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INSTITUT FRANÇAIS
LETTONIE

SPACE TRIPS SUMMER SCHOOL

SEVENTH FRAMEWORK PROGRAMME

Theme 9: SPACE

Riga, Latvia.

June 17-20, 2014.

The ESA Nuclear Power Development Programme

Keith Stephenson
European Space Agency

The ESA Nuclear Power Development Programme

Keith Stephenson, ESA Power & Energy Conversion Division

June 2014

Presentation Outline

1. ESA – The European Space Agency.
2. Overview of ESA nuclear power development programme.
3. Radioisotope selection and development of manufacturing capability.
4. Safety and Encapsulation
5. Power conversion: thermoelectric, Stirling engine and TA-MHD.

ESA FACTS AND FIGURES

- Over 50 years of experience
- 20 Member States
- Eight sites/facilities in Europe, about 2200 staff
- 4.1 billion Euro budget (2014)
- Over 70 satellites designed, tested and operated in flight
- 18 scientific satellites in operation
- Six types of launcher developed
- 200th launch of Ariane celebrated in February 2011

PURPOSE OF ESA

"To provide for and promote, for exclusively peaceful purposes, cooperation among European states in **space research** and **technology** and their **space applications.**"

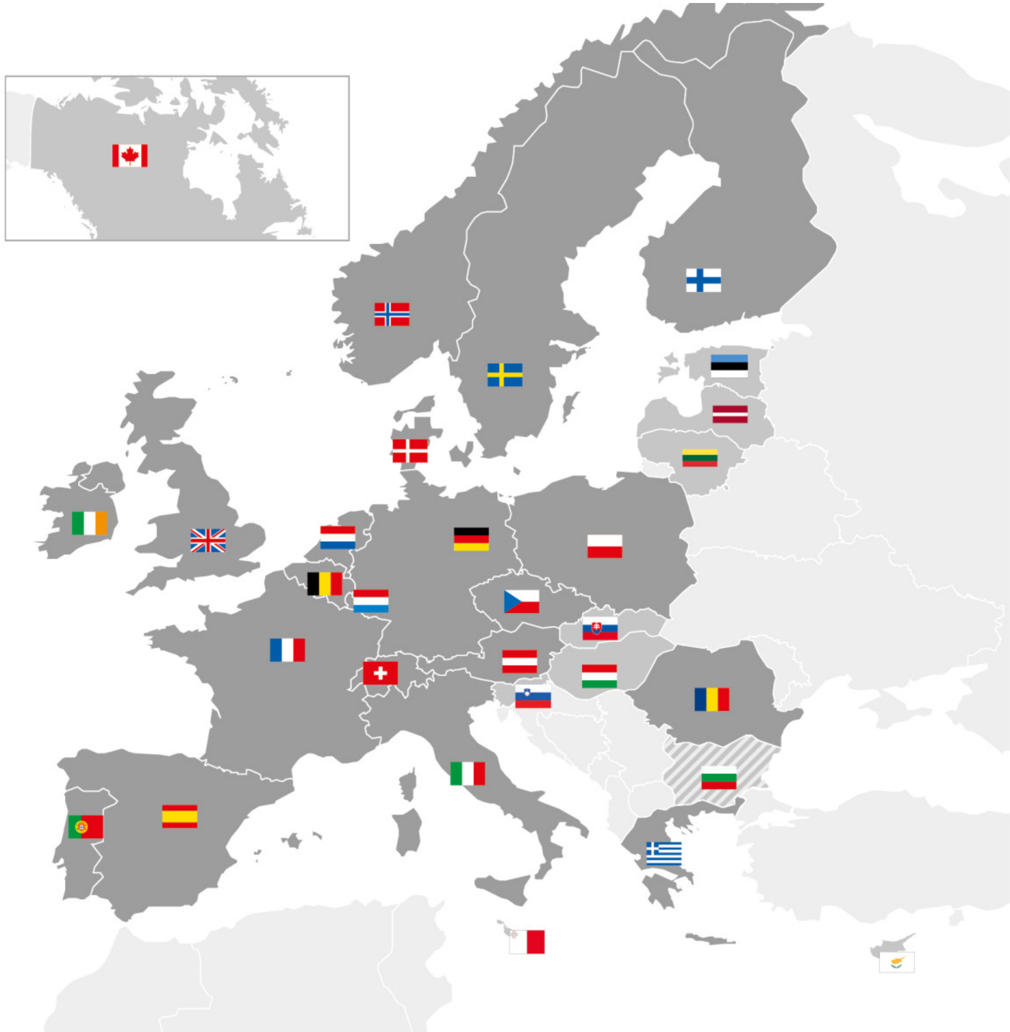
Article 2 of ESA Convention

20 MEMBER STATES AND GROWING

ESA has 20 Member States: 18 states of the EU (AT, BE, CZ, DE, DK, ES, FI, FR, IT, GR, IE, LU, NL, PT, PL, RO, SE, UK) plus Norway and Switzerland.

Eight other EU states have Cooperation Agreements with ESA: Estonia, Slovenia, Hungary, Cyprus, Latvia, Lithuania, Malta and the Slovak Republic. Bulgaria is negotiating a Cooperation Agreement. Discussions are ongoing with Croatia.

Canada takes part in some programmes under a long-standing Cooperation Agreement.

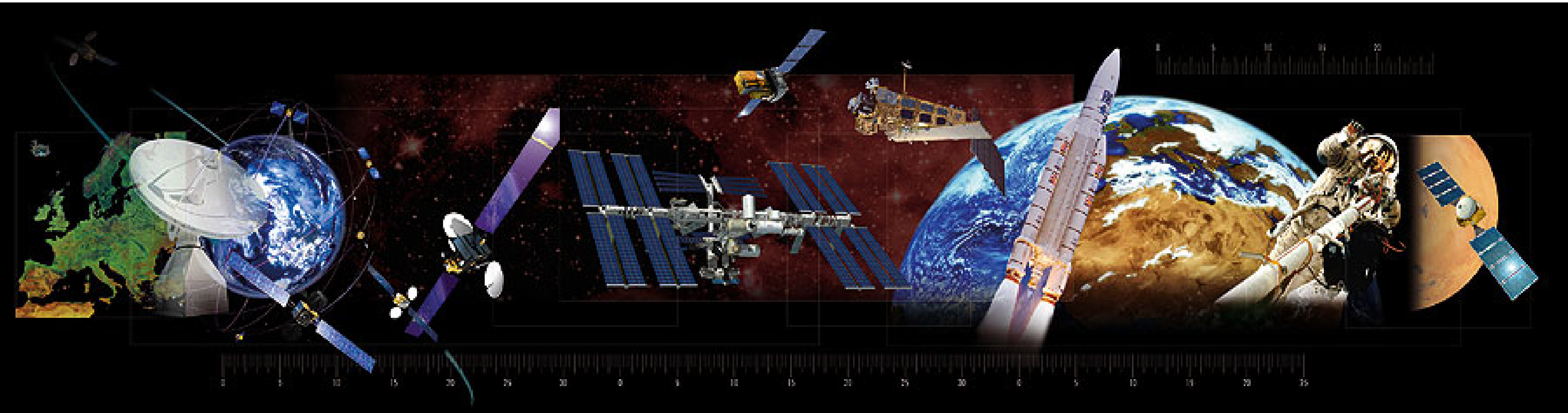


ACTIVITIES

ESA is one of the few space agencies in the world to combine responsibility in nearly all areas of space activity.

Space science*
Human spaceflight
Exploration
Earth observation
Launchers
Navigation
Telecommunications
Technology
Operations

* Space science is a **Mandatory programme**, all Member States contribute to it according to GNP. All other programmes are **Optional,** funded 'a la carte' by Participating States.

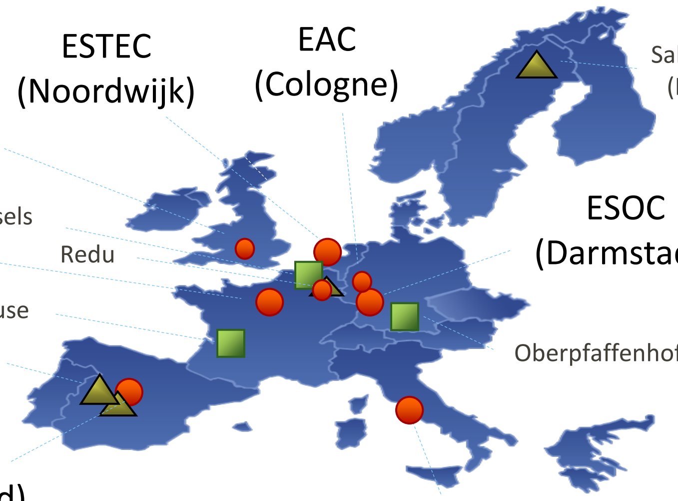


ESA’S LOCATIONS

ESA sites/facilities

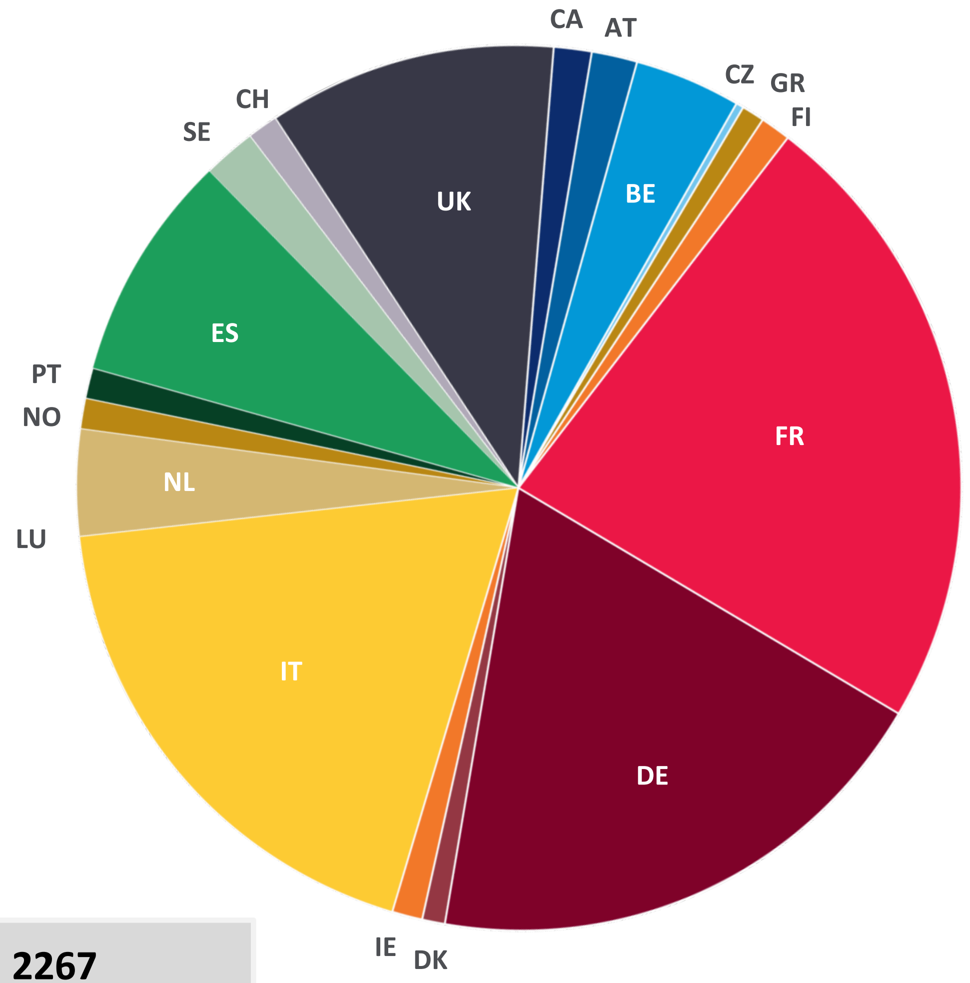
Offices

ESA ground stations



STAFF BY NATIONALITY IN 2012

Austria	40
Belgium	91
Czech Republic	5
Denmark	21
Finland	21
France	525
Germany	431
Greece	18
Ireland	30
Italy	420
Luxembourg	2
Netherlands	88
Norway	23
Portugal	25
Spain	188
Sweden	44
Switzerland	28
UK	237
Canada	29



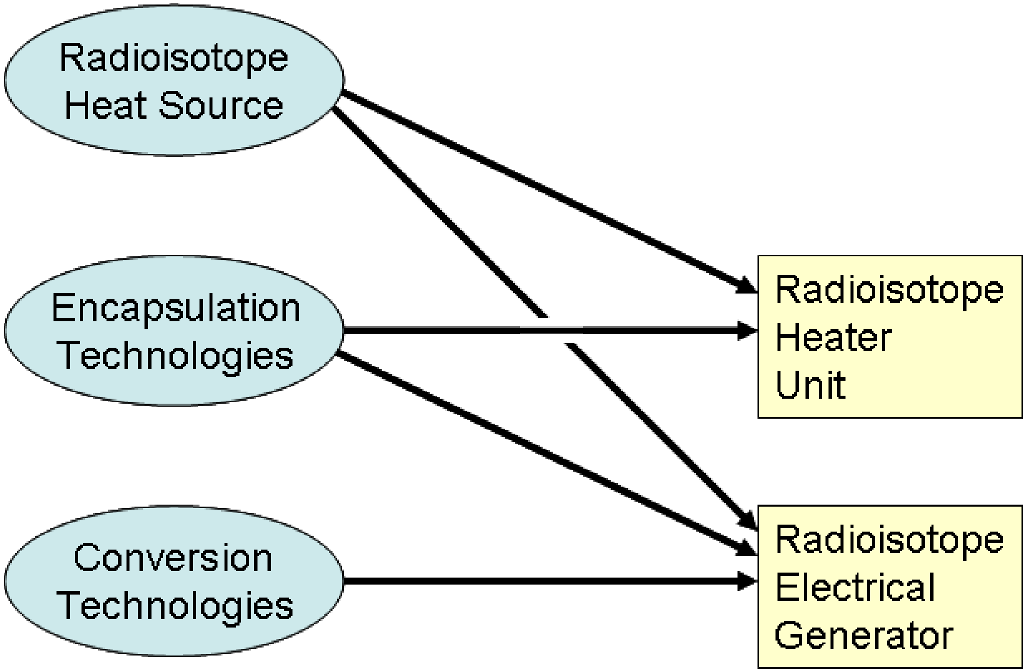
TOTAL INTERNATIONAL STAFF: 2267

Space Nuclear Power - European Activities

Historically, European space programmes have had no access to NPS other than via collaboration with USA (or potentially Russia).

In 2009, ESA initiated the first R&D contracts in a development programme that aims towards a European capability for RHUs and radioisotope electrical generators. At the moment, reactor technologies remain a future ambition.

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

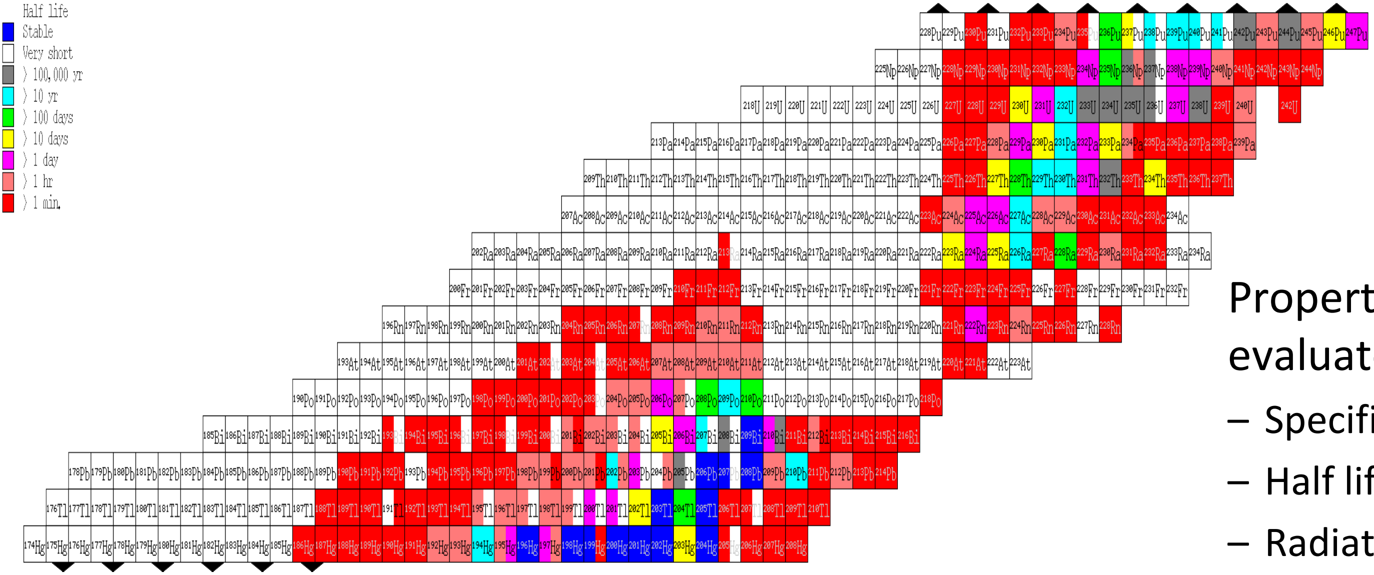


European Radioisotope Selection

Areva TA, CEA, TAS-I, SEA Ltd, UK NNL, Uni. Manc. Dalton Nuclear Institute

Two parallel contracts were placed in 2009:

- Areva TA (Technicatome), CEA and TAS-I.
- SEA Ltd, UK National Nuclear Laboratory (NNL) and Uni of Manchester Dalton Nuclear Institute.



Properties of interest to be evaluated:

- Specific heat output
- Half life
- Radiation outputs and shielding requirements
- Stable chemical forms
- Availability and cost (non-recurring and recurring)
- Regulatory aspects

The studies were conducted with no prejudice – started from the full table of the nuclides.

European Radioisotope Selection

Areva TA, CEA, TAS-I, SEA Ltd, UK NNL, Uni. Manc. Dalton Nuclear Institute

The contracts produced similar shortlists:

	^{238}Pu	^{241}Am	^{244}Cm	^{90}Sr	^{148}Gd	^{3}H	^{113m}Cd
Suitable chemical form?	PuO_2	Am_2O_3	Cm_2O_3	$SrTiO_3$	Gd_2O_3	LiH	None? CdO_2?
Power (W/g) of the compound	0.411	0.105	2.57	0.220	0.54	0.10	0.19

- ✗ Cm244 - Neutron emission too high.
- ✗ Gd148 & Cd113m – Must be produced by particle accelerator.
- ✗ Sr90 – Bremsstrahlung photon emission too high.
- ✗ H3 – Low density, no high-temperature solid compound.

- ✓ Pu238, the well-established space power radioisotope, is the technically superior choice.
  - ✗ ..but is very expensive (requires reactor irradiation and multiple separation steps).
- ✓ Am241 has only one-quarter the power of Pu238, but may be more affordable to produce.

^{238}Pu Production Process

1. Extraction of reprocessing effluent solution containing ^{237}Np.
2. Transfer of effluents from reprocessing plant to laboratories.
3. Neptunium purification and conversion to oxide form.
4. Neptunium oxide targets fabrication.
5. Transfer of irradiation targets to a nuclear reactor.
6. Neptunium oxide irradiation in reactor.
7. Transfer of irradiated targets back to laboratories.
8. Plutonium extraction and conversion to oxide.
9. ^{238}Pu oxide pellets fabrication.

ROM estimate of production cost (in France, but UK was similar):

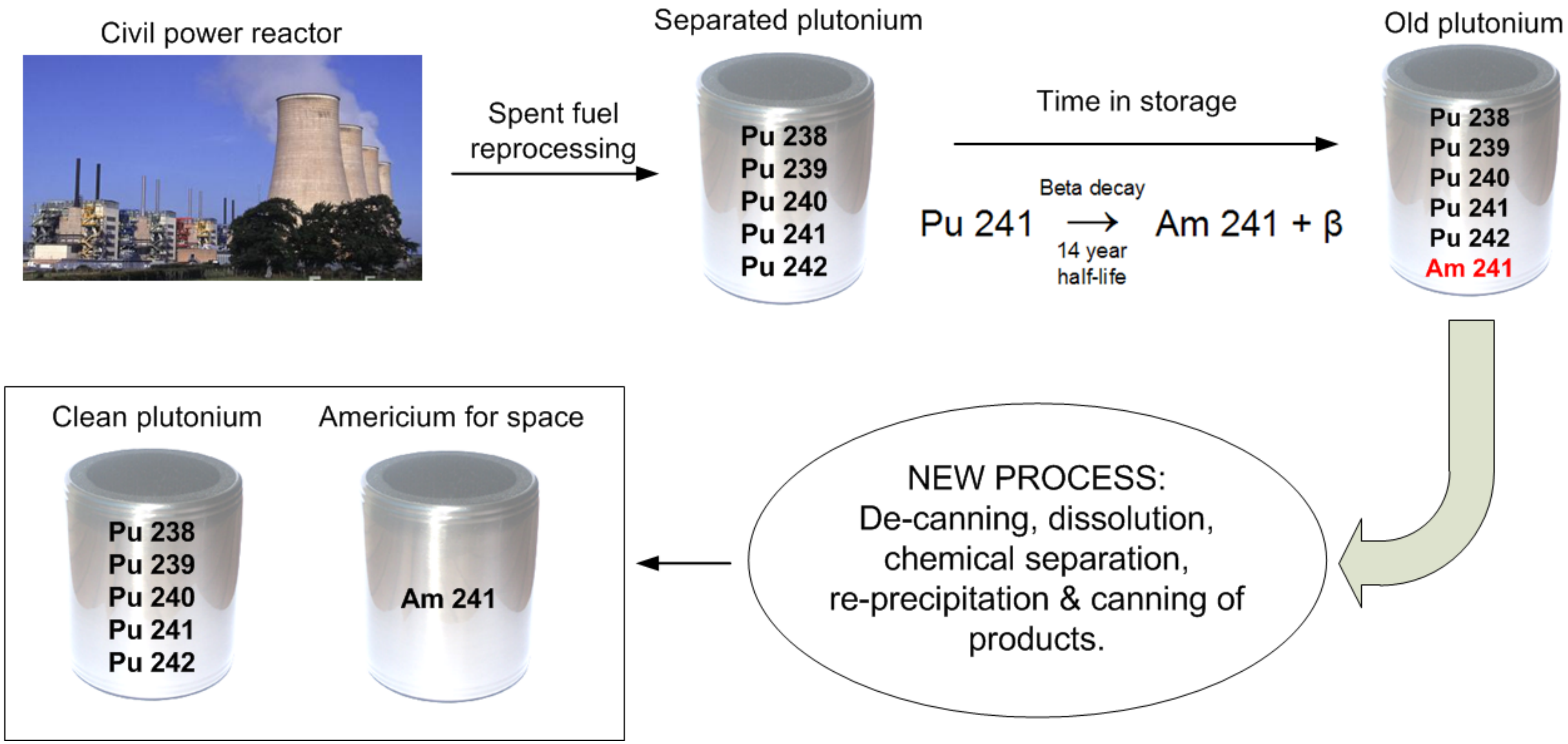
On the basis of 1kg/year of $^{238}PuO_2$ (the USA MMRTG uses ~5kg).

- Facility creation 400M€.
- Functioning budget 15 M€/y.
- Irradiation 10 M€/y. (Even assuming that a suitable reactor existed………..)

^{241}Am – a potential space power source for Europe

UK National Nuclear Laboratory.

A subsequent contract with the UK NNL was placed in order to produce a preliminary design and cost estimate for the creation and operation of a ^{241}Am production facility at Sellafield:



The Am plant cost estimate was completed in early 2012 :

- Pre-operational costs, (process development, design, building and commissioning) of 58M€ over 7 years.
- Operating costs of 14M€ per year.
- Post-operational costs of 7.5M€ for decommissioning.

These figures are for a plant capable of producing approximately 10kg of ^{241}Am per year.

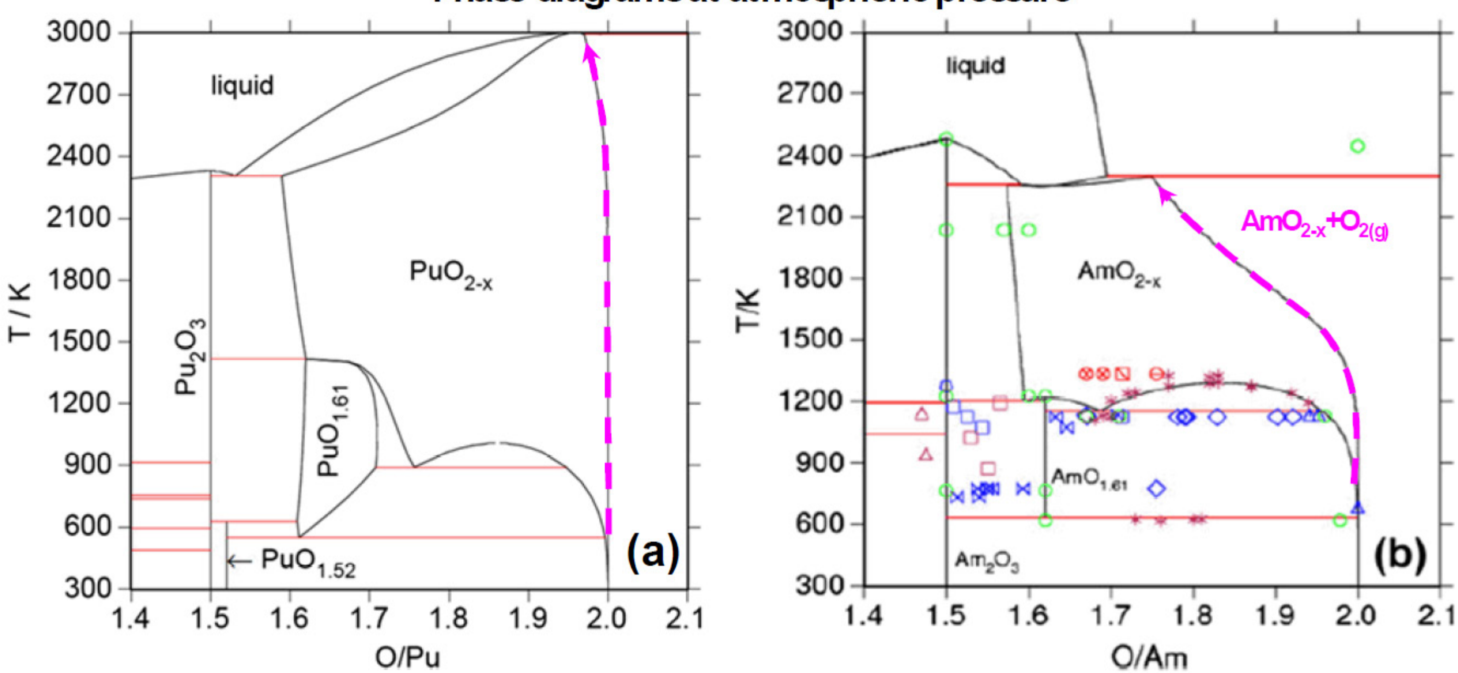
^{241}Am – a potential space power source for Europe

The Sellafield Nuclear Site in Cumbria, England

^{241}Am – a potential space power source for Europe

esa

Phase diagrams at atmospheric pressure



Phase Diagrams from: P. Gotcu-Freis, J.Y. Colle, C. Guéneau, N. Dupin, B. Sundman, R.J.M. Konings, A thermodynamic study of the Pu-Am-O system, Journal of Nuclear Materials 414 (2011) 408-421

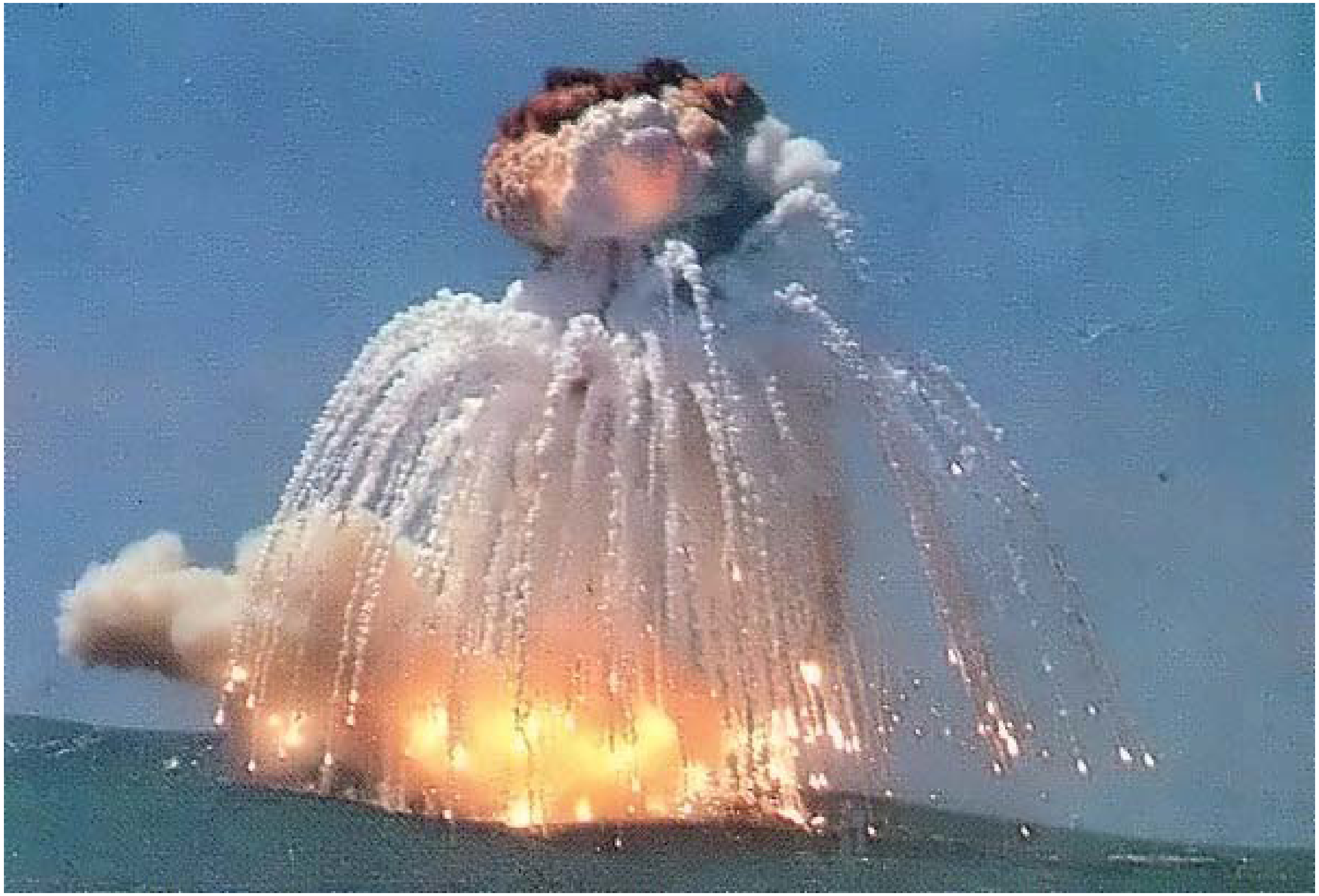
^{238}Pu is used in the dioxide form for space radioisotope systems.

But AmO_2 decomposes above ~1200 K (to $AmO_{2-x}+O_2$) so is NOT suitable.

Am_2O_3 looks more promising, with stability up to ~2400K in an oxygen-free environment.
However, there is phase change behaviour under oxidation, and a possibility of Am volatilisation under some conditions. These issues must be researched further…………

Safety Encapsulation

Radioisotope fuel must be encased within a system of physical barriers to prevent fuel dispersal under accident conditions.



Titan 34-D solid booster failure, 1986

The accident conditions relevant to space systems are uniquely challenging.

Potentially:

Blast shockwave
+
Fireball
+
Shrapnel
+
Re-entry heating
+
Ground Impact

IN SERIES!

Safety Encapsulation

SEA Ltd, UK National Nuclear Laboratory (NNL), University of Leicester and Lockheed Martin UK

Nuclear Fuel Capsule and Aeroshell Design Study

Contract with **SEA Ltd, UK National Nuclear Laboratory (NNL), University of Leicester and Lockheed Martin UK**.

November 2010 – March 2012.

This activity investigated two approaches to the low-TRL development of a European capability to encapsulate ^{241}Am radioisotope fuel:

1. A European analogue to the "conventional" (e.g. USA) approach of multi-layer encapsulation using refractory metals, carbon based insulators and carbon-carbon aeroshells.
2. A novel approach using ceramic-metallic (CERMET) composites manufactured with spark-plasma sintering (SPS).

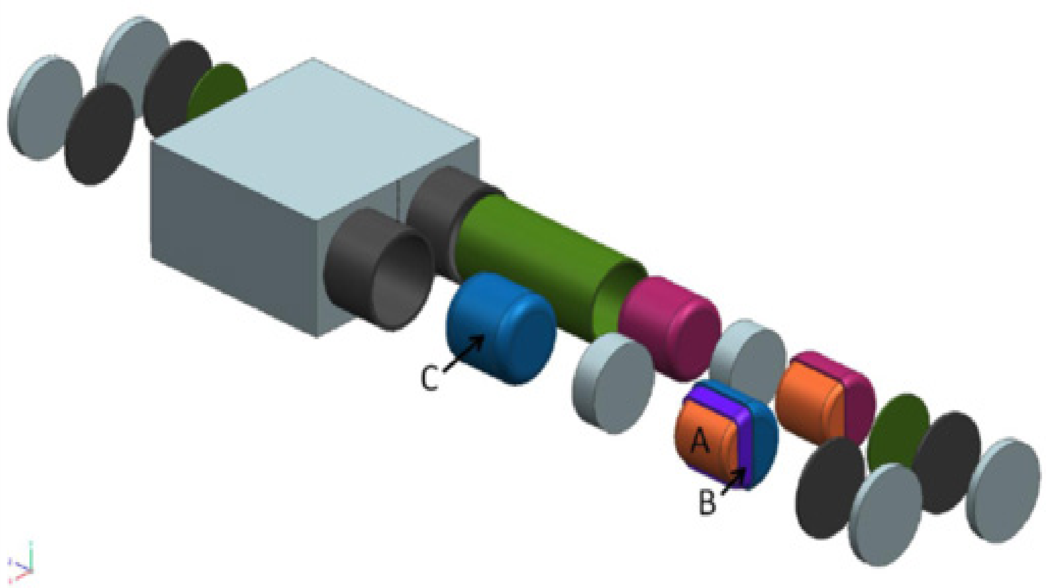


Figure 1-1 – Schematic representation of novel primary containment, compared to traditional fuel clad, within a conventional RTG aeroshell module: A – Fuel composite (70vol% Am_2O_3- 30vol% Nb; B – Inner primary containment (niobium); C – Outer primary containment (70 vol% ZrB_2- 30vol% SiC).

Layer	Composition	Function
Fuel A	70 vol% Am_2O_3 : 30 vol% Nb-alloy composite	Provide inherent integrity to fuel in case of beyond design basis accidents by providing some plasticity. Improve thermal conductivity, thermal expansion coefficient and counter any phase change effects in fuel.
Inner primary containment B	Niobium alloy	Ductile, high strength containment barrier compatible with high operating temperatures, good oxidation resistance.
Outer primary containment C	70 vol% ZrB_2 : 30 vol% SiC composite	Provide a hard, high-strength outer layer, oxidation resistant in seawater, hypersonic and fire environments environment.

Safety Encapsulation

SEA Ltd, UK National Nuclear Laboratory (NNL), University of Leicester and Lockheed Martin UK

Key results:

A first set of performance requirements has been derived for RHUs and RPS fuel modules, covering nominal operation and accident conditions.

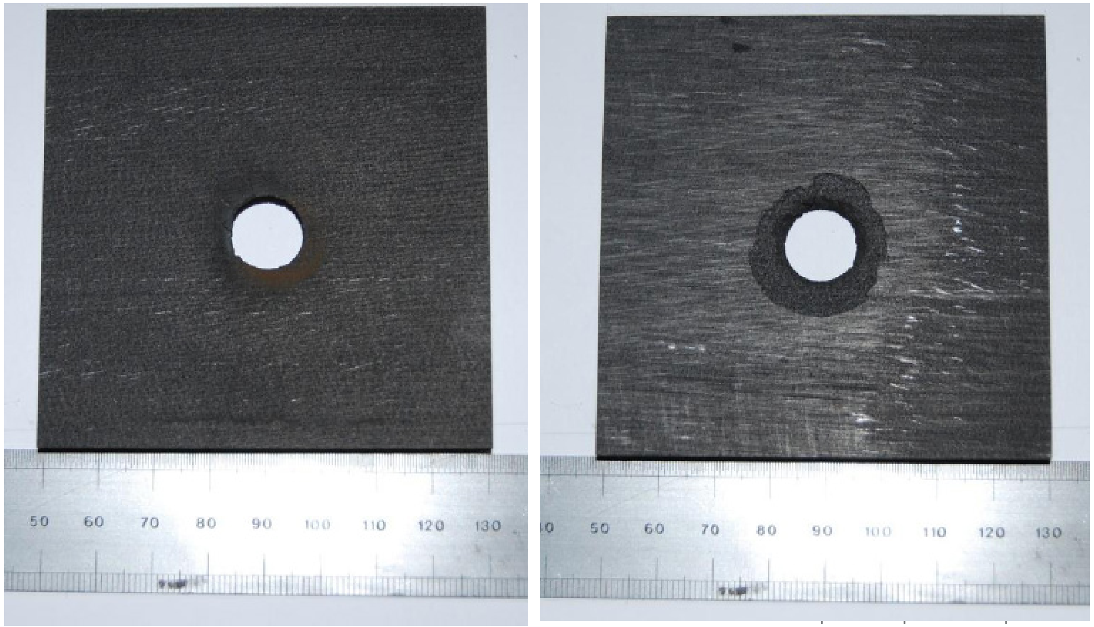
Encapsulation designs for RHUs and RPS fuel modules have been produced, based upon the established American LWRHU and GPHS, but modified to accommodate $^{241}Am_2O_3$ fuel, and using European materials.

Thermal, impact, re-entry and radiological modelling indicates performance similar to the USA systems.

The American GPHS aeroshell is made from “fine-weave pierced fabric” (FWPF) carbon-carbon material. *Mersen A035* C-C material was selected as most promising European analogue, and was subject to ballistic testing at the LMUK Ampthill gas-gun facility. Tests were designed to provide useful comparison with available data on the historical testing of FWPF at Los Alamos laboratory.

The results (projectile velocity decrement and deformation) were very close to those of the FWPF, giving confidence that the Mersen A035 material (or a 2.5D pierced version) was indeed potentially suitable.

Front and rear faces of Mersen A035 fine-weave c-c plate following ballistic testing with an aluminium alloy projectile



Safety Encapsulation

AREVA-TA, I2M, CEA, Herakles–Safran, TAS-I

A subsequent, larger safety/encapsulation contract was awarded to a French-Italian consortium:

Nuclear power systems architecture and safety study for safety management and fuel encapsulation prototype development (NPSAFE). 2012-2014

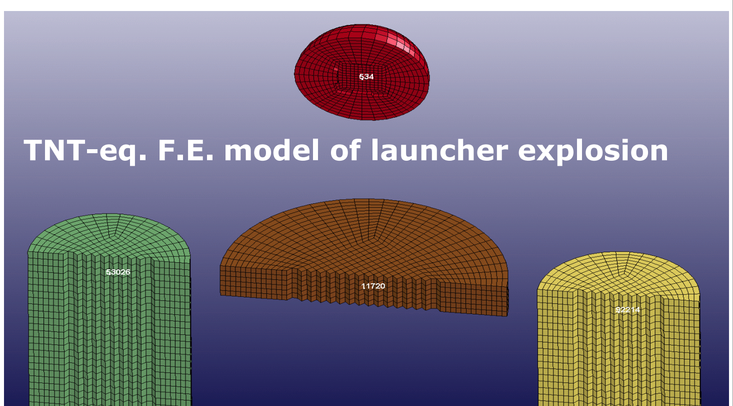
Aims of the NPSAFE activity:

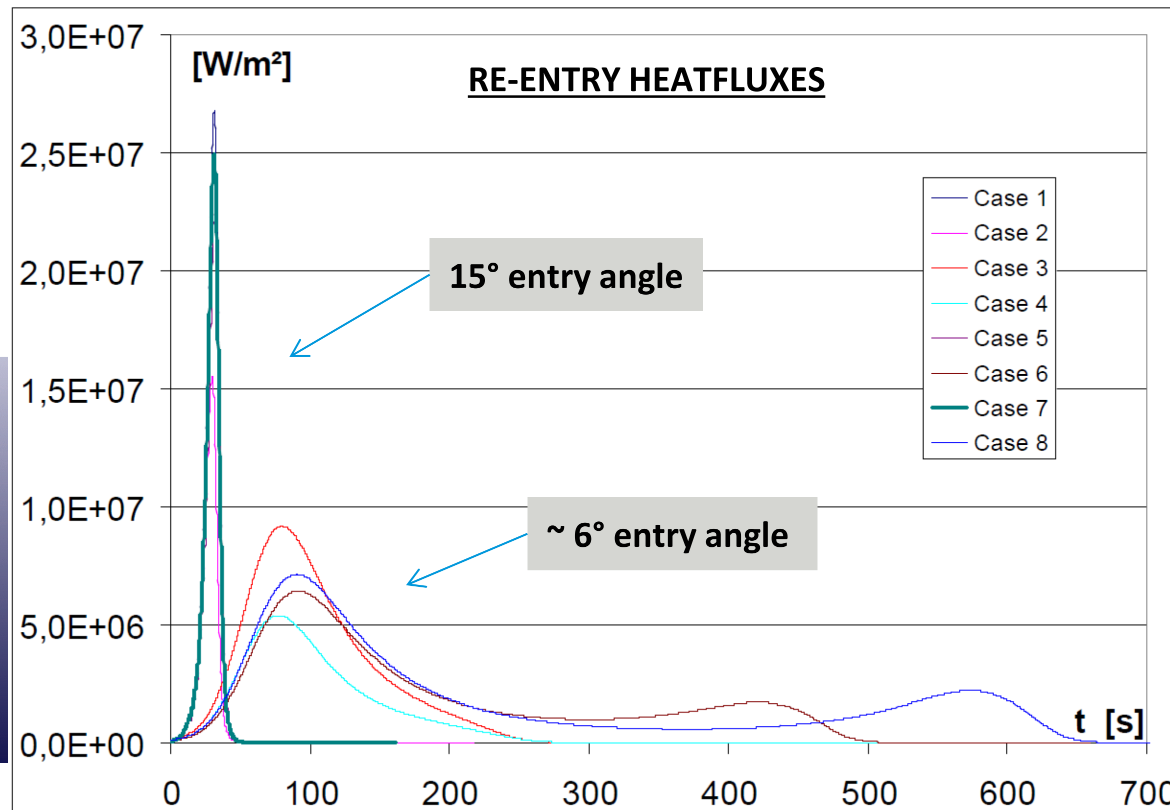
1. Worst case scenario (accident environment) definition.
2. Safety design at the full system level (using Stirling RPS)
3. Encapsulation design
4. Safety aspects

Companies:

AREVA-TA, I2M (Bordeaux Uni), CEA, Herakles–Safran.

Thales Alenia Space-Italia.



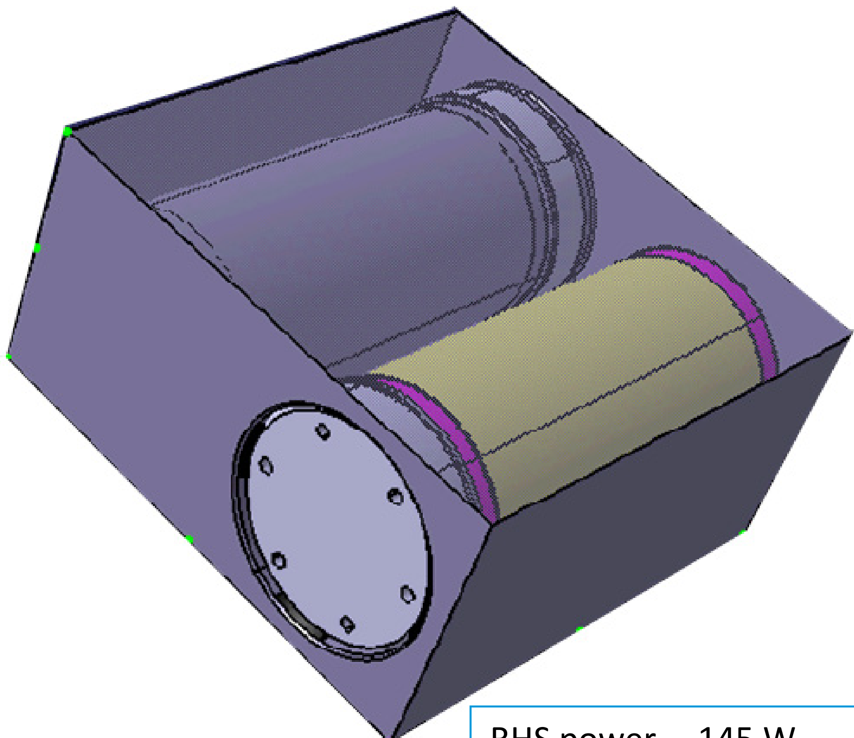


Safety Encapsulation

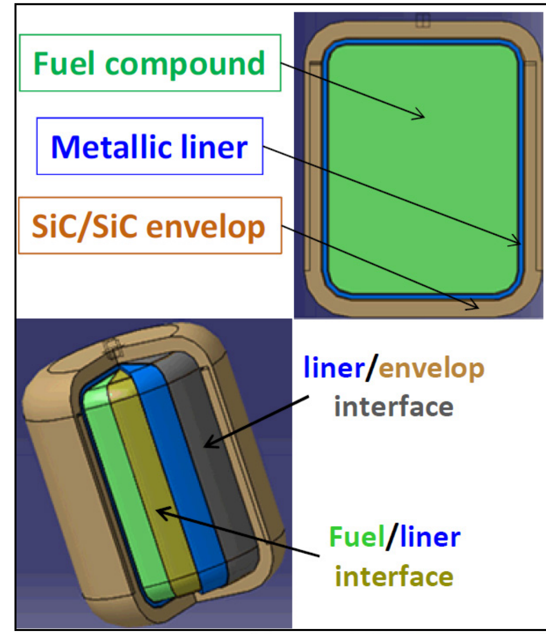
AREVA-TA, I2M, CEA, Herakles–Safran, TAS-I

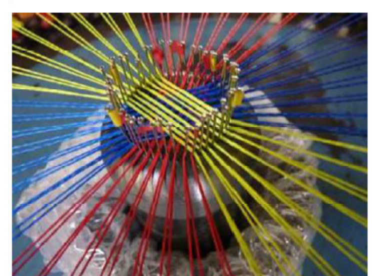
Areva TA and their team have produced a detailed design of a fully-European radioisotope heat source module.

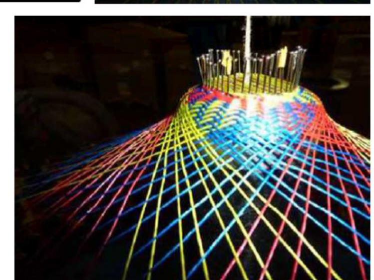
The design features an innovative fuel cladding of SiC-SiC composite. This concept is based on CEA's blind-end woven SiC technology developed for nuclear reactor fuel.



RHS power	145 W_{th}
RHS size	163x167x85mm
RHS mass	4.6 kg
RHS volume	2320 cm^3

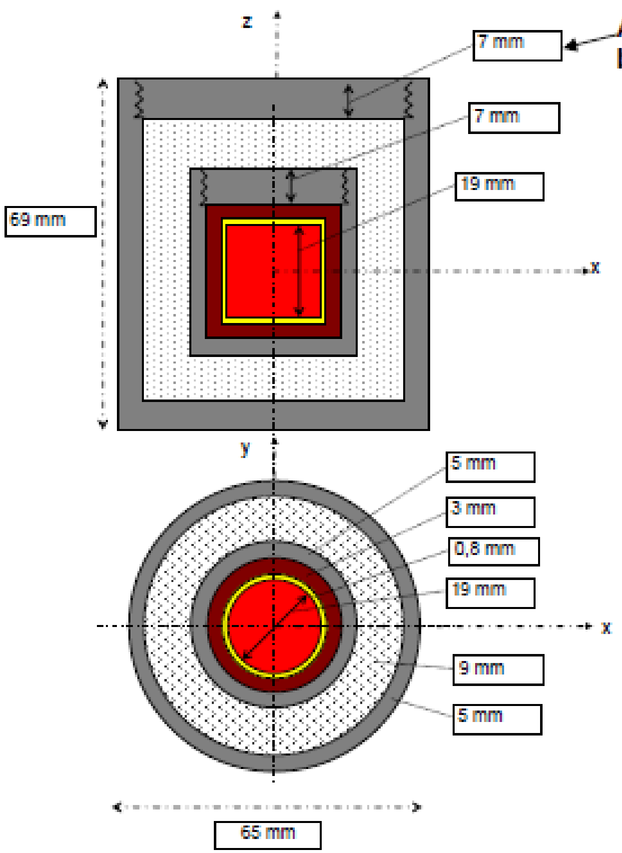


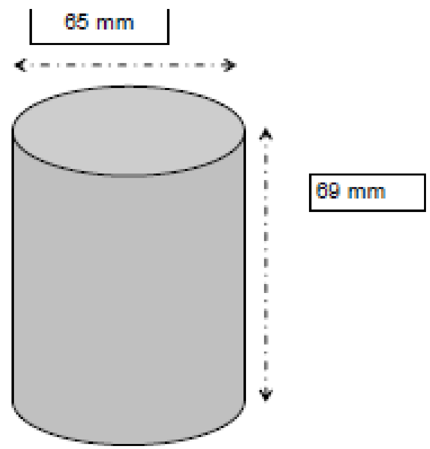




SMALL RHU sizing (5 W_{th} & 1 W_{th})

5 Wth RHU preliminary layout



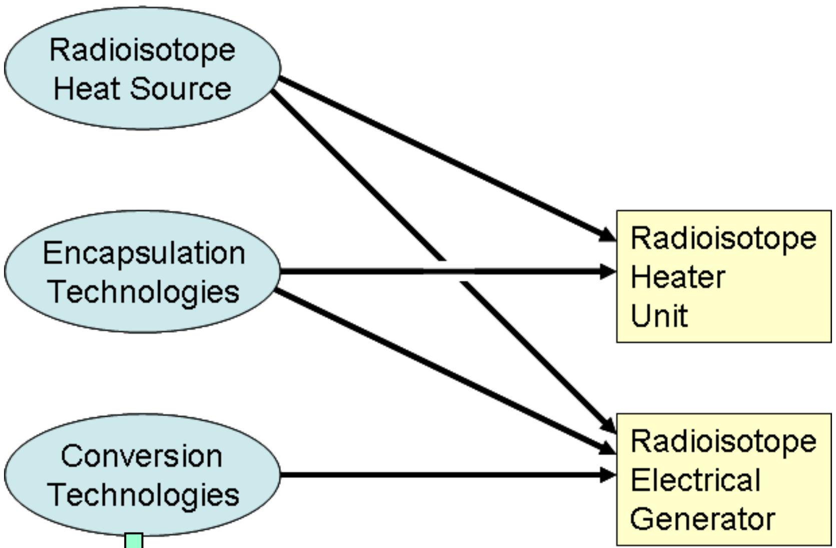


European 5W_{th} RHU

	RHU 5 Wth	RHU 1 Wth
Pellet diameter	19 mm	11 mm
Pellet height	19 mm	11 mm
RHU diameter	65 mm	55 mm
RHU height	71 mm	59 mm
RHU mass	620 g	170 g
RHU volume	230 cm^3	140 cm^3
RHU density	2.6 g/cm^3	1.2 g/cm^3
RHU specific power	8 Wth/kg	6 Wth/kg
RHU volumic power	0.02 W/cm^3	0.01 W/cm^3

LWRHU	Angel
^{238}Pu	^{238}Pu
1.1 Wth	8.5 Wth
2.7 g	20 g
40 g	200 g
17 cm3	76 cm3
2.3 g/cm^3	2.7 g/cm^3
28 Wth/kg	43 Wth/kg
0.06 W/cm^3	0.11 W/cm^3

European Activities – RPS System Development



- **Thermoelectric**
- Thermionic
- **Stirling Heat Engine**
- **Thermoacoustic -MHD**
- Beta-voltaic
- AMTEC
- Thermo-photovoltaics

Conversion technology selection must consider the use of Am241 with ¼ the power of Pu238.

- Proven heritage. Under development for low power (<50W_e) radioisotope generators.
- High efficiency. Under development for higher power (~100W_e) radioisotope generators.
- Low maturity, but could offer an advantageous blend of good efficiency with high reliability and low vibration

RTG Development

<u>THERMOELECTRIC CONVERTER SYSTEM FOR SMALL-SCALE RTGS</u>

This is a TRP-funded activity with the following objectives:

- Produce requirements specification for a small (1-50W_e) RTG.
- Develop the system architecture.
- Design a thermoelectric element (unicouple / module).
- Design, build and perform functional testing of a RTG breadboard (electrically heated, no nuclear materials).

Two parallel contracts were placed:

1. **The University of Leicester, The Fraunhofer Institute and Astrium UK.** With Queen Mary University of London and European Thermodynamics Ltd.
2. **Areva TA, Ecole des Mines de Nancy, SEA Ltd, TAS-I and Babrow Consulting**

Areva TA

This parallel contract focuses on the use of more innovative thermoelectric materials - magnesium silicide and higher manganese silicide (HMS). The design uses solid insulation material, offering the possibility of higher performance, perhaps at the expense of greater size and mass.

Testing of the breadboard showed excellent correlation with the parametric RTG model developed by Areva TA earlier in the contract, confirming technical understanding of the system-level behaviour.

In testing, the TE modules show greater electrical resistance than expected (from leg interconnections). At ΔT = 426K, and 123W input power, 2.4W_e was achieved (efficiency ~ 2%). Without the connection resistances, 5W_e would be achieved at an efficiency of ~ 4%).

Extra work scope was agreed to manufacture improved modules and to design and build a thermoelectric unicouple and module characterisation tool. The tool is capable of directly measuring the heat flow through a thermoelectric couple/module whilst simultaneously measuring the electrical output. In this way, the power conversion efficiency can be accurately measured.

Despite repeated efforts at Ecole des Mines de Nancy, the difficulties in manufacturing high aspect ratio (long, thin) modules were not overcome.

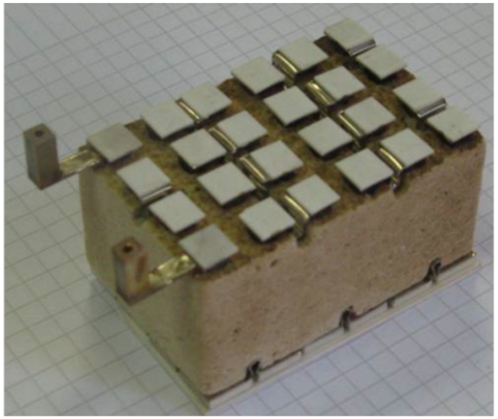


Figure 1– Thermoelectric module (EDM Nancy) n: Mg_2Si p: $MnSi_{1.75}$ + 2% Ge.

TE unicouple / module measurement tool

RTG Development

The University of Leicester, The Fraunhofer Institute , Airbus Defence & Space. With Queen Mary University of London and European Thermodynamics Ltd.

University of Leicester

The breadboard (with approximate mass of 3.5kg) originally produced a maximum power output of 3.5W_e from a thermal input of 83W_t, giving a system efficiency of ~ 4.2%.

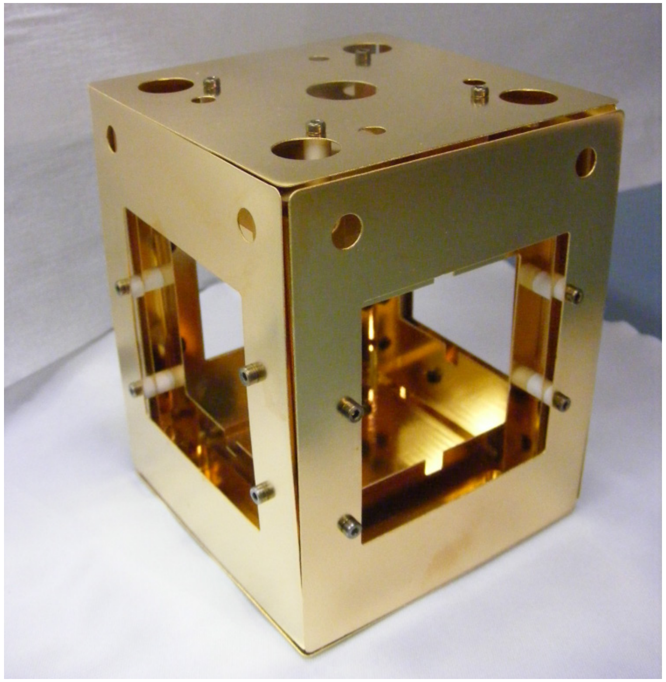
Extra work scope was agreed:

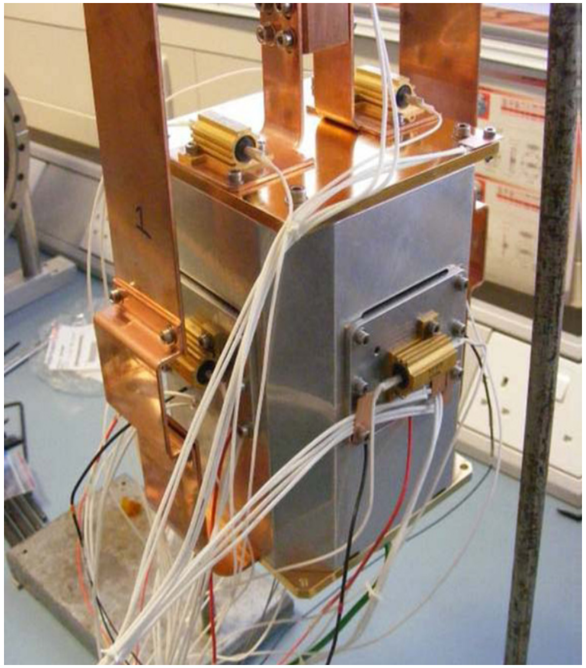
1. To develop and test improved thermoelectric modules using BiTe manufactured by spark-plasma sintering
2. To investigate improved insulation techniques for the RTG.

A gold-plated heat shield has been produced and tested. System efficiency increased to 4.6%.

Enhanced BiTe thermoelectric materials have been produced using B_4C addition and spark-plasma sintering to improve mechanical strength, enabling higher aspect ratio modules (long thin legs.

Latest breadboard testing with B_4C-enhanced modules has shown further performance increase to **~5% (~4W)**





RTG Development

The University of Leicester, The Fraunhofer Institute , Airbus Defence & Space. With Queen Mary University of London and European Thermodynamics Ltd.

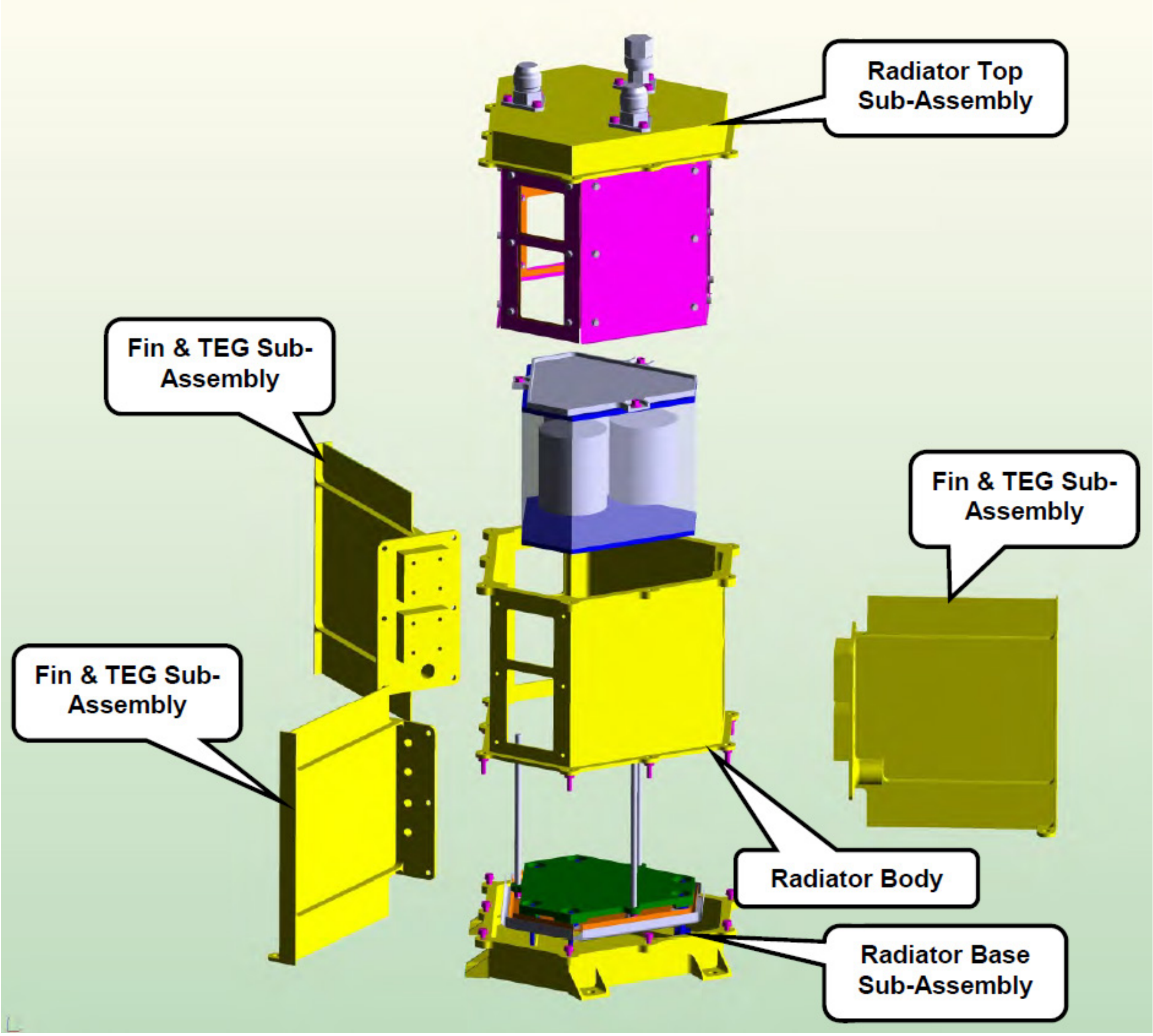
University of Leicester

In parallel with the experimental activities, Uni Leic. and subco Astrium UK have produced a detailed engineering design for a 10W RTG prototype.

The design is made considering the full flight environment requirements.

The mass budget is 10.6kg including margin.

Caveat: The heat source design is speculative at this stage.



Stirling RPS Development

SEA Ltd, Rutherford-Appleton Lab, Oxford Uni, CSL Belgium.

ESA MREP technology development activity:

Stirling Power Converter Technology Development Phase 1

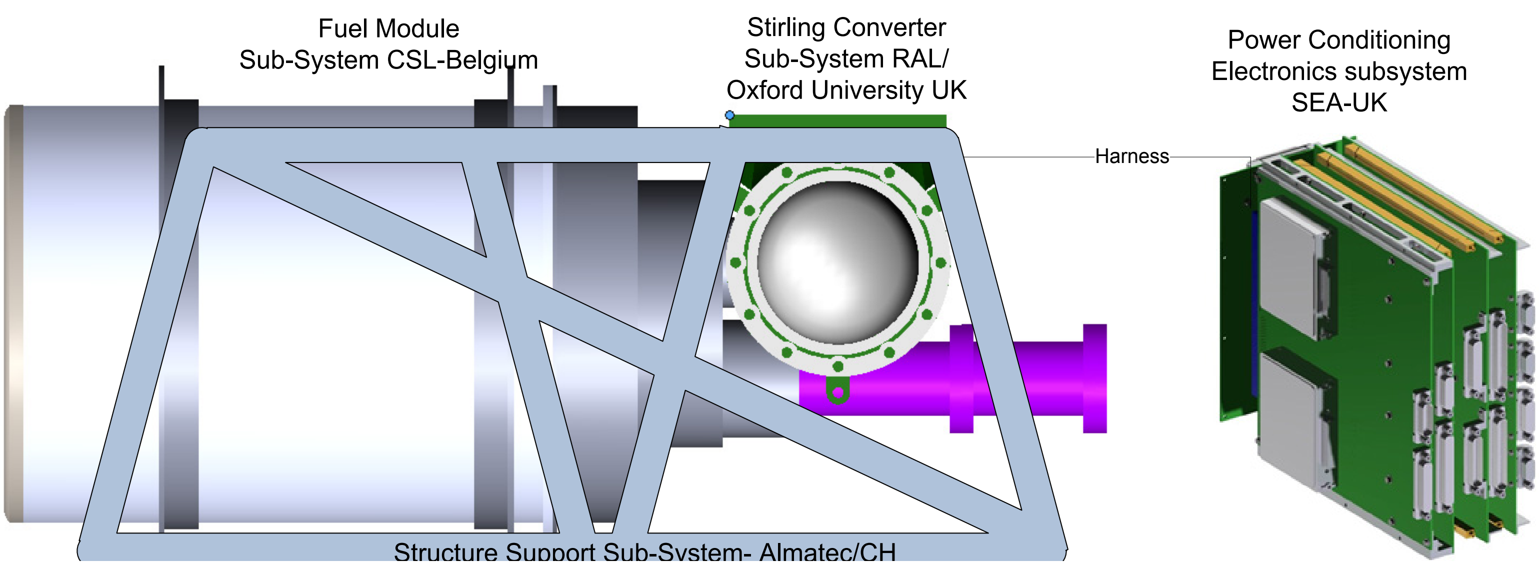
SEA Ltd, Rutherford-Appleton Lab, Oxford Uni, CSL Belgium. 2011 – 2014

To design, build and test an electrically-heated prototype of a Radioisotope Stirling Generator for use with ^{241}Am heat sources.

Building upon the work of the earlier ESA contract:

Stirling Engine Radioisotope Power System Requirements Study

SEA, Rutherford Appleton Laboratory & Oxford University. 2010.



System: SEA(UK)

Thermal: RAL (UK)

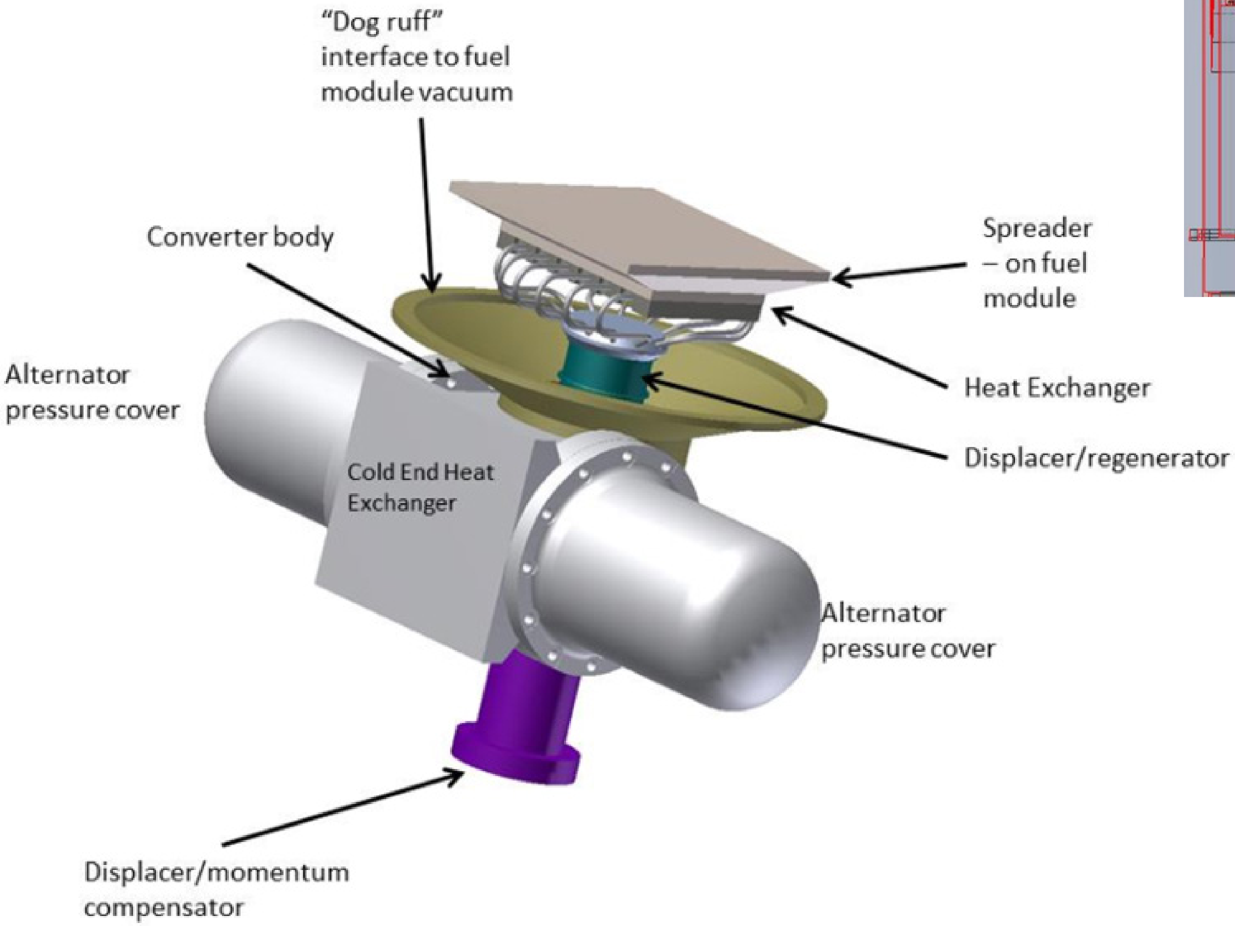
Launcher ops:
QINETIQ (Belgium)

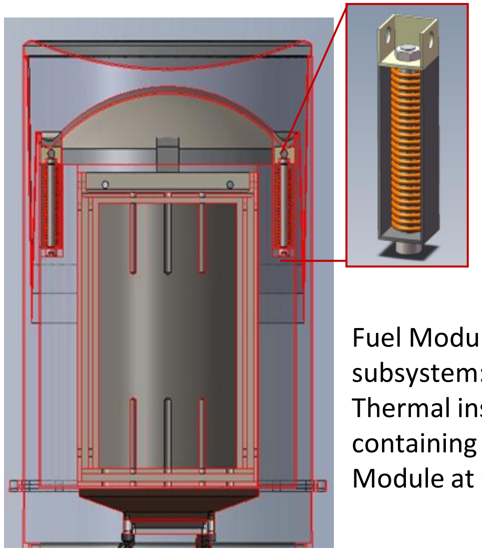
Stirling RPS Development

SEA Ltd, Rutherford-Appleton Lab, Oxford Uni, CSL Belgium.

Stirling converter subsystem is based on long life Stirling space cooler technology ("Oxford Mechanism" flexure bearing).

Back-to-back configuration for low exported vibration
Displacer & hot-end heat exchanger separated for simpler interface with fuel module





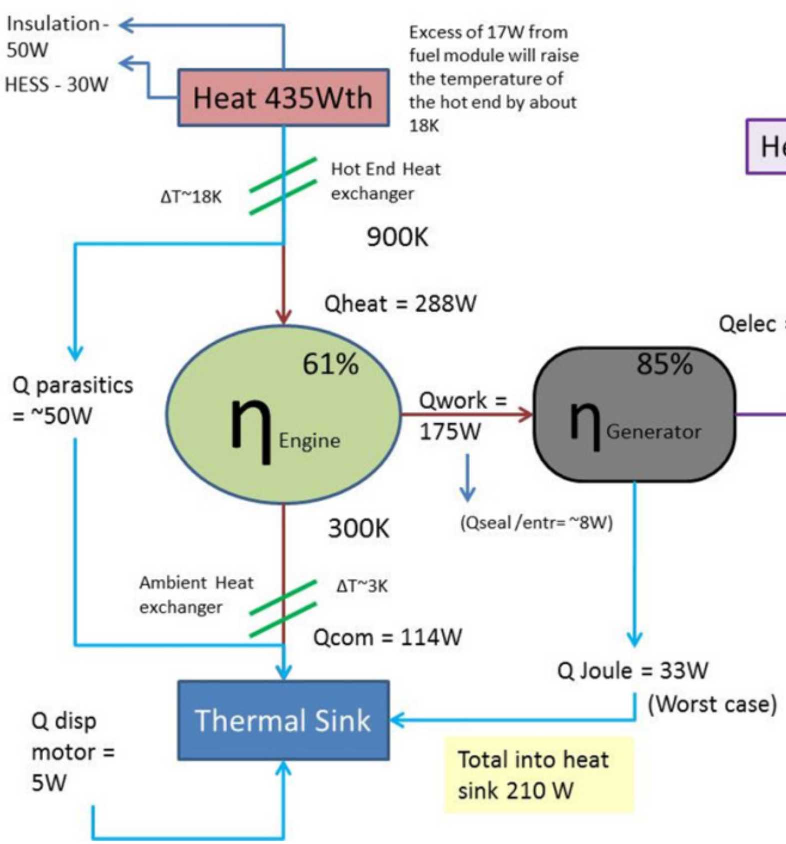
Stirling RPS Development

SEA Ltd, Rutherford-Appleton Lab, Oxford Uni, CSL Belgium.

Stirling RPS – Performance Targets.

Prototype manufacture is now underway

Sub-System	Flight Est.
$^{241}Am_2$ heat sources	16.5kg
Stirling Converter	8.9kg
Support Structure Subsystem	5.0kg
Fuel Module & HESS Subsystem	9.5kg
Pwr. Control Electronics	4.0kg
Margin (20%)	*8.8kg*
Total	53 kg
Total inc. radiator	**58 kg**



Heat Flow Map for the SPCS

Electrical Output: 127 W

Efficiency ~29%
Specific Power ~2 W/kg

Thermoacoustic / Magnetohydrodynamic Power Conversion. AREVA TA & CNRS

ESA Research Contract:

TA-MHD Electrical Generator Selection study.

AREVA TA & CNRS. 2009.

Building upon earlier work by Areva TA and CNRS on the TA + MHD power conversion concept, this activity further developed the design of a liquid-metal MHD inductive generator.

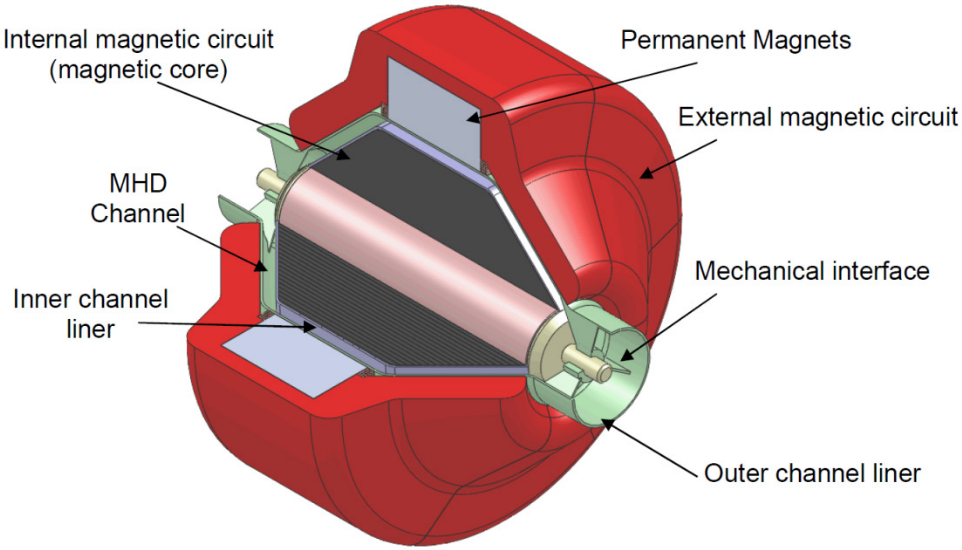
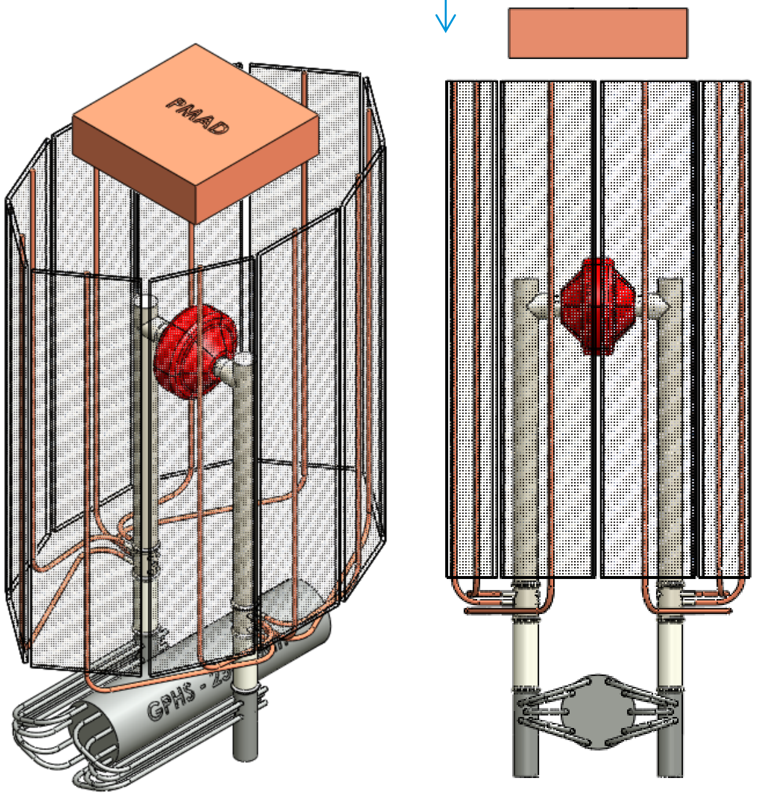
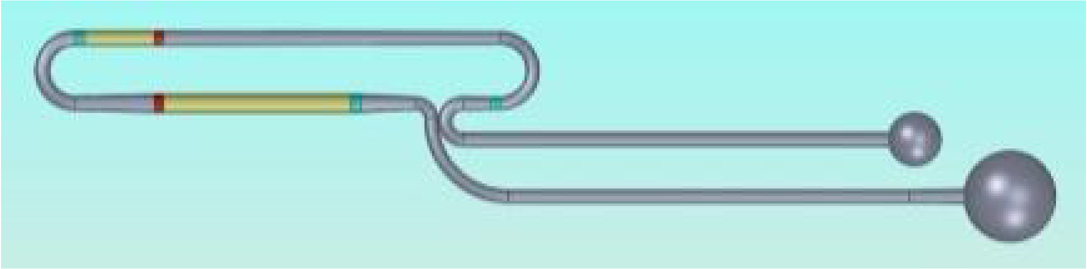


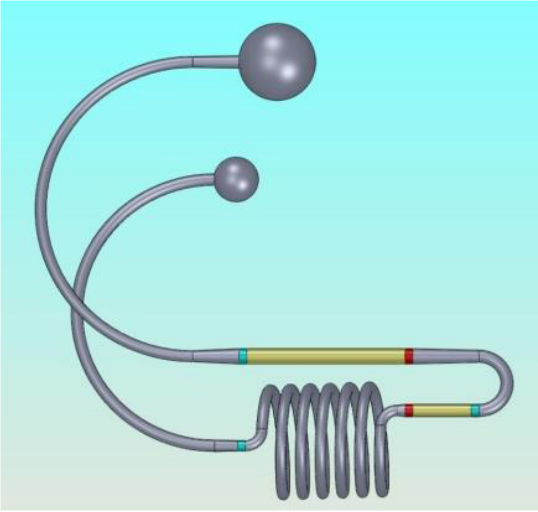
Illustration of how the CNRS MHD generator may be interfaced to a radioisotope-powered thermoacoustic engine.

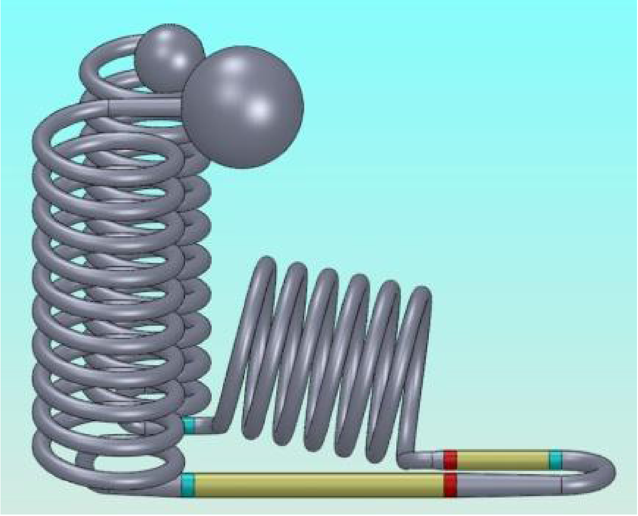


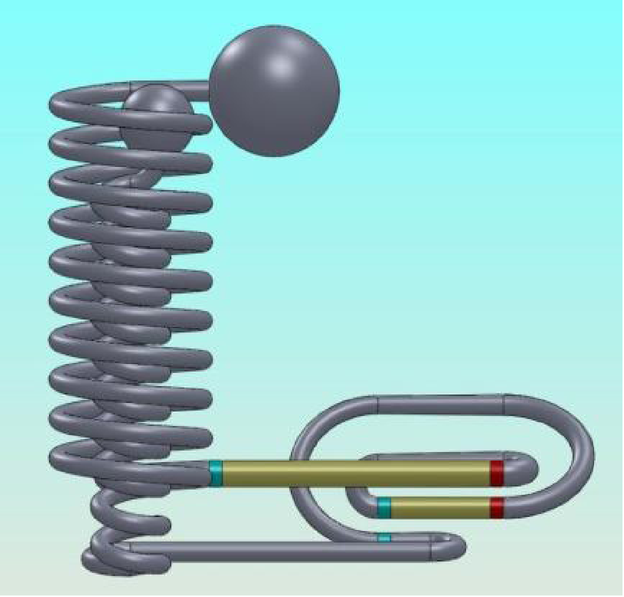
Thermoacoustic Power Conversion.
FOTEC Austria

ESA Innovative Triangle Initiative Activity:
Arbitrarily Shaped Stirling Engine. FOTEC (Austria) 2010 – 2011
Objectives:
Design small scale cascade thermoacoustic device for use with a radioisotope heat source).
Operate multiple heat exchangers with 1 heat source.
Miniaturize design for integration in satellites.
More than 100 W output power.









Finally…….

Thank you for your attention.