Disruptive Propulsive Technologies for European Space Missions

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TOPICS

- Introduction & Purpose
- Power range
- Past experience
- Applications and missions
- Technical options
- European capabilities & Russian and US capabilities
- Capability development
- Public acceptance and dissemination
- Safety
- Sustainability
- Resources
- Conclusions

Introduction

- **So far the 'Global Exploration Strategy, GES 2007' Focussed to**
  - **Explore inner solar system aspiring to missions to the Moon and Mars.**
  - **Next step would be the exploration outer solar system and beyond.**
    - Large, particularly manned, missions require power for propulsion, for a survivable habitat,operations.
    - Inner solar system => solar arrays (even further for low power)
    - Outer solar system => nuclear power is the only source of high power
  - **Nuclear power is recognised as a key enabling technology.**
    - Space nuclear power generator capability could benefit a wider range of applications high power instruments and asteroid mining
- **For propulsion:**
    - Radioisotope thermoelectric generators (RTG) or radioisotope heater units (RHU) are out of the scale, as well as Fusion technology (TBC in 20 years).
    - Fission nuclear power generator : nuclear thermal (NTP) => high thrust, nuclear electric (NEP) => high Isp.
- **US and Russian have nuclear power generator in orbit experience.**
    - In 2010 Russia MW class NPPS (nuclear power and propulsion system) has started and in USA low power at Los Alamos
    - In Europe recent studies show that Ariane 5 ECA allow launches up to about 200 kWe.
- **Together these developments => space nuclear power will become part of the plans and policies of the major space-faring nations.**

PURPOSE

- **The purpose is a discussion on such disruptive technologies**
- **To identify how Europe can develop them and especially space fission nuclear power.**
  - Outputs of the DiPoP project was relying on an international Advisory Board (in order to get results more realistic)
- **It takes account of**
  - potential applications,
  - technical options,
  - relevant expertise
  - infrastructure,
  - public acceptance, sustainability, safety
  - resource requirements
- **Finally, recommendations of the study are presented.**

POWER RANGE

- **The power level range for nuclear power sources**
  - few W_e (Small RHUs) to GW_e terrestrial electric fission power plants
  - For DiPoP it was decided to consider two power levels:
    - 30kWe
    - 200kWe
  - The 100 kW_e level has been studied previously
  - For nuclear electric power generation the higher range is constrained to about 200 kWe by Ariane 5 launcher fairing size
  - multi-MWe systems should be possible in the further future.
- **Nuclear thermal propulsion has been studied in lesser details**
  - infrastructure to develop and test it in Europe is very challenging.

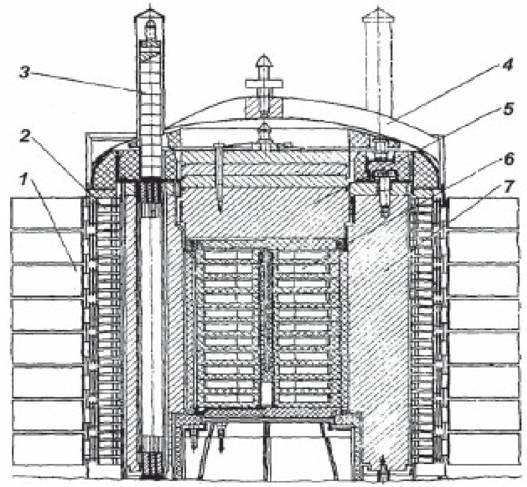
PAST EXPERIENCE

- **Projects**
  - Russia launched 35 missions (surveillance radar) with fission nuclear power. ROMASKA was developed as a prototype in Russia for space exploration. BOUK, powered the Russian RORSATS, TOPAZ1at higher power. Last launch in 88.
  - SNAP (10A) by US (1965) was the first fission nuclear power generator in space. US SP100 : some parts were developed and tested on the ground. US NERVA : a large amount of testing of NTP.
  - TOPAZ 2 was a combined Russian and US project (NEPSTP), abandoned, no launch.
- **Studies**
  - Subsequent studies have drawn heavily on the experience from these projects.
  - The studies have indicated that for higher power levels closed cycle Brayton (CBC) thermal to electrical power conversion is more simple while still efficient.
  - Studies on radiators (Fixed, Deployable, Droplets) and material for realising it.
  - …
  - HiPER The recent EC FP7 study included a Concept Design and Technical development Roadmap for a 200 kWe fission nuclear power generator.
- **NPPS and the Heavy Spaceship**
  - President of Russian Federation accepted a MW_e nuclear power and propulsion system (NPPS) from 2010 to 2018.

PAST EXPERIENCE

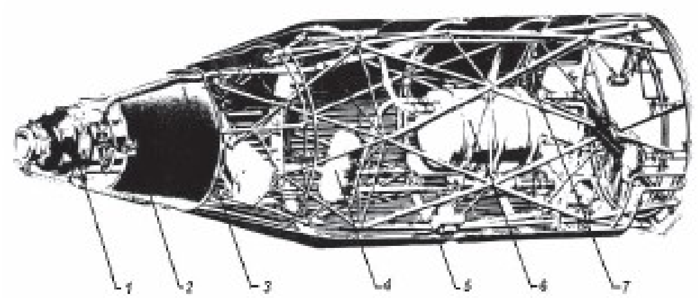
SNAP 10

ROMASKA

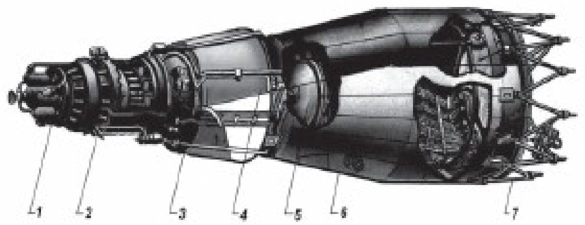


The Romashka NPS reactor converter layout: (1) radiator ribs, (2) thermo-electric elements, (3) control rod, (4) reactor vessel, (5) upper reflector, (6) reactor core, (7) radial reflector. Source: Kurchatov Institute.

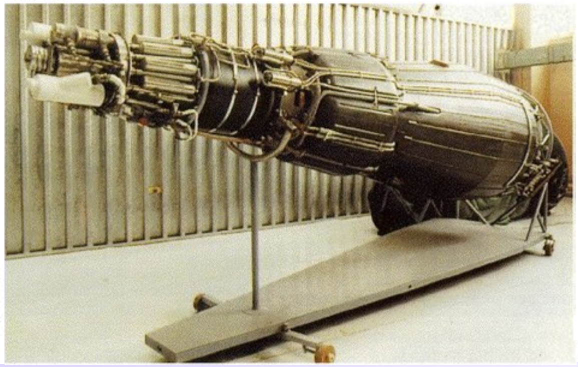
BOUK

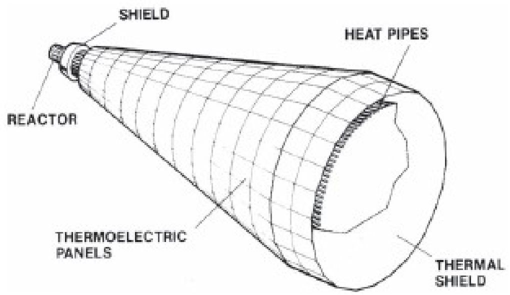


The BUK NPS layout: (1) nuclear reactor, (2) liquid metal circuit pipeline, (3) reactor shielding, (4) liquid metal circuit expansion tanks, (5) radiator, (6) TEG, (7) load bearing frame structure. Source: Kurchatov Institute.



The TOPAZ NPS layout: (1) caesium vapour supply system and control drum drive unit, (2) thermionic reactor converter, (3) liquid metal circuit pipeline, (4) reactor shielding, (5) liquid metal circuit expansion tank, (6) radiator, (7) frame structure. Source: Kurchatov Institute.





SP-100 nuclear power system (radioactively coupled system design). Source: Los Alamos National Laboratory.

TOPAZ1

TOPAZ2

SP100

APPLICATIONS AND MISSIONS

- Mars Manned (split) missions: humans chemical prop, infrastructure nuclear.
- Outer Planet Exploration: Jupiter sample return, Neptune orbital survey, lander.
- Heliosphere and beyond Exploration.
- NEO management: Earth threatening deflection/destruction, survey and mining.
- Planetary surface or 'space port' power generation.
- High power ground penetrating radar, ice-melting laser, long distance high data rate communications.
- Space-based NEO tracking radar.
- Removal of 'dead' spacecraft from earth orbit to reduce space debris.

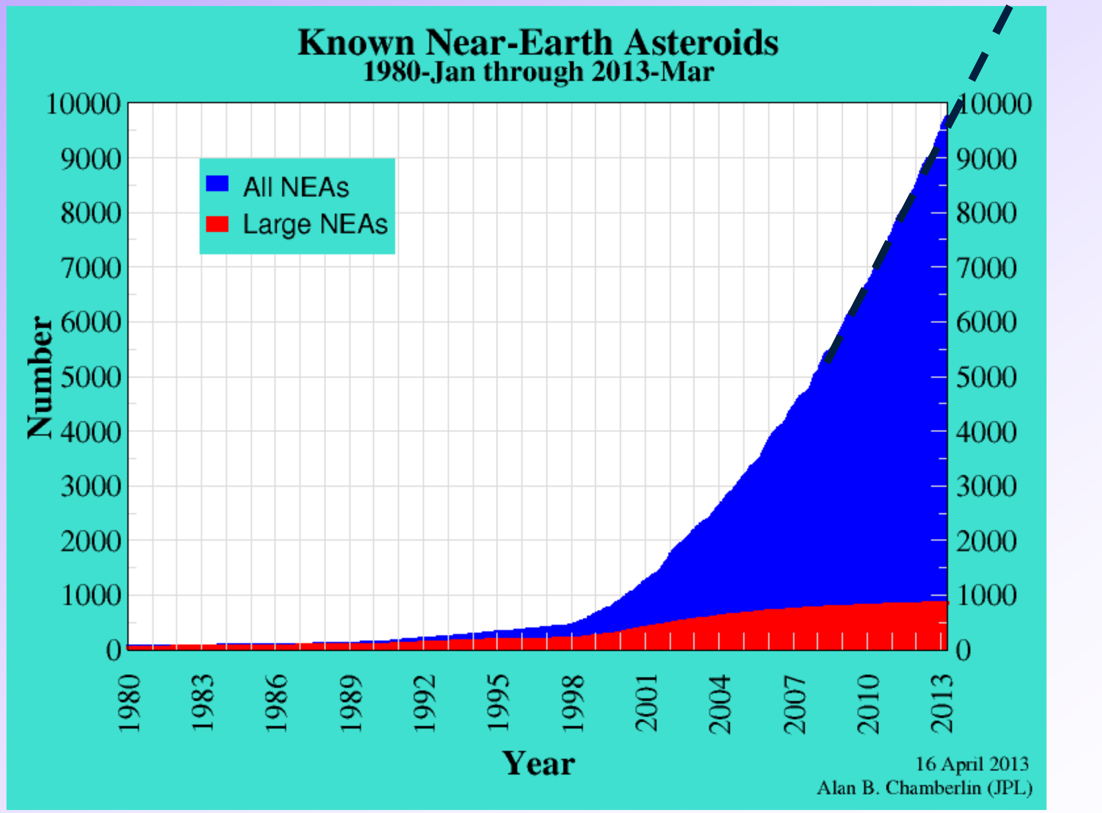
"As a general principle:
first a clearly needed application,
simple design =>mission success"

30 kWe Prioritisation:
Planetary surface power generation,
Small robotic exploration and NEO survey, high power radar.

200 kWe Prioritisation:
NEO deflection for earth collision avoidance, survey, mining, outer planet robotic exploration, large infrastructure transportation.

APPLICATIONS AND MISSIONS

- **200 kWe Prioritisation**
  - NEO deflection for earth collision avoidance
  - Defense of the planet
    - **For public acceptance of fission reactors** *if there is no other way of deflecting such asteroid*
    - Trend is for the number of NEO < 100 m to double in 10 years
    - Can lead to disastrous consequences
  - NEP larger deflection with long trip time
  - NTP faster trip time but lower angular deflection (by impact)

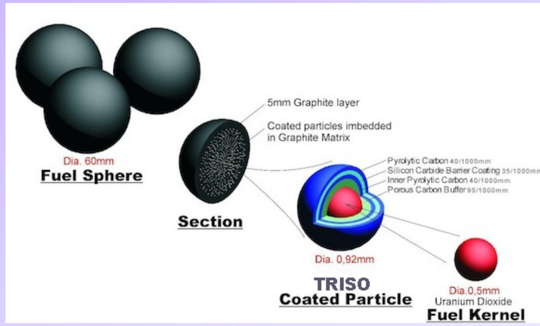


TECHNICAL OPTIONS

- 30 kW_e and a 200 kW_e nuclear power generator have commonalities
  - **Design Constraints**
    - Compatibility with an Ariane 5 ECA launch : >800km altitude, radiator in the fairing, safety criteria
    - Ten years of operation within a 15 year lifetime
    - Specific mass of 25 kg/kWe for a 200 kWe generated power or better
    - High temperature reactor (fast indirect or epi-thermal direct), conversion system (Brayton cycle)
    - Resilience to sudden load fluctuations
  - **Reactor Technologies**
    - pin-fuel fast reactors: indirect inter-cooled and recuperated (ICR) Brayton (compact, low mass)
    - particle-based fuel reactors: Direct ICR Brayton cycle
  - **Control Systems**
    - Operating principle ‘load following’ through negative thermal control, with a degree of ‘thermal lag’
    - Containment with beryllium reflectors
    - Control rods (more compact, low mass) or control drums (fewer shield penetrations, simple rotate)
    - Electrical or pneumatic drive (compatible with the temperature, high radiation environment (dry lubrication)

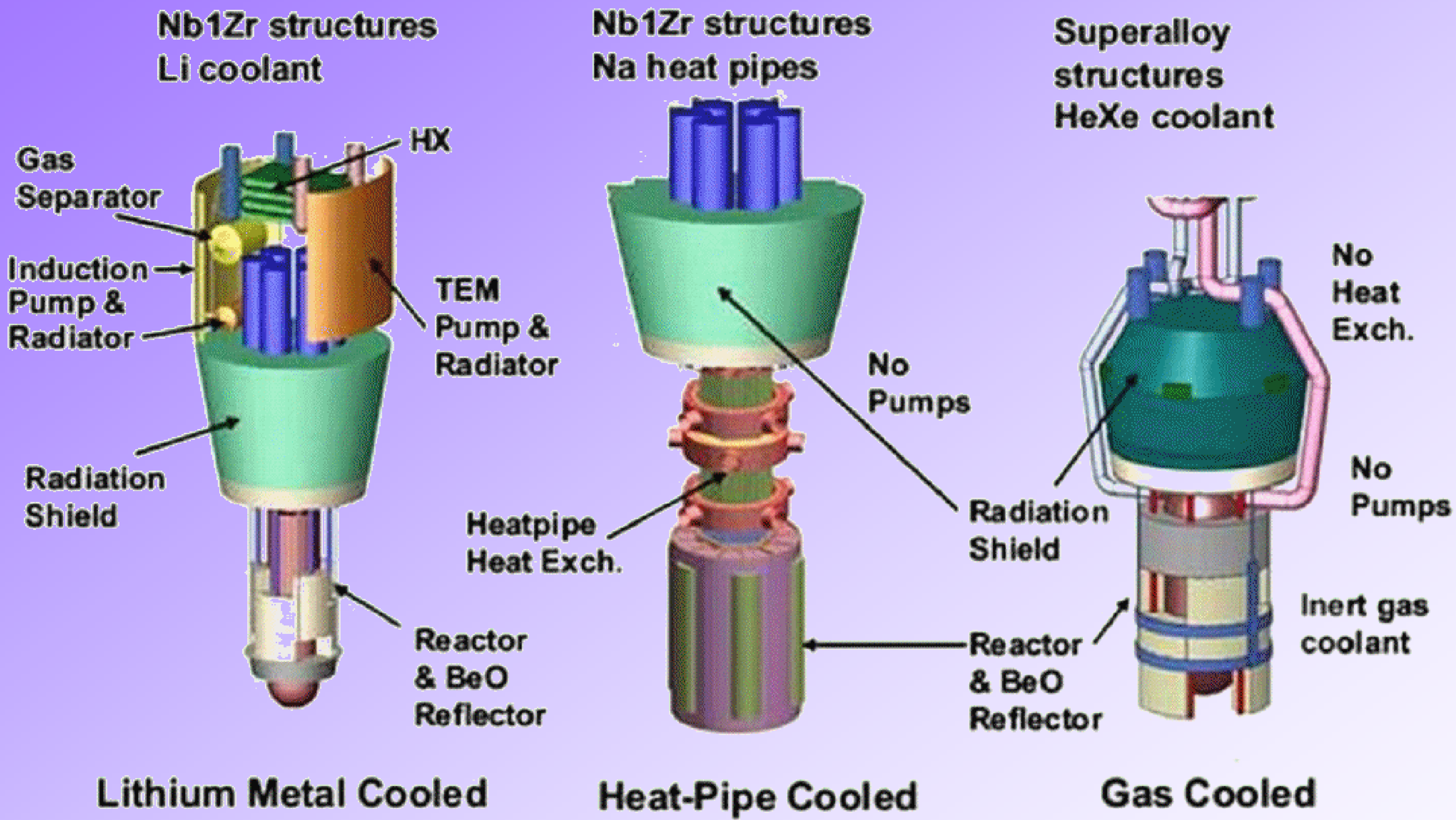
TECHNICAL OPTIONS

- **Fuel**
  - Ceramic oxide, carbide or nitride of uranium pellets although nitride fuel imposes materials compatibility constraints on the fuel cladding.
  - TRISO (Tristructural-isotropic) fuel particles, in carbon shells (or zirconium carbide)
  - Uranium-tungsten alloy formed into small elements/particles or into wire-wound structures may be lighter.
  - Enrichment to minimise reactor size (82-90% for the Direct Cycle and 93% for the Indirect cycle).
  - UO2 is by far the most studied fuel in Europe.



- **Shielding**
  - A layered (Beryllium, Lithium Hydride, Tungsten) (or with Beryllium Oxide to overcome Lithium hydride thermal sensitivities) shadow shield design for both 30kWe and 200kWe
  - Shadow angles up to 28° and a 22.5m separation boom.
- **Power Conversion**
  - Stirling Cycle attractive for 30kWe but there are doubts about higher power systems.
  - Direct ICR Closed Brayton Cycle (CBC) preferred (good efficiency, simplicity of design, no freezing of reactor cooling and turbo-alternator operating gas), Indirect ICR CBC is an alternative
  - Turbine rotation of ~ 45Krpm but for 200kWe turbine blade creep life above 1100 K will require new materials.

TECHNICAL OPTIONS



Drawings of reactor options, (P = 1 - 1.5 MWth)

TECHNICAL OPTIONS

- **Radiators**
  - Fixed radiators (compact and mass and area competitive at high temperature)
  - Deployable radiators and Also Russia is developing the droplet radiator
- **Electrical generation**
  - The turbo alternator output may be alternative current (AC) or direct current (DC) if rectified.
  - AC may be used to reduce harness mass
- **Power Management and Distribution (PMAD)**
  - Turbo-alternator output tailored to EP or radar tube operating voltage => reduced PMAD mass.
  - Battery size, coupling (DC/AC converter) and functions (commissioning, load ballast, etc) TBD
- **Summary**
  - The selection of CBC Brayton power conversion 30kW$_e$ and 200 kW$_e$ allows a high degree of focus in the technical options.
  - It is also helpful because of the inherent 'scalability' of the technology.
  - The main issues to be resolved are
    - Trade-off between liquid metal and gas cooled reactors
    - Operating temperatures (but for turbine without oxidising gas).
    - Materials which allow higher temperature operation for 10 year lifetimes will tend to make the relative simplicity of gas cooled systems more attractive.

EUROPEAN CAPABILITY

- **The European Working Group on nuclear power sources :**
    - *"A European roadmap for the development … should include a comprehensive inventory and assessment of all potentially relevant existing facilities and capabilities in Europe."*
  - Survey
    - it has been possible to conduct a 'representative' survey based on the key government organisations, nuclear research organisations and industry.
    - It is recognised that valuable research is also undertaken by many universities.
      - A questionnaire was sent to selected organisations requesting information on their expertise and infrastructure relevant to a space nuclear fission generator programme.
  - Results
      - The responses were sufficient to populate a European Organisation and Industry Capability Table.
      - This shows, even from the limited survey, potential EU capability in all the required areas.
      - The development of radiator and high power systems is within the capability of the main European industry.
      - Materials research associated with reactors and power conversion may also be relevant in this area.
      - Europe has the capability to launch and operate spacecraft
      - but has yet either to help establish binding international safety standards or a common European regulatory framework to ensure maximum safety and security
  - **The conclusion is that Europe has the potential capability in all aspects of a 30kW$_e$ or a 200 kW$_e$ space nuclear fission generator.**

RUSSIAN AND US CAPABILITY

Russia

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

US

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

Collaboration Potential

- “Putting together a European, Russian and US collaborative programme may be challenging (control, schedule and quality management issues).
- However European experience in managing multi-national programmes might be helpful.”
- Russia has indicated that collaboration on the Heavy Spaceship and NPPS programme would be welcomed.

CAPABILITY DEVELOPMENT

- **Europe**
  - The challenge for Europe to identify the technical advances required
  - Establish the necessary infrastructure
  - Develop the practical experience for the success
  - Exploiting synergies may be useful even if space systems will ideally operate at several hundred degrees Kelvin higher than current terrestrial Generation IV research reactors
- **Technical Advances**
  - Materials for high temperature gas cooled reactors (and liquid metal) including fuel, control and coolant routing
  - Materials for low mass and area, micro-meteoroid protected radiators
  - Low mass high temperature piping, etc., resistant helium absorption, for Brayton cycle
  - High temperature, long life (creep resilient) turbine design and materials (no turbo-prop turbine, no oxidising gas)
  - (For 200kWe) high temperature, very high power electrical components and subsystems, including batteries
- **Infrastructure**
  - Initially research in Europe could make use of existing nuclear and non-nuclear research facilities.
  - re-use of existing facilities (reactor testing buildings).
- **Practical Experience**
  - A programme of ‘cross-pollination’ between the nuclear and space communities
  - This could be supplemented by collaborative activities and extended to direct participation in a nuclear space project.
  - Creating practical experience it is dependent upon commitment to a sustained long term programme.

PUBLIC ACCEPTANCE AND DISSEMINATION

Credit Sandia Natinal Laboratories - USA

Credit CEA - France

- The importance of preparing public outreach study/material for nuclear space technology to be developed and proposed to EC / Europe was recognised.
- A similar approach had been used for the Prometheus programme (using the Keystone Centre in Colorado).
- The recent launch of RTGs and RHUs in the US still attracted small protest groups.
  - It was essential to assemble a team that both understood the technical issues and the public concerns.
  - This included both traditional concern about nuclear dangers and also whether it was a good way to spend government money (the case for private investment did not look strong).
  - The US experience was that the management of public acceptance could be a relatively small part of the budget if tackled early and effectively.
- Uranium enrichment was considered necessary to design a sufficiently compact space reactor
- This is one factor why a Public Acceptance assessment study is an early priority task before to take into account the suited recommendations.
- Thus important public considerations are safety and that government will spend tax money wisely. The following need to be established:
  - Definition of the economics of the technology,
  - The need of sustainability: long term output of the technology.
  - Good communication, Transparent and intelligible, to make people understand

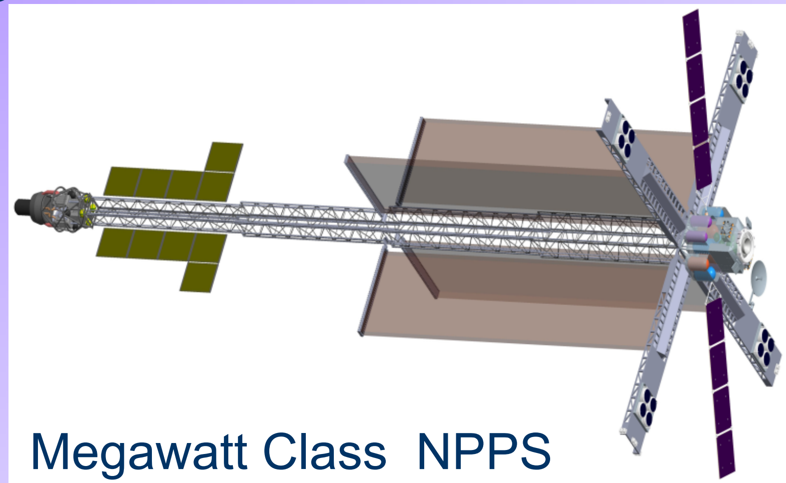
SAFETY

- **Safety guidelines for nuclear power sources in space are known**
- **Space and nuclear safety experts from “big ESA member states” are drafting a technically European framework that:**
  - Provides a predictable, efficient, "workable" process for ESA missions
  - Addresses the main concerns of participating member states,
  - Takes advantage of the existing European nuclear safety expertise and experience gained on the subject in US and Russia
  - Provides a technically sound basis for an early decision on processes, roles and responsibilities
- **This study was initiated under General Studies Programme in 2005.**
  - A letter exchange ESA-NASA during spring 2006 permits cooperation on sharing experience.
  - Russia strongly follows all national and international rules to guarantee safety of any application of nuclear power in space.

SUSTAINABILITY

- **To fund research for a space nuclear fission program is not probable without an identified application justified in terms of benefit for Europe, credibility and cost.**
  - But difficult to quantify the performance which may be achieved without further research .
- **In this sense, a dual-mode program** (build compact reactors capable of both industrial power generation and space propulsion and power) could free this impasse.
- **A way to start the iterative process would be a workshop** for the space science and exploration, space mission and spacecraft design and nuclear communities
  - Define specific research and development projects,
    - High temperature reactor (including controls) and fuel materials research
    - High temperature turbo-alternator materials research to overcome creep life limitations,
    - Low mass, high temperature radiator materials (not-porous to helium) research,
    - Low mass shielding configurations compatible with high temperature operation
    - Mass efficient power management and distribution
    - In-orbit commissioning and end-of-life disposal,
  - Identify trade-offs between objectives, performance, technical development, schedule and cost
  - Propose one or more candidate mission analysis to provide a baseline
  - Propose a program to achieve public awareness and secure public acceptance for a space nuclear fission
- **And enabling research projects in the EC Horizon 2020 programme**

RESOURCES

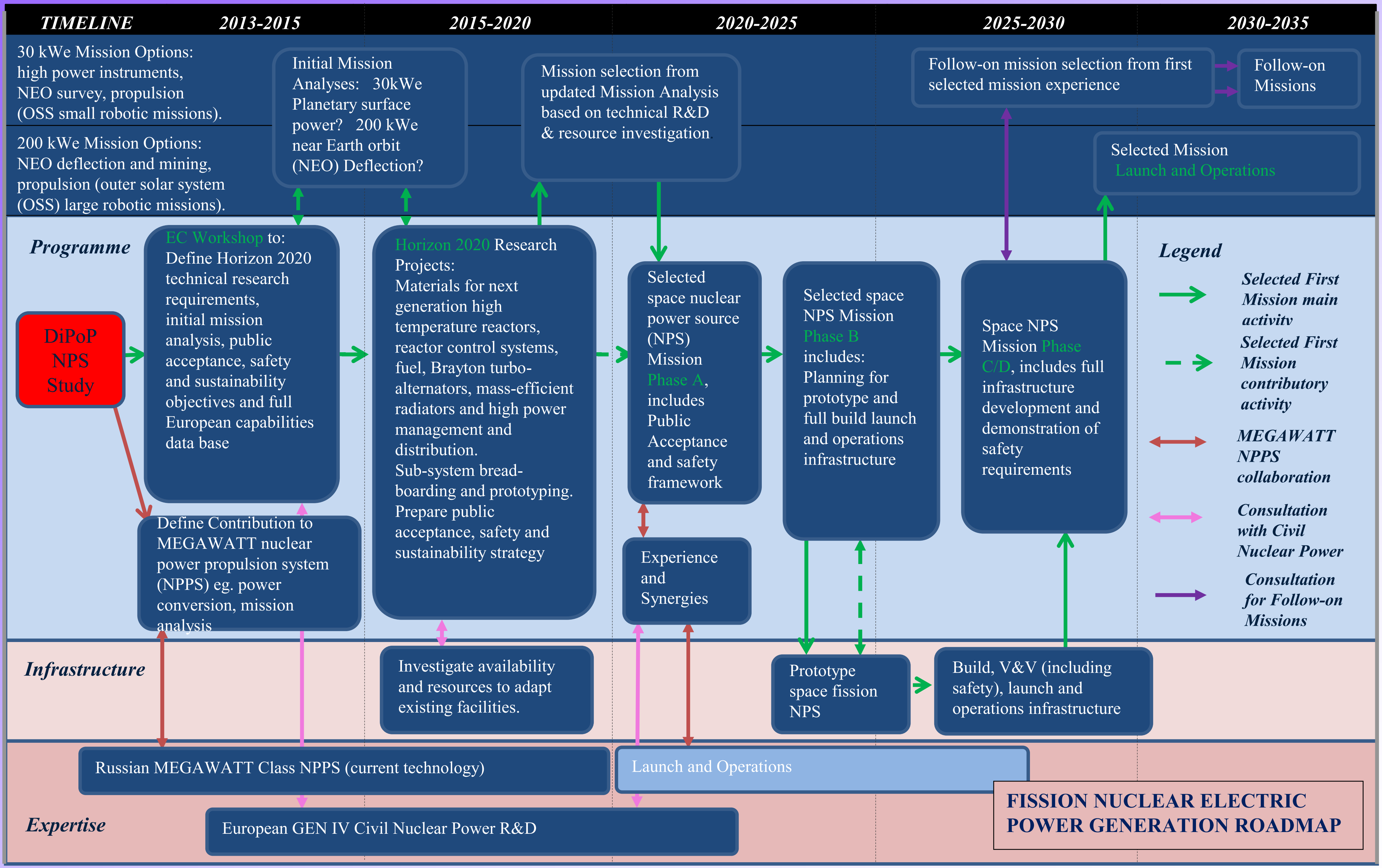


- **Clarify**: Prometheus B$7-9 versus NPPS B$0.5 (mission/ground qualification; new technology/current technology)
- **European Commission**: Horizon 2020 programme (materials research), Generation IV high temperature reactor research and development: longer term prototype space fission nuclear reactor development.
- **ESA**: General Studies programme (mission analysis), High power electrical system and high temperature radiator R&D.
- **National Governments**: Redundant nuclear research, development, build and test facilities and expertise, support Public Acceptance, Safety and Sustainability.
- **Industry**: R&D where there is a spin-off to other space or non-space applications within an acceptable return on investment timescale.

CONCLUSIONS

- **Past experience** indicates that fission nuclear power generation is **technically feasible.**
- **From the range of applications** for which space fission nuclear power is a need, **initial European missions candidate are:**
  - Generating electrical services for a remote planetary outpost and high power instrument for **30kW$_e$**.
  - NEO deflection (for Earth collision avoidance) or outer planet orbital surveying mission for **200kW$_e$** fission nuclear electric propulsion
- **Closed Brayton Cycle power conversion with direct gas cooled fast reactor or indirect liquid metal cooled**
- **Europe has the potential capability and interest but needs:**
  - Technical and infrastructure development,
  - Practical experience.
- **Collaboration: Europe Generation IV NPS, Russia MEGAWATT Class NPPS.**
  - Many useful synergies
- **Public Acceptance Management integral early part of any project.**
- **European Safety Framework** for nuclear power and infrastructure**: required.**
- **Sustainability requires long term programme of R&D for multiple missions.**
- **Evidence of sustainability** of the programme is seen as a **pre-requisite for both government and industry.**

CONCLUSIONS ROADMAP



Recommendations

- **The EC: Initiate** a program line in the Horizon 2020 programme for NPS for:
  - **Collaboration with Russia**,
  - **Collaboration with civil Generation IV** NPS research
  - **A workshop** of the science and exploration, space and nuclear communities to develop specific research tasks and propose candidate missions,
  - **Defining** high temperature, mass efficient materials and systems research objectives,
  - **Building** a comprehensive data base of relevant European expertise and infrastructure,
  - **Planning** infrastructure and expertise development,
  - **Agreeing** a timetable for implementation of the European NPS regulatory framework,
  - **Promoting** public awareness and acceptance of space fission NPS.
- **The ESA**
  - **Include** fission NPS mission Phase 0 study in the General Studies Programme,
  - **Promote** research into very high power electrical components and systems and radiator technology.

Thanks for your attention

Questions?

ADVISORY BOARD

Representatives

Europe: Dr Xavier Raepsaet, Senior Expert, Nuclear Energy Division, Commissariat à l'énergie atomique et aux énergies alternatives (CEA), Paris,

Russia: Alexander Semenkin, Head of Department, State Scientific Centre Keldysh Research Centre, Moscow,

United States: Alan Newhouse, Newhouse Consulting Ltd, Maryland (ex DoE and NASA project Prometheus Director).

Task

Review the Fission Nuclear Power Generation Roadmap and advise, based on practical experience, specific requirements to develop a European space fission nuclear power generating capability (alone or in collaboration).

SURVEY EUROPEAN CAPABILITIES

High Temperature Reactor Technology

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

Energy Conversion

CEA, CNES (France), SCK-CEN*, Demokritos*, MTA-EK, NCBJ, VUJE, NNL(UK)*, AREVA, ThalesAlenia (Italy, France), AMEC*, Rolls Royce*, SEA (Stirling UK), Snecma Moteurs (France) and Leicester University*. (* Study)

Power Management and Distribution

EC JRC, CNES, AREVA, Galileo Avionica* (Italy), AMEC*, EADS Astrium (France, Germany, UK) and Stuttgart University (Germany).

Project Management (including Public Acceptance, Safety and Sustainability)

ESA, CNES, DLR, VTT**, MTA-EK, ESF, ThalesAleniaSpace, Studsvick**, AMEC** EADS Astrium, SEA, Snecma Moteurs (France) and Stuttgart University (public acceptance). (** Consultancy)

Launch and Operations:

ESA, CNES and UK Space Agency (licensing).