Democritos: preparing demonstrators for high power nuclear electric space propulsion

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Abstract. The Democritos project aims at preparing demonstrators for a megawatt class nuclearelectric space propulsion. It is funded by Horizon 2020, the R&T program of the European Community. It is a new European and Russian project, including as partners: Nuclear National Laboratory (U.K.), DLR (Germany), The Keldysh Research Center (Russia), Thales Alenia Space Italia (Italy), Snecma (France), ESF (France) and CNES (France). IEAV (Brazil) will join as an observer. Democritos is the follow-up of the Megahit project (www.megahit-eu.org).

During Megahit project, a reference architecture was established for 1MWe nuclear electric propulsion INPPS (International Nuclear Propulsion and Power System) , and a roadmap was proposed to have a spacecraft available by the early 30's. The main aim of Democritos is to start implementing the Megahit roadmaps by preparing demonstrators for some of the necessary technologies. Democritos features a technical part, with preliminary design of the demonstrators and their test benches. It features also a programmatic part, which will deal with financial and organizational aspects of such an endeavour: the ambition of the project is to initiate or join international cooperations, as broad as possible, which will lead to the implementation of the demonstrators.

Keywords: Nuclear, electric, space propulsion, Democritos, Megahit.

THE CASE FOR MWE NUCLEAR ELECTRIC PROPULSION

Megahit project has dealt with 1 MWe level nuclear electric propulsion. As Megahit results confirmed it, this technology would yield increased capabilities for Earth protection and exploration missions.

The interest in such system depends mainly of its power (1MWe), the specific mass of the power system, and the specif impulse of the electric thrusters.
For the specific mass, the target was to get 20 kg/kWe, including the mass of the fission reactor, the shield, the thermal/electric conversion system, the radiator, the PMAD, the electric thrusters. This target of 20 kg/kWe was deemed achievable with medium term technological maturation and development.
For the electric thrusters, parametric studies were conducted ranging from 2000 sec to 9000 sec, which are specific impulse deemed achievable with hall effect thrusters and ion thrusters with medium term technological maturation and development for the highest values.
Typically, existing hall effect thruster can reach 3000 sec using Xenon, 4500 sec using Argon. Existing ion thrusters can reach higher specific impulse, up to 7500 sec, but at a cost of maximum thrust achievable.

With such hypothesis, four missions were considered as the most promising for such a system:

NEO (Near Earth Orbiter) 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.
Best strategy would be to deflect it by acting as a gravity tractor: we avoid then more complex and risky and complex strategy, such as harpooning or destruction of the asteroid
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 1MWe nuclear electric propulsion system with a specific impulse of 7000s would have allowed deflecting Apophis trajectory by 1 million kilometer (at its passage near Earth in 2036). If spacecraft leaves Earth in 2021, would reach Apophis in 200days and deflect it by staying a distance of 300m during 40 days.

Outer solar system missions
For **Europe** orbit: we could bring 3 to 10t of payload in 2.5 to 3.5 years depending on the specific impulse of the thrusters (6000s to 8000s).
In case of chemical propulsion using for direct scheme of transfer from the Earth surface to the near Jupiter orbit (without gravity maneuvers) with the same transfer duration (T = 2.5 years) the delivered payload mass will be in 10…20 times less (about 300 kg) in comparison with case of electric propulsion utilization. Some improvement in ballistic efficiency of chemical propulsion application may be achieved by using transfer schemes with gravity maneuvers.
For Titan orbit: similarly, from 3 to 12 t of payload could be brought in 3.5 to 6 years (specific impulse Isp 6000 sec to 9000 sec).

Lunar orbit tug
With a 1MWe tug and a launcher capable of launching 80t in a 800km orbit two times per year, 650t of payload can be brought in lunar orbit in 10 years.

Cargo support mission for manned Mars mission
Megahit spacecraft could bring 15t in near Mars orbit in 400 days with an Isp = 6000 sec. A chemical propulsion systems would make it possible to deliver for 200 days to near-Mars orbit the spacecraft with 9 t mass, which is approximately half as many as that of payload, delivered by the tug with the NPPS.

It should be noted that, apart from the payload mass, the spacecraft delivers to Mars the 1MW power source, that can be used for the payload power supplying (for instance, the radar complex).

As a conclusion we can say that 1MWe nuclear electric propulsion:

- Is a multipurpose system that will enable new breakthrough missions, related to earth protection, deep space exploration and support to manned lunar or mars missions.
- Will offer significant gain of payload mass compared to chemical propulsion. The gain gets even higher if we consider that in addition to a classical payload, the spacecraft brings with it a nuclear power system that can be used for purposes other than propulsion (electrical alimentation for radars for instance).

Within Megahit project, no comparison was performed between the performances of nuclear electric propulsion and thermonuclear propulsion. Such comparison was performed in other studies, such as the one in [3].
It is concluded that thermonuclear propulsion features a lower Isp in the range of 900 sec, but a much higher thrust, comparable with chemical propulsion. Therefore, compared with thermonuclear:

- Because of higher Isp, nuclear electric may offer either a higher payload, or a less heavy (and more affordable) spacecraft to transport the same payload.
- Because of lower thrust, with nuclear electric propulsion, the flight time to destination will be longer, which may be an issue for manned mission.

To sum up to the extreme, and if we focus only on a performance/cost aspect, thermonuclear propulsion seems best suited for faster manned mission, nuclear electric propulsion has many advantages as a cheap and efficient cargo/robotic exploration missions.

TECHNICAL CHALLENGES AND ROADMAP

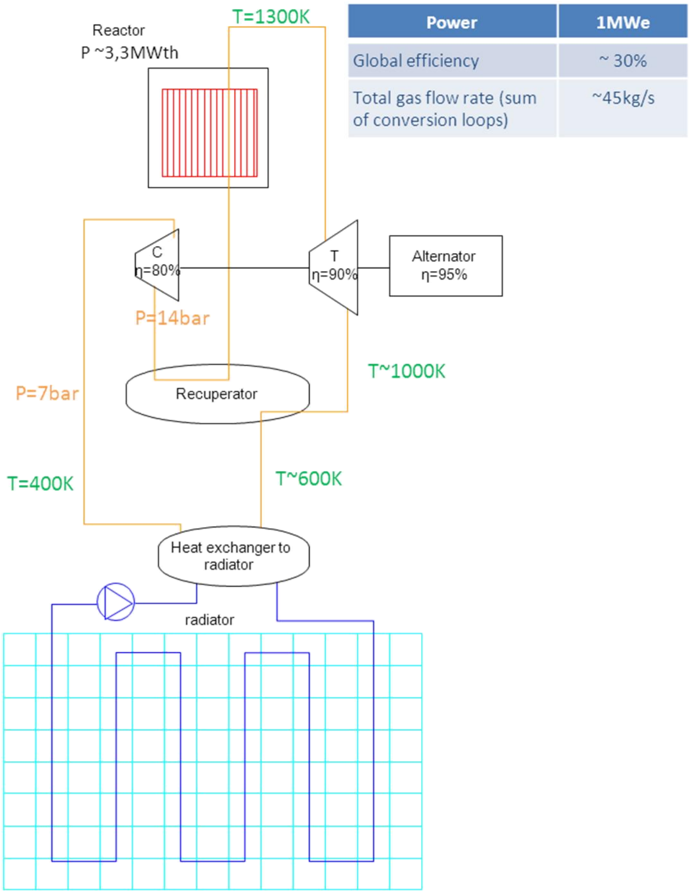
To be attractive with regard to more conventional propulsion system, nuclear electric must achieve the best specific mass for the power system. A target of 20 kg/kWe has been chosen as realistic, provided medium term maturation and development.

The Megahit consortium considered to this target a thermodynamic map with a rough mass budget.
First contributor is the radiator, which accounts for 30% of the mass and a surface of 500 m^2.

The most important point in the thermodynamic map is the temperature of the hot source (exit of the reactor/ inlet of the turbine).
Indeed, because of this high temperature that must be sustained during a very long lifetime (10 years to cover all possible missions), **some maturations/ new development will be required for:**

- The nuclear reactor (fuels, mechanical commands, absorbers, reflectors).
- The turbine blade and disk (turbine blades, especially, are subject to creep).
- The heat exchanger between primary and secondary circuit (if we choose an indirect cycle a heat exchanger is required).

The exact technological gap will be consolidated with more detailed design of these components. However, we expect that resistance of existing materials/technologies should be improved by 50 K – 100 K to meet the 1300 K target.



Power	1MWe
Global efficiency	~ 30%
Total gas flow rate (sum of conversion loops)	~45kg/s

FIGURE 1: Megahit reference thermodynamic map

In case of a temperature close to the expected 1300 K target, technological maturation remains interesting: as the highest temperature is achieved, the better specific mass for the power system can be reached.
With a temperature of 1600Kand an indirect cycle, for instance, it can be approached a specific power lower than 10 kg/kWe.

Existing conversion bearings will also need improvement to sustain 10 years of lifetime without maintenance.

A challenge will also be to demonstrate the **safety of the reactor**, even in case of launch failure.

The need to assemble many parts in orbit may require **advances in robotics**.

We concluded that, due to the many challenges and before building and testing the nuclear electric spacecraft INPPS, we will need lower power demonstrators, as part of technologies maturation and also to demonstrate the correct functioning of the system (for instance, a strategy for transient phases should also be defined, allowing coherent functioning between core, turbine, radiator and thrusters).
Because of this need for lower power demonstrators, Megahit consortium initiated the Democritos project.

DESCRIPTION OF THE DEMOCRITOS PROJECT

Democritos is the follow-up of the Megahit project. Its aim is to start implementing Megahit roadmaps, by preparing demonstrators for a MWe class nuclear electric space propulsion.

Democrtios is funded by Horizon 2020, the R&T program of the European Commission . It is a new European and Russian project, including as partners: Nuclear National Laboratory (U.K.), DLR (Germany), The Keldysh Research Center (Russia), Thales Alenia Space Italia (Italy), Snecma (France), ESF (France) and CNES (France). IEAV (Brazil) will join as an observer.

Democritos will feature a technical partand a programmatic part.

Technical Part

For the technical part, three sub-projects are considered:

DEMOCRITOS-GC (Ground Component). Aim is to perform preliminary design studies of ground demonstrator, including all the parts that are not nuclear. It will include design and drawings of all subsystems and ground based test benches. It will also investigate interaction of the major subsystems (thermal, power management, propulsion, structures and conversion) between each other and with a (simulated) nuclear core providing high power (about 200kW).

DEMOCRITOS-CC (Core Component): Aim is to perform preliminary design studies of ground demonstrator, for the nuclear part. It will include design and drawing of the nuclear space reactor, together with an analysis of the regulatory and safety framework.

DEMOCRITOS-SC (Space Component): Aim is to provide preliminary design of a nuclear electric spacecraft, with a detailed assembly and servicing strategy in orbit.

Programmatic Part

Programmatic part will be addressed in the sub-project DEMOCRITOS-PO (Programmatic):

Ambition is to build or join a broader consortium to implement the demonstrator project. The DEMOCRITOS-PO aims are to put in common the best technical talents, to share technical and financial resources with other organizations and to find synergies with space and non-space existing programs. Once this broader consortium is built, Democritos will propose an organizational and financial structure for the future demonstrators.

An important input for the financial structure will be to establish preliminary costs for the demonstrators and for the final spacecraft (development and production costs). Although it is not expected, that the development cost to be radically different from the cost of a cryogenic propulsive stage, this topic needs further investigation.

To achieve these goals, it will **be** used industrial and space agencies networks including the organization of a workshop with possible stakeholders by the end of 2015. It is also intended to benefit from coordination with ISEF and ISEC-G. It is also planed to present the DEMOCRITOS progress status at next ISEF meeting.

Final target is to have all the elements ready the end of 2016, in order to launch a demonstrator program in case a political consensus is reached at international level.

Opportunities for cooperation

Its is the belief of the Democritos consortium that such an international political consensus is possible within the following years.

Indeed, one can notice a rising interest in the international community for nuclear electric space applications

- ISEC-G has identified nuclear power for electric propulsion and planetary surface application as a critical technology that could “yield novel approaches to and significantly increased capabilities for exploration mission” [1]
- In Russia, with the participation of Roscosmos and Rosatom [the state agencies for space exploration and nuclear power, respectively], the Keldysh Research Center is developing a spacecraft using a megawatt class nuclear power propulsion system (NPPS)and the ground based tests of a prototype is expected to be completed in 2018.
- NASA released in 2014 a new Design Reference Architecture (DRA) for Human Exploration of Mars [2]. This DRA now includes an electronuclear design reference and chemical + solar design reference, and underscores the potential for both. Although no definitive choice is made between all the possible architectures, it appears that the 2.5MW electronuclear design allows the lowest number of SLS launches for a trip duration that is a bit higher than chemical or thermonuclear propulsion, but much lower than the chemical and solar propulsion.
- Apart from propulsion, NASA is developing Fission Power Systems (FPS) for use on the surface of the Moon, Mars, or other moons and planets of our solar system. As part of the FPS development, NASA is building and will test two demonstrators: one for the nuclear core (KRUSTY), one for the conversion system (TDU) [4], [5]. Although these demonstrators differ from what DEMOCRITOS proposes (10 kWe instead of 200 kWe, Stirling conversion instead of Brayton conversion), similarities exist in the logic and the objectives. These similarities may lead to possible cooperation.

  Although few details are available on this project, China also claims to develop its own FPS [6].

STRATEGY FOR TECHNOLOGY MATURATION

Reference technologies were identified during Megahit [2] for high power electric propulsion (for the European low power electric propulsion roadmap see under DiPoP www.DiPoP.eu). The Megahit are high TRL technologies (TRL>4), that can be available when the three demonstrators are built.

- Gas-cooled, highly enriched reactor, derived from ground applications.
- Brayton conversion, using turbines and alternators from aeronautics, able to sustain 1200K-1300K
- Heat pipes radiators.
- Low thrust Hall effect or ion thrusters, used in clusters.
- In orbit assembly similar to ISS.

The first goal of the DEMOCRITOS demonstrators will be to demonstrate all reference technologies can work together as the INPPS, and that this system can be operated efficiently and safely, during start, continuous mode, and shut down.

However reference technologies may have limited performance. Additional technological maturity could then be an asset.

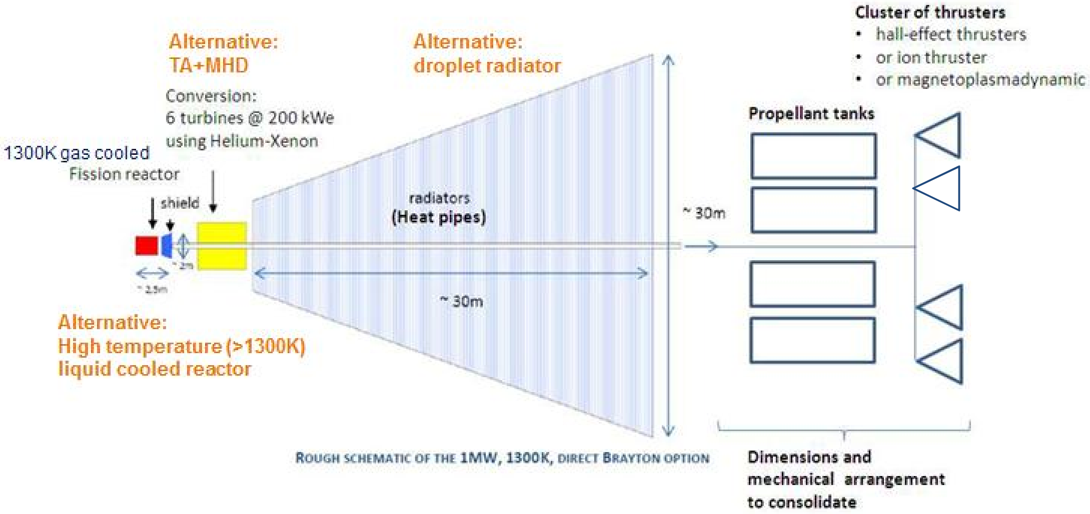


FIGURE 2: Megahit general architecture of the INPPS with reference and alternative technologies

In that perspective, alternative technologies have been identified during Megahit: those are lower TRL technologies that have improved performance and would increase the assets of nuclear electric propulsion. Most of these technologies present possible synergies with aeronautics, energy production on ground and other space programs.

- Liquid-cooled reactor, able of higher temperature, from 1300 K up to 1600 K.
- Brayton conversion, with turbine using new materials (ceramics, nobium alloys) able of higher temperature, from 1300 K up to 1600 K during five years of operation.
- Thermoacoustics + MHD as a more reliable and efficient alternative to Brayton.
- Droplet radiators.
- High thrust Electric thrusters, including MPD thrusters (Vasimir).
- Advanced and autonomous robotic in-orbit assembly.

Second goal of the demonstrator will be to participate to new technologies maturation. The Democritos members will then strive to make the Demonstrator as modular as possible, to first accommodate reference technologies, then to accommodate alternative technologies, as soons as they become available.

In parallel to Democritos, alternative technologies maturation will be proposed by the consortium in the frame of horizon2020.

CONCLUSION

High power space nuclear electric propulsion is an exciting challenge on technological and system level. ISEC-G has identified it as a critical technology that could yield significantly increased capabilities for exploration mission new missions. Among these new missions, Megahit had identified deep space exploration, cargo mission to support mars manned missions, and Earth protection against asteroids.

Democritos is an opportunity to enhance our ability to design and build nuclear electric propulsion. A core consortium already exists in Europe and Russia with Megahit partners, plus Snecma (France) that became Democritos member, similar like the Brazilian observer IEAV. Within Democritos, it will strive to make larger, attractive international consortiums emerge, to put in common technical and scientific talents, as much as technical and financial resources.

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