European Space Nuclear Power Programme: UK Activities

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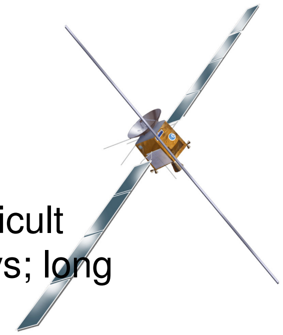
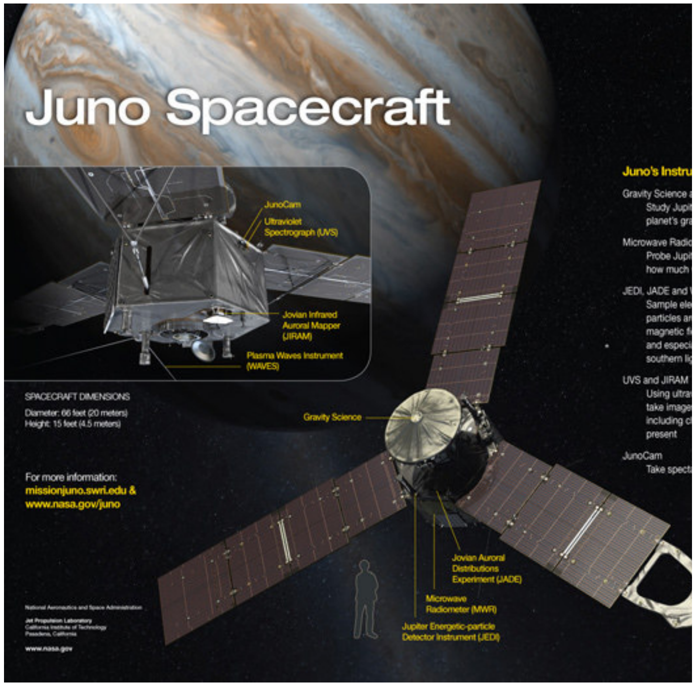
9th February 2012

Why Nuclear?

- **Solar power can be used with low risk:**
  - –For orbiters of Venus/Earth/Mars
- **Solar power can be used with more difficulty:**
  - –For Mercury orbiters
  - –For Mars landers
- Energy budget is marginal –surviving the night is difficult
  - –For cometary missions (Rosetta has 50m² arrays; long hibernations)
  - –(tbc) for Jupiter missions
- *"Juno will be the first solar-powered spacecraft designed to operate at such a great distance from the sun…" [NASA website]*
- JGO/JUICE/LAPLACE is specified as solar-powered –severely constrains operations – 51m² array, lithium ion batteries for peak and eclipse power





(source: Courtesy of NASA)

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- **Nuclear power is required:**
  - –For Saturn and beyond
  - –For lunar night
  - –For human Exploration (Reactors -EC responsibility?)
- **Nuclear power simplifies**
  - –Operations at Jupiter
  - –Mars landers/rovers

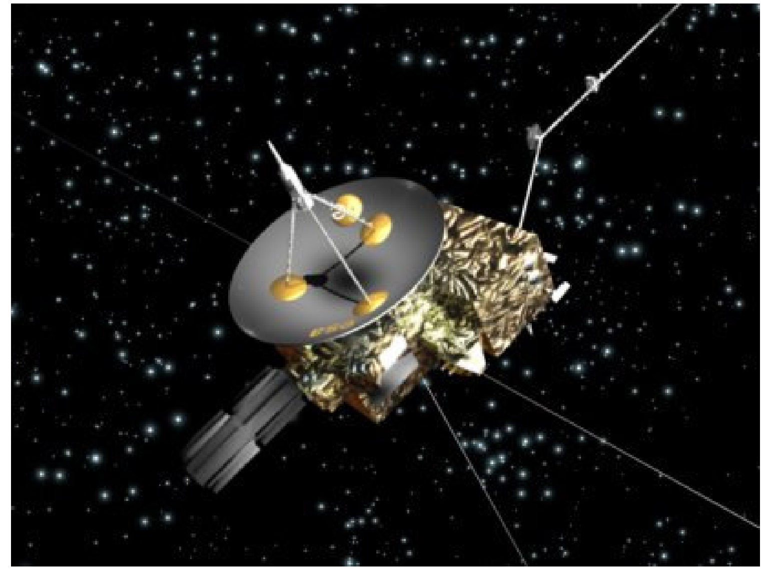
Current ESA plans:
- RHU
- RTG
- not Reactors

Heritage and science return

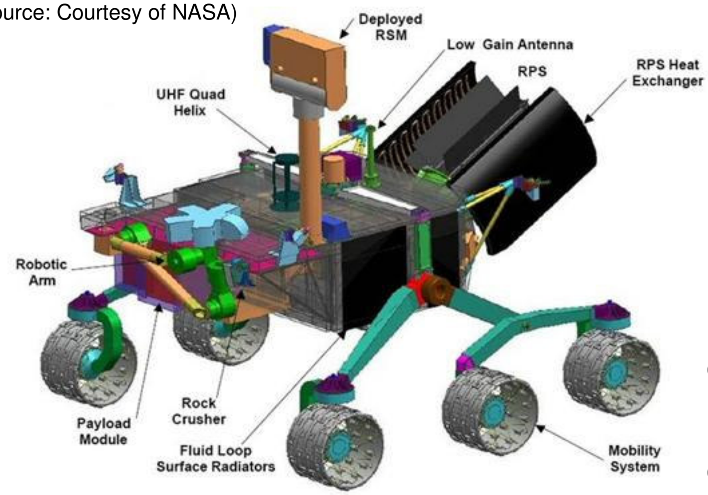
(source: Courtesy of NASA)

<Multi-Mission Radioisotope Thermoelectric Generator is planned for use on the Mars Science Laboratory mission.

>On 10 June 2009, Ulysses became the longest running ESA-operated spacecraft 18 years 246 days.



(source: Courtesy of NASA)



NASA's Mars Science Laboratory - Curiosity rover, powered by a Pu-238 fuelled radioisotope

thermoelectric generator.

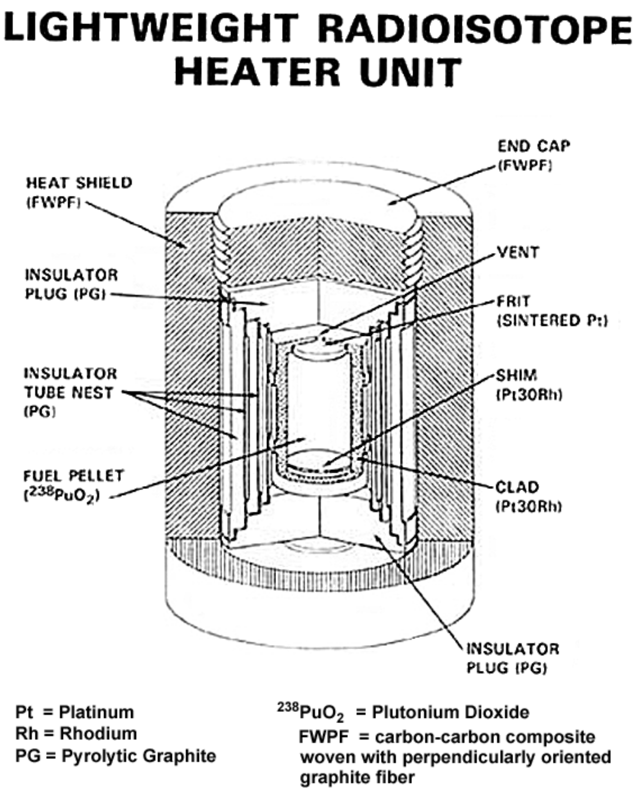
- Key advantage of operating continuously
- Enabling operation at vast distances from the sun.
- Independent of unavoidable variations in sunlight.
- Provide power for long periods of time (significantly longer than chemical batteries),
- Has little sensitivity to temperature, radiation, dust or other space environmental effects.
- Suited to missions involving autonomous, long-duration operations in the most extreme environments in space and on planetary surfaces.

RHU

- Hundreds flown to date (including 35 on Ulysses and 157 on Cassini-Huygens)
- Use Pu-238 as their fuel in its chemical form PuO_2

Characteristic	Russian Angel RHU	US RHU
Diameter (mm)	40	26
Height (mm)	60	32
Weight (g)	200	40
PuO_2 Mass (g)	20	2.7
Pu mass (g)		2.38
^{238}Pu mass (g)		1.91
Thermal Power (W)	8.5	1

(source: ESA Radioisotope Study Final Review – SEA Ltd)



- Decay of radioactive material generates heat
- RHU's are small pellets of encapsulated radioactive material
- Used to keep vital spacecraft systems warm

RTG

- Decay of radioactive material generates heat
- Heat used to generate electricity by thermal electric conversion

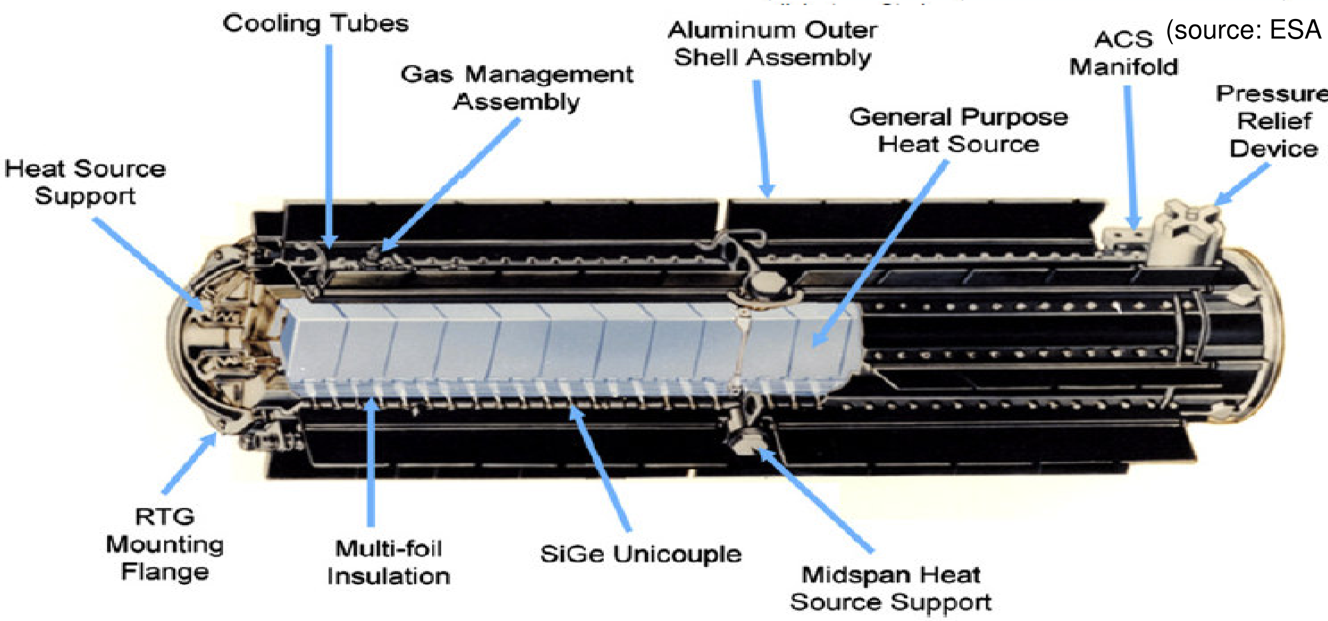
51 m² solar panels with a mass of 282 kg producing 539 We or 1.9 We/kg **.

As opposed to ~3We/kg to ~7 We/kg depending on the flavour of radioisotope generator.

- 41 RTGs flown on 23 US satellites; all used Pu-238 fuel

RTG Type	Number Flown	Number of Satellites	We BOL	Pu-238 (kg)	Mass (kg)
SNAP-3B	2	2	2.7	0.2	2
SNAP-9A	2	2	25	1	12
SNAP-19	11	4	40.3	1	14
Modified SNAP-19	4	2	42.7	1	15
SNAP-27	5	5	73	3.8	20
MHW-RTG	10	4	160	4.5	38
GPHS-RTG	7	4	285	7.7	56
MMRTG	Prototype Phase		125	3.4	43
ASRG	Prototype Phase		143/160	0.9	23

(source: ESA Radioisotope Study Final Review – SEA Ltd)



Key elements of NPS work plan 2009-2012

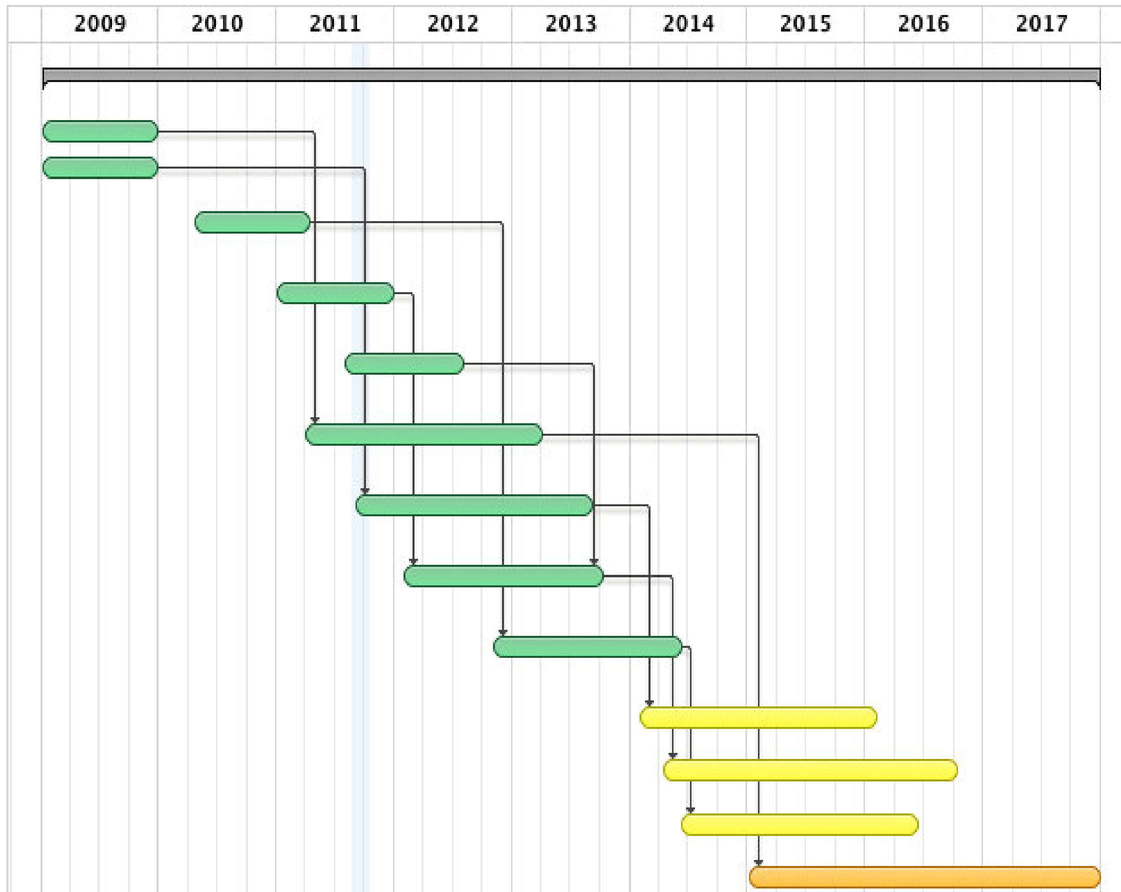
- Radioisotope production
  - Radioisotope selection
  - Production technique: how?, where?, cost?
  - Validation through sample programme
- Radioisotope encapsulation
  - Capsule design
  - Mechanical/thermal interface with converter
  - Prototyping (TR4), for RHU and RPS
- Conversion technique
  - Two power conversion techniques will be explored: Thermoelectric and Stirling engine.
  - Design and breadboards are foreseen in both cases
  - Thermoelectric conversion suitable for small-power generators

(As established by ESA Science and Robotic Exploration Advanced Studies and Technology Preparation)

European Roadmap

Task

- 1) **Space Nuclear Power Development Programme (RTG and SRG)**
  - 1.1) Isotope Evaluation
  - 1.2) Stirling Engine Requirements
  - 1.3) Small Scale RTG Development to TRL3 (TRP)
  - 1.4) Nuclear Aeroshell and Capsule TRL2-3 (TRP)
  - 1.5) Iridium Alloy Selection and Welding (New Member States – ESA)
  - 1.6) Isotope Production Phase 1 and 2 (MREP)
  - 1.7) Stirling Engine Development Phase 1 (MREP)
  - 1.8) Nuclear Aeroshell, Capsule & Launch Safety TRL4 (MREP)
  - 1.9) Small Scale RTG Development to TRL5 (MREP)
  - 1.10) Stirling Engine Development TRL 6 (MREP)
  - 1.11) Isotope Encapsulation TRL 6 (MREP)
  - 1.12) Small Scale Prototype RTG Development TRL6 (MREP)
  - 1.13) Isotope Production Phase 3? (MREP)



European Nuclear Power System Requirements

- **Lifetime: Up to 20 years**
- **Power:**
  - –RPS 100 We (~ 1538 W_{th} assuming 15% - 30% efficiency –typical for an RTG)
  - –RHU 5 W_{th}
- **Radiation levels produced by the isotope must be compatible with ground personnel and with operation of spacecraft electronics**

- **Chemical form of the radioisotope used as a heat source must be:**
  - –Chemically stable, even at high temperatures (~ 2000 K in case of launch failure)
  - –Chemically compatible, at the likely working temperatures, with the material used as first level containment
  - –Thermally stable such that it will not chemically or physically decompose at the likely working temperature (620 K for RHU, 1300 K for RTG)
  - –Have a known solubility in water such that the environmental impact in the case of accidental release can be calculated
- **Must be obtainable (in Europe) and affordable**

UK expertise

Company/University/Research Lab	ESA Programme Development Area/Expertise
Astrium UK	RTG Development, System Design
Cardiff University	Thermoelectric materials
European Thermodynamics	Thermoelectric Generators
Johnson Matthey Metals	Encapsulation & Aeroshell
Lockheed Martin, UK	Encapsulation & Aeroshell
Nanoforce Ltd	Encapsulation & Aeroshell; Thermoelectrics; Materials Processing
National Nuclear Laboratory	Radioisotope Production; Encapsulation & Aeroshell; Facilities
National Physical Laboratory	Metrology & Thermoelectric materials
Queen Mary University of London	Materials Science
Reviss UK	Radioisotopes & Transportation of Nuclear Materials
SEA	Stirling Conversion, Encapsulation & Aeroshell
RAL	Stirling Conversion
Rolls Royce	HiPER - Nuclear Electric Propulsion using reactor technologies
University of Leicester	RTG Development; Encapsulation & Aeroshell; Materials Science
University of Oxford	Stirling Conversion

Isotope selection

- Pu-238 has been the isotope of choice for five decades
- Proven track record
- Considerable USA and Russian investment in the technology
- Problem, sourcing is becoming an issue

UK team recommendations:

- Not enough separated isotopes in ESA for even one 100W RTG
- UK owns enough Pu-238 for 25 of 5W RHUs – insufficient for an RTG
- Potentially attractive immediate task
- Long term recommendation is Am-241
- Quantities exist in civil PuO_2 stocks
- Terrestrial applications (in addition to current use in smoke alarms) include oil well logging, moisture sensors, (with Be) neutron radiography, nuclear micro-batteries and terrestrial RTGs.
- (subject to detailed study) NNL facilities considered to be capable of handling the material

Characteristic	^{238}PuO	^{241}Am
Chemical form	PuO_2	Am_2O_2
Mass of compound for RTG (g)	3747	14700
Power (W/Kg)	0.411	0.105
Theoretical density (g/cm³)	11.5	12.7
Total volume (cm³)	326	1158.3
Power (W/cm³)	4.72	1.3
mp (K)	2673	2478
Thermal Con. (W/mK) $_{600K}$	6	1
Thermal Con. (W/mK) $_{1300K}$	3	1
Fabrication	ox	ox
Special handling	Box	Box
Solubility pH- $[M]_{TOT}$(M)	10^{-9}	10^{-6} to 10^{-4}

Isotope	Power output after 15 years (W_{th})	Power output after 20 years (W_{th})
^{238}Pu	1010	990
^{241}Am	220	220

(source: ESA Radioisotope Study Final Review – SEA Ltd)

Am-241

•100% isotopically pure Am-241 forms in separated civil plutonium from the decay of Pu-238

$$^{241}_{94}Pu \xrightarrow{\beta \quad 14.4\,y} {}^{241}_{95}Am$$

•Large quantities of 20+ year stored civil plutonium exists

•Aged civil PuO_2 contains 25-50g per kilo

•No need for irradiation in a reactor

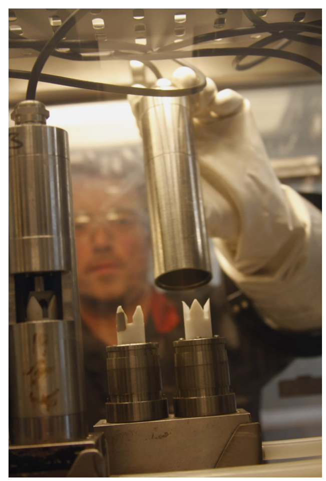
•Availability of Am-241 can compensate for other limitations: mass and energy conversion between Pu-238 is not linear.

•NNL has a full range of facilities for handling radioisotopes including actinides such as Americium and plutonium.

•A study is currently being undertaken on behalf of ESA to provide a conceptual design and costing for a plant to separate americium from civil plutonium.

•It is planned to separate the first Am-241 from civil plutonium at the NNLs facilities next FY using the flow sheet proposed for the full scale plant

•NNL have full ISO 9001/14001 accreditation for its facilities.



Centrifugal contactor system (^{238}Pu –^{241}Am separation)

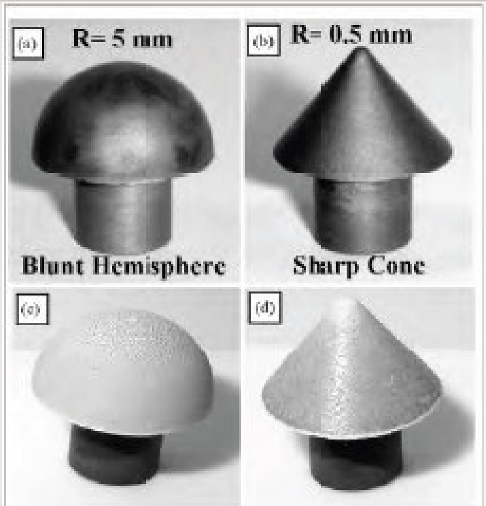
P2 line

Space Nuclear Power:

Encapsulation and Aeroshell

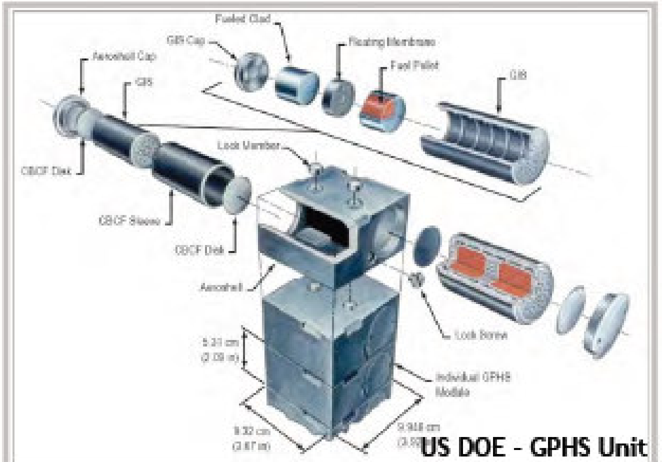
Develop a European modular radioisotope containment system that will interface to the RTG and Stirling system but meet the safety requirements for space nuclear power systems.

Aeroshell Materials



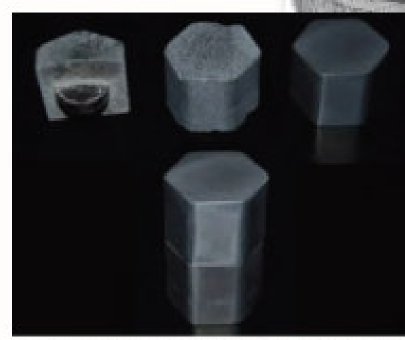
2. Visual appearance of the ceramic models before (a and b) and after test (c and d): R: radius of curvature.

Monteverde Et Al. 2010. (doi:10.1016/j.jeurceramsoc.2010.01.029)



US DOE - GPHS Unit

US DOE - Ir Clad Fuel



Metal Matrix Ceramic Matrix Composites

National Nuclear Laboratory | LOCKHEED MARTIN | SEA | University of Leicester

System Specifics

- **Containment compliance (launch safety)**
    - –No specific ESA or UK industrial activities
    - –Well understood to be a very large activity – Planning initiated
    - –Expected to be led by France (Ariane5, Kourou)
- **Encapsulation and Aeroshell**
    - –Study well under way
    - –Issues understood
    - –UK has the capabilities as do other European states
- **Thermal-Electrical conversion**
    - –ESA is pursuing two routes
    - Seebeck effect
        - –2 studies in progress
    - Stirling engine
        - –Requirements study complete
        - –Breadboard implementation -Bids under evaluation

Summary

- **Programme proceeding along the ESA roadmap**
  - Almost all planned activities under way
- **UK has all the technical expertise and capabilities required**
- **We welcome interest and collaboration from any other states.**