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Mars / Europa INPPS Flagship: All right for UN NPS Principles

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Abstract

The presentation gives an overview of the current plans for the INPPS (International Nuclear Power and Propulsion System) Flagship design as well as related scenarios for utilization and puts these efforts in context with related legal and political challenges. In the last years (2017/2018) significant technological progress has been achieved as the nuclear reactor, radiator and propulsion subsystems of INPPS Flagship have successfully passed partial ground testing. Thus, the next step towards the INPPS goal of efficient and effective transport missions to Mars / Phobos and Jupiter / Europa has been taken.

Hence, it is important to consider wider aspects for the overall mission implementation phase. Mission components such as the nuclear reactor as the power source for the propulsion system will have to comply with the 1992 UN principles relevant to the use of nuclear power sources (NPS) in outer space as well as scepticism at a time of low appetite for nuclear energy before implementation. Therefore in addition to an update on current technical state of art, this paper will look into the political questions related to the mission design, requirements of associated safety regulations and economic aspects for INPPS Flagship commercialization and international communication.

The paper will show that the rationales for pursuing the implementation of this flagship mission are derived from a technological push but also from wider strategic aspects that benefit a variety of stakeholders and serve multiple goals.

The interactive presentation will include videos related to INPPS Flagship, international interviews for Mars exploration mission by NPS, description of UN principles of NPS as well as commercialization and international communication aspects.
Keywords: 1) UN Principles for NPS 2) EC DEMOCRITOS & MEGAHIT & DiPOP projects 3) INPPS Flagship: Human & Non-human High Power Space Transportation Hybrid Space Tug, 4) INPPS Flagship Commercialization and Communication Aspects

Acronyms/Abbreviations

Artificial Intelligence (AI)
Third US human space flight program (Apollo)
Cosmonaut Training Center (Gagarin CTC)
Demonstrators for Conversion, Reactor, Radiator and Thrusters for Electric Propulsion Systems (DEMOCRITOS)
DEMOCRITOS Core Concept (DEMOCRITOS-CC)
Disruptive technologies for space Power and **P**ropulsion (DiPOP)
Humanoid Robots (HR)
intelligent Building Blocks for On-Orbit Satellite Servicing and Assembly (iBOSS)
International Nuclear Power and Propulsion System (INPPS)
International Space Station (ISS)
Medipix – family of read-out chips for particle imaging and detection developed by the Medipix Collaborations (Medipix)
Megawatt Highly Efficient Technologies for Space Power and Propulsion Systems for Long-duration Exploration Missions

(MEGAHIT)
Nuclear Safe Orbit (NSO)
Nuclear Electric Propulsion (NEP)
Nuclear Power and Propulsion System (NPPS)
Nuclear Power Source (NPS)
Nuclear Thermal Propulsion (NTP)
Power and Processing Unit (PPU)
Transport and Power Module (TPM)
Timepix – applications in imaging and detection of charged particles by Medipix (Timepix)

1. Introduction

The use of high power reactor / nuclear power systems (NPS) in space is essential in order to meet current and future challenges to carry out deep space flights – with non-human & massive payload as well as with humans to Mars. Such reactor NPS will be a game changer in non-human as well as human space exploration journeys.

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 a failure means that safety must always be an inherent part of studies, design and application of space nuclear power system.

This paper for the e-poster highlights the consideration of UN NPS principles to successfully achieve the MARS- or EUROPA International Nuclear Power and Propulsion System (INPPS) Flagship mission statement. INPPS was designed considering experiences and using heritage from the U.S. PROMETHEUS project, Russian NPPS / TPM / MW class reactor developments, which were used and extended in high power space transportation studies funded by the European Commission (EC). In these EC projects DEMOCRITOS, MEGAHIT and DiPoP, [1] consortium members like space organizations, space industry as well as SMEs and university institutes from Europe and Russia were involved. A Brazilian institute was guest observer in DEMOCRITOS and MEGAHIT. Additionally, in the DEMOCRITOS project, institutes from NASA Cleveland as well as JAXA Tokyo and Airbus Germany contributed in several ways to the DEMOCRITOS MARS- and EUROPA-INPPS Flagship design and subsystems, also during a concurrent engineering (CE) study at the DLR Bremen Concurrent Engineering Facility (CEF) [30,31]. The flagships are planned to be equipped with a MW class reactor. The space qualification of INPPS is already envisioned beyond 2025. Insofar, all internationally available knowledge and progress in science, technology and regulations are included in the INPPS Flagship development, launches, assembly and flight operation.

All UN NPS regulations [2] will be fulfilled by the following eight measures

1) early information about INPPS Flagship in respective panels and full view of the public,
2) first, different launchers carry all non-nuclear subsystems to higher Earth orbit (above 800 km – 1200 km, at least),

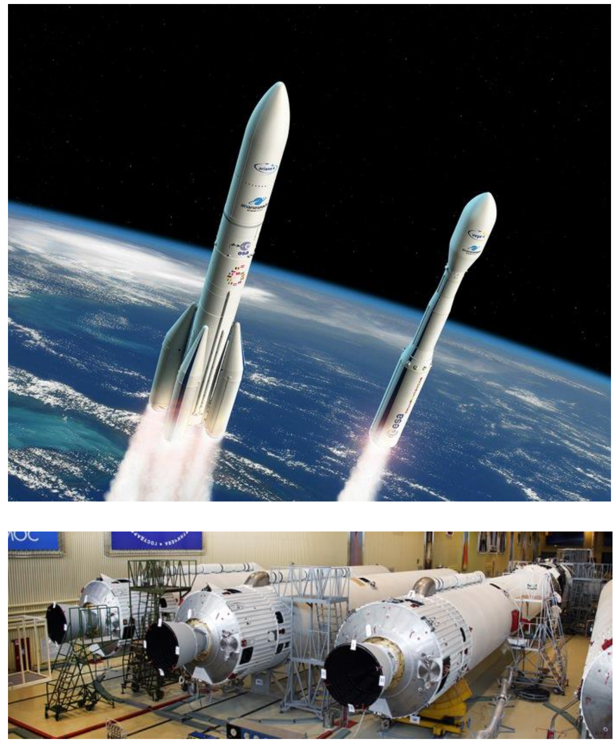

Fig. 1. Above – artist's view (ESA – D. Ducros) of European launchers Ariane 6 and Vega-C. First, all non-nuclear subsystems of INPPS will be launched by internationally selected and provided launchers. In MEGAHIT, for instance the VEGA performance map was calculated: about 1.5 t INPPS non-nuclear subsystems can be transported to an altitude of 800 km for INPPS assembly. Below – Angara rockets (source ROSCOSMOS, https://www.roscosmos.ru/473/). The launch complex for the second turn of Angara rockets is under construction in Vostochny Cosmodrome. Finally, a model from the Angara rocket family will transport the INPPS core sub-system from Russian Far East to high Earth orbit for INPPS assembly.

3) after complete successful robotic assembly of non-nuclear subsystems, a Russian heavy launcher transports the core to high Earth orbit and robotic assembly and mounting to non-nuclear subsystems will be carried out,
4) it follows the step by step activation of all subsystems and extensive testing of entire space system is carried out before interplanetary departure,

5) by real-time video and charged particle & electromagnetic radiation monitoring of the INPPS Flagship (via MEDIPIX / TIMEPIX on board) and
6) the launch of a co-flying monitoring small spacecraft to accompany INPPS in interplanetary cruise will be envisaged.

The INPPS international space system contributes to safety by

7) auxiliary kW-scale solar power supply by photovoltaic arrays for the assembly and non-nuclear operations phases, and
8) building blocks (like iBOSS) with standardized interfaces, which are used for many non-nuclear subsystems. Advantages are the maximum and flexible use of subsystems in both Flagships plus artificial intelligence (AI) applications for subsystem analysis including fault detection, isolation and recovery (FDIR).

In particular feature 8) with AI applications in building blocks and additional Flagship subsystems, contributes as a potential game changer in the way of safety and quality thinking compared to previous space flights: In the Flagship flights to Mars or Europa, as in any major space mission, there almost certainly will be some malfunctions in some of the Flagship's subsystems. The space environment is hostile and '… the systems needed to survive in it are complex. Our charge is not to avoid that risk at all costs, but to manage that risk intelligently'**.** [3]. Insofar the eight mission design features described above are also directed towards international contributions, acceptance, a prudent cost-risk balance, and finally INPPS Flagship operation cost reductions. INPPS flagship aims to become another amazing space project involving long-lasting international scientific and technical cooperation for the good of humanity following in this respect the example of e.g. Apollo or the ISS.

Therefore, the resulting MARS- and EUROPA-INPPS Flagships of the DEMOCRITOS project will be described in the next subchapter including details of UN NPS principles reviewed in relation to the Flagships.

2. INPPS Flagship and UN NPS principles

The next three subchapters describe the INPPS Flagship as a space system, UN NPS principles relevant for the use of INPPS and commercialisation and communication aspects of INPPS payload.

2.1 INPPS Flagship as a Space System

Overview of INPPS Flagship as a space system is summarized in [1]. Many technological and scientific aspects of Flagship subsystems are described in [3], but separately presented at the IAC 2019 in Washington, D.C. (see in [4] to [7]).

Because of the successfully completed ground based test of the MW reactor in Russia, the near-term focus of related activities is on space qualification of INPPS via the Mars and Europa interplanetary cruises in the period 2025 – 2035.

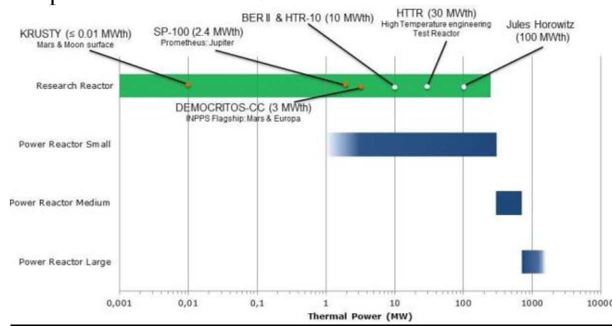

Fig. 2. All U.S. and Russian NPS (orange dots) for space applications are small research reactors according to IEAA safety requirements. For comparison small, medium and large power ranges for ground based power production reactors are also displayed (white dots).

Starting with the TPM developments in Russia (see NPPS with standard and droplet radiators in Fig. 3) and continued by common studies in the European-Russian DEMOCRITOS & MEGAHIT projects (see example of the MARS-INPPS with standard radiators in Fig. 4) currently extensions are started to design conical droplet as well as standard radiators for MARS-INPPS equipped with the MW class reactor from Russia and internationally contributed subsystems (see Fig. 5).

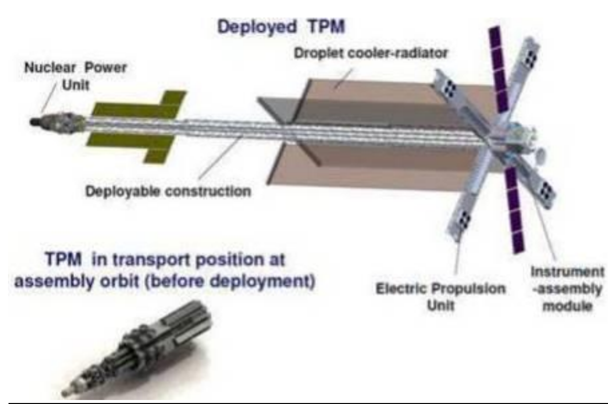

Fig. 3. Non-deployed and deployed TPM. In the deployed TPM, adjacent to the nuclear power unit is the standard (high temperature) radiator with two deployed wings (green). The droplet (lower temperature) radiator consists of four deployed wings and is displayed in semi-transparent grey for clarity.

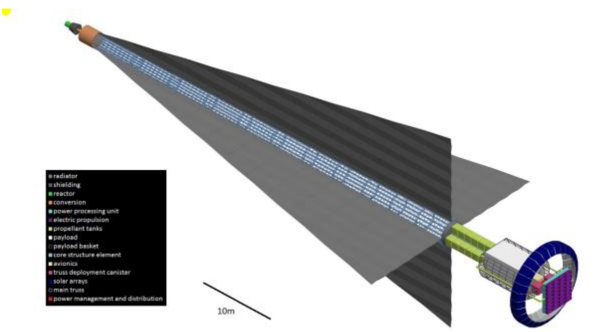

Fig. 4. The DEMOCRITOS MARS-INPPS Flagship with four standard (high temperature and lower temperature) deployed radiator wings (in grey). These wings at first glance appear as futuristic layout akin to that of the supersonic French-British Concorde and Soviet Tu-144 airliners but result from the best possible utilization of the radiation-shielded volume. Colours indicate all major subsystems, a size scale is also given.

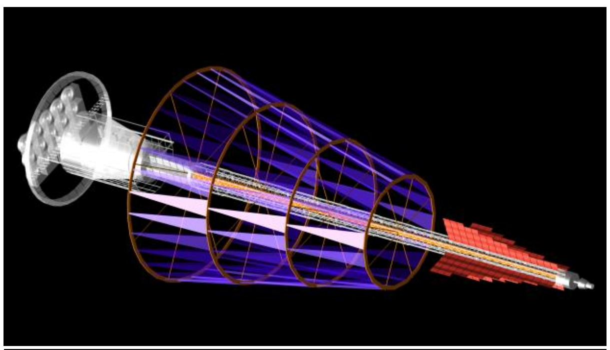

Fig. 5. Potential combination of TPM/NPPS and DEMOCRITOS MARS-INPPS, resulting from MW class reactor tests. From right to left – four deployed standard radiator plates (red) and conical droplet radiator rings (purple – again outlining the shielded volume) for a MARS-INPPS Flagship interplanetary cruise after 2025.

2.2 UN NPS Principles and INPPS related Objectives

Drafting of the ‘Principles Relevant to the Use of Nuclear Power Sources in Outer Space’ (UN NPS Principles) [8] began as a reaction to the Kosmos-954 incident. The satellite Kosmos-954 disintegrated over Canada in January 1978 [9]. It carried an operational nuclear reactor and scattered radioactive debris including fission products over a vast stretch of the Northwest Territories, Alberta and Saskatchewan [10]. Following a Canadian initiative, the Scientific and Technical Subcommittee (STSC) of UNCOPUOS established a Working Group on ‘Questions relating to the use of nuclear power sources in outer space’[11]. The aim was not to prevent or even prohibit the use of NPS, but to establish a set of principles that provide for the safe use of NPS in those missions which depend on such power sources. [12]

The UN NPS Principles supplement existing regulations concerning the use of NPS, e.g. IAEA rules, with specific standards for the use in outer space [13]. They take into account the specific dangers of space missions and contain guidelines and criteria for safe use in outer space, relating to mission design, type of reactor and fuel, [14] safety assessment [15] and procedures in case of re-entry [16] as well as responsibility and liability for consequences of the re-entry [17]. Acknowledging the dynamics of technical development, Principle 11 UN NPS Principles called for a revision no later than two years.

But the Legal Subcommittee of UNCOPUOS could not reach consensus on updating the Principles. Therefore, the STSC started the development of a safety framework in 2003. [18] It partnered with the IAEA and by the end of 2006 consensus was reached about the nature of the framework and its key characteristics. [19] The ‘Safety Framework for Nuclear Power Source Applications in Outer Space’ (Safety Framework) was then drafted from 2007–2009 by a ‘Joint Expert Group’ in partnership with the IAEA and agreed upon by the STSC in February 2009[20].

The Safety Framework provides guidance for governments, for management and technical guidance concerning the use of NPS in outer space. For each of those areas it contains recommendations, e. g. concerning safety policies and launch authorization (guidance for governments), responsibility and management for safety (guidance for management) as well as safety in design, risk assessment and accident consequence mitigation (technical guidance).

The UN NPS Principles have not reached the status of customary international law, due to lack of acknowledgement by states as legally binding rules. Nevertheless, most NPS missions so far - since their adoption - complied with them[21].

1. Principles Relevant to the Use of Nuclear Power Sources in Outer Space (Principles), approved by the General Assembly of UN in resolution 47/68 of December 14th, 1992[8].

The UN NPS Principles (see also in [2]) impose the following restrictions on the use of systems like the INPPS:

A) ‘Nuclear reactors may be operating…’
   - on interplanetary missions,
   - in sufficiently high orbits (800 km to 1200 km) and
   - in low-Earth orbits if they are stored in sufficiently high orbits after the operational part of their mission.

B) ‘Nuclear reactors shall use only highly enriched uranium 235 as fuel’.
C) ‘Nuclear reactors shall not be made critical before they have reached their operating orbit or interplanetary trajectory’.
D) ‘The design and construction of the nuclear reactor shall ensure that it cannot become critical before reaching the operating orbit during all possible events, including rocket explosion, re-entry, impact on ground or water, submersion in water or water intruding into the core.’
E) ‘In order to reduce significantly the possibility of failures in satellites with nuclear reactors on board during operations in an orbit with a lifetime less than in the sufficiently high orbit (including operations for transfer into the sufficiently high orbit), there shall be a highly reliable operational system to ensure an effective and controlled disposal of the reactor.’

2. Safety Framework for Nuclear Power Source Applications in Outer Space (Safety Framework), approved by the General Assembly of UN in resolution 64/86 of December 10th, 2009[21].

The Safety Framework notes that ‘according to current knowledge and capabilities, NPS in space are the only viable energy option to power some space missions and significantly enhance others. Several ongoing and foreseeable missions would not be possible without the use of space NPS.’

As emphasized in the Safety Framework, ‘nuclear safety should be considered from the earliest stages of design and development and throughout all mission phases.’ The design and development processes should therefore ensure the highest possible level of safety.

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 reactor fuel material (new core) and the risk of uncontrolled criticality (for example in case of uncontrolled impact in water, wet sand, or into or onto other media associated with possible geometry modification).

Technical solutions exist and have to be implemented during the conception of the reactor: reactor fuel must be sufficiently non-radioactive before and during the launch. The fuel dispersion risk can for example be reduced by using a highly resistant vessel or liner similar to those in isotope thermoelectric generators, for example, aboard the Mars rover ‘CURIOSITY’. In case of launch failures the risk can be reduced by safety absorbers, avoiding poisonous compounds and materials, removal of reflectors during launch, and further additional measures. Efficiency of those solutions will have to be demonstrated. Risk of dispersion of highly radioactive material (fission products) into the terrestrial environment after reactor start-up in space is addressed by operating the reactor only once it has reached a sufficiently high orbit or preferably an escape trajectory.

There is another risk factor in space which could influence INPPS safety – possible collisions with space debris. A preliminary analysis has shown that the minimum altitude of the INPPS nuclear safe orbit should be in the range of 800 to 1,000 kilometres from the perspective of orbital decay by atmospheric drag, somewhat dependent on solar activity predictions. However, this is also the orbit range with by far the highest density of near-Earth artificial space debris (see Fig. 6 below and [22], [23]). Consequently, in order to meet guidelines for minimizing the probability of collisions with other space objects, altitudes between 1,200 and 2,000 km are being considered as preferable initial operational altitudes for INPPS Flagship. Only going beyond 2,000 km altitude, the spatial density of debris again becomes less than that at the ISS’ orbital altitude around 400 km which appears an acceptable level for human spaceflight. Beyond, elevated artificial debris levels may locally be expected near the NavSat shell of orbits at about 20,000 km altitude and near the geostationary satellite belt around 36,000 km altitude. However, orbital altitudes above 615 km have not been surveyed extensively by in-situ collectors or sensors, and population data there depend significantly on extrapolation from detectable debris (>10 cm … >1 m at high altitudes) and low Earth orbit scaling from tracked particles to fine debris impacts found on long-term exposed surfaces([23],[24]).

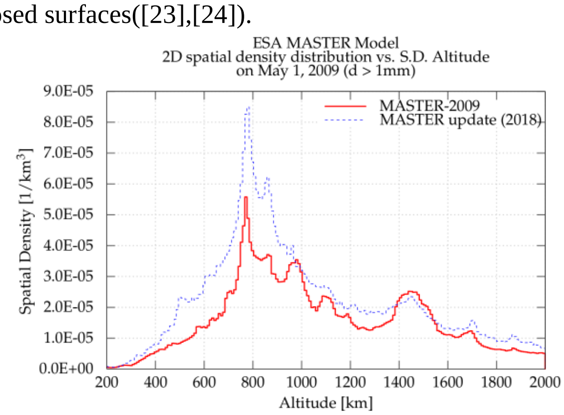

Fig. 6. Evaluation of spatial density in LEO for space debris particles with d > 1 mm.

With respect to Germany, DLR is interested and involved in the following non-nuclear INPPS aspects:

- in research and technology of the non-nuclear subsystems boom, electric thrusters, building blocks including AI, Mars / Europa payload and secondary photovoltaic power supply,
- in research and technology of the autonomous robotic high Earth assembly and
- in flight operation.

Moreover, in Russia (for example KeRC), in Europe (for instance within DEMOCRITOS consortium members and at ESA) and in Germany (like at DLR) a deep understanding and complete acceptance of UN NPS rules is given. Because of project progress for all INPPS Flagship subsystems it sounds logical, that Russia may prepare soon a statement about NPS in space.

2.3 INPPS Flagship: International Cruise Communications and Economic Aspects for Commercialization

The immediately discernible difference between human Moon and Mars flights is the direct departure from the vicinity of Earth and the long duration, which decrease at first glance the attraction and attention of the public. The mission is travelling for months to only a small red star in the sky, compared to the highly visible Moon which is reached within a few days. The INPPS Flagship non-human and human launches, stay and return from Mars have the potential to be directly amazing for humankind. Additionally, the less 'visible' non-human INPPS flight or the extended time of the crew's cruise in space to Mars and back may well be comparable in their inspirational impact with the public to ISS activities which are perceived by a large audience as amazing, beyond being a symbol of international cooperation.

A sketched pathway orientation, how the additional amazing attractiveness will be reached: until today, many successful efforts were done to obtain impressions from space by audio and visual transmissions from space down to Earth for the public. It started with audio signals from Sputnik 1 accessible to radio amateurs worldwide, and extended to Gagarin's TV transfer, the worldwide live broadcast of the Apollo Moon missions, and movies from the early space stations Salyut and Skylab. Currently, internet live-streams from the ISS have on the one hand become already normal to the media (which in a way shows that spaceflight has become a permanent feature of life on Earth) but also capture the attention and imagination of a growing audience subscribing to such channels. However, considering reports by astronauts on their life aboard space stations or their experiences with lunar dust after returning to the pressurized Lunar Module on the Moon, for a real and realistic perception from space, three human senses could still be additionally included with the INPPS payload basket by downlink transmissions – kinaesthetic, olfactory and gustatory perceptions. With these, all five human senses (visual, auditory, kinaesthetic, olfactory and gustatory) would give a complete 'feeling' from space time during interplanetary cruise.

Via humanoid robots in the INPPS communication payload section, not only video and audio signals but also the three additional human senses could be implemented as far as possible in ways remotely measurable and transmittable to Earth to accompany expedition activities. Advanced high data rates achievable via laser communications to Earth orbiting telecommunication satellites could make activities aboard tangible for all in near real time. Basic results of experimental studies at Gagarin CTC for the use of HRs with cosmonaut participations for deep space explorations are described in paper [24]. Compared to Apollo and the ISS, this would be the first higher quality communication promotion of INPPS Flagship space flights.

The second, higher-quality inclusion of the worldwide public which is envisaged is virtual reality derived from the INPPS communication payload section. First efforts started at DLR and German SMEs to install, for example, virtual class and conference rooms in the payload section to reach out by virtual reality means (including up to five human senses for the user on ground). Time slots for observations with on-board astronomical telescopes may be also offered, beyond the usual advantages of space-based astronomy also creating long stereoscopic baselines with Earth for simultaneous activities. Finally, the demand of a market for on board virtual reality from the cruising flagship in space time to Mars and Europa for the real users on Earth ground will be well worth exploring.

Both higher quality communication concepts not only promote worldwide support of first non-human MARS-/EUROPA-INPPS Flagship flights. They also prepare in the best possible ways the first human MARS-INPPS Flagship flight. Just as Apollo inspired 50 years ago a generation, the generations of today will have at least once in their lifetime the experience of a historical space event, including the younger generation together with their still living Apollo-inspired parent generations. Insofar, INPPS Flagship is worldwide unique, peaceful, and endowed with two economic growth aspects.

The first economic aspect for INPPS Flagship commercialization is primarily given by international economic developments respectively prospects to reach the space qualified Flagship by 2025, the interplanetary non-human Mars and Europa flights, and then the ultimate goal of a human MARS-INPPS Flagship cruise. That means it will create - with time and along the ways during the years - economic and international benefits.

A second economic aspect is the new interplanetary economy, here via commercialisation of INPPS Flagship payload capabilities. iBOSS [25] and NANORACKS – originally initiated in LEO [26] are building blocks and modules which may also be applied in and mounted to the INPPS payload basket. Different products – from simple processed goods to high-tech products – may be produced under near zero gravitational force conditions during interplanetary cruise, but also during Earth or Mars departure and approach periods. These manufactured 'Made in Interplanetary Space' items are released or transported back to Earth by small spacecraft (possibly down to cube-sat size). These new trademark items open completely new business cases. This is a logical step after present first space commercialisation enterprises such as the reusability of launchers. Interplanetary economy would work in parallel to the already well established orbital economy and potentially a developing lunar economy (see in [27]). Interplanetary economy on board of INPPS Flagship will also further advance the US horizon goal – human missions to Mars (compare with [28]).

3. Realizable Conclusions

Considering the financial, technological and programmatic challenges related to space missions using nuclear power systems, it is believed that such missions could only be done with a concerted effort of several interested space powers (as it was the case for the International Space Station). Each space power could propose their equipment and components to use them in the INPPS technical subsystems or as scientific, commercial and communication payloads. Besides payload, these could also include NPS, for example the NASA kW power reactor (designed for providing 1 to 10 kW of electrical power [29]) for detachable scientific spacecraft or landers, or to supply electricity and thermal power on surface of Mars or the Moon.

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In memory for Hartwig Bischoff (†), who was a colleague and friend. He was in charge for NEP at European Commission and initiated and strongly supported the three European Commission funded projects.

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