Disruptive Propulsive Technologies for European Space Missions

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Abstract

Advanced space technologies have been reviewed and analysed in view of heavy interplanetary missions of interest for Europe and European industry capabilities. Among the missions of interest:

- Heavy robotic missions to outer planets,
- Asteroid deflection missions,
- Interplanetary manned mission (at longer term).

These missions involve high speed increments, generally beyond the capability of chemical propulsion (except if gravitational swing-by can be used).

For missions beyond Mars orbit, the fission nuclear energy sources become competitive with solar panels.

Two electrical power levels have been considered: 30 kWe and 200 kWe. The lowest power level (30 kWe) is more suited to surface energy source (Moon or Mars manned base) or to relatively small automatic platforms. The 200 kW power level is more suited to heavy robotic missions, including efficient asteroid deflection.

Nuclear Thermal Propulsion (NTP) has been also considered, especially for asteroid deflection. NTP may be compatible with late detection acting by direct impact.

The public acceptance of these new technologies has been analysed, showing the necessity to provide safe ground testing facilities as well as a mission scenario excluding re-entry of an activated space nuclear reactor.

1. Introduction

So far the 'Global Exploration Strategy' [1] has focussed on a roadmap to explore the inner solar system ultimately aspiring to crewed missions to the Moon and Mars. It is recognised that the next step will be the exploration of the outer solar system and beyond. In particular, manned, missions require significant power for propulsion, to maintain a survivable habitat and to conduct useful operations at their destination.

Increasing use is made of electrical power for propulsion, exploiting the very high specific impulse achievable to limit propellant mass to manageable quantities. Within the inner solar system this power can be mostly generated by

solar arrays. In the outer solar system nuclear power remains the only practical means of generating the very high power levels identified in mission analysis to deliver significant payload within acceptable timescales [2].
Nuclear power is recognised [3] as a key enabling technology for the Global Exploration Strategy. High power generation is one of the fundamental capabilities which are a common essential requirement for both inner and outer solar system exploration. Mission analysis has consistently demonstrated that nuclear electric propulsion is an enabling technology, for instance for a sample return mission to a Jovian moon or to put a spacecraft into orbit around Neptune. More recently, in the HiPER project [5], mission analysis also identified that space nuclear power generation could benefit a wide range of applications. In the longer term, the power available could also be exploited for high power instrumentation and even for asteroid mining.
Propulsion is one of the main users of the higher power nuclear fission applications. In principle space high power propulsion can be met by nuclear thermal (NTP) or nuclear electric (NEP) propulsion technologies. Most recent studies however have focussed on NEP because, although the systems are more complex, the much higher specific impulse achievable makes the very significant reduction in propellant mass very attractive for long duration missions or the higher thrust achievable can lead to reduce significantly the mission's duration for an equal mass of propellant.
In practice, nuclear electric power generation has a wider range of potential applications such as power for habitats on the Moon and Mars.
Radioisotope thermoelectric generators (RTG) or radioisotope heater units (RHU) do not provide power on the scale of fission nuclear power generators and they are therefore not considered further in this paper. Fusion technology is also excluded. It is still too immature in space applications for now.
Nuclear power has been integral to US and Russian space plans for many years and both countries have experience in orbiting nuclear power generators [4]. Activity in this area lapsed during the last decade because of the focus on the inner solar system and funding constraints. However, the interest on NEP has been revived by the Russian MW-class nuclear power and propulsion system (NPPS) [7] concept combined with a heavy launcher capable of lifting 70 to 130 tons LEO payload, and in US in the area of low power range at LANL (Los Alamos National Lab). Recent studies have shown that Ariane 5 ECA and the Atlas 5 heavy launcher could lift higher power generators of power up to about 200 kWe. Together these developments indicate that space nuclear power will increasingly become part of the plans and policies of the major space-faring nations.

2. Purpose

The purpose of the paper is to present a discussion on such disruptive technologies and to identify how Europe can develop them and especially space fission nuclear power systems. It takes account of potential applications, technical options, relevant expertise and infrastructure, resource requirements and safety, sustainability and public acceptance. Finally, the conclusions of the study are presented along with a concluding roadmap. Those are outputs of the DiPoP project [11], that in order to make it the more realistic, was relying on an international Advisory Board where two major meetings occurred within 8 months interval.

3. Power Range

The power level range of different nuclear power sources varies from small RHUs emitting watts to terrestrial civil nuclear thermal electric fission generators in the GWe range (where subscript "e" stand for electric power and not for thermal power). For DiPoP it was decided to consider the potential applications and technical options for space fission nuclear electric power generation at two power levels: 30kWe and 200kWe (100 kWe level has been studied previously). For nuclear electric power generation the higher range is constrained to about 200 kWe by the Ariane 5 launcher fairing size, although multi-MWe systems should be possible in the further future.
Nuclear thermal propulsion has been studied in lesser details, considering that the infrastructure to develop and test it in Europe is very challenging.

4. Past Experience

Projects
Russia and the US have launched experimental reactors supported by terrestrial research and development. Russia launched some 35 missions to operate nuclear-powered surveillance radars. However, adapting the technology for NEP did not advance beyond research and development. The Fig. 1 show the known past experience in US and Russia. SNAP (10A), launched by the US in 1965 was the first fission nuclear power generator in space. ROMASKA was developed as a prototype in Russia for space exploration missions. BOUK, powered the Russian RORSATS. TOPAZ1 was a higher power, more efficient and more compact successor to BOUK and made 2 experimental flights. TOPAZ2 was a development of TOPAZ1 for space exploration but the combined Russian and US project (NEPSTP) was abandoned before launch. Some parts of the US SP100 project were developed and ground tested. A

large amount of testing of nuclear thermal propulsion was conducted under the US NERVA programme but no devices were launched.

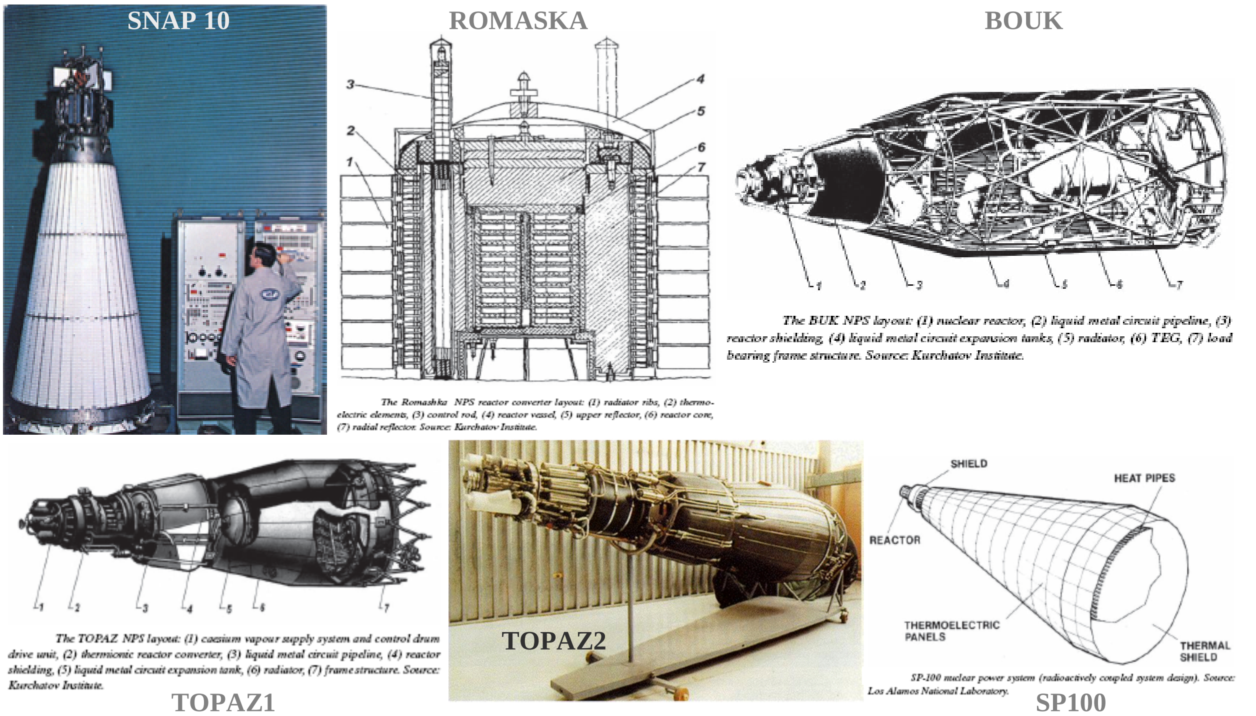


Figure 1: Past US and Russian experience

Source: [12] Atomics International, Kurchatov Institute., Los Alamos National Laboratory

Studies

Subsequent studies have drawn heavily on the experience from these projects. Sample return mission payloads including a lander and re-ascent vehicle are likely to be several tons in mass. A 6 year round trip to Mars or a 10 year round trip to a Jovian moon, with a year's stay time in each case, needs tens or hundreds of kWe depending on specific impulse (I_{sp}) and propellant mass used.

The studies have indicated that for higher power levels closed cycle Brayton thermal to electrical power conversion is significantly more efficient. Although, new materials may help raise thermo-electric energy conversion from 5 to say 10%, the 17 to 20% efficiency claimed for the Brayton cycle still brings significant specific mass benefit. The relative simplicity of gas cooled reactors is an advantage in terms of long life, but experience to date has been with liquid metal cooling. Liquid metal cooling is more complex (needs additional pumps and heat exchanger), and requires significantly more energy to heat the coolant and reactor to an operating temperature for commissioning or for 'cold' re-starts.

Fixed, body mounted metallic radiators have high mass and area unless the operating cycle temperature can be raised significantly (radiator size varies with temperature to a fourth power law). Deployable radiators are lower mass but larger area and need an additional heat exchanger. There is the added complexity of packaging a large structure for launch and deploying it safely. Lighter materials such as carbon-carbon composites offer new options for fixed radiators.

HiPER

The recent EC FP7 study, High Power Electric Propulsion: a roadmap for the future included a Concept Design and Technical development Roadmap (SEP, Rolls Royce plc and Acta srl) for a 200 kWe fission nuclear power generator [5,6].

NPPS and the Heavy Spaceship [7]

Most recently, taking into account the high potentialities of nuclear space energy to increase the effectiveness of space activities, 'ROSKOSMOS' and 'ROSATOM' have proposed a project to create a heavy spaceship with a powerful nuclear power and propulsion system (NPPS). This project was approved by the President of Russian Federation and accepted for realization in the 2010-2018 timeframe as follows:

2010—2012 conceptual designs of NPPS.

2015—2017 testing of NPPS, production and delivery of NPPS to the heavy spaceship.
2014-2017 production and test of non-nuclear systems of the heavy spaceship.
2018 end of ground development.

5. Applications And Missions

Background

Applications requiring or able to benefit from space nuclear power generation have been researched. At the lower end of the scale are high power instruments such as ground penetrating radar. The higher power tends to be more needed for propulsion. Some applications, such as asteroid/NEO mining or power plants for surface infrastructure (say, on the moon or Mars) may be achieved with lower or higher power levels. Although not specifically listed there are secondary benefits from high power such as high data rate for very long distance (laser) communications.

The lower power level of 30 kWe was selected for DiPoP study to investigate which applications might be benefited in practice, and whether there were advantages in terms of technical options, European capability, resources, public acceptance, safety and sustainability.

The higher power level (200 $kW_{e)}$ was selected in the HiPER and DiPoP studies because current European studies indicate this is the maximum consistent with the lift capability of the Ariane 5 ECA launcher. Current alternative launchers (such as the Atlas V heavy lift) or more efficient power conversion may permit some increase but not enough for the megawatts of power normally associated with manned missions.

The NPPS and heavy spaceship development is linked to manned space missions with access to a larger launch lift capability. The HiPER Concept Design is scalable from 100 kWe to 2 MWe. Thus, although manned missions were not considered in DiPoP, many of the capabilities and resources required are directly applicable.

Also, with a 200 kWe NEP-powered spacecraft it would be possible to send the infrastructure required at the destination (say a landing and re-ascent module) ahead separately in slower time. A smaller (than combined infrastructure and human) module for the humans can then be sent separately by fast chemical or nuclear thermal propulsion once it is known that the infrastructure has safely arrived at for the destination.

Range of Potential Applications

Identified potential applications are:

- Nuclear electric propulsion.
- Ground Penetrating Radar and High Power Lasers for surveying remote planets,
- Planetary outpost surface Infrastructure including electrical and thermal support,
- Asteroid and comet deflection
- Asteroid Management: surveying and mining
- Removing ‘Dead’ Spacecraft or Debris (a ROSCOSMOS study).

Prioritising Applications and Missions

The Advisory Board advised that: “As a general principle it was advisable to select an application for which there is a clear need, make the mission as technically uncomplicated as possible to reduce technical risk and to (as far as possible) ensure success. Once a successful precedent has been established, more sophisticated missions may be investigated.”

The 30 kWe generator appears best suited to planetary outpost power generation and missions designed around high power instruments (combined with EP for interplanetary trajectory needs).

The 200 kWe (or greater) is needed for NEO mitigation and to transfer infrastructure for a split manned mission to Mars. Use as surface power generator is further in the future.

In itself robotic outer solar system exploration is a family of missions ranging from Jovian moon sample return to orbital surveys of Neptune, Pluto, and the Kuiper Belt. It has the potential to be the basis of a sustainable programme allowing non-recurring development costs to be amortised across several missions.

The application Asteroid and comet deflection also known as NEO mitigation has to be highlighted here because even if ccurrently there is no known threat in the next 100 years, one know that the pattern of Earth crossing NEOs changes unpredictably and not all potentially hazardous NEOs are currently tracked. For example the trend for the known number of NEO asteroids of diameter lower than 100 m, which can impact the Earth with possible major disastrous consequences, according to Fig. 2, will double in the next 10 years: this was seen very recently with the Siberian shower of unknown objects for example, hopefully this time without any noticeable consequences. Clearly the defense of the planet can be seen as a compelling argument for public acceptance of fission reactors (or even NTP) if there is no other way of deflecting a large earth-bound NEO asteroid, keeping in mind that safety and sustainability would have to be at least as good as for other application. The conclusions of this analysis can be summarised as the fact that a first step is to define the different activities in sufficient detail to be able to cost them realistically. The impact of not implementing the Roadmap recommendations may therefore prove catastrophic in the not too distant future.

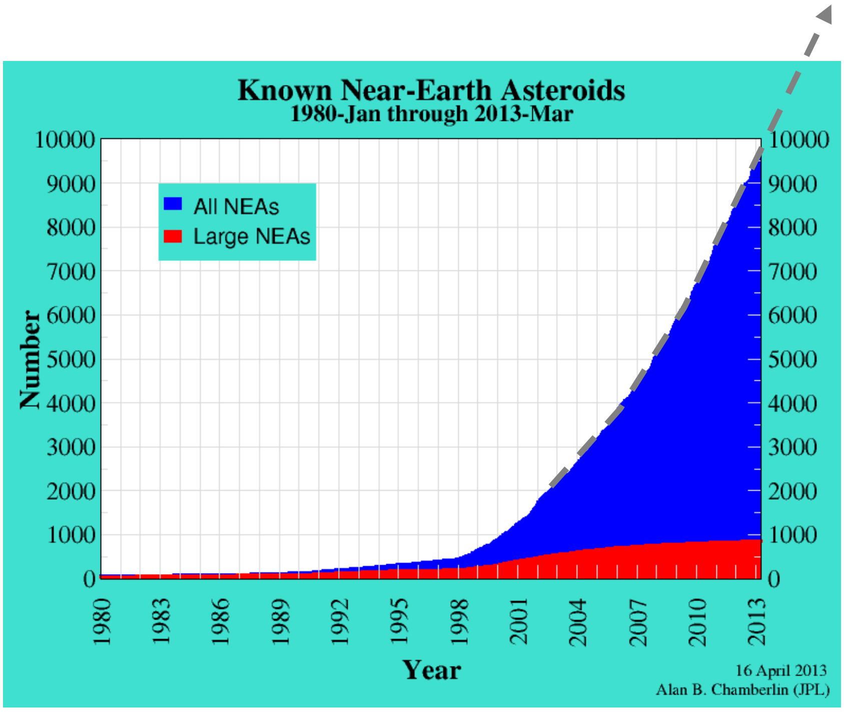


Figure 2: Number of known Near Earth Objects (Asteroids) up to March 2013, with possible trend added
Source : http://neo.jpl.nasa.gov/stats/, 26 May 2013

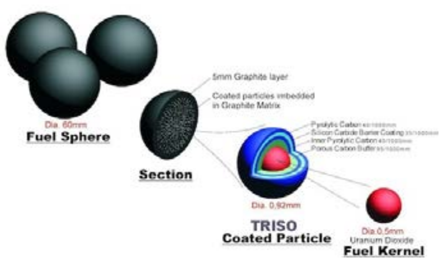
6. Technical Options

A review of technical options for a 30 kWe and a 200 kWe nuclear power generator revealed a fair degree of commonality between the two findings.

Design Constraints
Design constraints (identified in HiPER [5]) are:
- Compatibility with an Ariane 5 ECA launch : >800km in-orbit commissioning altitude, radiator compatible with the Ariane 5 fairing, Launch safety criteria (e g water immersion).
- Ten years of operation within a 15 year lifetime,
- Specific mass of 25 kg/kWe for a 200 kWe generated power or better,
- High temperature reactor (fast indirect or epi-thermal direct) and conversion system (Brayton cycle),
- Resilience to sudden load fluctuations,

Reactor Technologies
The preferred options were pin-fuel fast reactors for indirect inter-cooled and recuperated (ICR) Brayton because of compact, low mass features or particle-based fuel reactors for Direct ICR Brayton cycle.

Fuel
Consideration was given to ceramic uranium oxide, carbide or nitride pellets, although nitride fuel imposes materials compatibility constraints on the fuel cladding. TRISO fuel particles (sketched at right) , in carbon shells (or zirconium carbide), were also considered for 200 kWe and is the preferred approach for 30 kWe. Uranium-tungsten alloy formed into small elements/particles or into wire-wound structures may be lighter. For 200 kWe in HiPER high levels of enrichment were assumed to minimise reactor size (82-90% for the Direct Cycle and 93% for the Indirect cycle). UO2 is by far the most studied fuel in Europe.



Source: Pebble Bed Modular Reactor (SOC)

Control Systems
The operating principle is ‘load following’ through negative thermal control, accepting a degree of ‘thermal lag’, and containment with beryllium reflectors. Control rods give a more compact, low mass core but control drums require

fewer shield penetrations and are simpler to rotate reliably. Both electrical and pneumatic drive should be compatible with the temperature field and high radiation environment (dry lubrication may be required).

Shielding
A layered shadow shield design (Beryllium, Lithium Hydride, Tungsten or with Beryllium Oxide to overcome Lithium hydride thermal expansion sensitivity) was adopted for both 30kWe and 200kWe; Shadow angles were up to 28° and a 22.5m separation boom was planned.

Power Conversion
In principle Stirling Cycle is an attractive option for 30kWe but there are doubts about high power Stirling systems. Direct ICR Closed Brayton Cycle (CBC) was narrowly preferred for 30kWe and accepted as an option for 200kWe for good efficiency, simplicity of design, no freezing of reactor cooling and turbo-alternator operating gas. Both 30kWe and 200 kWe considered turbine rotation of ~ 45Krpm but for 200kWe turbine blade creep life above 1100 K will require new materials. Indirect ICR CBC is an alternative for both 30kWe and 200kWe (more compact reactor but added complexity of liquid metal pumping, and melting liquid metal for commissioning, cold starts, etc).

Radiators
Both fixed and deployable radiators are options for the 200 kW power level. At very high temperature operation, fixed radiators become compact and mass and area competitive. Also, it should be mentioned that Russia is developing a droplet radiator which allows lower system temperatures but requires a large area when deployed.

Electrical generation
The turbo alternator output may be alternate current (AC) or direct current (DC) if rectified. AC may be used to reduce harness mass but there are potential complications in interfacing with EP or a high power instrument and the DC battery.

Power Management and Distribution (PMAD)
Turbo-alternator output could be tailored to EP or radar tube operating voltage, resulting in a reduced PMAD mass.
Battery size, coupling (DC/AC converter) and functions (commissioning, load ballast, etc) shall be studied.

Summary
The selection of CBC Brayton power conversion for both 30kWe and 200 kWe allows a high degree of focus in the technical options. It is also helpful because of the inherent ‘scalability’ of the technology. The main issues to be resolved are the trade-off between liquid metal and gas cooled reactors and the operating temperatures. Materials which allow higher temperature operation for 10 year lifetimes will tend to make the relative simplicity of gas cooled systems more attractive.

7. European Capability (Expertise And Infrastructure)

The EWG (European working group) on NPS for Space [8] recommended (Short Term Actions) that: “*A European roadmap for the development and use of nuclear power sources for space should be elaborated, differentiating in terms of the typology and the timescale. It should include a comprehensive inventory and assessment of all potentially relevant existing facilities and capabilities in Europe*.”

Survey
A comprehensive survey of ‘all potentially relevant existing facilities and capabilities in Europe’ was beyond the scope of DiPoP. However it has been possible to conduct a ‘representative’ survey based on the key government organisations, nuclear research organisations and industry. It is recognised that valuable research is also undertaken by many universities.
A questionnaire was sent to selected organisations requesting information on their expertise and infrastructure relevant to a space nuclear fission generator programme.

Results
The responses were sufficient to populate a European Organisation and Industry Capability Table. This shows, even from the limited survey, potential EU capability in all the required areas.
The development of suitable radiator and high power systems is within the capability of the main European Space industry. Materials research associated with reactors and power conversion may also be relevant in this area. Europe has the capability to launch and operate spacecraft but has yet either to help establish binding international safety

standards or a common European regulatory framework to ensure maximum safety and security in all activities related to the use and launch of nuclear power sources.
The conclusion is that Europe has the potential capability in all aspects of a 30kWe or a 200 kWe space nuclear fission generator.

8. Russian And US Capability

Russia
Current Russian capability is best reflected by progress in the Heavy Spaceship and MWe NPPS. This suggests considerable progress in the enabling materials research identified as necessary for a European nuclear fission generator programme. It would also appear that the design concepts are similar in principle to those proposed for 30kWe and 200kWe European projects but on a larger scale.

US
The US capability was summarised by the Advisory Board as "a wealth of practical experience in space nuclear power" which Europe will need to learn to be effective in the development and application of the technology. Space nuclear R&D is being maintained in the US but the expertise in mission development and manufacture no longer really exists.

Collaboration Potential
The First Advisory Board meeting concluded that "Putting together a European, Russian and US collaborative programme may be challenging (control, schedule and quality management issues). However European experience in managing multi-national programmes might be helpful."
Since then Russia has indicated that collaboration on the Heavy Spaceship and NPPS programme would be welcomed.

9. Capability Development

Europe
The challenge for Europe is to make identify the technical advances required, establish the necessary infrastructure and to develop the practical experience for the successful delivery of a space fission nuclear power project. Although space systems will ideally operate at several hundred degrees Kelvin higher than current terrestrial Generation IV research reactors, exploiting synergies may be useful.

Technical Advances
The enabling research identified includes:
- Materials for high temperature liquid metal and gas cooled reactors including fuel, control and coolant routing arrangements,
- Materials for low mass and area, micro-meteoroid protected radiators,
- Low mass high temperature piping, etc., resistant to helium absorption, for Brayton cycle operating gas,
- High temperature, long life (creep resilient) turbine design and materials (actually for CBC the turbines could benefit from materials not working with oxidising gas contrary to terrestrial turbo-prop turbines materials),
- For 200kWe, high temperature, very high power electrical components and subsystems, including batteries.

Infrastructure
Initially research in Europe could make use of existing nuclear and non-nuclear research facilities. As a longer term objective the EWG on NPS for Space [9] recommended that "*Fission reactors for power and propulsion should be considered more intensively. A first objective should be the development of a prototype at ground level*." This would be necessary for project definition (Phase B1).
It may be possible to alleviate infrastructure cost and schedule by re-use of existing facilities. For example, it is understood that several former reactor testing buildings are still in good shape at Saclay and Cadarache for research reactors no longer used such as Rapsodie. If the safety systems and air filtration units are still operative it is not necessary to invest in a new "class 1" building and safety studies are also simplified since they are reusing former ones.

Practical Experience
A programme of 'cross-pollination' between the nuclear and space communities would be a good starting point. This could be supplemented by collaborative activities and extended to direct participation in a nuclear space project. Creating practical experience it is dependent upon commitment to a sustained long term programme.

10. Public Acceptance And Dissemination

The importance of preparing public outreach study/material for nuclear space technology to be developed and proposed to EC / Europe was recognised. A similar approach had been used for the Prometheus programme (using the Keystone Centre in Colorado). The recent launch of RTGs and RHUs in the US still attracted small protest groups. It was essential to assemble a team that both understood the technical issues and the public concerns. This included both traditional concern about nuclear dangers and also whether it was a good way to spend government money (the case for private investment did not look strong). The US experience was that the management of public acceptance could be a relatively small part of the budget if tackled early and effectively.
Uranium enrichment was considered necessary to design a sufficiently compact reactor for space. This is one factor why a Public Acceptance assessment study is an early priority task before to take into account the suited recommendations. The fact that at launch the uranium is "new" and so weakly radio-active as shown in fig. 3 with the handling operations of the fuel is a major fact for enabling a positive Public Acceptance of fission reactor for space applications.

Figure 3: New uranium fuel hand operation (possible because so weakly radio-active)

Thus important public considerations are safety and that government will spend tax money wisely. The following need to be established:
- Definition of the economics of the technology,
- The need of sustainability: long term output of the technology.
- Good communication: avoid news like "millions burn down on launch pad crash".

11. Safety

The safety guidelines for nuclear power sources in space are provided in numerous documents [10].
Space and nuclear safety experts from "big ESA member states" are drafting a technically sound European framework that:
- Provides a predictable, efficient, "workable" process for ESA missions,
- Addresses the main concerns of participating member states,
- Takes advantage of the existing European nuclear safety expertise and experience gained on the subject in US and Russia,
- Provides a technically sound basis for an early decision on processes, roles and responsibilities.

This study was initiated under General Studies Programme in 2005. A letter exchange ESA-NASA during spring 2006 permits cooperation on sharing experience. Russia strongly follows all national and international rules to guarantee safety of any application of nuclear power in space.

12. Sustainability

Europe is unlikely to fund enabling research for a space nuclear fission programme until an application (or range of applications) has been identified which is justified in terms of benefit, credibility and cost. It is difficult to determine benefit, credibility and cost until the enabling research has helped to quantify the performance which may be achieved. In this sense, a dual-mode program, to build compact reactors capable of both industrial power generation and space propulsion and power, could free this impasse. A way to start the iterative process would be a workshop [11] for the space science and exploration, space mission and spacecraft design and nuclear communities with a view to:
- Define specific research and development projects, including cost and schedule, to deliver the performance required for the identified science and exploration objectives based on the initial assessments made in the DiPoP project:

  - High temperature reactor (including controls) and fuel materials research (potentially in collaboration with Generation IV civil nuclear power development),
  - High temperature turbo-alternator materials research to overcome creep life limitations,
  - Low mass, high temperature radiator materials (not-porous to helium) research,
  - Low mass shielding configurations compatible with high temperature operation and efficient spacecraft architectures
  - Mass efficient power management and distribution and associated safety features,
  - In-orbit commissioning and end-of-life disposal,
- Identify trade-offs between objectives, performance, technical development, schedule and cost.
- Propose one or more candidate mission analysis to provide a baseline for evolution of the Technical Roadmap (in practice a family of mission analyses would be a sensible investment to establish a range of potential applications and give confidence of a multi-application program).
- Propose a program to achieve public awareness and secure public acceptance for a European space nuclear fission program.

Either ESA or the EC could sponsor a workshop (EC sponsorship is understood to be proposed). The output of the workshop and mission analysis can then provide a basis to determine specific enabling research projects in the EC Horizon 2020 programme and further mission analysis could be sponsored by ESA as part of the General Studies programme.

13. Resources

Estimating the cost and schedule of a European fission nuclear power programme is difficult because there appears to be wide divergence in the evidence from past and current comparable programmes. Estimates range from B$0.56 for the NPPS programme (up to completion of pre-flight testing) to B$7-9 for the US Prometheus project. Realisation of Prometheus in the JIMO mission envisaged a 14 years duration (KO 2003 launch in 2017). The NPPS schedule starting in 2010 indicates readiness for launch in 2019.

A schedule proposed in HiPER for a European 200kWe nuclear fission generator envisaged 3 years feasibility study, 4 years project definition, 10 years development and build for launch and a 10 year mission. The starting point does not have the benefit of the NPPS expertise and infrastructure and it was assumed that ESA would require lengthy ground testing to manage risk acceptably. The proposed schedule may therefore be too conservative.

The EC was currently funding the DiPoP project and has funded the recent HiPER study. HiPER delivered a technical roadmap for the development of a 200 kWe space nuclear fission generator. A DiPoP deliverable is a ‘organisational’ roadmap for the delivery of 30 kWe and 200 kWe space nuclear power generators, Fig. 4.

ESA is currently sponsoring projects on low power (radio-isotope) sources for exploration projects but maintaining a ‘watching brief’ on EC fission R&D. Funding from other government organisations and industry in the short term is likely to be dependent upon ‘spin-off’ into profitable non-space (or non-nuclear space) applications.

14. Conclusions

Past experience indicates that fission nuclear power generation is technically feasible. Subsequent studies indicate the need for significant technical development in Europe to realise the performance identified in the range of proposed applications.

From the range of applications for which space fission nuclear power is potentially necessary initial candidate selections of European missions are:

- Generating electrical services for a remote planetary outpost and high power instrument was selected for 30kWe.
- Earth threatening NEO deflection or outer planet orbital surveying mission for 200kWe fission nuclear electric propulsion. The performance needed for these applications would also support other identified applications.

Closed Brayton Cycle power conversion with either an indirect liquid metal cooled or direct gas cooled fast reactor is selected for both power levels.

Materials research into the high temperature operation (but with non oxidising gas) needed to achieve optimal mass efficiency for space reactors, Brayton turbo-alternators and radiators. Research is also needed into very high power electrical equipment and switching.

A representative review of the capabilities of European government organisations research centres, industry and universities indicated potential expertise and infrastructure for all aspects of a European space nuclear fission programme.

Generation IV civil terrestrial reactor research includes high temperature liquid metal and gas cooled projects ; there are many useful synergies, particularly in associated materials research..

Potential interest in a European space nuclear fission programme was expressed by many of the organisations contacted in the survey and covered all aspects. Evidence of sustainability of the programme is seen as a pre-requisite for both government and industry.

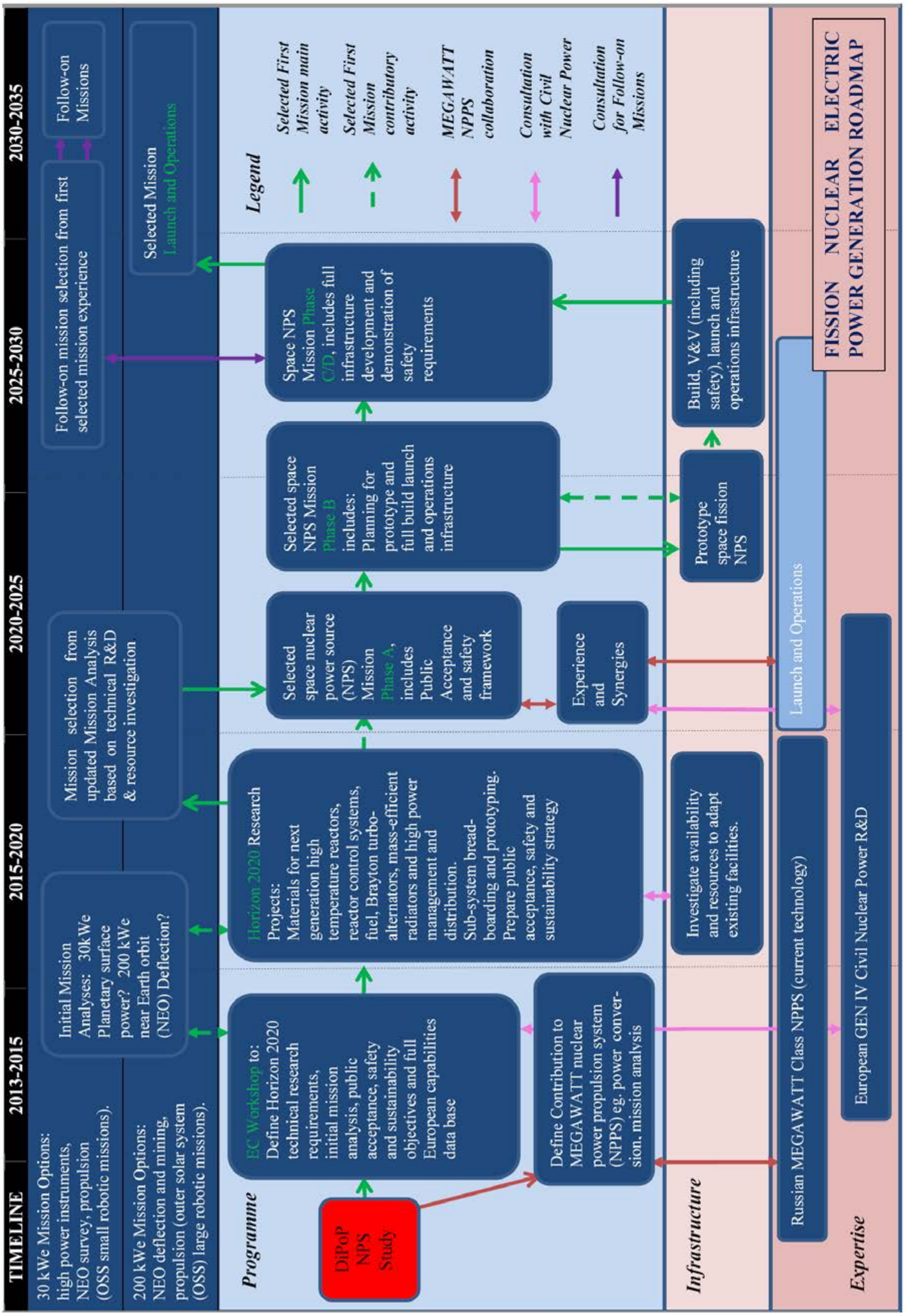


Figure 4: DiPoP Fission Nuclear Power Generation Roadmap up to 2030 and beyond

In Russia opportunities have been identified for collaboration. Although fission nuclear thermal propulsion and fission nuclear electric propulsion are identified by NASA as critical technologies, there is no current US nuclear

fission powered project. The US remains active in working with Europe to help establish a European regulatory safety framework for nuclear power in space.
European capabilities will have to be developed in terms of technical advances, infrastructure and practical experience. Technical advances are initially mainly in the field of materials research and, in due course, in a prototype research reactor. Practical experience is essential for success in such a programme. The principles of securing public awareness and public acceptance for a European space fission nuclear power programme are well understood.
As highlighted in the roadmap presented in Fig. 4, an iterative process is required to start a sustainable space fission nuclear power programme. Justifiable missions must be selected to determine the required performance of the nuclear generator. A workshop to initiate the process would allow initial mission and research assessments to enable definition of research projects for the EC Horizon 2020 programme and mission analysis through ESA. The outcomes can then be used to define the feasibility and project definition for a sustainable programme line.
The cost and schedule for a European nuclear fission programme is difficult to determine. Comparison with the US Prometheus and Russian NPPS programmes suggested significant differences. A feasibility study is required however to determine them sufficiently accurately for planning.

15. Acknowledgments

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16. Appendix: MEGAHIT project (Megawatt Highly Efficient Technologies for Space Power and Propulsion Systems for Long-duration Exploration Missions)

MEGAHIT is a new project funded by the European commission 7th Framework program, started in March 2013 and coordinated by the European Science Foundation [13]. This project has two main objectives: to create a European scientific and technical community around high power nuclear electric propulsion in Europe with a strong Russian partnership and to build a roadmap oriented towards megawatt level or even multi-megawatt power level with the interested stakeholders. The roadmap will also consider international cooperation beyond Europe and Russia. In order to achieve these goals, a workshop is planned in Brussels on 2nd to 4th of December 2013.

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