IS THERE A FUTURE FOR FISSION NUCLEAR ELECTRIC PROPULSION
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Abstract

This attempt to answer the question 'is there a future for fission nuclear electric propulsion?' is based on the findings of two recent studies. Technical issues were investigated in the High Power Electric Propulsion; a roadmap for the future (HiPER) project by Space Enterprise Partnerships (SEP), Rolls Royce and Acta srl. Applications, expertise (and experience), infrastructure, resources, public acceptance, safety and sustainability were then investigated in the Disruptive Technologies for Power and Propulsion (DiPoP) study. The DiPoP team comprised SEP, KopooS Consulting, ISIS_R&D, DLR and the University of Stuttgart. The DiPoP space fission nuclear electric findings were reviewed by an Advisory Board of European, Russian and US experts. Both studies received funding from the European Union Seventh Framework Programme (FP7/2007-2013).

I Introduction

The key to answering the question, 'is there a future for fission nuclear electric propulsion?' is in determining collectively if:

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- There are justifiable applications which can only (or best) be achieved with the technology,
- Europe can successfully master the technology with or without collaborating with other nations,
- The resources can be found to deliver a safe and sustainable programme,
- There would be sufficient public support for such a programme and the political will to deliver it.

A. Applications

A range of potential applications was identified in the DiPoP study including sample return to a Jovian moon, missions to the outer planets and the heliosphere, asteroid deflection and asteroid mining, multiple large infrastructure transportation (space tug) and a large planetary in-situ power source. Although 200 kWe is not sufficiently powerful for a manned mission to Mars because the trip time is too long, it could carry cargo taking the infrastructure for descent and ascent to the Martian surface in advance of the manned spacecraft. By saving mass, much less power would then be needed for fast transit by a manned spacecraft, which could rendezvous with the infrastructure in orbit around Mars. The most compelling application in principle was assessed as asteroid deflection, if a large earth-threatening asteroid is detected with sufficient warning time. (Nuclear thermal propulsion is assessed to require less warning time, but at much higher risk of not achieving a successful deflection.)

B. Technology

A basic assumption in the HiPER project[1,2] was compatibility with an Ariane 5 ECA launch to a minimum injection altitude of 800 km before the reactor could be allowed to go critical. Although essentially an artificial constraint, this introduced a basis for design discipline accepting that the technology is scalable to a launcher with a greater lift capability. The aim of the study was evaluate the maximum size of fission nuclear electric generators that could fit within this constraint. Indirect, liquid-metal cooled and direct gas cooled reactor, with Brayton cycle power conversion, conceptual designs were assessed to be the most promising candidate technologies.

The initial concept design, based on state-of-the-art technology, encountered two principal limiting factors: Brayton gas turbine high temperature creep life and the high density of nickel alloy fixed radiators. Additional constraining factors included electrical equipment temperature control, efficient high power distribution, commissioning and cold start energy budgets, potential conflicts between reactor radiation protection and thruster efflux impingement and design consistent with an acceptable launch centre of mass.

A technical development roadmap identified a research programme to overcome or mitigate these constraints. Incremental increases in turbine creep life and temperature look feasible but with increasing technical risk. Developments in carbon-carbon tubing, sealed to prevent porosity to the Brayton cycle operating gas, can reduce mass significantly. Strategies to manage the additional constraints were also proposed. In principle these technical developments indicated that a 200 kWe generator, capable of a return trip to a Jovian moon (assuming a lifetime ~ 10 years) could be achieved with a single Ariane 5 ECA launch.

C. Capability

Europe has no direct experience of space fission nuclear electric propulsion although there is early research into low power radio-isotope devices. Current civil generation IV nuclear power research includes high temperature gas cooled direct Brayton cycle technology, but there are significant differences in research objectives; highly enriched fuel for mass efficiency in space is at odds with terrestrial objectives to reduce enrichment and focus on maximising burn-up, for example. However there is scope for some common research objectives, particularly in high temperature materials.

The US has experience of space fission nuclear power but the technology has not been a high priority in recent years. Russia has embarked on the Megawatt Class Nuclear Power and Propulsion System (NPPS) building on the experience from the earlier Buk (RORSAT) and TOPAZ programmes. Started in 2012 the objective is understood to complete ground testing for a nominal launch date of 2019 using currently available technologies. Russia therefore has the infrastructure in terms of development, test, qualification and launch for a space nuclear fission electric propulsion programme. In principle the US could adapt facilities to provide the infrastructure for development, test and qualification. Launch is a more open question. Europe might be able to convert redundant nuclear submarine facilities for testing and qualification but would also have to develop a prototype test reactor.

D. Resources

Resource requirement assessments revealed a wide disparity between time and cost quoted for different projects. Much of this was because the scope was different (eg full development and mission against just development). However several themes emerged from resource investigations. Potential interest in collaboration was indicated by several organisations where there might be synergies between terrestrial generation IV fission reactor R&D and space requirements. The possibility of converting redundant military facilities for reactor research was also voiced. More importantly a direct invitation to participate in the Russian NPPS project was made during a DiPoP Advisory meeting. A way of harnessing all these potential resources would probably be a necessary starting point and building on current Russian expertise, experience and activities would be the key to minimizing resource requirements.

E. Public Support and Political Will

Public acceptance is thought to be achievable provided that the application can be shown to be necessary with a sensible use of resources. Safety, based on previous experience, is also thought to be manageable although Europe still has to develop a Safety framework for launch of a nuclear powered spacecraft. Sustainability will depend on agreement to a family of nuclear electric powered applications because the investment in a single mission could not be justified.

The evidence is that the capability for a space nuclear fission electric powered mission exists and could become a reality early in the next decade. The question as to whether there is the will to make it happen still probably needs to be answered. If such a mission is seen to be the least risky way to prevent a large asteroid striking the earth and causing major damage, there is a high probability of attracting public support and the necessary resources. In practice warning times dictate that the capability would need to be developed before such a threat was detected. This paper discusses the likelihood that other, less clear-cut arguments for space nuclear fission electric power will prevail.

II. Applications

A. The NEO Threat

During the DiPoP study a view emerged that preventing the threat of a large NEO impacting the Earth would be the most compelling incentive to develop a space nuclear electric or nuclear thermal propulsion capability. The deflection techniques considered range from ‘pushing’ (either physically or using gravitational attraction), suited to NEP, or ‘impact’, suited to NTP. ‘Pushing’ tends to be associated with greater control but requires more time for rendezvous with the NEO and the ‘pushing’ operation.

There are large uncertainties associated with existing predictions of the threat from NEOs. Currently the NASA JPL NEO Programme Sentry Risk Table identifies no NEOs which pose a significant hazard to Earth as assessed by both the Palermo and the Torino scales. The survey covers 404 NEOs and their impact potential to 2110 as of August 2012. Although the impact probability is low in all cases (<1/500) most of the objects will approach the earth on at least 4 occasions during the period until 2110 and updating may change the probability. Also the majority of objects have not been tracked recently. The chart in Figure 1 shows the cumulative total known near-Earth asteroids versus time, with the blue area showing all near-Earth asteroids, and the red area showing only large near-Earth asteroids (those with diameters roughly one kilometre and larger). One can also note according to the trend of the known number of Near Earth Asteroids that the number of known NEOs will double in the next 10 years.

At this stage it may be deduced that there is no immediate risk but that the situation could change. The recent Russian event provides a sobering example. There would also appear to be equal probability that an earth-threatening NEO could be detected in time to develop a NEP protection mission or only in time for NTP or not in time for either. Justification for the cost of a NEP or NTP protective mission could be compared with the potential damage, as rated on the higher numbers of the Torino Impact Hazard Scale which estimates that:

- A certain impact causing local damage may occur about every 50 years,
- A certain impact causing major regional damage may occur between once every 10000 and 100000 years,
- A certain impact threatening life on earth may occur at less than 100000 years.

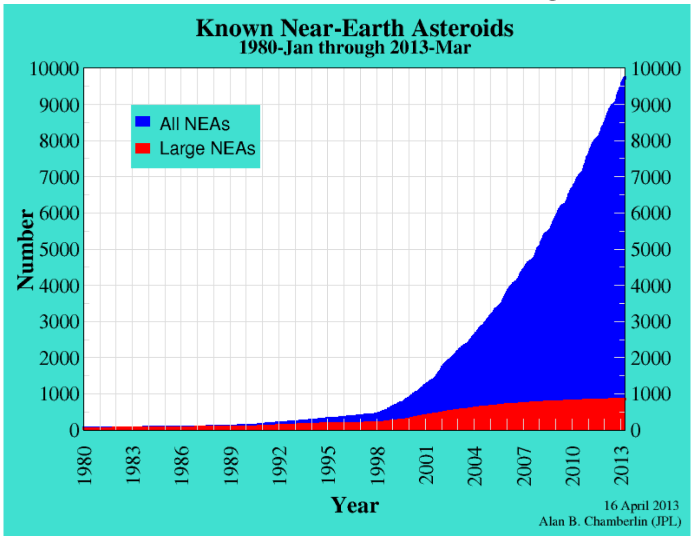

Figure 1. Cumulative Total of Known Near-Earth Asteroids.
Source : http://neo.jpl.nasa.gov/stats/, 26 May 2013

In practice the cost of developing a NEP capability to prevent any of these eventualities is likely to be less than the cost of recovery from the damage caused. This of course has to be seen in the context of the probability of an event occurring. A cost-benefit analysis based on best and worst case scenarios would be helpful in educating national agencies and the insurance industry and helping to form public opinion. This analysis also has to take account of the time to develop the capability which may be a major factor in the mitigation of risk.

B. NEP or NTP

Each situation must be considered on its merits but in DiPoP[3,4] a simple sample comparison was made between the Ariane 5 launch of a 5MW NTP (direct impact) and a 200 kWe NEP (gravitational deflection) to give some idea of the advantages and disadvantages of each method.

Assuming a NEO asteroid mass of 200,000 ton (diameter = 60 m) and an NTP mass at impact 3 ton, relative speed 15km/s and transverse impact speed 0.225 m/s, the time to reach a 7000 km deviation is estimated to be 360 days. The advantages are fast trip time and full angular deflection obtained at impact. The disadvantages are that the initial firing arc at Earth escape must be very precise and the mid-course correction by NTP requires a large store of liquid hydrogen during months of transit and a large volume hydrogen tank.

For the same NEO characteristics, 200 kWe NEP giving 8 N of thrust over 6 months will give a larger deflection (0.64 ms^{-1}) but will take much longer to rendezvous with the NEO in the first place. So, if there is time NEP would appear to be the more attractive option because there is more control and lower risk of ineffective impact or even missing.

C. Assessment

When asked about nuclear power in space at recent conferences, European and US space agencies have expressed a view that they could develop space nuclear fission if it was needed, but currently there were higher funding priorities. This tends to overlook the possibility that there may not be sufficient time to develop the capability. Russia aims to have ground tested the NPPS by 2019 to be ready for such an eventuality. However it will require a new heavy lift launcher to deliver such a [presumably] large spacecraft to orbit.

Another view developed during DiPoP was that once space nuclear fission had been demonstrated to be safe, affordable and effective the case could be made for other applications. These included NEO survey and mining, sample return missions to outer planets, missions to the heliosphere and beyond, high power radars and laser communications and power plants on remote planetary settlements. Human spacecraft powered by NEP was discounted because trip times would be too long. However the use of NEP to deliver essential infrastructure to a remote planetary destination (including for example descent and ascent capability) in advance of the main human mission remains worth considering. NEP might well offer enabling or even cost benefits to all these applications if it had already been developed. Apart from NEO deflection it is much more difficult to see how the investment case might be made to develop the capability for any application individually.

Most recently the arrival of Voyager 1 at inter-stellar space, after 36 years, and the equally remarkable progress of Voyager 2, has demonstrated that nuclear power is essential for the exploration of the outer solar system and beyond. Both spacecraft have achieved unbelievable results with relatively low power radio-isotope power sources. It is only logical therefore that major future missions will need the higher power levels provided by nuclear fission to reduce trip times and service larger more capable payloads.

III Technology

A Constraints

To cover the full range of applications considered, design features for a European nuclear power generation concept design were investigated in the HiPER project. In summary these are:

- Compatibility with an Ariane 5 ECA launch to a minimum 800km in-orbit commissioning altitude,
- 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 for cold start in orbit and resilience to sudden load fluctuations,
- Launch safety criteria for water immersion, etc.

A Concept Design for a 200 kWe NEP system in HiPER identified a need to improve the mass efficiency for compatibility with the Ariane 5 launch constraints. (One may argue that the constraint is somewhat artificial but the principle remains valid.) One approach is to raise the operating temperature of a direct cycle gas cooled reactor to 1300K or even 1500K. This permits a much smaller fixed radiator but exceeds creep life for current turbo-alternator materials. Another is to develop a deployable radiator for a 1200K indirect cycle metal cooled reactor, but fitting into the Ariane 5 faring is complicated. Also one is still very borderline as far as turbo-alternator creep life. In both cases research into lower mass radiator materials would almost certainly be needed.

B. Technical Developments

The HiPER study also identified a number of system issues which require further R&D. These include high power electrical equipment (some of which may have to operate at very high temperatures), buffering of sudden large load changes (such as all EP thrusters shutting down unexpectedly), power for in initial in-orbit commissioning and recovery from subsequent in-orbit shut-downs. Other considerations included the mass distribution to achieve a sufficiently low centre of mass for launch, and architectures which combined maximum thrust efficiency with mass efficient radiation shielding.

Although the highest technical risk was assessed to be associated with achieving very high reactor and turbo-alternator operating temperatures, all the other issues are also technically challenging. The main issues to be resolved therefore are the trade-off between liquid metal and gas cooled reactors and the operating temperatures which can be achieved. Although there may be helpful developments 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 make the relative simplicity of gas cooled systems more attractive. The trade-off studies can therefore only be usefully conducted following the materials R&D.

C. Assessment

Many advanced concepts, although established in principle, have to wait for technical advances before their potential can be realised. Even then there is normally a process of evolution over decades or even centuries. A good example is the submarine which was relatively ineffective in an age of wood and fabric construction but which has become a very sophisticated vehicle in the days of high strength alloys, modern electrical systems, steam propulsion and nuclear power. Similarly, new ceramic or carbon/carbon materials with sophisticated coating barriers may offer the materials breakthrough in higher temperature Brayton cycle power conversion, which will herald a new age of space fission nuclear power.

The question of technology therefore remains open, but the evidence suggests it is more a case of 'when' rather than 'if'. In principle a space fission system can be built with existing materials but probably not to the performance and affordability that would be seen as acceptable or achievable with a European launch vehicle. In practice, as with most advanced concepts, technical advances, particularly in materials are needed to realise the full potential of the technology. A great opportunity to research the technological advances needed is the EC Horizon 2020 programme.

IV Capability

A. European Capability

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. From the representative review the following organisations were identified as having relevant experience and expertise for a space fission to a greater or lesser extent:

- **High Temperature Reactor Technology:**

  EC JRC (Germany, Netherlands), CEA (France), SCK-CEN (Belgium), VTT (Finland), Demokritos* (Greece), MTA-EK (Hungary), NCBJ (Poland), VUJE (Slovakia), PSI (Switzerland), NNL(UK), CV-Rez (Czech Republic), AREVA (France, Germany), Studsvick (Sweden), AMEC (UK), Rolls Royce and Leicester University* (UK).

- **Energy Conversion (including high temperature radiator design):**
CEA, CNES (France), SCK-CEN*, Demokritos*, MTA-EK, NCBJ, VUJE, NNL(UK)*, AREVA, ThalesAleniaSpace (Italy, France), AMEC*, Rolls Royce*, SEA (Stirling UK), Snecma Moteurs (France) and Leicester University
- **Power Management and Distribution:**
EC JRC, CNES, AREVA, Galileo Avionica* (Italy), AMEC*, EADS Astrium (France, Germany, UK) and Stuttgart University (Germany).
- **Project Management (including Public Acceptance, Safety and Sustainability):**
ESA, CNES, DLR, VTT**, MTA-EK, ESF, ThalesAleniaSpace, Studsvick**, AMEC** EADS Astrium, SEA, Snecma Moteurs (France) and Stuttgart University (public acceptance and safety framework).
- **Launch and Operations:**
ESA, CNES and UK Space Agency (licensing).

The experience for those marked with an '*' was in studies and those marked with '**' is essentially in consultancy. 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.

B. Russian and US Capabilities
In Russia the MEGAWATT Class Nuclear Power and Propulsion System (NPPS) project indicates a much more advanced capability for NEP than in Europe. At the second Advisory Board meeting the Director General of the Keldysh Research Centre gave a direct invitation to Europe to collaborate in the project. This can have a very significant influence on any plans to develop a European space fission nuclear programme, particularly in the initial acquisition of practical experience of the technologies. It was therefore strongly recommended that Europe investigate collaboration in this programme within the context of proposals for a future European space nuclear fission power development

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.

C. 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.

D. Assessment
A well-defined programme of research objectives based on teaming between space and non-space organisations with the necessary expertise is needed before it is possible to make any quantitative assessment of the ability of Europe to deliver the necessary technical advances. In principle that appears feasible, but the potential for fission nuclear power applications of new low mass, high temperature materials with adequate creep life or even basic robustness has yet to be evaluated. A workshop to define research objectives for the Horizon 2020 programme is planned for December 2013. Progress in defining the workshops will be a measure of European capability to deliver the necessary technologies. At the same time, collaboration with Russia is an equally necessary step to gaining practical experience in

delivering space fission nuclear power. Developing a European capability either alone or in partnership with other countries depends on both these initial steps.

V Resources

A. Historical Precedents

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 was ~14 years, and programme costs were B$ 7-9; NPPS inception to launch was ~ 8 years and development cost was 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 same quality control of the US nuclear submarine programme. It included an expensive fuel development project and a full mission (JIMO). The MEGAWATT Class NPPS is based largely on current technology and is able to draw on other Russian civilian development programmes. The projected costs are understood only to cover development and ground testing.

B. Potential European Resources

No significant differences were detected in assessments of cost and schedule for 30 kWe and 200 kWe power levels and it was concluded that because the higher power level has the greater utility it should be the baseline for any resource assessment. Funding for initial research and collaboration with the NPPS project could be made available in the Horizon 2020 programme. The ESA General Studies programme could fund initial mission analyses. In the longer term it may be possible to share development activities with the terrestrial Generation IV research programme. At some stage however significant investment will be required for a prototype system and the supporting infrastructure, possibly aided by the conversion of redundant submarine test and evaluation facilities. Significant upgrading to and licensing for the Kourou space centre would also be necessary unless launch facilities could be found elsewhere. Currently the project MEGAHIT is building a roadmap for MW-class nuclear electric in-space propulsion within the European Commission Horizon 2020 programme, to create an international community and collaboration opportunities for a nuclear power based space flight (see www.megahit-eu.org).

C. Assessment

In principle these resources could be made available. In practice the immediate challenge is to secure funding for initial research, collaboration and mission analysis in Horizon 2020 and ESA.

VI Public Acceptance, Safety and Sustainability

A. Public Acceptance:

The First Advisory Board considered the DiPoP Technical Note “Preliminary Recommendations for Public Acceptance”. The note illustrated 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). This study identified the different communities who must be considered and strategies for winning and keeping their support. 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 is essential to assemble a team who understands both technical issues and public concerns. This includes both the concern about nuclear dangers and also whether it is a good way to spend government money (the case for private investment does not look strong unless the insurance industry can be engaged). The US experience was that 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 is considered necessary to design a sufficiently compact reactor for space This and other factors is why a Public Acceptance assessment study is a priority task before starting the assessment study on 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 actions must be carried on and followed in order to achieve public acceptance:
- Public outreach,
- Implementation of safety,
- Application of space nuclear power in a mission with adequate sustainability.

Questions which may need to be answered are:
- 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? What are the alternative targets for funding?
- Can we manage the risk so that there is negligible danger to people and property, or contamination of distant planets or objects?
- Are we alone in making a case for space nuclear fission power?
- What are the penalties of not investing in space nuclear fission power generation?
- What is the motivation of stakeholders and interest groups?

B. Safety
A generic study of Safety and Sustainability in the DiPoP Study examined the actions required in Europe to support a space fission nuclear power programme. The study also included an analysis of the lessons learned from the recent Fukushima nuclear accident. It concluded 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 [who] 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

C. 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 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 projects,
- 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 nuclear and space organisations to assess the equipment performance required and the associated cost and schedule,.
- Building a full database of the relevant European expertise and infrastructure to support the technical development, e.g., by building on the initial DiPoP representative survey,
- Establishing a timetable to achieve a European NPS regulatory safety framework.

D. Assessment

In principle public acceptance, safety and sustainability is achievable. In practice a lack of recognition of the critical importance of any part of these activities could create a situation which could, at best, be only retrievable at considerable expense and, at worst, be irretrievable.

VII Is there a future for Space Fission Nuclear Power?

Considering the applications, one may draw the conclusion that there could be and should be a future for space fission nuclear power. In principle European capabilities could be developed to deliver the necessary technologies although the level of performance and associated cost-benefit which might be achieved is unclear without further research. Also developing the necessary practical experience to successfully manage a space fission nuclear programme will be challenging without collaboration with Russia (or, possibly, the US). In principle safety and sustainability are both manageable and there are enough potential applications to justify a long term programme to amortise development and qualification across a number of missions[5]. More details may be found of the DiPoP dissemination website[6].

In practice it appears that it will need a very compelling reason to persuade the general public, which in turn tends to influence government thinking, that space fission nuclear power is safe, affordable and necessary. Deflecting a large earth-bound NEO is the most obvious case, but there is a significant risk that the warning time may be too short to develop and deploy the technology successfully. The future is therefore somewhat dependent upon near-term investment in the enabling technologies, particularly materials to progress the state of the art and so reduce future development schedules. Synergies with terrestrial Generation IV nuclear development and other high temperature, mass-efficient applications may help make the case to do this.

There is no fundamental reason why space fission nuclear power should not have a future. Provided man continues to explore the boundaries of our solar system and universe the question is more likely to be ‘when’ rather than ‘if’.

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