Deep Space Transportation Enhanced by 20kW-Class Hall Thrusters

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Abstract

Deep space is the new frontier for human exploration, with Moon and Mars identified as fundamental targets. Improving in-space transportation capabilities has been recognized as one of the critical enabler for sustainable and affordable space programs in Earth proximity and beyond. Envisioning the presence of future deep space infrastructures, cargo transferring becomes a major issue that can benefit from improvements in in-space propulsion technology. Electric propulsion could represent the turning point, thanks to the combination of new system architectures and technology advancements, e.g. cluster architecture and magnetic shielding, and improved capability of on-board power generation. High-power Hall Thrusters are considered the most promising solution for future space exploration, thanks to a favourable thrust to power ratio, higher than Gridded Ion Engines. Reusable platforms, based on Hall Thrusters, could represent a valid alternative to chemical-propelled spacecraft. These systems

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Preprint submitted to Acta Astronautica *October 1, 2019*

could be exploited to support human presence in deep space, delivering life support items and providing on-orbit servicing capabilities. In this paper, the typical mission analysis tools have been exploited to analyse the selected scenarios. The analysis highlights possible advantages achievable adopting high-power Hall Thrusters on board reusable platforms. Since the design of these spacecraft envisions the adoption of a 20kW-class Hall Thruster string, the mass and power budgets are obtained for those subsystems that are most affected by this critical technology. Then, the feasibility of each scenario is assessed considering the needs defined not only by the traffic plan, in terms of loading/unloading cargo and transfer duration, but also by the peculiar mission and physical constraints. Last, the different platform design solutions are compared with respect to their electric propulsion configurations, in order to identify the possible commonalities in terms of architecture and technology, in line with the current trend of modularity and affordability.

Keywords: `Space Tug, Electric Propulsion, Transportation, Hall Thruster.`

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1. Introduction

The need to explore the unknown and push the limits beyond known boundaries have been always intrinsic in the human nature. In the space field, it can be translated into an expansion of human presence across the Solar System. According with the 2018 Global Exploration Roadmap [1], the Moon will represent the intermediate step necessary to pave the way for the future exploration towards Mars. To enable these challenging achievements, sustainable and affordable space programs should be envisioned, following an incremental approach for both the enabling technologies development and strategic capabilities enhancement. With this intention, the NASA Office of Chief Technology published the NASA Technology Roadmaps in 2015[2], where the main critical development needs for space exploration are subdivided in fourteen Technology Areas (TAs). In particular, the technologies related to the in-space propulsion area (TA2) have been identified as high-priority. Among them, electric propulsion stands out, which led NASA to include this technology in the 2017 NASA Strategic Technology Investment Plan [3].In addition, the Electric Propulsion Innovation & Competitiveness (EPIC) project, funded by the European Commission, aims to define an integrated roadmap for the coordination and implementation of a Strategic Research Cluster (SRC) in order to sustain the european activites on electric propulsion technologies [4] Since the first in-space demonstration performed in 1964 by the soviet Zond-2 [5] and followed by the NASA's Space Electric Rocket Test1 (SERT-1)[6], an international effort ensured a rapid evolution of electric propulsion technology, developing new concepts with improved performance in order to widen the range of possible fields of application. Exploiting the advantages carried by this typology of propulsion systems, different historic milestones have been reached, setting new records in the space field. Some examples are the first lunar transfer performed by SMART-1 in 2003 [7], the NASA JPLs Dawn spacecraft [8] that first orbited around two solar bodies, and the first sample return mission performed by the Japanese Hayabusa [9].

In the last decades, thanks to the improved capabilities of on-board power generation, renewed efforts have been posed in high-power electric propulsion. In particular, Hall Thrusters (HT) have been identified as one of the most suitable electric propulsion technology for future space transportation and exploration programs. In fact, this typology of thrusters combines several advantages, such as high values of thrust-to-power ratio, specific impulse, efficiency, a relatively long operational lifetime and a high reliability. Since the nineties, several high-power HTs have been designed and tested to investigate all different operational aspects during the high-power operations. In Russia, Fakel developed the 25kW-class "SPT-290" [10, 11], the first prototype tested up to 30 kW and able to produce up to 1.5 N of thrust with an anodic specific impulse up to 2950s. In the western countries, the activities related to high-power HTs started after the collapse of the iron curtain with the NASA T-220, developed by NASA Glenn Research Center in 1998 [12]. This 10kW-class thruster put the first cornerstone for the following extensive research activities on high-power HT at NASA Glenn

Research Center. In 2000, the NASA-457M was developed and tested up to 72kW, generating 2.9N of thrust [13]. The development of this thruster was followed by the smaller NASA-300M in 2004, a 20kW HT operated with both xenon and krypton, demonstrating an anodic efficiency peak of 73% and 68%, respectively [14][15]. In parallel, many private companies have designed and tested their own high-power HTs, targeting power levels up to 20kW, considered of particular interest for commercial applications [16].

Examples of these private initiatives are represented by the Busek BHT-20K [17] and the PPS-20K ML [18], developed by Snecma in the framework of the ESA's HiPER project [19].

However, only three high-power HTs are currently facing the qualification process. The first one is represented by the Advance Electric Propulsion System (AEPS) Hall Thruster, developed thanks to the combined effort among Aerojet Rocketdyne, NASA Glenn Research Center and NASA JPL. This thruster demonstrated to operate at nominal power of 12.5 kW, generating a thrust over 589 mN and an anodic specific impulse up to 2800s. The AEPS Hall Thruster, also known as HERMeS, has been originally developed in the framework of the activities related to the Asteroid Redirect Robotic Mission (ARRM) [20]. The second thruster, the 20kW-class HT20k [21, 22], has been developed by SITAEL, starting from the experience gained from the development of a lower power thruster [23]. The HT20k has been designed to operate over a wide range of operational points, ensuring stable operations over the entire envelope. In both thrusters, the magnetic shielding [24] has been implemented to decrease the erosion of discharge chamber walls, thus extending their operational lifetime. In Russia, Fakel is developing a 25kW-class thruster named SPT-230[25]. The engineering model was tested in xenon with a cathode-centre configuration. The test results suggest the operational feasibility over a wide range of power (from 4.5 kW up to 25 kW) and discharge voltages (between 300V and 800V). During a long-duration test, the thruster accumulated over 160 hours of operation in long-time firing modes. For the experience gained during these tests, the thruster design was revised and a new model is under manufacturing.

All these efforts would play a crucial role in the future robotic and human exploration scenarios in Earth, Moon and Mars environment, providing valid alternatives to the current chemical-propelled solutions, typically envisioned as transportation systems. Indeed, until now spacecraft designated for resupply and cargo transfer missions have been based on chemical engines, such as the Russian Progress, the Japanese H-II, the Americans Dragon and Cygnus, and the European Automated Transfer Vehicle (ATV) [26]. Despite the possibility to design evolved versions of these systems for deep space missions [27], a possible alternative could be the adoption of a reusable spacecraft based on electric propulsion, as presented in [28, 29, 30, 31]. However, most of these studies considered very high levels of power provided by either nuclear power sources or advanced design solutions, for which an extensive and expensive development and qualification campaigns would be required.

In this paper, a solar electric space tug has been envisioned, operating in Earth, Moon and Mars environments, to transfer unmanned cargo payloads and to provide logistic support to the future human exploration activities.

This concept has already been investigated in literature [32, 33, 34, 35, 36, 37]. The present contribution considers mission feasibility analysis under a different approach. The HT20k was chosen as reference while performing a comparison of different electric propulsion subsystem (e-PROP) architectures. The necessary mission requirements and constraints were then derived exploiting common mission analysis tools. The same reusable transportation system was conceived for four identified mission scenarios where peculiar needs were set. As such, the current goal is to identify a range over the thruster operative envelope which has to be common to all the selected scenarios.

The remainder of this paper is organized as follows. In Section 2, the main development steps of this thruster are reported, along with both its design characteristics and performance. The typical mission analysis tools have been exploited to investigate the identified scenarios. Main outcomes concerning the functional characterization of the corresponding platforms, are reported in Section 3, highlighting their technological and operational commonalities. In the same Section, the Concept of Operation (ConOps) of each scenario is presented, distinguishing them in terms of reference orbits, cargo mass transferred, traffic plan and operational time-line. In Section 4, the main results are provided, once the design tool exploited for the spacecraft sizing is briefly presented. These results are related to an extensive investigation carried out analysing several operational points of the HT20K along with different e-PROP architectures. The main objective was the identification of a set of optimal operational points, common to all scenarios and the related platforms. Finally, main conclusions are drawn and future investigations are presented.

2. HT20k Hall Thruster

In HT, a large transversal electron current is generated between two electrodes by means of an interposed magnetic field. This current, from which the name of these devices is derived, ionizes the propellant injected from the anode and, at the same time, allows the sustainment of an electrostatic field that accelerate the ionized particles without the adoption of immersed grids [38]. Among all different electric thrusters, one of the main advantages of the HTs is their scalability to different power levels with a relatively small variation of the thruster dimensions.

All these characteristics together, combined with a remarkable heritage of in-flight operations [39], make these thrusters the most promising technology to be adopted on-board a wide range of missions. These technological advantages, coupled with the increasing availability of power on board of satellite platforms, are encouraging several spacecraft manufacturers to focus on the implementation of high-power Hall thruster systems for both scientific and commercial applications. In Europe, SITAEL is leading the research on high-power HTs since 2015, when the activities on high-power Hall thrusters initiated under a Technological Research Project (TRP), funded by ESA. [40, 41]. Figure 1 summarized the main projects and milestones followed for the development of this thruster.

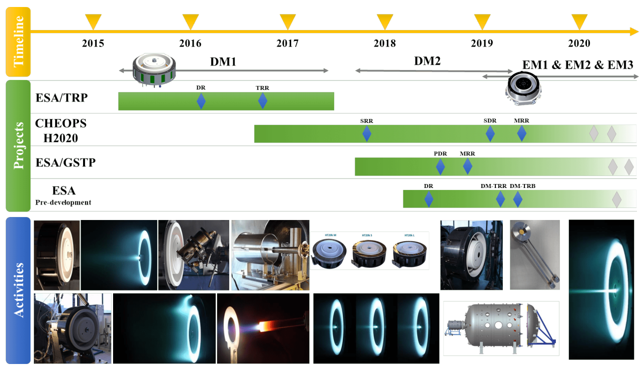

Figure 1: HT20K development history, including main projects and milestones.

The first development model (so-called "DM1") was conceived for a preliminary understanding of both performance and operation in this class of power. After the design and manufacturing phases, the thruster was tested in two consecutive experimental campaigns, with a centrally mounted high-current cathode, the "HC60" (see Figure 2). During the first campaign, the DM1 reached stable operative conditions over a range of power levels ranging from 10 kW up to 20 kW and discharge voltages from 300 V to 1000 V. Table 1 summarizes the range of performance achieved [21]. The thruster was then continuously fired for a total of 30 hours to evaluate its thermal behaviour. Unlike the first experimental campaign, the second characterization focused on low-voltage operations with relative positions of the electrodes. A comparison with the previous experimental results allowed to investigate the behaviour of the thruster under different configurations and operative conditions. A short 150-hours endurance test with xenon followed the two characterization campaigns. The main outcomes of this latter test was the assessment of the performance under wear conditions [42].

The experience gained on the HT20k DM1 and the SITAEL's 5 kW-class HT5k [43, 45] led to the development of a second model, the DM2, for which the magnetic shielding configuration was introduced. This model features a flexible magnetic circuit for the assessment of different channel geometries which was one of the main objective of the DM2 characterization campaign. Therefore,

Table 1: Delta-v budgets for the selected mission scenarios.

Parameters	**Values]**
Discharge Power [kW]	10-20
Discharge Voltage [V]	300-1000
Thrust [mN]	300-1100
Specific Impulse [s]	2000-3000
Discharge Power [%]	<68

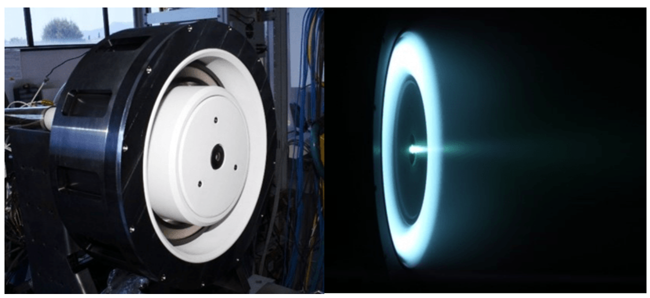

Figure 2: HT-20K Development Model 2 (DM2).

the DM2 was designed with three different configurations having an incremental dimension of the discharge channel width. Minor modification on the magnetic circuit and poles allows to maintain the same magnetic field topology. The data recorded during the characterization campaigns of the three configurations were used for improving the existing Hall thruster scaling models.

The valuable heritage gathered with the DM1 and DM2 led to the design of an engineering model (EM) of the shielded HT20k during the ESA Pre-development programme. The assembly phase and the first environmental tests will be performed before the end of 2019.

The EM design implements several technological improvements developed as a part of two parallel project. First, the ESA/GSTP project focused on operation at high-voltage and high-specific impulse. In this context, a number of tests and analyses were performed in order to investigate technological solution to a set of identified criticalities concerning the design of thruster itself. Second, the H2020's Consortium for Hall Effect Orbital Propulsion System (CHEOPS) programme focuses on the adoption of high-power HT for exploration and space transportation scenarios. In this programme, the technical feasibility of a complete high-power HT system is investigated, including the adoption of different propulsion subsystem architectures. Both these project allowed the tailoring of the EM design with innovative solutions for further improve both performance and reliability of the thruster.

The EM thruster unit (TU) will be tested at the beginning of 2020 in order to verified the compliance with the requirements defined in the on-going programmes. In several following tests, the TU-EM will be tested for more than 3000 hours with both xenon and krypton. A detailed description of the on-going activities could be found in Ref. [46] and Ref. [47].

3. Mission and System Drivers

A reusable electric space tug was introduced in according with the current trend of increasing mission sustainability and affordability through a reduction of overall mission costs. Conceived as an alternative to the more classical chemical-based cargo spacecraft [48], the space tug is able to perform end-to-end transfer of unmanned payload between two operative orbits. More details on this typology of platform can be found in Ref. [49]. These capabilities can be exploited to support the future human outpost in Near Earth Orbits (NEO), lunar and Mars environment, in accordance with the near/medium term objectives of space exploration [1, 3, 50]. The main criteria, introduced for the scenario selection process, consider the possibility to extend the cargo transfer capabilities through the exploitation of a space tug in different environments.

As a result, four transfer scenarios have been derived:

1. TRANS n.1: transfer from Low Earth Orbit (LEO) up to Geostationary orbit (GEO);

2. TRANS n.2: transfer from Near Rectilinear Halo Orbit (NRHO) down to Low Lunar Orbit (LLO);
3. TRANS n.3: transfer from High Mars Orbit (HMO) down to Low Mars Orbit (LMO);
4. TRANS n.4: transfer from Geostationary Transfer Orbit (GTO) up to NRHO.

The scenarios n.1 and n.4 have been introduced in order to provide supplies and refurbishment of an envisaged infrastructure placed in transfer arrival orbit, GEO and NRHO, starting from LEO and GTO, respectively. Considering the steady increasing of both institutional and commercial initiatives in GEO, scenario n.1 considers an orbital fuel depot in order to provide refuelling capabilities in GEO. According to a NASA analysis regarding on-orbit service needs [51], this depot could be exploited by visiting spacecraft to be refuelled before transfer injection manoeuvre. Instead, in scenario n.4, the space infrastructure envisaged in NRHO is the Lunar Orbital Platform - Gateway (LOP-G). This multi-modular deep-space station includes a Power and Propulsion Element (PPE) to provide power and propulsion capability, a small habitat to host the crew, a logistic module for supplies and trash storage, airlocks for extra-vehicular activities (EVA) and also docking ports for the visiting spacecraft. The LOP-G capabilities could be further extended in the future in order to support the human exploration of the lunar surface [52, 53].

In scenario n.2, the space tug performs the transfer of a cargo module from the NRHO down to the LLO, supporting surface activities delivering cargo and logistic materials. With the same objective of supporting surface exploration, scenario n.3 considers the transfer of a cargo module in Mars environment, between HMO and LMO. In the Mars scenario, the envisaged orbital infrastructure is based on a multi-modular space station such as already planned for Cislunar exploration. Since 2010, Lockheed Martin have developed a concept of an orbital Mars space station with its own transfer capabilities. The so-called "Mars Base Camp"(MBC) concept was designed on strong foundation of to-day's technologies [54], considering also proposed technological advancements identified by NASA in order to reach Mars [55]. In this work, the MBC concept is taken as reference for the definition of mission requirements and constrains in the Mars environment.

In these two last scenarios, a generic cargo module has been considered as payload to be transfer in proximity of Moon and Mars, respectively. This assumption was necessary to generalized the analysis and properly compared the transferred masses with the other scenarios. However, the tug payload should be intended as an unmanned logistic lander able to perform the required manoeuvres to safely land the payload.

Taking into account the common functionality of the spacecraft introduced in the four scenario here described, they have been analysed in parallel. In Section 3.1, a general description of the spacecraft subsystem mainly affected by the adoption of electric propulsion technology is given.

As specified in Section 3.2, the operational commonalities of the four scenarios have been highlighted in terms of: (i) mission phases, (ii) propulsion technology employed in different phases, (iii) refuelling strategies, and (iv) cargo modules transferred. Then, each scenario has been characterised considering distinguish aspect of the tug operations, such as: (i) reference orbits, (ii) maximum transfer time and (iii) traffic plan. These latter operational peculiarities have a strongly influence on the design of the spacecraft.

3.1. Functional Analysis Outcomes

From a system point of view, the adoption of high-power Hall Thrusters implies high power demand that the Electric Power Subsystem (EPS) shall be able to provide, also during eclipses periods. On the other hand, the significant power request also implies high heat fluxes to be dissipated by the Thermal Control Subsystem (TCS), which in turn represents a crucial subsystem to due to the demanding spacecraft thermal requirements. Another subsystem deeply affected by the adoption of electric propulsion technology is the Attitude and Orbit Control Subsystem (AOCS). Indeed, due to the continuous thrusting profile, this subsystem has to provide proper attitude and trajectory control capabilities during the entire mission despite the presence of external and internal disturbance sources. Moreover, the electric space tug shall rely on additional subsystems such as: Telemetry, Tracking and Command subsystem (TTC) , to provide communication, telemetry and tracking capability, and Command and Data Handling subsystem (CDH), to provide spacecraft command capabilities. Last, to complete this overview on the spacecraft subsystems, it is important to mention the Structure and Mechanism (STRUCT) subsystem, which main functionalities are: (i) to provide structural integrity; (ii) to sustain the characteristic loads during each mission phase; (iii) to provide sustainment for the internal elements; and (iv) to provide structural interfaces with the other elements involved in the mission, e.g. launch vehicle and cargo module.

3.2. Concept of Operations Outcomes

From an operational point of view, the identified scenarios have a different impact on the design of the platform. One of the main operational similarities among them allows to generalize the mission phases with respect to the presence of the envisaged space infrastructure (e.g. a space station) in either (a) departure or (b) arrival orbit.

In the first case (case a), the tug undocks from the station with the cargo module and, after the necessary departure manoeuvres and GO-command reception, the tug starts the transfer manoeuvres towards the target orbit. Once the transfer phase is completed, the space tug has to wait the release command to initiate the rendezvous manoeuvre that will bring the spacecraft to reach the target orbit where the cargo shall be released. After that, the tug returns to the initial orbit and docks with the space infrastructure, waiting for the next transfer mission. These general phases are characteristic of the scenarios TRANS n.2 and TRANS n.3, where a space infrastructure is present on the initial departure orbit. TRANS n.1 and TRANS n.4 consider a space infrastructure located at the arrival orbit (case b). In these scenarios, the space tug waits the arrival of the cargo module in its release orbit where it is injected by a launch vehicle.

Then, after the assessment of the cargo current attitude, position and operational status, the tug performs a rendezvous manoeuvre to approach the cargo module and docks with it, before beginning the electric orbit raising (EOR) manoeuvre up to the target orbit. Last, the spacecraft performs a last rendezvous and docking manoeuvre to reach the space infrastructure located in the final orbit, where the cargo module is independently managed by the station crew. Meanwhile, the tug undocks from the space infrastructure in order to return to the initial orbit.

Unlike EOR phases where electric propulsion is exploited, for rendezvous and docking chemical thrusters are used, mainly to speed up possible collision avoidance manoeuvres as detailed in [56].Furthermore, it is adopted in order to avoid surface degradations of both chaser and target vehicles, which could rise due to electric thruster plume impingement during close proximity operations. This assumption is further sustained by the regulation for proximity and docking operations for crewed spacecraft [56]. Moreover, the mono-propellant thrusters are also used for reaction wheels desaturation.

Moreover, it is important to point out that, between two consecutive transfers, logistic operations, among which on-orbit refuelling operations, may take place. Specifically, in order to guarantee the spacecraft reusability, a specific refuelling strategy has been envisioned, defined in terms of location, fuel demand, and refuelling system. Indeed, refuelling operations take place on the initial orbit but two different possibilities have been considered, depending if the tug is either docked to a space infrastructure (scenarios TRANS n.2 and TRANS n.3) or not (scenarios TRANS n.1 and TRANS n.4). In the first cases, the space infrastructure provides the capability to store the propellant and refuel the space tug. Conversely, in the second cases, a dedicated refuelling system, i.e. the so-called Orbital Refuelling System (ORS) is adopted. The ORS, once injected in the proper orbit by a launch vehicle, has its own autonomous attitude control capabilities, necessary to maintain the right attitude during proximity operation that brings the space tug to rendezvous and dock the ORS. For what concern the cargo module, its design is on the Multi-Purpose Logistic Module

(MPLM), previously exploited within the Shuttle program. On the other hand, each scenario has a peculiar resupply demand. In particular, for the scenarios TRANS n.1, TRANS n.2 and TRANS n.3, four different sub-cases have been selected, each one characterized by a different payload mass, from 5000 kg up to 20000 kg. This range was derived in order to intercept the wet mass variation of the current cargo modules [57] up to the higher mass of both ISS [58] and MBC modules [54, 59].

For what concern the scenario TRANS n.4, the cargo mass has been estimated considering the replenishment demand required by the LOP-G and its crew, which can be estimated to about 12.37 kg/person/day as presented in [52]. According to the current plans, the future Cislunar station shall host four crew members for at most 30 days every year. Nevertheless, thanks to its habitable volume, the space community foresees that duration and frequency of crew missions on-board the LOP-G would increase up to 180 days. Hence, in this paper, four different sub-cases have been considered, each one characterized by a different crew permanence, ranging from 1 month up to 6 months, as later described. As a consequence, the estimated cargo masses for the four different sub-cases are reported below in Table 2.

Table 2: Estimated cargo mass for TRANS n.4.

Crew visit period [days]	**Estimated cargo mass [kg] (*)**
30	2708.98
60	5417.97
90	8126.95
180	16253.90

(*) It considers also the mass of the empty module [52]. An additional mass safety margin of 20% is then considered as regulated in [60] for pre-phase A studies.

In the follows, each scenario will be thoroughly described in terms of reference orbits, traffic plan, maximum transfer duration Δt_{max}, and maximum interval among two consecutive missions Δt_{cons} whereas Table 3 summarizes the main inputs for the cargo mass and traffic plan that have been set for each scenario. On the other hand, Table 4 provides the main orbital parameters of

Table 3: Design input parameters: cargo mass and traffic plan parameters.

	Cargo [t]	Δt_{cons} **[months]**	Δt_{max} **[months]**	**Tugs**
TRANS n.1	[5,10,15,20]	24	10.5	1
TRANS n.2	[5,10,15,20]	12	4.5	1
TRANS n.3	[5,10,15,20]	19	8	1
TRANS n.4	(Tab.2)	12	(*)	[1:3]

(*) Evaluated as a function of the fleet configuration (see[54] and [61]).

the reference orbits related to Earth, Moon and Mars environments in terms of: (i) periastrum and apoastrum altitude, h_{peri} and h_{apo}, respectively; (ii) orbit inclination i; and (iii) orbit eccentricity e.

Table 4: Orbital parameters for the selected reference orbits.

Parameter	**LEO**	**GTO**	**GEO**	**NRHO**	**LLO**	**HMO**	**LMO**
h_{peri} **[km]**	250	250	35786	2263	100	3746	150
h_{apo} **[km]**	250	35786	35786	75000	100	37149	150
i **[deg]**	28.5	6	0	90	90	0	0
e	0	0.73	0	0.92	0.0	0.82	0.0

3.2.1. Scenario TRANS n.1: from LEO to GEO

This scenario considers a transfer between LEO and GEO orbits, which features are provide in Table 4. According to the constraint set in [62], the corresponding traffic plan shall assume that to complete the transfer from LEO to GEO, the spacecraft shall take at most one year and, considering a waiting period of 1.5 month every transfer as in [52], each EOR phase shall last at most 10.5 months. Each cargo module can be transferred every 24 months according to the constraint set in [62], thus setting the maximum total transfer duration to 21 months, since the LEO waiting phase has been extended to three months. Figure 3 represents the corresponding Design Reference Mission (DRM).

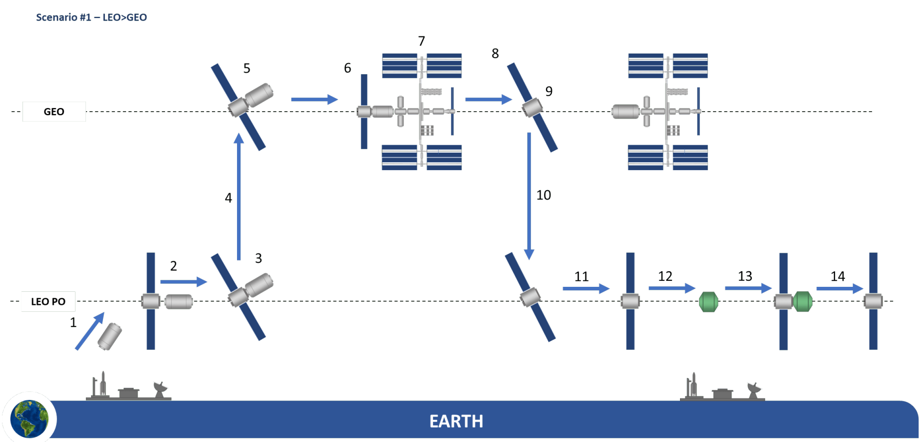

Figure 3: DRM for TRANS n.1. The ORS is represented in green.

3.2.2. *Scenario TRANS n.2: from NRHO to LLO*

The second scenario envisages the transfer of logistic payloads from the LOP-G to a 100 km frozen LLO once a year to support the operations on the lunar surface. In this case, still considering three months dedicated to logistic operations, the EOR phase shall last at most 4.5 months. The estimation of this value depends on the assumption of one cargo transfer per year, where the crew on-board the LOP-G can manage the tug operations autonomously from the ground control. The DRM of the scenario here described is shown in Figure 4.

3.2.3. *Scenario TRANS n.3: from HMO to LMO*

Figure 5 shows the DRM for the third scenario, in which a space tug provides support to Mars surface operations transferring cargo modules from the future Mars station to LMO. The MBC concept has been considered as reference scenario for the envisaged orbital infrastructure in terms of mission duration,

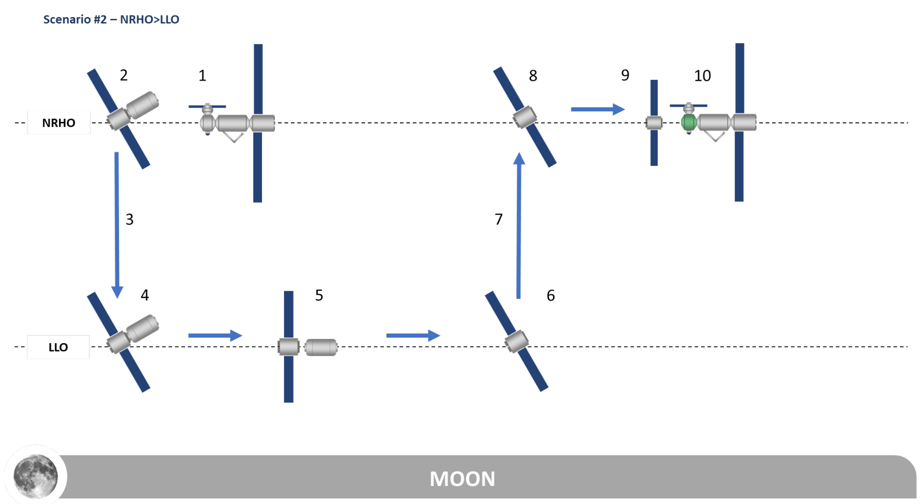

Figure 4: Design Reference Mission for TRANS n.2.

initial orbit and traffic plan [54]. Further details are provided in Table 3. The maximum transfer duration is set to eight months, considering one sortie in LMO every MBC's Mars visit, which is planned to stay in martian orbit for a maximum of one year[59].

3.2.4. Scenario TRANS n.4: from GTO to NRHO

This transportation scenario considers the adoption of the space tug in support to the LOP-G, located in a NRHO, providing life support items such as food, water and oxygen, as well as useful items for the crew activities on board the Gateway. The DRM related to this scenario is shown in Figure 6. In this scenario, the initial orbit is a GTO, which main orbital parameters are listed in Table 3. The possibility to exploit multiple tugs working in parallel has been envisioned, thus correspondingly varying the maximum transfer time from 4.5 month for the one fleet configuration up to 16.5 months for the three-tug configuration. Further details can be found in [63, 61].

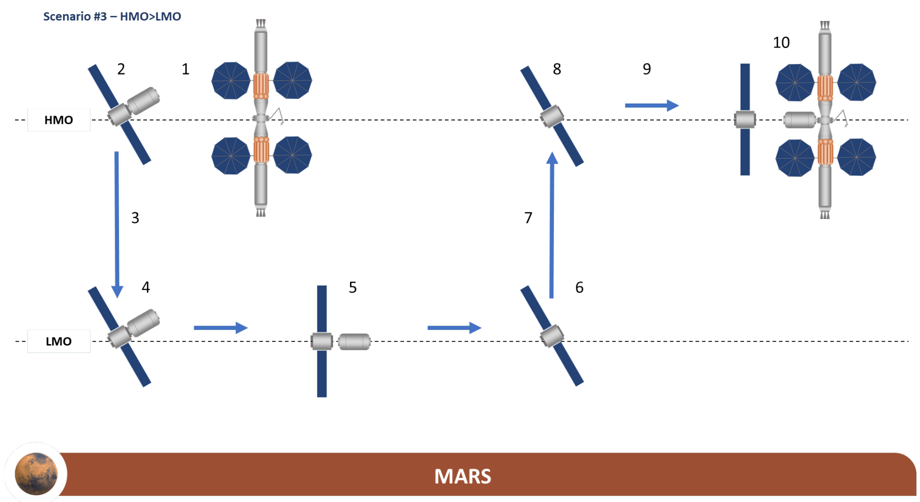

Figure 5: Design Reference Mission for Scenario n.3.

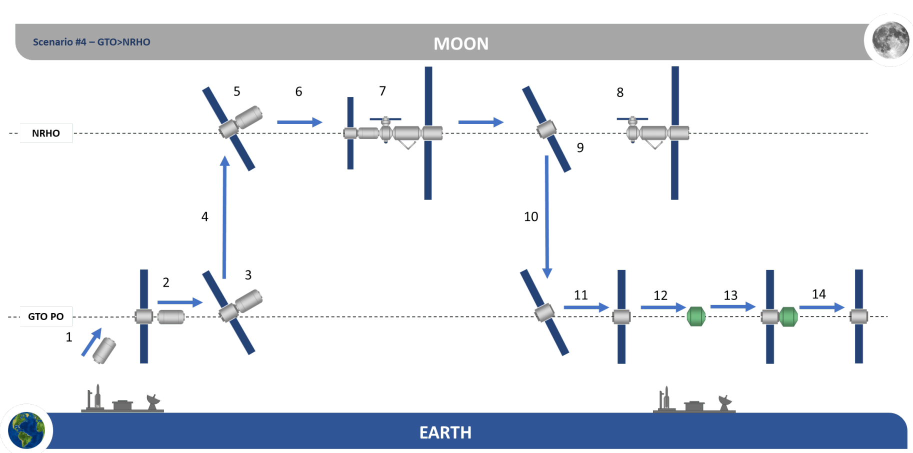

Figure 6: Design Reference Mission for TRANS n.4.

4. Design results

4.1. MISS Design Tool

The so-called Mission and Space Systems (MISS) design tool, a multi-input/multi-output software suite developed in a MATLAB environment, has been exploited to preliminary assess the design and the main budgets of high-power solar electric space tugs equipped with the HT20k presented in Section 2. As described in [52], MISS has been conceived to be flexible and easily reconfigurable with respect to different mission scenarios to analyse which propulsive core is based on high-power solar electric propulsion. The MISS architecture is mainly organized in three areas, as shown in Figure 7.

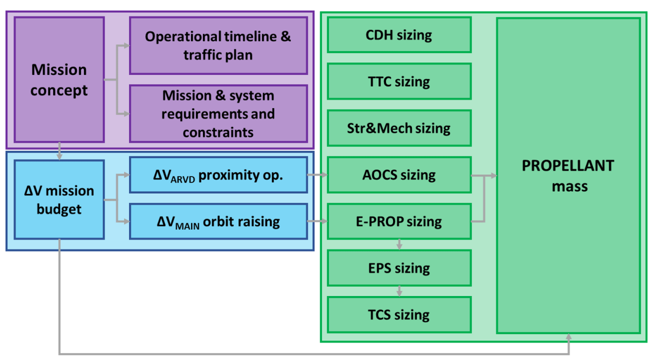

Figure 7: MISS Design Tool.

The first one is the mission scenario initialization (purple blocks), which involves three main tasks. Inputs are provided by the mission analysis: (i) initial and target orbits features; (ii) implementation of the traffic plan features in terms of loading/unloading cargo properties, e.g. type of cargo to be transferred, operational timeline, such as maximum transfer duration, time between flights and number of vehicles involved in the mission, in case a fleet of tugs is involved, and performance characteristics, as resupply mass to be delivered/brought back, and cargo module mass and volume; and (iii) mission and system requirements and constraints. Then, the second task consists in the definition of the delta-v budgets (light-blue blocks) for both EOR and Automated Rendezvous and

Docking (ARVD) phases, in which HT20k and AOCS actuators are exploited, respectively. Last, the core of the design tool revolves around the preliminary sizing of the platform subsystems (green blocks), aiming to the definition of the main system budgets. With respect to chemical-propelled platforms, the mass and power distribution among the platform subsystems is substantially affected by the adoption of high-power HTs. For the design of both e-PROP and EPS, a bottom-up approach has been exploited. For the other subsystems the mass budget is obtained exploiting pre-defined mass breakdown. Further details can be found in [61].

The spacecraft sizing is completed preliminary estimating the propellant consumption, through the Tsiolkovsky equation:

$$m_p = m_f \left(e^{\Delta V / I_{sp} g} - 1 \right) \tag{1}$$

where: $\mathrm{m_f}$ is the final mass, $\Delta \mathrm{V}$ is the variation of the orbital velocity , $\mathrm{I_{sp}}$ is the specific impulse and “g” is the gravitational acceleration. The transfer time is instead evaluated exploiting a 5th-order polynomial function in the thrust-over-mass ratio.

4.2. Sizing results

As anticipated in the previous Section, the four transportation mission concepts are characterized in terms of the cargo mass to transfer, obtaining a total of 16 mission scenarios.

Each tug is mainly characterized by its e-PROP, which architecture drives the corresponding design and related mass, power and transfer duration budgets.

The e-PROP configuration can be first characterized in terms of number of operative HT20k that can be contemporary switch on providing the thrust, which number can vary from 1 up to 6. Each thruster is further characterized by peculiar performance, corresponding to one of the 103 operative points over the HT20k reference performance map. Last, the same operative point can be further characterized by one of the five different operational time conceived, varying from 10000 h up to 30000 h. Hence, for each scenario, 3090 different spacecraft design can be obtained exploiting MISS.

Among them, not all the solutions results compliant with the mission and system requirements defined in terms of: (i) maximum transfer duration, defined by the corresponding traffic plan and operational timeline; and (ii) maximum number of HT20k in the e-PROP cluster, including not only the operative thrusters but also the stand-by thrusters, which number is defined as a function of the ratio among the total mission duration and the HT20k operational lifetime, and the redundant HTs.

Thus, the 49440 spacecraft design solutions have been filtered with respect to the compliance with the requirements and the results have shown that no feasible solutions exist for either the TRANS n.1 and TRANS n.2 concepts, as well as for the 180 days LOP-G replenishment scenario. Considering the selection criteria previously introduced, the required transfer time resulted higher than the maximum transfer time imposed for all the unfeasible scenarios. In order to obtained feasible solutions, for the same spacecraft architectures, a longer transfer should be assumed. On the other hand, several spacecraft design configurations for TRANS n.3 and TRANS n.4 satisfy the requirements and the main outcomes are reported hereafter, starting from the definition of the related delta-v budget, summarized in Table 5.

Table 5: Delta-v budgets for the selected mission scenarios.

Scenario	Delta V [km/s]
TRANS n.3	1.1339
TRANS n.4	4.3924

In the following, first the selected spacecraft design results are described in terms of transfer duration, i.e. the time required to the spacecraft to transfer the specific cargo from the cargo injection orbit to the target one, as a function of three different parameters: (i) total thrust available, given by the product between the number of operative HT20k and the specific thrust given by the corresponding operational point; (ii) the total wet mass of the spacecraft, including also the cargo mass; and (iii) the platform total power demand. Analysing Figures 8-14, first it is possible to highlight some common behaviours shared among all the scenarios as described hereafter.

1. The transfer duration trend shows an almost hyperbolic behaviour with respect to all three parameters, highlighting the relevant interdependence among them.
2. At the same thrust, total wet mass and power demand, the transfer duration decreases if the HT20k lifetime increases.
3. To reduce the transfer duration, the thrust available has to increase faster than the platform wet mass, since the polynomial function that links these three parameters is strictly decreasing.
4. If the power demand increases, the transfer duration can decrease if, at the same time, the corresponding thrust-over-mass increases as well.

Indeed, at the same power level, multiple solutions can correspond to different mission durations.

Going into the details for the TRANS n.3 scenarios, Figure 8, Figure 9, Figure 10 and Figure 11 provide the preliminary results for the transportation scenario among HMO and LMO transferring payloads from 5 up to 20 tons. First, the families of curves t-thrust highlights the asymptotic behaviour for thrust higher than 8 N. In particular, for the 5 tons subcase the horizontal asymptote is close to 50 days whereas for the other three subcases is close to 100 days. Moreover, vertical asymptotes can be observed in both Figure 8 and Figure 9, representing the minimum thrust, total wet mass and total power demand which corresponds to the maximum transfer duration. In particular, comparing these two scenarios, it is possible to notice that for thrust higher than 4 N, the significant increase in the thruster performance does not correspond to a relevant improvement from the transfer duration point of view, i.e. about one months, at the expense of much higher power demand, above 80 kW, and

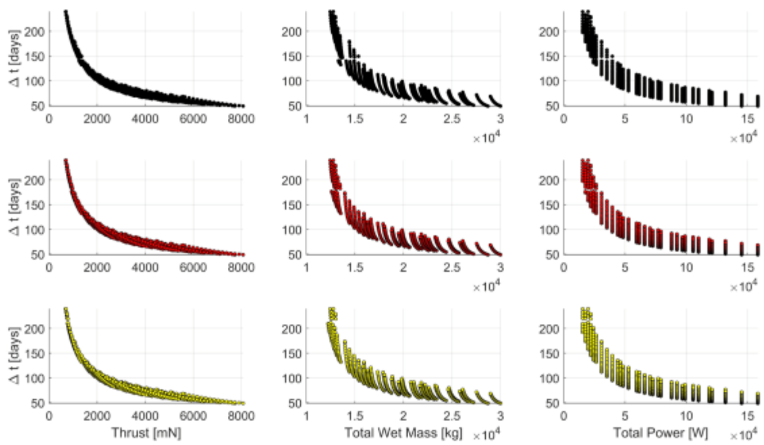

Figure 8: TRANS n.3 5 t: transfer duration wrt total thrust available, total wet mass, and total power demand for 3 lifetime levels, i.e. 20000h (black circle), 25000h (red circles) and 30000 h (yellow circles).

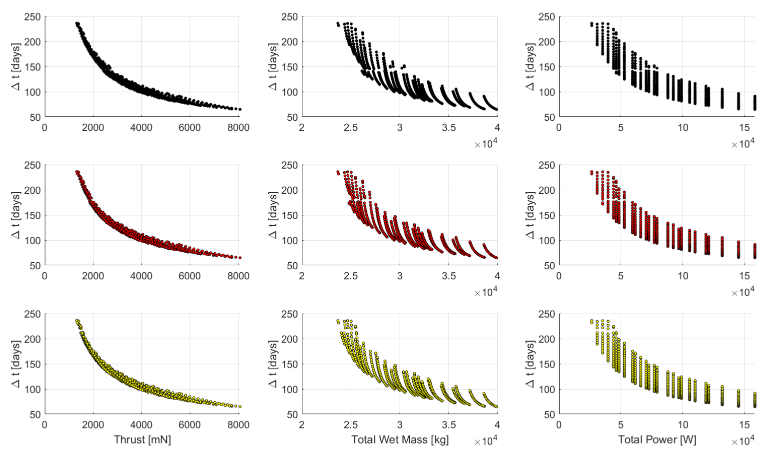

Figure 9: TRANS n.3 10 t: transfer duration wrt total thrust available, total wet mass, and total power demand for 3 lifetime levels, i.e. 20000h (black circle), 25000h (red circles) and 30000 h (yellow circles).

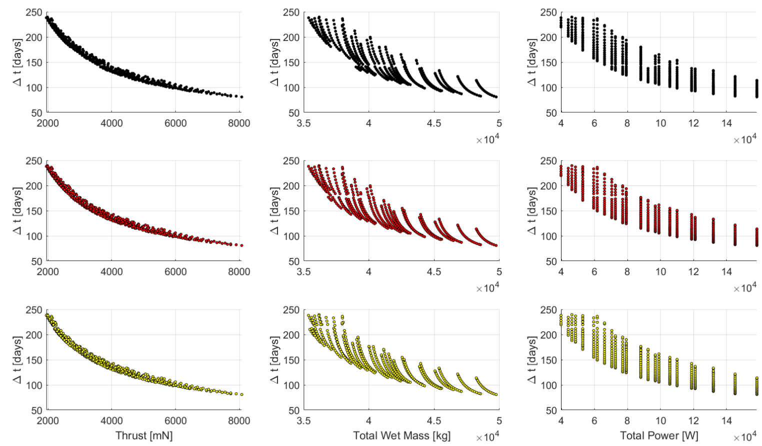

Figure 10: TRANS n.3 15 t: transfer duration wrt total thrust available, total wet mass, and total power demand for 3 lifetime levels, i.e. 20000h (black circle), 25000h (red circles) and 30000 h (yellow circles).

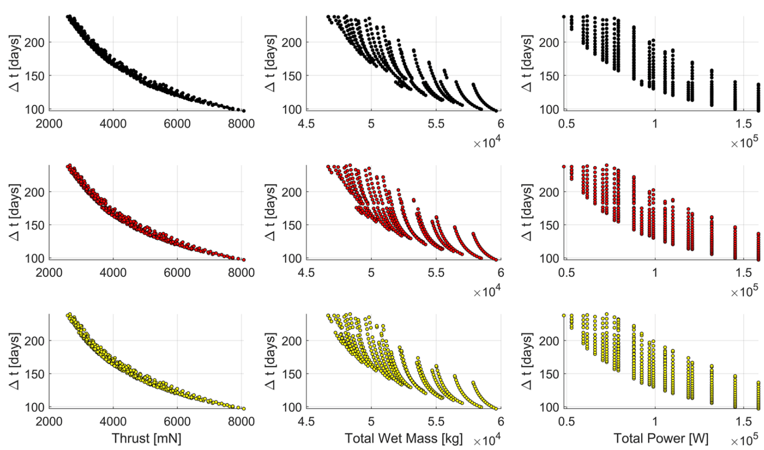

Figure 11: TRANS n.3 20 t: transfer duration wrt total thrust available, total wet mass, and total power demand for 3 lifetime levels, i.e. 20000h (black circle), 25000h (red circles) and 30000 h (yellow circles).

+50% for the mass budget.

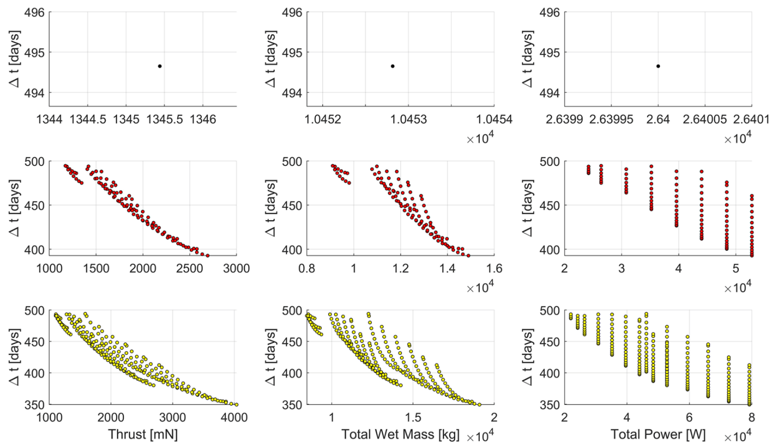

Figure 12: TRANS n.4 30 days: transfer duration wrt total thrust available, total wet mass, and total power demand for 3 lifetime levels, i.e. 20000h (black circle), 25000h (red circles) and 30000 h (yellow circles).

On the other hand, Figure 12, Figure 13 and Figure 14 provide the preliminary mass, power and delta-t budgets related to the space tugs supporting the replenishment of the LOP-G for the three different scenarios, defined according to the crew mission permanence on board the Gateway: (i) 30 days; (ii) 60 days; and (iii) 90 days. First, it can be observed that the number of feasible solutions are significantly less than the previous ones. Moreover, only the 30 days scenario presents spacecraft configuration complaint with the requirement for 20000 h of HT20k lifetime, corresponding to 1.34 N of thrust, a total wet mass of about 10 tons for a power demand of 26 kW. On the other hand, the 90 days scenario has feasible solutions only for a lifetime of 30000 h, whereas the minimum lifetime for the 60 days scenario is equal to 25000 h. As anticipated before, the asymptotic behaviour is less evident. Moreover, the minimum transfer duration is close to 400 days for all the scenarios even if the effect of lifetime on these parameters is still quite clear, mainly for the 30 days scenario. From

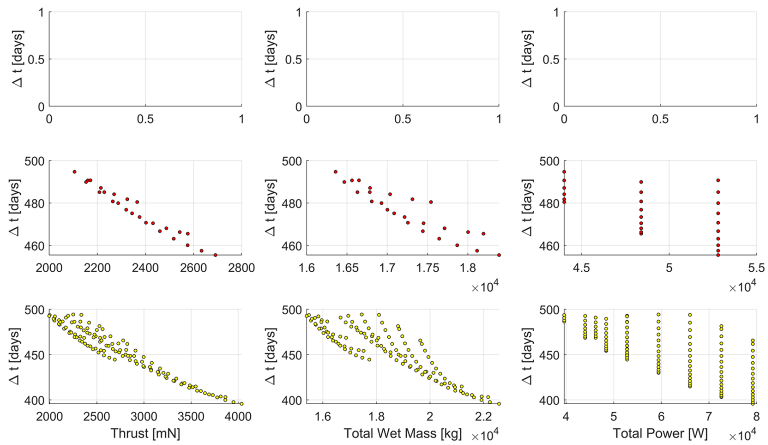

Figure 13: TRANS n.4 60 days: transfer duration wrt total thrust available, total wet mass, and total power demand for 3 lifetime levels, i.e. 20000h (black circle), 25000h (red circles) and 30000 h (yellow circles).

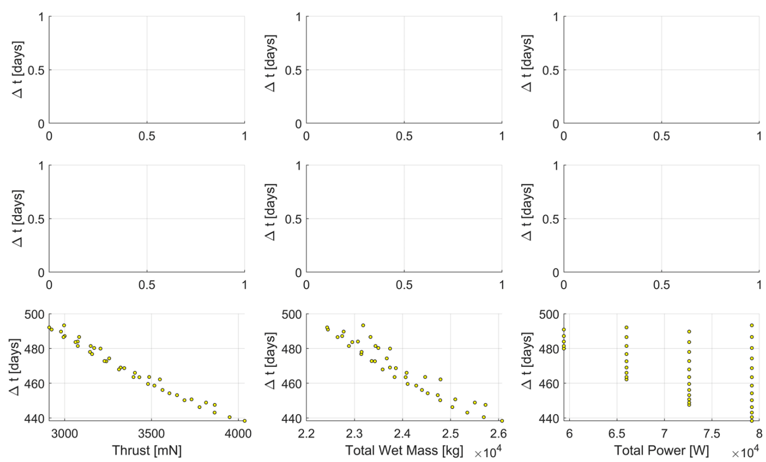

Figure 14: TRANS n.4 90 days: transfer duration wrt total thrust available, total wet mass, and total power demand for 3 lifetime levels, i.e. 20000h (black circle), 25000h (red circles) and 30000 h (yellow circles).

the power demand point of view, the differences among the three scenarios are significant and its range decreases while the cargo mass increases. To conclude this analysis, the selected scenarios have been compared from the HT20k performance point-of-view. Thus, the corresponding performance maps have been overlapped, grouped by thruster lifetime. In particular, Figure 15 and Figure 16 represents the overlapped maps for TRANS n.3 for HT20k lifetime of 20000 h and 25000 h, respectively. It is possible to notice that, expect for the two operational points characterized by the lowest thrust and input power in Figure 15, all the other operative points correspond to feasible spacecraft design configuration. For the 25000 h, the whole set of points provides complaint performance as shown in Figure 16. Thus, the 30000 h scenarios provide the same results, i.e. all the points correspond to feasible platforms.

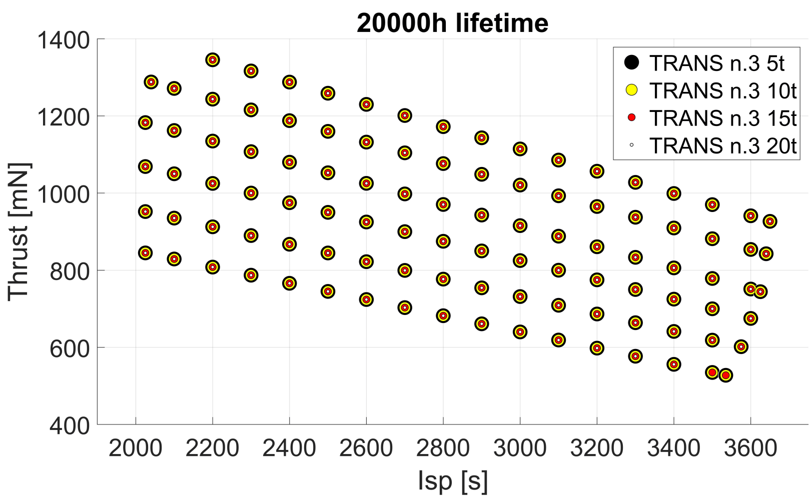

Figure 15: Overlapped performance maps for TRANS n.3 and HT20k 20000 h lifetime.

On the other hand, for the LOP-G replenishment scenarios, only one operative points results sufficient to satisfy the mission and system constraints, considering 20000 h of lifetime and corresponding to 1.345 N and 220 s of specific impulse. On the other hand, from Fig.17 it can be observed that all the operative points result complaint for the 30 days scenarios whereas only those

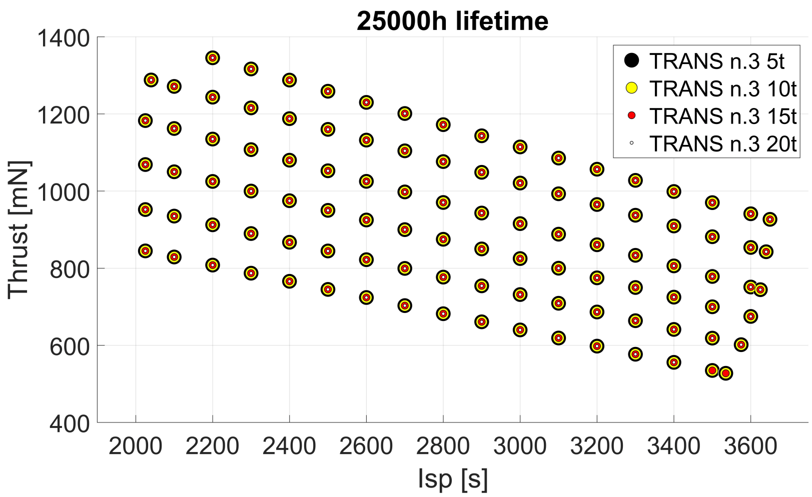

Figure 16: Overlapped performance maps for TRANS n.3 and HT20k 25000 h lifetime.

related to an input power greater than or equal to 20 kW and thrust higher than 1 N correspond to feasible spacecraft design for the 60 days scenario.

Overlapping all three performance maps for a 30000 h of lifetime (Fig.18), it is possible to notice that the area of the map where the same operative points are shared among all three scenarios is limited to input power from 18 kW up to 24 kW, for thrust higher than 1 N and for a significant large range of input voltage, up to 800 V for a maximum specific impulse of 3600 s.

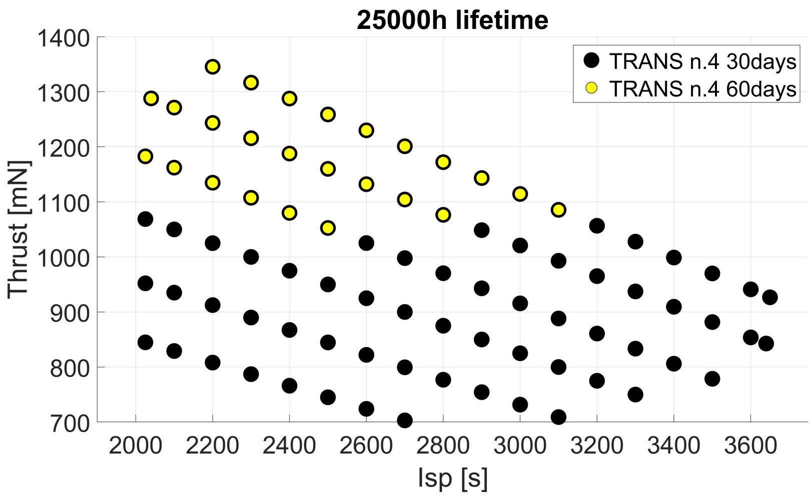

Figure 17: Overlapped performance maps for TRANS n.4 and HT20k 25000 h lifetime.

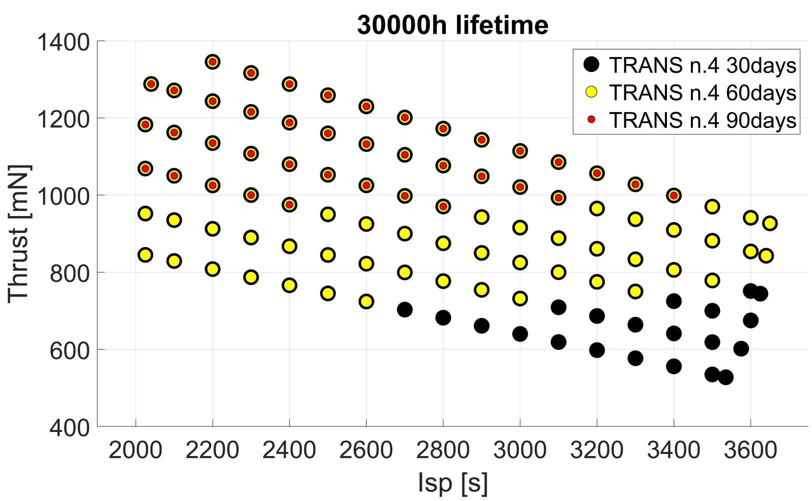

Figure 18: Overlapped performance maps for TRANS n.4 and HT20k 30000 h lifetime.

5. Conclusions

High-power electric propulsion could represent a valid solution for a wide range of future mission scenarios. Among all the possibilities identified by the space community, including space agencies and private companies, the adoption of this technology for space transportation could enhance more sustainable and affordable space missions. In this paper, four different scenarios have been identified that could benefit from exploiting high-power electric propulsion for transferring cargo modules among different operative orbits. The capability to perform Electric Orbit Raising (EOR) manoeuvres is provided by the 20kW-class Hall Thruster HT20k developed by SITAEL. This thruster has the peculiarity to implement the magnetic shielding approach, which allows to extend the thruster operative lifetime. In terms of transportation system, an electric space tug is proposed as valid alternative to the more classical chemical-propelled spacecraft. The space tug has been envisaged to operate in three different environments, where corresponding scenarios have been derived: (TRANS n.1) transfer of cargo payload between Low Earth Orbit (LEO) and Geostationary orbit (GEO) in support to an envisaged infrastructure in GEO; (TRANS n.2) transfer of cargo payload between Near Rectilinear Halo Orbit (NRHO) and Low Lunar Orbit (LLO) in support to the human activities on lunar surface; (TRANS n.3) transfer of cargo payload between High Mars Orbit (HMO) and Low Mars Orbit (LMO) in support to human operation on the Mars soil; (TRANS n.4) transfer of cargo payload between Geostationary Transfer Orbit (GTO) and NRHO in support to the future cislunar space station.

These four mission scenarios has been analysed, highlighting their commonalities from both functional and operational viewpoints, the latter defined in terms of operative orbits, traffic plan, maximum transfer time, and fleet configuration. Then, the design phase for each scenario focused on the identification of HT20k operative points that correspond to spacecraft design solutions compliant with peculiar mission and operational requirements. On the other hand, the final analysis targeted the identification of the optimal HT20k operational performance range that result common to all the selected scenarios, thus providing useful hints for defining the optimal operating point to be targeted in the next HT20k development phase. However, the design phase highlighted that feasible solutions could be obtained only for the scenarios involving cargo transfer among High and Low Mars Orbits (TRANS n.3), on one side, and among Geostationary Transfer Orbit and the Lunar Orbital Platform-Gateway (TRANS n.4), on the other side. The results also show that the target operational area over the HT20k performance map shall envisions operative points characterized by at least 30000 h of operative lifetime, input power from 18 kW up to 24 kW, specific impulse between 2000 and 3400 s, a thrust level higher than 1 N and input voltage up to 800 V.

Future works will focus on investigating new transportation scenarios and design alternatives while providing useful hints for identifying the optimal range of HT-20k operational parameters.

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