
| Output Power (electrical DC @28V) | 100 | $W_e$ |
| Thermal Power (total) | 435 | $W_{th}$ |
| Lifetime (minimum) | 50 | khours |
| Conversion Efficiency | 23 | $\%W_{e\text{-}dc}/W_{th}$ |
| Specific Power | 1.51 | $W_{e\text{-}dc}/kg$ *(flight mass)* |

| Configuration *(designed to produce 100 We DC @28V)* | Breadboard (measured) | *Flight-like* (estimates) |
|---|---|---|
| Sub assembly | Mass (kg) | |
| Stirling Converter (SCSS) | 10.90 | 10.9 |
| Fuel Module (FMSS) | 12.49 | 12.5 |
| Heat Source | 6.82 | 13.8 |
| Support Structure | 14.50 | 15 |
| Power Control Electronics (PCE) | 11.23 | 4.0 |
| Spacecraft radiator | N/A | 9.6 |
| Total (ERSG) | **55.94** | **66** |

The breadboard ERSG performance tests will measure the absolute power output and the conversion efficiency of this system. The flight-like specific power will remain an estimate. The estimated mass of the flight-like system's radiator assumes 350 $W_{th}$ being rejected at 300 K and that the radiator weighs 12 $kg/m^2$. This is potentially pessimistic since it may be possible to combine the functions of mechanical support structure and radiator to some extent once a specific set of mission requirements has been established.

## SYSTEM ARCHITECTURE

A schematic for the heat flow through the breadboard ERSG is shown in Figure 2. Mechanically, the ERSG comprises four major subsystems: The Stirling Converter Subsystem (SCSS), the Fuel Module Subsystem (FMSS), Power Control Electronics (PCE), and the support structure. Nominally, the interface between the FMSS and the SCSS is 900 K and the SCSS rejection interface is 300 K.

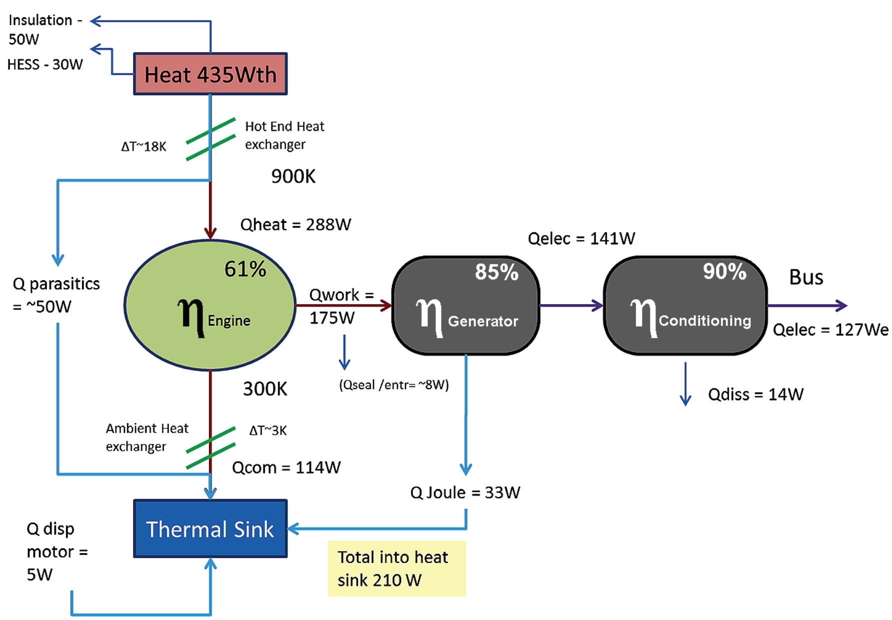


**Figure 2.** Schematic of the ERSG heat flow.

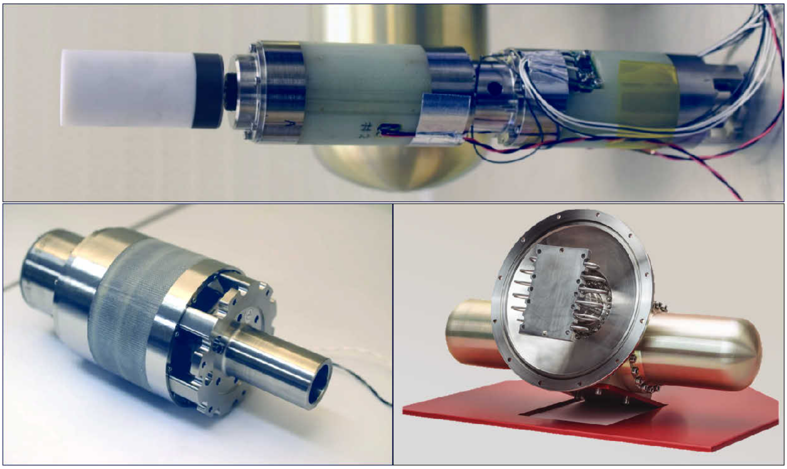

**Figure 3.** Balanced displacer assembly (top). One of the two alternators (bottom left). SCSS displaying the hot end interface (bottom right).

### Stirling Converter Subsystem

The SCSS is arranged in a gamma configuration, reciprocates at 90 Hz, and has a fill pressure of 45 $bar_{(a)}$. The benefits of this configuration are the same for the ERSG as it is for many cryocooler applications: separate independent mechanisms provide a greater freedom to optimise the mechanical design of the system, and flexibility during operation and testing. The breadboard ERSG comprises three sub-assemblies: two alternator assemblies, one balanced displacer assembly, and the body assembly. The SCSS and sub-assemblies are shown in Figure 3.

Each of the mechanisms (alternators and displacer) have been tuned so that the moving mass, suspension spring rates and pressure waves combine to make an efficient resonant system. Furthermore, careful choice of geometry and materials has been shown to eliminate eddy current damping. All mechanisms utilize linear motors with full flexure suspension which underpins the non-contact lubricant-free engineering success demonstrated in long-life cryocoolers. In order to minimize exported vibration, the alternators are arranged in a head-to-head configuration; likewise the displacer motor is balanced by a momentum compensator coaxially mounted directly behind it. Each motor/alternator mechanism has a bespoke capacitive position transducer as an integral part. This allows for active vibration cancellation and, when combined with the pressure transducer telemetry, enables PV work loops to be derived.

*Alternators*

The alternators are moving-magnet linear motors based on an architecture first developed by Sunpower Inc.[8] This style was chosen for its high energy density, but its complexity limits it to medium to large scale mechanisms. Optimized radially-magnetized magnets minimize stray flux and maximize efficiency. The alternator piston and cylinder bore are part of the same modular assembly allowing alignment and characterization of the mechanism prior to integration with the rest of the SCSS.

*Balanced Displacer*

The displacer is pneumatically balanced under nominal conditions but, for stability, control, and in order to minimize exported vibrations, the displacer is driven by a motor and balanced by a momentum compensator. The displacer motor and the momentum compensator motor are both novel moving-magnet linear motors designed by RAL and were previously reported in ICC 19. [4,5] This style is highly optimized for small to medium sized mechanisms.

The displacer piston is made from a ceramic in order to withstand the extreme absolute temperature at the hot end of the SCSS, and so that conduction losses are minimized. The piston is hollow in order to tune the mass to resonate at 90 Hz, avoiding the need for stiffer springs that would have the undesirable effects of making the resonance peak sharper and increasing the peak stress in the spring arms. In order to avoid extreme pressure differentials between the internal volume of the piston and the expansion space of the SCSS, the pressure within the internal volume of the displacer piston must be equalized with that in the back shell of the displacer. The displacer piston is filled with a high temperature *pyrogel* insulation and radiation shields to minimize convective and radiative internal losses.

*Body*

The body assembly is the mechanical, electrical, and thermal interface for each of the mechanisms within the SCSS and between the SCSS and the other sub systems. There are two distinct components of the body assembly:

- The *Central Mounting* – this provided all structural mounting points to other sub-systems and mechanisms; the electrical interfaces; all ambient-thermal interfaces; and all vacuum seals.
- The combined *Regenerator & Hot End Heat Exchanger Assembly* – defines the high temperature thermal interface; maintains the temperature gradient across the engine; and absorbs the significant differential thermal expansion. This component is predominately made from Inconel 718.

Combining the space-proven engineering principles of long-life cryocooler mechanisms with the high temperature materials required for the ERSG has been challenging.

A typical cryocooler (operating from room temperature) cannot experience a temperature gradient larger than 300 K, whereas the ERSG experiences a 600 K thermal gradient under nominal conditions with scope to increase this further, either by increasing the hot-end temperature or by the thermal rejection interface being chilled. Differential thermal expansion impacts the materials selection and the mechanical design to a far greater extent than with a cryocooler. This is most obvious when viewing the spider-like hot end heat exchanger (HEHE) shown in Figure 3. The HEHE is additively manufactured from Inconel 718 and is joined to a regenerator that is coaxially located outside of the displacer bore. This configuration saves mass, reduces piston drag, and minimizes the complexity of the displacer piston. The HEHE is also the point where the cylindrical symmetry of the displacer piston meets the cubic symmetry of the heat source. The additive manufactured parts and associated pipework make this transition relatively painless.

The heat flux through the central body is larger than that in a typical cryocooler and forced the selection of grades of aluminum with a high thermal conductivity. The impact of this was that it was particularly challenging to achieve a consistent hermetic seal against high pressure and vacuum owing to aluminum being especially soft and easy to deform. Welding the electrical feedthroughs also required a process to be developed, again, to ensure the joint was sealed. Furthermore, in order to ensure that the heat of compression can be rejected effectively, the compression space is not a simple bore leading to a transfer line. Instead a complex sun-flower-like pattern of radial fins was wire eroded into the compression space to maximize surface area whilst minimizing pressure drop.

## Fuel Module Subsystem

The FMSS insulates the heat source from the external environment and provides a conduction path through a Nickel plate to the SCSS. The construction is similar to a pair of concentric Dewars, each with an evacuated space between two thin walls. The inner high-temperature container is made from Inconel 718 and the outer container from stainless steel. This construction has been optimized for minimal mass with a given thermal loss budget. During acceptance testing the FMSS demonstrated a predictable temperature profile, which allowed calorimetry to be conducted. The FMSS experienced internal peak temperatures in excess of 1200 K during acceptance testing.

The FMSS testing also demonstrated the hot end safety system (HESS). The HESS is required to ensure the ERSG has the inherent ability to prevent overheating of the fuel cells within the FMSS, and thereby ensure environmental protection and safety. In the event of overheating, a thermal fuse allows the lid of the FMSS to be ejected - compromising the insulation and allowing excess heat to radiate away. This is a single use system that can be reset on ground, but not after launch.

**Heat Source**

The differences between the heat sources for the breadboard ERSG and a flight version are considerable. The breadboard ERSG is using a bespoke and controllable resistive heater; whereas, in flight, the ERSG will require three 145 $W_{th}$ americium-241 radioisotope fuel cells each with a mass of 4.6 kg. Americium-241 produces a quarter of the specific thermal power of plutonium-238 (used in all NASA RTGs) but can be extracted and purified from the European civil nuclear stockpiles.

**Power & Control Electronics**

The PCE has two functions:

- *Power conversion* of the SCSS alternating power output to a tightly specified 28 V DC supply whilst constantly demanding 100 $W_e$ from the SCSS. In order to maximize the power transfer from the SCSS, the PCE has been built to operate at high efficiency with a power factor of one. The PCE has been designed to appear as a resistive load (from the point of view of the SCSS). This ensures that the PCE internal dynamics have little effect on the upstream thermomechanical system, whilst providing an intuitive negative feedback loop between the current drawn and the amplitude of the mechanism within the SCSS.
- *Converter control* provides active vibration reduction to the balanced displacer, protects the mechanism from over stroking, and performs housekeeping functions. The philosophy underpinning the active vibration control has been reported previous at ICC 19;[4] with in-orbit data from the Planck satellite that showed the ability to reduce total mechanism vibration by four orders of magnitude

**Support Structure**

The support structure is designed to provide mechanical stability to the FMSS and SCSS during performance testing. It has been specified to withstand mechanical environmental testing including launch vibration testing.

## SCSS ACCEPTANCE TESTING

This section provides an overview of some of the characterisation testing conducted on the mechanisms of the SCSS prior to integration with the ERSG. Although a detailed and extensive acceptance-test campaign has been completed for all of the major sub-system, the SCSS is the most relevant to this journal on cryocooler engineering.

There are two broad categories of acceptance test conducted on the SCSS:

- Characterization – produce data that can be used to validate design modelling or update the system performance prediction. These tests build confidence that the predicted *sub-system performance will be achieved.*
- Functional – empirically demonstrate that the workmanship of the sub-system is within specification. These tests build confidence that the predicted *sub-system lifetime will be achieved.*

**Characterization of the SCSS**

Characterization test results matched design modeling predictions with good agreement for both the alternator and displacer motor architectures. Example motor constant and spring rates are compared with modelled predictions in Figure 4. The total spring rate and suspension spring rate are both measured directly, whereas the magnetic spring rate is derived from the previous two measurements. The magnetic (or reluctance) spring results from the interaction of the mov-

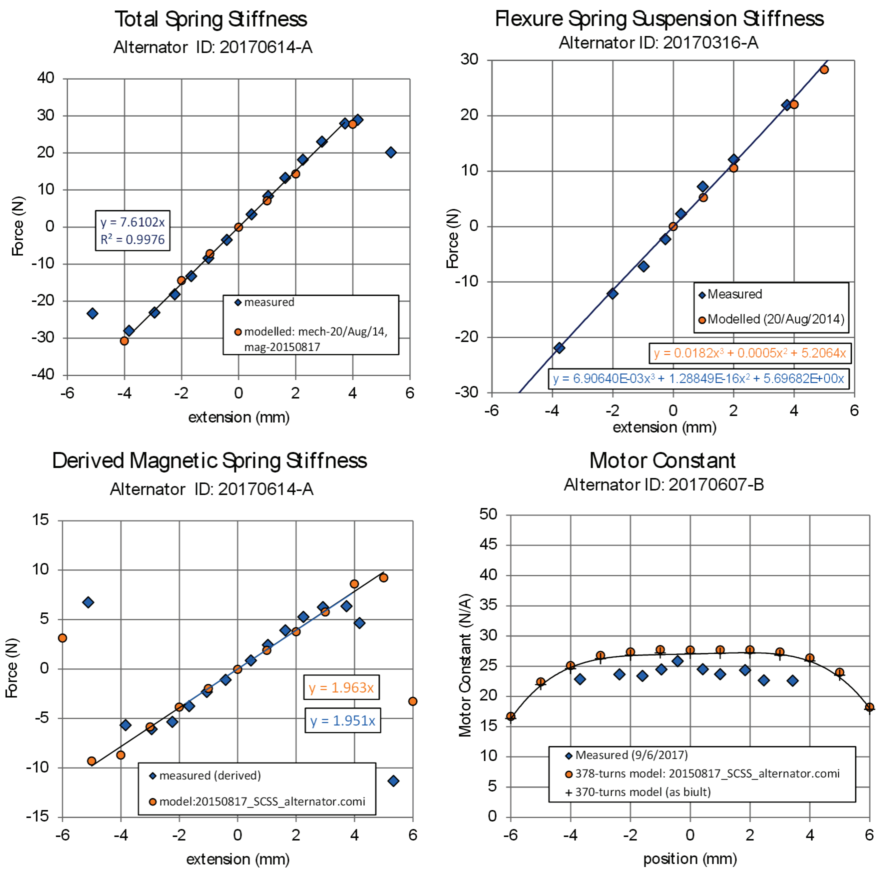


**Figure 4.** A selection of alternator characterization test results compared with modelling predictions. Displacer testing demonstrated similar agreement.

ing magnet with the static magnetic yoke. The motor constant is measured directly at several positions. The motor constant measurements for alternators were particularly prone to noise because small perturbations in the position of the motor were translated into significant currents within the coil.

At every possible opportunity, the alternator and displacer mechanisms have been designed to be highly tuned with minimum damping. The Q-tests for an example alternator and momentum compensator (shown in Figure 5) demonstrate that low-level damping can be achieved with eddy current reduction techniques. The relative impact of these techniques was discussed in ICC 19.[5] Several loss mechanisms have been studied in detail. The electrical and magnetic loss mechanisms are categorized as either dynamic or static losses. The dynamic losses are studied when the mechanism is in motion, and the static are studied when the piston is clamped in a fixed position. By varying current, positon, and frequency, each of the following can be quantified: Joule heating, core losses, and eddy currents. The absolute contribution of each loss is small and therefore difficult to measure. In order to verify the analysis, the inductance of each motor was derived from an equivalent circuit model and compared to the inductance prediction made by static magnetic FEA. The agreement between analysis and FEA modeling for the displacer inductance (Figure 5) was superb and validated this approach; however, there was noticeable difference for the alternator inductance. The FEA predicts that the alternator inductance is a function of both mechanism position and current, which is not accounted for in the loss analysis.

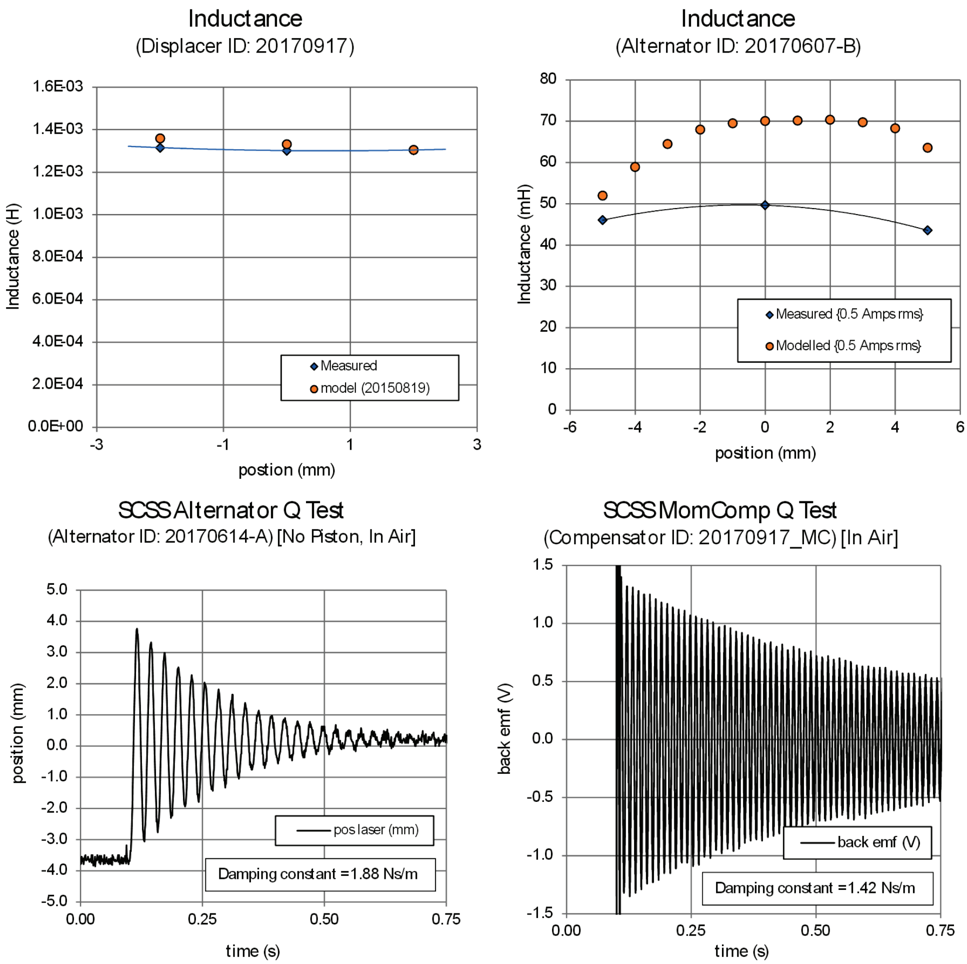


**Figure 5.** Displacer/Alternator inductance compared with modelling (top), blue trend lines are results derived from experimental data. The Q-tests measure a mechanism's free-oscillation damping characteristics for an alternator and a momentum compensator (below).

## Functional Testing of the SCSS

Among other measures, leak rates, weld trials, and materials testing have all contributed to the enhanced confidence that the ERSG will demonstrate the same long-life characteristics expected from a cryocooler. Each of the four mechanisms has been run on the bench for several weeks intermittently with a combined number of cycles approaching $10^9$.

The results of the suspension life-testing are shown in Figure 6. The suspension for the alternators and balanced displacer use different flexure springs, which required separate validation. The springs experienced reversed bending at ~90 Hz for at least $10^7$ cycles (a threshold generally accepted as demonstrating infinite fatigue life) at the maximum stroke in operation, before the amplitude was increased and cycling was repeated. This process continued until the suspension failed. Both spring designs failed at >140% max stroke.

## NEXT STEPS

Performance tests will demonstrate the first power production from the breadboard ERSG, and we hope to report on these results in the near future. The Heracles (lunar missions) program has identified a need for an RPS system and that an ERSG could meet their requirement.[6,7] We will aim to establish the requirements of the Heracles missions for an ERSG to better inform our evaluation of the performance data.

## ACKNOWLEDGMENT

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