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Nuclear Power & Space Exploration

The nuclear technology-equipped Perseverance robot successfully landed on Mars on 18 February 2021. This monograph highlights **the contribution of nuclear energy to the production of electricity and heat in space and planet exploration missions**.

The space exploration missions of NASA (US National Aeronautics and Space Administration) require safe, reliable and long-lived systems to provide power and heat to spacecraft and their scientific instrumentation.

Nuclear technology has notable applications in fields such as art, industry, agriculture, medicine and, also, space exploration.

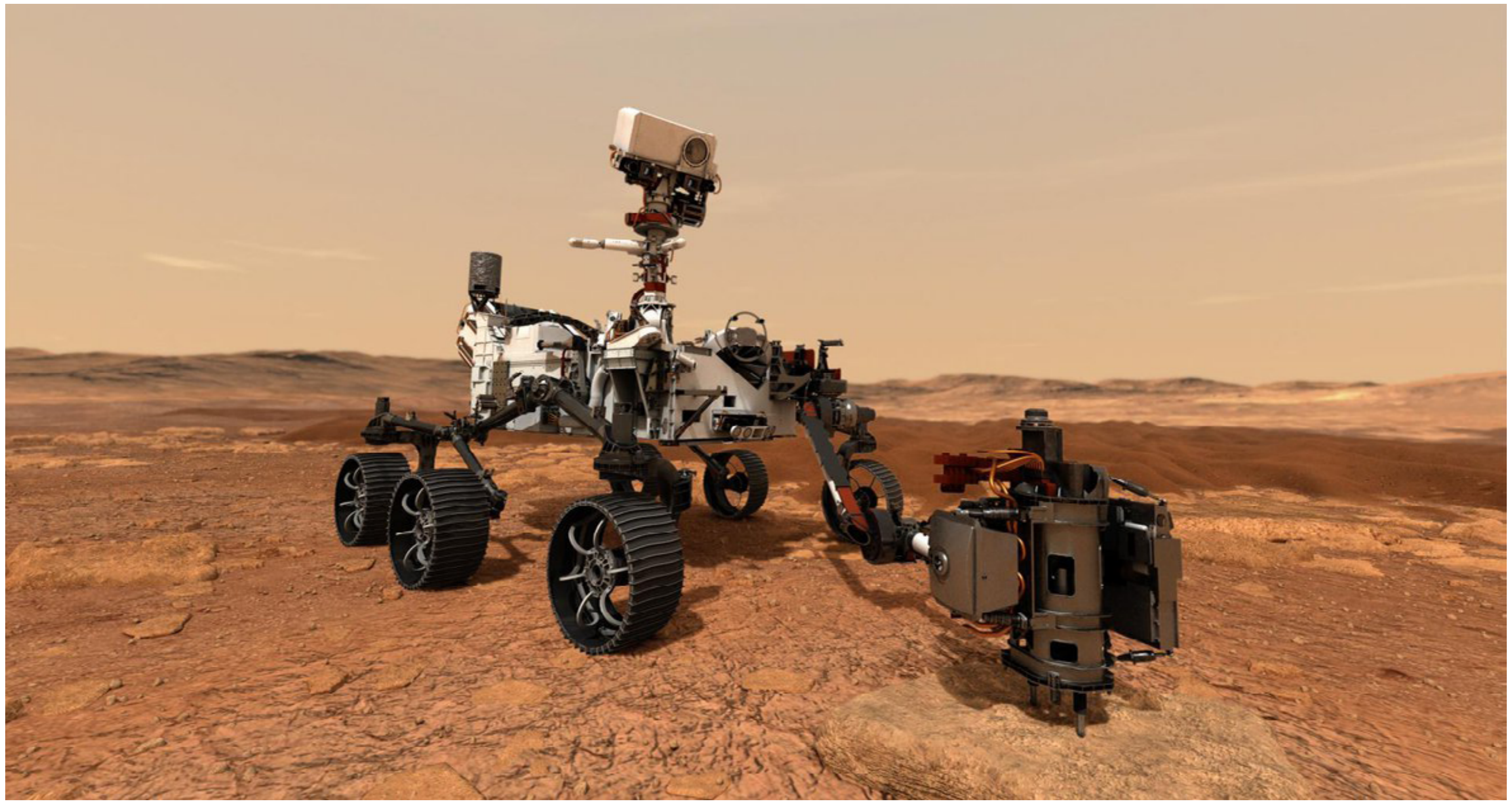


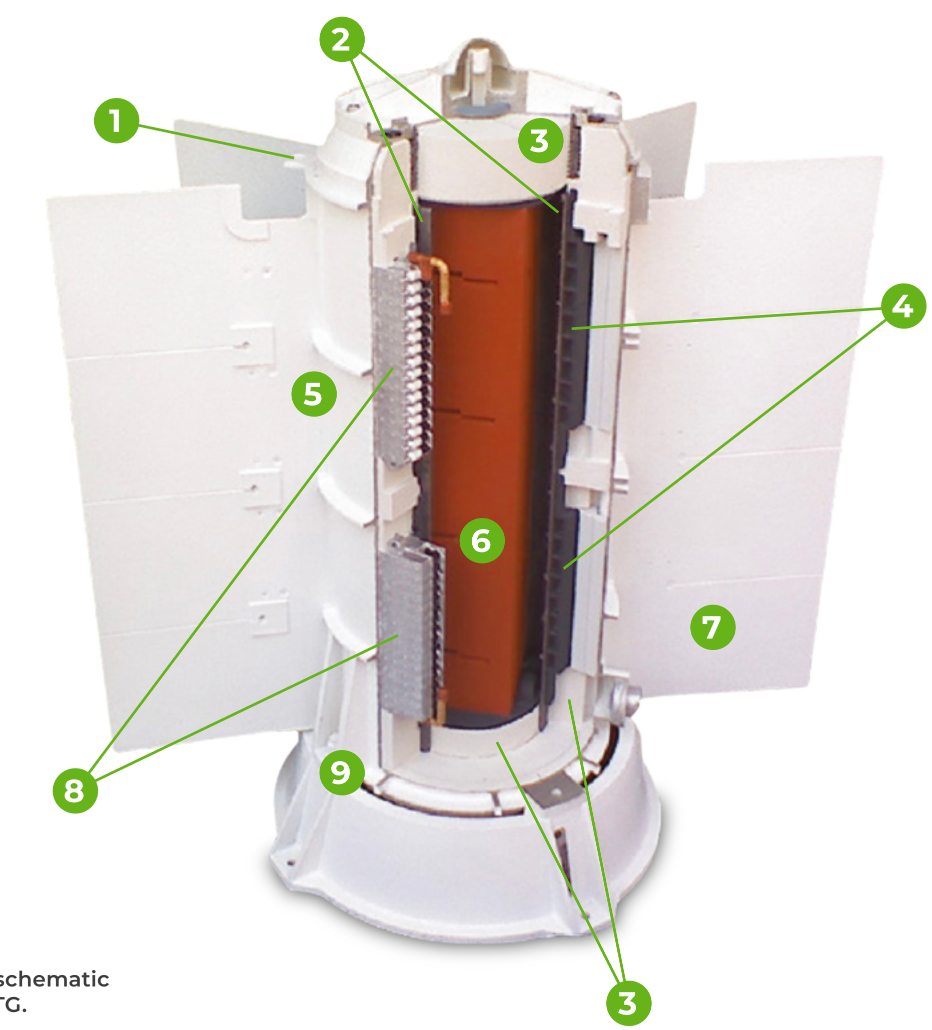
Image of the Perseverance robot. Source: NASA

An already proven technology that meets the abovementioned requirements is the so-called Radioisotope Power System (RPS). One of the models of this type of system is the Radioisotope Thermoelectric Generator (RTG), **a nuclear system for space applications that converts heat into electricity without the need for any moving parts**.

The U.S. Department of Energy (DOE) **has developed for NASA several generations of these systems that supply both electricity and heat for a large number of space exploration missions**. The Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) was designed with the flexibility required to run both on planets with an atmosphere, such as Mars, and in the vacuum of outer space. **It is capable of producing an electrical output of 125 Watts (W) upon launch**, an amount of power that is suitable for most needs with the high level of safety required.

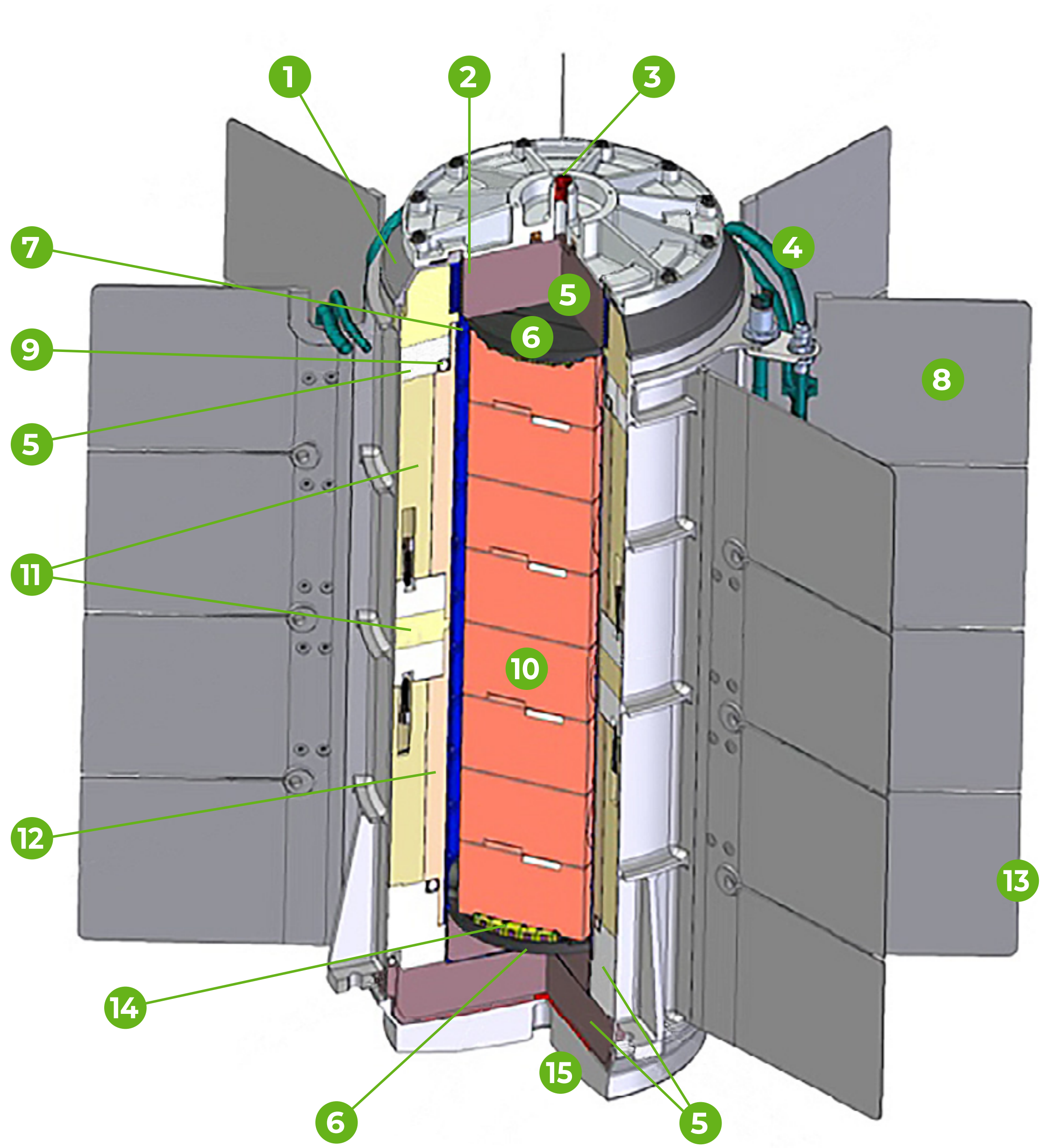
The main elements of MMRTGs can be seen in varying degrees of detail in the following images:

Radioisotope Power Systems supply electricity and heat in many space exploration missions



Simplified schematic of an MMRTG.
Source: NASA

1 Cooling tubes
2 Heat source liner
3 Thermal insulation
4 Heat distribution block
5 Housing
6 8 GPHS module stack
7 Fin
8 Thermoelectric modules
9 Mounting interface



Detailed schematic of an MMRTG.
Source: NASA

1 Fueling end cap (Al 2291, Al 1100, tantalum, SS 304L bi-metal plate)

2 Bellows (Haynes 25)

3 Loading cover (AL 2219-T852 forging)

4 Cooling tubes (Al 6063-T4 machined fittings, 6061-T4 tubing, 316L to Al 6064 bi-metal fittings)

5 MinK insulation (TE 1400)

6 GPHS interface plate (FWPF 3-D CC)

7 Heat source liner (Haynes 25)

8 Aptek 2711 white thermal coating

9 Thermoelectric getter (Zr housed in Pd)

10 GPHS module stack (GFE)

11 Mircotherm insulation (Super G)

12 Heat distribution block (Poco graphite AXF-5Q1)

13 Fin (Al 6063-T6)

14 Heat source getter (Zr housed in zirconia cloth & Haynes 25 retainer secured with Pt/Rd wire)

15 Mounting end cover (Al 2291-T852 forging)

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MONOGRAPH

History of RPSs in space missions

RPSs that convert heat to electricity into an entirely reliable manner have been used in eight orbital missions around the Earth, in eight more to the outer planets, and in the post-Apollo 11 Apollo missions to the Moon.

The missions beyond the Solar System were Pioneer 10 and 11, Voyager 1 and 2, Ulysses, Galileo, Cassini, and New Horizons to Pluto and even beyond the Kuiper belt. The RTGs onboard the Voyager 1 and Voyager 2 have been in operation since 1977 and continue to send back valuable scientific data after reaching the vacuum of interstellar space. **All in all, the U.S. has sent 26 spacecraft equipped with 45 RTGs into space since 1961.**

How does an RTG work?

RTGs convert heat generated by the natural decay of radioactive isotopes into electricity. They have two main components: a heat source, which contains a radioisotope (mainly plutonium-238), and solid-state thermocouples, which convert its decay heat into electricity.

The conversion of heat into electricity is the working principle of thermocouples and was discovered by the German scientist Thomas Johann Seebeck two centuries ago, when he noticed that when two different conductive materials are joined forming a closed circuit and their junctions kept at different temperatures, a potential difference is created. Unlike solar panels, these systems are not dependent on solar radiation, which makes them ideal for missions into the deep space, atmospheres that receive insufficient solar radiation and environments that may damage these panels.

1 "N" leg cold shoe
2 "P" leg cold shoe
3 TAGS
4 PbSnTe
5 Hot shoe
6 PbTe

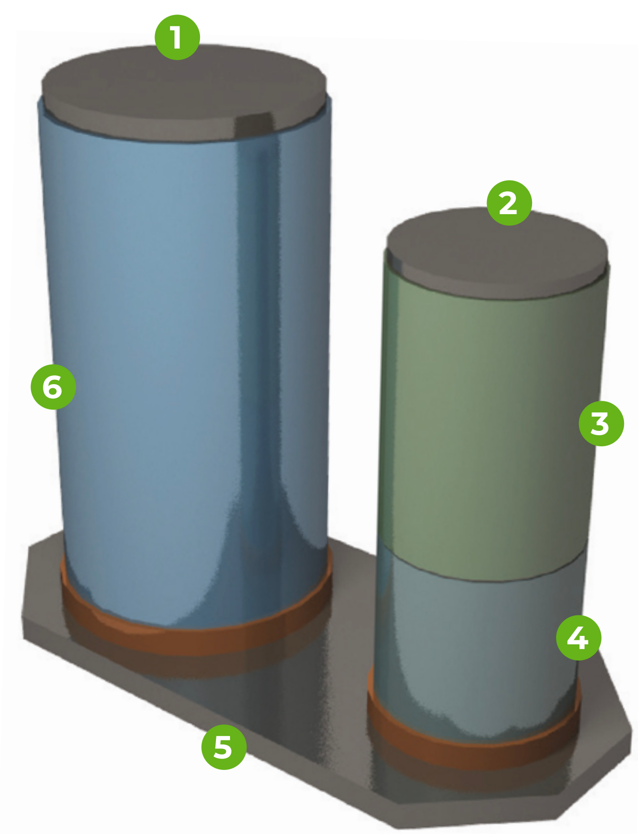
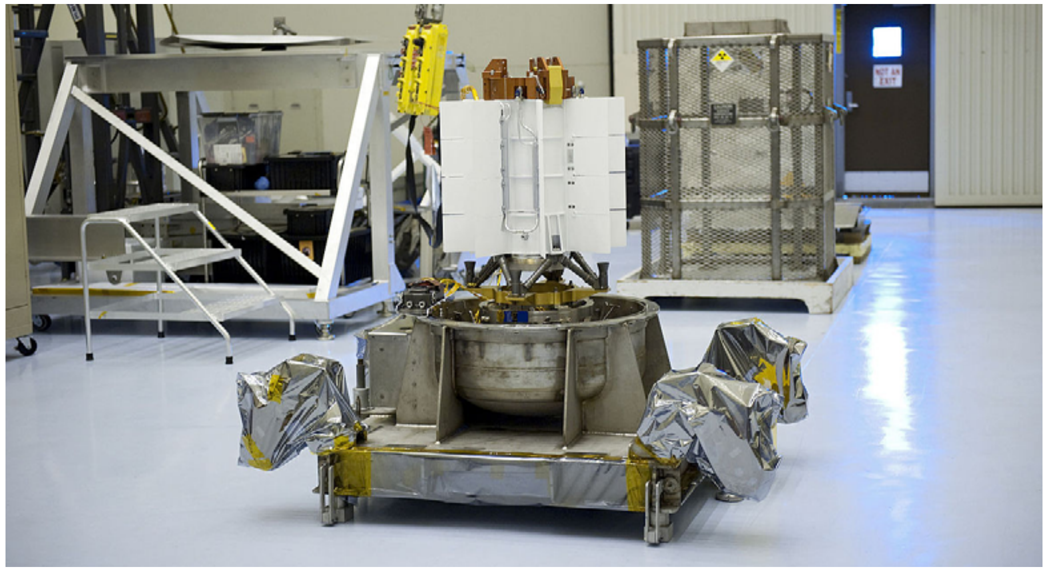


Image showing the general arrangement of a thermocouple similar to those in RTGs.
Source: NASA and the U.S. DOE

The output power of thermocouples is a function of the temperature of each junction and the properties of the constituent materials. The thermocouples used in RTGs use heat from the natural decay of radioactive isotopes such as plutonium-238 to heat the hot side of the thermocouple junction and the cold of space or of the atmosphere of other planets on the cold side.

MMRTGs get their power from eight General-Purpose Heat Sources (GPHS) powered by plutonium-238 dioxide. These eight modules initially output 2 kW of thermal power, which is equivalent to 125 W of electrical power.

The thermocouples, or thermoelectric couples, of MMRTGs are designed based on composites known as PbTe/TAGS, where PbTe refers to a compound made of lead and tellurium that is obtained from rocks called halites and TAGS is the abbreviation for a material including tellurium (Te), silver (Ag), germanium (Ge) and antimony (Sb).



Process of assembly of the MMRTG of the probe sent to Mars in the Mars Science Laboratory.
Source: NASA and the U.S. DOE

Virtual image of the Ingenuity helicopter flying in the vicinity of the Perseverance robot.
Source: NASA

MMRTGs are designed to produce 125 W of electrical power at the outset of a mission, which drops to 100 W after 14 years of service. In relative terms, an MMRTG's weight of 45 kg results in a favorable ratio of 2.8 W/kg at the beginning of its service life. **Its design allows it to operate both in the vacuum of outer space and in the atmospheres of planets such as Mars**.

The MMRTG of the Perseverance robot is also used to charge a set of lithium-ion batteries to provide enough energy density to power a robot helicopter called Ingenuity, whose purpose is to make short flights over Mars' surface as well as allowing it to survive the "Red Planet"'s cold night, when temperatures can be as low as -90°C, without its instrumentation being damaged.

Safety and design

MMRTGs are designed with multiple safety levels with the aim of preventing or minimizing the risk of loss or dispersal of its nuclear material under a wide range of hypothetical accident conditions.

As illustrated in the figure below, **their plutonium dioxide ceramic structure, which makes them extremely robust**, the iridium sheath that encases them, graphite sleeves that further increase fuel protection and the rough carbon fiber material that forms the outer containment box for the eight GPHSs are their most salient components.

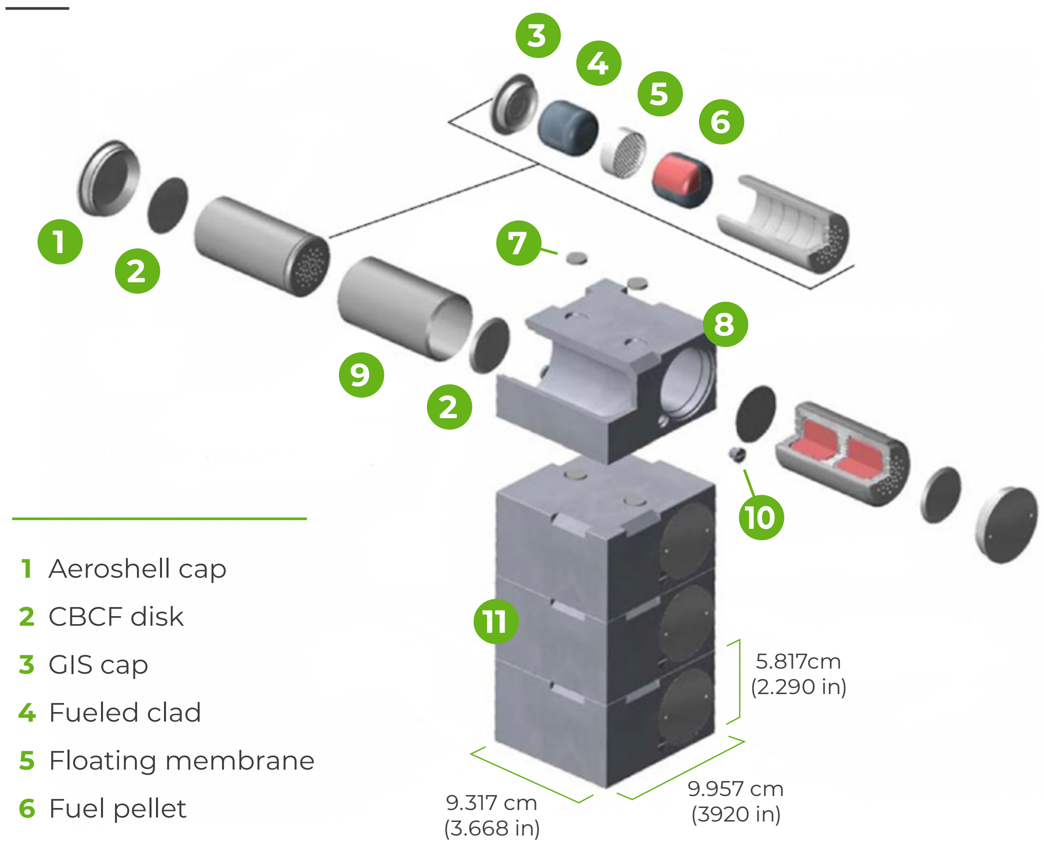
Each MMRTG contains 4.8 kg of plutonium-238 dioxide, which initially provides about 2 kW of thermal power, which as mentioned above is equivalent to 125 W of electrical power, at deep outer space ambient conditions.

MMRTGs measure approximately 64 cm in diameter—measured between heat dissipation fins—and 66 cm in height. They weight around 45 kg.

The GPHS module, which is identical to the one that powers the Perseverance robot, provides protection in the event of an impact against the ground and in situations of reentry into the Earth's atmosphere that could end up in an accident. RPSs have not caused any accidents—but have been aboard the spacecraft of three space missions that failed for other reasons. It should be noted that, in all three cases, the RPSs worked as designed. As an example of this, in 1968 the launch of a weather satellite was aborted, and the capsule holding the radioisotope was recovered in such good condition that it was possible to use it in a subsequent mission.

Components of a GPHS.

Source: NASA and the U.S. DOE



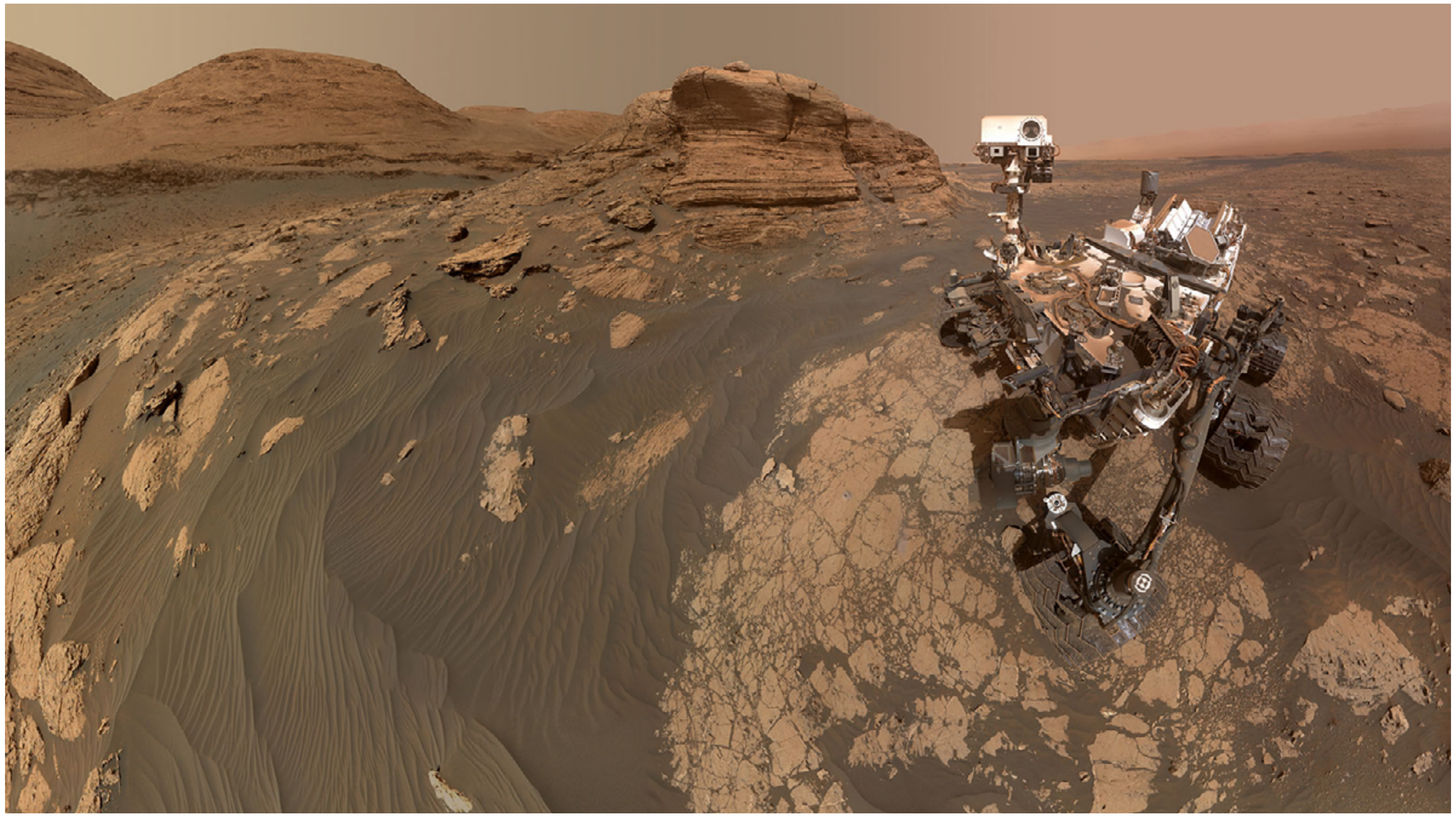
1 Aeroshell cap
2 CBCF disk
3 GIS cap
4 Fueled clad
5 Floating membrane
6 Fuel pellet
7 Lock member
8 Aeroshell
9 Carbon-bonded carbon fiber (CBCF) sleeve
10 Lock screw
11 Individual GPHS module

Experience with MMRTGs

NASA's first MMRTG-equipped unit was the Curiosity rover, which was launched in November 2011, successfully reached Mars on 6 August 2012 and is still in service—well beyond its expected life. After 2,700+ days in operation, it has become the most advanced robot ever sent to another planet and has already achieved its most important goal by determining that its landing site—the Gale crater—may have supported microbial life in the distant past.

Looking to the future, an MMRTG has also been chosen as the power unit for the planned Dragonfly mission, which will consist in an aerial robot designed to explore the surface and dense atmosphere of Saturn's mysterious moon, Titan.

The Curiosity rover, which was launched in 2011, was equipped with nuclear technology for the first time in history



The Curiosity robot today. Its MMRTG, a white cylinder with fins for dissipating heat, can be seen at its rear.
Source: NASA