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THE BENEFITS OF USING NUCLEAR ELECTRIC PROPULSION IN SPACE.

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Nuclear Electric Propulsion (NEP) can offer multiple advantages in regards to space exploration. Significant gains can be realised in flight time (by eliminating the need for gravity assists, even for deep space missions), on-board power availability (with a power level an order of magnitude higher of what is available today) and payload mass delivered to the selected target. To deliver a spacecraft in the 2030-2040 timeframe, necessary ground and space demonstration missions will be required. The readiness of the system will be reached by testing of all key technologies on ground and in orbit on subsystem and system level. This includes the core, conversion, thermal management, power management and propulsion subsystems as well as the assembly of all subsystems in orbit by autonomous or remote control robotics. The MEGAHIT project has produced an incremental development plan for the realisation of a NEP spacecraft in the 2030-2040 timeframe. It has developed the high level requirements for a multi-use NEP spacecraft and investigated the preliminary mission architecture for two reference missions: an asteroid mission for planetary protection/exploration and a deep space exploration mission. By using the power source of a nuclear core, power in the range of 1MW will be achievable that can then utilised by the spacecraft for advanced electric propulsion, using clustered ion or hall thrusters. Furthermore, synergies that exist between the proposed spacecraft project development plans and on-going R&D in the nuclear, advanced materials and aeronautics industry highlight the technological and societal benefits from such an endeavour. These synergies also include the potential risks associated with the project and the propose risk mitigation actions and regulations in order to reduce those risks. A spacecraft that is able to deliver and operate a multi-ton payload to the outer planets or to an asteroid would provide a step change in current mission ability and provide real benefit. NEP is seen as a key enabling technology for such a spacecraft, providing additional mission options that are currently not practicable.

I INTRODUCTION

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) PROMETHEUS project[1,2].

In Europe, investigative work has been done for nuclear power sources in the frame of the DiPOP and HiPER projects[3,4], for power levels in the kW range.

II THE MEGAHIT VISION

The MEGAHIT project (more details can be seen on the IAC-14,C3,5-C4.7,7,x21402 paper in this session) envisages the creation of a nuclear electric spacecraft, with a power source that could provide more than 1 MW of energy. The project timescales envisages a mission launch later than 2030 (>16 years).

II.I MEGAHIT reference

Some key base line characteristics for such a nuclear powered space flagship (to be referred as MEGAHIT spacecraft) are:

- 30 m or greater spacecraft length;
- An estimated radiator area of 1000 m2;
- Spacecraft mass of 40 t;
- Electric propulsion system specific impulse range ~ 3000 to 8000 seconds;
- A nuclear reactor to achieve power at a high level (>1 MW);
- Assembly and departure from a sufficiently high orbit (800 km or higher, for safety considerations);
- System that can function 5 years in full power on a total lifetime of 10 years;
- Reactor shall remain subcritical at all times during launch, even in case of a launch failure.

These characteristics serve to give an idea of the magnitude of the proposed spacecraft[5], with a concept drawing seen in Figure 1.

This paper will focus on the potential benefits that would stem from such an endeavour, during the technology development phases that would enable the project to go ahead as well as the benefits of the flagship itself in terms of capabilities. The paper will conclude with the regulatory framework that should be applied to the project, public communication issues and the international cooperation landscape of such an endeavour.

III DEVELOPMENT SYNERGIES

The MEGAHIT roadmap was intended to highlight the development steps necessary for enabling the MEGAHIT spacecraft and as such it identified the main technology issues that such an endeavor will face. It is obvious that such a large project will be a serious undertaking and it is important to identify co-development opportunities with industrial sectors outside space. In the following sections, we will outline some of the fundamental development steps necessary for the MEGAHIT spacecraft that show promise for such co-development.

III.I Reactor and conversion system

The reactor powering the MEGAHIT spacecraft would be a compact, fast spectrum reactor. The final configuration has not yet been identified, as design trade off studies are needed in order to do so. This is true for most of the MEGAHIT spacecraft subsystems as well. Section III.VI will give an overview of future plans to prepare for such design studies.

At this time, the most prominent options are either a direct cycle He-Xe gas-cooled reactor with epithermal to fast spectrum and core outlet temperature of 1300K.or an indirect cycle Lithium liquid metal-cooled reactor with fast spectrum with core outlet temperature 1350K. These options have the advantage of having the highest technology readiness level (TRL) amongst other potential configurations.

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.

III.II Power conversion

A turbine able to sustain operation for 5 -10 years at 1300K or higher is needed 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.

III.III Thermal management

There are two key aspects in the MEGAHIT spacecraft radiators: the first is obviously its 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 [7,8].

III.IV Electronics

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.

III.V Spacecraft Assembly and Deployment

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.

III.VI Future Design studies

The MEGAHIT project did not involve details design plans for the critical subsystems, as it was never indented to do so. A new H2020 project that will start in 2015 plans to start investigation on the previously mentioned critical technologies and key issues, in a series of demonstrator project designs. The DEMOCRITOS project* aims to:

A) Investigate the interaction of the major subsystems (thermal, power management, propulsion, structures and conversion) between each other and with a (simulated) nuclear core providing high power, in the order of several hundred of kilowatts. The consortium aims to develop preliminary designs of all the subsystems and the required test bench of the necessary *ground experiments* with the purpose of maturation of the related necessary technologies. An experimental test bench will consists of:

* DEMOCRITOS (Demonstrators for Conversion, Reactor, Radiator And Thrusters for Electric Propulsion Systems) is an H2020 Space project. It is projected to start in 2015, with a 2 year duration.

1. gas heater instead of reactor with power up to several hundred kW, simulating a nuclear core;
2. turbo machinery with an electric generator with output power up to several KWs;
3. Power Management And Distribution (PMAD) of a corresponding power with electric load;
4. basic elements of thermal control system, including a heat pipe radiator;
5. electric thrusters (Hall or Ion type). Power and number of thrusters will be consolidated within the DEMOCRITOS project and deployable structures.

B) Perform system architecture and robotic studies that will investigate in detail the overall design of a high power nuclear spacecraft, together with a pragmatic strategy for assembly in orbit of such a large structure coupled with a nuclear reactor. This *space demonstrator* will provide the preliminary design of the nuclear power spacecraft and its subsystems, detailed assembly and servicing strategy in orbit as well as proposal for in space demonstration missions with the aim of maturing various necessary technologies that either do not fit within the ground demonstrator or have the opportunity to fly in synergy with other European or international initiatives.

C) Perform *Nuclear reactor studies* to provide feedback to the simulated as well as conceptualize the concept of nuclear space reactor and outline the specifications for a Core Demonstrator, including an analysis of the regulatory and safety framework that will be necessary for such a demonstration to take place on the ground.

It is expected that during the DEMOCRITOS project several detailed co-development strategies will be identified and potential interested parties from other industrial areas will be approached by the project consortium.

IV POTENTIAL MISSIONS

The MEGAHIT project focused on three family of missions, that emerged as the most promising for a MEGAHIT class spacecraft. Preliminary mission analysis was conducted by the Keldysh Research Centre.

IV.I NEO deflection:

Asteroids are a potential threat to life on Earth. Unfortunately, most of the potentially dangerous asteroids are not known yet. Thus the ideal would be to have a system ready to be launched to deflect big asteroids. On simple deflection mean is to act as a «gravity tractor». The exercise was done on the deflection of Apophis which was thought to be a serious hazard until recent observation in January 2013 discarded the risk of impact in 2036 (a NEO of Apophis size has ~300 m diameter and ~10^{10} kg weight).

A spacecraft with 1 MW power source can increase the distance of asteroid flyby near the Earth in 2036 up to 1 million km and even more. In case of initial spacecraft mass equal to 20 t and specific impulse value ~ 7000 initial analysis shows that the payload delivered to the asteroid orbit will be of the order of 16t. Required duration of asteroid orbit gravitational correction will be about 40 days in a 2021 Apophis approach asteroid or 200 days in case of the approach in 2027.

IV.II Outer solar system missions

Several tons of payload could be sent in Europe or Titan within 3 years. A chemical stage, without gravity assist manoeuver, would put only ~500 kg of payload in this orbit (the Cassini orbiter and probe had a combined payload mass of 670 kg, whereas Galileo had a payload mass of 118 kg). The use of nuclear power propulsion system of megawatt power level will allow creating automatic interplanetary stations with high payload mass and available on board power for advanced study of Solar System distant objects, interplanetary and interstellar matter at a great distance from the Sun.

Preliminary analysis shows that with an initial spacecraft mass of 40 t, the payload mass delivered into a Europa orbit will vary in the range of 3 - 10 tonnes, depending on the specific impulse (in the 6000 – 8000s range). The duration of the SC transfer to a Jupiter satellite orbit, lies within the range T = 2.5 – 3.5 years The duration of EPS operation during the transfer depends on specific impulse value and lies within 1.7 – 2.3 years.

IV.III Cargo missions

NEP enables the transfer of significant mass (several tons) to the Moon or Mars, without the need for a high number of launches[9].

Assuming that the mass of the payload delivered to the Moon surface, should be no less than 15 - 20 t (mass of manned base module for example), then the mass of the payload delivered by the tug to the low near-lunar orbit in one cycle should be at least 30 - 40 t. In case of 1 MW tug usage, the Launch Vehicle will require lifting capacity for the payload modules insertion of no less than 70 - 80 t. If the lunar tug would make 2 trips per year, 650t of payload can be brought in lunar orbit in 10 years.

For a Mars mission, the duration of the transfer defines the optimum value of the specific impulse and the payload mass. The variation in the specific impulse in the range from 4500 s to 9000 s involves the increase of the transfer duration from 350 to 600 days and the growth of the payload mass from 11 to 18 t respectively.

Mission analysis results show that there are two optimal ranges of electric propulsion system specific impulse values: 2500 - 4000 s (near Earth and Moon orbits) and 4000 – 8000 s (Mars and deep space missions).

V OTHER CONSIDERATIONS

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 following sections highlight some of this issues.

V.I Regulations and safety considerations

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[†] . 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.

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.

VI 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

[†] 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

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.

VI.I International cooperation

Launching parts and modules of a MEGAHIT class spacecraft would provide significant business opportunity for all space and space facing. The event will push economic, technological as well as scientific and cultural synergies.

The asteroid / Mars initiatives of the U.S.A. favour a third ambitious space programme (compared to Apollo and ISS). This initiative should be realized internationally, due to financial, public, political, technological, scientific and cultural reasons. The international situation related to a high power space mission demands a strong, but balanced – by diplomatic channels too - political guidance for a MEGAHIT class space flagship realization. Insofar, this effort would contribute to long term peaceful cooperation in space and on ground for the advantages of all participants.

VII CONCLUSIONS

The undertaking of the development of a large, 1MW class spacecraft powered by a nuclear reactor offers significant benefits to the nations that might join the effort.

A) There are significant synergies in technology development with the nuclear, aeronautic and defence industries, with other possibilities for technology transfer with sectors that deal with high performance electronics and advanced materials.
B) New capabilities are offered by such a spacecraft, such as the possibility of deflection of a large asteroid (Earth Protection) within a reasonable time-frame, an order of magnitude increase in payload delivery to the outer planets (tens of tons instead of hundreds of kilograms) and the possibility to land significant mass to the Moon and Mars, enabling human exploration and long duration outposts (several tons per trip
C) The necessity to update and enhance the current legal and safety framework will ensure the safe operation of NPS in space.
D) The public support campaign that will be required will set the communication roadmap for large international megaprojects that require support for controversial topics.
E) Significant business opportunities for the participating nations.
F) Another significant space initiative to follow Apollo and ISS

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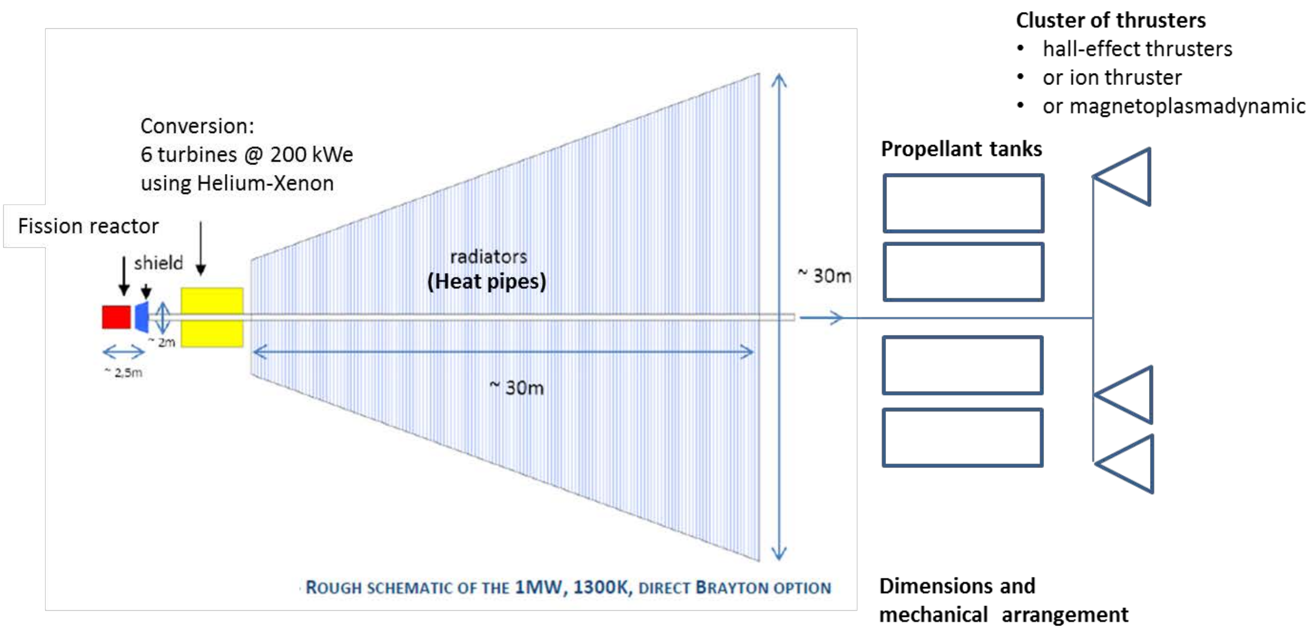

Figure 1: Schematic of the MEGAHIT reference vision