Nuclear Power Sources for Space Applications - a key enabling technology

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RTG prototype shown to President Eisenhower on 16 January 1959 (Washington Evening Star, 16 January 1959)

Primary Power Sources

		Earth	inter-planetary space	planets, moons …
Solar	converted into fossil fuels, biomass, wind and other forms of climate/weather dependent power generation)	+	-	~
	direct via solar-thermal or solar-electric conversion processes	+	+	+
Gravitational	tidal power sources, hydropower (solar+gravity)	+	-	~
	Power generated via orbital dynamics (e.g. tethers)	-	+	-
	Planetary calorific power	+	-	+
Nuclear	exploiting binding energy differences during element conversions (fission, fusion, decay)	+	+	+

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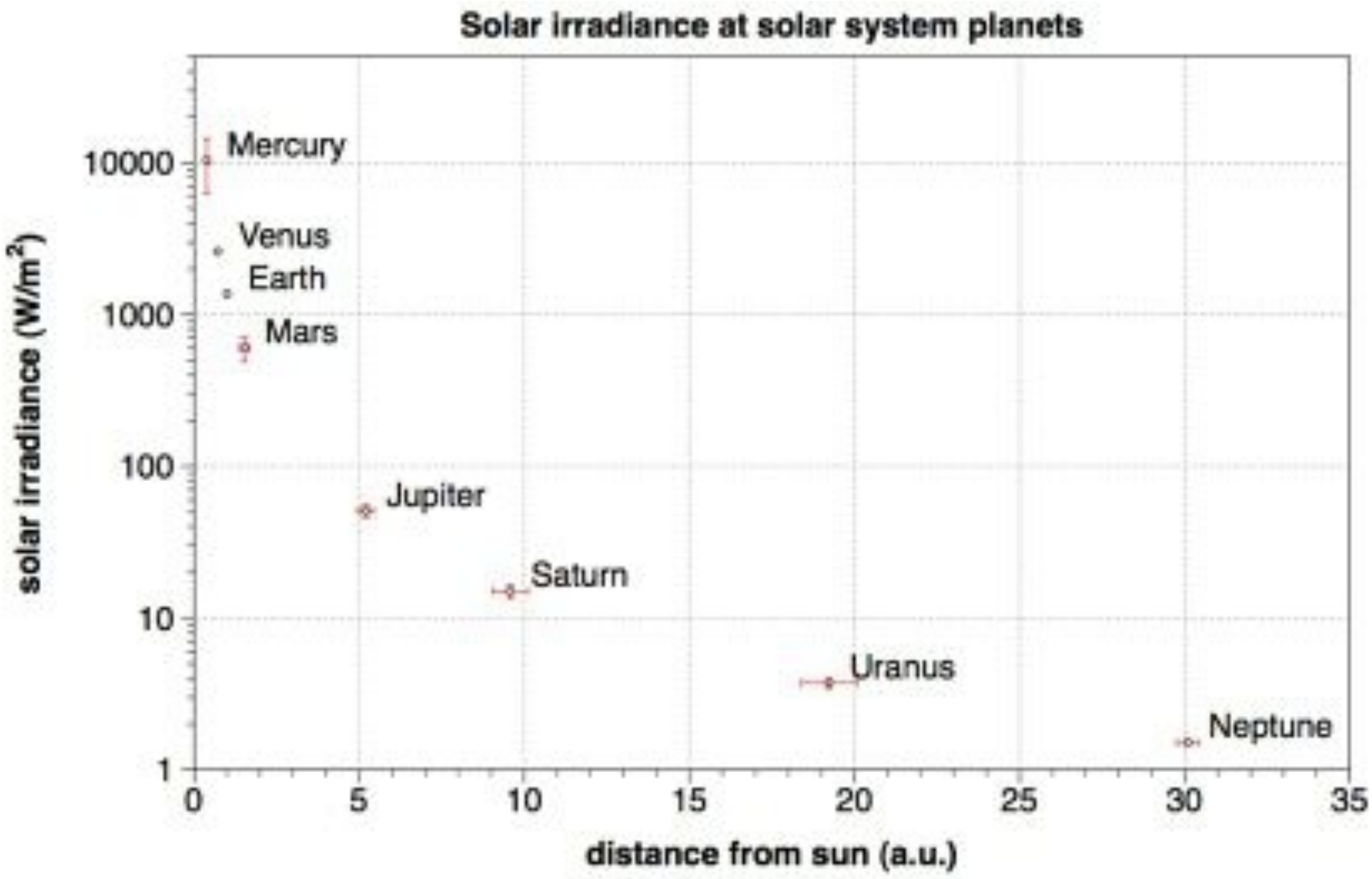
Comparison Solar - Nuclear (space)

	Solar	Nuclear
Advantages	cheap reliable easy/standard AIV process many suppliers	reliable (RPS) (outer planets, craters & poles of planets and moons etc) very long lifetimes (RPS) very high power levels (reactors) independent (no significant orbit / orientation /distance from sun dependence)
Disadvantages	orientation control of s/c decreasing intensity r^{-2} limited to inner solar system orbit dependent (occultation) size deployment, joints	expensive safety risk, launch risk no market for / few suppliers difficult AIV process lengthy launch approval unpopular, image

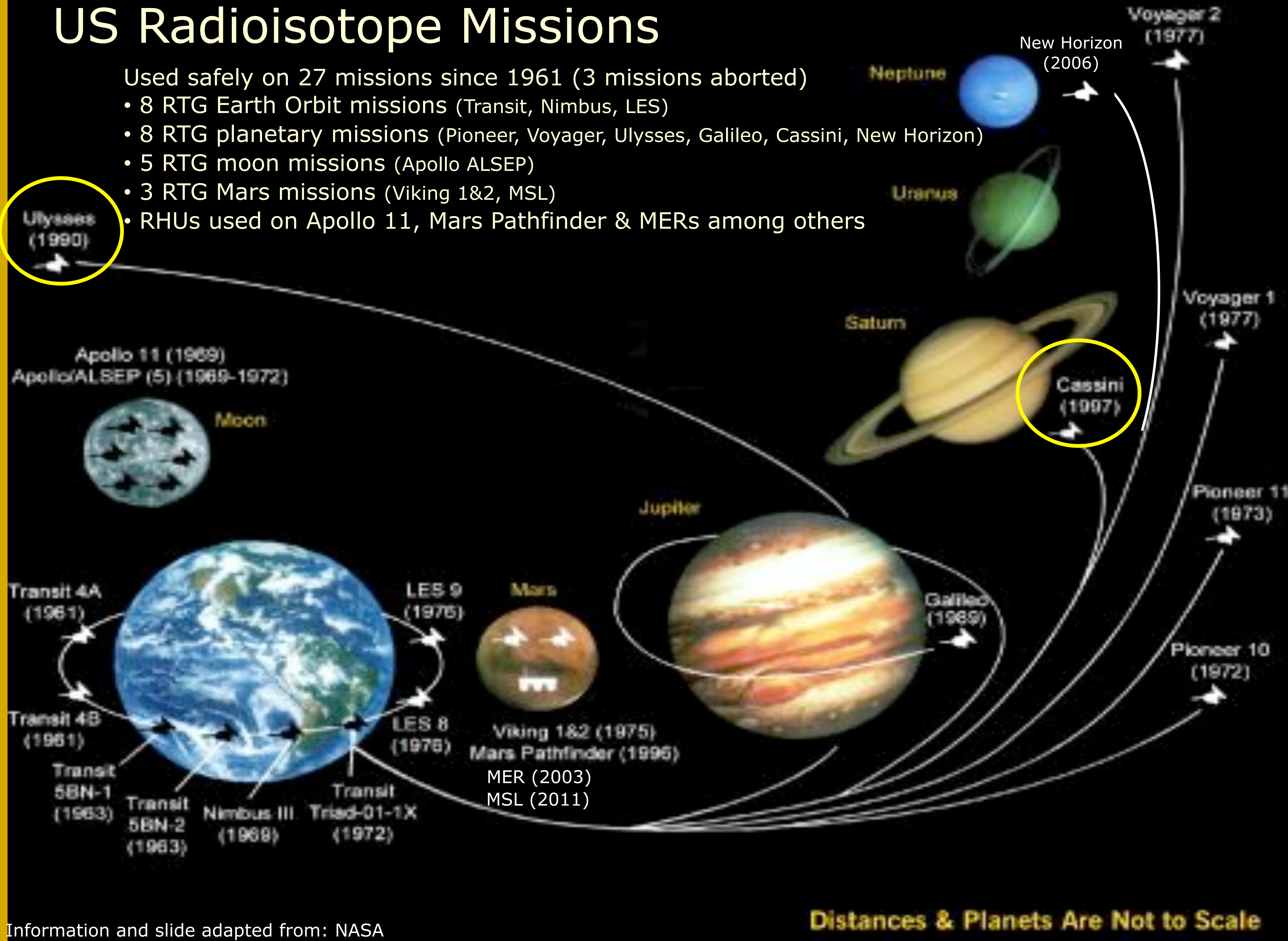
Decrease of solar irradiance with distance to the sun



US Radioisotope Missions

Used safely on 27 missions since 1961 (3 missions aborted)

- 8 RTG Earth Orbit missions (Transit, Nimbus, LES)
- 8 RTG planetary missions (Pioneer, Voyager, Ulysses, Galileo, Cassini, New Horizon)
- 5 RTG moon missions (Apollo ALSEP)
- 3 RTG Mars missions (Viking 1&2, MSL)
- RHUs used on Apollo 11, Mars Pathfinder & MERs among others



Distances & Planets Are Not to Scale

Information and slide adapted from: NASA

Outline

Power Sources in Space

Key differences between space and terrestrial NPS applications

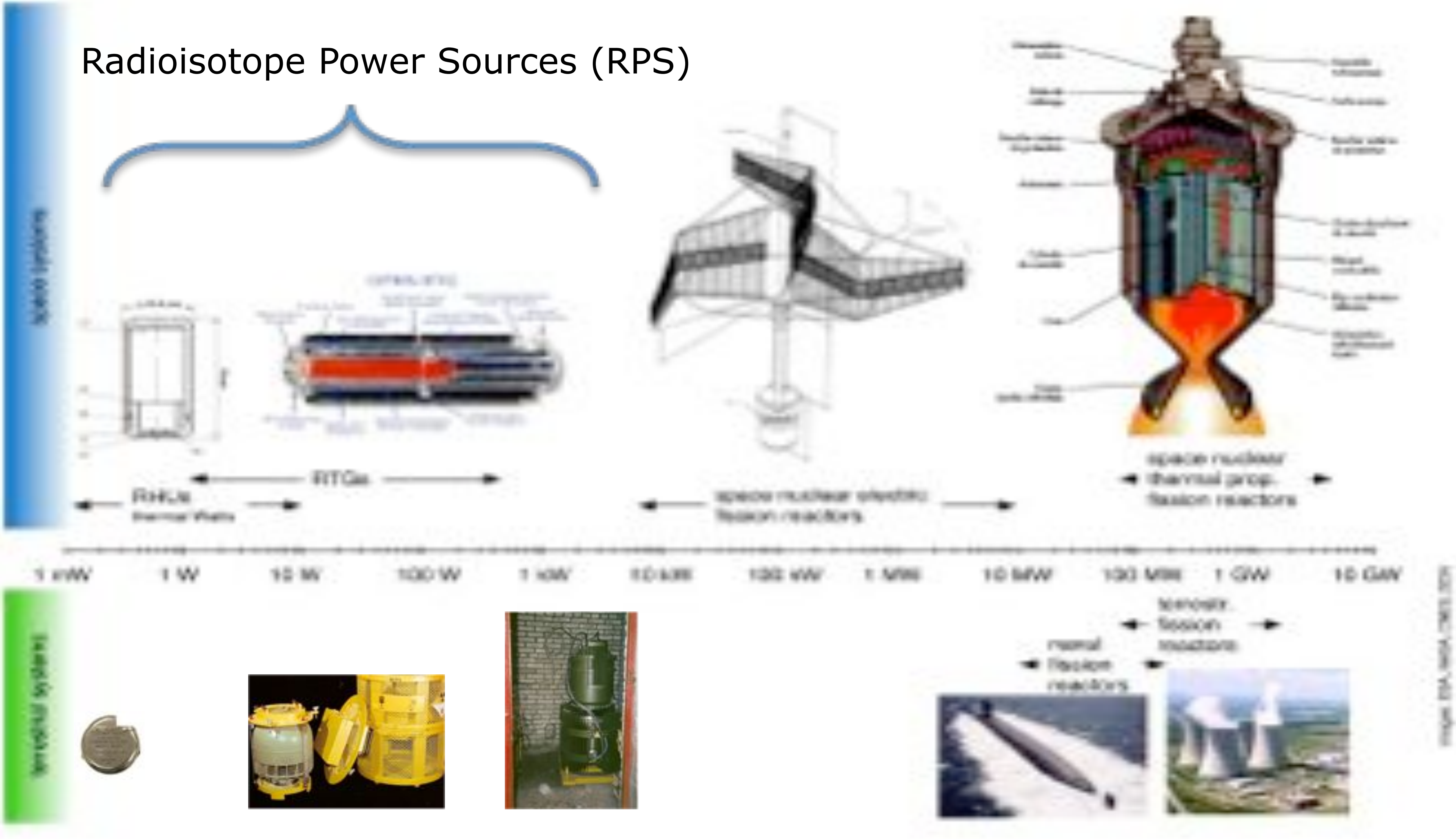
The Specific International Safety Framework for space NPS

Recent and Ongoing European Activities related to Space NPS

Science Enabled by space NPS

Power Levels

Radioisotope Power Sources (RPS)



Differentiating Factors: Space NPS vs. Terrestrial Applications

Some similarities between space and terrestrial NPS:

- Based on same physical principles and basic technologies
- Advanced science and engineering
- Emphasis on safety (and related issues of public perception)
- Potential, in some cases, for consequences from accident scenarios to cross international boundaries
- High level of reliability and protection of workers, public, environment
- Analytical and engineering methods, to some degree

Differentiating Factors: Space NPS vs. Terrestrial Applications

Factors leading to fundamental technical differences:

- Nature of the applications
- Launch and related constraints (mechanical stresses, launch failure)
- Operating environment: e.g. heat rejection only possible through radiation to cold space, robustness against space radiation environment
- Nature and autonomy of operation for systems
- Mass constraint for space applications: impact on quantity of radioactive material & design
- Frequency and duration of use
- Distance to, and effects of normal operation and potential accidents on, populated areas
- Complexity and designed reliability of systems (no repair possibility for most of space applications)
- Use of passive and/or active systems
- End of service

Classification - Type of Energy

NPS - Source of Heat (for the thermal control of spacecraft)

- Radioisotope Heater Units (RHU)
- Nuclear Reactors

NPS - Source of Electricity (for spacecraft operations)

- Heat to electricity conversion (from radioisotope decay or nuclear reactions) e.g, use of thermoelectric (RTG), thermionic, or thermodynamics (e.g. Stirling)
- Non-thermal conversion (e.g. beta-voltaics, opto-electrics, piezo-electric)

NPS - Source of Impulse (for the spacecraft propulsion)

- Nuclear electric propulsion systems (reactors or RTGs)
- Nuclear thermal propulsion systems (reactors)

Flown NPS

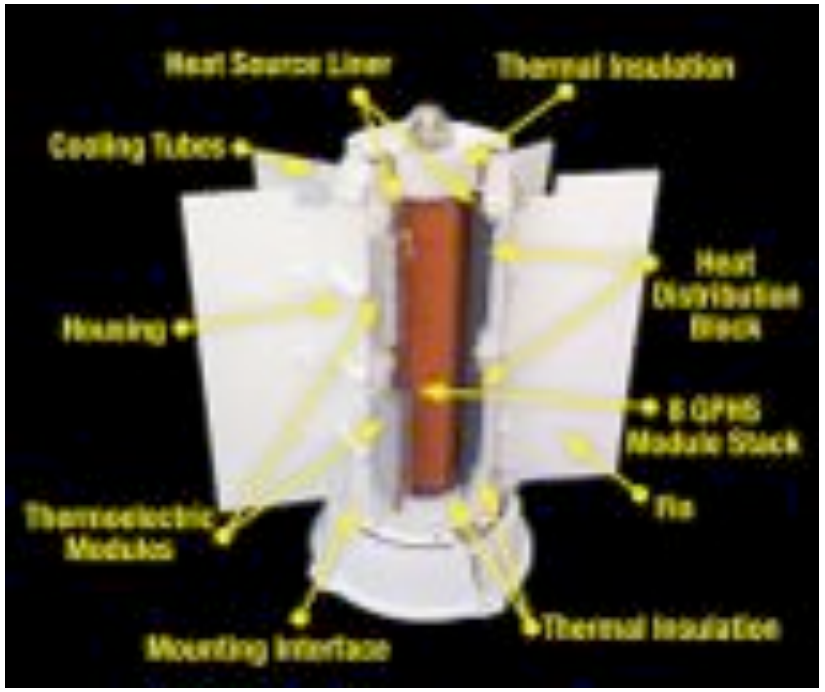


image credits: NASA, BIAPOS, JPL, Summerer

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NPS Safety Framework
Content and Current Status

- Safety Framework adopted by UN COPUOS Scientific and Technical Subcommittee (STSC) in February 2009
- agreed to by IAEA Commission on Safety Standards in April 2009
- published jointly by STSC and IAEA in October 2009
- released after passing of COPUOS report at UN General Assembly

Safety Framework for Nuclear Power Source Applications in Outer Space

Jointly published by the

United Nations Committee on the Peaceful Uses of Outer Space
Scientific and Technical Subcommittee

and the

International Atomic Energy Agency

IAEA

IAEA
International Atomic Energy Agency

Preface & Introduction & Objective

- a guide for national purposes; provides voluntary guidance, not legally binding
- complement the IAEA Safety Standards Series by providing high-level guidance that addresses unique nuclear safety considerations
  - ➡ *normal operating and potential accident conditions are radically different*
  - ➡ *launch and outer space environments create different safety design & operational criteria*
  - ➡ *space mission requirements lead to unique mission-specific designs for space NPS, spacecraft, launch systems and mission operations*
- complements national & international safety guidance and standards for terrestrial activities
- focus on the entire application (space NPS, spacecraft, launch system, mission design and flight rules)
- protection of people and the environment in Earth’s biosphere from potential hazards associated with relevant launch, operation and end-of-service mission phases of space NPS applications.
- it does not cover
  - ➡ *the protection of humans in space*
  - ➡ *the protection of environments of other celestial bodies*
- reflects an international consensus on measures needed to achieve safety and applies to all space NPS applications without prejudice.
- guidance for programmatic and technical aspects of safety, including the design & application

Structure of the Safety Framework

1. Introduction
   - 1.1. Background
   - 1.2. Purpose
   - 1.3. Scope
2. Safety objective
3. Guidance for governments
   - 3.1. Safety policies, requirements and processes
   - 3.2. Justification for space nuclear power source applications
   - 3.3. Mission launch authorisation
   - 3.4. Emergency preparedness and response
4. Guidance for management
   - 4.1. Responsibility for safety
   - 4.2. Leadership and management for safety
5. Technical guidance
   - 5.1. Technical competence in nuclear safety
   - 5.2. Safety in design and development
   - 5.3. Risk assessments
   - 5.4. Accident consequence mitigation
6. Glossary of terms

Guidance for governments

- provides guidance for governments and relevant international intergovernmental organisations (e.g. regional space agencies) that authorise, approve or conduct space NPS missions.
- Governmental responsibilities include
  - ➡ *establishing safety policies, requirements and processes;*
  - ➡ *ensuring compliance with those policies, requirements and processes;*
  - ➡ *ensuring that there is acceptable justification for using a space NPS when weighed against other alternatives;*
  - ➡ *establishing a formal mission launch authorisation process; and*
  - ➡ *preparing for and responding to emergencies.*
- For multinational or multi-organisational missions, governing instruments should define clearly the allocation of these responsibilities.

Guidance for management

- provides guidance for management of the organisations involved in space NPS applications.
- comply with governmental and relevant intergovernmental safety policies, requirements and processes to satisfy the fundamental safety objective
- Management responsibilities include
  - ➡ *accepting prime responsibility for safety,*
  - ➡ *ensuring the availability of adequate resources for safety and*
  - ➡ *promoting and sustaining a robust safety culture at all organisational levels.*

Technical guidance

- pertinent to the design, development and mission phases of space NPS applications
- encompasses the following key areas for developing and providing the technical basis for the authorisation and approval processes and for emergency preparedness and response:
  - ➡ *Establishing and maintaining a nuclear safety design, test and analysis capability;*
  - ➡ *Applying that capability in the design, qualification and mission launch authorisation processes of the space NPS application (i.e. space NPS, spacecraft, launch system, mission design and flight rules);*
  - ➡ *Assessing the radiation risks to people and the environment arising from potential accidents and ensuring that the risk is acceptable and as low as reasonably achievable;*
  - ➡ *Taking action to manage the consequences of potential accidents.*

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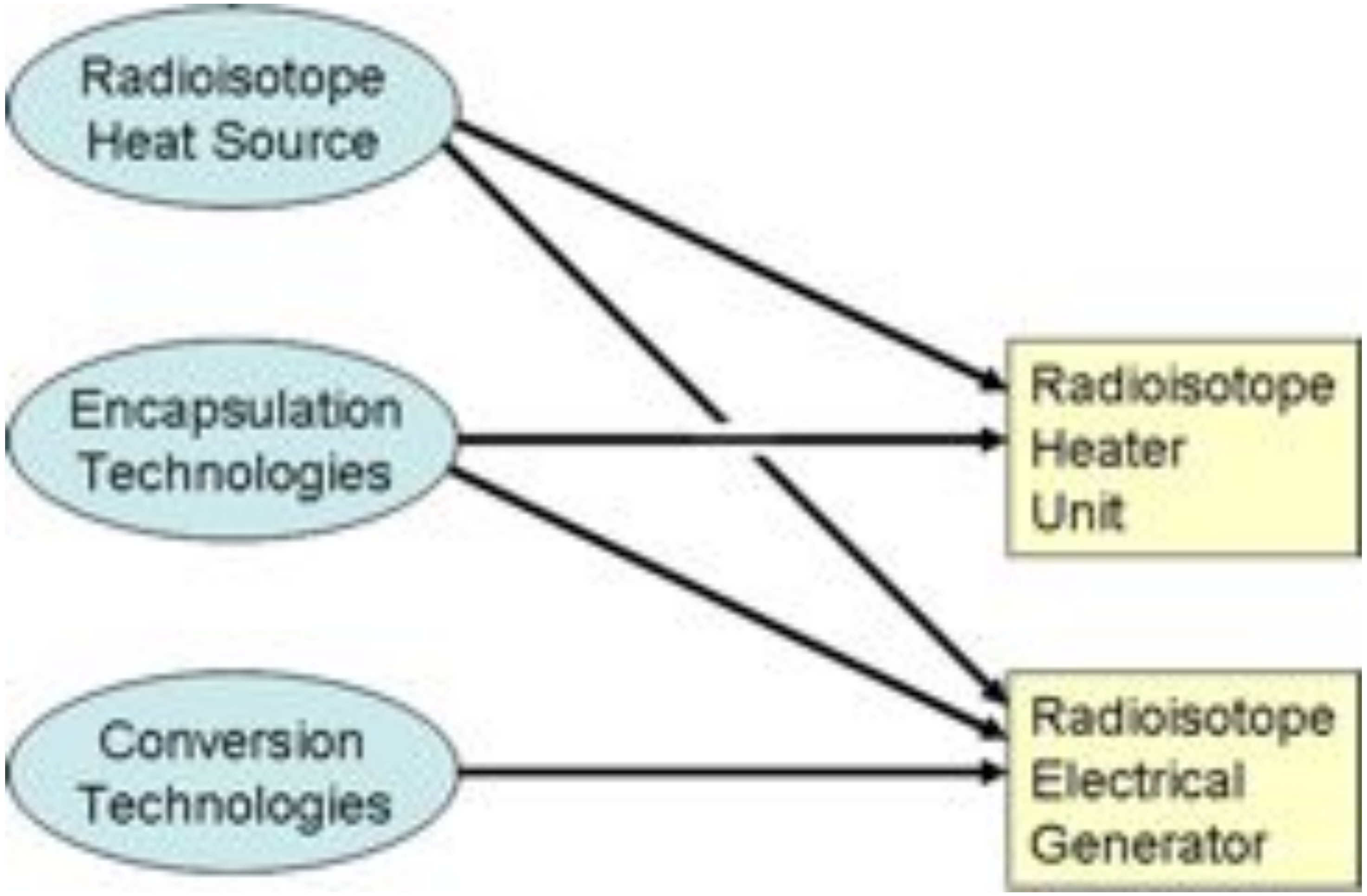
ESA RPS Development Programme

- Historically, European space programmes have had no access to NPS other than via collaboration with USA or 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 high-level, ESA's development activities are pursuing three technological building blocks, which will enable two main classes of space NPS:



A European Radioisotope for Space Power

- Two parallel research contracts were placed to identify and assess radioisotopes with potential for use in European space NPS.
- The contracts produced similar shortlists:

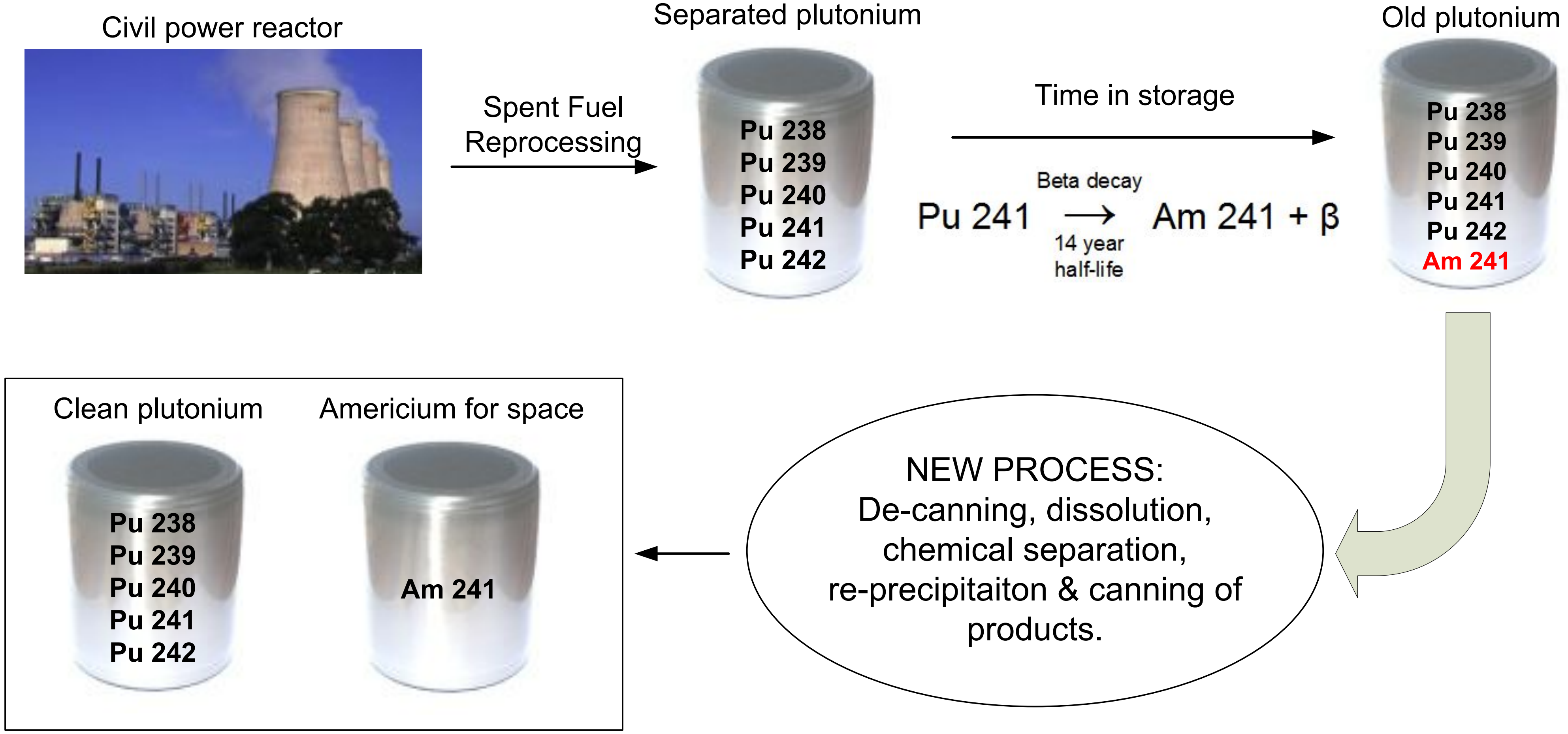
	^{238}Pu	^{241}Am	^{244}Cm	^{90}Sr	^{148}Gd	^{3}H	^{113m}Cd
Chemical form	PuO_2	Am_2O_3	Cm_2O_3	$SrTiO_3$	Gd_2O_3	LiH	None very suitable (CdO_2?)
Power (W/g) as compound	0.411	0.105	2.57	0.220	0.54	0.10	0.19

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

- ✓ Pu238 – The best choice for specific power (W/g), but the production route involves multiple chemical separation steps, and reactor irradiation. = EXPENSIVE.
- ✓ Am241 – Specific power one-quarter of Pu238, but with manageable mass impact at spacecraft system level, and may be more affordable to produce…

Am241 Production

- The UK National Nuclear Laboratory is working for ESA to research and design an Am241 production facility at Sellafield, Cumbria:



Civil power reactor

Spent Fuel Reprocessing

Separated plutonium

Pu 238
Pu 239
Pu 240
Pu 241
Pu 242

Time in storage

$$\mathrm{Pu}\ 241 \xrightarrow[\text{14 year half-life}]{\text{Beta decay}} \mathrm{Am}\ 241 + \beta$$

Old plutonium

Pu 238
Pu 239
Pu 240
Pu 241
Pu 242
Am 241

NEW PROCESS:
De-canning, dissolution, chemical separation, re-precipitaiton & canning of products.

Clean plutonium

Pu 238
Pu 239
Pu 240
Pu 241
Pu 242

Americium for space

Am 241

Encapsulation & Safety

Radioisotope fuel must be encased within a system of physical barriers to prevent fuel dispersal under accident conditions (e.g. launcher explosion, re-entry, earth impact)…..

Nuclear Fuel Capsule and Aeroshell Design Study

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

Two-lane parallel approach to the low-TRL development of a European capability to encapsulate ^{241}Am radioisotope fuel:

1. A European analogue to the conventional (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).

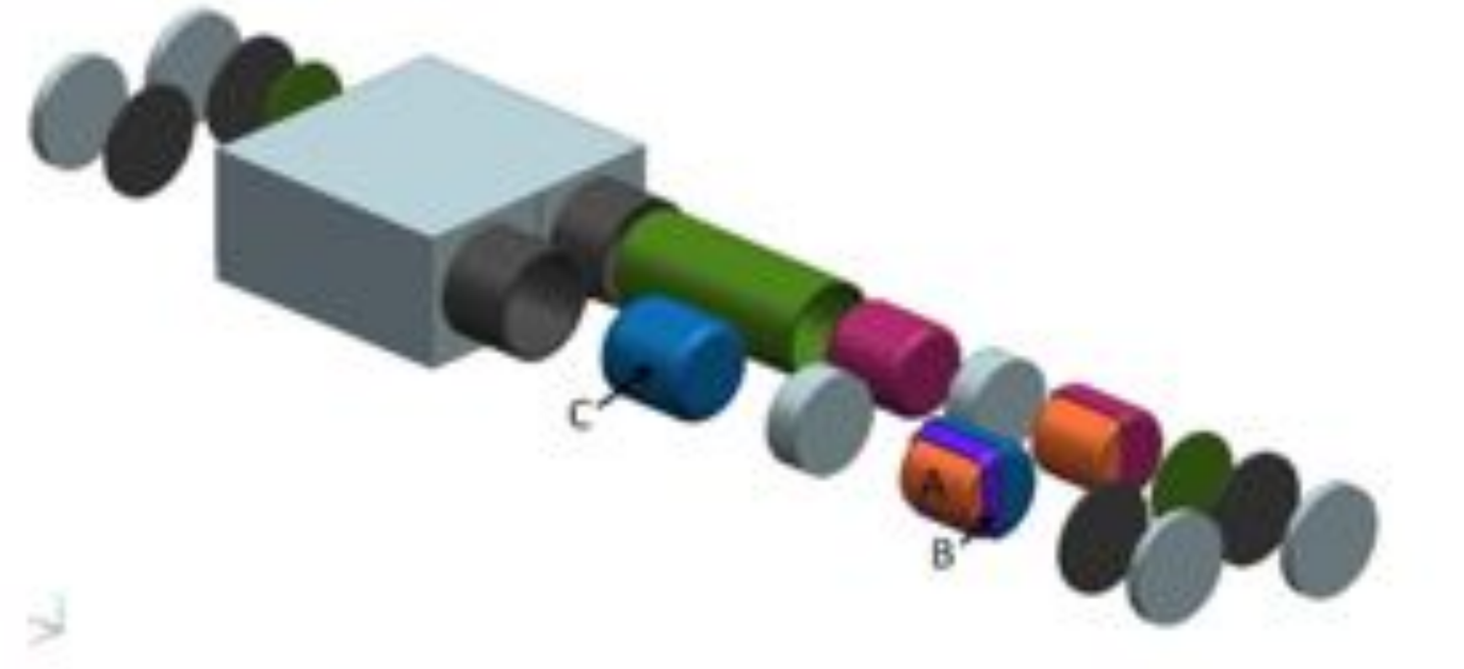


Figure 1-1 – Schematic representation of novel primary containment, compared to traditional fuel clad, within a conventional RTG aeroshell module: A – Fuel composite (70vol% Am_2O_3- 30vol% Nb; B – Inner primary containment (niobium); C – Outer primary containment (70 vol% ZrB_2- 30vol% SiC).

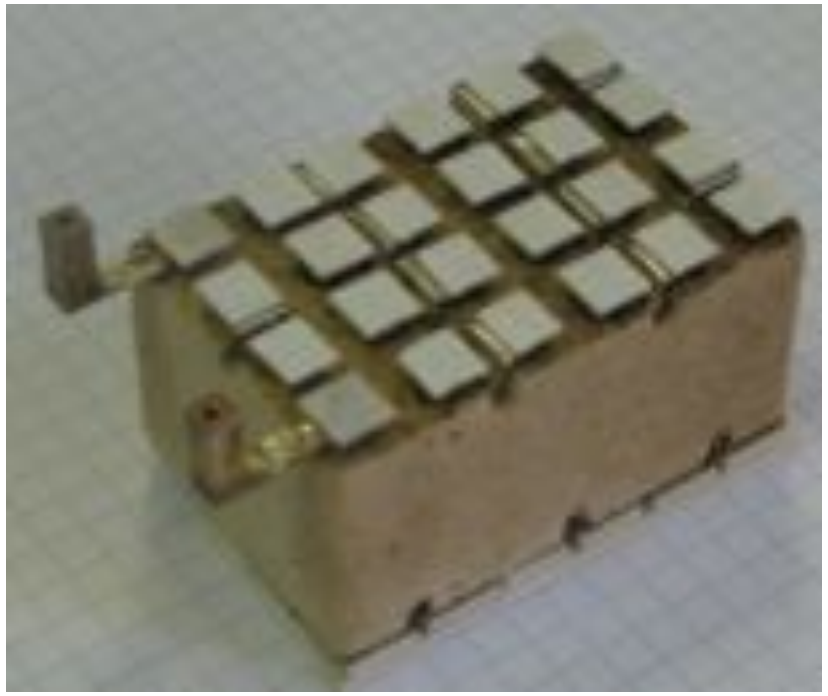
A wider-scope contract is now underway with a consortium led by Areva TA of France:

Nuclear Power Systems Architecture for Safety Management and Fuel Encapsulation Prototype Development (NPSAFE)

RTG Development

***Thermoelectric Converter System for Small-Scale RTGs* Parallel R&D contracts:**

1. **University of Leicester**, Fraunhofer Institute and Astrium UK.
2. **Areva TA**, Ecole des Mines de Nancy, SEA Ltd, TAS-I and Babrow Consulting

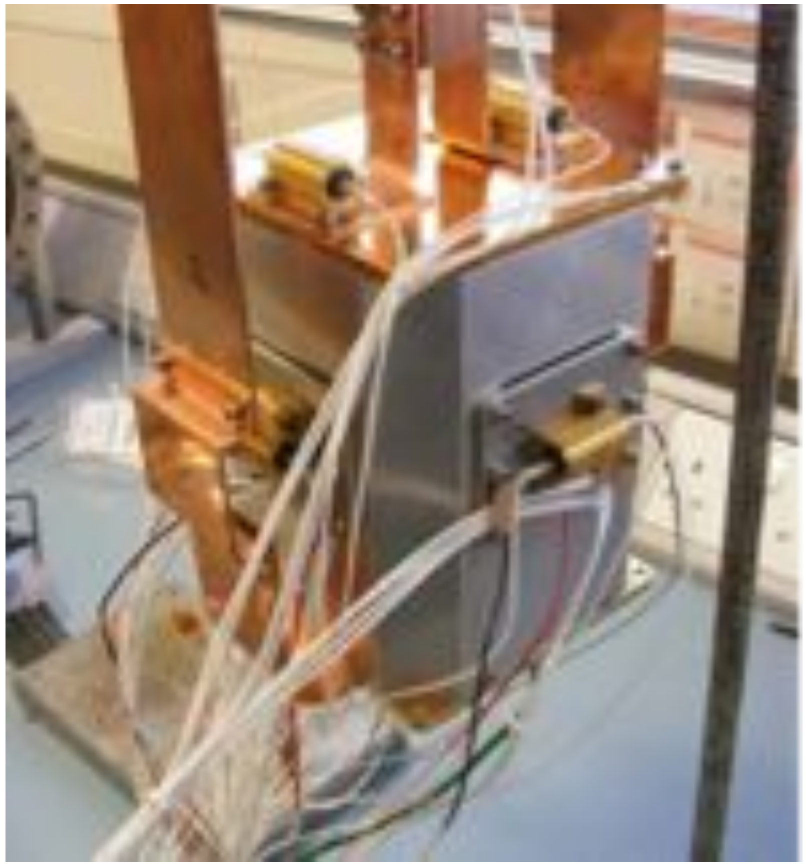


Innovative Mg-Si / Mn-Si-Ge thermoelectric module by Ecole des Mines de Nancy

Both of these contracts have been succeeding in manufacturing and testing electrically heated RTG prototypes.

Work continues under contract extension in both cases.

ESA's strategy is to develop RTGs in the lower power range (few We few tens of We for acceptable mass, robust system with no moving parts).



Prototype RTG (electrically heated) prepared for testing at the University of Leicester

Stirling Radioisotope Generator Development

In the larger power range (above few tens of W_e), an engine is used to efficiently convert heat into electrical power for limiting the size, weight and fuel requirements of an RPS, especially given the lower specific power of Am241 as compared to Pu238.

Stirling Engine Radioisotope Power System (SRG) Requirements Study:

SEA Ltd, Rutherford Appleton Lab, and Oxford University.

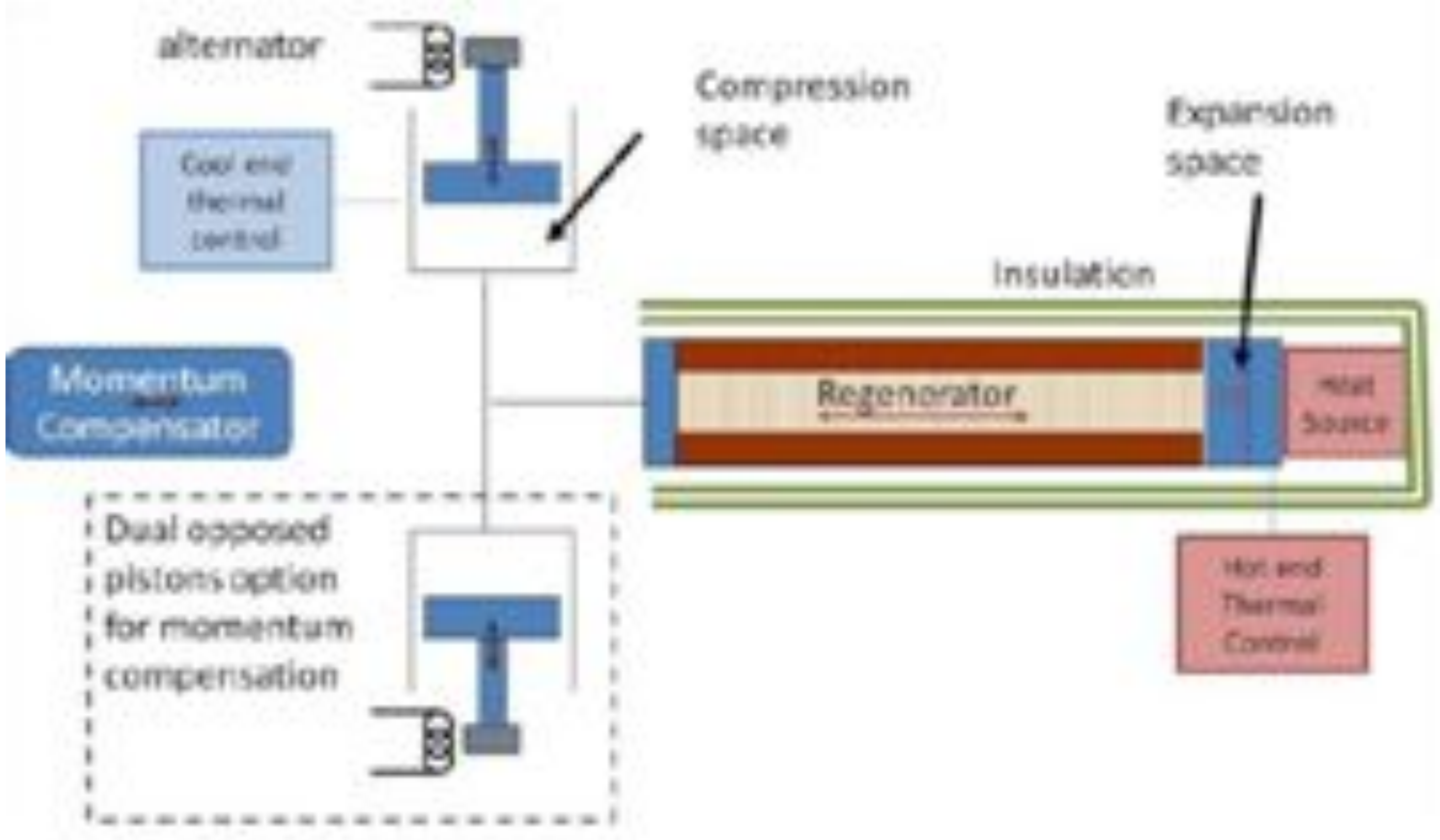
This 1st-stage paper study derived the detailed system requirements for a European space SRG.

It highlighted the potential to exploit the existing UK expertise in long life space Stirling coolers using the flexure bearing "Oxford Mechanism" .

A larger development and prototyping contract is now underway:

Stirling Converter Technology Development Phase 1

SEA, RAL, University of Oxford (UK)
QINETIQ SPACE NV, CSL (B)



Stirling converter in gamma configuration (one option under evaluation)

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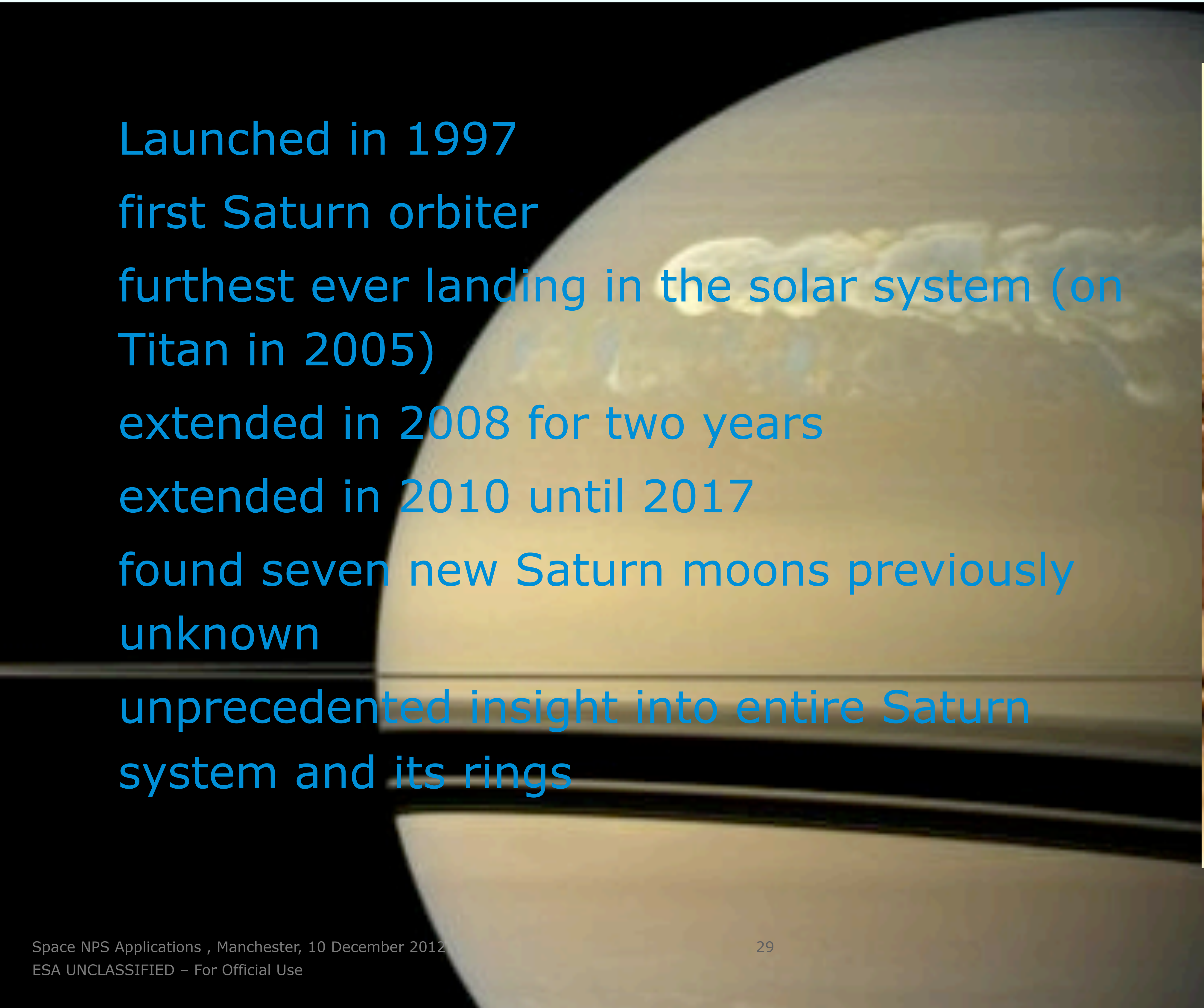
Cassini - Huygens



Launched in 1997

first Saturn orbiter

furthest ever landing in the solar system (on Titan in 2005)

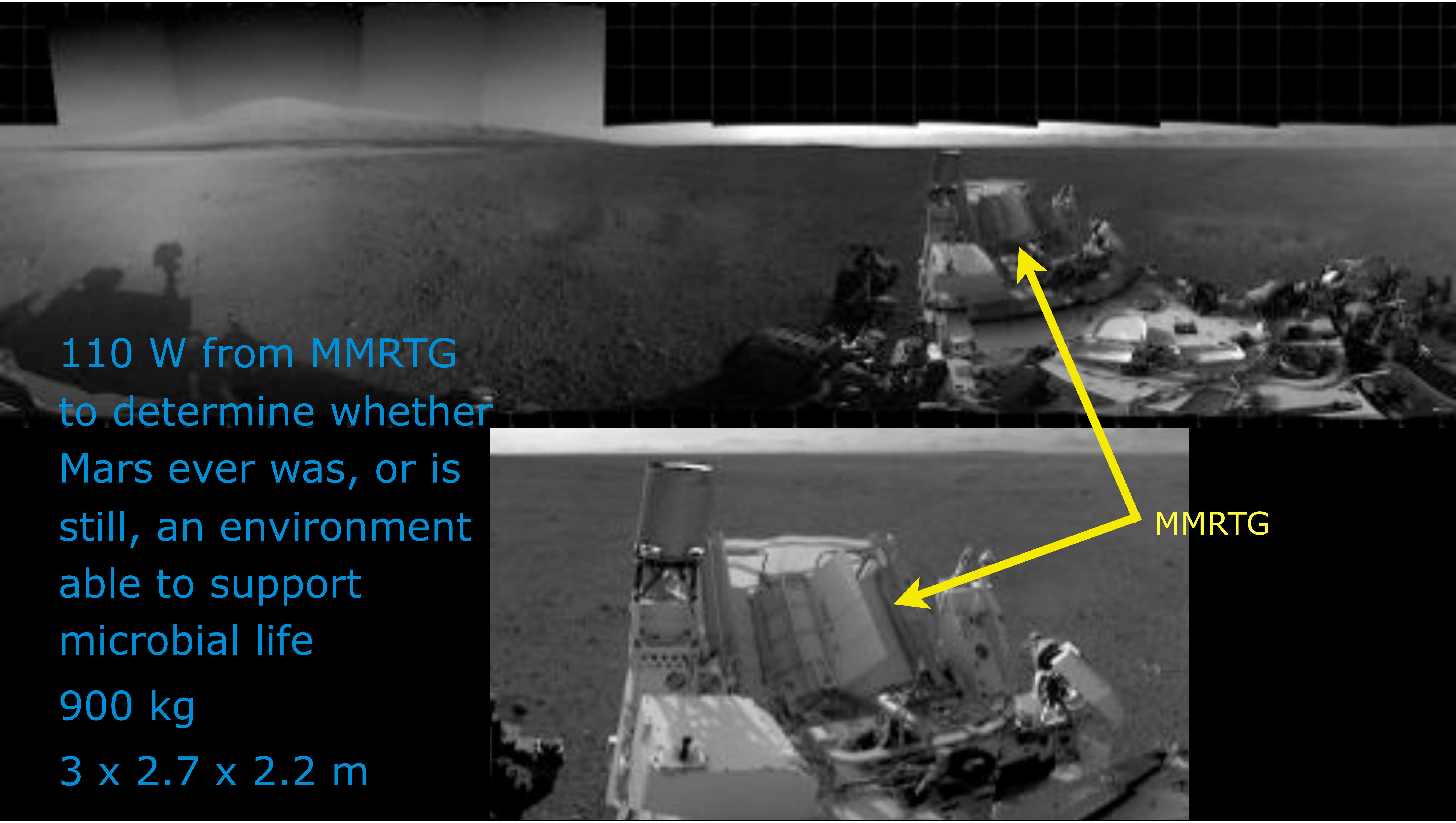
extended in 2008 for two years

extended in 2010 until 2017

found seven new Saturn moons previously unknown

unprecedented insight into entire Saturn system and its rings

Mars Science Laboratory - Curiosity



110 W from MMRTG

to determine whether Mars ever was, or is still, an environment able to support microbial life

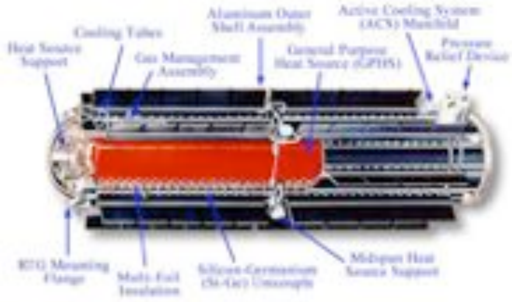
900 kg

3 x 2.7 x 2.2 m

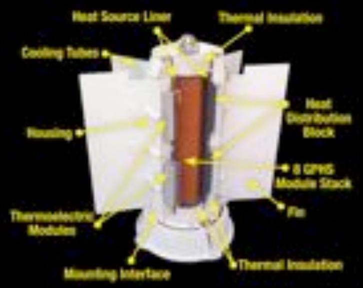
Image credit: NASA/JPL-Caltech

~40W

158W



~292W



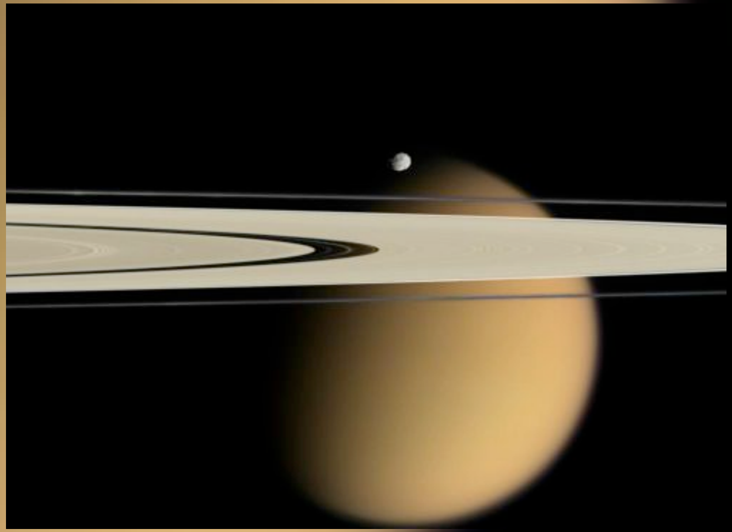
~110W

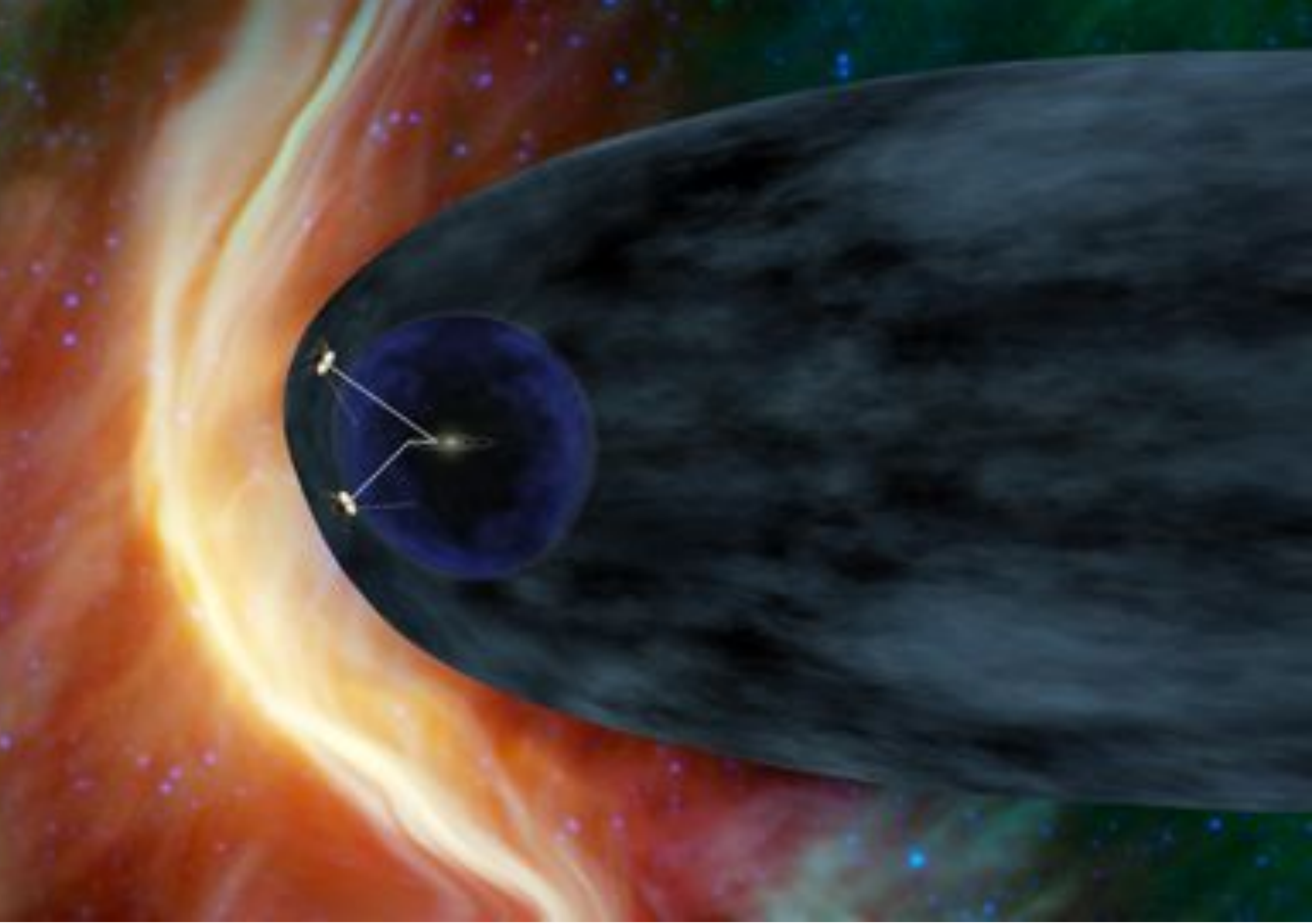
Pioneer 10,11
Viking 1,2

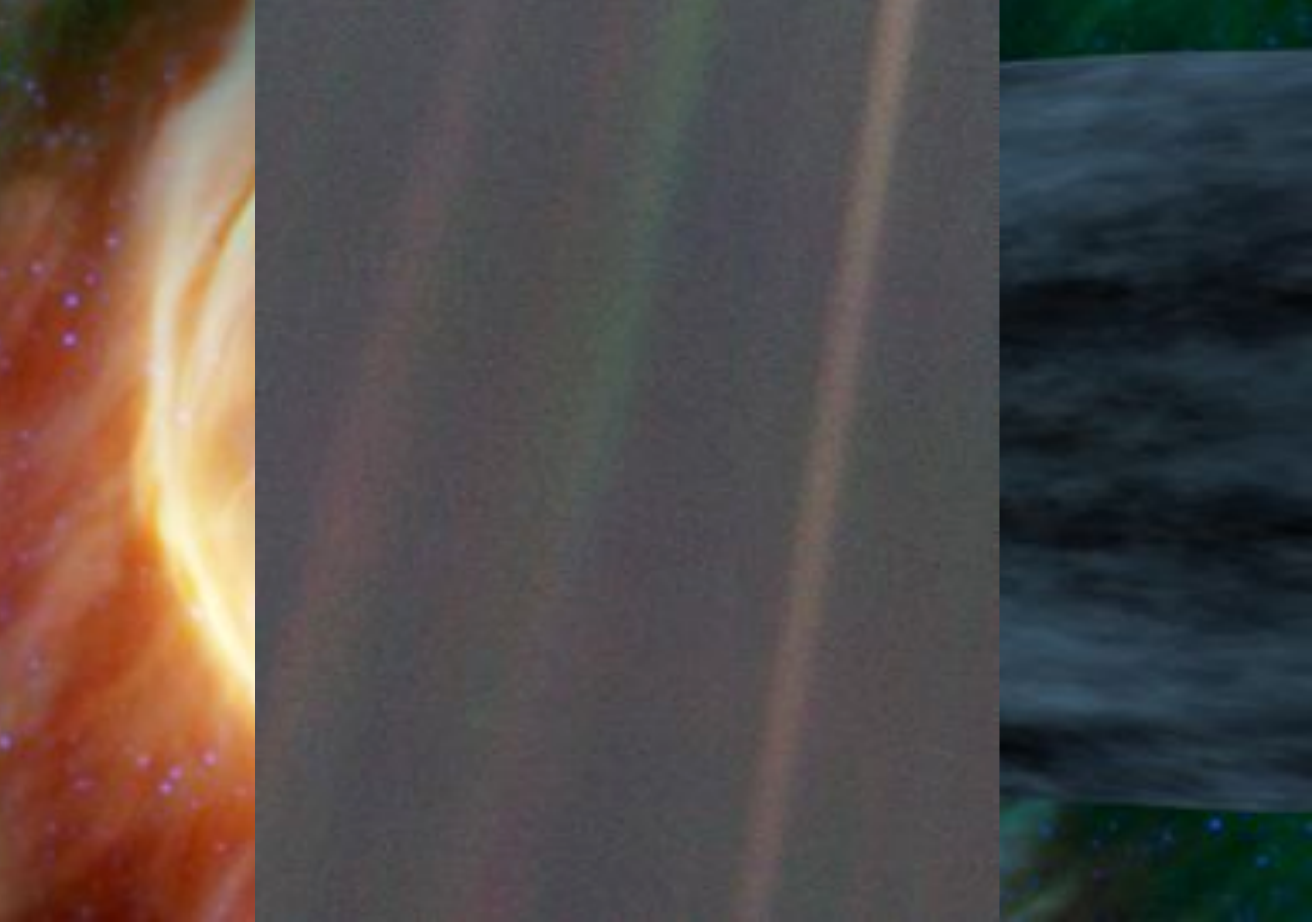
Voyager 1,2

Galileo, Cassini, Ulysses & New Horizon

MSL







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