Power solutions for cold dark environments

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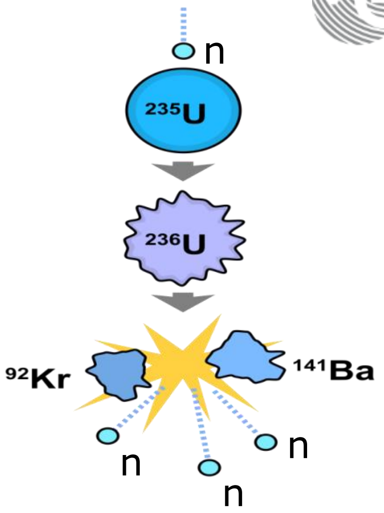
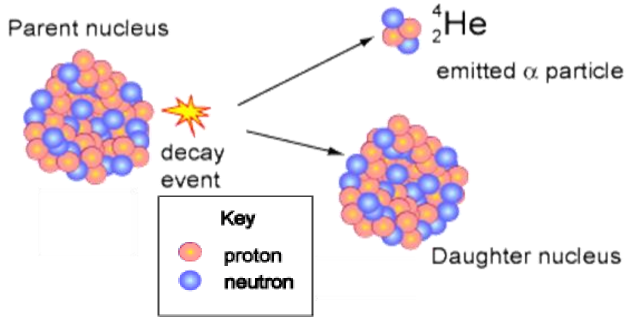
Nuclear power in space: categories

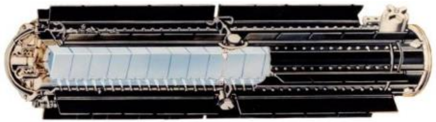
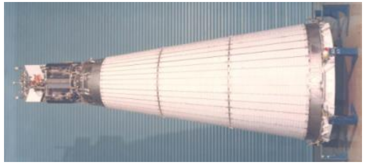
- **Fission reactor**
  - Using the same basic principle as electrical utility nuclear reactors on earth.
  - A neutron-induced chain reaction, splitting heavy nuclei (so far, U-235) into lighter products, releasing energy (heat) in the process.



- **Radioisotope power source**
  - These devices contain an amount of radioactive material to generate heat directly via natural radioactive decay. No reactions (fission, fusion etc.) occur, just simple decay of an unstable nucleus.
  - Can't be turned off!



Electrochemical vs. nuclear power

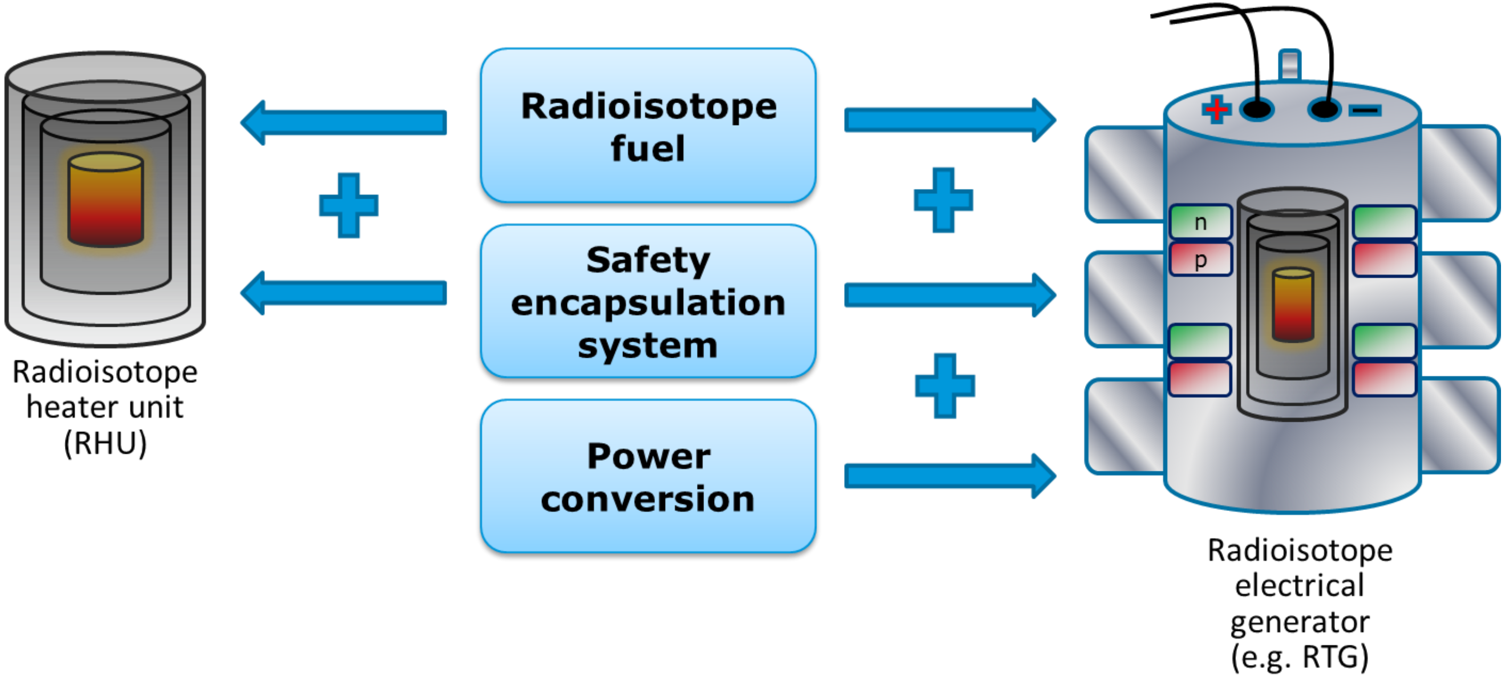
	 Primary Battery	 Radioisotope Thermoelectric Generator (RTG)	 Space Reactor
Power density	< 100 W/kg	5 W/kg	2 - 30 W/kg
Energy density (1 year mission)	< 10^3 Wh/kg	< 10^5 Wh/kg	< 10^6 Wh/kg
Energy density (10 year mission)	< 10^3 Wh/kg	< 10^6 Wh/kg	< 10^7 Wh/kg

Q: How long does a mission need to be for RTGs to be lighter than batteries?

A: $\frac{\text{[a few hundred Wh/kg] (batteries)}}{\text{[a few W/kg] (RTGs)}}$ = about a hundred hours = **a few days**

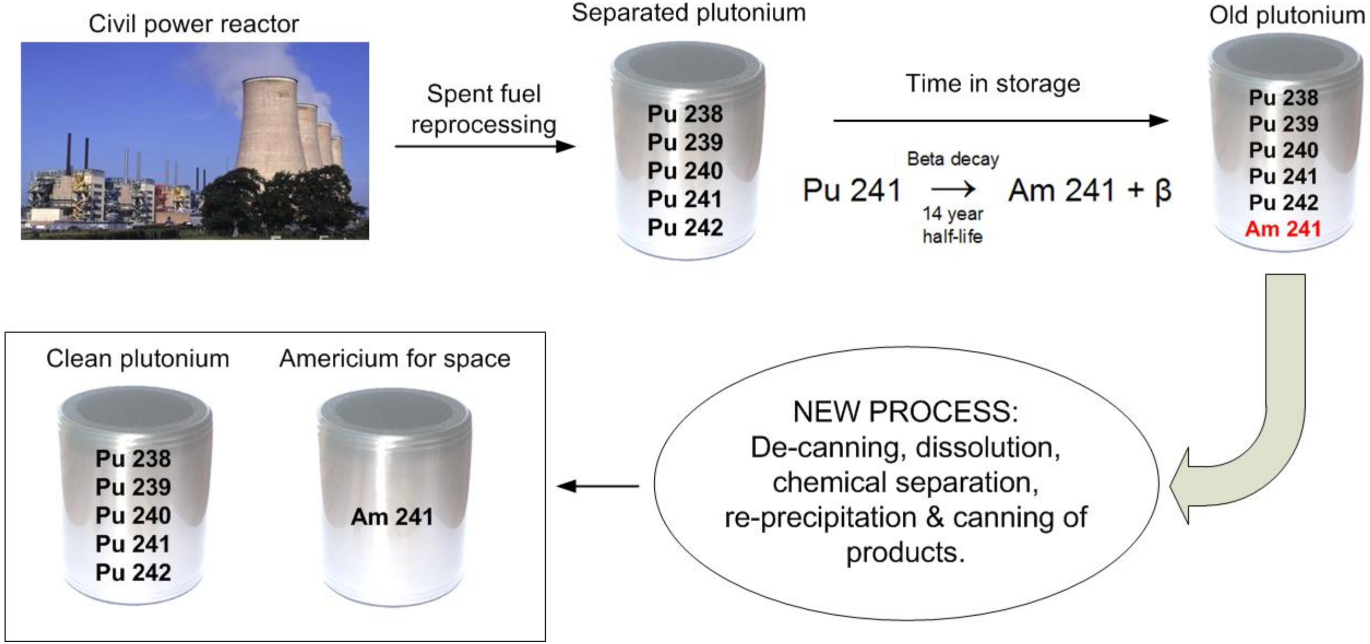
ESA radioisotope power development

ESA's development activities are pursuing three technological building blocks, which will enable two main classes of space NPS:



Extraction of ^{241}Am from civil Pu stocks

New process under development by the UK National Nuclear Laboratory (NNL) at the Sellafield Nuclear Reprocessing Site.



Am241 – Development of a production capability

Latest contract is complete, Dec 2013 - Nov 2015: *European Isotope Production Phase 2*.

Results:

- The continued support of key stakeholders has been established (Sellafield Ltd, UK gov, UK nucl. regulator).
  - This point is critical – the process relies upon the UK plutonium stockpile as a feed material.
- The separation process to extract americium from aged plutonium dioxide has been demonstrated at full-scale plant Am concentration levels with no detriment to the recovery (> 99%) or purity (> 99%) of the Am produced. This raises the TRL level from 3 to 5.
- The requirements for building a full scale facility and dealing with the radioactive waste streams generated are now fully understood.
- The safety case, facilities, equipment and people required to separate Am on the ~10g scale is now in place.

Centrifugal contactors performing extraction of Am241 from Pu solution.

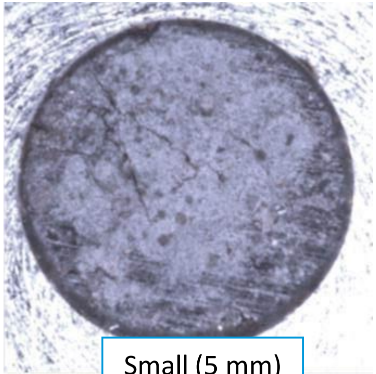
Testing the electrolytic dissolution of PuO_2 at the 500 ml scale.

Am241 – development of a production capability

- Thermodynamic modelling has demonstrated the difference in behaviour between americium and plutonium oxides. Americium oxide loses oxygen much more readily than plutonium and will readily reduce to AmO_{2-x} (x= 0 – 0.5) in a low oxygen atmosphere above 800°C.
- Am volatility is not problematic under the sintering conditions performed so far.
- Preliminary pelleting trials have been performed on a small (~3 g) amount of material. The reduced Am_2O_3 form is readily generated even in the absence of a reducing hydrogen atmosphere, consistent with reported thermodynamic data.
- An ^{241}Am criticality mass limit of 10 kg is expected to be implementable and arguments could be constructed to allow higher amounts for specific well defined geometries.

Purity analysis of Am in solution (left) & powder (right).

	AP4		AmO_2	
	(g/L)	%w/w	g/gAm	%w/w
Np	0.0202	0.34%	0.0007	0.07%
U	0.0015	0.03%	0.0003	0.03%
Pu	0.0025	0.04%	0.0002	0.02%
Am	5.8610	99.59%	0.9988	99.88%
Ag	0.00004	0.001%	6.5E-06	0.00%



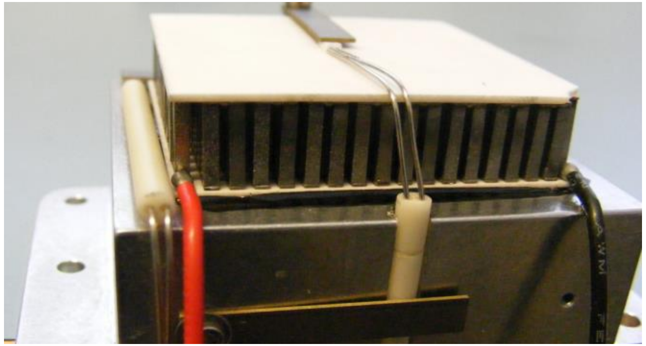
Small (5 mm) Am_2O_3 pellet

RTG development

The University of Leicester, Airbus Defence & Space, Lockheed Martin UK, Queen Mary University of London and European Thermodynamics Ltd.

Previously in 2014…

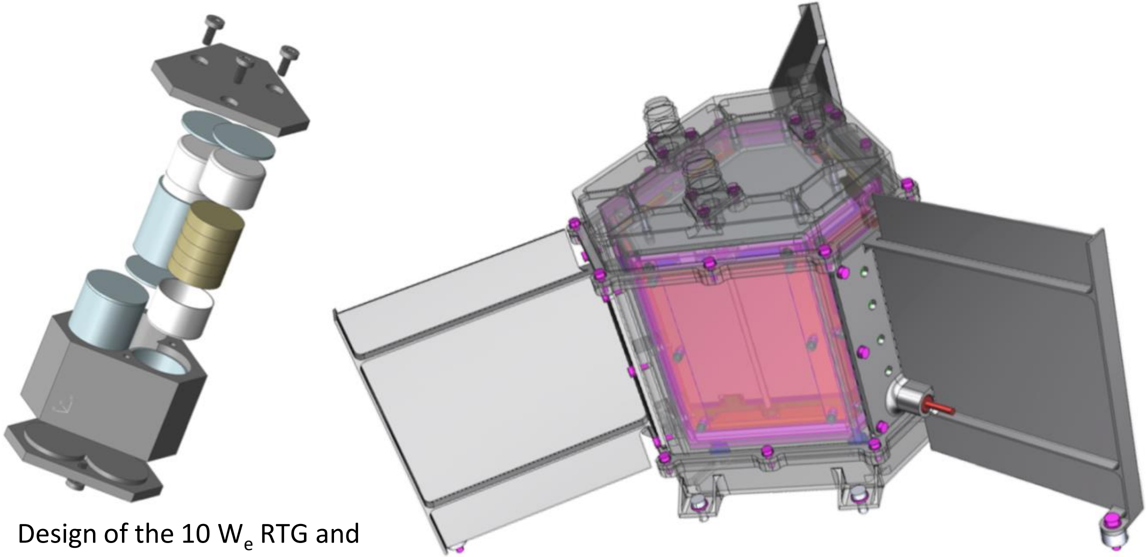
The first RTG breadboard (with approximate mass of 3.5kg) produced a maximum power output of 4.1W_e from a thermal input of 83W_t, giving a system efficiency of ~ 4.9%.



A custom Bi-Te thermoelectric module prepared for installation in the 1st RTG breadboard

Now in progress: Activity to develop the RTG to TRL4:

Including the manufacture of a 10 W_e, 10 kg "elegant breadboard" RTG including a non-nuclear, but otherwise fully flight-representative heat source.

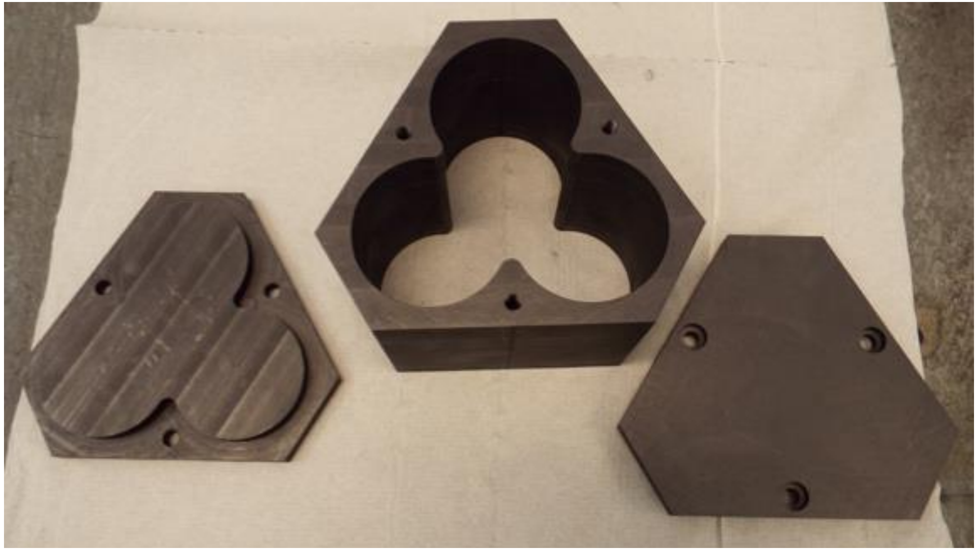


Design of the 10 W_e RTG and associated 200 W_t heat source.

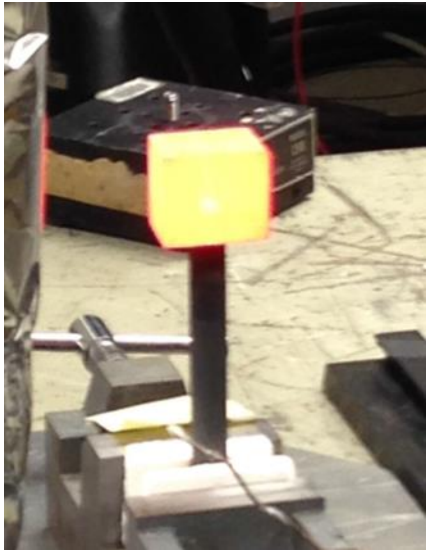
RTG development

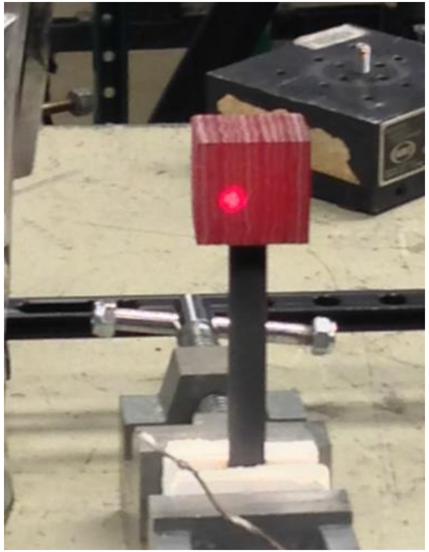
The University of Leicester, Airbus Defence & Space, Lockheed Martin UK, Queen Mary University of London and European Thermodynamics Ltd.

Latest status @ September 2017:



Carbon-carbon composite aeroshell for the 200W_t Am241-fuelled heat source.





Images of C-C composite after laser ablation test, cooling down from >3500°C to room temperature.

RTG development

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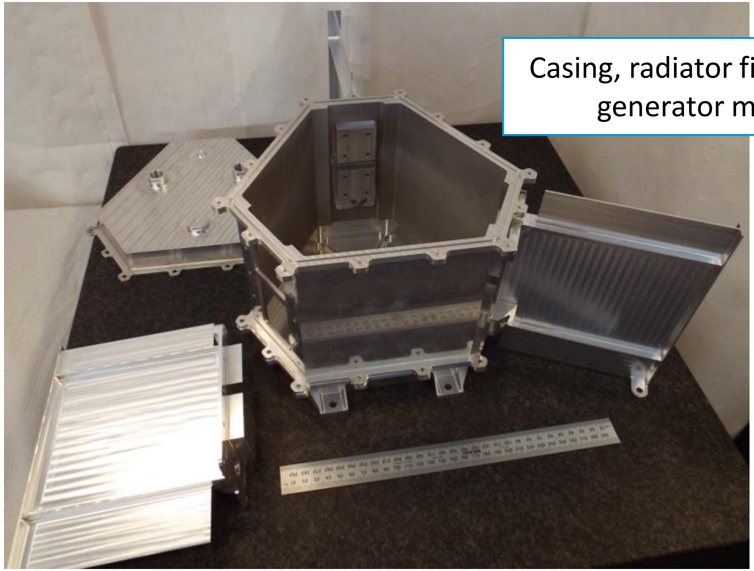
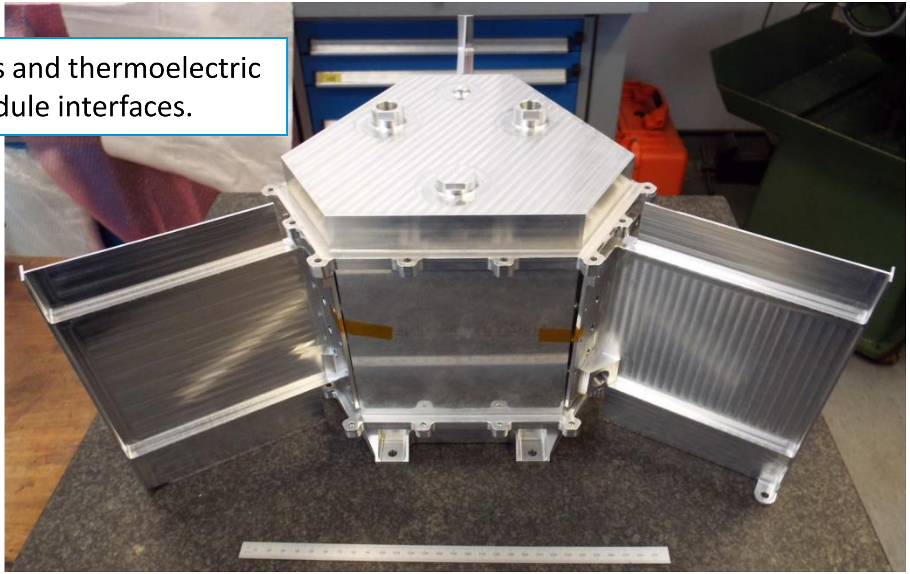


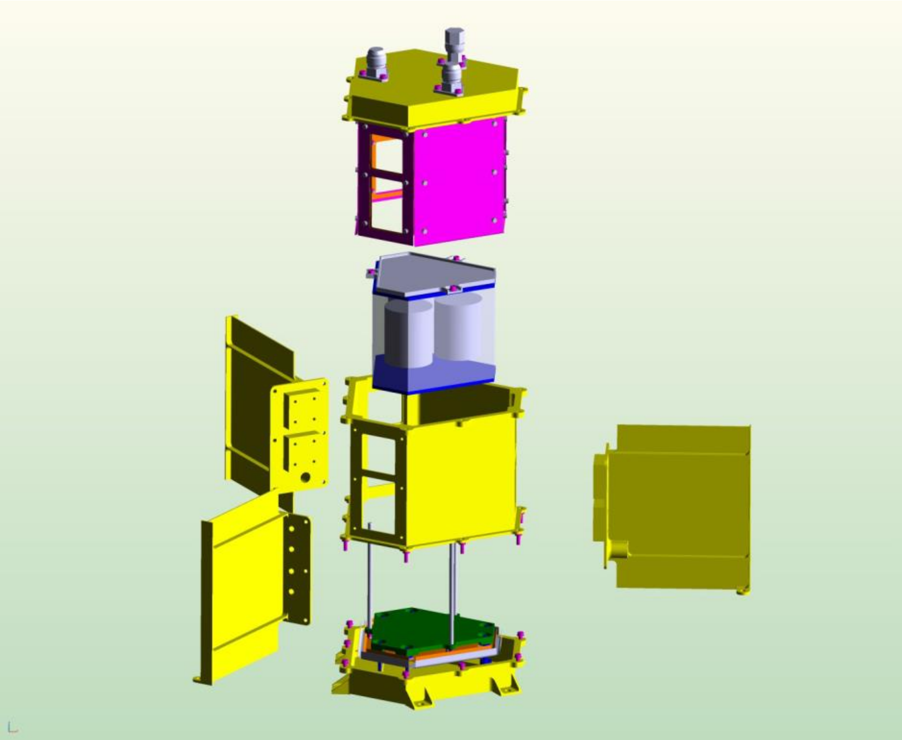


Casing, radiator fins and thermoelectric generator module interfaces.

System testing will begin this autumn, leading to activity completion in Q1 2018.

RTG development

The University of Leicester, Airbus Defence & Space, Lockheed Martin UK, Queen Mary University of London and European Thermodynamics Ltd.



Thermal Aspects

This design, like other space RTGs, is designed to reject heat to space via radiators.

The European design, due to the lower power fuel (^{241}Am) and associated selection of Bi-Te thermoelectric materials, works at much lower temperatures than previous USA devices.

Testing of the previous generation model found optimum results with temperatures of 127°C and 27°C across the TEG modules, but was limited by lab cooling system performance. A cold end running 10-20°C lower would likely give improved efficiency.

This is a perfect range to implement direct sea-water cooling.

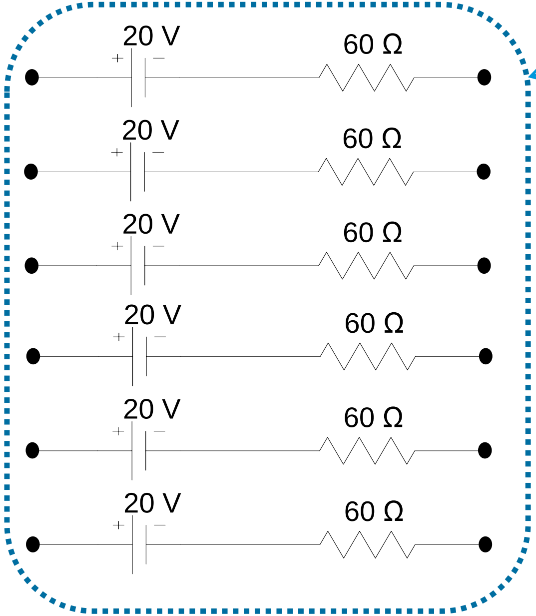
The current design as illustrated is hermetically sealed, and designed to run with internal vacuum or inert cover gas.

A deep water version would need to be engineered for greater pressure differential, but the design concept is compatible.

RTG development

The University of Leicester, Airbus Defence & Space, Lockheed Martin UK, Queen Mary University of London and European Thermodynamics Ltd.

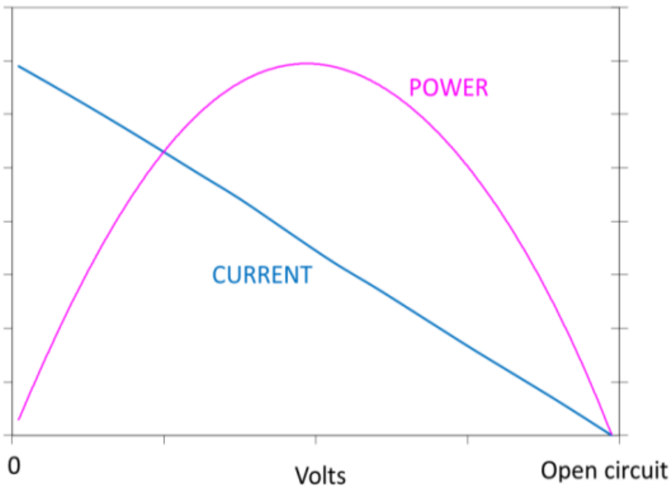
Electrical Aspects



DC equivalent circuit of the European 10 W_e RTG (TBC).

In principle the 6 TEG modules could be arranged as follows:

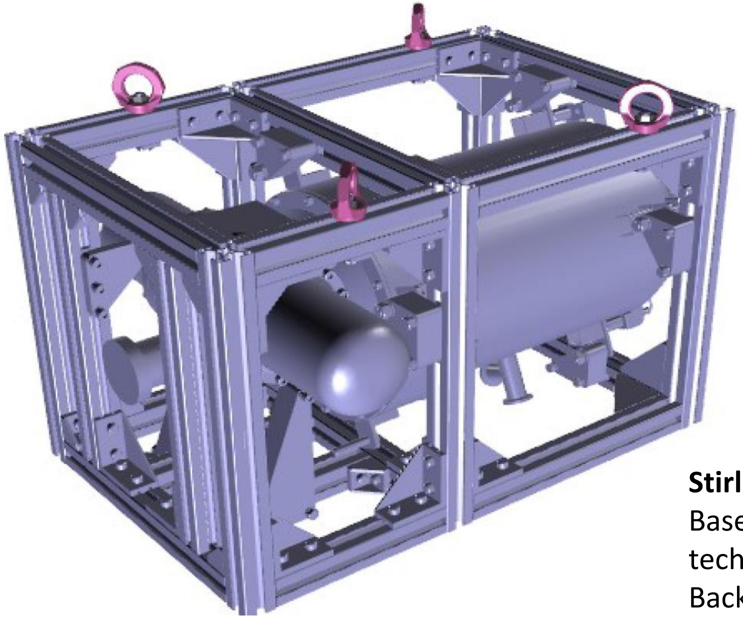
Configuration	Max power (10W) @		into a load of
1s 6p	10 V	1 A	10 Ω
2s 3p or 3p 2s	20 V	0.5 A	40 Ω
3s 2p or 2p 3s	30 V	0.33 A	90 Ω
6s 1p	60 V	0.17 A	360 Ω



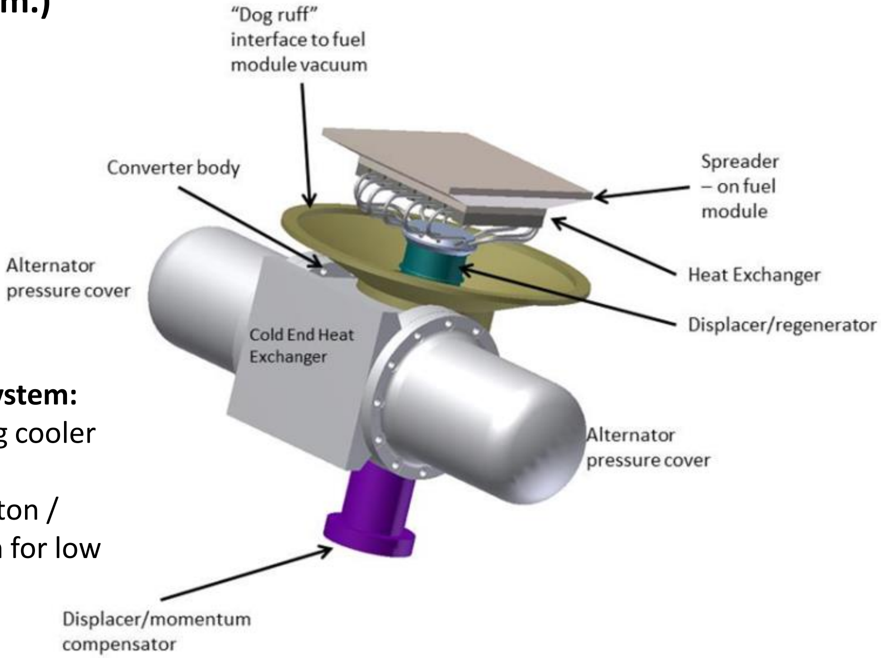
Radioisotope Stirling generator development

TAS-UK, STFC RAL, Oxford University, QinetiQ Belgium.

Now in progress: An activity to design and prototype a 100 W Stirling converter system for use with Am-241 radioisotope fuel. (53 kg full system mass budget, including fuel but excluding heat rejection system.)



CAD of full system in lab mechanical frame



Stirling converter subsystem:

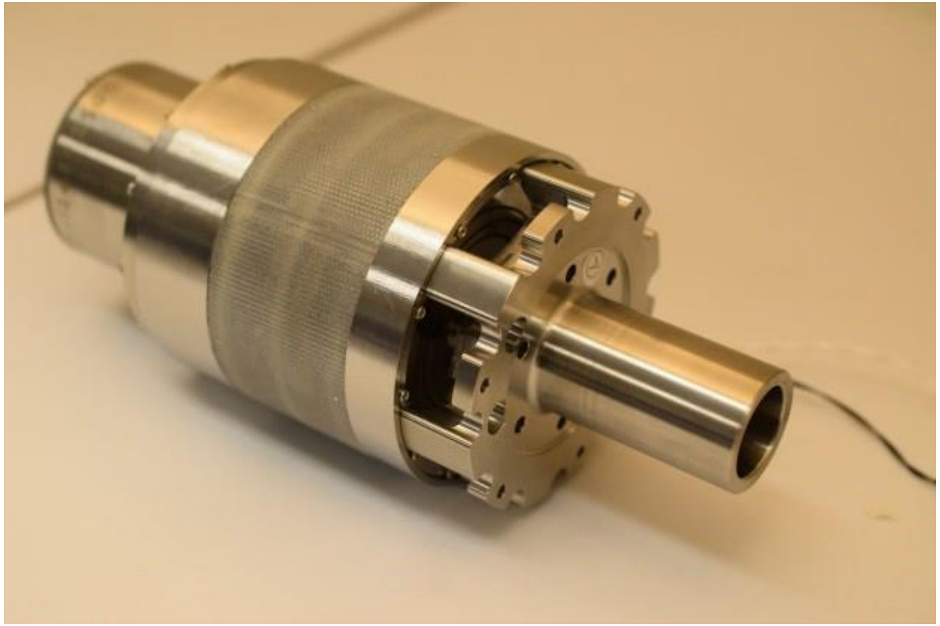
Based on proven Stirling cooler technology.

Back-to-back power piston / alternator configuration for low exported vibration.

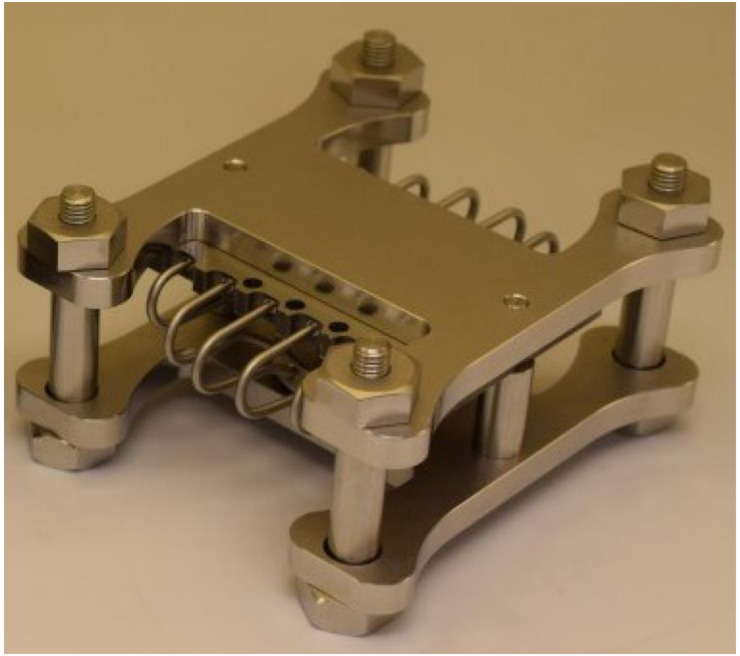
Radioisotope Stirling generator development

TAS-UK, STFC RAL, Oxford University, QinetiQ Belgium.

Latest status @ September 2017:



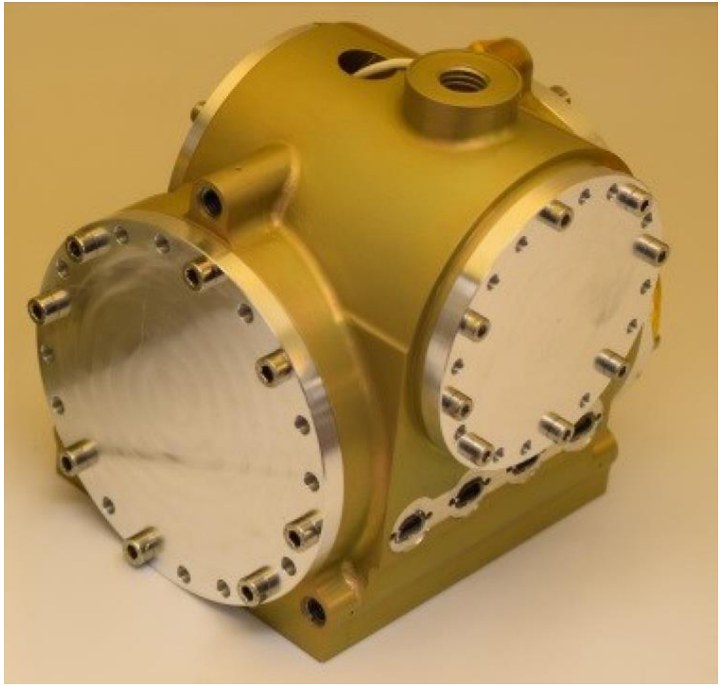
Alternator assembly



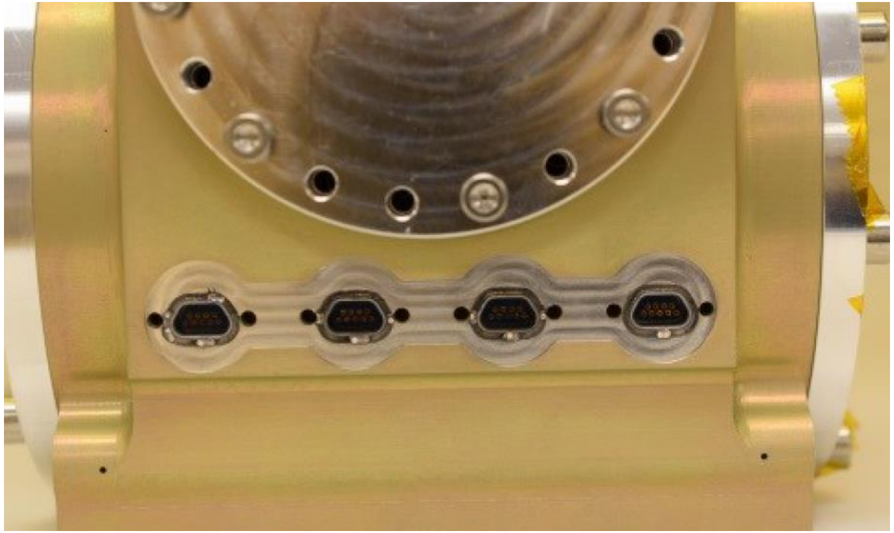
3D printed inconel heat exchanger

Radioisotope Stirling generator development

TAS-UK, STFC RAL, Oxford University, QinetiQ Belgium.



Main converter body



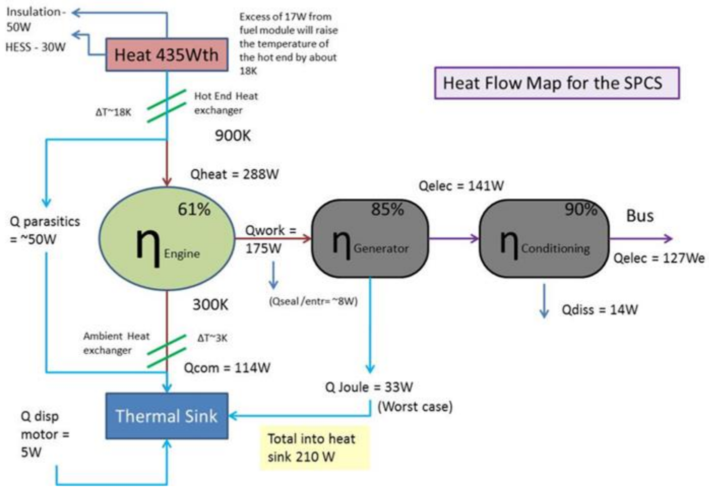
Body detail showing welded electrical feedthroughs

Radioisotope Stirling generator development

TAS-UK, STFC RAL, Oxford University, QinetiQ Belgium.

Thermal Aspects

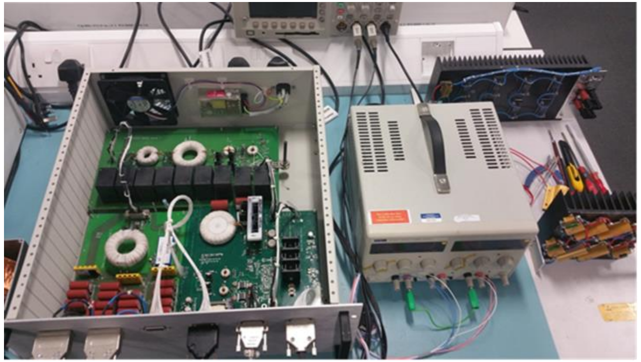
The ESRG prototype design does not include a heat rejection system, but only a cold-end interface which is intended to run at approximately 300K, 29°. This means that the final heat rejection system (direct radiative, fluid loop, etc.) can be designed to suit the mission / spacecraft application. Heat rejection to seawater could be implemented in a simple and compact way



Electrical Aspects

The ESRG's alternators produce AC power at ~ 90Hz. This is converted to DC in an electronic unit that implements power factor correction and controls the Stirling engines via feedback to the active driven displacer.

The prototype system under construction will produce 28V DC as a final output, given that this is a common spacecraft standard. In principle, an ESRG version for other applications could output at any desired DC or AC voltage



Radioisotope Stirling generator development

TAS-UK, STFC RAL, Oxford University, QinetiQ Belgium.

Component testing and subsystem integration is underway in Q3 & 4 2017.

System testing will follow, scheduled for completion in Q2 2018.

To conclude….

The conclusions of Nov 2016 remain valid:

- Nuclear power systems are the only way to provide **sustained** power in the absence of sunlight.
- **Radioisotope** power systems are best suited to provide heat and electrical power in the watts-to-hundreds of watts scale.
- **Timescale** of the application is important. For missions / applications less than a few days, nuclear power systems are not optimum, as conventional batteries are competitive in mass. Where mass/size is not so penalising, of course this trade-off moves to longer times…
- ESA's research activities are developing innovative **americium**-fuelled radioisotope power systems, specifically:
    - **Heater unit**, ~3 W thermal power
    - **Small RTG**, 5 to 20 W electrical power
    - **Stirling generator**, ~100 W electrical power.

The focus of further discussion could be on potential ROBEX applications, to identify those which may be enabled or optimised by radioisotope systems as compared to electrochemical batteries.