A DEEP SPACE HABITAT FOR EXPLORATION

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The paper describes a habitable module to be used for long duration space exploration missions. The Deep Space Habitat (DSH) is conceived as a cis-lunar orbital infrastructure and a space-ship for deep space exploration missions. It will represent the first outpost beyond LEO, being deployed at the first Earth-Moon Lagrangian point (EML1), and is envisaged as a human-tended infrastructure with crew visits periodically foreseen. The DSH has to be firstly used as a platform for research and to demonstrate a set of critical technologies and associated operations required to perform a deep space human exploration mission (e.g. to a NEO). In this regard, placing the module at EML1 allows reproducing conditions that would be encountered during a travel to an asteroid (or to Mars), thus guaranteeing the possibility to test specific technologies in a more significant environment with respect to what possible on ground or in LEO (e.g. effects of radiations on human body outside the protection of the Van Allen belts and radiation protection system test). Besides being a technology test bed, the DSH will support lunar human exploration missions, providing a staging post and a safe haven for crew working on the Moon surface. The overall architecture of the DSH has derived from a set of system trade-off performed accordingly to the objectives to be accomplished: the most important features are described within the paper. The DSH deployed at EML1 can be seen as a first unit to be utilized as a precursor for a habitation module to be actually adopted for hosting the crew during a deep space mission (to a NEO or to Mars). Indeed, a second unit is envisaged, which exploits the experience gained through its precursor, having a common core with it and implementing technologies previously tested on it. Only minor changes shall be envisioned due to the peculiarities of the mission for which it is used. In particular, the description of the second unit presented in the paper refers to a specific reference mission to a NEO lasting one year. The first part of the paper focuses on the main performed trade-offs, as well as the obtained results, in terms of both system architecture and operations, highlighting the major differences between the two envisioned units. The second part is devoted to the critical and enabling technologies, with particular attention to advanced regenerative ECLSS, rapid prototyping and radiation protection system.

I. INTRODUCTION

The next step in human space exploration is to travel beyond Low Earth Orbit (LEO). This would carry important benefits to society, including: technological innovation, development of commercial industries and important national capabilities and contribution to our expertise in further exploration.

Human exploration can contribute appropriately to the expansion of scientific knowledge and it is in the interest of both science and human spaceflight that a credible and well-rationalized strategy of coordination between them is developed.

In this regard, a deep space habitat (DSH) is necessary to enable future space exploration missions. The experience gained through the ISS could be exploited to develop a module able to support different human missions towards deep space targets. The module shall have some specific characteristics deriving from the peculiarities of the mission operations and of the environment it has to withstand that strongly influence the design of the pressurized habitat where the astronauts have to live for quite a long period.

According to the necessity of a habitation module to enable travels beyond LEO, TAS-I has carried out a preliminary analysis of a possible architecture for the deep space habitat.

The paper reports a description of the main characteristics of the deep space habitat, highlighting the rational process followed to define its architecture.

II. RATIONALE AND ASSUMPTIONS

The deep space habitat is conceived as a cis-lunar orbital infrastructure and a space-ship for deep space exploration missions. It would represent the first outpost beyond LEO, supporting the human presence beyond LEO for extended stays. It will represent a platform for scientific research and technology development for space exploration as well as a support for crew transportation architecture to Moon surface and further destinations, as for instance Near Earth Objects (NEO).

Furthermore it will give the opportunity to increase the science return from lunar robotic surface exploration. In particular, relating to this latter point and concerning remotely controlled surface robotics, the exploration activities were assumed to be concentrated on the near side of the Moon, most likely in proximity of the South Pole.

A Heavy Lift Launch system with LEO launch capability of 100 MT and a fairing diameter of 6m was considered as available.

The DSH is envisioned as a human-tended facility, and visits of crew of four astronauts are periodically foreseen (every 6 months), for a maximum permanence duration of 2 weeks. It is axially attached to a Propulsion Module (PM), not considered as part of the DSH system and whose features were not analysed, which is in charge of providing attitude and orbital control.

Additionally, the DSH is meant to demonstrate a set of critical technologies and associated operations required to perform a human exploration mission to a NEO. In particular, it is designed to enable a full NEO mission rehearsal in a relevant environment (i.e. outside Val Allen belt).

The considered NEO reference mission foresees a crew of 4 astronauts and has an overall duration of about 12 months, including about 10 days to be spent in the proximity of the NEO, where a certain number of EVAs are to be performed. In particular, along the entire mission 7 nominal EVAs are foreseen for the NEO operations, and 2 contingency EVAs are considered for external maintenance. The overall reference NEO mission spacecraft is composed of:

- Two transfer stages (TS) utilizing Nuclear Thermal Propulsion (NTP): one (called TS2) will provide the ΔV for inserting the S/C into the NEO Transfer Orbit (~3750 m/s), while the other (called TS1) is in charge of providing the ΔV for braking the S/C around the NEO (~4000 m/s) and the ΔV for the trans-Earth injection (~550 m/s)
- The long duration habitat for hosting the crew (DSH derived)
- A capsule for the Earth re-entry of the crew
- A service module for the NEO proximity operations

The spacecraft is envisioned to be assembled in orbit, where the different parts are brought by means of 2 Heavy Lift Launch Vehicles and a crew vehicle for transportation of the crew.

III. METHODOLOGY AND MAJOR TRADE-OFFs

III.I Requirements Definition

The requirements assessment process was carried out according to the main objectives identified for the module. It shall be envisaged as an infrastructure capable to support human missions beyond LEO for extended stays, to allow performing scientific research and technology development for Space Exploration and increasing science return from lunar robotic surface exploration, and to support crew transportation architecture to Moon surface and further destination (i.e. NEOs).

Some of the Mission and System Requirements, used to perform the concept selection and preliminary design of the module, can be summarized in the ones listed hereafter. The DSH shall provide:

- habitable volume for a crew of 4 astronauts for up to 12 months;
- controlled internal environment and adequate conditions for the crew activities;
- protection against external environment (a radiation shelter to protect 4 astronauts against SPE shall be envisaged);
- communications with ground, guaranteeing high data rate transmission;
- at least 3 docking ports, compatible with IDSS, to allow connections with visiting vehicles;
- autonomous operation capability, being monitored and controlled from ground while un-crewed (experiments' remote control and monitoring from ground);
- tele-operation capability of robotic systems deployed on the surface of the exploration target (Moon, NEO, …).
- interface with robotic sample return probe and sample analysis capability;
- crew EVA capability.

III.II Major Trade-offs

Several trade-offs were carried out in order to define the DSH architecture. The main trades identified at system level were about:

- deployment strategy,
- deployment location,
- system architecture,
- radiation shielding approach.

In addition to the just mentioned system trades, other trades were performed regarding:

- ECLSS closure level,
- logistics storage methodology,
- EVA capability.

In the following a brief description of the trade-offs is reported, highlighting the obtained results.

Deployment strategy

The first trade-off was performed in order to select the most suitable strategy of deployment to accomplish the mission objectives of the module.

The DSH is conceived as a testing platform for new technologies to be used in further exploration missions (e.g. to NEO, Mars), as well as to allow long duration human mission rehearsal. A stepwise approach is foreseen to demonstrate capabilities for supporting long duration missions in deep space environment and, in this respect, the system shall be upgradeable on-orbit for supporting increasing duration missions or hosting new technologies demonstrators.

Three different options were identified and analysed:

- one module to be partially re-used as NEO exploration vehicle, after having been upgraded on-orbit;
- one module to be fully re-used as NEO exploration vehicle;
- two different units: the first unit envisioned as a station (in EML1-2 or LLO) for the test of the technologies, and the second unit conceived for the NEO mission; in this case, a common core is foreseen to make the tests representative and reduce the delta development.

The three options were compared to each other in order to identify the major advantages and disadvantages of each one and finally the option envisaging two units was selected as the most convenient. As a matter of fact the first two options imply a longer lifetime and therefore more risks, and moreover a less optimized design (e.g. solar arrays sized for "wrong end of life"). Furthermore, supporting lunar exploration and testing critical technologies would require different capabilities with respect to those required for deep space missions. Finally, developing two units would allow having a permanent cis-lunar station, even during and after the NEO mission.

Deployment location

Three possible locations for the deployment of the DSH were traded: the Earth-Moon Lagrangian (EML) points 1 and 2 and a Low Lunar Orbit (LLO).

The LEO option was immediately discarded because of the DSH main objectives. Indeed, it is conceived to support human mission beyond LEO for extended stays, to be firstly used as a platform for research and to demonstrate a set of critical technologies and associated operations required to perform a deep space human exploration mission (e.g. to a NEO). In this regard, placing the module at one of the Lagrangian points or in LLO allows reproducing the conditions that would be actually encountered during a travel to an asteroid (or to Mars), thus guaranteeing the possibility to test specific technologies in a more significant environment with respect to what possible on ground or in LEO. For example, one of the major issues of human space missions is represented by the long exposure to space radiations; in this respect the DSH, being placed outside the protection of the Van Allen belts, would allow better analysing the effects of radiations on human body as well as test and validation of the radiation protection system to be adopted. In addition, the psychological effects of a long permanence far from Earth shall be analysed before moving further towards deep space targets.

The three identified options were compared to each other considering the following figures of merit:

- accessibility to and from Earth;
- telecommunications capability with Earth;
- lunar tele-operations capability (Robotics are assumed to be on the near side of the Moon, in the South Pole zone);
- station-keeping requirement;
- accessibility to and from the Moon surface;
- deep space accessibility (for the reference NEO mission the spacecraft assembly is assumed to be performed in LEO);
- sun availability;
- psychological effects: since the DSH shall allow also a Deep Space mission rehearsal, being further away and not seeing the Earth was considered better (being more challenging for the crew) than the opposite situation;
- space environment hazard;
- public outreach.

As result of the trade-off, EML1 resulted to be the best place where to deploy the DSH mainly because of its superior capability to support tele-operation of lunar surface robotics, of the almost constant sun availability (for power generation) and of the direct TLC visibility with the ground segment.

The DSH deployed in EML1 will offer the possibility to test and check new long term autonomous systems, e.g. regenerative ECLSS, which represents an important point in the design of long duration missions due to the strong constraints in terms of mass.

Moreover, in-situ diagnostic and maintenance capabilities could be improved in view of more challenging missions, where coming back to Earth is not a possible option in case of failure of any equipment.

Another crucial aspect for missions very distant from Earth is that any acute illnesses or injuries that might happen to the crewmembers have to be dealt with on board of the spacecraft. For this reason, tele-operated surgical robotic systems shall be adopted and the deep space module deployed in EML1 could allow the test of these technologies in order to identify the most significant criticalities and improve them before their adoption in a real deep space mission.

Besides being a test bed for new technologies, the deep space habitat deployed in EML1 is envisioned to support lunar human exploration missions, providing a staging post and a safe haven for crew working on the Moon surface, increasing the science return from lunar surface robotics, providing servicing of transportation system elements.

System architecture

Different architecture concepts were identified and traded to define the most suitable one according to the objectives. The module can be envisaged as a single element or as an assembly of more elements. In particular in case of single element it can be entirely rigid or entirely inflatable, while in case of assembly of more elements it can be composed of a combination of a rigid node and a rigid habitation module, or a combination of a rigid node and an inflatable habitation module. Among these alternatives, the option foreseeing a single inflatable element was easily discarded, since it does not match the requirements. As a matter of fact, one of the requirements for the DSH is that at least three docking ports shall be available in order to allow at least 3 simultaneous visiting vehicles and a single inflatable module cannot provide them.

Therefore, the traded options were:

- single rigid element,
- rigid node plus rigid habitat,
- rigid node plus inflatable habitat.

These configurations were compared with each other considering as figures of merit the development complexity, the volume over mass ratio, the flexibility and/or growth capability and the operational complexity, mainly linked to the internal outfitting.

As result of the trade-off, the configuration with a rigid node attached to an inflatable habitat was selected, since it provides the best optimization of the volume over mass ratio, which is very important especially in view of future longer missions. Moreover this configuration has quite a good flexibility allowing for later docking of additional modules, such as logistics storage modules, laboratories for scientific research or a module for tourism.

The module is envisaged as a modular assembly and reconfigurable in space, which was considered a preferable approach with respect to an integrated on ground configuration.

Radiation shielding approach

The long exposure to space radiations is one of the most critical issues to be taken into account for missions beyond LEO, outside the protective shield provided by the Van Allen belts. For this reason, a specific analysis was performed in order to identify the best approach to be adopted for protecting the crew against radiations.

First of all, a high level trade between an active and a passive methodology was carried out, considering as figures of merit the complexity of the system, the safety and reliability, the impact on other subsystems (e.g. the interference that an active system could imply with other subsystems) and the mass.

The passive approach turned out to be the most convenient. Furthermore, present TRL of active technologies is very low.

For the reference mission of one year to a NEO, the protection provided by structure and racks/equipment was preliminarily evaluated sufficient as protection against GCR to remain below the maximum acceptable dose. An equivalent area density of $15g/m^2$ of Aluminium is assumed, which corresponds to 20 cSv/year for GCR at solar maximum and 40cSv/y for GCR at solar minimum. The inflatable part is assumed to exhibit the same shielding capability as the rigid one. This means that the total dose is within the allowable limits (50cSv/y).

On the contrary, a dedicated shelter is mandatory as protection against SPE.

For more challenging missions (e.g. towards Mars), additional shielding shall be foreseen and/or the option to switch to an active solution shall be considered.

The second step for the radiation shielding analysis was the selection of the material to be used. Materials having high hydrogen content were considered because they are the most effective for high-energy charged particle shielding per-unit-mass.

Among those, the most interesting ones are liquid hydrogen, water and HDPE (High Density Polyethylene). Liquid hydrogen would be the best shielding solution but it is discarded since it is difficult to manage (very low temperature cryogenic liquid).

Hence, the trade-off was actually performed between water and HDPE. Due to the closure level of ECLSS envisaged for the module (as will be addressed in the following within the paper), the amount of water on board is minimal, thus additional quantity of water should be carried exclusively for this purpose.

Considering as figures of merit the mass, the system complexity and the versatility of the system, the polyethylene was chosen as shielding material, which implies a mass difference of about 300 kg for the same shielded volume and for providing the same protection against SPE.

It is worth to notice, that the possibility to exploit, as an additional shielding contribution, the water available on board (even if it is only about 170 litres) was analysed. In particular, two alternatives were examined: one foreseeing water stored in the rear and top/bottom walls of the crew quarters and one foreseeing water stored in the walls externally with respect to the racks. For both the configurations the gain in terms of radiations dose reduction resulted to be too low to justify such increase in the system complexity.

ECLSS closure level

As already addressed, the DSH shall be a testing platform for new advanced technologies in support to future exploration missions, e.g. to NEO. In this regard, due to the long duration of the mission to NEO, the possibility to have regenerative system must be considered. The different levels of closure of the

ECLSS that can be selected and that were traded are a completely open loop, ECLSS with water regeneration and ECLSS with air and water regeneration. The different options were compared with each other, considering as figures of merit for the trade-off:

- the equivalent mass, which includes the mass of the resources, the mass of spares required for ensuring 2 failures tolerance and an equivalent mass due to the impact on power and thermal control S/Ss,
- the maintenance: both operations to be performed and required hardware are considered,
- the applicability to deep space mission.

As the duration of the mission increases, the advantage of a closed loop system in terms of mass reduction becomes more and more significant. Finally, the selected solution is the one envisaging an air and water regeneration system.

Logistics storage methodology

The amount of initial resources to be stored on the DSH at launch was calculated for a period of 20 days, because one of the requirements for the DSH is to support the permanence of the astronauts for up to 20 days in case of contingency. Since the DSH is conceived as a crew-tended facility, a periodic resupply is foreseen when the crew visits the module (approximately every 6 months), while the resources for facing 20 days of contingency (as per requirements) shall be always hosted on board.

Afterwards, the overall mass required in LEO to deliver the DSH to EML1 (that means essentially the wet mass of the DSH plus the wet mass of the Transfer Stage) was computed in order to verify the compatibility with the assumed launcher and to understand if a dedicated logistics module is necessary.

For completeness, such evaluations were performed also considering the resources required for mission duration of 1 year (as per the reference NEO mission) and for the cases in which the DSH was to be deployed in EML2 or in LLO. Table 1 shows the details of the mass and volume evaluations for considered scenarios.

		Minimal Mission (20 days contingency)	Full NEO mission
Mission duration [days]		20	365
ERH	Resources/logistics [tons]	5	10
	Dry mass [tons]	20.5	21.5
Required volume [m^3]		55	82
		24 racks	36 racks
Mass in LEO [tons]	If ERH deployed in EML1	74	88
	If ERH deployed in EML2	69	82
	If ERH deployed in LLO	79	94

Table 1: Launchability VS Logistics

For the evaluation of the overall system mass in LEO, a mass of 6 tons of the propulsion module was assumed. It has to be noticed that, given the scope of the study, no dedicated analysis was performed on the propulsion module and the associated mission profile and that the purpose of this mass estimate was to preliminary verify the compatibility with the launcher and to exclude the necessity for a dedicated logistics module.

EVA capability

For what concerns the EVA capability of the system, the trade to be performed was whether to introduce an airlock or not. Depending on the mission, different EVAs are to be performed, e.g. for maintenance, for exploration, for managing external payloads.

In particular, for the reference mission to NEO of 1 year, 7 nominal EVA, for NEO proximity operations, plus 2 contingency EVA, for external maintenance, are envisaged.

Hence, a dedicated airlock is required for this mission. In addition, several other EVA support items are to be envisaged (e.g. Enhanced-Manned Manoeuvring units, EVA tools, …). In case the nominal EVAs are scrapped in favour of a different approach to proximity operations (e.g. dedicated proximity exploration vehicle), EVA through controlled depressurization could be a possible option (even though more risky).

Moreover for a long term EML1 station, the presence of an airlock is the only viable approach to perform EVAs.

IV. ARCHITECTURE CONCEPT

In this section the ERH overall architecture is presented, as obtained from all the trade-off described in the previous paragraphs.

Two units are foreseen: the first one is deployed in EML1 while the second one is in charge of accomplishing the mission to the NEO.

A common core characterizes the two units, and only minor modifications are envisaged for the second unit with respect to the first one due to the peculiarities of the missions they have to accomplish.

A schematic overview of the resulting architecture of the first unit is shown in Fig.1. It is composed of a Rigid Node attached to an Inflatable Module. The presence of the node with its 4 radial ports ensures the possibility to have 3 visiting vehicles simultaneously attached and to eventually expand the module. The implementation of the inflatable technology is foreseen since, in view of very long missions, the comfort of the crew becomes a more and more significant design parameter.

The rigid node is axially attached to a Propulsion Module (depicted in green in Fig.1), not considered as part of the DSH system, which is in charge of providing orbit/attitude control.

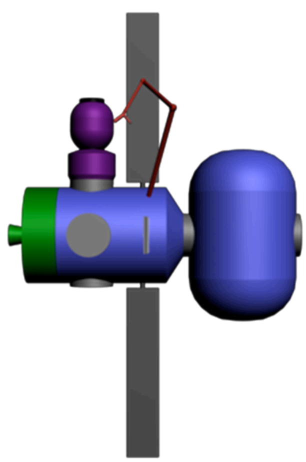

Fig. 1: Deep Space Habitat architecture: nominal configuration

One of the four radial ports of the node is used for attaching the airlock, which was introduced because different EVAs are to be performed (for external maintenance, for exploration, for managing external payloads). Moreover, additional EVA support items are envisaged, such as Enhanced-Manned Manoeuvring Units (E-MMU), EVA tools, etc. The airlock is composed of a rigid Equipment Lock and an Inflatable Crew Lock. E-MMUs and EVA tools are stored in in dedicated compartments on the external surface of the Equipment Lock.

For protecting the crew against radiation a passive shielding is envisioned. In particular the protection provided by the structure and equipment is sufficient for protecting against GCR, while a dedicated high density polyethylene shelter is envisaged for protecting the crew against SPE. These evaluations refer to a NEO reference mission lasting 1 year (the EML1 station shall allow a rehearsal of such a mission).

A robotic arm is introduced in the architecture to reconfigure the module from the launch configuration to the operational one (additional details are provided in the following within the paper) and to support external maintenance.

The habitat is sized to ensure an overall crew habitable volume of at least $80m^3$ (that means optimal $20m^3$/crew member) and an overall pressurized volume of ~$240m^3$. The main features of the pressurized elements can be synthesized as follows:

- the Inflatable Habitat, characterized by a rigid core and multi-layer wall, has a total pressurized volume of ~$155m^3$, with an external size of ~8m x 5m;
- the Rigid Node is sized to guarantee a pressurized volume of ~$84m^3$, with an external size of ~ 4.5m x 5m;
- the Airlock is characterized by an equipment lock of ~ 2m x 1m and an inflatable crew lock of ~ 2m x 2m, providing a volume of ~$10m^3$.

The overall mass of the deep space module amounts to almost 26 tons, including resources and crew systems sized for 20 days of maximum stay of a crew of four astronauts. The module is deployed with this amount of resources and its resupply is foreseen with the periodic visits of the crew. The power subsystem is constituted of solar arrays (2 flexible wings, with high efficiency triple junction cells) and Li-ions batteries. The solar arrays were sized to satisfy the requirement of 15-16 kW (total area of about $90m^2$[*]). The thermal control subsystem was sized in order to guarantee that all the equipment operate within the allowable temperature range along the entire mission. In particular, it comprises a passive thermal control system, characterized by the Multi Layer Insulation (MLI) and heaters, and an active thermal control system, using water on the internal loop and ammonia for the external one. Deployable thermal radiators (2 wings) are envisaged, capable of rejecting up to 8 kW each (to manage crew metabolic heat as well as on-board equipment waste heat).

V. DEPLOYMENT CONCEPT

The first unit is deployed in EML1 and represents the testing platform for new technologies to be used in

[*] This value includes also redundancy on the arrays panels.

further exploration missions (e.g. to NEO, Mars), as well as support for the exploration of the Moon. In particular the main tasks it shall accomplish are:

- remote control of surface robotics by on-board astronauts (demonstration towards future exploration, actual lunar surface robotic assets),
- sample acquisition and on-board analysis (demonstration towards future exploration, actual lunar samples),
- safe haven for crew performing lunar missions,
- science/technology research (e.g. crew operations and human psycho-physiology in deep space, long term autonomous system, …),
- servicing of transportation system elements (e.g. maintenance/refuelling and testing of landers),
- staging post for the crew of lunar ascent/descent vehicles.

Hereafter, a description of the reference mission profile for the DSH first unit is reported (see Fig.3).

The module is launched to LEO by means of a HLLV (100 MT lifting capability), together with the Propulsion Module (PM) and the Transfer Stage necessary for transferring it to the Earth-Moon Lagrangian point, which is envisaged to use Nuclear Thermal Propulsion. After having injected the spacecraft in the transfer trajectory towards EML1 (ΔV~3116m/s), the TS is expended. The braking to put the spacecraft in EML1 orbit (ΔV~650m/s) is provided by the PM, which is also in charge of station-keeping (~40m/s per year).

In the launch configuration the inflatable elements are deflated and the airlock is mounted on top of the module, the solar panels and the radiators are in stowed configuration, as well as the robotic arm (see Fig.2).

The external appendices are deployed before the injection of the spacecraft into the transfer trajectory; the Airlock relocation and the deployment of the Inflatable Habitat are performed in LEO as well, in order to allow easier recovery actions in case of issues related to these potentially critical operations.

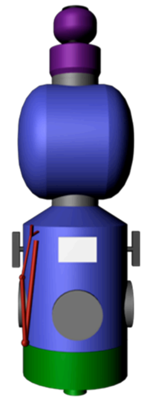

Fig. 2: Deep Space Habitat architecture: launch configuration

During its operative life (10 years), periodic crew visits are envisaged. Two launches are foreseen for delivering to LEO the Crew Transfer Vehicle (CTV) with 4 astronauts, the lunar lander (if a mission to the Moon surface is envisaged) and the transfer stage (TS), necessary for providing the ΔV to inject the spacecraft into the trajectory towards EML1. The CTV and the lunar lander dock to 2 DSH radial ports. During the mission on the Moon surface, the CTV remains attached to the DSH. After the lunar mission has been accomplished, the CTV un-docks from the DSH and begins the travel back to Earth which ends with a direct re-entry of the capsule in the Earth atmosphere.

It is worth to notice that, if the nuclear propulsion will no be available, more launches will be necessary.

In particular, with nuclear thermal propulsion, the total launch mass of the assembled spacecraft (DSH + PM + TS) amounts to ~ 74 tons[†], which is compatible with the launcher capability (100MT).

If chemical propulsion is to be adopted, the total launch mass of the assembled spacecraft would amount to ~110 tons[‡], thus slightly exceeding the envisaged launcher capability.

[†]computed assuming a specific impulse Isp=900s for TS and Isp=400s for PM.

[‡]computed assuming a specific impulse Isp=400s for both PM and TS.

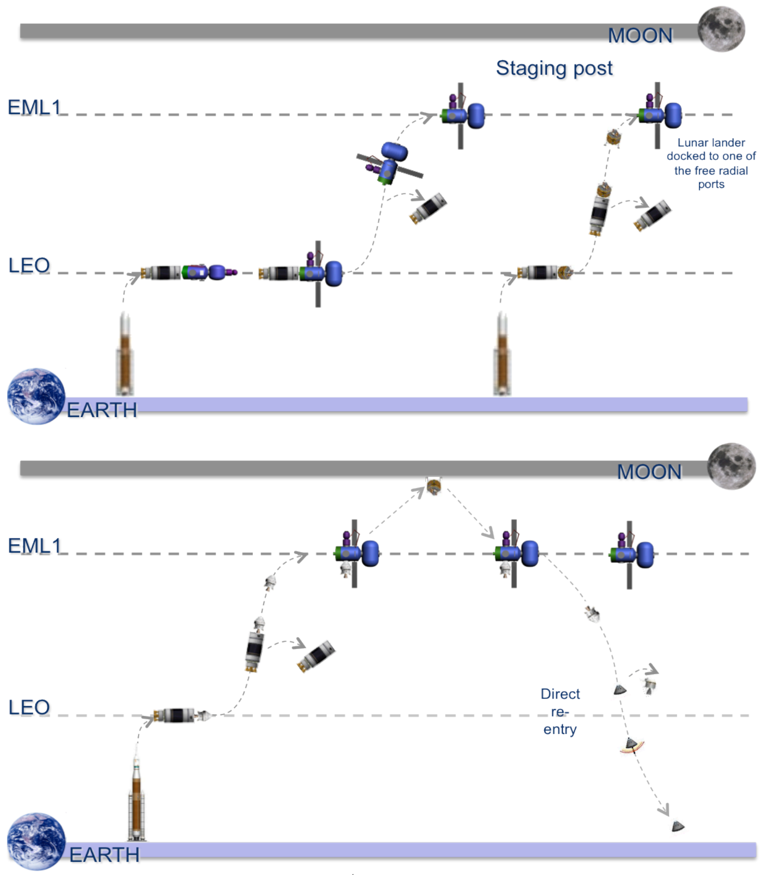

Fig. 3: DSH 1st unit mission profile

VI. DSH SECOND UNIT

Introducing the deep space habitat in different mission architectures, it becomes the habitat where the astronauts have to live during the entire mission to an asteroid or to Mars. In this respect, the module described up to now can be seen as a first unit to be utilized as a precursor for the habitation module to be actually adopted for hosting the crew during the deep space mission.

The second unit will exploit the experience gained through its precursor, having a common core with it and implementing those technologies previously tested on the first unit. Only minor changes shall be envisioned due to the peculiarities of the mission for which it is used, as for example the overall lifetime. In a NEO mission the DSH will be part of more complex transportation architecture and will likely have different interfaces with the propulsive module to which it is attached. In addition the three free radial docking ports will not be necessary, while an additional axial docking port would be necessary for safety and operational complexity reason.

Finally, the DSH used for the NEO mission will be permanently inhabited, thus not requiring remote control and monitoring of the experiments from ground. A schematic view of the habitat to be used for deep space exploration missions is reported in Fig.4.

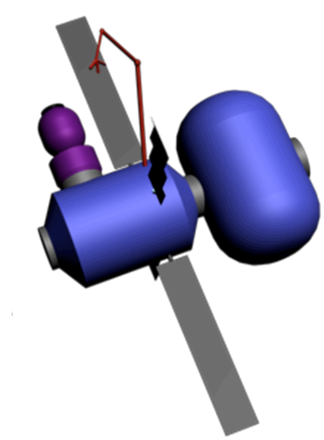
Fig. 4: Deep Space Habitat 2nd unit for deep space mission accomplishing

The overall mass of the DSH 2nd unit amounts to about 30 tons, which include the resources and systems needed to accomplish a 12 months NEO mission. The average power requirements during the NEO mission is about 14kW and the solar arrays resulted to be slightly smaller than the 1st unit ones, even due to the different lifetime.

Fig.5 illustrates the NEO mission profile implementing nuclear propulsion: the DSH is foreseen to be outfitted at a LEO post-ISS before departure towards the NEO and two transfer stages will be necessary to accomplish the reference mission.

Using chemical propulsion at least 5 transfer stages would be necessary for providing the total required ΔV. Therefore at least 5 launches plus one launch for the crew would be necessary. This would hugely increase the operational complexity, for both the on-orbit assembly phase and mission execution.

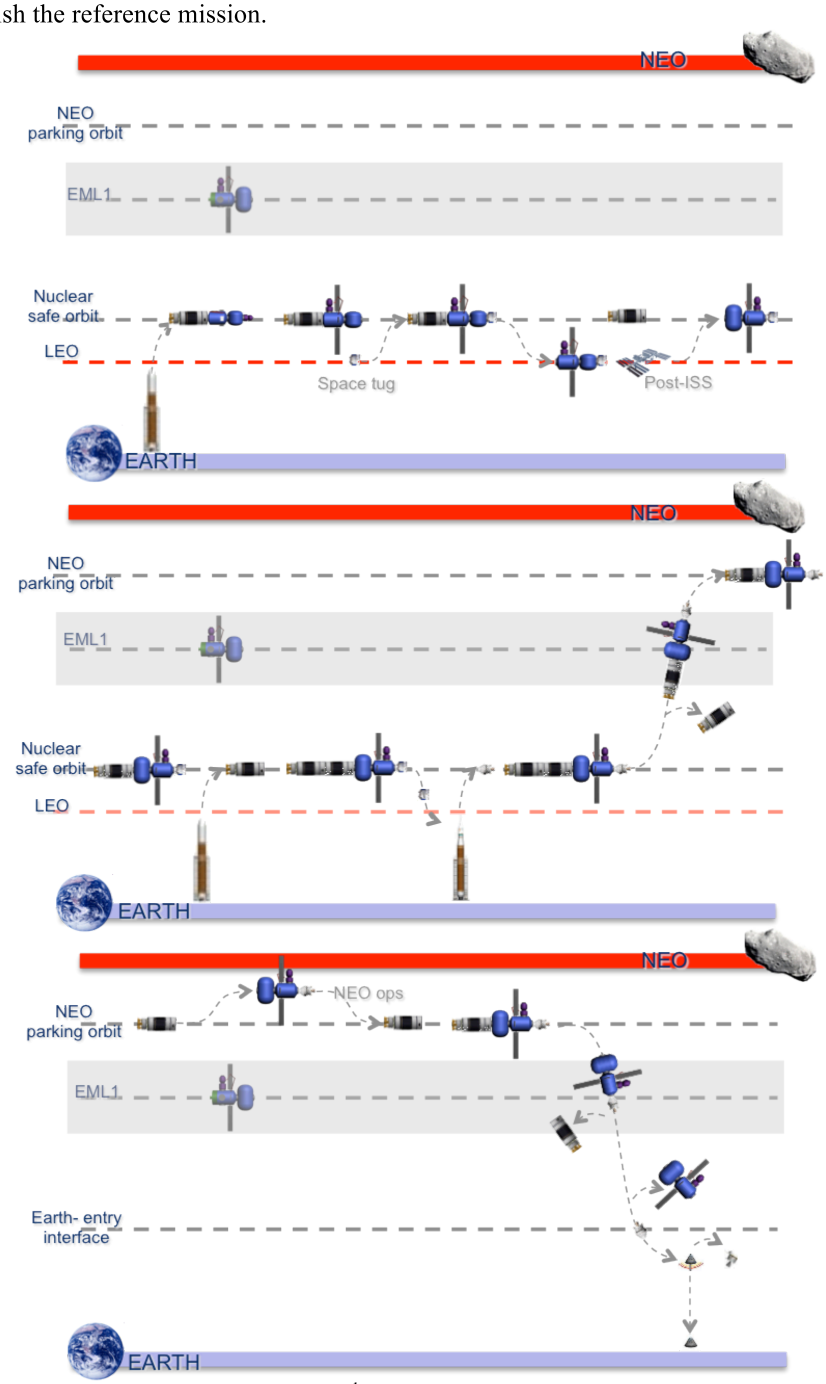

Fig. 5: DSH 2nd unit NEO mission profile

VII. CRITICAL TECHNOLOGIES

The DSH implements several key-technologies, which will be necessary for future space exploration missions. In particular the cis-lunar infrastructure is going to represent a test-bed for those technologies not still available and that need to be ready to enable further space exploration.

The most significant technologies to be implemented in the DSH are listed in Table 2. For each critical technology, the table addresses the current European TRL, the development time up to TRL 5, as well as the needed demonstrators.

Technology	Category	Current EU TRL	Dev. time up to TRL 5 (years)	Need Date for TRL 5 (PDR)	Main Tech Demonstrators	Demonstrators' Location
Advanced Regenerative ECLSS (hi-reliability)	*Life Support, Habitation and ISRU*	4-5	1-3	2019	Full-scale ECLSS system demonstrator	LEO (ISS/Post-ISS)
IBDM	*Robotics*	4-5	1	2019		
Radiation Shielding System	*Life Support, Habitation and ISRU*	4	4	2019	Full-scale Radiation shelter demo	Cis-lunar (outside Van Allen Belts)
In-situ Diagnostic / Maintenance	*Life Support, Habitation and ISRU*	3	2-3	2019		LEO (ISS/Post-ISS) (for new elements maintenance)
Sample Transfer[§] – Via EVA	*Robotics*	2-3	2-3	2019	Full-scale Sample retrieval system (KIBO-like hatch)	Cis-lunar (lunar samples retrieval)
Sample Transfer[§] – Via hatch	*Robotics*	3-4	1			
In orbit Sample Analysis Lab	*Life Support, Habitation and ISRU*	3-4	2-3	2019	Full-scale lab demo	LEO (ISS/Post-ISS)
Tele-operations of Surface Robotics	*Life Support, Habitation and ISRU*	4-5	1-2	2019	Full-scale demonstrator	cis-lunar (e.g. tele-ops of lunar surface assets)
Enhanced Manned Maneuvering Units	*Robotics*	2-3	5	2019	E-MMU demonstrator	For HW LEO (ISS / Post-ISS) For ops and psychological aspects cis-lunar
0g Countermeasures	*Life Support, Habitation and ISRU*	2	4-5	2019	Artificial gravity demo	Centrifuge in LEO (ISS/Post-ISS) Spinning in cis-lunar
Inflatable Structures Technology	*Life Support, Habitation and ISRU*	4	2	2019	Full-scale module demo	LEO (ISS/Post-ISS)

Table 2: DSH Critical Technologies

[§] The sample transfer option that finally was chosen is that through EVA, since the reference NEO mission foresees EVA as nominal activity during the NEO proximity operations.

VIII. CONCLUSIONS

This paper has presented a pressurized habitation module intended as a Deep Space Habitat (DSH) in support of future space exploration missions beyond LEO. Within the paper the methodology and the major trade-off performed are described, as well as the main results in terms of architecture and operations.

Two units are envisaged for the DSH. The first unit is envisioned as a men-tended cis-lunar infrastructure deployed in the first Earth-Moon Lagrangian point, to be exploited for scientific research and technological tests. It represents the precursor for the second unit to be implemented in a human exploration mission to a NEO. The features of the module described in the paper refers to a mission lasting about 12 months, with about 10 days spent around the NEO during which several EVAs are envisaged to explore the surface.

The DSH analysed in the paper can be also seen as the habitation module to be implemented in a human mission to Mars, given that specific modifications are introduced to match the requirements deriving from the different objectives and environment to withstand.

Within the paper the rationale behind the major architecture and design choices was discussed and the most critical technologies were highlighted.

In particular, an advanced regenerative environmental control and life support system is envisioned, in order to save mass, even in view of implementing the module in more demanding missions.

Being the DSH the module where astronauts have to spend most of the time during a deep space mission, it must ensure a safe environment and protect the crew from space hazards. In this regard, it is mandatory to provide protection against space radiations, especially in case of SPE occurrence. For this reason, a dedicated shelter was included in the habitat design.

X. LIST OF ACRONYMS

CTV – Crew Transfer Vehicle
DSH – Deep Space Habitat
ECLSS – Environmental Control and Life Support
EML – Earth-Moon Lagrangian point
E-MMU – Enhanced Manned Manoeuvring Unit
EVA – Extra Vehicular Activity
GCR – Galactic Cosmic Rays
HLLV – Heavy Lift Launch vehicle
IBDM – International Berthing and Docking Mechanism
IDSS – International Docking Standard System
ISRU – In-Situ Resources Utilization
ISS – International Space Station
LEO – Low Earth Orbit
LLO – Low Lunar Orbit
NEO – Near Earth Object
NTP – Nuclear Thermal Propulsion
PM – Propulsion Module
S/C – Spacecraft
SPE – Solar Particle Event
TAS-I – Thales Alenia Space - Italy
TRL – Technology Readiness Level
TS – Transfer Stage

XI. REFERENCES

Ref. 1: M.A. Viscio, F. Fenoglio, “Exploration Research Habitat Concept”, SD-RP-AI-0735, TAS-I, 2011

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