FISSION NUCLEAR POWER GENERATION ROADMAP

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ABSTRACT

This document is the deliverable D30.2 of the WP 30

The Roadmap is an initial assessment of the European capability to develop space applications and missions requiring fission nuclear power generation. The assessment takes account of past projects and studies and expertise and infrastructure developed in Europe, Russia and the US. It also takes account of anticipated future applications and missions and critical issues such as safety, sustainability and public acceptance of space fission nuclear projects.

At the second Advisory Board meeting the Director General of the Keldysh Research Centre Moscow invited Europe to participate in Russia's MEGAWATT Class nuclear power and propulsion system (NPPS) development. This is a unique opportunity for Europe to gain essential practical experience of space fission nuclear power.

KEY WORDS DiPoP, Roadmap, Fission, Nuclear, Power.

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EXECUTIVE SUMMARY

The purpose of the Updated Roadmap is to identify how Europe can develop and use space fission nuclear power. It takes account of potential applications, technical options, relevant expertise and infrastructure, resource requirements and safety, sustainability and public acceptance. It follows from the initial assessment of European capabilities in the Draft Roadmap and the recommendations of the first Advisory Board meeting. The objective is to present a credible development plan and to make recommendations for a programme of research and development to realise it. The roadmap has also been updated from advice from the second Advisory Board meeting.

The main criticism of the Draft Roadmap at the First Advisory Board was that it was not clear where it was leading to. The suggestion was made to target an initial mission which required fission nuclear power and had a high probability of success within an acceptable budget. In identifying target applications the scope has been restricted to nuclear electric and not nuclear thermal applications for two reasons: nuclear electric can be used for both propulsion and as a high power source for in-situ planetary infrastructure support and high power instruments; whereas potential infrastructure to support a nuclear electric programme exists in Europe creating a nuclear thermal development facility appears very problematic

Two sizes of nuclear electric generator have been investigated in the DiPOP study: 30 kWe and 200 kWe. For the 30 kWe generator providing power for in-situ planetary infrastructure is selected as the target application. Concerns were raised at the First Advisory Board at the difficulties of landing a mass of several tons safely on a distant planetary surface but the recent successful arrival of Curiosity on Mars gives confidence that this challenge can be met. The application is seen as consistent with longer term ambitions to explore the solar system and to establish outposts on remote planets. Habitation, and even a large robotic facility, on the dark side of the moon or Mars will require electrical power on this scale and fission nuclear generation appears the only feasible source for some time.

Nuclear electric propulsion (NEP) for large scale exploration of the outer solar system is selected as the target application for the 200 kWe nuclear generator. A mission to counter an earth threatening NEO by deflection might become more important but currently no significant threats have been identified for the next 100 years. A sample return mission to a Jovian moon would be very attractive but putting a large surveying platform into orbit around Neptune or Pluto is less complicated and therefore lower risk and less expensive. Once in orbit the nuclear power can be used to operate high power radars and lasers and high data rate communications back to earth. In principle this might be achievable by a smaller spacecraft and power sources but it would take longer and have limited surveying capability by comparison. The second Advisory Board gave priority to the 200 kWe generator as it was considered that 30 kWe of surface power could be provided on the Moon or Mars with solar panels and fuel cells.

A review of the technical options for realising each application revealed a high degree of commonality in principle. Both fast liquid metal and gas cooled reactors are mass-efficient and there is a fine difference when comparing the lower mass of liquid metal with the less complicated gas cooled design. For the 30 kWe generator Stirling cycle power conversion is a strong candidate but closed Brayton cycle is considered to be mechanically more robust. For 200 kWe the advantages of Rankine cycle can only be realised at much higher powers and closed Brayton cycle conversion offers the best efficiency. Radiator design and material requirements are similar but whereas 30 kWe power management and distribution is compatible with current technology, 200 kWe requires a new generation of components and subsystems. The second Advisory Board did not consider that the lower power would offer any significant saving in development costs.

A ‘representative’ survey of European capabilities confirmed the existence of expertise and potential or existing infrastructure to support high temperature reactor technology, power conversion, radiator and electrical systems, project management, storage and transportation (including launch and operations). Research in Generation IV high temperature liquid metal and gas cooled reactors has some synergy with space requirements although space requires higher operating temperatures to optimise mass efficiency. A number of European organisations are conducting materials research which could help to increase operating temperatures and also benefit higher temperature, lower mass turbo-alternator and radiator design. Europe has well established civil and submarine nuclear and space project management capabilities although some cross-pollination between the two disciplines will be needed. Synergies with Generation IV research facilities may be exploited during the early part of a space programme, particularly for materials research. Industrial civil and submarine development facilities could be adapted for a space programme for full development. Whereas terrestrial civil nuclear storage and transport would apply equally for space considerable work is still needed to establish a full safety and regulatory compliant framework for launch from French Guiana (Kourou) and operations by ESA.

The representative survey indicated a broad level of interest in participating in a European nuclear fission space programme. Evidence of sustainability of the programme is seen as a pre-requisite for both government and industry.

Russia is developing the Heavy Spaceship and MWe (nuclear power and propulsion system) NPPS and seeking collaboration. This is based on current technology made possible by the extra lift capacity of the Angara launcher (under development) and lower temperature operation made possible with the droplet radiator. For the US nuclear thermal (NTP) and nuclear electric (NEP) propulsion remain critical capabilities but there is no active mission planned using these technologies. The US is cooperating with Europe in developing a regulatory safety framework for nuclear power in space.

To realise its potential for a space nuclear fission programme Europe needs technical and infrastructure development and to acquire relevant practical experience. Russia has invited Europe to participate in the heavy spaceship with NPPS project and this is potential way to gain experience. For more mass efficient development research is required into materials for high temperature systems which has some synergy with Generation IV terrestrial civil high temperature reactor development. The scope to adapt existing redundant infrastructure to support a prototype space reactor requires further investigation. Practical experience may be acquired through work on more advanced collaborative space nuclear projects.

The principles for achieving public awareness and acceptance are well understood and it is recognised that this is an essential pre-requisite for a space nuclear fission programme. Monitoring and cooperation with this aspect of current ESA radio-isotope project activities is recommended. Similarly achieving progress in establishing a regulatory safety framework for European space nuclear power systems remains an important objective together with identifying the infrastructure to demonstrate that it is implemented.

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: for example, Prometheus (a full development and mission) inception to JIMO launch ~14 years and programme costs B$7-9; NPPS (based on current technology and benefitting from parallel projects) inception to launch ~ 8 years and development cost B$0.56. In HiPER for 200kWe a tentative schedule (including enabling research) was ~ 20 years from inception to launch allowing for 10 year life testing of critical systems. A feasibility study, based on a specific application, is required the cost and schedule of a European project.

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. Enabling, mainly materials, research is needed to understand if the required performance can be achieved at acceptable cost and schedule. A workshop to initiate the process is recommended to define missions and research objectives within the EC Horizon 2020 programme supported by mission analysis through ESA. The outcomes can then be used to define the feasibility and project definition for a sustainable programme. Participation in the Russian MEGAWAT Class NPPS project is a unique opportunity for Europe to gain experience of space fission nuclear power and the invitation from the Director General of the Keldysh Research Centre to participate merits prompt consideration.

A view of the Advisory Board is that it would take a decade to make the technical advances to realise the next generation of space fission nuclear power. Based on Russian and US experience (and taking account of HiPER and other European studies) this indicates that Europe's first nuclear fission spacecraft could be launched in the 2030-35 timeframe. It also assumes that critical research starts in the Horizon 2020 programme in 2015 and that initial results are able to support mission analysis during the same period and both support first mission project Phases A and B.

A schematic of the Roadmap is in Diagram 1 below. It illustrates the links between Mission selection and definition, technical development, developing expertise from synergies with other programmes and creating the required infrastructure. The links represent the iterative processes required to optimise mission performance specification with technical progress and the expertise and infrastructure available. They also include 'feed-through' into follow-on missions to create a sustainable programme. Recommendations are focussed on the nearer term enabling technical research and development, mission analysis and gaining practical experience. This includes mapping European resources, identifying infrastructure needs and public acceptance and safety.

DIAGRAM 1. DiPoP FISSION NUCLEAR POWER GENERATION ROADMAP SUMMARY

The Roadmap for Fission Nuclear Power Generation Roadmap development is illustrated diagrammatically below. The general picture of the roadmap is shown with the 4 main areas of tasks: Missions, Technical Programs, Infrastructure and Expertise. The interactions between those tasks are sketched within the time frame and the fundamental path of the actions to be performed is highlighted.

The primary objectives are to:

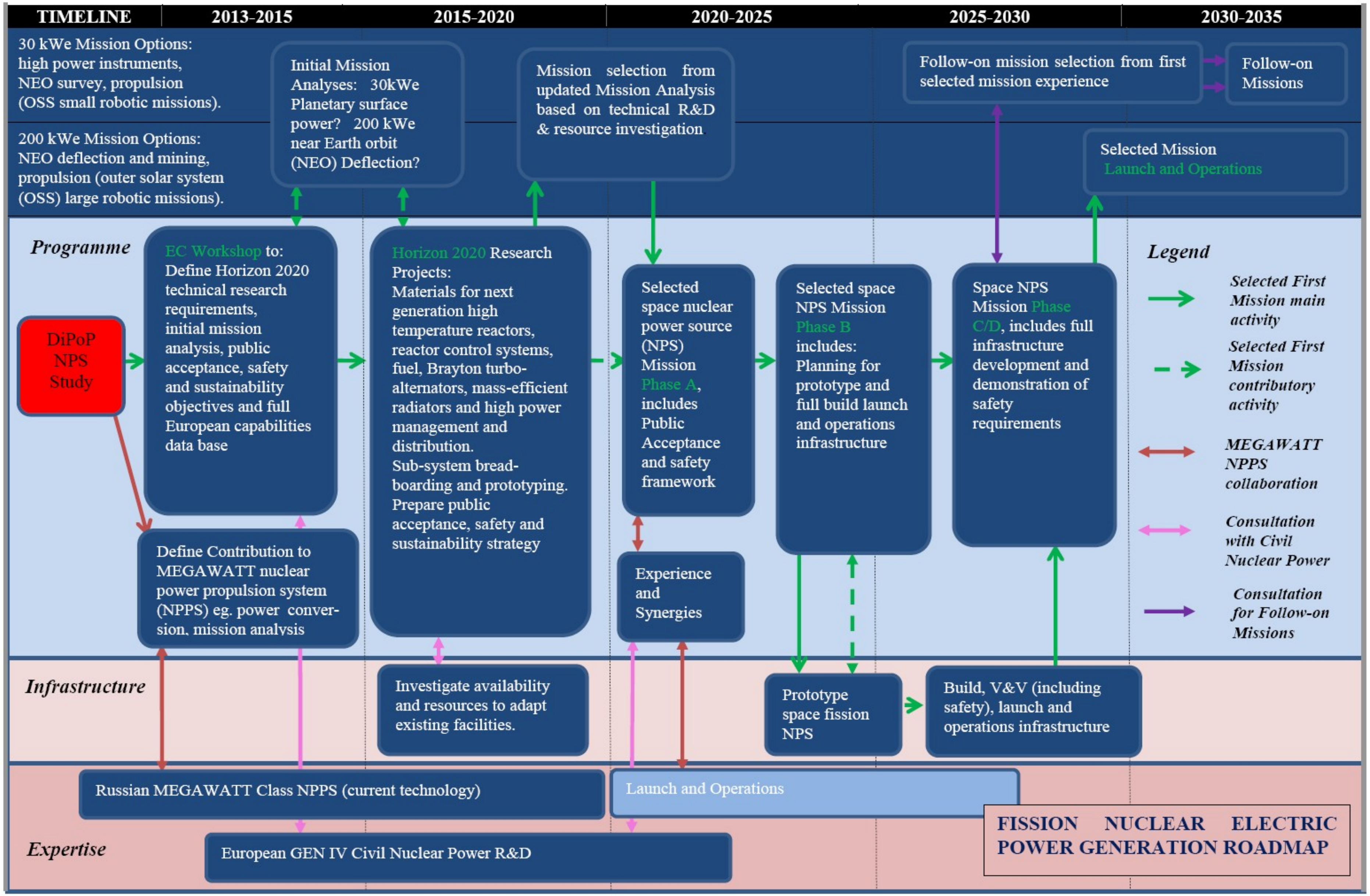
- Build practical experience in current space and relevant terrestrial fission nuclear power generation through collaboration in Russia's space Megawatt Nuclear Power and Propulsion System (NPPS) and European Generation IV civil power programmes,
- Initiate a workshop in 2013 to:
    - Define the Horizon 2020 technology research and development tasks for next generation high temperature, mass-efficient space fission nuclear power generators and compile a full data base of relevant European capabilities.
    - Identify the most promising candidate missions for mission analysis and define mission requirements.
- Select by analysis a candidate first European nuclear fission powered space mission based on: mission 'value', assessed technical risk, supporting infrastructure requirements, resources that can be made available and a supportive level of public acceptance,
- Develop the candidate mission programme taking advantage of the experience, and any synergies with, the Megawatt NPPS and Generation IV Civil power programmes and the adaptation of existing infrastructure where this is cost effective.
- Select follow-on missions to establish a sustainable programme based on mission analysis prioritisation and the lessons learned.

The Director General of the Keldysh Research Centre has invited Europe to participate in the Megawatt NPPS project which started in 2011 and is due to complete ground testing in 2018.European organisations working on Generation IV civil nuclear power development have expressed potential interest in a space fission nuclear power programme, particularly in the field of high temperature systems development where there are some potential synergies.

Proposed Horizon 2020 research includes:

- High temperature gas and liquid metal cooled reactors, reactor control systems, long-life fuel and shielding,
- High turbo-alternator inlet temperature with long creep life compatible with alternator electrical temperature limits,
- High temperature, low mass fixed and low temperature deployable radiators,
- Mass efficient high power (and possibly high temperature) electrical power management and distribution,
- Architecture, commissioning and safety optimisation to be compatible with launch and launch vehicle constraints,
- A campaign to progress the work of the European space nuclear regulatory framework and to manage public acceptance.

The ESA General Studies Programme is proposed for the mission analysis to select a candidate first mission and priorities for follow-on missions.


TIMELINE
2013-2015
2015-2020
2020-2025
2025-2030
2030-2035
30 kWe Mission Options: high power instruments, NEO survey, propulsion (OSS small robotic missions).
200 kWe Mission Options: NEO deflection and mining, propulsion (outer solar system (OSS) large robotic missions).
Initial Mission Analyses: 30kWe Planetary surface power? 200 kWe near Earth orbit (NEO) Deflection?
Mission selection from updated Mission Analysis based on technical R&D & resource investigation
Follow-on mission selection from first selected mission experience
Follow-on Missions
Selected Mission Launch and Operations
Programme
DiPoP NPS Study
EC Workshop to: Define Horizon 2020 technical research requirements, initial mission analysis, public acceptance, safety and sustainability objectives and full European capabilities data base
Horizon 2020 Research Projects: Materials for next generation high temperature reactors, reactor control systems, fuel, Brayton turbo-alternators, mass-efficient radiators and high power management and distribution. Sub-system bread-boarding and prototyping. Prepare public acceptance, safety and sustainability strategy
Selected space nuclear power source (NPS) Mission Phase A, includes Public Acceptance and safety framework
Selected space NPS Mission Phase B includes: Planning for prototype and full build launch and operations infrastructure
Space NPS Mission Phase C/D, includes full infrastructure development and demonstration of safety requirements
Legend
Selected First Mission main activity
Selected First Mission contributory activity
MEGAWATT NPPS collaboration
Consultation with Civil Nuclear Power
Consultation for Follow-on Missions
Define Contribution to MEGAWATT nuclear power propulsion system (NPPS) eg. power conversion, mission analysis
Experience and Synergies
Infrastructure
Investigate availability and resources to adapt existing facilities.
Prototype space fission NPS
Build, V&V (including safety), launch and operations infrastructure
Russian MEGAWATT Class NPPS (current technology)
Launch and Operations
Expertise
European GEN IV Civil Nuclear Power R&D
FISSION NUCLEAR ELECTRIC POWER GENERATION ROADMAP

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1 INTRODUCTION

1.1 Background

So far the 'Global Exploration Strategy' ***[GES]*** has focussed on a roadmap for exploration of the inner solar system aspiring to expeditionary missions to the Moon and Mars. It is recognised that the next step will be the exploration of the outer solar system and beyond. Large, particularly 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 keep propellant mass to manageable quantities. Within the inner solar system the majority of this power can be 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 in acceptable timescales ***[HiPER D-2.7].***

Nuclear power is recognised ***[CSA]*** 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 illustrated that nuclear electric propulsion is an enabling technology for a sample return mission to a Jovian moon or to put a spacecraft into orbit around Neptune for example. More recently in the HiPER project, mission analysis also identified that a space nuclear power generator capability could benefit a wider range of applications. These included multiple large infrastructure transport missions making significant savings by reducing repeat launch mass to the payload only. In the longer term, the power available could also be used for exploitation such as high power instruments and 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 or nuclear electric technologies. Most recent studies however have focussed on nuclear electric propulsion because, although the systems are more complex, the much higher specific impulse achievable makes the very significant reduction in propellant mass very attractive for lengthy missions.

In practice nuclear electric power generation has a wider range of potential applications such as power for habitats on the Moon and Mars or even at a future 'ISS' at a key location such as a Lagrange point. The purpose could be to maintain significant infrastructure or provide a 'space harbour' for multiple missions where a 'space tug' could collect of deliver its 'cargo'.

In the near term missions are increasingly using low power nuclear devices, such as radioisotope thermoelectric generators (RTG) or radioisotope heater units (RHU). These are very inefficient and do not provide power on the scale of a fission nuclear power generator and they are therefore not considered further in this study even if for some applications this technology is sufficient. Fusion technology is also excluded. It is still too immature to have confidence in space applications. Also nuclear fusion thermo-nuclear facilities are expected (at this stage of knowledge) to have a minimum output power, of around 100 MW (ITER), which is several orders of magnitudes above the foreseen mass and power for this study.

Nuclear power has been integral to US and Russian space plans for many years and both countries have nuclear power generator in orbit experience ***[IAA SG2].*** Activity lapsed during the last decade because of the focus on the inner solar system and funding constraints. With the GES ***[CSA]*** interest is being revived initially in the context of lower power systems to support space habitats but with the development for very high power propulsion systems for robotic and eventually human deep space exploration. At a plenary session of the International Astronautical Congress in Prague in September 2010, Anatoly Perminov, Head of Roscosmos announced that Russia was developing a new generation of heavy launchers capable of lifting 70 to 130 tons of payload to LEO. Recent studies have shown that Ariane 5 ECA and the Atlas 5 heavy launcher could lift higher power nuclear power generators up to about 200 kWe and the Russian development would open the way to scaling up to MWe size power. In Europe an anti-nuclear climate is shifting to acceptance partly for climate change and partly for economic reasons. Together these developments indicate that space nuclear power will increasingly become part of the plans and policies of the major space-faring nations.

1.2 Purpose

The purpose of this Roadmap is to identify how Europe can develop and use space fission nuclear power. It takes account of potential applications, technical options, relevant expertise and infrastructure, resource requirements and safety, sustainability and public acceptance. It follows from the initial assessment of European capabilities in the Draft Roadmap and the recommendations of the first Advisory Board meeting. The objective is to present a credible development plan and to make recommendations for a programme of research and development to realise it.

1.3 Power Range

The power level range of different nuclear power sources (from small RHUs emitting watt to nuclear thermal propulsion reactors in the gigawatt range) and the comparison with terrestrial nuclear power sources (surface and submarine reactors) is shown in Figure 1.

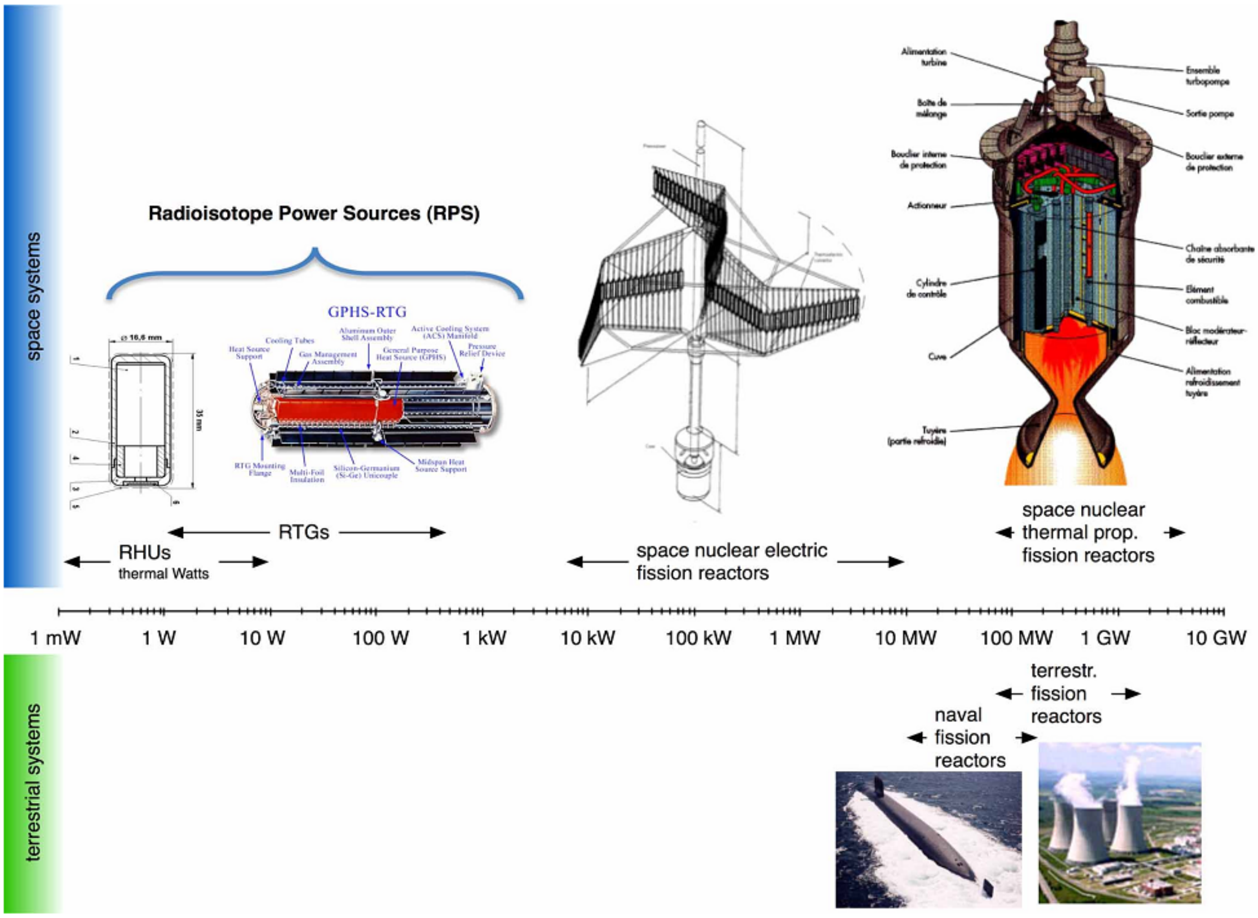

Figure.1. Power-level ranges of different typical space and terrestrial nuclear power sources (from Summerer and Stephenson, 2010).

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. It would be interesting to see what could be achieved with the lower power level and whether there were any significant differences in the capability and resources to deliver it compared to higher levels. For nuclear electric power generation the higher range is constrained to about 200 kWe by launcher capability although multi-MWe systems should be possible in the further future. Nuclear thermal propulsion has not been considered in detail because providing the infrastructure to develop and test it in Europe is considered very challenging.

1.4 Past Experience

The starting point for this Roadmap is past experience.

1.4.1 Projects

Russia and the US launched experimental reactors supported by terrestrial research and development. Russia launched some 35 missions to operate surveillance radar using fission nuclear power. Adapting the technology for nuclear electric propulsion did not advance beyond research and development. The main details of past and current projects and studies are given in Appendix A The key design features of the space nuclear fission projects which achieved launch or significant ground testing are summarised in Figure 2 below. (The table excludes testing for nuclear thermal applications in the NERVA programme.)

SPACE FISSION NUCLEAR POWER GENERATOR PROJECTS						
Project	SNAP-10A	Romashka	Bouk	Topaz-1	Topaz-2	SP-100
Country	USA	Russia	Russia	Russia	Russia/USA	USA
Development Status	Flight test	Prototype	32 Flights	2 Flights	Ground test	Prototype
Timescale	1965	1961-66	1970-78	1987	1992	1992
Reactor Type	Thermal	Fast	Fast	Thermal	Epi-thermal	Fast
Fuel	U-ZrHx	UC2	UO2	UO2	UO2	UN
Conversion Type	Thermo electric	Thermo electric	Thermo electric	Thermionic	Thermionic	Thermo electric
Neutron spectrum	thermal	fast	fast	thermal	epithermal	fast
Thermal Power KW	45.5	40	100	150	135	2000
Core temperature °C	585	1700	N/K	1500	1900	1377
Electrical Power KWe	0.5	0.5 - 0.8	3.5	6	5.5	100
Efficiency %	~1	~2	~3.5	~4	~3.7	~5
Mass kg	435	N/K	930	980	1061	5422
Specific Mass kg/Kwe	870	N/K	266	163	193	54
Control	Be	Be	Be	Be	Be	Be
Coolant	NaK	Louvres	Li	NaK	NaK	Li
Design Operation Years	1	1.5-2	1	0.9	3	10
Actual Operation Years	0.1	≤ 0.4	0.5	0.96	1.5	

Figure 2: Space Fission Nuclear Power Projects to Date.

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 but was not put into orbit. BOUK, which powered the Russian RORSATS, was similar in concept to SNAP (10A) but higher power. 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 to demonstrate nuclear electric propulsion was abandoned before launch. Not all parts of the US SP100 project were developed and tested on the ground and the mission was not launched. (The reactor was not assembled and insufficient fuel was made available.) A large amount of testing of nuclear thermal propulsion was, however, conducted under the US NERVA programme but no devices were launched.

1.4.2 Technologies

The most commonly considered reactor technologies to date have either been liquid metal or gas cooled with the radioactive fuel either in pins or particle beds. Liquid metal reactors tend to be more compact and therefore have less mass and less shielding mass because they are smaller. To achieve the necessary gas flow, gas cooled reactors are larger and heavier at least at industrial scale. On the other hand, liquid metal initial melting in space is a critical operation for liquid metal or Rankine cycle reactors

Thermal to electrical power conversion has tended to be thermo-electric or thermionic in the past but studies indicate that substantial improvements in efficiency can be achieved by Brayton or even Rankine cycle turbo alternators. Gas cooled reactors offer a direct cycle power conversion because the reactor coolant gas (for example a mixture of helium and xenon) is also the turbo alternator operating gas. A liquid metal cooled reactor operates indirectly through a heat exchanger which offsets some of the mass advantages from the smaller reactor. Brayton and Rankine cycle systems tend to become more attractive at higher power. For this reason the lower power generator is considered separately in WP31 and the medium to higher power generator in WP32. In both cases the objective of the work package is to assess the impact of nuclear fission power on European and partner space policies in terms of applications, technology, infrastructure and investment.

1.4.3 Studies

Subsequent studies have drawn heavily on the experience from the projects in Section 1.4.1. Mission analysis indicated that while a number of missions to the outer solar system could be feasible with the power levels provided by TOPAZ higher power gave significant benefit. Also much longer operating times would be required than had been demonstrated in orbit so far. 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, requires tens or hundreds of kilowatts of power depending upon the trade-off between specific impulse (Isp) 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, for example, 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. (Specific mass tends to be the key design driver for space nuclear generators.) The technology is scalable from tens of kilowatts to Megawatts but at lower power the complexity of the rotating machinery is a disadvantage compared to thermo-electric or thermionic conversion with no moving parts.

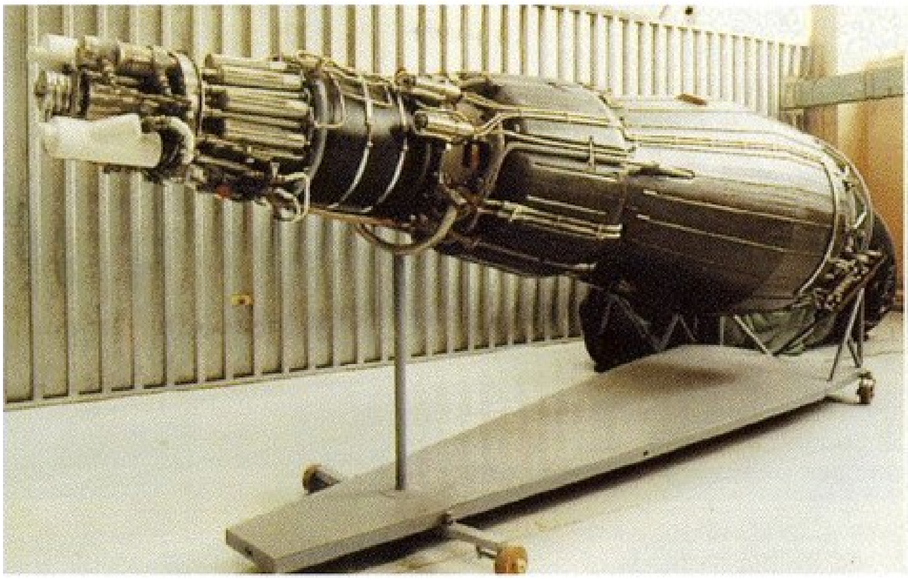

Figure 3 TOPAZ 2 or ENISEY (Courtesy NASA)

The studies have also examined the relative merits of gas cooled, heat pipe cooled and liquid metal cooled reactors. Although the relative simplicity of gas cooled reactors is an advantage for long lifetimes experience to date has been with liquid metal cooling. Gas cooled reactors tend to be larger to permit sufficient flow of gas over the reactor fuel without too great a system pressure drop which adversely affects the power conversion efficiency. This can result in reactor and shield mass penalties. Liquid metal cooling requires both a primary and a secondary coolant loop (liquid metal and gas) with the attendant additional pumping and heat exchanger requirements. Liquid metal cooled reactors require significantly greater energy to raise the coolant and reactor to an operating temperature. Future requirements are likely to prevent critical reactor operation below altitudes of 800 km. This energy is therefore likely to be required both for initial commissioning and for a 'cold' re-start in space if required.

Fixed, body mounted metallic radiators have been used in the missions to date. For the higher powers this type of design becomes high mass and area unless the operating cycle temperature can be raised significantly (radiator size varies with temperature to a fourth power law). Bumper tube protection from micro-meteoroids can in increase area by 30% and mass by 70%. Deployable radiators based on heat pipes and cooling panels require only micro-meteoroid protection for the main radiator cooling loop. Consequently they are relatively low mass but much larger area. In addition to the requirement for an additional heat exchanger (between the Bratyon cycle operating gas and the radiator coolant) there is the added complexity of packaging such a large structure for launch and deploying it safely. Alternatively, advances in lighter materials such as carbon fibre may offer new options for fixed radiators (provided that absorption of the coolant gas can be prevented).

Design lifetimes for the earlier projects tended to be constrained by fuel (or caesium in the case of TOPAZ) consumption. The concern for future larger generators is probably more associated with designing, building and operating 'maintenance free' equipment in challenging environments for 10 years or so, particularly critical items such as reactor control rods, coolant pumps and rotating machinery.

1.5 Current Activities

1.5.1 HiPER

The most recent EC sponsored study, High Power Electric Propulsion: a roadmap for the future included a Concept Design and Technical development Roadmap (developed by SEP, Rolls Royce plc and Acta srl) for a 200 kWe fission nuclear power generator ***[HiPER CD & RM]***.

1.5.2 NPPS and the Heavy Spaceship

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) ***[NPPS]***. This project (now called the MEGAWATT Class NPPS) was approved by the President of Russian Federation and accepted for realization during a period 2010-2018. During a period 2010—2012 will be the conceptual designs of NPPS and the heavy spaceship with computer modelling to substantiate the construction with required reliability and nuclear and radiation safety in emergencies. In 2015 should be done ground based testing of the NPPS systems and the working documentation for the heavy spaceship. During a period 2015—2017 should be done testing of NPPS, production and delivery of NPPS to the heavy spaceship. During a period 2014-2017 should be produced and tested non-nuclear systems of the heavy spaceship. The ground finishing development of the heavy spaceship, including the life tests of NPPS and preparation to the flight tests will be finished in 2018.

So far cooperation between the leading enterprises of ROSCOSMOS and ROSATOM has been established with the SSC Keldysh Research Centre responsible for the project and the NPPS. RSC Energia is the development centre for the heavy spaceship. The N.A. Dollezhall Research and Development Institute of Power Engineering (NIKIET) ROSATOM is the development centre for the reactor activity and the Kurchatov Institute is the research supervisor of the reactor facility development supported by ODB Fakel, VNIEM and the Design Bureau of the Chemical Engineering industry.

1.5.3 Megahit

It is understood that the EC will approve a new study of space fission electric power generation, Megahit for MWe power levels. The study should start in 2013.

2 APPLICATIONS AND MISSIONS

2.1 Applications

2.1.1 Background

Applications requiring or able to benefit from space nuclear power generation are described in Appendix B1. 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 (on say the moon or Mars) may be achieved with lower of higher power levels. Although not specifically listed there are secondary benefits from high power such as high data rate very long distance communications.

The lower power level of 30 kWe was selected for DiPOP study to investigate what applications might be sensibly delivered with a smaller system and whether there were any advantages in terms of technical options, European capability, resources (including cost and schedule), public acceptance, safety and sustainability.

The higher power level of 200kWE 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. This is because the mission design driver for manned missions is high thrust to achieve rapid transit times and reduce exposure to harmful effects such as radiation and weightlessness. Also manned missions tend to require considerably more supporting infrastructure.

The NPPS and heavy spaceship development and Megahit studies are understood to have access to a larger launch lift capability (Angara). The HiPER Concept Design is scalable from 100 kWe to 2MWe. Thus although manned missions were not considered in DiPOP many of the capabilities and resources required are directly applicable and can provide a useful input to the Megahit study.

Also, with a 200 kWe NEP 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 module for the humans can be sent separately by fast chemical or nuclear thermal propulsion once it is known that the infrastructure has safely arrived at for the destination.

2.2 Range of Potential Applications

The range of potential applications for 30 and 200 kWe nuclear electric power is summarised as follows.

2.2.1 Removing 'Dead' Spacecraft or Debris.

ROSCOMOS has studied the possibility of a large spacecraft capturing large pieces of space debris (such as 'dead' spacecraft or rocket upper stages) in Earth orbit and safely de-orbiting them. The concept envisages special cargo platforms for the de-orbiting once captured and a nuclear electric propulsion (NEP) 'space-tug. Higher powers of several hundred kilowatts of electrical power offer the most efficient design solution.

2.2.2 Ground Penetrating Radar and High Power Lasers.

High power (~30 kW) ground penetrating radar can map subsurface structures to depths of several kilometres. For science and exploration this provides a very useful remote sensor to investigate what lies beneath the surface for general surveying of for more specific reasons such as selecting a future landing site. It is of particular interest in looking for sub-surface water (or ice) in the search for evidence of (past) life or below the ice on a Jovian moon. In the future it can help select suitable sites for surface infrastructure particularly is they are to be providers of in situ resources. Although mining is mainly considered in terms of asteroids or NEOS because the escape energy is low for small bodies there is also the possibility of finding deposits of rare elements. Similar power is also appropriate for high power lasers for long range very high data rate communications or 'punching holes' in ice.

2.2.3 Surface Infrastructure

Nuclear power is well suited for surface infrastructure because it provides continuous power day and night (slightly higher at night because the radiator operates more efficiently at lower surface temperatures). The energy will be required to support robotic or human (fully or periodically occupied) for planetary outposts. Although the colonisation of the solar system may seem a distant future objective long lead times will shrink the timescale. Smaller power plants (~30kWe) will meet the requirements of initial settlements but larger established colonies may need megawatts of power to maintain a habitable environment, manufacture in situ resources and provide services such as charging electrical rovers.

Smaller power plants may also be suitable for space ports located at Lagrange points. This concept has become of interest for mission rendezvous (such as for a space tug to collect or deposit its cargo/payload) because the low gravity saves on the energy required to lift off from a planetary surface.

2.2.4 Asteroid Mining

There are a large number of asteroids or NEOs in convenient earth crossing orbits which are expected to have deposits of valuable elements. The Japanese Hyabusa mission demonstrated a small sample return from an asteroid. The evidence is therefore that larger more ambitious missions are feasible.

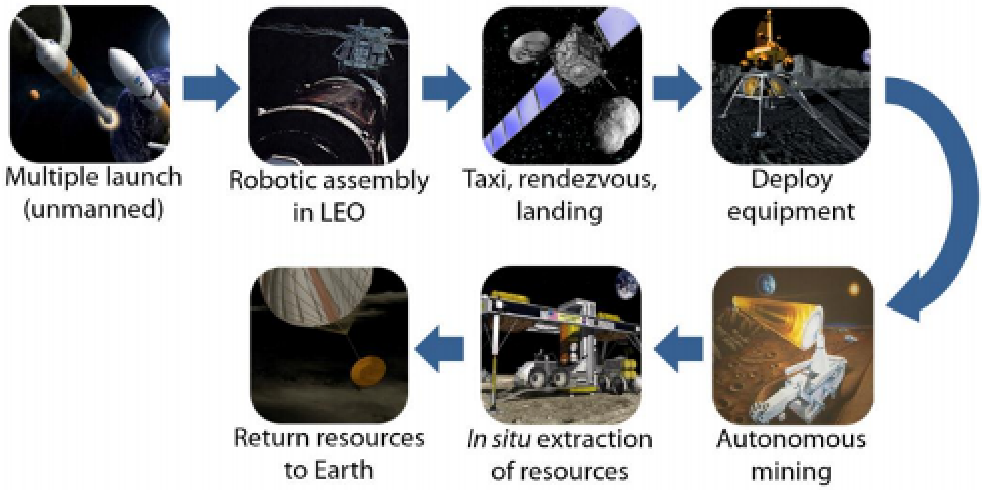

Figure 4 Illustration of Asteroid Mining Mission Phases.

Mining operations however need to take account of the substance of the asteroid as well as its movement. The resilience of the structure to a large spacecraft landing on it and removing significant quantities of material requires further investigation. More fundamentally the economics of asteroid mining depend on a wide range of factors which are difficult to determine and may change with political and economic circumstances on earth. One aspect which may help is that trip times are relatively short so that a space tug might be able to make several missions. The main trade-off would then be between fast/low Isp/high thrust/high propellant mass and slower/high Isp/lower thrust/lower propellant mass.

2.2.5 Asteroid and Comet Earth Collision Avoidance

Studies have shown that the gravitational attraction of a very large spacecraft can change the orbit of a near earth object (NEO) capable of inflicting severe damage by impacting the earth. The gravitational attraction has to be applied for a significant period of time and the spacecraft has to travel to a point in the NEO orbit where the gravitational force can be successfully applied. A large nuclear electric space tug is well suited to the mission requirements but such a mission would need considerable forward planning. Studies indicate that significant orbital change can be achieved but concern that there could be a miscalculation compounding the risk should not be underestimated.

2.2.6 Propulsion

The propulsion applications are principally based on the need for high power as solar energy decreases with distance from the Sun. These range from sample return missions to Mars and Jovian moons to taking scientific instruments to the edge of the heliosphere at the outer boundary of the solar system. Initially the missions are for science and exploration of the solar system. In the very longer term they could be the enabler of distant colonisation and possibly missions beyond the solar system. Nuclear power is the only technology which can enable us to reach these distant destinations with sizeable payloads. Although more complex the high Isp benefits in terms of economical propellant budgets make a strong case for nuclear electric as opposed to nuclear thermal propulsion but hybrid systems may need to be considered. Studies have made the case for smaller, less ambitious missions such as a one way transit to orbit Neptune with as little as 5 kW of power. Jovian moon sample return and asteroid mining however could benefit from 200 kW. Shorter distance missions to move large infrastructure to nearer planets or Lagrange points would also benefit from the higher power.

In the longer term, manned missions to Mars are expected to require megawatts of electrical power. The International Space Exploration Coordination Group (ISECG) now anticipates that the moon will be the stepping stone for a future Mars manned mission. The techniques including inter-planetary propulsion, in-situ infrastructure and descent/ascent will be proven on the moon first.

2.3 Prioritising Applications and Missions

The following advice was given at the First Advisory Board meeting was: “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.” A review of the potential applications, following this principle, is in Appendix B2 and led to the following conclusions.

Both the 30 kWe and the 200 kWe NEP space fission nuclear generators have the potential to fulfil a range of space science and exploration applications.

The 30 kWe generator appears best suited to planetary outpost power generation and missions designed around high power instruments. (At the First Advisory Board Meeting a mission to provide electrical power to a lunar outpost was identified as one of the easier to justify applications (Reference*** page 6). It was also thought that confidence would need to be built with robotic missions before consideration of a manned nuclear fission project.) Electrical power generation may also be the most likely future synergy with terrestrial applications. The smaller generator could also be used for NEO surveying or propulsion for small robotic science and exploration missions.

200 kWe (or greater) is needed for NEO mitigation and to transfer infrastructure for a split manned mission to Mars. While the probability of an earth threatening NEO remains low and the commercial case for NEO mining has yet to be made, robotic exploration of the outer solar system appears the best justification for developing a space fission nuclear power generator of this size. This size of generator could also power the NEP transfer of enabling infrastructure for a human mission to Mars. Use as surface power generator is likely to be 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, etc. Together with a need to provide power for planetary outposts, this has the potential to be the basis of a sustainable programme allowing non-recurring development costs to be amortised across several missions. Following the advice at the first Advisory Board meeting, depending on the science and exploration return, an orbital survey of an outer planet (possibly with a lander) may offer the best combination of benefit, affordability and probability of success.

3 TECHNICAL OPTIONS

A review of technical options for a 30 kWe nuclear fission generator is in Technical Note D31.2 30kWe Fission Power Source General Configuration Options, DiP-Isi-TN-001 D31.2 dated 31/08/2012 (Enclosure 1). The technical options for a 200 kWe nuclear power generator were also considered in the HiPER Nuclear Power Generation Concept Design ***[HiPER CD].*** In the end there was a fair degree of commonality between the two findings as summarised below.

3.1 Reactor, Control and Safety, Lifetime, Shield and Fuel

3.1.1 Design Constraints

The design features are based on those identified in HiPER Nuclear Power Generation Concept Design and the associated technology development roadmap. In summary these are:

- Compatibility with an Ariane 5 ECA launch to a minimum in-orbit commissioning altitude of 800km,
- Ten years of operation within an overall 15 year lifetime,
- Specific mass of 25 kg/kWe for a 200 kWe generated power or better (ie 5 tons mass and radiator dimensions compatible with the Ariane 5 fairing),
- Brayton cycle power conversion,
- High temperature reactor (fast indirect or epi-thermal direct) and conversion system,
- Robust design and resilience to sudden load fluctuations,
- Launch safety criteria for water immersion, etc.

3.1.2 Reactor Technologies

- Pin-fuel fast reactors: accepted as a potential core for inter-cooled recuperated (ICR) Brayton because of compact, low mass features.
- In-core thermionic reactors: rejected because of limitations of thermionic systems***[HiPER CD]***
- Particle-Bed and Pellet-Bed Reactors: accepted as potential core for Direct ICR Brayton cycle ***[HiPER CD]***.
- Refractory Metal Fast Reactors: recognised as viable alternative to particle and pellet bed reactors but not considered to have any advantages in terms of specific mass for 200 kWe but preferred for 30 kWe.
- High temperature ceramic reactors: not considered.

3.1.3 Control Systems

- Principles: the operating principle is ‘load following’ through negative thermal control, accepting a degree of ‘thermal lag’, and containment with beryllium reflectors.
- Control Rods: initially considered only for pin fuel fast reactors for Indirect cycle; subsequently also considered for direct cycle particle bed to reduce the core volume and provide emergency shut-down capability [a reflector is required in all cases; drums increase core radius but control rods may increase the gap between core and shield leading to a larger shield.].
- Control Drums: initially considered for 200kWe direct cycle particle bed to reduce shield penetrations and gap between the core and the shield (thus reducing shield size and specific mass);

subsequent trade-offs indicated that mass penalty of the larger core and shield out-weighed the penalties of shield penetrations.[See comment for control rods.]

- Control mechanisms: for 200 kWe both electrical and pneumatic drive were seen as intrinsically problematic at the operating temperatures envisaged and R&D was recommended to find the optimal solution; sprung rods were envisaged for emergency shutdown.

3.1.4 Coolant Routing

- Indirect cycle liquid metal: HiPER (200 kWe) assumed 10cm diameter pipe routed in spiral around the outside of the shield and partly embedded in it to reduce scattering; insulation may be needed to reduce heat loss and to remain within temperature limits for lithium hydride.
- Direct cycle gas: HiPER assumed 20cm diameter pipe routed in spiral around the outside of the shield and partly embedded to reduce scattering; insulation almost certainly required to reduce heat loss and remain within temperature limits for lithium hydride.
- Heat pipes: not considered in HiPER because of the difficulty in managing large shield penetration. (Note: the US SAFE 300 (100kWe design was based on heat pipes operating at 1450°K but the SAFE 400 (400kWe) primary coolant was flowing gas). Gas cooling also adopted for 30 kWe.

3.1.5 Lifetime:

Both 30 kWe and 200 kWe assumed reactivity for 10 years operations but design for 15 years overall lifetime to allow for non-operational or 'stand-bye' operation (eg when in orbit around a target planet). In principle shorter or longer operation can be scaled but initially 10 years appeared the best fit from mission analysis for typical missions (eg Jovian moon or Saturn ring sample return, Neptune orbit, multiple NEO sample return, planetary outpost power generation, high power instruments, etc.). However at the second advisory board it became clear that a 10 year operating life could require expensive fuel development. Mission analysis to establish actual operating requirements is therefore recommended.

3.1.6 Safety:

Both 30 kWe and 200kWe assumed critical operation below 800km altitude unlikely to be acceptable; in principle any altitude may be considered provided there is an acceptable risk assessment ***[HiPER CD]***; resistance to criticality from prolonged immersion in sea water or wet sand is also a safety criteria.

3.1.7 Fuel

- Ceramic oxide, carbide or nitride of uranium pellets: all were considered in HiPER; oxide fuel is an established standard, with well-known burn-up performance, but nitride was favoured for SP-100 because it achieves a higher density of fissile material. However, nitride fuel imposes materials compatibility constraints on the fuel cladding.
- TRISO fuel particles in carbon shells (or zirconium carbide shells as a potentially superior development) were considered for 200 kWe Direct gas cooled Brayton. The particles are held by perforated structures, permitting flow of the coolant gas. The moderating effect of the carbon in a particle bed or a pellet bed softens the neutron spectrum, so that these are epithermal reactors; the core power density is necessarily lower (than in a pin-fuel fast reactor) because fissile material is a relatively small volume fraction of the particle/pellet fuel. For longer life (25+ years) the arrangement proposed by Michael Worrall and Zeev Shayer ***[DiPOP 32.2]*** is of interest. High-Temperature Gas-Cooled Reactor (HTGR) concept utilizing cylindrical fuel pellets filled with TRISO particles. Highly enriched uranium (HEU) is placed at the core of each fuel block and is used as the main driver fuel, while thorium rods are placed near the outside and act as breeder fuel for U-233. In each fuel assembly, the fuel rods are arranged within either a graphite or beryllium oxide matrix. This is the preferred approach for 30 kWe. (For pebble and particle bed reactors, core power density depends on the critical size, not the amount of fuel. Carbon is not a good moderator leading to a larger critical size than liquid metal where the power density is smaller. The fuel power density is bigger for the pebble bed and particle reactor but burn up is high. Liquid metal has low fuel burn up, easier reactivity control and long operational life.)

- Uranium-tungsten alloy formed into small elements/particles or into wire-wound structures; this was also considered because such concepts may be lighter or more compact than particle/pellet bed reactors, depending on the volume fraction of uranium in the refractory alloy fuel.
- Enrichment: 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).

3.1.8 Shielding:

- Principle: a layered shadow shield design was adopted for both 30kWe and 200kWe optimised to attenuate both neutrons and gamma radiation, including secondary gamma, and limit scattering.
- Shielding Materials considered (with some variations in design approach):
  - Beryllium: selected for neutron attenuation/reflection a.
  - Beryllium Oxide: a possible alternative to Lithium Hydride to overcome (Lithium Hydride) thermal constraints
  - Boron Carbide: considered as an additional material for high thermal conductivity properties.
  - Boron metal: not selected as properties are less attractive than Boron Carbide and tungsten.
  - Lithium Hydride: selected for gamma attenuation despite thermal constraints.
  - Tungsten: selected for gamma attenuation (preferred to iron for strength) but location within the shield is sensitive in maximising the attenuation of secondary gamma.
  - Zirconium Hydride: not considered competitive with tungsten or Lithium Hydride.
  - Uranium bearing materials (including depleted uranium): no advantage over tungsten and more difficult to manufacture, etc.
  - Borated stainless steel: no advantages over tungsten,
  - Xenon tanks: shielding properties of xenon can provide additional shielding once an overall system design is known, (envisaged as a significant mass saving for 30kWe),
  - Internal heavy structures: shielding properties of internal heavy structures such as turbo-alternators could also be taken into account when an overall design is known
- Shadow angle: Shadow angle is 28° if the full Ariane 5 ECA fairing volume is used; an option of reducing to 24° with a very high temperature direct cycle gas cooled Brayton was also considered for the 200kWe Concept Design; 30kWe offers potentially narrow shadow angles.
- Penetrations: In HiPER, radiation ‘leakage through’ through control rod slides was considered undesirable but manageable subject to more in-depth analysis. Leakage through rotating control drum mechanisms was considered less of a concern. The geometry of a proposed more compact direct cycle reactor core limited the shield penetration to the control rod drive because the control rods themselves could be located between the shield and the core when withdrawn.
- Boom Length: For 200kWe calculations were made for a 22.5 metre boom. It was assumed that his was stowed for launch and extended in orbit before commissioning the nuclear power generator for compatibility with the Ariane 5 ECA fairing dimensions and to minimise structural mass.

3.2 Power Conversion Design Options

3.2.1 Thermo-electric:

Rejected for both 30kWe and 200kWe because of low efficiency and high mass; also its modularity is such that specific mass does not improve much with power. The absence of moving parts is a potentially important advantage and recent higher efficiencies with semi-conductor thermo-electric devices may possibly make future review worthwhile. (It is still considered a good option for low power systems at low operating temperatures due to compactness. It is worth considering with a fast neutron reactor and heat pipes where high power density can offset the lower efficiency.)

3.2.2 Thermionic:

Rejected for both 30kWe and 200kWe because although thermionic power conversion is a simple, compact and mechanically durable there are suggestions that thermionic cell performance deteriorates with time; caesium vapour is consumed during operation and is therefore life-limiting and it is a low efficiency process. (Europe has no experience of this technology.)

3.2.3 Direct inter-cooled and recuperated (ICR) Closed Brayton Cycle (CBC):

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 despite mass penalties of larger reactor core for gas flow and shield. Both 30kWe and 200 kWe considered turbine rotation of ~ 45Krpm but for 200kWe turbine blade creep life above 1100°K was identified as a problem requiring significant materials R&D.

3.2.4 Indirect (ICR) Closed Brayton Cycle (CBC):

Accepted as an option for both 30kWe and 200kWe for similar reasons to direct cycle and with the advantages of a more compact reactor and lower mass shield; the drawbacks are the added complexity of liquid metal pumping, the reactor coolant/operating gas heat exchanger and melting liquid metal for commissioning, cold starts, etc.

3.2.5 Stirling cycle:

In principle this is an option for 30kWe because of NASA research and development and the possible exploitation of radio-isotope power conversion development. But there are doubts about as seal loss through temperature gradient, cylinder interconnect dead volumes and off-resonance pistons in higher power systems. HiPER rejected Stirling for 200kWe as more appropriate for lower power systems and no perceived benefit in the complexity associated with multiple systems.

3.2.6 KRC (Potassium Rankine Cycle):

Rankine cycle looks attractive for >MWe but was rejected for 200kWe in HiPER because the high vapour temperature required was considered very ambitious (particularly in regard to turbine material properties), an operating principle of isentropic expansion is an unattainable ideal, vapour expansion to 80% quality is not likely to be achievable in practice, and the target 30% efficiency figure included no allowance for parasitic electrical consumption (actual efficiency was expected to be closer to that for Brayton).

3.2.7 Alkali Metal Thermo-Electric Conversion (AMTEC):

Rejected for both 30kWe and 200kWe because the technology is in an early stage of development and there are understood to be technical problems associated with the management of two-phase flow, high-pressure low-flow pumping of liquid metal condensate and avoidance of electrical short circuits through the liquid metal condensate flow path.

3.2.8 Magneto-Hydro-Dynamic generation (MHD):

Rejected for both 30kWe and 200kWe because the concept is undeveloped and there are technical issues about the life of the ionisation electrodes.

3.3 Radiator Options

3.3.1 General Considerations.

The radiator can be the largest mass contribution to the power generation system, particularly at lower operating temperatures. Fixed radiators are more compact and of a simpler construction. The coolant circuit in the deployed radiator design is normally isolated from the main (Brayton) operating gas by a heat exchanger. Any damage to the operating gas coolant circuit leading to a pressure drop leads to catastrophic system failure. Protecting this circuit from micro-meteoroids (or any other cause of damage) is therefore a critical feature. At very high temperature operation fixed radiators become very compact and mass competitive.

3.3.2 Fixed Radiators.

A fixed radiator design for 200kWe was considered based on nickel alloy pipework with an outer layer of barrier tubes for micro-meteoroid protection. At turbine inlet temperatures below 1300°K the volume for a 200 kWe generator exceeded volume of the Ariane 5 ECA fairing. If it can be sealed to prevent helium absorption carbon tubing, at 25% of the specific mass of nickel alloy, can make a major improvement to the overall system specific mass. Carbon/carbon is preferred for 30kWe.

3.3.3 Deployable Radiators

Deployable radiators are the only viable option for 200kWe lower temperature operation (on Ariane 5 ECA). A protected coolant loop with heat pipes and radiating panels gives inherent protection against micro-meteoroids but with the penalty of twice the radiating area of a fixed radiator and the additional complexity of heat exchangers and pumps ***[HiPER RM].*** There are also potential concerns about the radiation scattering from a large radiator weakening the effectiveness of the shadow shield and the possibility of heat pipes freezing and difficult to re-start in low power or power down operation.

3.3.4 Droplet Radiator

There has been a resurgence of interest in droplet radiators able to achieve up to a seventh of the mass of a heat pipe radiator for 1-100 MWth heat sources [DiPOP31.2]. Areas are still significant and require deployable structures and sensitivity to micro-meteoroids, spacecraft charging and magnetic fields present challenges. SSC Keldysh RSC plan to demonstrate a prototype on the ISS in 2013. If successful much of the need for very high temperature operation could be removed.

3.4 Electrical Power Management and Distribution (PMAD) Options

3.4.1 AC or DC Power Generation.

A Brayton turbo-alternator can deliver AC or DC current. Where the main supply is for NEP AC will permit a lower mass harness if there is some distance between the power generator and the electric propulsion. Rectification to DC will be required for the input to Hall Effect (HET) and Magneto Plasma Dynamic (MPD) thrusters. AC may be acceptable to gridded ion engines (GIEs) because of the need to transform to very high beam voltages. AC may not however be compatible with the use of a large (DC) battery for initial commissioning and acting as a load ballast. For 30kWe current DC technology can meet most needs; for 200 kWe a new generation of components and subsystems must be space qualified. Electrical equipment associated with the turbo-alternator is likely to have to withstand high temperatures and require cooling.

3.4.2 PMAD Mass Management

For 200kWe in particular a large battery, if required for initial commissioning and cold starts in space, will dominate the PMAD mass (HiPER estimated 40kWhr (Direct Cycle) and up to 100 kWhr (Indirect cycle). The greater energy is required to melt the liquid metal coolant and the surrounding structures to a point where the primary coolant loop can function and criticality can commence.

The alternative is a gas generator, for heating, and a smaller battery to start the turbo-alternators. The battery would also needed to smooth the power demand on the generator as thrusters were fired up (In HiPER thruster power was rated at 25kW for GIE and HET and 100kW for MPD; the turbo-alternators cannot tolerate more than a 10% over-speed which is less than the change in per-centage power drawn by any of the thrusters.)

For 200kWe another important issue is harness length if there is some distance between the electrical generator and the thrusters. In HiPER a configuration which protected the thrusters from direct exposure to reactor radiation and spacecraft structures from thruster efflux required a harness length in excess of 50m and estimated mass ~ 100-200 kg. Alternative strategies, such as high temperature super-conductors, are attractive in principle but would have to deal with several challenges: the high temperature of the spacecraft from the waste heat, connectivity issues associated with the extendable boom and (possibly) connection to a payload module in orbit. A very narrow thruster plume, such as the DS4G ion thruster, may permit the thruster and reactor to be located at the same end of the spacecraft. Attention would need to be paid to shield shaping to minimise thermal, gamma and neutron direct irradiation.

3.4.3 Sudden Large Load or Supply Change Management

In HiPER for 200kWe two mechanical safety devices were incorporated into the concept design to help protect against sudden major load loss causing the turbo-alternator to over-speed: a by-pass valve and an emergency, sprung-control rod to shut down the reactor (this also acted as protection against criticality during launch and was withdrawn on achieving a 'safe' orbit). A 'beam-out' on a single thruster with an automatic recovery in < 1s would not affect the turbo-alternator. The loss of a single thruster for an extended period could probably be managed by operation of the by-pass valve initially. The loss of the complete payload for more than a few seconds would probably require the emergency shutdown. An option is to provide a 'dummy load' either for each thruster or the whole propulsion load. It would have to be capable not only of absorbing excess generated power but also damaging transients. Again, in principle, the battery can assist in this to some extent. Even at 30kWe precautions must be taken to protect the power plant.

3.5 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 which can be achieved. Although there may be helpful development elsewhere Europe requires a materials research programme for high temperature reactor and control systems, including fuel, and high temperature turbo-alternators and radiators. Currently the relative advantages and disadvantages of Indirect and Direct systems appear finely balanced. Materials which allow higher temperature operation for 10 year lifetimes will tend to make the relative simplicity of gas cooled systems more attractive. The trade-off studies can therefore only be usefully conducted following the materials research.

4 EUROPEAN CAPABILITY (EXPERTISE AND INFRASTRUCTURE)

4.1 Background

The European Working Group on Nuclear Power Sources for Space ***[ENPS]*** recommended (Para 6.2.1 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*."

A range of European organisations and industry have relevant expertise and infrastructure to support a space fission nuclear power programme. They fall broadly into the following categories:

- Government Agencies with nuclear, space and research responsibilities.
- Nuclear Research Organisations with (or with access to) 'hot reactors'.
- Nuclear industries
- Non-nuclear space industry
- Universities.

4.2 Survey

4.2.1 Scope

A comprehensive survey of 'all potentially relevant existing facilities and capabilities in Europe' goes 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. (The survey was more for generic space fission nuclear power capabilities than specifically a 200 kWe generator because of the high degree of commonality in many aspects.) It is recognised that valuable research is also undertaken by many universities but with two exceptions (universities of Stuttgart (Germany) and Leicester (UK)) the view was taken that the research would be associated with relevant research organisations.

4.2.2 Conduct

A questionnaire was sent to the selected organisations requesting information on their expertise and infrastructure relevant to a space nuclear fission generator programme in the fields of:

- High temperature reactor technology: liquid metal and gas cooled fast reactors, reactor control mechanisms, coolant pipes and pumps, fuel production, shadow shielding, safety features, storage and transportation and in-orbit commissioning.
- Energy conversion: high efficiency thermo-electric systems and materials, high temperature Brayton cycle, radial turbo-alternators, power regulation, heat exchangers, leak-free encapsulation, power regulation, mass-efficient fixed radiators, deployable radiators and micro-meteoroid protection.
- Power management and distribution: high power rectifiers and switching, high power low mass bus, high power batteries and shunts.
- Project management (including public acceptance, safety and sustainability): requirements definition, feasibility assessment, system definition and design, prototyping, qualification, proto-flight build, launch and in-orbit support, safety and regulator issues and public acceptance.
- Launch and operations: transport to the launch site, assembly for launch, launch, in-orbit commissioning, operations, disposal and anomaly response.

4.2.3 Organisations

The organisations selected were:

- Government Agencies: ESA, CNES, DLR and UK Space Agency.
- Research Organisations: SCK-CEN (Belgium), CEA (France), ESF (Strasbourg), VTT (Finland), EC JRC (Germany and Netherlands), Demokritos (Greece), MTA EK (Hungary), NCBJ (Poland), VUJE (Slovakia), Studsvick AB (Sweden), PSI (Switzerland) and NNL(UK).
- Nuclear Industry: CV Rez (Czech Republic), AREVA (France), AMEC (UK), Rolls Royce plc (UK), and SEA (UK). (AREVA includes ex-Siemens in Germany)
- Non-nuclear Space Industry: Snecma (Safran) (France), Galileo Avionica (Italy), ThalesAlenia Space (Italy) and EADS Astrium (UK) (the EADS Astrium response is pan-European not just for UK).
- Universities: University of Stuttgart for public acceptance, safety and sustainability of an NEP programme and Leicester University because of its role in support of the UK Space Agency).

4.2.4 Relevance

Expertise and infrastructure for research into Generation IV high temperature reactors was considered highly relevant although operating temperatures are still lower than ideal for space. Expertise and infrastructure for the management of nuclear projects covering design, build, commissioning and operation was considered equally relevant as was the conduct of launch and operations. (Although there are a number of research reactors and projects to develop new high temperature research reactors a space fission reactor development programme would almost certainly require a dedicated facility. One possibility could be through the adaptation of existing industrial civil and submarine propulsion facilities.)

Examples of adapting existing facilities are recently produce coated fuel particles and the testing of a few fuel elements for the ANTARES project in MASURCA (a critical mock-up initially dedicated to a Fast Breeder reactor project).

Expertise and infrastructure for thermal management and developing large space structures was considered relevant for radiator design and build. Similarly experience in developing high power space systems is important (although the survey did not extend to propulsion) as is the ability to build large and complex spacecraft. For Brayton cycle power conversion it is recognised that there is a wide range of relevant capability within and outside the aerospace industry.

In all cases it is recognised that the operating temperatures in current research programmes are lower than required for a mass efficient 30 kWe or 200 kWe space nuclear fission generator. To operate at the higher temperatures requires significant material research and this capability in organisations and industry was also considered highly relevant.

4.2.5 Results

The results of the survey are in Appendix C. Not all the organisations have replied to date and some gave more general responses rather than complete the questionnaire itself. The responses were supplemented (especially in the absence of a response) from details provided on the organisations' web sites. In several cases helpful telephone conversations provided additional information.

The responses were sufficient to populate a 'European Organisation and Industry Capability Table' (Appendix C, Annex 2). This shows, even from the limited survey, potential capability in all the required areas. In most areas it also shows some depth of expertise and research infrastructure, particularly in the field of high temperature reactors, fuel, materials, power conversion, safety and sustainability. The main division of capabilities is:

- High temperature reactor technology: EC JRC, CEA, SCK-CEN, VTT, Demokritos*, MTA-EK, NCBJ, VUJE, PSI, NNL(UK), CV-Rez, AREVA, , AMEC, Rolls Royce and Leicester University*.
- Energy conversion: CEA, CNES, SCK-CEN*, Demokritos*, MTA-EK, NCBJ, VUJE, NNL(UK)*, AREVA, Snecma (Safran), ThalesAlenia (radiator), AMEC*, Rolls Royce*, SEA (Stirling) and Leicester University*.
- Power management and distribution: EC JRC, CNES, AREVA, Galileo Avionica*, AMEC*, EADS Astrium and Stuttgart University.
- Project management (including public acceptance, safety and sustainability): ESA, CNES, DLR, VTT (consultancy), MTA-EK, ESF, ThalesAleniaSpace, , AMEC (consultancy) EADS Astrium, SEA and Stuttgart University (public acceptance).
- Launch and operations: ESA, CNES and UK Space Agency (licensing).

[Note: * denotes study only.]

Although not specifically requested in the questionnaire the majority of organisations active in high temperature technology research also have relevant materials research capabilities.

The development of suitable radiator and high power systems requires the adaptation of relevant terrestrial techniques to the space environment. This is within the capability of the main European Space industry and research organisations but requires the associated research and development. Materials research associated with reactors and power conversion may also be relevant in this area.

Terrestrial arrangements for the storage and transport of nuclear equipment are equally applicable to space apart from launch and operations. 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.

4.2.6 Summary

In summary, Europe has potential capability in all aspects of a 30kWe or a 200 kWe space nuclear fission generator development but significant research would be required to realise the capability. Nor should the practicalities of converting what is essentially a research capability at this stage into a full development project be underestimated.

4.3 Interest

With few exceptions the organisations contacted expressed potential interest in a space fission nuclear power generator programme. There is however concern, particularly amongst industry, that research for such a long term gestation programme should be 100% funded. Although growing, space energy technology is still very small compared to its terrestrial counterpart and there is much greater motivation for industry to invest resources (expertise and infrastructure) in the larger terrestrial market. Evidence of a sustained space nuclear programme is therefore an important factor.

5 RUSSIAN AND US CAPABILITY

5.1 Russia

Current Russian capability is best reflected by progress in the Heavy Spaceship and MWe NPPS described in Section 1.5.2 and Appendix A. 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. The heavy lift capability of the Angara launcher development will be required for the MWe sized nuclear fission generator and even then there may be a requirement for some in-orbit assembly. Consideration is also being given to an emergency re-entry capsule to safely de-orbit the reactor in the event of a launch failure.

Lessons learned from progress in analysis and the preparation of a preliminary design package are relevant if they can be shared. The impression gained was that the development was based on current technology rather than significant new research and development indicating taking advantage of lower operating temperatures made possible with the droplet radiator. It was interesting that Brayton cycle turbo-alternator technology was suggested as a possible avenue for collaboration.

5.2 US

The US capability was summarised at the First Advisory Board meeting 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 and would have to be redeveloped. In principle the infrastructure of a space nuclear programme exists but may be difficult to access and expensive to adapt to future programmes. However there is at least a baseline capability which does not really exist in Europe”.

5.3 Collaboration Potential

At the First Advisory Board meeting a conclusion was that “Putting together a European, Russian and US collaborative programme is likely to be challenging because of sensitivities about control, schedule and quality management. Although sharing the costs would help the overall cost would inevitably be higher than the sum of the individual contributions. 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. It is understood that for the foreseeable future Russia has only Government as a source of investment. As it is published in ROSCOSMOS web site the declared price of the NPPS (project is 17 billion rubles (about M$ 560) in total for the period up to 2018 year. For Russia international cooperation is welcome. There is a clear understanding that sensitive issues such as using nuclear power and rocket technologies will require legal basis on a government level but hope that such cooperation will be supported by western governments. European support was identified as a potentially useful contribution to a collaborative programme.

6 CAPABILITY DEVELOPMENT

6.1 Europe

The challenge for Europe is both to make the technical advances identified, 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 with appear to be one way to make progress. Another would be through collaboration (with Russia).

6.1.1 Technical Advances

The areas of enabling research identified include:

- 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 pipework, etc., resistant to helium absorption, for Brayton cycle operating gas,
- High temperature, long life (creep resilient) turbine design and materials,
- (For 200kWe) high temperature, very high power electrical components and subsystems, including batteries.

6.1.2 Infrastructure

Initially research in Europe could make use of existing nuclear and non-nuclear research facilities. Organisations currently working on Generation IV civil reactor technology development have indicated a potential interest in collaborating with a space programme. As a longer term objective the European Working Group on Nuclear Power Sources for Space ***[ENPS]*** Section 6.2.3 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 has been suggested that the cost and schedule of providing the necessary infrastructure may be alleviated 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. Having the facility in a centre with many trained people can also be an economy factor.

6.1.3 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. Practical experience is nebulous but essential for a successful programme. It takes a long time and much effort to create and is all too easy to destroy. Creating it is dependent upon commitment to a sustained long term programme.

6.2 Russia and the US

Russia is in the process of developing a space nuclear fission programme drawing on past expertise and past and current infrastructure. From the minutes of the First Advisory Board meeting it is understood that the US would probably need to make a major investment in infrastructure and practical experience to re-start a space fission nuclear power programme. However some of the enabling research is well ahead of Europe. At the Second Advisory Board meeting a direct invitation was made by the Director General of the SSC Keldysh Research Centre for European participation in the MEGAWATT class NPPS programme. The potential scope for participation is understood to include political support for a space fission nuclear programme, turbo-alternator technology and materials research.

7 PUBLIC ACCEPTANCE AND PUBLIC DISSEMINATION

7.1 Background

The First Advisory Board considered DiPoP Deliverable D33.1 giving "Preliminary Recommendations for Public Acceptance" ***[DiPOP 33.1]***. The paper illustrates the potential hazards and how they may be overcome using the example of public concern over re-routing an inter-city rail link in Germany (so-called Stuttgart21). It identifies the different communities who must be considered and strategies for winning and keeping their support. An update of the Preliminary recommendations is in ***[DiPoP33.3]*** and a short synopsis of the principle of public acceptance using the main conclusions is at Appendix D.

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 who both understood the technical issues and the public concerns. This included both the 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 (and quite the opposite if not).

High uranium enrichment was considered necessary to design a sufficiently compact reactor for space This and other factors was why a Public Acceptance assessment study is a priority task before starting the assessment study on the nuclear reactors in order to take into account the suited recommendations. Public acceptance can be achieved by an interdisciplinary approach in which both aspects of knowledge dissemination and infrastructure, relevant for the safe performance of a project that involves nuclear power in space, have to be considered. In principle a minimum of three ruling facets has to be followed in order to achieve a public acceptance:

- Public outreach,
- Implementation of safety,
- Application of nuclear power in space in a mission with an adequate sustainability.

7.2 Questions Which May Need to be Answered

Public Acceptance should also be considered in the workshop proposed in Section 9.1 below. For space fission nuclear power public acceptance may expect good answers to the following questions:

- What is the benefit of exploring and potentially exploiting the outer solar system and beyond?
- Is nuclear power the only way we can do this effectively?
- Are the benefits worth the cost? Or should we be spending the money on other much needed developments? (ie we need to know within reason what the alternative investments might be)
- Can we manage the risk so that there is negligible (ideally no) danger to people and property or contamination of distant planets or objects?
- If nuclear power will replace established conventional space products how do we show that investment in the new technology is more advantageous than resisting change to preserve the old technologies?
- Are we alone in trying to make a case for space nuclear fission power or is this an aspiration in other countries? If so is there an opportunity to combine our efforts?
- What are the penalties of not investing in space nuclear fission power generation?
- What motivation of stakeholders and interest groups should be considered and how can conflicts of interest be avoided?

7.3 Factors Which May Affect Public Support

For the general public an important consideration is that government is spending their taxes wisely. For the stakeholders and interested parties the following need to be established:

- Definition of economics of technology,
- Need of sustainability: long term output:

- Benefit to individuals' wealth and consumption
- Benefit to individuals' pursuit of happiness
- Expense of space technologies
- Maintaining high competences in industry
- Paying for engineer/scientists
- High performance of engaged individuals
- Communication: avoid news like "millions burn down on launch pad crash".

7.4 Radio-isotope Experience

Public acceptance for the radio-isotope nuclear power sources in space will set an important precedent for nuclear fission power sources.

8 SAFETY

8.1 Background

A generic study of Safety and Sustainability ***[DiPoP33.2]*** examines the actions required in Europe to support a space fission nuclear power programme. The study also includes an analysis of the lessons learned from the recent Fukushima nuclear accident. It concludes that this was a preventable accident. Nothing occurred which would prevent adequate safety arrangements for a European nuclear space programme.

The use of nuclear power systems (NPS) was considered by the Joint Expert Group of the Scientific and Technical Subcommittee (of the United Nations Committee on the Peaceful Uses of Outer Space) and the International Atomic Energy Agency, Development of a Safety Framework for Nuclear Power Source Applications in Outer Space, 3rd IAASS (International Association for the Advancement of Space Safety) Conference, Rome, Italy, Oct. 2008.

In the "Principles Relevant to the Use of Nuclear Power Sources In Outer Space, 1992", Principle 4, the Safety assessment states:
"A launching State […] shall, prior to the launch, through cooperative arrangements, where relevant, with those which have designed, constructed or manufactured the nuclear power sources, or will operate the space object, or from whose territory or facility such an object will be launched, ensure that a thorough and comprehensive safety assessment is conducted. This assessment shall cover as well all relevant phases of the mission and shall deal with all systems involved, including the means of launching, the space platform, the nuclear power source and its equipment and the means of control and communication between ground and space."

8.2 Europe

<u>8.2.1 ENSaF</u>

The European Space Nuclear Safety Framework (ENSaF) is drafting a European Space Nuclear Safety Framework. It recognizes that:

- US and Russian setups demonstrate the need to involve organizations not present in the regular launch approval process,
- Space and nuclear safety experts from "big ESA MS" are drafting a technically sound European framework that:
  - provides a predictable, efficient, "workable" process for ESA missions
  - addresses the main concerns of participating MS
  - 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
- The study was initiated under General Studies Programme in 2005

- A letter exchange ESA-NASA during Spring 2006 permits for cooperation on sharing experience within ENSaF
- ENSaF is in close alignment with IAEA-STSC safety framework for NPS.

At the second Advisory Board meeting the point was made that the agreement of a safety framework is a starting point. Provision must also be made for the infrastructure to demonstrate that the safety requirements have been met. In principle this can only be done once the safety framework is agreed. In practice it is necessary to take full account of the infrastructure requirements during the agreement process in order to ensure that the safety framework is achievable and affordable.

8.2.2 Structure

High level development(s) are congruent with US safety rationale that has a heritage of some 40 years. Mid-level (ENSAF) development is in alignment with IAEA/STSC Safety Framework which in turn is congruent with the US approach. At working level the US approach is reported in the UN COPUOS NPS Workshops. Consequently it may be necessary to investigate access to Russian and US safety demonstration infrastructure as part of the safety framework agreement process.

8.3 Russia and the US

The following statement was provided by the Keldysh Research centre: “In Russia information about the NPPS Project is published on regular basis in accordance with international rules. Russia strongly follows all national and international rules to guarantee safety of any application of nuclear power in space. Till now we have a support on the Government level and from scientific society in our country and all over the world and hope to have such a support further.” The US already has established safety standards for nuclear power in space.

9 SUSTAINABILITY

9.1 Initiating a Sustainable Programme

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. A programme to start the iterative process needs to include mix of short term and longer term activities which would include the following:

- Identifying and prioritising science and exploration objectives and priorities for applications requiring fission nuclear power (by the science and exploration communities),
- Making a Short Term collaboration in the Heavy Spaceship and NPPS project (as invited by SSC Keyldysh Research Center general director) potentially including Turbo-alternator technology with a view to gaining practical experience of a space fission nuclear power project,
- Making an assessment of the technical development needed to achieve the performance of high temperature Brayton power conversion including both reactor and turbo-alternator technology.
- Initiating a workshop with all relevant European (and potential collaborating nations) nuclear and space organisations to:
  - Making an assessment of the equipment performance required to achieve the identified science and exploration objectives based on the initial assessments made in the DiPOP project, and the associated cost and schedule, including research and development of:
    - 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 programme).
- Propose a programme to achieve public awareness and secure public acceptance for a European space nuclear fission programme.

- Build a full database of the relevant European expertise and infrastructure to support the technical development building on the initial DiPoP representative survey,
- Establish a timetable to achieve a European regulatory safety framework for nuclear power sources in space and the infrastructure to deliver it.

9.2 Implementation

9.2.1 Lead Organisation and Schedule

Either ESA or the EC could convene a workshop as proposed. (It is understood that there are provisional plans for the EC to sponsor a workshop on Space Nuclear Fission Power generation in 2013.) 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. A workshop in 2013 is compatible with research starting in 2015 the Horizon 2020 programme.

9.2.2 Collaboration

If potential collaborating organisations were invited to the workshop the scope for mutually beneficial research collaboration and mission analysis can also be explored within this context. Potential collaboration can be considered from terrestrial European nuclear and non-nuclear organisations as well as other countries.

Participation in the MEGAWATT Class NPPS project is a unique opportunity for Europe to develop practical experience of space fission nuclear power. Early consideration of the invitation to participate is needed to be compatible with this project's schedule. Identifying research and development activities which are compatible with this objective and investigation of suitable funding arrangements by the EC in advance of the workshop is therefore recommended.

9.2.3 Planning

The MEGAWATT NPPS project is understood to be based on current technologies. However HiPER and other studies have demonstrated significant benefits in mass efficiency with higher temperature systems. These mass efficiency benefits are critical for improved performance, reducing launch constraints and consequently improved affordability. Initially progress to high temperature systems depends on developing materials with long creep life at high temperature and stress and resilience to environmental effects. This research is also expected to have potential applications outside space nuclear fission power.

The anticipated outputs from the materials research and the mission analyses will provide the necessary information for feasibility and project definition for future selected missions. The planning of this activity should where possible take account of lessons learned from the MEGAWATT Class NPPS project.

10 RESOURCES

10.1 Cost and Schedule

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. In fact the programmes are not really comparable because they have different starting points, differing applications and there is considerable uncertainty about many aspects of technical maturity, expertise and infrastructure. Estimates range from B$7-9 for the US Prometheus project to B$0.56 for the Heavy Spaceship and NPPS programme up to completion of pre-flight testing. Realisation of Prometheus in the JIMO mission envisaged a launch in 2017 after the project was started in 2003 (and cancelled in 2005) after an expenditure of ~M$100 (mostly in close out costs). The NPPS schedule starting in 2011 indicated readiness for launch in 2019/20 at a fraction of the projected Prometheus cost.

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 conservative but until more is known, particularly about likely performance requirements, is a current 'best guess'.

From the second Advisory Board meeting it was understood that cost and schedule were highly dependent on the scope to use currently proven technology. For example, developing a new fuel to give longer life was a major additional expense in the Prometheus programme. High temperature reactor design is estimated to require a 10 year research and development schedule. Once essential mission and performance requirements are better understood a better assessment of cost and schedule may be possible. The workshop and feasibility study as proposed in Section 9.1 could contribute to this assessment.

10.2 European Funding

10.2.1 Background

European Working Group on Nuclear Power Sources for Space ***[ENPS]*** made the following mid-term recommendations (Para 6.2.2):

- *Upstream research on nuclear power sources for space should be included as part of public expenditures (e.g. EC financial perspectives, national activities, European Investment Bank) (50 M€ for 2007-13).*
- *In terms of motivation, applications and resources, nuclear power sources for space in general and fission reactors in particular clearly involve a larger set of actors than space agencies. The European Commission as the most appropriate European entity shall federate the various interests*
- *Nuclear power sources for space involve a wide range of nuclear and non-nuclear technologies. Europe should concentrate its efforts on those aspects that offer synergies with other systems, especially energy conversion technology.*

10.2.2 European Commission.

The EC is 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 this 'organisational' roadmap for the delivery of 30 kWe and 200 kWe space nuclear power generators. . With the workshop suggested in Section 9.1 above, collectively these projects can achieve two conditions for consideration of a European space nuclear fission programme (noting that only a fraction of M€50 identified for 2007-13 has been allocated so far):

- A draft long term plan with agreed mission objectives and technical development, cost and schedule estimates,
- Identify specific research objectives for consideration in the EC Horizon 2020 programme.

10.2.3 European Space Agency.

ESA is currently sponsoring projects on low power (radio-isotope) sources for exploration projects but maintaining a 'watching brief' on EC fission R&D. ESA has a general studies programme which can be used for selected mission analyses.

10.2.4 Other Government Organisations and Industry

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 because the development timescale is too long for a reasonable return on investment. Governments and industry may also need to be persuaded that space fission nuclear power is a sustainable programme with a long term future.

11 CONCLUSIONS AND RECOMMENDATIONS

11.1 Conclusions

11.1.1 Precedent

Past experience indicates that fission nuclear power generation is technically feasible. Subsequent studies however indicate the need for significant technical development in Europe to realise the performance identified in the range of proposed applications. Current Russian plans for the MEGAWATT Class NPPS development are understood to be based on existing lower temperature nuclear fission reactor and power conversion technologies. This is made possible through the development of the droplet radiator.

11.1.2 Applications

There is a wide range of applications for which space fission nuclear power is potentially necessary mainly associated with the exploration of the outer solar system and supporting remote planetary robotic or manned infrastructure. Applications for two levels of power were considered: 30 kWe and 200kWe. Following the First Advisory Board meeting's advice, to select an initial mission which had demonstrable value but was straightforward enough to offer a high probability of success at affordable cost, applications were prioritised. Generating electrical services for a remote planetary outpost was selected for 30kWe. NEP and high power instrument operation for an orbital surveying mission to an outer planet is thought to best fit the criteria for 200kWe. The performance required for these applications would also support other applications. For 30kWe these include NEP small robotic missions to the outer solar system, NEO surveys and high power instrument operation. For 200 kWe they include NEO deflection and mining and large infrastructure (possibly in support of a manned mission) inter-planetary transport.

However the Second Advisory Board considered that power levels of 30-50 kWe could be provided on the Moon or Mars with solar panels and fuel cells. They therefore recommended an initial focus on the 200 kWe fission nuclear generator. Although no immediate threat from a NEO has been identified an NEP mission for NEO deflection was seen to be potentially the most likely application to gain support. Governments have a duty to protect their citizens and the public is more likely to see this as a justifiable investment than the exploration of the outer solar system.

As a 'rule of thumb' based on past studies and projects a 10 year operating life was seen as a requirement for the nuclear fission generator. The second Advisory Board suggested that it might be wise to review this requirement because of possible impact on development costs. Most applications orbital transfers are a mixture of thrust and 'coast' so that the actual full power operating time for the generator is significantly less than the mission time. Although this may not necessarily help the problems of 'creep life' in turbo-alternators it may avoid expensive, long-life fuel development.

11.1.3 Technical Options

A review of technical options indicated a preference for closed cycle Brayton power conversion with either an indirect liquid metal cooled or direct gas cooled fast reactor for both power levels. Stirling cycle power conversion is efficient and well researched in the US and subject of ESA radio-isotope based projects in Europe. At 30kWe it was considered that Brayton technology is marginally more resilient and is scalable up to MWe power levels. Materials research into the high temperature operation needed to achieve optimal mass efficiency for space reactors (including coolant and control systems), Brayton turbo-alternators and radiators is necessary to determine the trade-off between liquid metal and gas cooled. Research is also needed into very high power electrical equipment especially if required to work at high temperatures. The second Advisory Board also advised against totally rejecting thermo-electric and thermionic power conversion although Europe has no space expertise in these areas.

The heavy spaceship with NPPS programme requires the higher lift capability of the Angara launcher currently in development. Even with this development it may be necessary to launch major parts of the heavy spaceship on separate launchers and assemble it in space. The higher temperature materials and techniques identified in the HiPER study could significantly improve mass efficiency reducing launch costs, complexity, risks associated with in-orbit assembly and commissioning time. However the second Advisory Board envisaged the development timescale to develop high temperature reactor (including controls), shield and turbo-alternators to be of the order of a decade.

The second Advisory Board called attention to the difficulties caused to electrical equipment by high temperatures. The lower temperature operation of the Heavy Spaceship with NPPS was an advantage in this respect. The droplet radiator has considerable mass advantages over deployable heat pipe radiators (fixed radiators appear too large) but still requires large areas with implications for shielding and radiation scattering.

11.1.4 European Capabilities and Interest

A representative (rather than comprehensive) 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. These are designed to operate at up to several hundred degrees below optimal temperatures for space systems and are rather larger. However, there are many useful synergies, particularly in associated materials research, which suggest opportunities for mutual benefit.

The survey included nuclear and non-nuclear space industry whose capabilities included power conversion, structures (eg radiators), power management and distribution and project and mission management. Europe also has the facility to launch and operate conventional major space programmes and is active in developing a safety framework to include nuclear mission in the future.

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.

11.1.5 Russian and US Capabilities

In Russia the Heavy Spaceship and NPPS project indicates a much more advanced capability for NEP than in Europe. Opportunities have been identified for collaboration. Although NTP and NEP 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. It was anticipated that any short term US developments would tend to focus on power conversion rather than reactor development.

11.1.6 European Capability Development

European capabilities will have to be developed in terms of technical advances, infrastructure and practical experience. The technical advances are initially mainly in the field of materials research and in due course a prototype research reactor. There is the possibility of some joint use of Generation IV research facilities and renovating and using redundant, relevant infrastructure from civil and submarine projects. Practical experience is essential for success in such a programme. Opportunities for key personnel to work in relevant collaborative projects should be investigated.

At the second Advisory Board Russia invited Europe to participate in the Heavy Spaceship and NPPS project. It was suggested that European support for the project would be very helpful. There may also be scope for European participation in space turbo-alternator development. In the longer term research into materials for high temperature reactor, shield and turbo-alternator technology would also be useful. This would also appear to be the only current opportunity for Europe to gain practical space nuclear fission experience.

11.1.7 Public Acceptance

The principles of securing public awareness and public acceptance for a European space fission nuclear power programme are well understood. Monitoring progress and possibly collaboration with the radio-isotope nuclear space community is advisable.

11.1.8 Safety

Progress toward achieving a European regulatory safety framework for the use of nuclear power in space is necessary for both radio-isotope and fission nuclear power sources. The activity must also take full account of the infrastructure to demonstrate meeting the safety requirements. Nothing from lessons learned from the Fukushima accident would prevent establishing a sound space nuclear safety framework in Europe.

11.1.9 Sustainability

An iterative process is required to start a sustainable European space fission nuclear power programme. Justifiable missions must be selected to determine the required performance of the nuclear generator. Enabling, mainly materials, research is needed to understand if the required performance can be achieved at acceptable cost and schedule. 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.

In principle Europe needs initially to consider in more detail the requirements and resources for a European space fission nuclear power programme to determine strengths, weaknesses and priorities. In practice collaboration with Russia (and possibly other countries) appears the only practical, affordable and sensible way forward. Participation in the MEGAWATT Class NPPS project is a unique opportunity for Europe to gain practical experience of space fission nuclear power. In the longer term research in high temperature materials can deliver mass efficiency and performance to improve affordability.

11.1.10 Resources

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: for example, Prometheus inception to JIMO launch ~14 years and programme costs B$7-9; NPPS inception to launch ~ 8 years and development cost B$0.56. In HiPER for 200kWe a tentative schedule (including enabling research) was ~ 20 years from inception to launch allowing for 10 year life testing of critical systems.

This is partly because of the different range of expertise and infrastructure in Europe, Russia and the US and partly because the different projects have very different starting points. Prometheus was essentially a new development of a relatively high temperature reactor incorporating the quality control in the US nuclear submarine programme. It included an expensive fuel development project and a full mission (JIMO). The heavy spaceship and NPPS is based largely on current technology and is able to draw on other Russian development programmes.

To some extent Europe also has current technology experience but it has not been considered in the direct application to space. Nor does Europe have the parallel programmes, or relevant practical experience, on which to draw. A practical way ahead would be modest investment in the heavy spaceship and NPPS programme (to gain practical experience) in parallel with materials and sub-system research and development of higher temperature nuclear fission generators. On this basis better assessment of the resources required for a European programme could be made at the proposed workshop. A feasibility study, based on a specific application, is then required however to determine them sufficiently accurately for planning.

11.1.11 Roadmap Schedule

A view of the Advisory Board is that it would take a decade to make the technical advances to realise the next generation of space fission nuclear power. Based on Russian and US experience (and taking account of HiPER and other European studies) this indicates that Europe's first nuclear fission spacecraft could be launched in the 2030-35 timeframe. It also assumes that critical research starts in the Horizon 2020 programme in 2015 and that initial results are able to support mission analysis during the same period and both support first mission project Phases A and B.

11.2 Recommendations

It is recommended that:

11.2.1 The EC is invited to initiate a program line (within the Horizon 2020 programme) to:

- Identify and prioritise science and exploration objectives and priorities for applications requiring fission nuclear power (by the science and exploration communities),
- Make a Short Term collaboration in the Heavy Spaceship and NPPS project (as invited by SSC Keyldysh Research Center general director) potentially including Turbo-alternator technology with a view to gaining practical experience of a space fission nuclear power project,
- Make an assessment of the technical development needed to achieve the performance of high temperature Brayton power conversion including both reactor and turbo-alternator technology.
- Hold a workshop with all relevant European (and potential collaborating nations) nuclear and space organisations 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 programme).
  - Propose a programme to achieve public awareness and secure public acceptance for a European space nuclear fission programme.
- Build a full database of the relevant European expertise and infrastructure to support the technical development building on the initial DiPoP representative survey,

- Establish a timetable to achieve a European regulatory safety framework for nuclear power sources in space and the infrastructure to deliver it.

11.2.2 ESA makes provision for:

- Mission analysis of candidate missions identified in the workshop within the General Studies programme,
- The feasibility study of a candidate mission with a view to defining the resources required to deliver it either by Europe alone or in collaboration.

12 REFERENCES

12.1 Notes:

Only general references are listed here. References for projects and studies are listed in Appendix A. References for applications for space fission nuclear power are listed in Appendix B. References for Public Acceptance, Safety and Sustainability are listed in Appendix D.

12.2 References:

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[NASA-TM] ESAS Final Report, NASA-TM-2005-214062, November 2005.

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[DiPoP30.1] DiP-Sep-PL-001 D30.1 Fission Power Roadmap Draft02 Date: 20/02/2012

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[DiPoP32.3] DiP-Sep-TN-003 D32.3: 200KwE Fission Nuclear Power Source for Space Applications Date: 13/10/2012

[DiPoP33.3] DiPoP - IRS - D33.2 - Final Report on Public Acceptance and Recommendation on Public Dissemination Dated: 7/11/2012

[DiPoP33.3] DiPoP - IRS - D33.3 - Generic Study of Safety and Sustainability Issue 04 Dated: 31/10/2012

[DiPoPAB01] DiP-AB-MM-001 D30 DiPoP First Advisory Board Minutes Issue 02 Dated 17/02/2012

[DiPoPAB02] DiP-AB-MM-002 D30 DiPoP Second Advisory Board Minutes Issue 02 Dated 28/09/2012

13 ABBREVIATIONS AND ACRONYMS

AMTEC	Alkali Metal Thermo-Electric Conversion
Be	Beryllium
CBC	Closed Brayton Cycle
CEA	Commissariat à l'énergie atomique et aux énergies alternatives
CNES	Centre National d'Études Spatiales
CV-Rez	Czech Research Centre
DiPoP	Disruptive technologies for space Power and Propulsion
DS4G	Dual-stage 4-grid
EC JRC	European Commission Joint Research Centre
ENSaF	European Space Nuclear Safety Framework
ESA	European Space Agency
GES	Global Exploration Strategy
HEMP	High Efficiency Multi Stage Plasma Thruster
HET	Hall effect thruster
HEU	Highly enriched uranium
HiPER	High power Electric propulsion: a Roadmap for the future
HTGR	High temperature gas reactor
HUMEX	Human exploration
IAASS	International Association for the Advancement of Space Safety
IAEA_STSC	International Atomic Energy Agency, Scientific and technical Sub-committee
ICR Brayton	Intercooled, recuperated Brayton
IPR	Intellectual property right
ISECG	International Space Exploration Coordination Group
ISPU	In-situ power utilisation
ISRU	In-situ resources utilisation
ISS	International space station
JIMO	Jupiter iced moon orbiter
KOM	Kick off meeting
kWe, kWt	kW electric, kW thermal
LEO	Low earth orbit
Li	Lithium
MHD	Magneto-Hydro-Dynamic
MPD	Magneto-plasma dynamic thruster
MT	Midterm review
MTA-EK	Hungarian Academy of Sciences Centre for Energy Research
MTG	Micro-turbine-generator
MWe	MW electric
NaK	Sodium Potassium
NCBJ	National Centre for Nuclear Research (Poland)
NEO	Near earth object
NEP	Nuclear electric propulsion
NERVA	Nuclear Engine for Rocket Vehicle Application
NNL	National Nuclear Laboratory
NPG	Nuclear power generator
NPPS	Nuclear power and propulsion system
NPS	Nuclear power source
NR	Nuclear reactor (fission)
NTP	Nuclear thermal propulsion
PERT	Program Evaluation and Review Technique

PM#	Progress meeting
PMAD	Power Management and Distribution
PPU	Power processing unit
PSI	Paul Scherrer Institute
RHU	Radioisotope heater units
RTG	Radioisotope thermoelectric generators
SAR	Synthetic aperture radar
SCK-CEN	Belgian Nuclear Research Centre
SEA	Systems Engineering and Assessment
SEP	Space Enterprise Partnerships
SF-MPD	Self-magnetic field Magneto-plasma dynamic thruster
SNAP- 10A	Systems Nuclear Auxiliary Power Program (First fission reactor tested in space by US in 1965)
SP	Solar power (photovoltaic)
SP	Solar power
SRC	Source
TLC	Tele-command
TPPU	Thermal power processing unit
TRISO	Tri iso-structural
TRL	Technology readiness level
U_ZrHx	Uranium-zirconium hydride
UC_2	Uranium carbide
UN	Uranium Nitride
UN-COPUOS	United Nations Committee on the Peaceful Uses of Outer Space
UO_2	Uranium Oxide
VTT	Technical Research Centre of Finland
VUJE	Nuclear Power Plant Research Institute Trnava
WMD	Weapons of Mass Destruction
WP	Work package