DESIGN DESCRIPTION OF A PLANNED BREADBOARD DEVELOPMENT OF A STIRLING POWER CONVERSION SYSTEM (SPCS) FOR THE EUROPEAN SPACE AGENCY (ESA) POWERED BY A SIMULATED NUCLEAR FUEL MODULE

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ABSTRACT

The design of a breadboard power converter system for use with radioisotopic heat sources will be described. This design is based on the Stirling cycle, taking advantage of long-life technologies developed for past European space cooler systems. Electrical output is a conditioned DC bus of approximately 100 W_e. The design consists of a Stirling Converter Subsystem, Fuel Module Subsystem, Power Conditioning Electronics and Support Structure. The critical functions of a future Stirling radioisotope power generation system have been identified as safety, long-life, efficiency, mass and scalability. The breadboard (supported by 2 independent models) has been designed to investigate these areas fully and to raise their technology readiness levels (TRLs). Testing of the breadboard is currently planned to start in 2014.

1 INTRODUCTION

Photovoltaic cells are well established as the appropriate primary power source for most space missions. However, for long duration missions that cannot rely on harnessing the power of the sun, electrochemical processes are simply too low in energy density to provide useful sustained power. The heat generated by the decay of a radioisotope can be used to generate electricity; such a device is called a radioisotope thermoelectric generator (RTG). Current space applications use thermoelectric conversion systems which have no moving parts, generate DC power, and demonstrate proven long-term reliability. On the downside, even state-of-the-art systems have a conversion efficiency of less than 7%. This low efficiency has a threefold negative impact: firstly on the mass of the device, secondly on the cost of the nuclear fuel, and thirdly on the quantity of waste heat which has to be rejected. In recent years, there has been much interest in the development of high efficiency dynamic power conversion technologies as an alternative to thermoelectrics in space radioisotopic systems. One of the most promising dynamic systems is the Stirling cycle, which can theoretically achieve Carnot efficiency, which is 66% with a 900 K ‘hot end’ and a 300 K ‘cold end’. European Stirling systems already have extensive space heritage when employed as cooling devices, but the high temperatures required by a heat engine introduce significant challenges.

2 SYSTEM DESIGN

2.1 Stirling Power Conversion System

The Stirling power conversion system (SPCS) consists of 4 subsystems: Stirling Converter Subsystem (SCS), Fuel Module Subsystem (FMS), Power Control Electronics (PCE), and Support Structure. The flow of energy around the SPCS is shown in Figure 1.

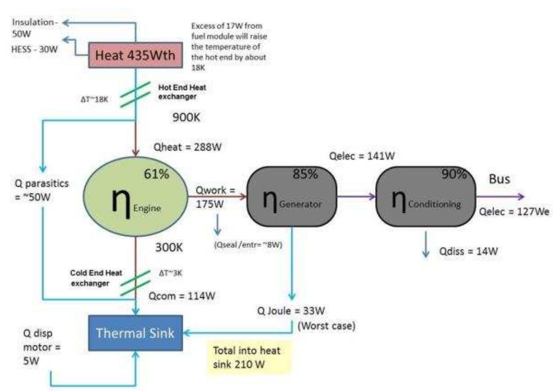

Figure 1: Energy flow map for the SPCS

After 80 W_{th} assumed losses through the insulation, the structure and the Hot End Safety System (HESS), the majority (288 W_{th}) of the 435 W_{th} total heat will flow to

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the hot end of the engine. The engine converts the heat to approximately 127 W_e at 28 V DC (the spacecraft bus voltage) and rejects 210 W_{th} to the environment via the cold end interface.

An overview of the SPCS showing the thermal, mechanical and electrical interfaces is given in Figure 2.

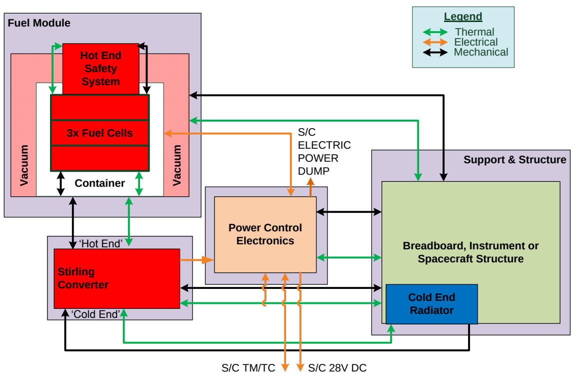

Figure 2: SPCS overview showing thermal, mechanical and electrical interfaces.

An estimate of the flight configuration masses are given in Table 1.

	estimate	w. margin
Stirling Converter Subsystem**	**9.4 kg**	**10.4 kg**
Fuel Module Subsystem**	**10.2 kg**	**11.2 kg**
Fuel Cells*	**13.8 kg**	**13.8 kg**
Support Structure Subsystem***	**5.5 kg**	**6.6 kg**
Radiator*	**5.0 kg**	**5.0 kg**
Power Conditioning Electronics***	**4.0 kg**	**4.8 kg**
		51.8 kg

* - 0% margin, ** - 10% margin, *** - 20% margin

Table 1: Foreseen flight configuration mass estimate

The mass of 3 fuel cells is 13.8kg, these 3 fuel cells produce a total of 435 W_{th} and the SPCS, with a total mass of 51.8 kg, is expected to produce 100 W_e (28V DC). This thermal fuel source compares (see Table 2) with the NASA developed Advanced Stirling Radioisotope Generator (ASRG) which uses 2 General Purpose Heat Sources (GPHS) totalling 3.2 kg mass, 500 W_{th}, (with lower surface area than for americium-241) and produces 130 W_e. This is achieved with an ASRG mass of 32 kg [1]. Although the SPCS is heavier than its US counterpart, this is primarily due to the mass of the fuel cells.

In a separate ESA study, americium-241 was concluded to be the best option for a European radioisotopic power system due to the shortage of European plutonium-238 supplies and the cost of producing it in sufficient quantities [2]. The SPCS described here overcomes the significant problems associated with such a large mass of radioisotopic material stored at 900 K (also with a larger surface area). Note a 'cold end' radiator mass of 5kg is added to allow comparisons to be made with other similar systems. For breadboard testing, a heat sink will be attached instead of this radiator.

USA GPHS 250 Wthermal (values given are per GPHS	European 145Wthermal americium (latest Areva design work values)
(ASRG uses 2 of these)	(SPCS uses 3 of these)
entire module: 1.6kg	entire module: 4.6kg
PuO2: 0.6kg	Am2O3: 1.4kg
Pu: 0.52kg	Am: 1.27kg
Pu238: 0.44kg	Am241: 1.27kg
99mm x 93mm x 58mm	160mm x 150mm x 83mm

Table 2: Comparison of US and European radioisotope thermal sources

Figure 3 shows the dimensions and the major subsystems of the SPCS in an isometric layout, including the structure of the FMS and the hot end safety system (HESS). The system is shown here without the Support Structure or Power Conditioning Electronics.

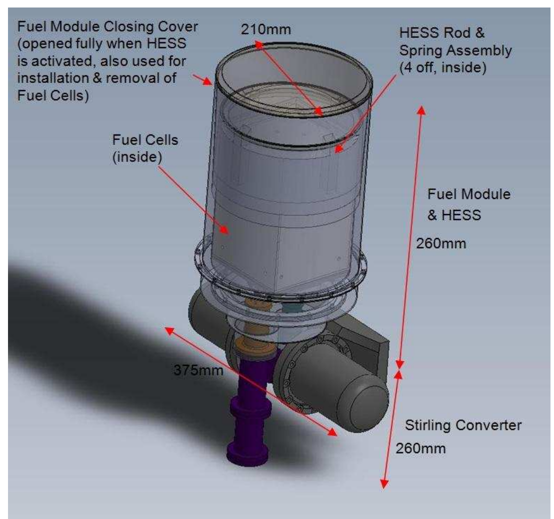

Figure 3: SPCS layout

2.2 Stirling Converter Subsystem (SCS)

The SCS is in a gamma configuration with a displacer that reciprocates at around 90 Hz by the use of a novel linear motor. A momentum compensator is attached to the rear of the displacer motor to reduce the exported vibrations. The displacer shuttles the working gas (helium at about 45 bar) from the hot end to the ambient temperature end. This causes a pressure wave which drives the power pistons. The power pistons are opposed to each other in order to provide momentum compensation. Their geometry and mass is optimised such that, together with the suspension springs and the gas pressure swing, the system is resonant. Linear alternators are connected to the power pistons which are optimised to maximise electrical conversion. The functional blocks of the SCS are depicted in Figure 4.

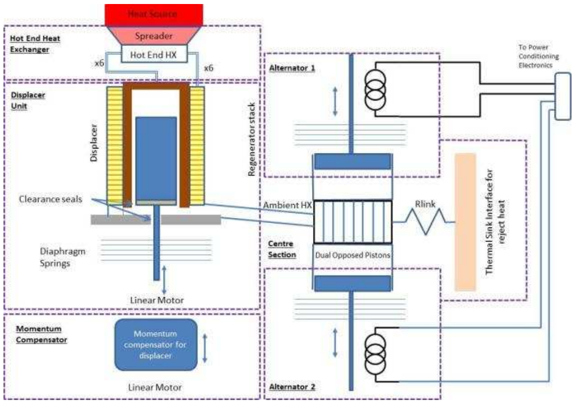

Figure 4: SCS functional blocks

The isometric general arrangement of the SCS is depicted in Figure 5.

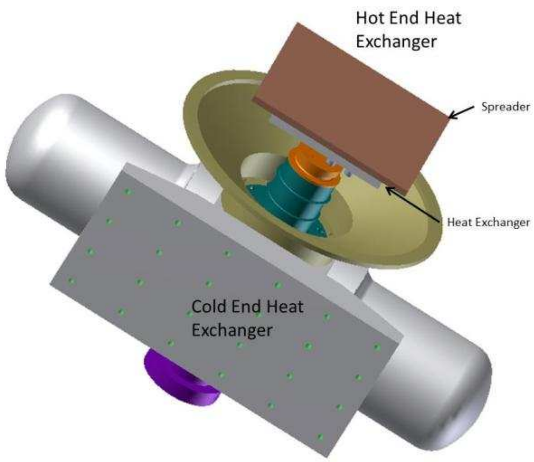

Figure 5: SCS general layout

2.3 Fuel Module Subsystem (FMS)

The FMS contains a stack of three fuel cells, filled with americium oxide ($^{241}Am_2O_3$), which are inserted into the FMS prior to launch. The FMS provides a good thermal path from one surface of the hot 920 K (650 °C) fuel cells to the Stirling converter hot end, while insulating them from the external environment. The insulation consists of a Dewar 'vacuum flask' design. A double wall container is used, with the inter-wall volume evacuated (with foam insulation only used between the fuel cells and internal cylinder). This solution was chosen over the use of foam insulation throughout because it is much lighter and more compact. The warm inner cylinder and base are made of Inconel 718 and the outer cylinder is made of stainless steel. The general layout of the FMS and its integration with the SCS is shown in Figure 6.

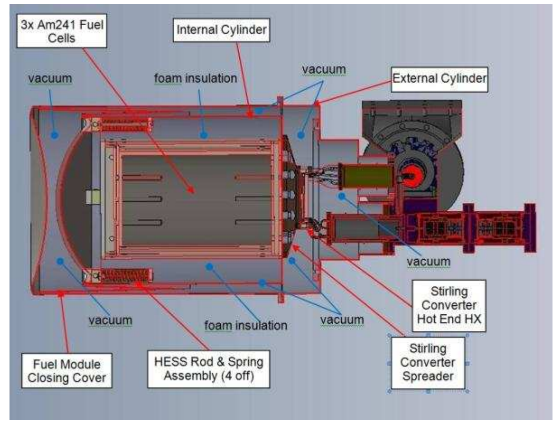

Figure 6: General layout and integration of the FMS and the SCS

Additionally, a passively activated Hot End Safety System (HESS), shown in Figure 7, is used to prevent the overheating of the fuel cells within the FMS. The HESS is a one shot device that can be reset on ground after operation but cannot be reset after launch.

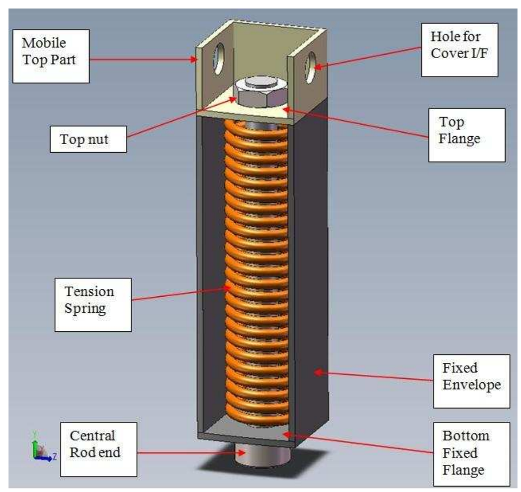

Figure 7: Hot end safety system (HESS) assembly

The three radioisotope fuel cells are all assumed to be at a boundary temperature of 1200K and each fuel cell will generate 145 W_{th}, providing 435 W_{th} in total. The fuel cells will be thermally insulated with high melting point materials from external environments such as those found on Earth, in Space or on Mars.

2.4 Power Conditioning Electronics (PCE)

The PCE conditions the power output of the SCS to provide the spacecraft bus with a tightly regulated 28 V DC supply, whilst retaining a constant 100 W_e demand on the SCS through active power dumping. The PCE is required to operate at the highest power conversion efficiency and maintain the power factor at unity in order to achieve maximum power transfer from the AC generator.

The PCE is also required to provide protection to the system such as implementing over-voltage protection to downstream loads, under-voltage lock out when the AC supply is out of limits and peak current limiting of power switches.

To assist in minimising vibration, the PCE presents a balanced resistive load to the SCS. There are also monitoring functions for primary and secondary side housekeeping telemetry data.

The PCE is divided into two functional parts; the power conversion electronics and the converter control electronics. The electrical interfaces between these subsystems and the SCS are shown in Figure 8.

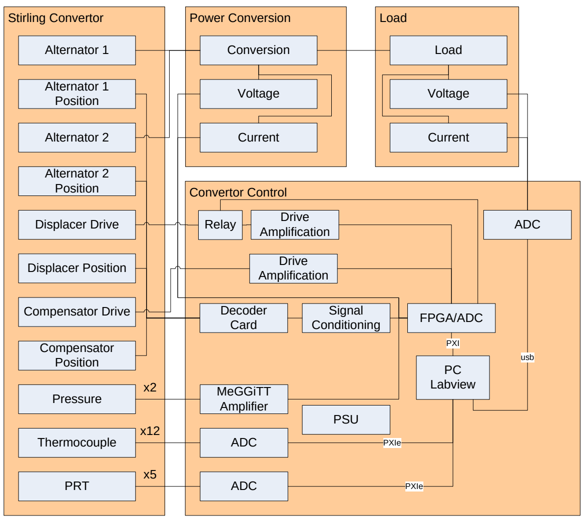

Figure 8: Electrical interfaces between the Stirling converter and the PCE

2.5 Support Structure

The breadboard Support Structure (see Figure 11) is designed to support the mass of the FMS and SCS during breadboard testing. The breadboard testing will also include low level sine mechanical testing to gain initial insights to the behaviour of the operational SPCS under vibration. It will also accommodate the 2.5 mm of differential thermal expansion that exists at the 'Hot End Interface'; the internal mechanical interface between the fuel module heat spreader and the SCS hot end exchanger.

3 THERMAL ANALYSIS

The thermal analysis had two objectives, firstly to estimate the temperatures that would be experienced during breadboard testing and secondly to assess performance in an operational environment. Figure 9 shows the temperatures that are expected when the breadboard is connected to a heat sink and the SCS 'hot end' is at 900 K.

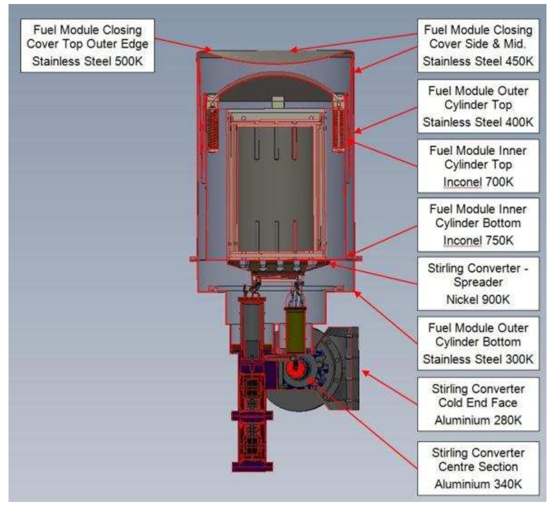

Figure 9: Indication of breadboard operating temperatures

For an assessment during an operational environment, a $0.6m^2$ radiator thermal model has been added to the cold end interface, which rejects excess heat, and its performance was assessed. The system was modelled in several likely environments. The environments were: ground test, transport, storage, launch site, launch, space phase and Mars surface (cold and hot). An indication of the system's operating temperatures is shown in Figure 10.

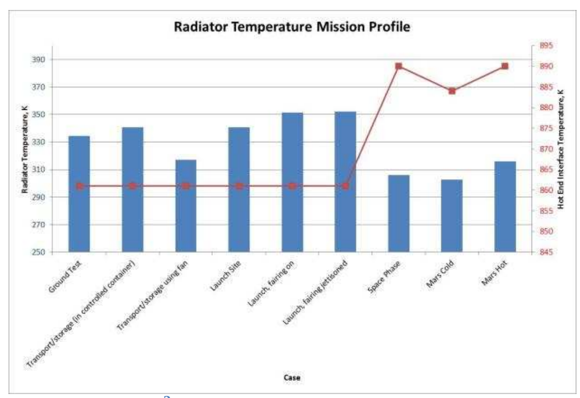

Figure 10: $0.6m^2$ Cold End Radiator temperature during mission (with Hot End Interface Temperature)

The most extreme conditions were during the hot launch phase which would last a few minutes, the longer periods for ground transport and storage, and the Martian summer and winter. The coefficients for heat transfer by convection on the radiator surface were applied to match Earth or Mars air flow. The temperature of the hot end interface will vary depending on the heat taken in by the converter.

For all the operational environments considered, the radiator temperature would vary between 300 and 355 K and the hot end of the converter would operate from 890 to 860 K conversely. This was assuming a fixed amount of heat, 256 W_{th}, was rejected by the radiator and the SPCS was continuously operating.

4 BREADBOARD DESIGN

The project's objective is to reduce the development and technology risk of a future flight SPCS by having some near-flight representative hardware in areas of the SPCS where there are uncertainty or unknowns (within the resources of the project). The SCS will be a flight representative design built for low level vibration tests and thermal vacuum experiments. This approach will allow important mechanical and thermal aspects of operation to be de-risked.

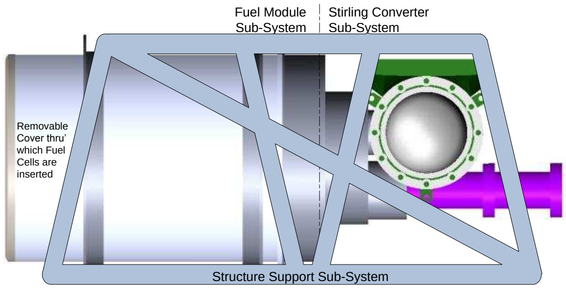

Figure 11: SPCS Breadboard Layout

The power conversion electronics will be based on a flight design using commercially equivalent parts; however it will be partitioned in to 8 individual boards to facilitate investigation of the interaction between the SCS and the power conditioning. The converter control electronics will be based on NI boards and LabVIEW software. This provides extended diagnostic functionality to what is required for flight. This functionality will help characterise performance of the SPCS in order to inform future missions. The PCE Power Conditioning and NI boards will be enclosed in a 19 inch rack to allow for modifications and upgrades.

The Support Structure is required to provide and maintain mechanical alignment between the SPCS subsystems (excluding the PCE), both during assembly and testing. The HESS will be mass and volume representative and the build will be suitable for low level sine testing since mechanical vibration loads will be considered in the design process. During testing, the Fuel Module simulator will not contain any radioactive isotope; instead it will be a thermal power, mass and volume representative simulator. It will use three independent heaters (which can be controlled by an NI board that will be integrated into the PCE 19 inch rack) to simulate the internal thermal characteristics of the flight Fuel Module.

The thermal hardware around the Fuel Module simulator will be near flight representative in mass, dimensions and geometry. For testing on the ground the 'cold end' radiator will be block cooled by water kept at a stable temperature by use of a controlled chiller unit.

5 MODELLING

The breadboard SPCS is supported by two independently derived models of the SCS and one model of the complete SPCS system, which has been implemented in MATLAB/Simulink. The system model includes a thermodynamic model of the Stirling engine, a dynamic model of the alternator and a detailed model of the PCE. A resistive load is used to draw 100 W_e from the system. This model allows the system to be analysed as a whole, including interactions between each part of the system to identify how unforeseen changes may affect total system performance. Once fully aligned with the breadboard SPCS, the model will eventually facilitate the optimisation of the SPCS design.

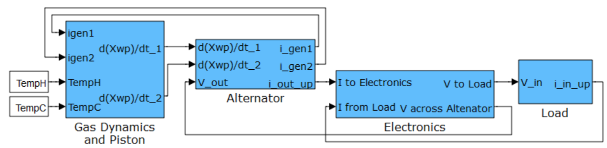

Figure 12: Simulink Model Layout

6 LAUNCH SITE CONSIDERATIONS

The project has investigated the launch site requirements for the handling of nuclear isotopes and has developed draft operational procedures for handling and integrating the SPCS on the spacecraft at the launch site. This also includes the items of information for the safety submission related to the SPCS. The results of this investigation can be used for the preparation of the launch campaign and when writing the Spacecraft Operations Plan (POS).

7 CONCLUSIONS AND FUTURE WORK

The SPCS project had a successful Critical Design Review in December 2013 at which the breadboard detailed design was presented as well as results of modelling and analysis. The breadboard SPCS is currently being manufactured and its expected size and mass, when flight qualified, make it a feasible alternative to photovoltaic cells on many interplanetary and lunar missions. The final design of the SPCS will be updated in the future to match the final design of the fuel cells where further gains to the power output and mass is expected.

8 REFERENCES

[1] 'Advanced Stirling Radioisotope Generator (ASRG) - NASA Facts'
http://solarsystem.nasa.gov/rps/docs/Final%20ASRG%20Fact%20Sheet%20v2%209-3-131.pdf

[2] '241Americium as a potential power source for space missions', L. Cordingley, T. Rice, M. J. Sarsfield, K. Stephenson, T. Tinsley