SPACE NUCLEAR POWER SYSTEMS BASED ON AMERICIUM-241: ENABLING EUROPEAN SPACE EXPLORATION MISSIONS

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Introduction: Space nuclear power systems have been under development as part of a European Space Agency (ESA) programme, which has focused on proof of concept technologies and advancing the technology readiness level of radioisotope based systems based on ^{241}Am. As a science driven technology programme, this initiative has brought the space and nuclear industries together to create new technologies that benefit space exploration, the wider economy and new markets. The European Horizon 2020 programme enables Europe and its international partners to address the technology challenges of future space exploration missions. Multi-disciplinary teams will be able to propose single technology projects or larger projects clustered around several technologies. The European Commission (EC) has demonstrated support for advanced power and propulsion techniques by funding preparatory roadmapping activities on high power reactor-based electric propulsion systems for future exploration programmes. A coordinated approach and structured collaboration and cooperation within Europe and with international partners is needed if this technology programme is to succeed.

Radioisotope power sources are an important technology for future European space exploration missions as their use would result in more capable spacecraft, probes that can access distant, cold, dark and inhospitable environments. Missions using nuclear power present better value for money, with one mission delivering the science that might only be achieved from several missions using solar power. In many cases nuclear systems can enable missions that are very challenging.

European Space Nuclear Power Programme and International Collaboration: The current ESA space nuclear power programme is aimed at addressing key technology developments as well as dealing with the safety and through-life aspects of taking a nuclear power system through to launch. A structured collaborative programme with international partners who have existing launch safety frameworks, testing infrastructure, as well as invaluable experience and knowhow could be adopted as part of Europe's strategy to develop a European space nuclear power system in order to reduce the development time and contain the overall development costs. Building on the historical successes of working with the US on missions powered by nuclear power sources would appear to be an attractive option.

Radioisotope based systems are the primary focus of this paper; however, the authors recognise that the topic of space exploration encompasses robotic and human exploration; electrical power generation and propulsion over a range of power levels requiring a number of nuclear power solutions ranging from 1 W radioisotope heater units (RHUs) through to 100 W electric radioisotope power systems to kW electric reactor systems and beyond [1]. An incremental programme of objectives to tackle future missions must be sustained at an appropriate level and must build on the work already carried out to date as part of the ESA programme on developing radioisotope-based space nuclear power systems, which started in 2008 [1,2]. The ESA programme is based on developing radioisotope based power systems in the 10 W to 100 W range using ^{241}Am, which would complement higher power density radioisotope systems by providing greater flexibility in the scale of power system which translates into a greater variation in mission design and science data return.

Science Drivers: Radioisotope power sources and heater units have been used in robotic missions to the outer Solar System (Pioneer, Voyager, Cassini-Huygens, Galileo, New Horizons) [3], planetary surface missions (Lunokhod, Viking, Pathfinder, MER Rovers, Curiosity) [4, 5], human exploration missions (Apollo) [5] and Earth orbiting missions (Transit, Nimbus) [3]. Science communities around the globe continue to propose innovative mission concepts that rely on nuclear power.

The Outer Solar System: Scientific interest is increasing in the outer planets of the solar system and their satellites. This is particularly true of Uranus and Neptune and also due to the fact that little is known about these bodies given that Voyager was the last probe to provide any data. Missions to these bodies are not possible without nuclear power and would be ideal targets for collaborative international scientific and technology programmes. The icy and gas giants have played a significant role in driving the current conditions in the solar system particularly given that most of the mass is the solar system resides in these large bodies. The idea of using our own solar system to understand the formation of extra solar planets is supported by the fact that Neptune and Uranus-like extra solar planets are common [6] and presents an additional compelling argument in favour of future missions to the icy giants. Uranus and Neptune differ significantly from Jupiter and Saturn (gas giants) and there are many unanswered questions related to their interiors, oblique rotation, magnetic fields, composition and ring systems. Answering these questions will also advance our understanding of what drives the formation of ice giants as opposed to gas giants. In addition, the satellites of the icy giants present interesting targets. Triton (a satellite of Neptune) is geologically active [7] with a thin atmosphere and is classed as a captured Kuiper Belt object, which makes it an ideal laboratory for understanding how dwarf planets like Pluto form. Arridge et al. [8,9] and Masters et al. [10] have provided detailed scientific cases for European led missions to explore the Uranus and Neptune systems respectively citing the need for a European space nuclear power source in flight ready configuration by the end of the 2020s. The white papers by Arridge [9] and Masters [10] to the recent ESA call for L-class missions received significant international support from more that 300 scientists from ESA member states, USA and Japan. Synergies with white paper submissions to NASA's Planetary and Heliophysical Decadal Surveys [11,12] and the previous compelling case made by Arridge et al. for an M-class mission in Uranus Pathfinder [8] confirm a global interest in these planetary systems.

Enabling Technologies: The ESA space nuclear power programme is built on structured collaboration within Europe with UK and French-Italian teams entrusted to drive the preliminary designs of radioisotope power systems. Two key technologies in the ESA programme are described below.

Isotope Production: In Europe isotope selection studies have identified ^{241}Am as the isotope of choice [13, 14] for radioisotope based systems. Americium fuel in oxide form can be produced economically (when compared to producing ^{238}Pu in Europe) by using chemical separation methods developed by the UK's National Nuclear Laboratory to extract it from stored reprocessed civil fuel [13].

Radioisotope Thermoelectric Generators: The top-level requirements include: targeting of modular and scalable designs that can meet power outputs in the 10-50 W range, deployment on planetary surfaces (Mars) and in deep space, development of thermoelectric generators using available technology solutions as well as commercial production methods and processes. ESA entrusted UK team led by the University of Leicester and French-UK team led by AREVA TA to develop laboratory prototype systems targeting TRL3. Two thermoelectric generator solutions have been developed and tested: a low-temperature solution based on bismuth telluride (UK) and a high temperature solutions based on magnesium and manganese silicide materials (AREVA) targeting for higher temperature operation**.** Electrically heated RTG laboratory prototypes were designed, manufactured and tested to investigate the performance, detailed designs, challenges of RTG systems and to validate the thermal models.

Conclusion: Space exploration missions and associated challenges are an important source of innovation, which can lead to a transfer of technologies to the benefit of other sectors of the economy. The space and nuclear industries working together to solve challenges facing space exploration fits perfectly in a number of the Europe 2020 priorities, part of the initiative to secure Europe's global competitiveness. It fosters the development of a knowledge-based, innovation-based, competitive and sustainable economy. A lot of progress in cost effective programmes has been made in recent years in Europe and a significant critical mass of knowledge has been created by harnessing the capabilities of the terrestrial nuclear industry as well as the space industry to create a programme that will give Europe and its partners a competitive edge in future robotic and human exploration endeavours.

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