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SPACE FISSION NUCLEAR POWER – A ROADMAP FOR EUROPE

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ABSTRACT

There have been a number of studies of fission nuclear power generation for space applications over the past decade. Mostly they focus on technical development required or perceived achievable. The EC FP7 Disruptive Technologies for Power and Propulsion (DiPOP) Study is investigating the wider issues. Which applications might attract the investment to develop space fission nuclear power generation? What expertise and infrastructure must be developed and what existing capabilities may be relevant? Which organisations might invest in developing the capability and for what reasons? What is required for public acceptance, safety and sustainability of space fission nuclear power?

At the request of the EC the DiPOP project has arranged for an international Advisory Board of experts to give guidance and review progress. The European Advisory Board member is from the Commissariat à l'énergie atomique et aux énergies alternatives (CEA). The Russian and United States Advisory Board members have first-hand experience of space fission nuclear power projects.

A Fission Nuclear Power Generation Draft has been created with the guidance of the Advisory Board. It draws on past and current projects and studies and identifies a programme of work to fully investigate the issues. Results from research during the summer of 2012 will be used to update the Roadmap to a final version for review in September and publication in October. This paper will give a preliminary presentation of the findings.

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INTRODUCTION

So far the ‘Global Exploration Strategy’[1] has focussed on a roadmap to explore 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[2].

[1] The Global Exploration Strategy: the Framework for Coordination, May 2007.

[2] HiP-AST-D-2.7-i1r1 HiPER Consolidated Mission Analysis 8th December 2011.

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Nuclear power is recognised[3] as a key enabling technology for the Global Exploration Strategy. High power generation is one of the fundamental capabilities which are a common essential requirement for both inner and outer solar system exploration. Mission analysis has consistently 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 (NTP) or nuclear electric (NEP) 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 much greater than 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[4]. Activity lapsed during the last decade because of the focus on the inner solar system and funding constraints. With the GES 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 for climate change and 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.

PURPOSE

The purpose of the 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 an 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.

POWER RANGE

The power level range of different nuclear power sources is from small RHUs emitting watts to terrestrial civil nuclear thermal electric fission generators in the gigawatt range. 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

[3] IAC-10-A3.1.1 Assessing Space Exploration Technology Requirements as A First Step To-Wards Ensuring Technology Readiness For International Cooperation In Space Exploration by CSA, NASA, ESA and JAXA October 2010.

[4] IAA Commission III SG2 Nuclear Space Power and Propulsion Autumn 2007.

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 Ariane launcher capability although multi-MWe systems should be possible in the further future. Nuclear thermal propulsion has not been considered because providing the infrastructure to develop and test it in Europe is considered very challenging.

PAST EXPERIENCE

Projects

Russia and the US have launched experimental reactors supported by terrestrial research and development. Russia launched some 35 missions to operate surveillance radar with fission nuclear power. Adapting the technology for NEP did not advanced beyond research and development.

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.

Studies

Subsequent studies have drawn heavily on the experience from these projects. 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, needs tens or hundreds of kWe depending on 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, 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, which tends to be the key design driver for space nuclear generators. The technology is scalable from tens of kilowatts to Megawatts but the complexity of the rotating machinery is a disadvantage compared to thermo-electric or thermionic conversion with no moving parts.

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 pumps and heat exchanger. Future requirements are likely to prevent critical reactor operation below altitudes of 800 km. Liquid metal cooled reactors require significantly more energy to heat the coolant and reactor to an operating temperature for commissioning or a 'cold' re-start.

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

Earlier project design lifetimes were constrained by fuel (or caesium) consumption. For future larger generators, designing, building and operating 'maintenance free' equipment critical items such as reactor control rods, coolant pumps and rotating machinery in challenging environments for 10 years or so is also a concern.

HiPER

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

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5 HiPER Nuclear Power Generation Concept Design HiP-SEP-D-3.9-i1r0 dated 31st May 2011.

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NPPS and the Heavy Spaceship[7]

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

APPLICATIONS AND MISSIONS

Background

Applications requiring or able to benefit from space nuclear power generation have been researched. At the lower end of the scale are high power instruments such as ground penetrating radar. The higher power tends to be more needed for propulsion. Some applications, such as asteroid/NEO mining or power plants for surface infrastructure (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 which applications might be sensibly delivered and whether there were advantages in terms of technical options, European capability, resources, 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.

The NPPS and heavy spaceship development and is understood to be directed at manned space missions with access to a larger launch lift capability. 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.

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 (than combined infrastructure and human) module for the humans can then be sent separately by fast chemical or nuclear thermal propulsion once it is known that the infrastructure has safely arrived at for the destination.

Range of Potential Applications

Identified potential applications are:

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

Prioritising Applications and Missions

The First Advisory Board advised that: “As a general principle it was advisable to select an application for which there is a clear need, make the mission as technically uncomplicated as possible to reduce technical risk and to (as far as possible) ensure success. Once a successful precedent has been established, more sophisticated missions may be investigated.” A review of the potential applications, following this principle led to the conclusion that 30 kWe and the 200 kWe

[6] HiPER Nuclear Power Generator Roadmap HiP-SEP-D3.8-ill0 dated 6th May 2011.

[7] Project of Creation of Heavy Spaceship with Megawatt-class NPPS. A. S. Koroteev, V. N. Akimov, C. A. Popov

NEP space fission nuclear generators can potentially 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. 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 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. 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 (the criteria suggested by the Advisory Board).

TECHNICAL OPTIONS

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

Design Constraints

Design constraints (identified in HiPER[8]) are:

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

Reactor Technologies

The preferred options were pin-fuel fast reactors for indirect ICR Brayton because of compact, low mass features or particle-bed and pellet-bed reactors for Direct ICR Brayton cycle. In-core thermionic reactors were rejected because of limitations of thermionic systems and refractory metal fast reactors are a viable alternative to particle and pellet bed reactors. Though not considered to have advantages in terms of specific mass for 200 kWe they are preferred for 30 kWe.

Control Systems

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

Fuel

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

Shielding

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

Power Conversion

In principle Stirling Cycle is an attractive option for 30kWe because of NASA research and development and the possible exploitation of radio-isotope power conversion development. But there are doubts about seal loss through temperature gradient, cylinder interconnect dead volumes and off-resonance pistons in higher

[8] HiPER Nuclear Power Generation Concept Design HiP-SEP-D-3.9-i1r0 dated 31st May 2011.

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power systems. Direct inter-cooled and recuperated (ICR) Closed Brayton Cycle (CBC) was narrowly preferred for 30kWe and accepted as an option for 200kWe for good efficiency, simplicity of design, no freezing of reactor cooling and turbo-alternator operating gas 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. Indirect (ICR) Closed Brayton Cycle (CBC) is an alternative for both 30kWe and 200kWe for similar reasons to direct cycle, 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.

<u>Radiators</u>

Both fixed and deployable radiators are options. At very high temperature operation fixed radiators become compact and mass and area competitive.

<u>Power Management and Distribution (PMAD)</u>

Options to consider are:

- AC or DC current,
- Mass efficient very high power distribution,
- Battery size and functions (commissioning, load ballast, etc),
- High temperatures.

<u>Summary</u>

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 this 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.

EUROPEAN CAPABILITY (EXPERTISE AND INFRASTRUCTURE)

The EWG on NPS for Space [9] recommended (Short Term Actions) that: “*A European roadmap for the development and use of nuclear power sources for space should be elaborated, differentiating in terms of the typology and the timescale. It should include a comprehensive inventory and assessment of all potentially relevant existing facilities and capabilities in Europe*.”

<u>Survey</u>

A comprehensive survey of ‘all potentially relevant existing facilities and capabilities in Europe’ was beyond the scope of DiPOP. However it has been possible to conduct a ‘representative’ survey based on the key government organisations, nuclear research organisations and industry. It is recognised that valuable research is also undertaken by many universities.

<u>Conduct</u>

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.
- PMAD: 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.

<u>Relevance</u>

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

[9] European Working Group on Nuclear Power Sources for Space Report, March 2005. Section 6.2.1

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 submarine nuclear facilities.)

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 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 was also considered highly relevant.

Results

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. 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. 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 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.

The conclusion is that Europe has the 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.

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.

RUSSIAN AND US CAPABILITY

Russia

Current Russian capability is best reflected by progress in the Heavy Spaceship and MWe NPPS. This suggests considerable progress in the enabling materials research identified as necessary for a European nuclear fission generator programme. It would also appear that the design concepts are similar in principle to those proposed for 30kWe and 200kWe European projects but on a larger scale. It is less clear how a spacecraft of this size will be launched and commissioned at a 'safe' altitude.

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".

Collaboration Potential

The First Advisory Board meeting concluded 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.

CAPABILITY DEVELOPMENT

Europe

The challenge for Europe is 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 may be one way to make progress. Another would be through collaboration.

Technical Advances

The enabling research identified includes:

- Materials for high temperature liquid metal and gas cooled reactors including fuel, control and coolant routing arrangements,
- Materials for low mass and area, micro-meteoroid protected radiators,
- Low mass high temperature 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.

Infrastructure

Initially research in Europe could make use of existing nuclear and non-nuclear research facilities. As a longer term objective the EWG on NPS for Space[10] recommended that "*Fission reactors for power and propulsion should be considered more intensively. A first objective should be the development of a prototype at ground level*." This would be necessary for project definition (Phase B1).

It may be possible to alleviate infrastructure cost and schedule by re-use of existing facilities. For example, it is understood that several former reactor testing buildings are still in good shape at Saclay and Cadarache for research reactors no longer used such as Rapsodie. If the safety systems and air filtration units are still operative it is not necessary to invest in a new "class 1" building and safety studies are also simplified since they are reusing former ones.

Practical Experience

A programme of 'cross-pollination' between the nuclear and space communities would be a good starting point. This could be supplemented by collaborative activities and extended to direct participation in a nuclear space project. 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.

PUBLIC ACCEPTANCE AND DISSEMINATION

The importance of preparing public outreach study/material for nuclear space technology to be developed and proposed to EC / Europe was recognised. A similar approach had been used for the Prometheus programme (using the Keystone Centre in Colorado). The recent launch of RTGs and RHUs in the US still attracted small protest groups. It was essential to assemble a team 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.

Uranium enrichment was considered necessary to design a sufficiently compact reactor for space. This is one factor was why a Public Acceptance assessment study is an early priority task before to take into account the suited recommendations.

[10] European Working Group on Nuclear Power Sources for Space Report, March 2005. Section 6.2.3.

An important public consideration is safety and that government is spending their taxes wisely. The following need to be established:

- Definition of the economics of the technology,
- The need of sustainability: long term output in terms of:
  - Benefits to wealth and consumption,
  - Benefit to individuals' happiness,
  - Acceptable space technologies spend,
  - Maintaining industrial competences,
  - Paying for engineer/scientists,
  - High engaged individual performance.
- Good communication: avoid news like "millions burn down on launch pad crash".

SAFETY

"*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*[11]."

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 member states,
- Takes advantage of the existing European nuclear safety expertise and experience gained on the subject in US and Russia
- Provides a technically sound basis for an early decision on processes, roles and responsibilities

The study was initiated under General Studies Programme in 2005. A letter exchange ESA-NASA during spring 2006 permits cooperation on sharing experience. The US has established safety standards for nuclear power in space. 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.

[11] Principles Relevant to the Use of Nuclear Power Sources In Outer Space, 1992", Principle 4

SUSTAINABILITY

Europe is unlikely to fund enabling research for a space nuclear fission programme until an application (or range of applications) has been identified which is justified in terms of benefit, credibility and cost. It is difficult to determine benefit, credibility and cost until the enabling research has helped to quantify the performance which may be achieved. A way to start the iterative process would be a workshop for the space science and exploration, space mission and spacecraft design and nuclear communities with a view to:

- Identifying and prioritising science and exploration objectives and priorities for applications requiring fission nuclear power,
- Making an initial assessment of the required equipment performance to achieve them,
- Making an initial assessment of the technical development to achieve the performance and associated cost and schedule,
- Initiating a database of the relevant European expertise and infrastructure to support the technical development building on the initial representative survey,
- Identifying potential trade-offs between objectives, performance, technical development, schedule and cost.
- Proposing 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.
- Assess the progress required to achieve a European regulatory safety framework for nuclear power sources in space.

Either ESA or the EC could sponsor a workshop (EC sponsorship is understood to be proposed). The output of the workshop and mission analysis can then provide a basis to determine specific enabling research projects in the EC Horizon 2020 programme and further mission analysis could be sponsored by ESA as part of the General Studies programme. A workshop in 2013 is compatible with research starting in 2015 the Horizon 2020 programme. Inviting potential collaborating organisations from outside Europe would allow investigation of the scope for mutually beneficial research collaboration and mission analysis.

Longer Term the outputs from the materials research and the mission analyses will provide the necessary information for feasibility and project definition for a selected mission.

RESOURCES

Estimating the cost and schedule of a European fission nuclear power programme is difficult because there appears to be wide divergence in the evidence from past and current comparable programmes. 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 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). 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.

An EWG on NPS[12] recommendation was: *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.

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 this Roadmap, 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.

ESA is currently sponsoring projects on low power (radio-isotope) sources for exploration projects but maintaining a 'watching brief' on EC fission R&D. Funding from other government organisations and industry in the short term is likely to be dependent upon 'spin-off' into profitable non-space (or non-nuclear space) applications because the development timescale is too long for a reasonable return on investment. Governments and industry also need to be persuaded that space fission nuclear power is a sustainable programme with a long term future.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

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

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

- Generating electrical services for a remote planetary outpost was selected for 30kWe.
- An outer planet orbital surveying mission (NEP and high power instrument) for 200kWe.

(The performance for these applications would also support other identified applications.)

Closed cycle Brayton power conversion with either an indirect liquid metal cooled or direct gas cooled fast reactor is selected for both power levels. (Stirling cycle power conversion is efficient for 30kWe, well researched in the US and in ESA radio-isotope based projects but considered marginally less resilient

Materials research into the high temperature operation needed to achieve optimal mass

[12] European Working Group on Nuclear Power Sources for Space Report, March 2005 Section 6.2.2

efficiency for space reactors, Brayton turbo-alternators and radiators. Research is also needed into very high power electrical equipment operating at high temperatures.

A representative (rather than comprehensive) review of the capabilities of European government organisations research centre, 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 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.

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.

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.

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.

The principles of securing public awareness and public acceptance for a European space fission nuclear power programme are well understood.

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.

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 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.

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. Some better assessment of the resources required for a European programme may be possible at the proposed workshop. A feasibility study is required however to determine them sufficiently accurately for planning.

RECOMMENDATIONS

Provisional recommendations of the Roadmap are:

- To update the Roadmap from comments and advice from the Advisory Board,
- Invite the EC and ESA to initiate the workshop and mission analysis activities with a view to creating the basis for a European space nuclear fission programme,
- Invite the EC to make provision for enabling research in the EC Horizon 2020 programme.