TECHNICAL NOTE D32.3
200 KWE FISSION NUCLEAR POWER SOURCE FOR SPACE APPLICATIONS

Prepared by R. Blott C Ferrari, C Bruno

Agreed by R Blott

Approved by R Blott

Authorized by C. Koppel 15/10/2012

EC Approval

Date:

SEVENTH FRAMEWORK PROGRAMME

Traceability File name:
DiP-Sep-TN-003 D32 3 200kWe Fission NPS for Space Applications02.doc

Distribution List

DISTRIBUTION	Type
Research Executive Agency *Ms. Gabriella Soos/ Mrs. Paula Mota Alves*	Electronic SESAM
KopooS Consulting Ind. *Mr. C. R. Koppel*	ftp.DiPoP.eu/DiPoP1/ProjectDocumentsReleased
Space Enterprise Partnerships *Mr. R. Blott*	ftp.DiPoP.eu/DiPoP1/ProjectDocumentsReleased
D.L.R. *Mr. F. Jansen*	ftp.DiPoP.eu/DiPoP1/ProjectDocumentsReleased
University Stuttgart *Mr. G. Herdrich*	ftp.DiPoP.eu/DiPoP1/ProjectDocumentsReleased
C.A.U. *Mr. H. Kersten*	ftp.DiPoP.eu/DiPoP1/ProjectDocumentsReleased
ISIS- RD *Mr. C. Ferrari*	ftp.DiPoP.eu/DiPoP1/ProjectDocumentsReleased

Document Change Record

Issue	Date	Page and / or Paragraph affected
01	29.08.2012	First Issue
02	13/10/2012	Incorporating Kopoos comments and updates
03		

AUTHOR (S)	ORGANIZATION (S)	ADDRESS
R. Blott	Space Enterprise Partnerships (SEP)	Bennetts, Eastergate Lane, Eastergate, West Sussex, PO20 3SJ, UK
C. Ferrari, C. Bruno	ISIS_R&D	Viale Guglielmo Marconi 893, Rome 00146,

TITLE	200 KWe FISSION NUCLEAR POWER SOURCE FOR SPACE APPLICATIONS	CI CHECKED: <u>YES</u> NO

CODE	TYPE OF DOCUMENT	TIME COVERED	ISSUE DATE
DiP-Sep-TN-003 D32 3 200kWe Fission NPS for Space Applications02.doc	Deliverable		29.08.2012

PROGRAMME		TITLE	FUNDING ORGANIZATION
<u>YES</u>	NO	Seventh Framework Programme	European Commission

PROGRAMME ELEMENT		TITLE	FUNDING ORGANIZATION
<u>YES</u>	NO	DiPoP Disruptive Technologies For Space Power And Propulsion	European Commission

MONITORING PERSON	CONTRACT No.	ADDRESS
Mrs. Gabriella Soos Mrs. Paula Mota Alves	284081	European Commission DG Enterprises and Industry Space Research and Development Brussels - Belgium

ABSTRACT

This document is the deliverable D32.3 of the WP 30

The Technical Note is an Updated Report on 200 kWe fission power source applications, infrastructure, technical options and a potential investment assessment for nuclear power source (NPS) Advisory Board review. Interest in EU and Industry for a 200kWe nuclear reactor (NR) will be investigated and reported. It is an internal document.

KEY WORDS DiPoP, Fission, Nuclear, Power, 200 kWe.

AVAILABILITY

(X) Approved for public release; distribution is UNLIMITED

(   ) Approved for LIMITED distribution; no part of this document can be disclosed to third parties without written permission

(   ) CLASSIFIED document for internal use only; no part of this document can be disclosed outside the company

Table of contents

FIGURES:

Access to the supporting Appendices to this document may be considered on a case by case basis with the permission of those who contributed the information. Applications to access the documents are to be made to: The Director, Space Enterprise Partnerships Ltd, Bennetts, Eastergate Lane, Eastergate, West Sussex, PO20 3SJ, UK; rjb@space-enterprise-partnerships.com; +44 (0) 5601325706, +44 (0) 7894831239.

1 INTRODUCTION

The purpose of this technical note is to assess:

- Which space applications can most benefit from a 200 kWe fission nuclear power generator,
- The resources Europe requires to develop the capability, and,
- The potential for realising it.

It takes account of technical progress in Europe and relevant resources and capabilities in Russia and the US.

2 REFERENCES

A. HiPER Nuclear Power Generator Roadmap HiP-SEP-D3.8-ill0 6th May 2011.
B. The Fission Nuclear Power Generator Roadmap Draft (Dip-Sep-PL-001- D30.1 dated 20th February 2012).
C. HiPER Consolidated Mission Analysis HiP-AST-D-2.7-i1r1 dated 8th Dec 2011.
D. AIAA 93-1814, Nuclear Power and Propulsion for Missions to Mars and the Outer Solar System, Zubrin, Martin Marietta, dated June 1993.
E. World Nuclear News (WNN) 28th May 2010.
F. World Nuclear Association review of small nuclear power reactors April 2012.
G. Development Programme of Innovative Reactor Systems in the World, C. Renault, F Carre, CEA, Tsuruga, Japan, 12th September 2008.
H. NASA Stirling Space Engine Final Report, Manmohan Dhar August 1999.
I. Design Considerations for Lightweight Space Radiators Based on Fabrication and Test Experience With a Carbon-Carbon Composite Prototype Heat Pipe Albert J. Juhasz NASA Glenn Research Center September 2002.
J. Re p o r t of the European Working Group on Nuclear Power Sources for Space *30 March 2005.*
K. Notes of the First DiPoP Advisory Board Meeting Held at DLR Offices Washington DC Monday 6th February 2012.
L. Nuclear Electric Propulsion/Power Processing Unit Report Dip-SEP-RP001-D23.2 dated May 2012.
M. NASA JPL NEO Programme Sentry Risk Table http://neo.jpl.nasa.gov/risk/.
N. Technical Note "DiP-Sep-TN-003 D32.2 200kWe Fission NPS Configuration Options03 dated 13/10/2012.

3 Design Features

The design features are based on those identified in Reference A 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,
- 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.

On purely technical grounds it is difficult to determine clear benefit between the fast indirect and epi-thermal direct design. Fast reactors are more compact, have much lower mass and have been the baseline for space projects to date. The mass advantages tend to be offset by the mass of the heat exchanger between the primary liquid metal and secondary Brayton cycle operating gas coolants. This also limits the temperature input to the turbo-alternator which drives up the size and mass of the radiator. If materials can be found to give the 10 year creep life for the rotating machinery and the radiator at the higher operating temperatures offered by the direct cycle, the reduction in radiator mass will compensate for the larger reactor and shield.

For many reasons, including public acceptance of a space fission nuclear power programme, minimising technical risk will have a high priority. The direct cycle is inherently a simpler design concept and therefore expected to be more attractive in this respect. It also requires much less energy for commissioning than that needed to raise the indirect cycle reactor to the melting point of the liquid metal coolant.

Space fission nuclear power generator design can benefit from core coolant exit temperatures in the range 1300-1500°K and mean radiator temperatures in the region of 650-850°K. Radiator size decreases with increasing temperature in a fourth power law relationship and the higher temperatures give very significant reductions in mass and radiating area. Core exit temperatures in this range have been achieved in Russia and the US. Terrestrial high temperature Generation IV research in Europe to date is limited to maximum core exit temperatures ~ 1100°K. Achieving the higher temperature range will require research into materials for core, fuel, radiator and possibly shield design.

4 APPLICATIONS

4.1 Rationale

A range of potential applications for nuclear electric propulsion were identified in Annex B to Reference B (The Fission Nuclear Power Generator Draft Roadmap). There are two main criteria for deciding which of these are most appropriate and therefore most likely to attract funding and commitment. One is in the comparison of applications for nuclear electric (NEP) and nuclear thermal (NTP) propulsion (see D23.2 and D23.3). The other is need for a 200 kWe power level. In making these comparisons account is taken of:

- Which applications are the most likely to justify investment in the technology?
- Can the technology deliver the application (and how well)?
- Are there public acceptance, safety or sustainability issues which make it very difficult to deliver?
- In broad terms, what are the cost and schedule implications?

- Are there any spin-out or spin-in benefits which would make investment in such a programme more attractive?

4.2 Challenges

There are challenges in assembling the evidence to answer these questions for several reasons:

- Circumstances which affect the importance of applications can change (eg the initial detection of an earth bound NEO); we cannot forecast this precisely but we can use a probability analysis to provide a more quantative basis for assessment,
- It is difficult to quantify the uncertainty associated with performance analysis and development roadmaps in determining to what extent a technology can deliver an application; this is particularly true for more advanced studies not supported by physical development,
- Although it is possible, in principle at least, to specify and assess the resource requirements to achieve safety and sustainability, gauging public acceptability inevitably has high levels of uncertainty,
- There tends to be wide diversity in cost and schedule estimates ranging from the very optimistic to the cautious (an analysis of the causes of the cost and schedule overruns in recent civil nuclear power projects may be some help),
- The particular requirements of space nuclear fission power generators tends to make it difficult to identify ‘spin-in and spin-out’ at the ‘macro’ level and identifying lower level possibilities requires detailed research in many fields,

4.3 Approach

We start by considering all the potential applications and the evidence available to indicate the appropriateness of the 200 kWe NEP power plant. A by-product is to identify the additional evidence required achieve an acceptable level of confidence in application evaluation including knowledge of all the uncertainties, even if they cannot be quantified. On this basis, the initial consideration of applications is:

- Manned missions to Mars (all-nuclear power and split mission: humans by chemical propulsion and nuclear power to deliver landing, ascent and orbital maintenance infrastructure only),
- Exploration missions to the outer planets (Jupiter and Saturn sample return, Neptune and Pluto orbital survey and possibly lander, etc.),
- Exploration missions to the outer boundaries of the solar system (and beyond),
- NEO management: sample return, mining and deflection/destruction of threats to the earth,
- Planetary surface or ‘space port’ power generation,
- Planetary exploration high power instruments: ground penetrating radar, ice-melting laser, long distance high data-rate communications, etc. (also may be a space-based NEO tracking radar for trajectories obscured by the sun).

Of these we can eliminate at an early stage all-nuclear manned missions to Mars because the power level is too low for the fast transit required. However, 200 kWe could at face value be quite appropriate for the infrastructure transportation of a ‘split-mission’ approach. A nuclear space-tug would transport the infrastructure for descent to the planet, habitation there and ascent to the return vehicle in advance of the manned capsule.

This could then be sent at minimum mass by chemical propulsion when the infrastructure was in orbit around Mars.

At the other end of the scale high power instruments are not likely to need 200 kWe and these applications are more likely to be satisfied by the lower 30kWe generator. Initial planetary surface or spaceport power requirements are also considered to more likely to be met with a 30 kWe generator in the shorter term. Delivering a high mass payload safely to a planetary surface is a tricky operation and a smaller power plant is likely to require rather less energy for excavating a site to give good radiation protection. However the recent successful landing of NASA's Curiosity rover on Mars is a useful step in landing large mass infrastructure on the Red Planet.

Initially, therefore the preferred applications are the exploration of the outer planets in the solar system and 'NEO' management, particularly in dealing with an earth-bound threat. These two applications still embrace a range of mission requirements of varying complexity but falling within the general design features in Section 3.

4.4 Missions to the Outer Planets

4.4.1 Jovian Moon Sample Return.

As an example, the HiPER analysis considered the delivery of a 2 ton descent capsule to the surface of a Jovian moon and the return of a 50 kg sample containing capsule to earth within 10 years (Reference C). The analysis was based on starting from and returning to the Earth/Moon first Lagrange point, an NEP system of 7 tons and a spacecraft mass of 1.5 tons (excluding the payload of 2.05 tons). The mission required 2.34 tons of xenon propellant for the outward leg and 1.67 tons for the return. Interestingly thrust was only required for about 50% of both the outbound and return legs and not during the 11 month stay around the target moon. This would suggest that the NEP 'full power' requirement is closer to 5 than 10 years and a low power or standby condition for the best part of 5 years would also be required.

4.4.2 Uranus, Neptune and Pluto.

Analysis of various NEP and NTP strategies for missions to the outer planets in Reference D also suggests that a one way mission to Uranus would include several years of 'coasting' when the propulsion system would be 'shut down'. The analyses were made for smaller spacecraft and payloads and lower Isp electric propulsion so there is no direct comparison with the HiPER analysis. However one way missions to orbit Neptune and Pluto are likely to take longer than 10 years so that the 10 year lifetime is required when allowing for the 'coast' phases of the journey.

4.4.3 Performance Criteria

The 10 year lifetime would therefore appear to give a large margin for the Jovian moon sample return and might even encompass two missions or a more complex mission with visits to more than one moon. There would appear a reasonable margin for a Uranus orbiter to be rather less margin for a Neptune or Pluto orbiter. The latter assumptions are based on much earlier mission analyses using a different size spacecraft, nuclear power range and propulsion system and different launchers. Consequently the uncertainty is high and needs further dedicated mission analysis for the 200kWe nuclear power generator and high Isp gridded ion engine (or alternatives).

The 7 ton NEP system mass and 1.5 ton spacecraft mass contain margins which are based on assumptions of technical development. The target for the nuclear power generator was 5 tons leaving 2 tons for PMAD, electric propulsion and margin. The uncertainty surrounding the ability to achieve the identified technical development is difficult to quantify at this stage.

4.4.4 Public Acceptance, Sustainability and Safety

Besides complete satisfaction of all safety aspects public acceptance may be expected to require clear evidence that there is benefit in these types of mission and in doing them with nuclear power. The science case for missions of comparable expense, such as the James Webb Space Telescope, appears to have been made initially within the science community. However NASA has invested extensively in PR, making good use of the Hubble observations, to court public approval. As yet the focus on solar system exploration has been mostly from the Sun to Mars and the case for major exploration of the outer planets on balance still has to be made.

Interestingly, the case for using low power nuclear devices for outer solar system exploration (eg Cassini) has achieved a general level of acceptance. This is probably because the relative cost is lower (but by no means small) because the devices are smaller and a general lack of understanding of the radio-active properties of fission and radio-isotope generators. It may be possible to build on this baseline to seek public acceptance for larger fission devices provided the benefits are fully seen to justify the cost. The key questions are likely to be ‘what will we find out’ and ‘is there any other way of doing it’?

4.4.5 Cost and Schedule

Currently there are only 2 metrics for cost. The first is an unofficial estimate of B$10 for the US Prometheus project (at 2005 prices) and the second is B$0.56 for the Russian Heavy Spaceship and NPPS. The former is thought to be an estimate based on all project phases including an expensive fuel development to give 10 years of operating life. The second is understood to cover ground testing up to flight qualification but not to include reactor development. A European programme cost would depend on the starting point for the development, the scope and size of the project and any collaborative activity.

A full development schedule and 10 year mission is proposed in the HiPER Roadmap (Reference A). It includes 3 years of feasibility studies followed by 4 years project definition (Phase A/B1) and 10 years development and build (Phase C, D) before allowing a year for launch and 10 years for the mission. The feasibility studies are aimed at risk management of high technical risk mainly associated with very high temperature power conversion, mass and area efficient radiator design, high power electrical equipment and other precursor issues such as infrastructure planning. Project Definition is an iterative process because of the inter-dependence of many of the requirements. There may be scope to accelerate this process depending on early assumptions about technical options. The length of Phase C, D is in some part determined by the life testing procedures for critical equipment, particularly if some aspects can be started earlier in pre-feasibility or Phase A. The state of development of terrestrial very high temperature gas cooled (fourth generation) reactor technology may also be significant.

This timescale if started in 2013 could envisage the launch of a sample return mission to a Jovian moon in about 2030 and return of the sample in 2040 at an average cost ~ M€435 a year (using the Prometheus projection). Alternatively if a larger launch vehicle was available and the design could be based on lower temperature, less mass efficient technology, cost and schedule may be reduced significantly. The uncertainties are such that these figures should be treated with considerable caution until refined by detailed study but do give an initial guideline against which the benefits of the mission might be measured.

4.4.6 Spin-out and Spin-in

Very high temperature gas cooled reactor research does approach the required space operating temperatures (≥1300°K) and this may well offer opportunities for 'spin-in' or even 'spin-out'. But there are differences. Terrestrial reactors tend to be larger than those compatible with the Ariane 5 ECA lift capability. The helium coolant gas is coupled by a heat exchanger to a separate thermal to electrical power conversion operating fluid/gas. In space the need to minimize specific mass leads to a mixture of helium and xenon for both cooling and power conversion.

There should be 'spin-in' from terrestrial high power PMAD equipment and if techniques such as high temperature super-conductors are developed this could lead to some spin-out.

4.5 NEO Management

4.5.1 Earth Threatening

If the threat of a large NEO impacting the Earth could be prevented by a nuclear electric or nuclear thermal spacecraft this would be a compelling incentive to develop the technology. This leads to three questions: is there a significant threat in the foreseeable future, could a nuclear spacecraft prevent a catastrophe and can we have the capability ready in time? (In short there is a damage cost and risk versus NEP development and effectiveness equation to be populated!)

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. To assess whether investment in either NEP or NTP or both for this application evidence is required to determine the following:

- The probability of a NEO, capable of inflicting significant damage, colliding with the earth in the next 50/100/1000 years,
- The probability that a (potential) collision could be forecast in time to develop an NEP capability which could make a successful deflection at long distance (10-12 years from the start of development say),

- The probability that a (potential) collision could be forecast in time to develop an NTP capability which could make a successful interception closer to earth (7-8 years from the start of development say),
- The probability that the NEO would be detected too late to take any corrective action,
- The probability that timely deployment of an NTP spacecraft would achieve a successful deflection,
- The probability that timely deployment of an NEP spacecraft would achieve a successful deflection,
- An assessment of the damage which might be caused by a large NEO impact,
- An assessment of the cost of and NTP or NEP (or both) programme.

Again there are very large uncertainties associated with the evidence which does exist. A reasonable assumption is that the current global space infrastructure can track most NEOs of significant size and there exists the computation power for orbital prediction. Currently the NASA JPL NEO Programme Sentry Risk Table (Reference M) 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 below shows the cumulative total known near-Earth asteroids versus time with the blue area showing all near-Earth asteroids while the red area showing only large near-Earth asteroids (those with diameters roughly one kilometre and larger).
One can note according to the trend of the known number of Near Earth Asteroids that the number of known NEO will double in the next 10 years:

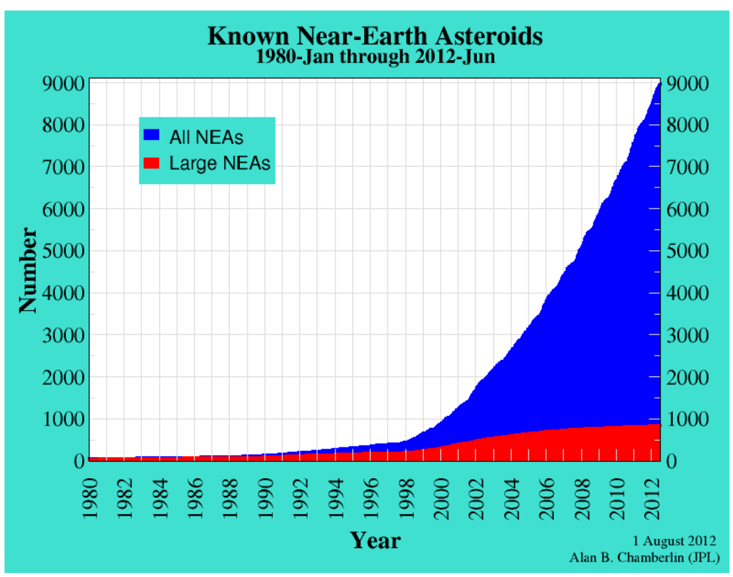

Figure 1: Cumulative total known near-Earth asteroids versus time.

At this stage it may be deduced that there is no immediate risk but that the situation could change. There would also appear to be equal probability that an earth-threatening NEO could be detected in time to develop an NEP protection mission or only in time for NTP or not in time for either. Justification for the cost of and NEP or NTP protective mission could be compared with the potential damage as rated on the higher numbers of the Torino Impact Hazard Scale (Figure 2). Consideration might also be given to slightly lower scale numbers associated with predicted close passes and a level of uncertainty of the probability of collision.

Certain Collisions (Red Zone)	8	A collision is certain, capable of causing localized destruction for an impact over land or possibly a tsunami if close offshore. Such events occur on average between once per 50 years and once per several 1000 years.
	9	A collision is certain, capable of causing unprecedented regional devastation for a land impact or the threat of a major tsunami for an ocean impact. Such events occur on average between once per 10,000 years and once per 100,000 years.
	10	A collision is certain, capable of causing global climatic catastrophe that may threaten the future of civilization as we know it, whether impacting land or ocean. Such events occur on average once per 100,000 years, or less often.

Figure 2: Extract from the Torino Impact Hazard Scale.

4.5.2 Comparison with NTP

Comparison between NEP and NTP is considered in the Final Report Advanced Propulsion Systems & Power Procession Unit (Deliverable D23.4) and is not part of this Technical Note. Each situation must be considered on its merits but a simple sample comparison between the Ariane 5 launch of a 5MW NTP (direct impact) and a 200 kWe NEP (gravitational deflection) gives some idea of the advantages and disadvantages of each method.

Assuming a NEO asteroid mass of 200 000 tons (diameter = 60 m) and an NTP mass at impact 3 tons, 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 the initial firing arc at Earth escape must be very precise and the mid-course correction by NTP requires a large store liquid hydrogen during months of transit and a large volume of hydrogen tank.

For the same NEO characteristics 200 kWe NEP giving 8N of thrust over 6 months will give a larger deflection (0.64ms^{-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.

4.5.3 NEO Mining

An advantage of NEP compared to NTP is that the spacecraft could also be employed on NEO mining missions should the business case be made for such missions.

4.5.4 Performance Criteria

In principle neither the NEO threat nor the NEO mining require the 10 year lifetime for robotic exploration missions. In practice the strategy for the NEO threat could be to maintain the spacecraft in a convenient orbit (such as Earth/Moon L1) for long periods rather than add in the time and risk associated with launch and Earth escape in what would almost certainly be a time pressure situation. For NEO mining the spacecraft acting as a 'space tug' could perform multiple journeys (which is much more economical than a dedicated launch for each mission). There might even be scope for combining the operations so that the space tug was on mining missions until a threat was discovered and then re-tasked to deflect it to a safe orbit. Alternatively, the higher technical risk margin associated with a shorter operating life may be seen as a benefit in its own right for a critical mission to deflect an earth-bound NEO.

The 200kWe power level may seem low for 'pushing' and analysis is needed to establish the effectiveness over a sustained period so that the strategy can be properly evaluated. This power level may appear a little high for mining operations but again an analysis is required and there remains the option to operate the reactor at lower power. On this basis the performance criteria for the exploration mission still appears valid for NEO management activities.

4.5.5 Public Acceptance, Safety and Sustainability

Clearly defence of the planet is a compelling argument for Public acceptance if there is no other way of deflecting a large earth-bound NEO. However the arguments for safety and sustainability would have to be at least as good for every other application and also give assurance that the mission would be successful.

4.5.6 Cost, Schedule Spin-in and Spin-out

The initial cost, schedule and 'spin-in'/'spin-out' considerations for NEP may be assumed to be as for the exploration mission (Section 4.4.5 and 4.4.6). (NTP is addressed in WP 23 and deliverable D23.3.)

4.6 Applications Analysis Conclusions

A 200 kWe NEP space tug has the potential to fulfil a range of exploration and NEO management missions and might also be able to transfer infrastructure for a split manned mission to Mars. From current knowledge, NEP is seen to be more flexible than NTP for orbital manoeuvring (rendezvous with sample capsule ascent) or NEO 'pushing'.

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. The design parameters for this application are compatible with NEO management and infrastructure transfer to Mars and possibly other large infrastructure transfer tasks. A 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. This has the potential to be the basis of a sustainable programme allowing non-recurring development costs to be amortised across several missions.

5 TECHNICAL AND CAPABILITY CONSIDERATIONS

5.1 General Situation.

An initial survey of relevant capabilities to support a European space fission nuclear programme lead to the following conclusions:

5.1.1 Reactors and reactor control systems:

5.1.1.1 Submarine Reactors:

There is extensive expertise and infrastructure in France and the UK in the design, development, manufacture and operation of nuclear fission submarine propulsion systems. The relevant features are mobility and long life without re-fuelling. However these reactors operate at lower temperatures, are water cooled and do not require the mass efficiency demanded by space applications. Propulsion is by steam turbine. Submarine reactors tend to be 60 or more times more powerful than the size of space reactor which could be launched on Ariane 5.

5.1.1.2 Civil Power Reactors:

The capability to design, develop, manufacture and operate first and second generation civil power fission nuclear generators exists in France, Germany and UK. The current European focus is mainly on the Generation III pressurised water reactor (PWR) and the technology remains significantly different from that required for space. The EC Allegro (Ref E) gas cooled fast reactor is a more relevant prototype but it is still in the design stage and will operate at lower temperatures and also is not mass efficient. A recent World Nuclear News (March 2012) survey (Reference F) of small reactors identifies China's HTR 10 and HTR-PM and South Africa's PBMR, together with General Atomics' GTMHR and EM2, the Antares-AREVA SC-HTGR, the Adams Atomic Adams engine and the Russian MT SPNR. Even the smallest of these are at least several times more powerful than a compatible size with the Ariane 5 launch and the operating temperatures still tend to be lower than optimal for a space application.

5.1.2 Research and Development:

Global innovative reactor design concepts are well summarized in Reference G. There has been research into materials to support higher temperature operation but as yet no prototype of a high temperature reactor has been designed or built in Europe. Even the Allegro project for which the build is currently planned between 2014 and 2022 with an outlet temperature of 1100°K is some 400°K below the theoretically preferred outlet temperature of 1300-1500°K for a space nuclear power generator.

5.1.3 Fuel:

France and the UK have the expertise and the capability for the research, development and manufacture of nuclear fuels for submarine, civil power and space applications. Fuel enrichment is increasingly discouraged in applications where it is not essential but is necessary for compact, mass-efficient space applications. France and UK both have the expertise and infrastructure for the management, manufacture, use and disposal of enriched nuclear fuels and are currently active in fuel research programmes. The focus of much European Generation IV reactor research is to achieve high burn-up rates to reduce waste management difficulties.

5.2 Shielding:

Shielding for terrestrial applications tends to be very different to that optimised for space. On the ground the shielding is omni-directional but the external environment is relatively benign and mass is not a critical issue. In space mass efficiency and the environment are key design drivers leading to the application of different materials. Design studies have identified appropriate shielding strategies for space but the practicalities of arranging coolant pipework and control drive mechanisms compatible with thermal constraints while maintaining the shielding effectiveness are less well established.

5.3 Power Conversion

Mass efficient power conversion tends to require much higher operating temperatures and maintenance free long term operation than terrestrial applications. To some extent the gap has reduced in recent years as a result of developments in the aircraft industry. However many of these are commercially sensitive and details are difficult to access in open literature. Also, creep life requirements for high temperature aircraft rotating machinery still tends to be a fraction of the 10 years anticipated requirement for a space nuclear power generator.

In practice it is expected that a space nuclear power generator would need to operate at low power or in a form of 'stand-by' conditions for significant periods of time. If used for a Jovian moon sample return for example the spaceship would probably need to be in orbit around the moon for several months with no need for the main propulsion. As a space tug over shorter distances transporting infrastructure to Sun/Earth L2 or Mars there would also be waiting times for payloads to be ready for collection. Even for long transits the need to maximise gravity assist manoeuvres could lead to mixes of 'boost and coast' phases rather than continuous boost. A deeper investigation of the more likely requirements in practice may lead to an assessment of less sustained stress on components and ameliorate creep life constraints.

5.4 Alternative Power Conversion Strategies:

From research to date there is no evidence to suggest that alternative power conversion strategies to Brayton are likely to have any significant advantage but relevant developments are listed below, where known, as background information. For more detail see Technical Note D32.2 200 kWe Fission Nuclear Power Source Configuration Options (Reference N).

5.4.1 Thermo-electric.

Advanced research in France and the US with semi-conductor materials has indicated that power conversion efficiencies in the 11-18% range may be possible.

5.4.2 Thermionic:

It is understood that research in France has demonstrated sealing techniques which reduce the leakage of caesium and enable much longer lifetimes than achieved in the Russian TOPAZ reactor

5.4.3 Stirling cycle:

The NASA Stirling Space Engine Programme (Reference H) achieved an output of 12.5kWe at 22% efficiency from a demonstrator to validate a full design capability of 25 kWe at 25% efficiency. Current European Stirling engine research is aimed at the much lower power levels associated with RTGs and RHUs.

5.4.4 Magneto-hydro-dynamics (MHD).

MHD is often billed as ‘direct power conversion’ because it depends on electricity generated by passing an ionised gas or fluid through a magnetic field to create an electric current. In practice the pumping arrangements to maintain the flow of ionised gas or liquid and the ionising process itself have made the realisation of the technique challenging. No relevant European developments are known.

5.4.5 Rankine Cycle.

The Rankine cycle is widely used at lower temperatures in steam turbines but fluids with higher boiling points are required for space applications to achieve acceptable mass efficiency. In theory liquid metal such as potassium might be used but there is no current known European research into designing turbines, condensers and associated system elements for this purpose.

5.5 Radiators:

Europe has had no need for large high temperature radiators for space applications to date. NASA research and development into deployable medium temperature radiators is well documented and design options have been considered in several European studies. If high temperature reactor and power conversion becomes technically achievable then fixed radiators have the advantage of smaller size and are less complicated. If not then there is little alternative to the deployable radiator. In both cases there is considerable scope for research and development to optimise design options and there may be merit is hybrid approach where the main coolant lines are fixed but cooling fins or even heat pipes are deployed.

5.5.1 Fixed:

Conventional design used high density nickel alloy tubing. Carbon tubing with comparable strength and thermal properties can be as little as 25% of the mass of nickel alloy but is porous to helium which is a popular choice for all or part of the coolant gas. However research into very thin tantalum barriers within the carbon tubing for protecting fuel in the core may be able to be adapted to counter helium porousness in radiator or coolant pipes.

The addition of micro-meteoroid barrier tubes can add 30% to the areas and 70% to the mass of a fixed radiator. Here again the use of carbon could be of significant benefit. Europe has the expertise and the facilities to research low mass high temperature radiator and micro-meteoroid protection design but there is no known work in this area currently.

5.5.2 Deployable:
Normally reference is made to the work by NASA Glenn described in Reference I. The techniques could be adopted in Europe but would need some redesign to fit within an Ariane 5 ECA fairing, for example. Again the expertise and facilities exist in Europe for R&D in this area.

5.5.3 Droplet:
Droplet radiators are able to achieve up to a seventh of the mass of a heat pipe radiator for 1-100 MWth heat sources (Reference N). Areas are still significant, requiring 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.

6 EUROPEAN EXPERTISE AND INFRASTRUCTURE

6.1 Background

The European Working Group on Nuclear Power Sources for Space (Reference J) 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.

6.2 Survey

6.2.1 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.

6.2.2 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,
- Energy conversion,
- Power management and distribution,
- Project management (including public acceptance, safety and sustainability),
- Launch and operations.

The organisations selected were:

- Government Agencies: ESA, CNES, DLR and UK Space Agency.
- Research Organisations: SCK-CEN (Belgium), CEA (France), ESF (France), 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 group in 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).

6.2.3 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 submarine propulsion 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 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 200 kWe space fission generator. To operate at the higher temperatures requires significant material research and this capability in organisations and industry was also considered highly relevant.

6.2.4 Results

The results of the survey are in Appendix A. Not all the organisations replied 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 A, Annex 2). This shows, even from the limited survey, 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 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.

In summary, Europe has potential capability in all aspects of a 200 kWe space nuclear fission generator development but significant research would be required to realise the capability. A representative survey of where the capabilities may be found in in Appendix A.

6.3 Funding

6.3.1 Background

European Working Group on Nuclear Power Sources for Space 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.*

6.3.2 European Commission.
The EC is currently funding the DiPoP and Megahit projects and has funded the recent HiPER study. HiPER delivered a technical roadmap for the development of a 200 kWe space nuclear fission generator. DiPoP will deliver an organisational roadmap for the delivery of 30 kWe and 200 kWe space nuclear power generators. Megahit is planned to deliver a roadmap for a 1 MWe space nuclear power generator in collaboration with Russia.

Collectively these projects will identify specific research objectives as part of an integral long term plan for consideration in the EC Horizon 2020 programme.

6.3.3 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.

6.3.4 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.

7 RUSSIAN AND US EXPERTISE AND INFRASTRUCTURE

The consideration of relevant Russian and US capabilities is based on the advice given in Reference B.

7.1 Russia.

As described in Reference B, Appendix A. Current activity indicates expertise in high temperature gas cooled and fast liquid metal cooled reactors and thermo-electric and Brayton cycle energy conversion. Infrastructure exists or can be developed for R&D, development, manufacture, launch and operations. Russia also has experience of launching and operating a significant number of space fission reactors.

7.2 US.

As described in Reference B, Appendix A. Current US activity is mostly focussed on low power (radio-isotope) nuclear power generation but investigating higher power levels (~ 1 kWe) than in earlier programmes. Fission nuclear power development is currently on hold although there is a resurgence of interest in nuclear thermal propulsion (NTP). Expertise remains in all areas of civil, marine propulsion and space nuclear power generation but is declining in space fission nuclear power. Infrastructure exists to support civil and marine propulsion nuclear power design, development, manufacture, and support. In principle the facilities can be made available for space programmes but are subject to delay because of prioritisation for other urgent tasks (Reference K).

7.3 Collaboration Potential

In principle Europe has the potential to collaborate in all areas of s space nuclear fission generator development programme. However it is recognised that some areas may be commercially sensitive, especially those associated with materials development.

8 TECHNICAL OPTIONS

8.1 Options

The technical options are considered in Technical Note D32.2 200kWe Fission Nuclear Power Source Configuration Options (Reference N). The main conclusions are:

- The Ariane 5 ECA lift capability is a very significant constraint on the size of fission nuclear reactor technical options (although it is worth noting that Atlas V heavy lift does not offer significantly greater capability). Although this constraint may be obviated by future launcher developments it has been accepted for this study. Consequently the technical considerations are based on the separate launch of a nuclear 'space tug' of ~ 10 tons and a payload (nominally 5 tons) which can be attached in orbit.
- In principle either liquid metal or gas cooled reactor designs are viable technical options but the relative simplicity of gas cooled appears more attractive for long operating life. A detailed comparison in Phase A/B1 is necessary to fully quantify the strengths and weaknesses of each technology. Where possible synergy with terrestrial fourth generation very high temperature gas cooled reactor research and development should be exploited.
- Brayton cycle is the preferred option for power conversion. Pre-feasibility activity is needed to manage the risks associated with very high temperature operation and mass-efficient radiator design.
- The technical risk associated with PMAD options to optimize resilience, for load management, commissioning and cold re-start, and mass efficiency needs to be investigated in pre-feasibility. Synergy with very high power solar electric PMAD requirements and design should also be investigated. Account should also be taken of the influence of different thruster characteristics on the overall system architecture.
- A detailed understanding of the technical risk and quantification of the uncertainties associated with applications and other organisational issues such as public acceptance is required to establish the case for a full development programme. Pre-feasibility activity and Phase A/B1 are required to generate the level of detail required. A sustainable programme of applications and missions will also be needed to justify the investment in the development programme.

9 POTENTIAL INVESTMENT REQUIRED

9.1 Organisational and Industrial Considerations

From an organisational perspective space nuclear fission power would require very significant justification for both the financial cost and public acceptance. Missions which cannot be achieved without nuclear fission will need to be seen as vital to the long term exploration and exploitation of the solar system (and possibly beyond). Industry will need to be convinced of the long term benefit of committing to a nuclear fission programme and this would almost certainly require 100% R&D funding for materials and prototypes for which the lead time to any profitable production may be decades.

9.2 R& D Programme

The roadmap in Reference A identifies a proposed programme of technical development starting with precursor research into advanced materials and leading through the phases of a space project to launch and operations (see Section 4.5.4). A critical element to this programme would be a prototype reactor which will require a very large investment.

9.3 Expertise

There appears to be good scope to build on existing European expertise either alone or in collaboration with Russia and possibly the US. The investment would need to be controlled through carefully targeted research objectives within an agreed research and development programme. However the importance of developing practical experience of space fission nuclear power should not be underestimated.

9.4 Test Facilities

Initially research in Europe could make use of existing nuclear and non-nuclear research facilities. As a longer term objective the European Working Group on Nuclear Power Sources for Space (Para 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).

US test facilities are understood to be very highly utilised with little prospect of access to third parties in the US let alone Europe. The availability of Russian facilities is unknown. If there is availability it might be worth investigating hiring Russian test facilities for some research work but it is difficult to envisage the development of a European reactor without its own dedicated test facility.

9.5 Design and Build

The existing European project management of nuclear and space projects do provide a basis for a space nuclear fission generator development but will require some cross-pollination of the two cultures. Infrastructure investment will also be required but the cost and schedule 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.

9.6 Transportation, Launch and Operations

Europe has the expertise and infrastructure for conventional space launch and operations. There is also no reason to suspect that terrestrial storage and transportation arrangements for civil and submarine nuclear programmes cannot be adapted for space nuclear fission systems.

Extending the existing European launch and operations capability for low power (RTG and RHU) nuclear devices is under consideration and further extension to include fission nuclear power generators may be a logical step. However it is quite a big step. The US currently appears unlikely to accept the launch of fission nuclear power generators from its soil. Russia does have the most experience of fission nuclear power launch and operation. Cooperation with Russia might offer the most efficient way to acquire the necessary expertise.

Investment will be required to 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.

9.7 Cost

It is very difficult to estimate the cost of a European space nuclear fission programme. From Section 4.4.5 it may be seen that estimates can range from B$0.56 to B$10 depending upon what is and what is not included. It is important to remember that the Prometheus estimate was never validated and took account of an expensive fuel development programme. Equally the lower estimate only covers part of the ground development and testing. Compared to B$7 for the James Webb telescope a cost of B$10 does not appear impossible but at around twice the annual current ESA budget there is no doubt that the money would be difficult to find. The investment in expertise and infrastructure for a 'one-off' mission appears difficult to justify except in very exceptional circumstances. Consequently it would almost certainly be necessary to consider the cost of a self-sustaining programme which would need enough missions for the relevant industries to retain their core capabilities. No cost estimates for such a programme in Europe currently exist.

10 INTEREST IN A 200KWE NUCLEAR REACTOR

10.1 Background

There have been many studies of the technical requirements for a European space fission nuclear power capability in the past decade. While there are variations in the relative merits of potential technologies and techniques there remains a general consensus on the main requirements. The situation is best summarised in the 2005 Report of the European Working Group on Nuclear Power Sources for Space (Reference F). The report had the following recommendations for the long term:

- *Fission reactors for power and propulsion should be considered more intensively. A first objective should be the development of a prototype at ground level.*
- *Nuclear test facilities should be developed to demonstrate the viability and performances of fission reactor technologies for space, if existing facilities cannot be used or adapted.*

10.2 EC

The EC FP7 Space Research programme has a number of themes including space transportation and disruptive technologies. The research covers both the 'Strengthening of the foundations of space science and technology' and 'space transportation'. HiPER (Reference A), DiPoP and now the Megahit projects are in support of these research objectives and are the opportunity to identify the next research objectives in the Horizon 2020 programme. The EC also has a programme of fourth generation reactor research and development for which has many useful synergies with a future space programme.

10.3 ESA

The ESA space science and exploration (Aurora) programmes currently have missions or plan missions to the inner solar system, Mars and possibly the Moon. The MREP programme includes the investigation of RHUs and RTGs for powering landers with the view that they can also support future missions further into the outer solar system. A candidate for the next call for Large ESA science missions is Jupiter icy Moons Explorer (JUICE) which may use low radio-isotope power but does not contemplate nuclear electric propulsion or fission power generation.

10.4 Nations

From informal discussions there is understood to be potential interest by France, Germany and the UK in a space fission nuclear power generator in the longer term if justified by applications and subject to cost and resource availability. However at present there is insufficient information to form a judgement on which a programme could be started. Bi-lateral discussion with Russia and the US is encouraged as a way of learning more and investigating possibilities of cooperation.

10.5 Industry

Despite concern about the future of nuclear power for civil applications in some parts of Europe both UK and France are struggling to bring new reactors on line to meet future energy demands. Consequently appropriate resources are in high demand and the industry focus is on this relatively large and profitable programme. Similar arguments apply to submarine nuclear programmes. By comparison the 'business case' for a space fission nuclear power programme has yet to be made.

Industry is therefore only likely to be persuaded to divert resources from civil or submarine projects if the initial research is 100% funded and governments are seen to be totally committed to completing the programme.

10.6 Survey Findings

The responses to the survey questionnaire indicated widespread interest and potential enthusiasm for a space nuclear fission programme from government, research organisations and industry. The challenge of converting this enthusiasm to actual support is recognised but was still encouraging.

11 CONCLUSIONS AND RECOMMENDATIONS

11.1 Conclusions.

11.1.1 Applications

The analysis of applications is based on the assumption that a 200 kWe nuclear electric generator is the largest consistent with a European Ariane 5 ECA launch. Although this may be an artificial constraint the design concept developed in the HiPER project is scalable. The most suitable applications in order of priority are assessed to be:

- Robotic exploration of the outer solar system such as sample return missions to Jovian planets, orbital surveys of Neptune and Pluto and visits to the heliosphere.
- NEO management either in the form of diverting an earth threatening body or NEO mining.
- Large infrastructure transfers such as that required for a human visit to Mars (accepting that the humans travel separately by a faster method),
- A large power source for planetary infrastructure longer term.

Robotic exploration of the outer solar system alone can justify a family of NEP missions which would permit non-recurring costs to be amortised over a long term programme.

In principle NEP is likely to be less risky for diverting an earth threatening NEO than NTP if it can be deployed in time. Currently no significant collisions between a NEO and earth are predicted during the next 100 years. The probability that there would be time for an NEP, or only an NTP mission or none at all therefore appears much the same. Until such a probability emerges this application is expected to remain a relatively low priority.

The other applications could benefit significantly from a 200 kWe nuclear fission generator development although they might not be justification in their own right.

11.1.2 Capabilities

The limited survey of capabilities relevant to a space nuclear fission power programme confirmed that Europe has a wealth of relevant expertise and potentially suitable infrastructure. Adaptation of the current terrestrial Generation IV reactor research can provide a baseline and there are a number of synergies which may be exploited. The materials research capability to achieve the higher operating temperatures required for mass efficient space nuclear fission power also exists but would require a new research programme.

In principle the expertise and infrastructure also exists for the development of Brayton power conversion systems, large structures such as radiators and high power management and distribution systems. In practice research is needed for adaptation of these to the long, maintenance-free lifetime in the space environment and higher operating temperatures. The materials research by the reactor community may make a useful contribution and synergy needs to be sought with terrestrial applications with similar requirements.

Europe has an extensive capability for the project management of both nuclear and large space programmes. It also has a comprehensive capability for the storage and transport of nuclear materials and the launch and operation of conventional spacecraft. It has the capability to manage issues such as public acceptance but has yet to establish a regulatory safety framework which would allow Europe to launch a fission nuclear power plant.

11.1.3 Realising the Potential

To realise the potential to develop a space nuclear fission power generator requires:

- Agreement to future missions to explore the outer solar system robotically with 200 kWe NEP and the potential use of the technology for NEO management, large space infrastructure transfer and in situ power.
- A programme of materials research to show the feasibility of high temperature, mass-efficient, long-life, maintenance-free operations consistent with the design concepts identified in the HiPER project.
- Feasibility studies to compare liquid metal and gas cooled reactor designs leading to project definition based on a prototype system.
- A development, build, launch and operating mission or family of missions with the necessary investment in new or adapted existing infrastructure. This also requires some cross-pollination between the nuclear and space communities and a search for synergies with terrestrial nuclear power research and development.

A first step is to define the different activities in sufficient detail to be able to cost them realistically. This can then provide an input to the consideration of space nuclear fission power research in the EC Horizon 2020 programme.

Consideration should also be given to developing an industrial business case for a space nuclear fission generator programme. Without 100% R&D funding the very long gestation time precludes commercially viable returns on investment unless ‘spin-off’ to shorter term applications can be identified. Also industry needs to be confident that investment in personnel and infrastructure will have a long term, sustainable future.

11.2 Recommendations

It is recommended that:

- The conclusions of this technical Note are incorporated into the updating of The Fission Nuclear Power Generator Roadmap Draft (Dip-Sep-PL-001- D30.1 dated 20th February 2012) (Reference B).

APPENDIX A

EUROPEAN ORGANISATIONS WITH CAPABILITIES TO SUPPORT A SPACE FISSION NUCLEAR POWER GENERATOR PROGRAMME.

INTRODUCTION.

To assess the European capability and potential interest in developing a space fission nuclear programme a range of organisations were contacted. The number of organisations was not comprehensive but is considered to be sufficiently representative requested to make an initial assessment. The organisations were requested to identify relevant levels of expertise using the Capability Matrix at Annex 1 as a general guide to relevant capabilities.

The organisations contacted directly or indirectly are:

Government Agencies: ESA, CNES, DLR, ESF (Strasbourg), UK Space Agency (note that UK Space Agency response is through Leicester University acting as their agent).

Research Organisations: SCK-CEN (Belgium), CEA (France), VTT (Finland), EC JRC (Germany and Netherlands), Demokritos (Greece), MTA EK (Hungary), NCBJ (Poland), VUJE (Slovakia), Studsvick AB (Sweden), PSI (Switzerland) and NNL(UK). (The research organisations selection was based on those with active 'hot reactor' research programmes.)

Industry: CV Rez (Czech Republic), AREVA (France), Snecma (Safran group in France), Galileo Avionica (Italy), ThalesAlenia Space (Italy), AMEC (UK), EADS Astrium (UK), Rolls Royce plc (UK), and SEA (UK). (Note: AREVA includes ex-Siemens in Germany and the EADS Astrium response is pan-European not just for UK.)

Universities: It is recognised that many European universities have active nuclear research programmes. In general it is believed that relevant work is in partnership with the Research Organisations and therefore they have not been approached separately (apart from Leicester University because of its role in support of the UK Space Agency). The University of Stuttgart, as part of the DiPoP study is investigating the requirements for public acceptance, safety and sustainability of an NEP programme.

FINDINGS

All the organisations contacted were requested either to populate the Capability Matrix or just to make general comments as they considered appropriate. Not all the organisations replied or completed the Capability Matrix. In several cases there were clarification phone calls or meetings which provided more background information. The results for each organisation are recorded below and the results of the survey are summarised in the populated Capability Table in Annex 2 for ease of reference.

Government Organisations:

a) ESA (www.esa.int): ESA has a watching brief because nuclear electric propulsion (NEP) is not within the scope of current ESA research activities (although some potential consideration has been given to nuclear thermal propulsion (NTP)). ESA has funded earlier studies in NEP and is currently funding radio isotope electrical generator research and development. It provides technical support to REA (EC) in the assessment of the DiPoP project. At this stage ESA's main relevant capabilities are seen to be in project and mission management and launch and operations. There is also some potential capability in high temperature radiator and high power electric space systems and components research. [Contact: Keith Stephenson, Keith.Stephenson@esa.int.]
b) CNES (www.cnes.fr): Is active in NEP and NTP studies and completed the Capability Matrix in Annex 3. CNES is very experienced in mission and project management, launch, commissioning and operations. It also has practical expertise in the study, design and qualification of high temperature fluid circuits (relevant to Brayton cycle), heat exchangers and thermal management systems. Other expertise includes large deployable structures (relevant to radiators), micro-meteoroid protection and power regulation. [Contact: Elisa, elisa.cliquet@cnes.fr.]
c) DLR (www.dlr.de): DLR has a keen interest in identifying and nurturing disruptive technologies which will revolutionise future space activity. NEP and NTP are potential disruptive technologies. DLR has mission and project management expertise and access to a wide range of technical research activities which could support aspects of a European NEP programme. [Contact: Frank Jansen, Frank.Jansen@dlr.de.]
d) ESF Strasbourg: As an independent, non-governmental organisation dedicated to pan-European scientific networking and collaboration, the ESF has had a key role to play in mediating between a multitude of heterogeneous research cultures and agencies. The main interest in space fission nuclear power generation is in the coordination of the Megahit project. [Contact: Jean-Claude Worms, jcworms@esf.org.]
e) UK Space Agency (www.bis.gov.uk/ukspaceagency): UK Space Agency expertise is vested in Research Organisations and Industry such as NNL and Leicester University (see below). It is currently jointly sponsoring research and development in radio-isotope power generators. [Contact: Sue Horne, sue.horne@ukspaceagency.bis.gsi.gov.uk.]

Research Organisations:

a) SCK-CEN Belgium (www.sckcen.be): SCK-CEN's current main development is the MYRRHA project which includes all aspects of design, licensing, build and operation of heavy liquid metal (lead-bismuth) cooled fast reactor. SCK-CEN has past experience in sodium fact cooled reactor design and follows the developments in gas cooled fast reactor design. SCK-CEN researches material resilience to irradiation and high temperature stress and can offer unique irradiation facilities with especially the BR2, the most powerful material testing reactor outside the US. SCK-CEN is potentially interested in a programme to develop European space nuclear fission power generation in the areas of expertise identified. [Contact: Peter Baeten, pbaeten@SCKCEN.BE.]

b) CEA France (www.cea.fr): CEA is actively participating in many European high temperature liquid metal and gas cooled fast reactor developments including Phenix and Superphenix and Allegro and Antares. A completed Capability Matrix is at Annex 4. CEA expertise covers the study and design, and also potentially the build and test, for all aspects of reactor, reactor control, shield, coolant circuits and fuel for fast reactors. CEA also has access to comprehensive European critical and non-critical infrastructure for nuclear research, build and test. CEA has a full capability for the assembly, storage and transportation of fission nuclear systems and components. Research and development also includes heat exchangers, radiators and high power electrical systems. CEA has extensive experience of the project management of fission nuclear reactors in collaboration with industry and is interested in a potential European space nuclear fission power development. [Contact: Xavier Raepsaet, xavier.raepsaet@cea.fr.]

c) VTT Finland (www.vt.fi): VTT supports the efficient use of nuclear fission power and operates the TRIGA research reactor. No response to date. [Contact: ?]

d) EC JRC Germany and Netherlands (ec.europa.eu/dgs/jrc): The JRC I a leader in European (and Russian) research into reactor and nuclear fuel safety with a special interest in advanced nuclear reactors. The JRC-ITU's mission is to provide the scientific foundation for the protection of the European citizen against risks associated with the handling and storage of highly radioactive material. The JRC is also part of the Materials Performance assessment for Innovative Systems (MATTINO) project as part of the Euratom Nuclear Safety research programme and operates the research reactor at Petten. No response to date. [Contact: Dr Tamborini and Dr Nilsson, jrc-itu-info@ec.europa.eu, karl-fredrik.nilsson@jrc.nl?]

e) Demokritos Greece (ipta.demokritos.gr): Development of the Institute of Nuclear Technology – Radiation Protection (INT-RP) started in 1960 around the Research Reactor and was established as an independent Institute in 1986. Its seven laboratories include the Nuclear Research Reactor Centre and the Environmental Radioactivity Laboratory. The research reactor is being refurbished for a 20 year lifetime extension. No response to date. [Contact: Dr Stamatelatos, ion@ipta.demokritos.gr?]

f) MTA EK Hungary (www.kfki.hu/aeki/insitute): MTA EK is mainly active in the field of basic and applied research related to nuclear energy. The main research areas are reactor physics, thermal hydraulics, fuel behaviour studies, and material sciences, related aspects of informatics (simulators, core monitoring, etc.), health physics, environmental investigations, nuclear electronics and chemistry. MTA EK is the chief technical consultant of NPP Paks and key player in the power-upgrade, safety, life extension and maintenance activity of the utility and serves as a technical support organisation (TSO) to the safety authority in Hungary. The Institute operates the 10 MW Budapest Research Reactor, providing the scientific community of Europe (see Budapest Neutron Centre for details) with research possibility for neutron physics and applications. The Institute has acquired important experience with VVER-type reactors, both in experimental and in analytical fields. MTA EK is planning to host the Allegro research reactor development in partnerhsip with CV Rez (Czech Republic) NCBJ (Poland) and VUJE (Slovakia). A capability matrix has not been completed but MTA EK has expressed an interest in further work associated with gas cooled high temperature reactors (1.2), shadow shielding (1.6), safety (1.7), project management (4.1), feasibility studies (4.2), safety and regulatory (4.8) and safety (4.9). [Contact: Akos Horvath, Akos.Horvath@energia.mta.hu.]

g) NCBJ Poland (www.ncbj.gov.pl): The NCBJ is a leading research institute in Poland in the field of nuclear research. Although space propulsion poses very unusual challenges for "conventional" nuclear research institution, they do have experiences and facilities that may possibly be applicable in development of space nuclear reactor. These are:
   - Research reactor (with limited applicability, due to the thermal spectrum of neutrons),
   - Material hot - laboratory (not fuel lab - non-fissile materials only),
   - CFD analysis team, applicable for thermal-hydraulics analysis of the reactor,
   - Neutronics analysis team,

   They also have experience with calculation of contaminants' spread, which might be useful for risk evaluation in case of launcher failure or vehicle re-entry. As a member of "Allegro" project, the NCBJ is interested in the potential application of nuclear energy in space science and thinks that gas cooled fast reactor, due to its low mass and high temperature achieved (and thus good power/mass ratio), may be a very interesting option for nuclear propulsion and are open to any further questions in the topic. [Contact: Różycki Kajetan Kajetan.Rozycki@ncbj.gov.pl]

h)

i) PSI Switzerland (www.psi.ch): PSI's Laboratory for Reactor Physics and Systems Behaviour (LRS) forms part of PSI's Nuclear Energy and Safety Research Department (NES). The laboratory is engaged in both analytical and experimental R&D related to the operation of current and future nuclear power plants. Its strategic goal is to strengthen the sustainability of nuclear power via research to improve understanding of the complex phenomenology of nuclear safety and the physics of complete fuel cycle closure in the context of plutonium management and waste reduction. PSI's large facilities (the PROTEUS research reactor (being decommissioned), the Hot Labor and the SINQ) play a central role in LRS. In addition, the laboratory is actively involved in international collaboration on experimental reactor physics by carrying out experiments in foreign research reactors (e.g. EOLE in CEA Cadarache and BR1 in SCK.CEN). No response received to date. [Dr Zimmermann, secretary-lrs@psi.ch?]

j) NNL UK (www.nnl.co.uk): NNL has expertise in Fast reactor technology and MAGNOX and AGR reactors and participates in the EC FP7 GOFAST and SFR programmes. Study and design work is supported by non-critical infrastructure. NNL has both the expertise and the critical infrastructure for nuclear fuel study, design build and test. A completed capability matrix is at Annex 5. [Contact: Tom Rice, tom.g.rice@nnl.co.uk.]

Industry:

a) CV Rez Czech Republic (www.cvrez.cz): CV Rez is a spin-off company from the UJV Nuclear Research Institute with the main aim of research and development in innovations in the field of energy (particularly nuclear). CV Rez owns a unique research infrastructure including the LVR-15 and LR-0 research reactors. Through international teaming it also has access to the Jules Horowitz and Allegro reactor projects. CV Rez has not been contacted directly but interest from the Allegro project has been expressed by AEKI (see above). [Contact: TBD]
b) AREVA France, Germany (Siemens) (www.areva.com): AREVA has comprehensive expertise and supporting infrastructure in all aspects of terrestrial civil and submarine fission nuclear power generation. AREVA is engaged in generation IV and high temperature reactor research projects (with priority currently given to liquid metal fast reactors) and has experience and infrastructure at system level of Brayton cycle power conversion. For high power management and distribution AREVA has experience in terrestrial but not space systems but has a potential interest in space applications. Apart from launch and in-orbit support the Company has experience and infrastructure for all aspects of nuclear fission project management. A completed capability matrix is at Annex 6. AREVA has a strong interest in a European future space fission nuclear programme which they will progress through the Megahit project. [Contact: Jean-Pierre Roux (AREVA TA), jean-pierre.roux@areva.com.]
c) ESF France (www.esf.com):
d) Galileo Avionica Italy studied power management and distribution for a 200 kWe nuclear fission generator with SEP UK as part of the HiPER project. They have not been contacted directly as part of this study but are expected to be interested in potential future development. [Contact: Ferrando Emanuele emanuele.ferrando@selexgalileo.com]
e) ThalesAlenia Space Italy, France (www.thalesgroup.com/space): ThalesAlenia space is a member of the Megahit team and has delivered space equipment for all applications including commercial communications, a significant part of the ISS and science missions with very challenging thermal requirements such as Bepi Colombo. A capability matrix is attached showing specific areas of interest. [Gaetano Poidomani, Gaetano.Poidomani@thalesaleniaspace.com.]
f) VUJE Slovakia (www.vuje.sk): VUJE was established as an engineering company, transformed from the state research institute, to perform design, supply, implementation, research and training activities particularly in the field of nuclear (and conventional) power generation. VUJE recently joined the Allegro project. They have not been contacted directly but direct interest form the Allegro project has been expressed by AEKI Hungary (see above). [Contact: TBD]
g) Studsvick AB Sweden (www.studsvick.com): Studsvick offers engineering and consultancy services mainly in the area of nuclear safety and regulatory support, fuel and core engineering, materials, design, management, waste management and

de-commissioning. Do not consider to have any relevant capability at this time. [Contact: Arne Larsson, arne.larsson@studsvik.se?]

h) AMEC UK (www.amec.com): AMEC acquired the Serco Group Nuclear Technical Services in June 2012 and is active in the Allegro and GOFAS projects and advanced materials research for high temperature reactors. A completed Capability Matrix will be sent and AMEC is potentially interested in future space fission projects. [Contact: Richard Stainsby, Richard.Stainsby@amec.com.]

i) EADS Astrium UK, France, Germany (www.astrium.eads.net): Astrium is Europe's largest space company and is participating in the EC FP7 NEOShield study. They have an interest in the potential for NEO threat mitigation by NTP and NEP. Astrium has expertise in all aspects of space project research, management and delivery. A capability matrix is attached at Annex and Astrium has a potential interest in a future European fission nuclear programme for NEO mitigation. [Steven Eckersley, Steven.ECKERSLEY@astrium.eads.net.]

j) Rolls Royce plc UK (www.rolls-royce.com): Rolls Royce developed a concept design for a space 200 kWe fission nuclear power generator in the EC FP7 HiPER project. The company has the expertise and infrastructure for nuclear submarine power plant research, design, build and operation and is increasingly diversifying into terrestrial civil nuclear power. The company does not wish to divert resources from its core business until there is clear evidence that Europe will invest in a sustainable space nuclear fission power generation programme. There is therefore no completed capability matrix and no expression of potential interest at this time. [Contact: Anthony Donaldson, anthony.donaldson@rolls-royce.com.]

k) SEA UK (www.sea.co.uk): No capability matrix has been completed because current SEA activity is only with radio-isotope power generation. SEA is leading the development of the ESA Stirling Engine energy conversion approach for radio-isotope power sources which may be the optimum solution in the hundreds-of-watts range compared to Brayton cycle for multiple kW. However NASA has been investigating the application of Stirling cycle power conversion up to 40 kWe and therefore this work may have interest for a European 30 kWe nuclear fission power generator. [Chris Chaloner, Chris.Chaloner@sea.co.uk.]

l) Snecma (Safran group in France) was contacted briefly in 2011, but should be further contacted for their capabilities and expertise in gas turbine technology, energy conversion, power management & distribution and project management: (as KeRC is managing the Russian Megawatt project, such entity could manage similarly an European project) [Contact: André Beaurain, andre.beaurain@snecma.fr and Olivier Duchemin olivier.duchemin@snecma.fr].

Universities:

a) USTTUT Stuttgart, Germany (www.uni-stuttgart.de): The University of Stuttgart is leading the public acceptance, safety and sustainability for space fission nuclear power part of the DiPoP study. [Contact: Georg Herdrich, herdrich@irs.uni-stuttgart.de.]

b) University of Leicester UK (www.le.ac.uk): Current Leicester University focus is on radio-isotope power generation but a capability matrix has been compiled

(Annex 7) which specified a much wider interest including the study of future high temperature fission nuclear power generation, project management and public acceptance, safety and sustainability. Hey also call attention to the educational and training issues associated with space nuclear fission power development. [Contact: Richard Ambrosi, rma8@leicester.ac.uk.]

CONCLUSIONS.

It is fully recognised that the survey of capability is representative and not comprehensive and that there are other organisations, especially universities capable of and potentially interested in participating in a future European space fission nuclear power development. The survey does demonstrate that Europe has expertise in all relevant areas of a space fission nuclear power programme and much of the infrastructure to support it. In some areas there is considerable depth of expertise but in others there are weaknesses which would have to be addressed.

The European research into Generation IV reactors is currently for civil applications. The (fast) reactors tend to be larger than required for space applications and the focus appears to be more on liquid metal rather than gas cooled. An important design objective is to achieve a high level of fuel 'burn up' to reduce nuclear waste which is not necessarily a consideration for space applications. Also current reactor research does not envisage core exit temperatures much greater than 1100°K when space applications would benefit from temperatures in the range 1300-1500°K.

Although past experience in Russia (TOPAZ) and the US (SP100) suggest such temperatures are feasible Europe would need to make a significant investment in materials development to adapt existing high temperature reactor technology to operate at these levels. This research would not only apply to the reactor core and fuel but also need to demonstrate very high resilience in control mechanisms and coolant circuits and any interaction with temperature sensitive materials in shielding. It should be noted that all terrestrial developments are based on NEP and although terrestrial infrastructure may be adapted for a space programme this would not apply to NTP.

Similar arguments apply to fuel for space reactors but there are a number of organisations in Europe who appear well placed to do the necessary research and development. Nuclear fuel manufacturing and testing facilities also appear to be well able to support a space programme.

Although there is extensive experience in the technologies for power conversion it is to date mostly in terrestrial applications and at much lower operating temperatures than needed for mass-efficient space systems. The range of expertise in terrestrial equipment, existing lower temperature space thermal management and advanced (low mass and high temperature) materials provides the basis to design and build suitable space systems. Particular challenges are in long life (including creep), no maintenance Brayton or Stirling power conversion and compact, low mass radiators. As most of this research does not require critical build and test facilities the necessary infrastructure can probably be provided with modest adaptation of existing facilities.

European experience in high power space systems is currently constrained to DC power up to about 25 kWe. Much higher power levels are available in terrestrial systems and the expertise exists to research the application of these technologies and components to much higher space power levels. However a research programme and some infrastructure development would be needed.

There is in depth expertise and infrastructure for space mission and project management in Europe. There is also considerable experience in nuclear power plant project management and this experience and expertise would need to be integrated into the space management for a European space fission nuclear programme. It may be that some preliminary benefits can be realised form the current radio-isotope development programmes. A starting point is to develop a project management plan from pre-feasibility to mission completion as proposed in the HiPER Roadmap for a 200 kWe Space Nuclear Fission generator.

Europe's terrestrial nuclear transport and storage arrangements may be expected to apply equally to a space nuclear programme. Europe has its own launch capability and access to other facilities outside Europe (Kourou is considered within Europe for the purpose of this paper). However issues associated with launching a fission reactor, such as licencing, agreed safety criteria and public acceptance remain largely unresolved and will require considerable domestic and international effort.

ANNEXES:

1. European Organisation and Industry Capability Capture Matrix.
2. European Organisation and Industry Capability Table
3. CNES - European Organisation and Industry Capability Capture Matrix
4. CEA - European Organisation and Industry Capability Capture Matrix
5. NNL -European Organisation and Industry Capability Capture Matrix
6. Areva - European Organisation and Industry Capability Capture Matrix
7. AMEC - European Organisation and Industry Capability Capture Matrix
8. EADS Astrium - European Organisation and Industry Capability Capture Matrix
9. ThalesAleniaSpace European Organisation and Industry Capability Capture Matrix
10. University of Leicester, Queen Mary University of London, European Thermodynamics European Organisation and Industry Capability Capture Matrix.

ANNEX 1: EUROPEAN ORGANISATION AND INDUSTRY CAPABILITY CAPTURE MATRIX

No	CAPABILITY	EXPERTISE	INFRASTRUCTURE	INTEREST	COMMENT
1	**HIGH TEMPERATURE REACTOR TECHNOLOGY**	***Study, Design, Build, Test?***	***Non-critical R&D & test Critical R&D & test.***	***Yes No***	***Eg. Expertise or infrastructure adaptable from civil activity.***
1.1	Liquid metal cooled				
1.2	Gas cooled				
1.3	Reactor Control Mechanisms				
1.4	Coolant pipes and pumps				
1.5	Fuel Production				
1.6	Shadow shielding				
1.7	Safety Features				
1.8	Storage & Transportation				
1.9	In orbit commissioning				
2	**ENERGY CONVERSION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
2.1	High Efficiency Thermo-electric				
2.2	Thermo-electric materials				
2.3	Power regulation				
2.4	High temperature Brayton cycle				
2.5	Radial Turbo-alternators				
2.6	Heat Exchangers				
2.7	Leak free encapsulation				
2.8	Mass Efficient Fixed radiator				
2.9	Micro-meteoroid protection				
2.10	Deployable radiator				
2.11	Micro-meteoroid protection				
3	**POWER MANAGEMENT**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**

	AND DISTRIBUTION				
3.1	High Power Rectifiers				
3.2	High Power Switching				
3.3	High Power Low Mass Bus				
3.4	High Power Batteries				
3.5	High Power Shunt				
4	**PROJECT MANAGMENT**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
4.1	Requirements definition				
4.2	Feasibility Assessment				
4.3	System Definition & Design				
4.4	Prototyping				
4.5	Qualification				
4.6	Proto-flight build				
4.7	Launch and in-orbit support				
4.8	Safety & Regulatory				
4.9	Public Acceptance				
5	**LAUNCH AND OPERATION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
5.1	Transport to launch site				
5.2	Assembly for launch				
5.3	Launch				
5.4	In-orbit commissioning				
5.5	Operations				
5.6	Disposal				
5.7	Anomaly Response				

Notes:

1. Section 1 refers to space and terrestrial reactors recognising that to date there have only been studies into space reactors in Europe.
2. In Column 4 ‘critical’ is with respect to the state of the core/fuel neutronic reactivity (risk of criticality).

ANNEX 2: EUROPEAN ORGANISATION AND INDUSTRY CAPABILITY TABLE

ORGANISATION	HIGH TEMPERATURE REACTORS	ENERGY CONVERSION	POWER MANAGEMENT & DISTRIBUTION	PROJECT MANAGEMENT	LAUNCH & OPERATIONS	COMMENT
PAN-EUROPEAN						
ESA*	Monitoring	Monitoring	Research	Missions/Projects	Kourou	EC technical support
EC JRC (Germany)	Safety/Fuel					Advanced technologies
EC JRC (Netherlands)	Design/Research					Research reactor
ESF(Strasbourg)				Megahit		Advanced Research
GOVERNMENT						
CEA France*	Allegro[1]/ASTRID[2]	R&D				DiPoP Advisory Board
CNES France*		R&D	R&D	Missions/Projects	Kourou	
DLR Germany*				Missions/Projects		DiPoP
UK Space Agency*	Monitoring	Monitoring	Monitoring	Monitoring	Licencing	See Leicester University
SCK_CEN Belgium*	ELSY[3]/MYRRHA[4]	Study				Materials research
VTT Finland	TRIGA[5], Safety/fuel			Consultancy		Research reactor
Demokritos Greece	Advanced R&D	Study				
MTA-EK Hungary*	Allegro	Allegro		Projects		Materials and safety
NCBJ Poland**	Allegro	Allegro				Materials & space eqpt.
VUJE-Slovakia**	Allegro	Allegro				
PSI Switzerland	Safety/Fuel					Research reactor access
NNL UK*	GOFAST[6] & SFR[7]	Study				Safety/fuel/materials
INDUSTRY						
CV-Rez Czech Rep**	Allegro	Allegro				
AREVA	Allegro/ASTRID/	Allegro/Astride/	R&D	Research, civil &		Megahit

ORGANISATION	HIGH TEMPERATURE REACTORS	ENERGY CONVERSION	POWER MANAGEMENT & DISTRIBUTION	PROJECT MANAGEMENT	LAUNCH & OPERATIONS	COMMENT
France/Germany *	Antares[8]	Antares		submarine		
Snecma (Safran) France		Turbo-alternators		Projects		
Galileo Avionica Italy***			HiPER Study			With SEP UK ***
ThalesAlenia Space Italy*		Radiator		Missions/Projects		Megahit
Studsvick Sweden	Fuel/core design			Consultancy		Materials & safety
AMEC UK *	Allegro, GOFAST	study	study	Consultancy		Materials research
EADS Astrium UK*		Thermal & structure	R&D	Missions/Projects	Paradigm	NEO Mitigation Study
Rolls Royce UK ***	HiPER[9] Design	HiPER Design				
SEA UK *		Stirling Cycle		Projects		Radio-isotope focussed
UNIVERSITIES						
Leicester UK*	Study	Study				Radio-isotope/fission
Stuttgart Germany *	Safety		R&D	Public acceptance, sustainability		

NOTES:

* Have expressed a potential interest in a future European nuclear fission generator programme.

** Not consulted directly but should be considered in future projects.

*** Participated in the EC FP7 HiPER project.

1. Allegro is an EC FP7 high temperature gas cooled development reactor project.
2. ASTRID France is developing the Advanced Sodium Technical Reactor for Industrial Demonstration (ASTRID).
3. ELSY is a Generation IV mid-sized lead cooled fast reactor design..
4. MYRRHA is a project to develop a research lead cooled fast reactor.
5. TRIGA is a widely used non-power research reactor.
6. GOFAST a gas cooled fast reactor study (leading to the Allegro demonstration)
7. SFR are sodium fast reactor studies supporting Phenix and Super Phenix R&D.
8. Antares a high temperature gas cooled fast reactor design with gas (or steam) turbine power conversion.
9. HiPER – EC FP7 Study: High Power Electric Propulsion: a roadmap for the future (included solar and nuclear energy sources).

ANNEX 3: CNES - EUROPEAN ORGANISATION AND INDUSTRY CAPABILITY CAPTURE MATRIX

No	CAPABILITY	EXPERTISE	INFRASTRUCTURE	INTEREST	COMMENT
1	**HIGH TEMPERATURE REACTOR TECHNOLOGY**	***Study, Design, Build, Test?***	***Non-critical R&D & test Critical R&D & test.***	***Yes No***	***Eg. Expertise or infrastructure adaptable from civil activity.***
1.1	Liquid metal cooled				
1.2	Gas cooled				
1.3	Reactor Control Mechanisms				
1.4	Coolant pipes and pumps				
1.5	Fuel Production				
1.6	Shadow shielding				
1.7	Safety Features				
1.8	Storage & Transportation				
1.9	In orbit commissioning				CNES has satellite control centres that might be adaptable to specific in orbit commissioning operations
2	**ENERGY CONVERSION**	**EXPERTISE**	**INFRA-STRUCTURE**	**INTEREST**	**COMMENT**
2.1	High Efficiency Thermo-electric				
2.2	Thermo-electric materials				
2.3	Power regulation				
2.4	High temperature Brayton cycle	Expertise in study, design, qualification of fluid circuits (high temperature, cryo temperatures) and turbo-pumps			
2.5	Radial Turbo-alternators				
2.6	Heat Exchangers	Expertise in heat exchangers and more generally thermal control for satellites that could be used in the frame of other systems			
2.7	Leak free encapsulation				
2.8	Power regulation	Expertise in rocket engine regulation (European and national projects)			

2.9	Mass Efficient Fixed radiator				
2.10	Micro-meteoroid protection	Expertise gained in the frame of satellites that might be to some extent applicable to nuclear systems			
2.11	Deployable radiator	Expertise gained in the frame of satellites that might be to some extent applicable to nuclear systems			
2.12	Micro-meteoroid protection				
3	**POWER MANAGEMENT AND DISTRIBUTION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
3.1	High Power Rectifiers				
3.2	High Power Switching				
3.3	High Power Low Mass Bus				
3.4	High Power Batteries				
3.5	High Power Shunt				
4	**PROJECT MANAGMENT**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
4.1	Requirements definition	CNES expertise is project management has been demonstrated through many satellite and launcher projects			
4.2	Feasibility Assessment				
4.3	System Definition & Design				
4.4	Prototyping				
4.5	Qualification	CNES Directorate of Launchers expertise gained with de development of Ariane launchers			
4.6	Proto-flight build				
4.7	Launch and in-orbit support	CNES Directorate of Launchers expertise gained with de development of Ariane launchers	French Guyana space centre, Toulouse satellite control centre		
4.8	Safety & Regulatory	CNES ensures the application of the space law			

4.9	Public Acceptance	CNES expertise in communication toward public			
5	**LAUNCH AND OPERATION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
5.1	Transport to launch site	Center in French Guyana ground infrastructure (ESA is the owner but CNES runs the centre)			
5.2	Assembly for launch				
5.3	Launch				
5.4	In-orbit commissioning				
5.5	Operations				
5.6	Disposal				
5.7	Anomaly Response				

ANNEX 4: CEA - EUROPEAN ORGANISATION AND INDUSTRY CAPABILITY CAPTURE MATRIX

No	CAPABILITY	EXPERTISE	INFRASTRUCTURE	INTEREST	COMMENT
1	**HIGH TEMPERATURE REACTOR TECHNOLOGY**	***Study, Design, Build, Test?***	***Non-critical R&D & test Critical R&D & test.***	***Yes No***	***Eg. Expertise or infrastructure adaptable from civil activity.***
1.1	Liquid metal cooled	Yes Only Study, design for space reactor	Non-critical and critical	Yes	PHENIX & SUPERPHENIX (both terrestrial reactors that operated in France) Large infrastructures available for these LMR. Important R&D program still underway.
1.2	Gas cooled	Yes Only Study, design for space reactor	Non-critical and critical	Yes	Former UNGG reactors runs in France in early 70s
1.3	Reactor Control Mechanisms	Yes Only Study, design for space reactor	Non-critical and critical	Yes	build and test
1.4	Coolant pipes and pumps	Yes Only Study, design for space reactor	Non-critical and critical	Yes	build and test Available infrastructures
1.5	Fuel R&D Fuel Production	Yes	critical	Yes	build and test Available infrastructures
	Material R&D, production	yes	Critical or not	yes	build and test Available infrastructures
1.6	Shadow shielding	Study, design	Non-critical and critical	Yes	Potential build and test
1.7	Safety Features	Study, design	Non-critical and critical	Yes	Potential build and test
1.8	Storage & Transportation	Yes	critical		Large CEA skill with their own experimental reactors and naval propulsion
1.9	In orbit commissioning	No			
					*(not specifically dedicated to space reactor applications).

2	ENERGY CONVERSION	EXPERTISE	INFRASTRUCTURE	INTEREST	COMMENT
2.1	High Efficiency Thermo-electric	Study, design	Non-critical and critical	Yes	Potential build and test
2.2	Thermo-electric materials	Study, design	Non-critical and critical	Yes	Potential build and test
2.3	Power regulation	Study, design	Non-critical and critical	Yes	Potential build and test
2.4	High temperature Brayton cycle	Study, design	Non-critical	Yes	Potential build and test
2.5	Radial Turbo-alternators	No		No	
2.6	Heat Exchangers	Yes			
2.7	Leak free encapsulation	Yes			
2.8	Power regulation	Yes			
2.9	Mass Efficient Fixed radiator	Study, design	Non-critical	Yes	Potential build and test
2.10	Micro-meteoroid protection	No	Non-critical	Yes	Potential build and test
2.11	Deployable radiator	Study, design	Non-critical	Yes	Potential build and test
3	**POWER MANAGEMENT AND DISTRIBUTION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
3.1	High Power Rectifiers				A specific CEA division is concerned by new energy technologies including energy management, innovative battery development, ...
3.2	High Power Switching				
3.3	High Power Low Mass Bus				
3.4	High Power Batteries				
3.5	High Power Shunt				
4	**PROJECT MANAGMENT**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
4.1	Requirements definition	Yes	Yes	Yes	Previous experience
4.2	Feasibility Assessment	Yes	Yes	Yes	Previous experience
4.3	System Definition & Design	Yes	Yes	Yes	In collaboration with the industrial
4.4	Prototyping	Potentially Yes	Yes	Yes	In collaboration with the industrial
4.5	Qualification	Yes	Yes	Yes	Reactor and system level?
4.6	Proto-flight build	Yes	Yes	Yes	In support to an industrial
4.7	Launch and in-orbit support	Yes	No	potentially	In support to the operator or space agency
4.8	Safety & Regulatory	Yes	Yes	potentially	In collaboration with IRSN

4.9	Public Acceptance	Yes	-	potentially	In collaboration with IRSN
5	**LAUNCH AND OPERATION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
5.1	Transport to launch site	Partially	Yes	Yes	Expertise exist at CEA for Nuclear fuel, Reactor, System assembly and transport
5.2	Assembly for launch	Partially	Yes	Yes	
5.3	Launch	No	No		
5.4	In-orbit commissioning	No	-		
5.5	Operations	Yes	-		
5.6	Final Disposal	No	-		Expertise in reactor decommissioning but not for final disposal in space
5.7	Anomaly Response	Yes	-	Yes	Reactor

ANNEX 5: NNL -EUROPEAN ORGANISATION AND INDUSTRY CAPABILITY CAPTURE MATRIX

No	CAPABILITY	EXPERTISE	INFRASTRUCTURE	INTEREST	COMMENT
1	**HIGH TEMPERATURE REACTOR TECHNOLOGY**	***Study, Design, Build, Test?***	***Non-critical R&D & test Critical R&D & test.***	***Yes No***	***Eg. Expertise or infrastructure adaptable from civil activity.***
1.1	Liquid metal cooled	Study & Design	Non Critical	Yes	UK expertise on Fast Reactor technology
1.2	Gas cooled	Study & Design	Non Critical	Yes	UK expertise on Magnox & AGR reactors also NNL is Part of the FP7 programmes on GOFAST &SFR
1.3	Reactor Control Mechanisms				
1.4	Coolant pipes and pumps				
1.5	Fuel Production	Study, Design, Build & test	Critical	Yes	NNL Operates a UO2 and Pu test fuel manufacturing capability allowing for manufacture and PIE
1.6	Shadow shielding				
1.7	Safety Features	Study & Design	Non Critical	Yes	Safety case support provided to UK operators and reactor vendors
1.8	Storage & Transportation				
1.9	In orbit commissioning				
2	**ENERGY CONVERSION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
2.1	High Efficiency Thermo-electric				
2.2	Thermo-electric materials				
2.3	Power regulation				
2.4	High temperature Brayton cycle				
2.5	Radial Turbo-alternators				
2.6	Heat Exchangers				
2.7	Leak free encapsulation	Study Design	Non Critical	Yes	Involvement in ESA Space batteries project.
2.8	Mass Efficient Fixed radiator				
2.9	Micro-meteoroid protection				

2.10	Deployable radiator				
2.11	Micro-meteoroid protection				
3	**POWER MANAGEMENT AND DISTRIBUTION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
3.1	High Power Rectifiers				
3.2	High Power Switching				
3.3	High Power Low Mass Bus				
3.4	High Power Batteries				
3.5	High Power Shunt				
4	**PROJECT MANAGMENT**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
4.1	Requirements definition				
4.2	Feasibility Assessment				
4.3	System Definition & Design				
4.4	Prototyping				
4.5	Qualification	Study & test qualification of Fuel	Critical	Yes	Fuel testing capability
4.6	Proto-flight build				
4.7	Launch and in-orbit support				
4.8	Safety & Regulatory				
4.9	Public Acceptance				
5	**LAUNCH AND OPERATION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
5.1	Transport to launch site				
5.2	Assembly for launch				
5.3	Launch				
5.4	In-orbit commissioning				
5.5	Operations				
5.6	Disposal				
5.7	Anomaly Response				

ANNEX 6: AREVA - EUROPEAN ORGANISATION AND INDUSTRY CAPABILITY CAPTURE MATRIX

No	CAPABILITY	EXPERTISE	INFRASTRUCTURE	INTEREST	COMMENT
1	**HIGH TEMPERATURE REACTOR TECHNOLOGY**	***Study, Design, Build, Test?***	***Non-critical R&D & test Critical R&D & test.***	***Yes No***	***Eg. Expertise or infrastructure adaptable from civil activity.***
1.1	Liquid metal cooled	Teaming on Astrid reactor French project	Yes	Yes	Expertise or infrastructure adaptable from civil activity.
1.2	Gas cooled	French HTR project	yes	yes	Priority given to LMCR
1.3	Reactor Control Mechanisms	Yes	yes	yes	
1.4	Coolant pipes and pumps	Yes	yes	yes	
1.5	Fuel Production	Yes (pwr, lmr)	yes	yes	
1.6	Shadow shielding	yes	yes	yes	
1.7	Safety Features	yes	yes	yes	
1.8	Storage & Transportation	yes	yes	yes	
1.9	In orbit commissioning	yes			
2	**ENERGY CONVERSION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
2.1	High Efficiency Thermo-electric	yes	yes	yes	RTGs development
2.2	Thermo-electric materials	yes	no	no	Specialized labs to be involved
2.3	Power regulation	yes	yes	yes	Experience in space power regulation
2.4	High temperature Brayton cycle	yes	no	yes	System level - HTR
2.5	Radial Turbo-alternators	no	no	no	
2.6	Heat Exchangers	yes	yes	yes	HTR
2.7	Leak free encapsulation				Not clear
2.8	Mass Efficient Fixed radiator	no	no	No	
2.9	Micro-meteoroid protection	no	no	no	
2.10	Deployable radiator	no	no	no	
2.11	Micro-meteoroid protection				See above
3	**POWER MANAGEMENT AND**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**

	DISTRIBUTION				
3.1	High Power Rectifiers	yes	yes	Maybe	No experience in space systems
3.2	High Power Switching	yes	yes	"	"
3.3	High Power Low Mass Bus	yes	yes	"	"
3.4	High Power Batteries	yes	yes	"	"
3.5	High Power Shunt	yes	yes	"	"
4	**PROJECT MANAGMENT**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
4.1	Requirements definition	yes	yes	yes	Many reactors under study or construction
4.2	Feasibility Assessment	yes	yes	yes	
4.3	System Definition & Design	yes	yes	yes	
4.4	Prototyping	yes	yes	yes	
4.5	Qualification	yes	yes	yes	
4.6	Proto-flight build	yes	yes	yes	
4.7	Launch and in-orbit support	yes	yes	yes	No experience
4.8	Safety & Regulatory	yes	yes	yes	
4.9	Public Acceptance	yes	yes	yes	
5	**LAUNCH AND OPERATION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
5.1	Transport to launch site	yes	yes	yes	Not experienced
5.2	Assembly for launch	yes	yes	yes	Not experienced
5.3	Launch	no	no	No	
5.4	In-orbit commissioning	yes	yes	yes	Not experienced
5.5	Operations	yes	yes	yes	Not experienced
5.6	Disposal	yes	yes	yes	Not experienced
5.7	Anomaly Response	yes	yes	yes	Not experienced

ANNEX 7: AMEC - EUROPEAN ORGANISATION AND INDUSTRY CAPABILITY CAPTURE MATRIX

1	**HIGH TEMPERATURE REACTOR TECHNOLOGY**	***Study, Design, Build, Test?***	***Non-critical R&D & test Critical R&D & test.***	***Yes No***	***Eg. Expertise or infrastructure adaptable from civil activity.***
1.1	Liquid metal cooled	Study, design, (historical) build and test		Yes	Designer and constructor of the sodium-cooled Prototype Fast Reactor at Dounreay. Member of EFR Associates with joint responsibility for the design of the European Fast Reactor, EFR.
1.2	Gas cooled	Study, design, (historical) build and test		Yes	AMEC and all of the predecessor companies which were merged into the nuclear business of AMEC were involved in the design, construction and commissioning of most of the 1st Generation Magnox power stations, all of the AGR power stations with subsequent involvement in international High Temperature Reactor (HTR) projects such as PBMR and NGNP. Founder member of the European HTR Technology Network. Involved for many years in the conceptual development of gas cooled fast reactors from UK fast spectrum variants of the AGR concept through to coordinating European research projects in FP5, FP6 and FP7.
1.3	Reactor Control Mechanisms	Study, design, (historical) build and test		Yes	Development and testing reactivity control systems for liquid metal fast reactors and AGR's.

1.4	Coolant pipes and pumps	Study, design, (historical) build and test		Yes	Development of liquid metal pumps for PFR and development and support of operation for AGR circulators. Design of high-integrity piping systems for liquid metal reactors.
1.5	Fuel Production			No	
1.6	Shadow shielding	Study, design		Yes	General shielding design and analysis capability using industry standard codes such as MCNP. No specific experience with shadow shielding but Monte-Carlo methods used for regular shielding are applicable. Recent acquisition of Serco Technical Services increases our shielding and criticality assessment capabilities significantly as well as the ownership of the ANSWERS software suite.
1.7	Safety Features	Study, design, build and test		Yes	Design and installation of digital reactor control and protection systems on existing plant. Design and build and testing of the emergency boron injection system on Sizewell B.
1.8	Storage & Transportation			No	
1.9	In orbit commissioning			No	
2	**ENERGY CONVERSION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
2.1	High Efficiency Thermo-electric			No	
2.2	Thermo-electric materials			No	
2.3	Power regulation			No	
2.4	High temperature Brayton cycle	Study		Yes	Studies of system design and analysis of transient behaviour for high temperature gas cooled reactors.

2.5	Radial Turbo-alternators			No	
2.6	Heat Exchangers	Study		Yes	Design of many heat exchangers for nuclear plant.
2.7	Leak free encapsulation			No	
2.8	Power regulation			No	
2.9	Mass Efficient Fixed radiator			No	
2.10	Micro-meteoroid protection			No	
2.11	Deployable radiator			No	
2.12	Micro-meteoroid protection			No	
3	**POWER MANAGEMENT AND DISTRIBUTION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
3.1	High Power Rectifiers			No	
3.2	High Power Switching			No	
3.3	High Power Low Mass Bus			No	
3.4	High Power Batteries			No	
3.5	High Power Shunt			No	
4	PROJECT MANAGMENT	EXPERTISE	INFRASTRUCTURE	INTEREST	COMMENT
4.1	Requirements definition	Study, Design and Build		Yes	Nuclear power station build and operational support - requirements capture for modifications, systems and components.
4.2	Feasibility Assessment	Study, Design and Build		Yes	Technology reviews of design options or methods.
4.3	System Definition & Design	Study, Design and Build		Yes	Definition of functional requirements and design, procurement, installation and testing of systems. Digital reactor protection systems for AGRs is one such example.
4.4	Prototyping	Study, design and		Yes	Development of mock-ups and prototype

		Build			systems. A recent example is the development of first-wall armour prototypes for the ITER
4.5	Qualification	Study, design and build		Yes	Testing and qualification of components as being fit to load into a reactor.
4.6	Proto-flight build			No	
4.7	Launch and in-orbit support			No	
4.8	Safety & Regulatory	Study, Design and Build		Yes	Number of safety submission for new and operating reactors prepared. Support provided to regulators for the licensing of innovative plant.
4.9	Public Acceptance			Maybe	We are very familiar with public acceptance issues surrounding conventional land and sea-based nuclear power generation.
5	**LAUNCH AND OPERATION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
5.1	Transport to launch site			No	
5.2	Assembly for launch			No	
5.3	Launch			No	
5.4	In-orbit commissioning			No	
5.5	Operations			Yes	We would be interested in ground-based commissioning operations
5.6	Disposal			Yes	Involved in a number of nuclear decommissioning and waste management projects.
5.7	Anomaly Response			Yes	Experience with fault diagnosis and troubleshooting in nuclear power stations

ANNEX 8: EADS ASTRIUM - EUROPEAN ORGANISATION AND INDUSTRY CAPABILITY CAPTURE MATRIX

No	CAPABILITY	EXPERTISE	INFRASTRUCTURE	INTEREST	COMMENT
1	**HIGH TEMPERATURE REACTOR TECHNOLOGY**[1]	***Study, Design, Build, Test?***	***Non-critical R&D & test Critical R&D & test.***	***Yes No***	***Eg. Expertise or infrastructure adaptable from civil activity.***
1.1	Liquid metal cooled	No	No	No	
1.2	Gas cooled	No	No	No	
1.3	Reactor Control Mechanisms	No	No	No	
1.4	Coolant pipes and pumps	No	No	No	
1.5	Fuel Production	No	No	No	
1.6	Shadow shielding	No	No	No	
1.7	Safety Features	No	No	No	
1.8	Storage & Transportation	No	No	No	
1.9	In orbit commissioning	No	No	No	
2	**ENERGY CONVERSION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
2.1	Thermo-electric	Yes	Yes	Yes	Designed RTG breadboard for ESA
Ditto	Stirling Cycle	Yes	Yes	No	Long heritage with cryocoolers Various Stirling converter studies in-house.
Ditto	Thermo-Photovoltaic	Yes	Yes	No	Internal R&D study
2.2	Thermo-electric materials	Mech Design	Critical R&D and test	Yes	
2.3	Power regulation	Yes	Yes	Yes	Power regulation is already required on Astrium's satellite fleet
2.4	High temperature Brayton cycle	No	No	No	Preferred approach for >1kW conversion
2.5	Radial Turbo-alternators	No	No	No	

[1] There is a group within Astrium Space Transportation, France who have a contract at ITER, which involves systems engineering of the fusion reactor. I have some contacts there if required/useful.

2.6	Heat Exchangers	No	No	No	For kW-MW class power
2.7	Leak free encapsulation	Yes	Yes	Yes	Hermetic encapsulation is already required on some components in Astrium's satellite fleet (we acknowledge that this is not really the same since we're talking about 500K min)
2.8	Power regulation	Same as 2.3	Same as 2.3	Same as 2.3	Suggest to remove this row as identical to no. 2.3
2.9	Mass Efficient Fixed radiator	Yes	Yes	Yes	Mass efficient fixed radiators are already widely utilised as part of Astrium's satellite fleet
2.10	Micro-meteoroid protection	Yes	Yes	Yes	Astrium's satellites are already designed to withstand the micrometeoroid environment
2.11	Deployable radiator	Yes	Yes	Yes	There have been internal studies, but deployable radiators are not implemented on our telecom fleet. Potentially of interest to high power radar spacecraft
2.12	Micro-meteoroid protection	As 2.10	As 2.10	As 2.10	Suggest to remove this row as identical to no. 2.10
2.13	Lightweight, high stiffness deployable Structures (e.g. for structure separating nuclear reactor and main spacecraft)	Yes	Yes	Yes	Astrium UK have significant interest in deployable structures for a range of space applications (e.g. for telescopes etc). Some breadboards have recently been developed under internal funding
3	**POWER MANAGEMENT AND DISTRIBUTION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
3.1	High Power Rectifiers	?	?	Yes	Bepi-Colombo experience
3.2	High Power Switching	Yes	Yes?	Yes	Bepi-Colombo experience

3.3	High Power Low Mass Bus	Yes	Yes	Yes	Bepi-Colombo experience
3.4	High Power Batteries	Yes	Yes	Yes	Bepi-Colombo experience
3.5	High Power Shunt	?	?	Yes	Bepi-Colombo experience
4	**PROJECT MANAGMENT**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
4.1	Requirements definition	Yes	Yes	Yes	Standard element in space projects
4.2	Feasibility Assessment	Yes	Yes	Yes	Standard element in space projects
4.3	System Definition & Design	Yes	Yes	Yes	Standard element in space projects
4.4	Prototyping	Yes	Yes	Yes	Standard element in space projects
4.5	Qualification	Yes	Yes	Yes	Standard element in space projects
4.6	Proto-flight build	Yes	Yes	Yes	Standard element in space projects
4.7	Launch and in-orbit support	Yes	Yes	Yes	Standard element in space projects
4.8	Safety & Regulatory	Yes	Yes	Yes	Standard element in space projects
4.9	Public Acceptance	Yes (PR office, Science and Engineering Ambassadors)	Yes	Yes	Astrium is directly involved with advocacy groups and media organisations to promote and exploit benefits of space
5	**LAUNCH AND OPERATION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
5.1	Transport to launch site	Yes	Yes	Yes	Standard element in space projects (Although a nuclear reactor is obviously a little different.)
5.2	Assembly for launch	Yes	Yes	Yes	Standard element in space projects
5.3	Launch	Yes	Yes	Yes	Standard element in space projects
5.4	In-orbit commissioning	Yes	Yes	Yes	Astrium supports in-orbit commissioning as per customer request
5.5	Operations	Yes	Yes	Yes	Astrium supports in-orbit operations as per customer request
5.6	Disposal	Yes	Yes	Yes	Standard element in space projects
5.7	Anomaly Response	Yes	Yes	Yes	Standard element in space projects

ANNEX 9: THALESALENIASPACE EUROPEAN ORGANISATION AND INDUSTRY CAPABILITY CAPTURE MATRIX

No	**CAPABILITY**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
1	**HIGH TEMPERATURE REACTOR TECHNOLOGY**	***Study, Design, Build, Test?***	***Non-critical R&D & test Critical R&D & test.***	***Yes No***	***Eg. Expertise or infrastructure adaptable from civil activity.***
1.1	Liquid metal cooled				
1.2	Gas cooled				
1.3	Reactor Control Mechanisms				
1.4	Coolant pipes and pumps				
1.5	Fuel Production				
1.6	Shadow shielding	Study		Y	Analysis of Transport Shielding
1.7	Safety Features				
1.8	Storage & Transportation				
1.9	In orbit commissioning				
2	**ENERGY CONVERSION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
2.1	High Efficiency Thermo-electric				
2.2	Thermo-electric materials				
2.3	Power regulation				
2.4	High temperature Brayton cycle				
2.5	Radial Turbo-alternators				
2.6	Heat Exchangers	S&D		Y	
2.7	Leak free encapsulation				
2.9	Mass Efficient Fixed radiator	S,D&T	Analytical tools	Y	(Thermal Test in External facility)
2.10	Micro-meteoroid protection	S,D,B&T	Analytical tools	Y	Overall capability (HVI test in external facilities
2.11	Deployable radiator	S,D&T	Analytical tools	Y	
2.12	Micro-meteoroid protection	S,D,B&T	Analytical tools	Y	Overall capability (HVI test in external facilities
3	**POWER MANAGEMENT AND DISTRIBUTION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**

3.1	High Power Rectifiers				
3.2	High Power Switching				
3.3	High Power Low Mass Bus				
3.4	High Power Batteries				
3.5	High Power Shunt				
4	**PROJECT MANAGMENT**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
4.1	Requirements definition	OK		Y	
4.2	Feasibility Assessment	OK		Y	
4.3	System Definition & Design	OK		Y	
4.4	Prototyping	OK		Y	
4.5	Qualification	OK		Y	
4.6	Proto-flight build	OK	Manufacturing and Integration Facilities	Y	
4.7	Launch and in-orbit support	OK		Y	
4.8	Safety & Regulatory	Study		Y	
4.9	Public Acceptance				
5	**LAUNCH AND OPERATION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
5.1	Transport to launch site	S&D		Y	Transportation of Space Infrastructure
5.2	Assembly for launch	OK		Y	
5.3	Launch				
5.4	In-orbit commissioning	OK	Ground Control Center	Y	
5.5	Operations	OK	Ground Control Center	Y	
5.6	Disposal	S&D		Y	
5.7	Anomaly Response	OK	Ground Control Center	Y	

Notes:

1. Section 1 refers to space and terrestrial reactor s recognising that to date there have only been studies into space reactors in Europe.
2. In Column 4 ‘critical’ is with respect to the state of the core/fuel neutronic reactivity (risk of criticality).

ANNEX 10: UNIVERSITY OF LEICESTER, QUEEN MARY UNIVERSITY OF LONDON, EUROPEAN THERMODYNAMICS EUROPEAN ORGANISATION AND INDUSTRY CAPABILITY CAPTURE MATRIX.

No	CAPABILITY	EXPERTISE	INFRASTRUCTURE	INTEREST	COMMENT
1	**HIGH TEMPERATURE REACTOR TECHNOLOGY**	***Study, Design, Build, Test?***	***Non-critical R&D & test Critical R&D & test.***	***Yes No***	***Eg. Expertise or infrastructure adaptable from civil activity.***
1.1	Liquid metal cooled	Study		Yes	Expertise in radiation modelling and expertise in reactor systems.
1.2	Gas cooled	Study		Yes	Expertise in radiation modelling and expertise in reactor systems.
1.3	Reactor Control Mechanisms				
1.4	Coolant pipes and pumps	Study		Yes	Interest in complex engineering systems. Concept studies not pressure vessel design.
1.5	Fuel Production	Study	Non-critical R&D (for experimental studies on fuel containment)	Yes	Expertise in encapsulation of fuels for RTGs translatable to reactor systems
1.6	Shadow shielding				
1.7	Safety Features				
1.8	Storage & Transportation			Yes	Expertise in radiation modelling.
1.9	In orbit commissioning			Yes	Expertise in space systems and space engineering
2	**ENERGY CONVERSION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
2.1	High Efficiency Thermo-electric	Study, Design, Build and Test	Critical R&D and test.	Yes	
2.2	Thermo-electric materials	Study, Design, Build and Test	Critical R&D and test.	Yes	
2.3	Power regulation				
2.4	High temperature Brayton cycle				

2.5	Radial Turbo-alternators				
2.6	Heat Exchangers	Study, Design, Build and Test	Critical and Non-critical; R&D and test.	Yes	Expertise in thermal management systems for terrestrial non-nuclear systems.
2.7	Leak free encapsulation	Study, Design, Build and Test	Critical and Non-critical; R&D and test.	Yes	Expertise in thermal management systems for terrestrial non-nuclear systems.
2.8	Power regulation				
2.9	Mass Efficient Fixed radiator	Study, Design, Build and Test	Critical and Non-critical; R&D and test.	Yes	Expertise in thermal management systems for space, radiators etc… for space missions.
2.10	Micro-meteoroid protection	Study, Design, Build and Test	Non-critical; R&D and test.	Yes	Expertise in micrometeoroid impact studies on space telescopes. Access to gas guns and accelerator systems.
2.11	Deployable radiator			Yes	Expertise in thermal management systems for space, radiators etc… for space missions.
2.12	Micro-meteoroid protection	Study, Design, Build and Test	Non-critical; R&D and test.	Yes	Expertise in micrometeoroid impact studies on space telescopes. Access to gas guns and accelerator systems.
3	**POWER MANAGEMENT AND DISTRIBUTION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
3.1	High Power Rectifiers				
3.2	High Power Switching				
3.3	High Power Low Mass Bus				
3.4	High Power Batteries				
3.5	High Power Shunt				
4	**PROJECT MANAGMENT**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
4.1	Requirements definition		Critical and non-critical facilities including: clean	Yes	Management of all aspects of space and non-space projects from basic R&D and
4.2	Feasibility Assessment			Yes	

4.3	System Definition & Design		rooms, thermal vacuum facilities, engineering design, hardware manufacturing, data centres for processing data from active missions.	Yes	phase A activities through to design, flight build, testing, integration and post launch support. Primary expertise in space and planetary missions. Power systems are linked to either science or exploration missions.
4.4	Prototyping			Yes	
4.5	Qualification			Yes	
4.6	Proto-flight build			Yes	
4.7	Launch and in-orbit support			Yes	
4.8	Safety & Regulatory				
4.9	Public Acceptance	Public perception of nuclear design		Yes	Achieved through education and courses tailored to future space nuclear power and exploration requirements. Outreach programmes.
4.10	Teaching and Training	Courses tailored to train future space nuclear power engineers.	University	Yes	There is broader capability in the UK that could be mobilised to target teaching and training courses that are relevant to future innovative space exploration missions.
5	**LAUNCH AND OPERATION**	**EXPERTISE**	**INFRASTRUCTURE**	**INTEREST**	**COMMENT**
5.1	Transport to launch site				
5.2	Assembly for launch				
5.3	Launch				
5.4	In-orbit commissioning				
5.5	Operations				
5.6	Disposal				
5.7	Anomaly Response				