PROJECT FINAL REPORT

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1 Final publishable summary report

1.1 Executive Summary

A significant number of exploration missions require nuclear propulsion for which power sources are essential and enabling key assets. Associated technological developments however require important financial efforts that can probably only take place in the frame of an international collaboration, sharing the efforts as this has been the case for the International Space Station. MEGAHIT, funded by the European Commission under the 7th Framework Programme for Research and Technological Development, is a supporting action aiming at building a European roadmap for Megawatt level nuclear electric propulsion, in preparation of the Horizon 2020 programme. MEGAHIT is driven by a consortium that is coordinated by the European Science Foundation and that includes CNES, DLR, Keldysh Research Center, the National Nuclear Laboratory from U.K. and Thales Alenia Space Italia. The consortium favoured an open and participative approach in order that all interested stakeholders - research centers, agencies and industry- within consortium or not, could establish common research objectives and initiate research alliances. This approach will allow building a scientific and technical community on the topic of Nuclear Electric Propulsion in Europe and Russia.

Megahit adopted an approach in 4 phases.

- **Phase 1: High level requirements.** Collected inputs from space agencies and research centers on mission-related high level requirements.
- **Phase 2: Reference vision.** Built a reference vision of what system we aim at, and what would be the best technological options.
- **Phase 3: Technological plans.** The rationale was that the best people for establishing technological plans are the stakeholders identified as being able to carry out the development. These stakeholders were associated through discussions and workshops on technologies they have expertise in. Main workshop was held in Brussels on December 2013 and was attended by about a hundred specialists.
- **Phase 4: Road-maps.** Aims at a synthesis of the three previous phases, translating into consistent road-maps what has been established in terms of key technologies and technological plans.

The MEGAHIT project delivered the high power International Nuclear Power and Propulsion System (INPPS) roadmap. With the already available low and medium power EC DiPoP (see EC DiPoP project results and references in Blott, R., Valentian D. 2012) roadmap for space nuclear propulsion, Europe is now in a position to offer worldwide it’s contributions to INPPS for the next decade.

The MEGAHIT reference spacecraft is a nuclear powered space flagship greater than 30 m length, with a radiator area of about 1000 m2 and mass of 40 t. It uses a nuclear reactor to achieve power at a high level (>1 MW).

The MEGAHIT project constructed the reference vision for such a spacecraft and analysed the necessary technology development efforts that need to take place in order to bring such project into fruition, with its final roadmap. MEGAHIT prepared the ground for technology demonstration projects within H2020.

1.2 project context and objectives

Nuclear propulsion is an essential and enabling key asset for a significant number of exploration missions. Associated technological developments however require important financial efforts that can probably only take place in the frame of an international collaboration, sharing the efforts as this has been the case for the International Space Station.

The interest of high power electric propulsion is recognised worldwide, presently by the EU Framework Programme (FP), but also for decades by the USA who invested in projects like SNAP-10, SP-100 and Prometheus, and by Russia, which is currently working on a MW-level, electrically propelled vehicle project (a reusable inter-orbit tug of 1MW). Russia is the most experienced country in the world concerning space reactors and has already developed and flown several of them in the 1980's and 1990's. Studies have been carried out in France and UK in the 1980's as well as in the 1990's.

For space exploration, advanced propulsion and energy sources are at the core of discussions. Indeed, very ambitious missions to the outer solar system, like sample return from moons of giant planets or manned Mars exploration, are challenges that are difficult, if not impossible, to undertake with current propulsion means. So, new and advanced energy and propulsion technologies are needed: from low and medium up to megawatt power range that must be considered as the final target and consequently a driver for the development.

These technologies have been addressed at national or international level by many working groups, notably by the European Working group on Nuclear Power Sources for Space. Its 2005 report stated that: "*…nuclear power sources are essential and enabling key assets for a significant number of exploration missions*". They appear in road-maps of ISECG (International Space Exploration Coordination Group, 14 nations), NASA and the FP7 work programme of the European Union.

MEGAHIT focuses on high power, Megawatt level systems. Clearly such a power range is not mandatory for robotic missions, but high power is the long term target. And this target must absolutely be taken into account in the development road-map of nuclear space technologies. Indeed, systems of tens or hundreds of kWe should fly before, but the technologies developed for these "precursors" must be scalable and re-usable in the future.

The MEGAHIT project aims to propose the technology plans for the realization of the MW nuclear powered spacecraft. A nuclear reactor as a power source is not a novel concept in space but Europe (Russia is the exception) has never flown a nuclear powered spacecraft before. From a technological point of view, it is a game changer. The nuclear core will allow power levels that will be almost impossible to achieve by any other means. Such project will also be game changing from a socio-ethical point of view – and insofar from cultural point of view too.

The first objective of MEGAHIT **was to construct a road-map for nuclear electric in-space propulsion activities within the EC Horizon 2020 programme**. Nuclear Electric Space Propulsion is seen and identified as a key enabling technology for future international space exploration mission. Space exploration is one of Europe's priorities and development of capabilities in this field will allow Europe to play a major role amid the space faring nations in the future. The EC H2020 programme is a unique opportunity for developing these capabilities.

Beyond this road-mapping, MEGAHIT had a second objective which is of importance: **to create a European community including Russian partners around Nuclear Space Power systems.** This second objective implies to involve European and Russian stakeholders – Research, Industry and Agencies - in the road-mapping.

Beyond Europe and Russia, represented by the Consortium, Nuclear in-Space Propulsion is addressed by the other space faring nations. **Analysis of the potential collaboration opportunities at international level** was also an important objective of MEGAHIT.

Megahit adopted an approach in 4 phases:

High level requirements: Phase 1 collected inputs from space agencies and research centers on mission-related high level requirements.

Reference vision: Phase 2 built a reference vision of what system we aim at, and what would be the best technological options.

Technological plans: The rationale of Phase 3 was that the best people for establishing technological plans are the stakeholders identified as being able to carry out the development. These stakeholders were associated through discussions and workshops on technologies they have expertise in. A workshop was held in Brussels on December 2013 and was attended by about a hundred specialists. The workshop had two goals: a) formalize the technological plans, and b) create a community, giving the opportunity to each stakeholder of having a complete view of the project, technologies and system

Road-map: This was the final phase of the project. It synthesised the three previous phases, translating into consistent road-maps what has been established in terms of key technologies and technological plans.

1.3 main S&T results

1.3.1 Background

In order to define a target power level and associated performance requirement for the reference vision, a review of mission analysis published in the literature as well as dedicated mission analysis have been done in the frame of MEGAHIT phase 1.

Inputs coming from past European projects and studies (FP7 project DIPOP and HIPE as well as French national studies have been taken into account. Interest of other nations on the topic of nuclear reactors for space or associated technologies have been evaluated leading to the establishment of the workshop guest list.

The most relevant option for a MW class NEP power and propulsion system would be a versatile vehicle capable of operating on various types of mission. Here is a first set of requirement that could be used for the evaluation of the different technologies and constitute the starting point for the MEGAHIT design:

- The specific mass for the power and propulsion system (excluding propellant but including thrusters) should be lower or equal to 20kg/kW, that is to say 20 tons for 1MW.
- Without more detail mission analysis a 10 year of equivalent days at full power should be considered as a preliminary target. This figure impacts strongly the reactor mass so it might be relevant to reconsider this figure once more detailed mission analysis are available.
- Radioprotection: since the vehicle is versatile and could be manned, the design of the spacecraft should limit the radiation doses (gamma rays and neutrons) at the payload to a level acceptable for humans. An option could be to have extra local protection when the spacecraft is manned in order not to penalize the robotic missions for which a level of fluence of 10^{13} n/cm² as in JIMO could serve as a reference.
- The system could have several conversion loops, in order to improve reliability by partial redundancy.
- Radiators should be foldable

A 20 ton system plus the associated payload would not be able to fit in a current launcher shroud so two options can be then be considered: assembly in orbit thanks to robotics, or launch with an ultra heavy launcher yet to be developed.

The MEGAHIT reference spacecraft is a nuclear powered space flagship greater than 30 m length, with a radiator area of about 1000 m2 and mass of 40 t. It uses a nuclear reactor to achieve power at a high level (>1 MW).

1.3.2 Recommended research & technology roadmap

The preferred research and technology options will be explained according to the subsystems in figure 1 – within the following chapters: reactor and shielding options, power conversion options, thermal control options, electrical power management and distribution options, electric propulsion options and payload options.

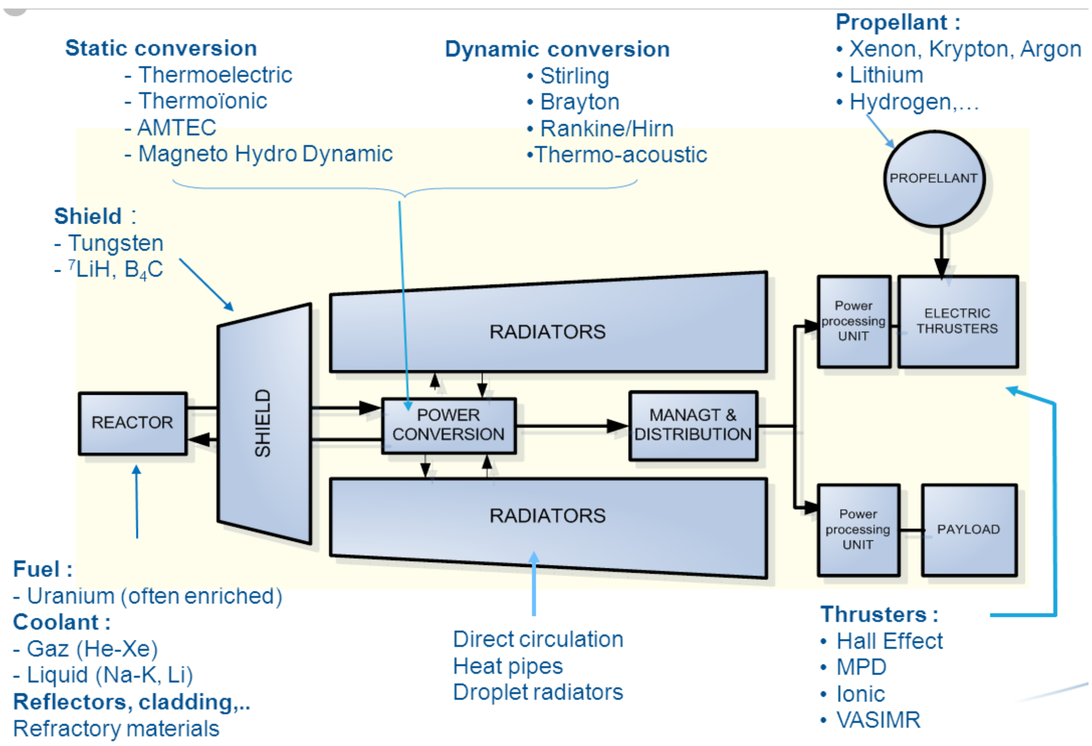

Figure 1: Reference for general architecture and list of candidates for subsystems for a 1MW nuclear electric spacecraft.

1.3.2.1.1 Reactor and shielding options

The most advanced technologies and studies for usable space reactors including fuel, core and shielding experiences and knowledge are available in Russia, U.S.A. and in Europe primary in France, UK as well as for example in Sweden (KTH Stockholm).

The MEGAHIT concept reactor will be a first-of-a-kind (FOAK) and there are a series of interdependent technology choices for the fuel, core, structures and materials and power conversion aspects of the MEGAHIT concept, so a roadmap that includes parallel investigations of the technology options is necessary. Demonstrating the start-up/shutdown and mission operating requirement for the reactors fuel & core - to satisfy conventional and nuclear safety and regulatory requirements, in a manner commensurate with its intended deployment in space -, will be a key to the successful vision realization of the whole MEGAHIT roadmap. At an appropriate point in nearby time (2015-2016), down-selection (also by means of the proposed DEMOCRITOS H2020 project) will be required to focus efforts on preferred, credible technologies. There will then need to be decisions on how the nuclear reactor and its subsystems are validated through simulated and practical demonstrations, both on the ground and in space.

There are two candidates for the MEGAHIT fast spectrum reactor concept, required to generate thermal power (greater than 3 MW, with an operating temperature of about 1300 K) for the nuclear electric propulsion system (target 1 MW electrical power overall) over a five to ten years operational life (Ross, D.N. et al., 2014). They are:

- direct, gas cooled reactor loaded with coated particle/composite fuel linked to Brayton conversion system and
- in-direct, liquid metal cooled reactor loaded with more conventional fuel, e.g. metallic encapsulated pins filled with fuel pellets, linked to Brayton conversion system.

Both reactor concepts warrant further assessment, together with assessment of power conversion system choices, until sufficient data are available to support a trade-off study of system mass versus technological risk that can determine the preferred reactor choice. With the completion of this trade-off study of reactor and conversion systems, a choice of the candidate fuel and core configuration for the reactor can be made.

The following critical technologies have been identified for the reactor, fuel and core system:

1) **Fuel & core configuration**: at this time there are several candidate technology options, dependent on the ultimate reactor system choice. Potential critical technologies identified are uranium oxides, nitrides, carbides or oxycarbide fuels in the form of pellets (clad in refractory metal pins), coated particles or composites (Akimov, V.N. et al. 2014).

2) **Power conversion interface**: High temperature heat exchanger materials (for an indirect cycle choice) and cobalt free turbine materials (for a direct cycle choice).

3) **Primary boundary**: protection materials (usage of thin multi-layer structures) and advanced manufacturing techniques

4) **Reflector & control**: moving parts (e.g., rotating drums or shutters) reliability and passive control system technology, such as gas expansion modules.

5) **System architecture**: diverse heat removal systems, coolant purification, make-up and loops and modular in-space assembly technology procedures for the reactor, because of the non-critical reactor launch.

Additionally, there are several enabling activities for establishing this subsystem associated with system performance and safety assessment. Specifically these include safety assessment methodology and processes for start-up/shutdown and mission operating requirements, whole-core performance modeling and simulation, coupled neutronics and thermal-hydraulics code development, reflector /absorber model development, shielding model development and whole-system transient analyses.

1.3.2.1.2 Power conversion options

The leading candidate for power conversion is the Brayton cycle with 1300 K as hot source temperature. A mixture of gaseous He-Xe transfers heat from the reactor and drives a turbine coupled to an alternator.

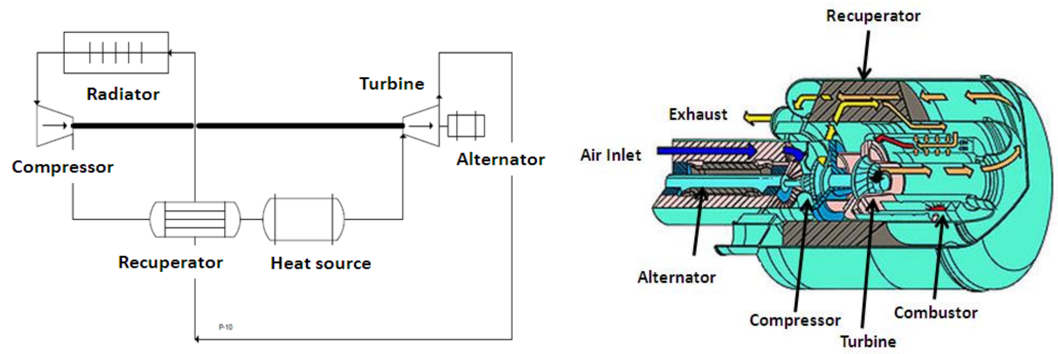

Figure 2: Brayton subsystem, with an example of architecture for the turboalternator part (cornestore microturbine).

Efficiency is good for such a conversion system (about 30 %) and a lot of experience is available from aeronautics engines, justifying its choice as the reference. With such a cycle the 20 kg/kWe target for the MEGAHIT reference spacecraft would be achievable, but there is still possibility to improve performance through increasing the temperature at the turbine inlet (possibly as high as 1600 K). The increased turbine inlet temperature improves performance through increased thermal efficiency, requiring a smaller reactor and turbine to produce the same amount of electrical power and thus requiring a smaller radiator to reject a smaller amount of waste heat (also offers the potential to reject waste heat at a higher temperature, again reducing the radiator size).

Unfortunately, some of the reactor technology options are not scalable with temperature as different coolant, fuel and material temperature limits will require radically different reactor configurations to operate at peak mass efficiency either at 1300 K or 1600 K. It is extremely difficult to extrapolate a given reactor technology between these two temperatures and for a given electrical power output, the trade-off studies would have to be repeated in order to examine the net change in mass, achieved across the whole of the power generation system. For example, a lithium cooled fast reactor driving an indirect Brayton cycle offers the least-mass solution with a turbine inlet temperature of 1300 K (Blott, R. and Valentian, D. , 2012). However, lithium boils at 1600 K and there is little margin for metallic fuel clad melting. A robust heat exchanger that can operate for an extended period at 1600 K, with the projected primary-secondary pressure differential, does not currently exist. The coolant boiling, fuel temperature and heat exchanger issues are solved by adopting a particle-fueled gas-cooled reactor driving a direct Brayton cycle. However, a gas-cooled reactor is heavier than a liquid metal-cooled reactor of the same power and, whilst the material issues associated with heat exchanger no longer exist, the material issues associated with the turbine, operating at high temperature and restricted to use of low-activation alloys, become significant.

A turbine/alternator assembly working during five to ten years, at 1300 K inlet temperature, without maintenance, is challenging. Some maturation of new technologies will be needed, and success is not guaranteed. The following critical technologies are identified for the conversion cycle:

1) A **turbine** able to sustain 1300 K (or higher) during five to ten years. The turbine blades are critical, but disks should be investigated too. Existing mono-crystal alloys, used in aeronautics for turbine blades (MC2, MCNG, TMS138a...), can sustain temperature between 1200 K and 1250 K during a ten years operation. Technology maturation will be required, in order to reach the required lifetime operation of the INPPS (10+ years). At the moment there is no requirement for turbine blade alloys to be compatible with use inside a nuclear reactor closed primary circuit. For the direct cycle option, the impact of erosion / corrosion products on the operability of the reactor needs to be considered. Whilst a high level of radioactive contamination of the primary circuit in space may be tolerable as long as sensitive electronics and payload are sufficiently shielded, this will be an issue in a ground-test facility.
2) **Bearings** able to sustain five to ten years operations without maintenance.
3) **Alternator** and **electronics** able to sustain high temperature. Alternator and electronics will need to operate in high temperatures because they will be linked to the very hot turbine. Some proper insulation may mitigate the problem but it is unsure if it will be sufficient.

An alternative to turbine/alternator as a conversion system has been considered in the scope of the MEGAHIT project. This alternative would be thermoacoustics coupled with magnetohydrodynamic (MHD) conversion. Thermoacoustics is a way to transform temperature energy into mechanical energy, in the form of acoustics waves. It is achieved by imposing a temperature gradient on a stack of long and thin volumes of gas. Convection movement is created and can turn under certain circumstances (good choice of internal and downstream volumes) into acoustic waves.

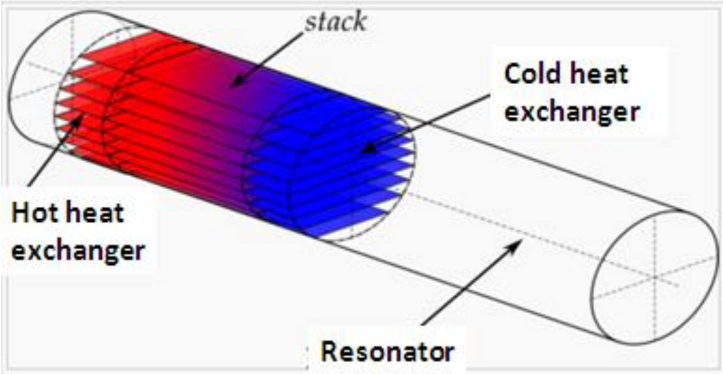

Figure 3: Main parts of a thermoacoustic conversion

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MHD is a way to transform mechanical energy into electrical energy. Thanks to thermoacoustics, alternative movement is induced into a conductive fluid. Placed into a magnetic field, this fluidic movement can induce electrical current into a coil.

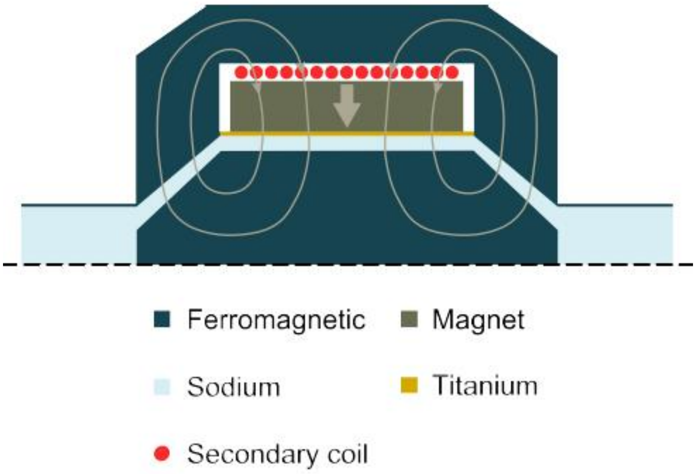


Figure 4: Main parts of a MHD conversion.

Thermoacoustics conversion is a rather new concept but is fast-growing. Many application can be considered for it, either in space or on ground (creation of electrical current from exhaust gases for instance). U.S.A., China and Europe are working on such system. A 200 We thermoacoustic plus MHD conversion demonstrator is under finalization at Riga university, with various European partners (Thales Alenia Space, Areva, Hekyom, CNRS and others). The performance of such system for INPPS space flagship remains to be consolidated in further studies.

1.3.2.1.3 Thermal control options

The thermal system of the MEGAHIT reference spacecraft are based on the following assumptions:

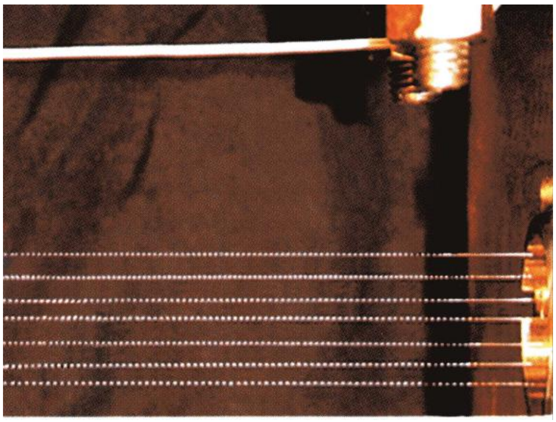
1) radiators will work on a high temperature heat pipes system,
2) the plate-type heat exchangers are needed for gas-gas as well as for gas-fluid heat transfer and
3) multilayer insulation have to be mounted on – and are - supported by light deployable structures for thermal shielding. The shielding could be improved with micrometeoroids and high energy

particle (galactic and solar cosmic rays) blocking capabilities to protect the behind located sensible parts of the space flagship.

In general, the critical aspects of the radiator system technologies are:

1) the **heat pipe assessment** considers high temperature operability between 400 K to 700 K) under zero-g and low-g conditions nearby celestial bodies (therefore the heat pipe performance map is needed as well as an evaluation estimation).
2) the **high temperature heat pipes** (HT HP) materials and fluid compatibilities,
3) the consideration about **HP freezing and re-start** during low power or power shut down operation (i.e. heaters dimensioning),
4) the **modularity** of heat pipes integrated in panels of the radiators system, as well as the modularity / **configuration** of the panels and the treatment of the panel thermo-optical properties,
5) **junctions** in the panel-panel and deployment system,
6) the **interfaces** between radiators system panels and HX-2 (means HX at intermediate temperature levels with "classical fluids", see below chapter HX) fluid loops, that means it has to be created an acceptable layout for the exchanging interface area and
7) the unfolding and external interface concepts for **the in-orbit assembly** of different radiators parts to create the entire radiators area.

The new, special case of droplets radiator system is the present *back-up* solution. Results with droplet radiator technology were received on-board MIR (successful Pelena experiment) and the International Space Station (ISS results are foreseen to be published at the end of 2014). The Si-based oil droplets have about one order of magnitude mass reduction (as a function of radiated heat) compared to plate droplet radiators (Koroteev, A.A. 2008).



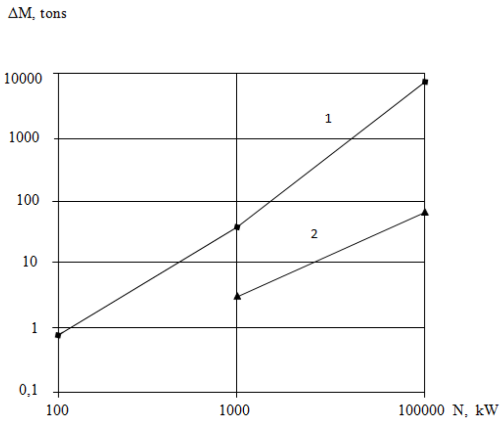


Figure 5: Left: in operation the oil-type liquid droplet radiator experiment Pelena. Right: Si-based oil (1) droplet radiator compared with Li plate radiator (2) as a function of radiated heat.

For the droplets radiators the following issues must be studied (to reach TRL 5-6 around 2025):

- the potential issues with an accelerated system (the present design is related for planet power plants applications and demonstration at MIR level were carried out without acceleration),
- the additional power to start-up effect to droplet radiators and
- the technology issue for film stability (related to the acceleration / deceleration phases of INPPS).

Under the consideration of droplet radiator system as a critical technology for the space flagship, there are the following aspects to be studied

- their sensitivity to INPPS space flagship motion, especially acceleration / deceleration,
- the sensitivity to micrometeoroids, mainly related as a sensible accumulator hardware and
- their sensitivity to space flagship charging and magnetic field changes, caused by space weather storms.

In the space flagship there will be two levels of HX: HX-1, the high temperature (about 1300 K) with material fluids and HX-2 working on intermediate temperature (about 700 K) levels with classical fluids. The preferred option for HX-1, HX-2 and the recuperator units are plate-type ones.

Currently, the thermal shielding of the space flagship is of a classical design, with the shielding performance of MLIs (Multi Layers Insulation). In future, improvements may direct towards no-linear structure layer distances. These MLIs are mounted on light deployed structures to protect subsystems like propulsion, payload and others depending on the locations of those (see figure 9). An extra micro-meteoroids blocking capability – or even high energy cosmic rays and solar energetic particles - of the MLIs would be favourable – having in mind that the huge cylindrical surface of NASA LDEF satellite – after its 69 month long spaceflight was highly barraged by micro-meteoroids. In addition the in-orbit deployment mechanisms are an issue for further robotic studies.

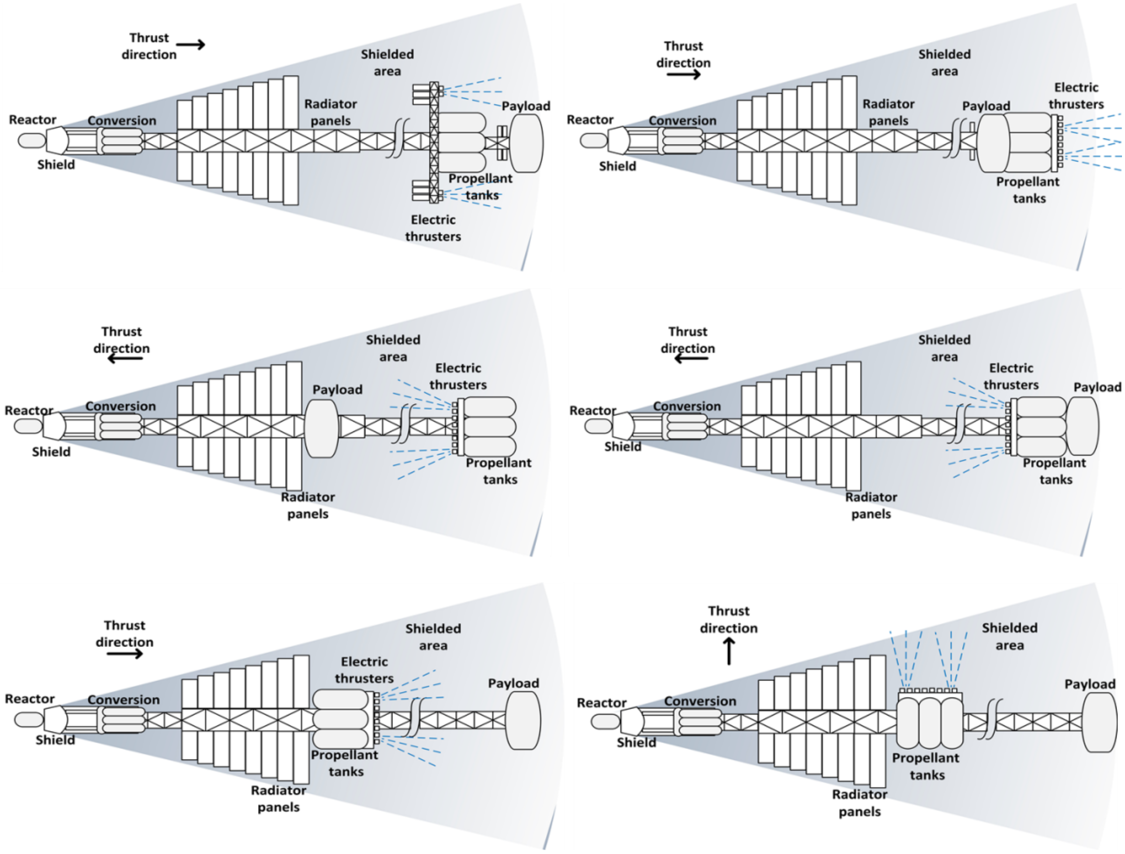


Figure 6: The MEGAHIT reference spacecraft modules are always mounted just behind the reactor with constant shielding structure angle (crosshatched in grey). A flagship cost factor: the shielding mass (shielding against radioactive core particles) must be differ

MEGAHIT consortium proposes the following summary of ten options for the thermal control system roadmap:

1) Ten years of operating life requires over-dimensioning or in-orbit refurbishment for coolant. The HT HPs radiators system panels should have an oversized number of HPs. For droplets radiators, the accumulator should be dimensioned to such extent with margins for the entire lifetime.
2) The HT HPs is a stand-alone system, without other hardware to be developed and / or qualified / tested. Droplets radiator has to adopt a specific actively pumped closed circuit with dedicated accumulator. These hardware has to be considered in the system developing phases.

3) The gas cooled reactors associated to direct cycle, needs less hardware to be developed than the indirect cycle with liquid metal as secondary coolant material.
4) Design and material requirements are requiring a new generation of components and subsystems for high temperature. Therefore European capabilities have to be confirmed in their existence or have to be extended or new specific infrastructures have to be created for the INPPS space flagship.
5) Validation of parts of the thermal control system: computer modelling, ground based / zero-g drop down test of radiator breadboards, use of ISS to test parts of the system (e.g. autonomous building of radiator).
6) Building of a smaller lower power system, with lower heat rejection and smaller radiators.
7) Application of existing HT HPs to receive and to maintain the TRL for the INPPS thermal control system.
8) Preliminary design of the entire thermal control system during the EC DEMOCRITOS Project, including implementation towards a complete (pressurized) gas/fluid, mechanical and electrical interface. This includes types, modes, numbers and interfaces of the junctions HPs-panel-to-HPs-panels.
9) Definition and comparison of deployability versus fixed radiator concepts study including robotic assembly.
10) Radiation vulnerable components have to be considered in detail.

Figure 7 displays a list of critical technologies of radiator systems with respect to their TRL and expected time schedule.

Materials research for radiators. E.g. Carbon-Carbon which would reduce mass considerably but currently beyond capability – Increase quality and production of materials.	TRL 6-7 in 2020
Autonomous (Robotic) technology for assembly of radiator is required	TRL 6-7 in 2020
Issue with heat pipes from cold start. Might need additional power/provision to ensure operational before start-up of reactor. Possibly some info from NASA research. Might need batteries, robotics	TRL 5-6 in 2018
For the moment heat pipes look like the best technology – much redundancy in service, failure of one heatpipe doesn't knock out whole cooling system. Maybe revisit after a few years.	TRL 6-7 in 2018
Any practical experience of droplet radiators in an accelerating system? Current development on ISS is in steady state situation. Possible experience from MIR. Could Electric/magnetic field stabilize this?	TRL 4-5 in 2020
Cold plate technology for active thermal control at higher temperature, especially for high power operation. -- Not fully available in Europe. In use on ISS but not European made. Not independent from US.	TRL 5-6 in 2020

Figure 7: Critical technologies of radiator systems.

Other important system constraints due to the radiator-core interaction:

1) impact from spacecraft on the radiators system design:
    a) the radiator inlet temperature is subject to change depending on operating temperature,
    b) the radiator has to be protected by the radiation shield and
    c) the radiator has to present ability to start and stop during the mission.
2) impact from radiators system design on spacecraft:
    a) Some power is constantly needed (the reactor cannot be completely shut-down)
    b) thermal/heat shielding for payloads.

1.3.2.1.4 Electric Power Management and Distribution

The PMAD (Power Management and Distribution) critical technologies for the reference spacecraft are:

1) the high voltage EEE parts (electrical, electronic and electromechanical) including EEE devices heat dissipation and tolerance for radiations,
2) regenerative fuel cells,
3) in case of usage issues related to superconductors,
4) the architecture for handling different sources (generator, battery, fuel cells, ...) including shunt mode technologies,
5) cable harness, bus bars and the big size coaxial cables,
6) the AC/DC converters capable of integrating power processing unit (PPU) for electric propulsion and
7) materials for isolation of cables respectively the electronic equipment.

The PMAD leading options for the seven critical technologies are:

1) high voltage EEE parts, such as current Silicon Carbide (SiC) and Gallium Nitride (GaN) based devices, as well as the Insulated-Gate Bipolar Transistors (IGBT). The need of technologies porting from green energy/hybrid vehicle/oil drilling applications to space application has been identified,

2) the heat dissipation of EEE devices with new materials should be studied to decrease heat dissipation and consequently increase the capability of working at high temperatures. In particular the development of packaging technologies suitable to operate at higher than 125 °C is needed.

3) In principle SiC components are the preferred candidates to operate at high voltage and high temperature regimes due to their intrinsic material properties. (China Aerospace Science and Technology Corporation (CASC) explored the use of diamond powders alloyed with copper to improve heat dissipation, this might push common development with CASC / China),

4) the EEE parts have to be tolerant against cosmic radiation. Therefore specific dedicated test campaigns in ground based accelerators have to be developed. For example cosmic ray shower induced short circuits in the German fast speed train ICE (see Jansen, F. 2010)),

5) regenerative fuel cell system (RFCS), closed loop regenerative H2/O2 fuel cell system, and closed loop polymer electrolyte membrane (PEM) fuel cell system and electrolyzer and fuel cell based on proton exchange membrane technology systems.

In general the feasibility of RFCS concept was demonstrated, but also the difficulty to meet the lifetime requirement. For both closed loop systems further studies are necessary in order to reach a satisfactory performance. Possible superconductor usage should be studied, as superconductivity increases substantially the current load a cable can carry. Interpretation of space experiences (with the AMS superconductor magnet (AntiMatter Spectrometer) on ISS) in combination with additional ground based related studies.

1.3.2.1.5 Electric Propulsion options

Details of high power electric propulsion (EP) systems like Hall, ion, VASIMIR (Variable Specific Impulse Magnetoplasma Rocket) and others were discussed in working package 3.4 related to specific mass, impulse, thruster unit power, operational lifetime or thruster dimension.

For example with respect to the last parameter, RIT (radio frequency ion thruster) can reach no more than about 25 cm diameter, but ion thruster reaches 50 cm or even greater. Magnetoplasmadynamic thrusters can achieve higher thrust, up to 500 kW. However their operational lifetime may not achieve the desired five to ten years. VASIMIR, is a promising thruster system with potentially higher lifetime – but it has a TRL that is considered very low.

European based electric propulsion system developments are strongly concentrated in British, French, German, Italian and Spanish space industries and organizations. Therefore two leading options for the Megahit reference spacecraft electric propulsion are favoured.

1) **Ion Thrusters**: Build in Russia, an ion thruster with power of 50 kW is possible at the existing technology level at specific impulse of 8000 s (for Kr) and higher. In Japan half power - 25 kW - ion thruster are studied.
2) **Hall Thrusters**: Application of Hall thrusters in Russia is justified in the specific impulse range of 3000 s to 4000 s, for Ar up to 5000 s. Available technologies allows to make thrusters with power level up to dozens kW. Increasing specific impulse may have negative effect on the operation stability and lifetime of Hall thrusters.

Russia and the United States are the main providers in the world for electrical propulsion dedicated to communication satellites (satcom). However, European companies, such as Snecma (France) or Qinetiq (UK), also propose such electrical propulsion.

The available systems of Snecma are based on Hall effect thrusters using Xenon. Snecma provides not only the thrusters but also fully integrated system including thrusters, tanks, PPU, filter units and fluid control subsystems.

The critical technologies for both preferred thruster types (ion and Hall) are

1) for ion thrusters:
    a. the **clustering of thrusters** including interaction between them,
    b. the **high voltage cables and sockets** (up to 5000 V),
    c. the **carbon ion optics** (is for instance developed in the USA) and
    d. **EMC** (electromagnetic capability),
2) for Hall thrusters:
    a. the **lifetime limit under high voltage regimes**,
    b. the **clustering of thrusters** including interaction,
    c. **high voltage cables / sockets** (up to 1000 V), EMC and
3) (both systems) the **long term propellant storage** (e.g. krypton, argon) and the thruster feed system and long term propellant storage on orbit.

There are two potential ways for creation of high power EP systems: the development and usage of single highest power thrusters and the use of bunches of several, simultaneously working relatively low power thrusters, i.e. thruster cluster.

The possibility of single thruster (Hall or ion) power increasing theoretically is not limited. Power increasing could be simply provided by the thruster size growing, however there are set of technical questions to be solved, such as: availability of special design materials of appropriate size for the thruster parts manufacturing, testing facilities possibilities to run the high power thruster fire tests. Only these reasons determine the upper power limit to about 100 kW for a single thruster.

Therefore, the most rational way to create EPS of megawatt power level is to use several simultaneously operating thrusters integrated into a cluster unit. A cluster - an integrated system, consisting of several, at-a-time operating engines, aimed at executing a common space flight task – enables application of new schemes of EP systems in which, e.g., functions of feeding and control for every thruster can be integrated in one device for all, and one cathode-neutralizer can serve for operation of several thrusters etc..

The number of thrusters in propulsion system should be defined using reliability of the system and taking into account reliability of each unit. Also it should be noted that development and qualification of 100 kW thruster is much more expensive than the same procedure for 50 kW thruster.

Taking into account all above mentioned options, the MEGAHIT reference spacecraft need 20 to 24 thrusters with 40 kW to 50 kW combined in several thruster modules. Important is the usage of only one type of EP thruster for certain MEGAHIT reference spacecraft mission, because the space operation of ion-Hall thrusters mixture will complicate the whole technology significantly.

The MEGAHIT recommendation for EP system should follow the optimal specific impulse I_{sp} range of

1) 2500 s to 4000 s I_{sp} for a Hall thrusters equipped MEGAHIT reference spacecraft or
2) 4000 s to 8000 s I_{sp} for an ion thrusters equipped spacecraft.

1.3.2.1.6 Payload options

According to Figure 6 the payload module can be mounted on five different locations of the MEGAHIT reference spacecraft. Primarily are the mass, size, number and physical-technological characteristics of the detectors, instruments or telescopes in the payload module dependent on the mission requirement. In chapter 3.3 ‘Mission Requirement Options’ three missions are discussed: NEO deflection, outer solar system and cargo missions to Moon and Mars.

Therefore – depending on the scientific interests respectively level, on technological capabilities and feasibility of funding – the payload selection should be carried out by an international advisory committee under the aspect of payload contributions from all continents. Moreover payload contributions must be highly visible and attractive for the public and scientific communities. The best mixture of payload funding will be public, private and public private partnership. In summary the payload module will be a measure to contribute significantly to the public and political acceptance of the flagship as worthy project.

1.3.3 MISSION SCENARIOS

Applications requiring or able to benefit from space nuclear power generation have been studied within a previous FP7 project, DiPoP and also by national entities within the consortium, mainly by CNES and by the Russian partner Keldysh. The identified potential applications for nuclear electric propulsion spacecraft in the Megawatt range are:

NEO deflection: Depending on the mass and trajectory of the NEO, a MW class system may be required to deflect it to protect the Earth. It could thus be advisable to develop a MW class system in order to be ready to intervene when a threat of this class will appear,

Robotic Exploration: A MW class vehicle would open new exploration mission classes like sample return from Jovian moons.

Space tugs: for the removal of 'dead' spacecraft or debris, orbital station assembly (lunar orbit or in L points) and general mission support.

Manned Mars Missions: A manned exploration mission to Mars would require a very high level of payload mass (several tens of tons to be put on the surface of the planet). Classical mission scenarios using chemical propulsion would require the equivalent of 8 to 10 Saturn-V equivalent rocket launches (in order to place about 1000 tons in Low Earth Orbit). For this specific mission the possibility of using nuclear thermal propulsion has been studied by NASA but it does not offer dramatic mass savings (7 ARES V launches would still be needed).

Conventional propulsion modes for such missions also have other important drawbacks: transfer times to Mars cannot be reasonably lowered below a minimum of 6 months (velocity at arrival would be dramatically increased and would need even heavier systems to brake the ship into Mars orbit). Moreover launch windows are scarce and tight: they occur approximately only once every two years and the minimum energy window is only once every 15 years. Length of the window is usually less than 1 month. This can be generalized to all exploration missions, either robotic or manned, to other celestial bodies. Several solutions are being studied to overcome the limits of classical propulsion.

Among them high power electric propulsion seems to be one of the most promising candidates. For example, a 10 to 20 megawatt level electric propulsion could offer the possibility to dramatically decrease the number of launches needed for a manned Mars mission (3 to 4 equivalents of Saturn-V like launches) and could also allow to reduce its transfer time down to 4 months ultimately if significant progresses on specific mass are done. This solution has been studied at least by the US, by Russia and by France.

As previously mentioned, nuclear power would anyway be mandatory for a manned Mars mission even in a mission using chemical propulsion as the main propulsion mean, be it for ground power, in-situ resource utilisation or in order to pre-deploy material with a slower but energy efficient vehicle.

1.3.4 international interest in space nuclear power and propulsion

The initial effort of MEGAHIT partners to contact interest parties in space agencies, research laboratories and industry, indicate a wide interest to the concept of nuclear power for space vehicles. The nations and organisations interests can be summarized as follows:

i. Several space nations (Russia, USA, France, UK, China) may be potentially interested to contribute to the MEGAHIT roadmap and to different MEGAHIT objectives, as they already have developed similar systems or concepts.
ii. European countries are able to contribute to nuclear power generation, robotics and propulsion tasks of the roadmap (Germany, France, Ireland, Italy, Spain, United Kingdom, Belgium and others).
iii. Russia would be the main driver for the nuclear propulsion system.
iv. Some nations (Australia, Brazil, Japan) show interest and potential capabilities for main subsystems, in particular electric propulsion or conversion
v. Other nations like Czech Republic, Slovakia, South Africa and South Korea may contribute to nuclear based scientific mission.

1.4 *Potential impact*

There has been a significant number of mission proposals for Nuclear Electric Propulsion (NEP) enabled spacecraft in the past. A summary of possible missions enabled with nuclear propulsion can be found in the National Academies report, in the frame of the (cancelled) NASA PROMETHEUS project. In Europe, investigative work has been done for nuclear power sources in the frame of the DiPOP and HiPER projects, for power levels in the kW range. The previous sections highlighted the technology options for the various spacecraft subsystems. This section will highlight potential synergies with other (non-space) industrial efforts as well as some societal aspects of the project.

1.4.1 Industrial synergies

Despite the uncertainties in the **reactor system choices**, it is clear that there is area for co-development with the Generation – IV reactors that are planned. The development of a compact space reactor is more complex that an earth system due to the requirement of a 10 years lifetime operation in the demanding space environment, with a required temperature higher than planned systems (1000K to 1273K for proposed Gen IV reactors). The most interesting co-development opportunity would thus be the *high temperature materials* , an area that will probably find other applications as well in aeronautics and aerospace.

A turbine able to sustain operation for 5 -10 years at 1300K or higher is needed in the **conversion system** to convert the reactor power to electricity. At present, aeronautic engine research is focused on mono-crystal alloys can sustain temperature close to 1300K. Additionally, bearings able to sustain 5-10 years without maintenance will also be an issue for the turbomachinery. Technology development in these areas will certainly find applications in aeronautics and defence industries and possible other areas that require high temperature operations.

For the specific case of the indirect-1300K cycle with a heat exchanger, studies of the behaviour of liquid metal in a radioactive environment are needed with the appropriate development of advanced materials. This is another area that nuclear industry cross development is possible.

The necessity for high temperature materials is one of the most critical issues. New material development is always a long and costly process with success not always guaranteed. Nevertheless, advanced materials is considered one of the key enabling technologies of the future[6], with strong synergy with aeronautics and nuclear research.

There are two key aspects in the MEGAHIT spacecraft **thermal control system**: the first is obviously radiator size and its deployment method and the second is the materials to be used for long time, high temperature operations. The technology development synergies in the latter are very similar to those of the core and conversion system.

Regarding the radiator deployment, additive manufacturing technologies may offer a solution, although technologies need to be investigated regarding the material use and the required surface finishing. This is a very interesting area of co-development, since additive manufacturing advances are being very actively pursued world-wide

Heat dissipation of **electronic devices** would also be an important issue, due the already large amount of excess heat in the MEGAHIT spacecraft. Possibly, new materials should be studied to decrease the heat dissipation and consequently increase the capability of working at high temperatures. During a workshop of the MEGAHIT consortium, it was pointed out that The China Aerospace Science and Technology Corporation

(CASC), is investigating the use of diamond powders alloyed with copper to improve heat dissipation, which is perhaps an opportunity for international cooperation. High temperature, high heat dissipation electronics will also find numerous applications in ICT industry, with interesting co-development opportunities for server farms/cloud computing applications. Another obvious synergy would be with defence and aeronautics industries for voltage, high temperature, rad-hard electronics.

Another possibility, albeit judged as a non critical issue, is the possible use of superconductors that can handle far more current than normal wire, due to the large power availability in the MEGAHIT spacecraft. Despite the fact that superconducting cables are not a-priori necessary, research on room-temperature superconductors is definitely one of the areas that co-development is possible with numerous other sectors and the potential for successful spin-offs is very high.

For a MW-class spacecraft large parts of the spacecraft e.g. thermal subsystem can be designed as autonomous systems, which can be launched separately and be **assembled in orbit**. Robust, lightweight, integrated and deployable structures are required. Technologies e.g. for components/systems integration to the structure, deployment technologies (e.g. for radiators), structural interfaces for high temperature parts (e.g. reactor and radiator area), technologies for active vibration control of structural response for mass reduction needs to be improved and developed. This is a general focus area of the space sector and a MEGAHIT level project will drive several technologies to 'usable' TRL levels.

One other area that will require extensive development is the robotic assembly. Due to the high parking orbit (~800km) , robotic operations will be the preferable option for the assembly of the spacecraft modules, which, given current and future launcher availability will be minimum two in number (2 20t segments or more). Necessary robotic technologies will have synergies with industrial robot development (manipulation, robotic joints etc) as well as with robotic agents such as autonomous and semi autonomous drones.

1.4.2 Legal and regulatory aspects

A project of such magnitude is not solely a scientific and engineering endeavour. It must operate under a precise legal framework, with strong support by the ultimate stakeholder, the paying public and must be initiated in a framework of international cooperation in order to be realised.

The presence of radioactive substances and materials or nuclear fuels in space Nuclear Power Sources (NPS) and their consequent potential to cause harm to people and the environment in Earth's Biosphere due to an accident means that safety must always be an inherent part of the design and application of space Nuclear Power System.

From the launch base to the "sufficiently high orbit" for safe operations, the current main risks that have to be dealt with in case of a launch failure are mainly the dispersion of radioactive material (new core) and the risk of uncontrolled criticality (for example in case of fall in water, wet sand, or other media associated with possible geometry modification).

Technical solutions exist and have to be implemented during the conception of the reactor: dispersion risk can for example be reduced by using a highly resisting tank, or coated spherical fuel particles; criticality accident car for example be reduced by safety absorbers, poisons, removal of reflectors during launch, dismantling of the core, partial removal of fuel or even partial orbit loading. Efficiency of those solutions will of course have to be demonstrated. Risk of dispersion of highly radioactive material (fission products) after reactor use in space is eliminated by the means of operating the reactor only once it has reached a sufficiently high orbit.

There are several steps to be taken regarding the regulatory framework of space reactors in order to ensure that harmful incidents to Earths biosphere do not happen. These are:

1. Establishment of a policy and strategy for safety in the use of NPS applications in outer space
2. Establishment of a framework for safety in the use of NPS applications in outer space
3. Establishment of an appropriate safety assurance regime
4. Ensure the independence of the safety regime
5. Prime responsibility for safety in the use of NPS applications in outer space
6. Coordination of different authorities with responsibilities within the safety assurance regime for the use of NPS applications in outer space
7. Provision for safe management of the end-of-service phases of NPS space missions with NPS applications
8. Competency for safety
9. Interfaces of NPS safety with nuclear security and with the system of accounting for, and control of nuclear material
10. International obligations and arrangements for cooperation
11. Sharing of operational experience
12. Establish policy and strategy for the justification of use of space NPS applications
13. Establishment of a framework for justification
14. Establishment of policy and strategy for authorization
15. Establishment of a framework for authorization
16. Establishment of a policy and strategy for emergency preparedness and response
17. Establishment of a framework for emergency preparedness and response.

There is also a need for requirement for clarification on the limitations on nuclear fuel choice imposed by the 1992 Principles for the relevant use of NPS in space[1] . It is stated that 'nuclear reactors shall use only highly enriched uranium 235 as fuel'. Governments and Regulatory bodies around the world are in general agreement about the undesirability of allowing the use of such highly enriched fuel, even in research reactors. Given the current moratorium on using highly enriched uranium for any reactor purposes, it would appear that space projects seeking to incorporate such fuel may be stopped at a very early stage of the design, especially within the context of an EC research programme.

<u>The proposed additions and updates to the regulatory framework will set in place concrete rules for safety measures and bring to the modern ages the exist laws and regulations. That would allow any interesting party to concentrate on science and exploration projects and will instill confidence in the use of nuclear power in space.</u>

[1] 47-68 UN-COPUOS Resolution « Principles relevant to the use of nuclear power sources in outer space » http://www.fas.org/nuke/space/principles.pdf

1.4.3 Communication and public support

A nuclear reactor as a power source is not a novel concept in space but Europe (Russia is the exception) has never flown a nuclear powered spacecraft before. A significant challenge will be to convince the European and worldwide public to support the act of putting a nuclear reactor in space.

The communication strategy for any such project become, thus, a vital aspect of the project strategy. In order to fly a nuclear power spacecraft the public not only needs to be informed of the project (as it is usually the case) but it should also be an engaged and supportive stakeholder. The latter should be reached in future and step by step.

It appears that factual knowledge of science has little influence on the attitude of the public, and campaigns to educate an apparently ignorant public did not significantly change its attitude towards the topic[10]. In contrast, emotional-driven campaigns proved to be quite successful for many NGOs, especially in the European countries [11]. Therefore, the communication plan must be augmented from a simple ‘information giving’ strategy, to an effective communication strategy that provides the right information to the right people at the right time and by the right way. This approach was very successful in the U.S with the launch of Mars Science Laboratory. Contrary to the previous experience with the Cassini spacecraft and the opposition against the presence of an RTG on-board, MSL launch faced no such problem thanks to a well thought out public communication campaign.

The experience gained from engaging the E.U public in an effort to gain support for a MEGAHIT class spacecraft, with the added complexity of separate member states and national publics, will provide a roadmap for the necessary public engagement strategy for very large Pan-EU projects and will perhaps help in streamlining such process, which are often delayed for several decades.

1.5 Main dissemination activities and exploitation of results

The main dissemination activities of the MEGAHIT project were:

a) The MEGAHIT website (see next section)

b) The MEGAHIT workshop, which took place in Brussels, Dec 2013 and gather more than 80 experts of the nuclear and space industry, including several agency representatives. The initial estimation of 60 experts was surpassed, with a total of 90 registered participants and 80 physical attending participants. The workshop attracted experts from EU, Russia, US, Brazil, China, Korea and South Africa. The workshop was a great success according to the participants and it enabled a fruitful exchange on the topic of NEP, which provided the MEGAHIT consortium partners with valuable material for the continuation of the project. Furthermore, the workshop proved very fertile ground for some informal discussion between the high-level experts that were attending the meetings and created communication channels between the space and nuclear industries.

c) several presentation of the project in important conferences such as the International Astronautical Conference (IAC), Conference on Nuclear and Emerging Technologies for Space (NETS) and others (more details in following sections).

d) High level networking with agency representatives. This activity was undertaken by consortium partners that were either participating in various conferences and meetings or with specific presentations of the projects for agencies (for example, MEGAHIT was presented to ESA-ESTEC experts in special presentation).

1.6 Project Website and contacts.

The web address of the MEGAHIT project is www.megahit-eu.org.

The list of contact points within the consortium are:

European Science Foundation (ESF):	Dr. Jean-Claude Worms (jcworms@esf.org) and
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