FUTURE SPACE EXPLORATION: FROM REFERENCE SCENARIO DEFINITION TO KEY TECHNOLOGIES ROADMAPS

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The human exploration of multiple deep space destinations (e.g. Cis-lunar, NEAs), in view of the final challenge of sending astronauts to Mars, represents a current and consistent study domain especially in terms of its possible scenarios and mission architectures assessments, as proved by the numerous on-going activities about this topic and moreover by the Global Exploration Roadmap. After exploring and analysing different possible solutions to identify the most flexible path, a detailed characterization of one out of several Design Reference Missions (DRM) represents a necessity in order to evaluate the feasibility and affordability of deep space exploration missions, specifically in terms of enabling technological capabilities. A human expedition to a NEA, milestone of the GER 'Asteroid Next' scenario, is considered the mission that would offer the largest suite of benefits in terms of scientific return, operational experience and familiarity on human deep space missions, test of technologies and assessment of human factors for future long-duration expeditions (including planetary bodies), evaluation of In-Situ Resource Utilization (ISRU) and, more specifically, opportunity to test asteroid collision avoidance techniques. The study started from the identification and analysis of feasible evolutionary scenarios for Deep Space Exploration. Different destinations were considered as targets, with particular attention to Earth-Moon Lagrangian points, NEA and Mars as an alternative path to a Moon campaign. In the frame of the scenario selected as the preferable one, a DRM to a NEA (reference target) was defined in detail in terms of architecture and mission elements, as well as of the subsystems composing them. Successively, the critical subsystems and the relevant key technologies were investigated in detail, from their status-of-the-art up to an assessment of their development roadmaps. They shall enable the DRM and support the whole scenario. The paper describes the process that was followed within the study and reports the major obtained results, in terms of scenarios and mission analysis. Furthermore the key technologies that were identified are listed and described highlighting the derived roadmaps for their development according to the reference scenario.

I. INTRODUCTION

The next step in the Human Space Exploration (HSE) is to travel beyond Low Earth Orbit (LEO), and in this regard numerous activities are being carried out by the major space agencies, industries and academia trying to assess the best path to be followed in the exploration of the solar system, with the final objective of a human mission to Mars and through multiple deep space destinations intermediate human missions (e.g. Near Earth Asteroids). An example of this type of study can be found in [1].

The most significant reference study is the Global Exploration Roadmap [2] whose latest version identifies two possible alternative paths, "Asteroid Next" and "Moon Next", providing a general preliminary description of the strategy to be followed.

According to the current scientific community interest in the analysis of future scenarios of exploration, a research activity, involving the System Engineering groups of Politecnico di Torino (Italy) and MIT (USA) with the support of Thales Alenia Space-Italy as industrial partner (MITOR 2012 project), was carried out. This research focused on the Human Space Exploration topic, from the definition of a possible scenario, with the assessment of the missions, both humans and robotics, up to the identification of the enabling technologies.

The study started from the identification and analysis of feasible evolutionary scenarios for Deep Space Exploration. Different destinations were considered as targets and a reference scenario was built on the basis of a "capabilities analysis". In the frame of the selected scenario Design Reference Missions (DRM) were characterized in terms of architecture and mission elements, as well as of the subsystems composing them*. Successively, the critical subsystems and the relevant key technologies were investigated. They shall enable the DRMs and support the whole scenario.

The paper describes the process that was followed within the study and reports the major obtained results, in terms of scenario and mission analysis. Furthermore the key technologies that were identified are listed and described highlighting the need for their development according to the reference scenario.

Within the paper only some example cases are described, to make the methodology more clearly understandable.

II. HUMAN SPACE EXPLORATION SCENARIO

The HSE scenario analysed in the frame of the MITOR 2012 project was built considering as final goal a human mission to Mars by the end of the 2030 decade.

In particular the NASA DRA 5.0 was taken as reference mission for the present study evaluations [4].

To build up the HSE scenario, the first step was characterized by the identification of the intermediate destinations concepts that most efficiently allow demonstrating the capabilities required for the reference human mission to Mars. It is worth noticing that all the study was based on a pure technical/performance approach, with no risk and cost analyses, as well as no political considerations, and the driving criterion for the scenario definition was given by the capabilities required for the final reference mission to Mars.

For the selected destination concepts the most evolutionary strategies, missions, architectures and elements to be implemented to incrementally move towards the first human mission to Mars, were analysed.

In the following sections a description of the various steps of the work is reported, with a highlight on the main obtained results.

II.I Reference Human Mission to Mars

The main reasons why the NASA DRA 5.0 was taken as reference for the present study were:

- the level of completeness of the work with detailed considerations also on elements, subsystems and technologies,
- the accuracy of the analysis supporting main trade-offs decisions and of justifications where only a qualitative assessment was performed.

The major mission attributes and high-level key decisions are reported in Table I.

Attributes/Key-decisions	Value
Timeframe	2035-2040
Mission duration	5 years
Mission type	Conjunction
Cargo pre-deployment	Yes
Mars Capture Method	Cargo: Aerocapture Crew: Propulsive
ISRU	Yes – LOX for ascent
In-space propulsion	Nuclear Thermal
Number of crew members	6 – all on surface
Surface exploration strategy	Commuter
Total IMLEO Mass	328 mT
Total Launches	9
Crew Mission Durations - days	
LEO	5
Outbound Cruise	174
Mars Orbit	20
Mars Surface	539
Inbound Cruise	201
Total – Deep Space	395
Total - Mission	939

Table I: NASA DRA 5.0 Mission attributes and key decisions

The NASA DRA 5.0 foresees two cargo missions to Mars in 2037:

- the first one is envisioned to pre-deploy assets on the surface, such as power plants, mobility, utility and communications elements, ISRU plan and the Mars Ascent Vehicle (MAV);
- the second one is envisaged to insert into a 1-sol Mars orbit the manned lander and the surface habitat, carrying also pressurized rovers for additional surface mobility capabilities.

The crew mission is planned to start two years later, given that all the LOX propellant needed for the ascent has been produced and stored in the MAV tanks.

The human mission is composed of the following phases: spacecraft assembly in LEO, outbound transfer, Mars orbit insertion, transfer of the crew to the manned lander, Mars entry, descent and landing, operations on the surface, ascent, rendezvous with the main orbiting S/C, inbound transfer and Earth direct re-entry.

In order to accomplish all these phases and the required functions a total 28 different elements, belonging to transportation, surface and in-space categories, are estimated to be required by NASA engineers with their specific concepts of operations, design drivers, functions to be accomplished and technologies to be implemented. An overview of which are these 28 elements is shown in Figure 1 (the number of units for each element is indicated as well).

* A methodology that was considered as reference is described in [3].

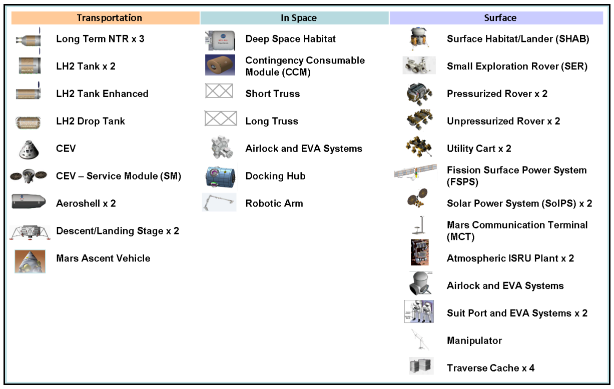

Fig. 1: Mars required elements.

For this reference human mission to Mars an analysis of the needed capabilities was performed.

The identified capabilities were listed into four main groups, which are Transportation, Operations, In Space Support and Surface Support, as shown in Figure 2.

TRANSPORTATION
High performance human transfer
High Speed Earth Manned EDL
High Capacity Cargo Transfer
Orbit Cargo Insertion (non propulsive)
Destination Cargo Entry
Destination Manned Entry
Destination Cargo D&L
Destination Manned D&L
Destination Manned Ascent
Destination Cargo Ascent

OPERATIONS
Advanced RvD
Long Range Communications (high data rate)
Medium Range Communications
Short Range Communications
Reduced gravity drilling & samples mgmt.
Low-g bodies anchoring, drilling & samples management
Robotic tele-operations
Safe In-Space Elements Separation

SUPPORT – IN SPACE
In-Space Multiple dockings
In-Space Cryogenic Fuel Management
In Space Advanced Power
In-Space Advanced Thermal
In-Space High Capacity Storage
In-Space Advanced Life Support
In-Space Advanced Human Health Support
In-Space Advanced Human Habitability
In-Space Radiation Protection
In-Space Advanced Robotics
In-space advanced EVA

SUPPORT - SURFACE
Surface Multiple dockings
Surface Cryogenic Fuel Management
Surface Advanced Power
Surface Advanced Thermal
Surface Advanced Life Support
Surface Advanced Human Health Support
Surface Advanced Human Habitability
Surface Radiation Protection
Surface Advanced Robotics
Atmospheric ISRU
Soil ISRU
Surface Advanced EVA
Low-g bodies mobility
Surface Mobility

Fig. 2: Mars required capabilities.

The HSE scenario was built on the basis of a "capabilities analysis", aimed at identifying the intermediate destinations missions which best allow a gradual achievement of those capabilities required for Mars.

II.II HSE Intermediate Destinations

To build up the scenario, once fixed the last mission (Mission to Mars NASA DRA 5.0), the intermediate destinations had to be selected.

Seven intermediate destinations were identified as possible targets in the path for exploration:

- Low Earth Orbit (LEO), considered mainly for the easy accessibility from Earth and for the presence of the already available International Space Station (ISS);
- Medium or High Earth Orbits (MEO/HEO), interesting because of their medium accessibility cost from Earth and for more Deep Space-like environment;
- Cis-Lunar space (Earth-Moon Lagrangian Points), which is characterized by a deep space environment and allows an increase science return from the Moon;
- Moon, for which both Sortie Missions and surface Outpost possibilities were considered, in order to perform exploration on the lunar surface as well as to prepare for Mars exploration;
- Near Earth Asteroids (NEA), which give the possibility to perform a significant mission (closer than Mars), with analogous Mars mission deep-space aspects;
- Mars Moons, considered as a possibility for a Mars mission rehearsal, with reduced complexity and tele-operations of Mars assets;
- Mars Orbit, as Mars mission rehearsal, with reduced complexity.

For these seven destinations several Mission Concepts were defined, deriving from the combination of alternative "first-level key decisions".

In particular tree diagrams were built, providing the alternative possible concepts for the various destinations. In Figure 3 the case of the cis-lunar space is reported, as an example. For the complete set of the tree diagrams, please refer to [5].

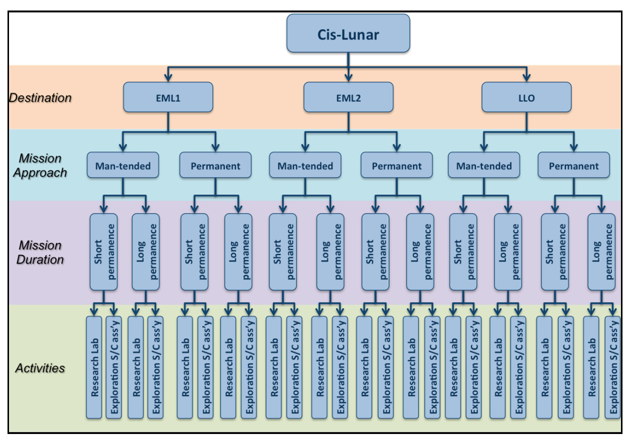

Fig. 3: Cis-Lunar Mission Concepts Tree Diagram

For this specific destination, the "first-level key decisions" are:

- destination: the first or the second Earth Moon Lagrangian (EML) point, or a Low Lunar Orbit (LLO);
- mission approach: men-tended infrastructure vs permanently inhabited station;
- mission duration: short (<2 weeks) vs long (>2 weeks) permanence on the station;

- activities to be performed: research vs exploration spacecraft assembly.

Each branch of the tree diagram represents a potential mission concept. In order to reduce the number of "candidate concepts", among which only one has to be selected[†], for each "first-level key decision" the alternative options were qualitatively compared with each other, and only the most significant solutions were maintained as possible options ("candidate concepts").

As result of these evaluations, two "candidate concepts" were selected, which are:

- Cis-Lunar 1, envisaging an EML1 men-tended station, with the short permanence option and to be used mainly as research laboratory;
- Cis-Lunar 2, envisaging an EML1 men-tended infrastructure, with the long permanence option and capable to support the assembly of exploration S/C.

Analogously to what described for the Cis-Lunar case, similar considerations were done for the other destinations, and finally 24 "candidate concepts" were identified [5]. Some details about the 24 "Candidate Concepts" are provided in Table II.

Destination	Candidate Concept	Main Features
LEO	ISS	• Permanent • Long Permanence • Research & techs test lab
	Equatorial Post-ISS	• Equatorial Post-ISS • Men-Tended • Long Permanence • Research Lab & Exploration S/C assembly
MEO/HEO	HEO1	• HEO • Men-Tended • Short Permanence • Research & techs test lab
	HEO2	• HEO • Men-Tended • Long Permanence • Exploration S/C assembly
Cis-Lunar	CL1	• EML1 • Men-Tended • Short Permanence • Research laboratory
	CL2	• EML1 • Men-Tended • Long Permanence • Exploration S/C support
Moon Sorties	MS1	• Direct Approach • Long Stay • Long Exploration Range • Pre-Deployed Cargo
	MS2	• Direct Approach • Short Stay • Short Exploration Range • All up Cargo
	MS3	• Staging in cis-lunar • Long Stay • Long Exploration Range • Pre-Deployed Cargo
	MS4	• Staging in cis-lunar • Short Stay • Short Exploration Range • All up Cargo
Moon Outpost	MO1	• Direct Approach • Men-Tended • Long Stay • Long Exploration Range • Pre-Deployed Cargo
	MO2	• Direct Approach • Men-Tended • Short Stay • Long Exploration Range • Pre-Deployed Cargo
	MO3	• Staging in cis-lunar • Men-Tended • Long Stay • Long Exploration Range • Pre-Deployed Cargo
	MO4	• Staging in cis-lunar • Men-Tended • Short Stay • Long Exploration Range • Pre-Deployed Cargo
NEA	NEA1	• LEO Departure • Pre-Deployed Cargo • No-landing • Exploration Vehicle
	NEA2	• LEO Departure • All up Cargo • No-landing • Exploration Vehicle
	NEA3	• Cis-Lunar Departure • Pre-Deployed Cargo • No-landing • Exploration Vehicle
	NEA4	• Cis-lunar Departure • All up Cargo • No-landing • Exploration Vehicle
Mars Moons	DMS1	• Deimos • LEO departure • Pre-deployed Cargo
	DMS2	• Deimos • LEO departure • All up Cargo
	DMS3	• Deimos • Cis-lunar departure • Pre-deployed Cargo
	DMS4	• Deimos • Cis-lunar departure • All up Cargo
Mars Orbit	MOr1	• LEO departure • Pre-deployed station • Men-tended
	MOr2	• Cis-lunar departure • Pre-deployed station • Men-tended

Table II: Selected "Candidate Concepts"

[†] It is assumed that only one concept for each destination has to be included in the overall HSE Scenario (see section *"II.III Capabilities Analysis"*)

II.III Capabilities Analysis

For the 24 "candidate concepts" an analysis of capabilities, both required and applicable[‡], was carried out in order to identify which of them are the most interesting to be included in the HSE scenario according to the philosophy behind the study (to maximize the capabilities achievement in view of the Mars mission).

The matrix shown in Figure 4 reports the obtained capabilities map, for the 24 selected "candidate concepts". The list on the left side of the matrix includes additional capabilities, with respect to those needed for Mars (see Figure 2), which were identified as necessary for the intermediate destinations, even if not required for the Mars mission.

[‡] "Required" means enabling or highly impacting on the overall mission/architecture, while "Applicable" is used if it is possible to be implemented and achieved, even if not strictly needed.

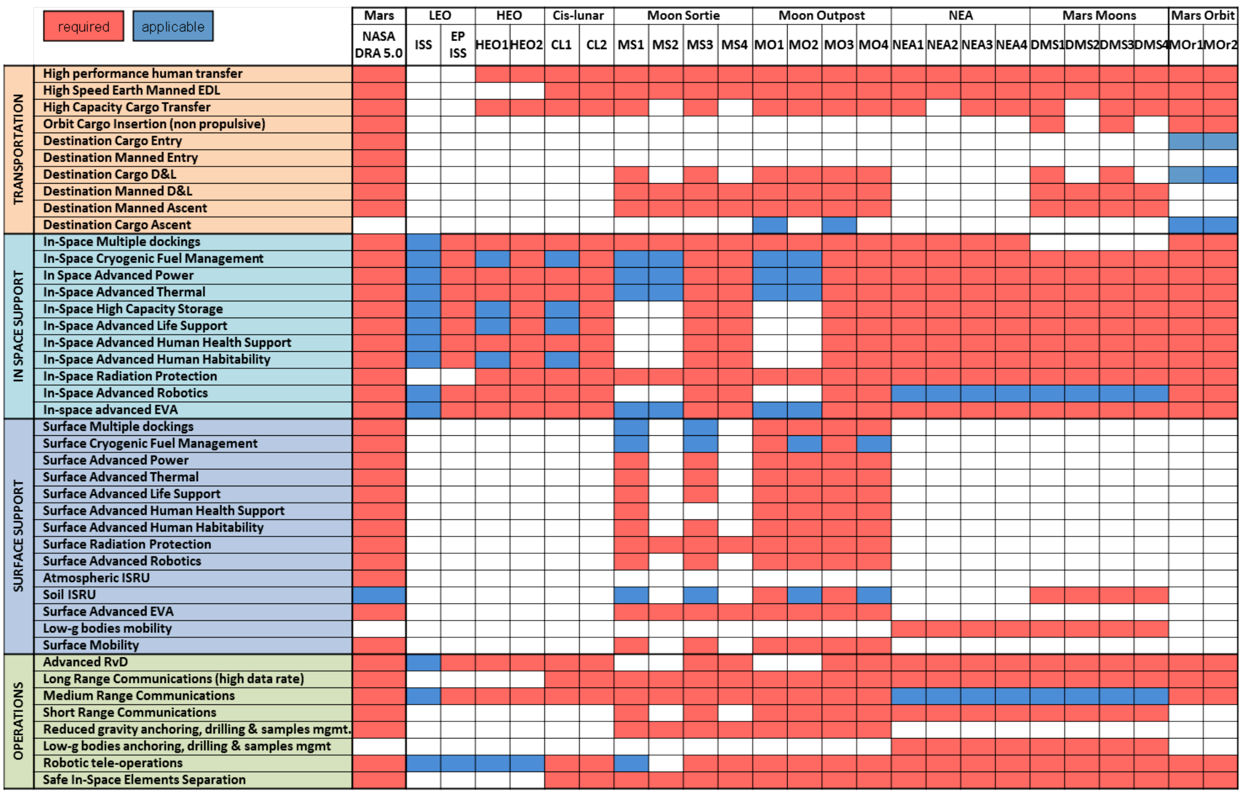

Fig. 4: Capabilities Map

This matrix provides a clear mapping of the capabilities through the various destinations and according to the concepts characteristics. The red cells indicate those capabilities are required, while the blue ones refer to the applicability of the specific capability at the different destinations. It is clear from the matrix that the ISS does not require any of the listed capabilities (that is logical being the ISS already complete and operative), but some of them can be applied there. This allows understanding that the first step shall be the exploitation as much as possible of the station to achieve those capabilities. Analogous observations can be done for the other concepts.

In particular, starting from this wide picture of concepts, the following objective of the "capabilities analysis" was to select the minimum number of destinations concepts allowing the demonstration and achievement of all the Mars Required Capabilities in intermediate locations (where they can be required or applicable).

To accomplish this task, the following driving criteria were followed:

- an incremental selection process was adopted, from closer and "easier" to further and "harder" destinations (from LEO to Mars Orbit);
- the possibility to reuse already existing space infrastructure was taken in account (e.g. ISS);
- coupled concepts were preferred since they allow more flexibility, adaptability and reusability of elements (e.g. Moon Sortie with staging in Cis-lunar station);

- no more than one concept for each destination was selected.

According to these criteria, the various concepts were analyzed and compared and finally five out of the 24 concepts were selected to be part of the overall HSE scenario. Specifically, the selected mission concepts are:

- ISS, that relies on an already existing infrastructure, for which all the in-space support capabilities (except for the Advanced Radiation Protection), and three Operations capabilities are applicable;
- CL2, coupled with Moon Sortie/Outpost and for which all the In-space Support capabilities are required (CL1 can be considered as a first operational phase of CL2);
- MS3, coupled with CL2 and for which three additional Transportation and two additional Operations capabilities are required (with respect to ISS and CL2), almost all the Surface Support capabilities and all In-space Support capabilities are required or applicable.
- MO3, coupled with CL2 and for which all the In space Support capabilities, the Advanced RvD, Surface Advanced Human Health Support and Soil ISRU are required (not in MS3); Surface Support capabilities can be demonstrated at increased level with respect to MS3 required;
- NEA1, which generally allows the same capabilities as CL2 except for some dedicated required capabilities (not needed for Mars) and two additional Operations Capabilities [6], [7].

The MEO/HEO concepts were both discarded, since they do not provide significant demonstration possibilities, also considering the ISS and CL2 concepts. Similarly the Mars Moons and Mars Orbit concepts were discarded, since they do not provide any significant advancement in the Mars required capabilities achievement.

With the five selected concepts, it appears from the matrix that there are still four missing capabilities needed for Mars and that can not be demonstrated in any of the other destinations. For this reason a sixth concept was introduced in the scenario, the Mars Preparation (MP) concept (see Figure 5). It includes some unmanned missions to Mars Orbit and Mars Surface, to demonstrate the missing capabilities, except for Destination Manned Entry that can be demonstrated only through human rated missions and elements.

<u>II.IV HSE Scenario Definition</u>

To build up the HSE Scenario, starting from the six mission concepts discussed in the previous section, all the missions and the relative architectures were defined.

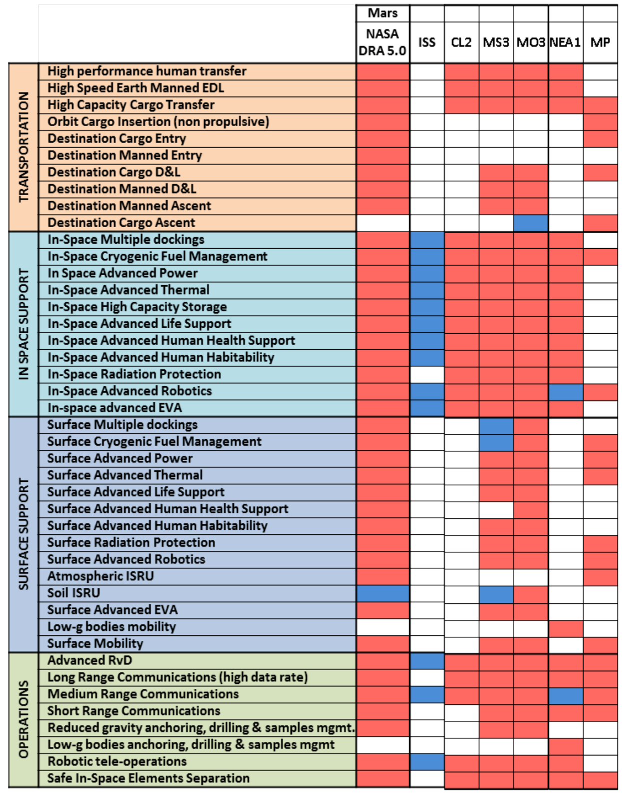

Fig. 5: Capabilities Map – Selected Concepts Summary

All the evaluations carried out to assess the missions, relied on some preliminary assumptions, hereafter reported:

- the assessment of all the destinations concepts was done always considering the NASA DRA 5.0 study as the main reference at all the levels, within the idea of an incremental path of Mars required capabilities demonstration;
- mission objectives different from the technological test for the Mars mission (e.g. scientific, research, space promotion) are only partially considered;
- the number of missions proposed for each destination concept is a minimum estimate; in case of failures the number of missions can increase, suggesting for repetitions (Apollo Program-like approach);
- mission aborts options are not considered in the human missions of any destination concept;
- no considerations on costs and risks are performed;
- dedicated calculations are performed for the evaluation of the transportation elements or stages;
- no models are used for the assessment of the logistic missions, in terms of their numbers and

upload capability; the reference values are first approximations based on past and current similar missions (e.g. ATV to the ISS);

- the Ground and the Launch segments were not considered in the missions' definition.

State-of-the-art and future planned launchers are considered and in particular the launchers listed in Table III are assumed for the present study.

Name	Availability	LEO P/L mass [MT]	Launch Site	Notes
Ariane 5 ES (A5_ES)	available	>20	Guiana Space Center	Unmanned
Ariane 5 ME (A5_ME)	2016	11.2 to GTO	Guiana Space Center	Unmanned
Falcon 9 Heavy (F9H)	2013 - 2014	53 (200km, 28.5°)	Cape Canaveral	Unmanned
Space Launch System (SLS_70)	2017	70	Kennedy Space Center	Unmanned
Space Launch System (SLS_100)	?	100	Kennedy Space Center	Unmanned
Space Launch System (SLS_130)	?	130	Kennedy Space Center	Unmanned
Crew-rated Atlas V (At5_M)	2016-2017	28	Cape Canaveral	Manned
Space Launch System (SLS_70M)	2017	70	Kennedy Space Center	Manned

Table III: Assumed Launchers

For each mission concept the analysis went through several steps.

First of all, several different options for major architecture-level attributes ("Second-level Key Decisions") were qualitatively evaluated.

The second step was the definition of the "General Strategy" to be adopted: the main phases were identified and described.

After having defined the general strategy, the type and the minimum total number of missions were determined.

At this point, all the architectures corresponding to the identified missions were built, and an assessment of the needed launchers and space elements was performed.

Obviously, the process just described was followed for each of the six mission concepts part of the overall scenario. In this paper only an example is discussed, that is the cis-lunar case (for the complete set of results please refer to [5]).

Example Case: Cis-Lunar

The process of analysis of the cis-lunar case for the definition of the missions and the architectures started from the identification and evaluation (qualitative) of specific "Second-level key decisions". These refer to major architecture-level attributes of the concept, for which different options were identified and compared.

For each key decision a specific option was then selected, according to the philosophy behind the study, taking in mind the final objective of the human mission to Mars (NASA DRA 5.0).

The key decisions for the cis-lunar destination are summarized in Table IV, in which the alternative options are shown, as well as the justification of the final choice.

Key decision	Options				Notes
Number of human Missions	3	**6**	>6		Six manned missions are considered: the first three (increasing durations) for research and technologies tests, the other three (6 months) in support of the Moon missions
Crew Members	2	3	**4**	>4	Crew size of 4 is considered, since it is representative of a Moon mission.
Cargo In-Space Propulsion	Cryogenic Propulsion System (CPS)	Nuclear Thermal Rocket (NTR)	Solar Electric Propulsion (SEP)		CPS is chosen because it is considered too challenging to have NTR (high capacity required) available for 2017, when the station is envisioned to be deployed.
Crew In-Space Propulsion	Cryogenic Propulsion System (CPS)	Nuclear Thermal Rocket (NTR)			CPS is initially adopted, while NTR is implemented in the later missions (after having been tested and implemented in the logistics missions)
Logistics In-space Propulsion	Nuclear Thermal Rocket (NTR)	Cryogenic Propulsion System (CPS)			NTR is adopted for the logistics missions which represent the first possibility to implement and get that capability (low capacity NTR)

Table IV: Second-level key decisions

In summary, six manned missions with a crew of four astronauts were considered. For what concerns the in-space propulsion, cryogenic propulsion is to be adopted for the station delivery at EML1 and for the first manned missions. Nuclear propulsion is instead adopted for all the logistics missions and for the last crew missions.

The following step was the assessment of the mission strategy. In particular for the cis-lunar case the mission strategy foresees three main phases.

The first phase starts with the deployment of the station (EML1-HAB) in EML1 [8], relying on cryogenic propulsion. During this phase of autonomous operations (before the first crew visit), the station is used for research (scientific experiments operated from ground) and test of technologies.

The station deployed in cis-lunar is intended as a men-tended infrastructure, and periodic crew visits are envisioned. In particular, the first three manned missions are of increasing duration (15 days, 3 and 6 months). In this second phase, besides scientific research and technologies tests activities, another activity to be considered is the tele-operation of robotics assets on the Moon surface.

The last phase is in support of the Moon missions and, in this regard, three manned missions are envisaged, in particular to perform tele-operation activities of robotic assets on the Moon surface and provide support for the Moon base deployment and activation, as well as support to crew operating on the Moon surface.

At this point, a more detailed characterization of the different missions was performed.

A minimum number of 13 missions was derived as needed. In particular they can be divided into three different mission types:

- Unmanned Cargo Delivery Mission, which refers to the unmanned mission for the delivery of the cis-lunar station in EML1;
- Unmanned Logistics Missions, needed for the resupply of the station (six missions are assumed in correspondence of the crew missions);
- Crew Missions, which represent the crew visits at the station (six total missions).

For the three types of mission just mentioned, four different mission architectures were identified.

The first architecture refers to the cargo delivery mission. The sequence of operations is schematically shown in Figure 6. The transfer stage utilizes cryogenic propulsion, to inert the station in the transfer trajectory towards EML1. A service module attached to the EML1-HAB is in charge of Halo orbit insertion and station keeping.

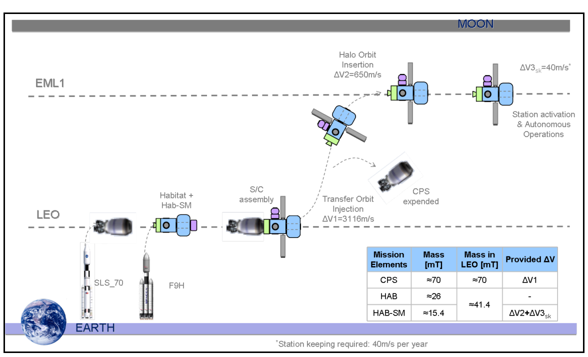

Fig. 6: Cis-Lunar Architecture – Cargo Delivery (HAB)

For what concerns the crew missions, two architectures were derived, as shown in Figures 7 and 8, implementing cryogenic and nuclear propulsion, respectively.

The first two human missions are assumed to implement cryogenic propulsion, since it appears quite unlikely to have nuclear thermal rockets available for manned missions in 2018.

Moreover it is assumed that before implementing nuclear propulsion in crewed missions, some experience shall be gained in unmanned missions (e.g. logistics missions).

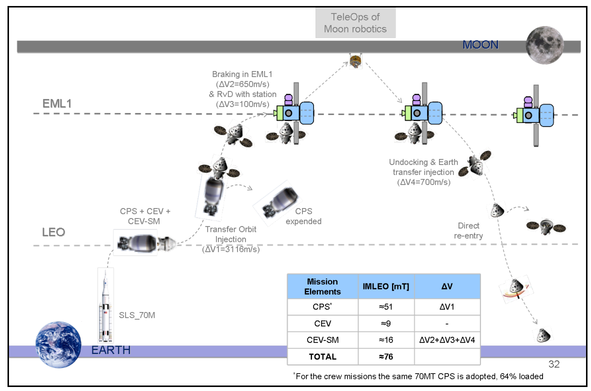

Fig. 7: Cis-Lunar Architecture – Crew Mission with Cryogenic Propulsion

The following missions (starting from 2020) instead implement nuclear propulsion, after having been tested and implemented in the unmanned logistics missions.

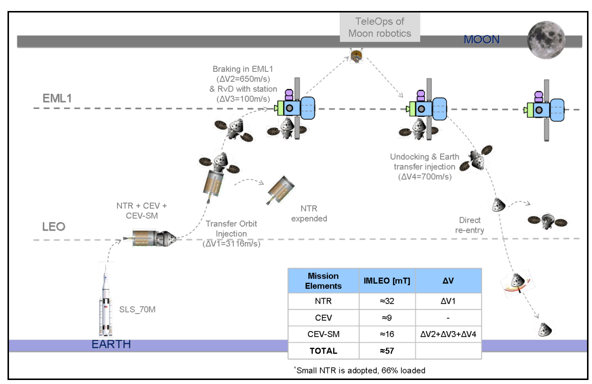

Fig. 8: Cis-Lunar Architecture – Crew Mission with Nuclear Propulsion

The crew missions rely on the use of a Crew Exploration Vehicle (CEV) – like system with its service module [4].

The last identified architecture is shown in Figure 9 that reports the sequence of operations of the logistics missions. The logistics delivery module is assumed to be an ATV-like system.

This architecture envisages the use of a Nuclear Thermal Rocket (NTR), since the first mission, in order to validate this technology.

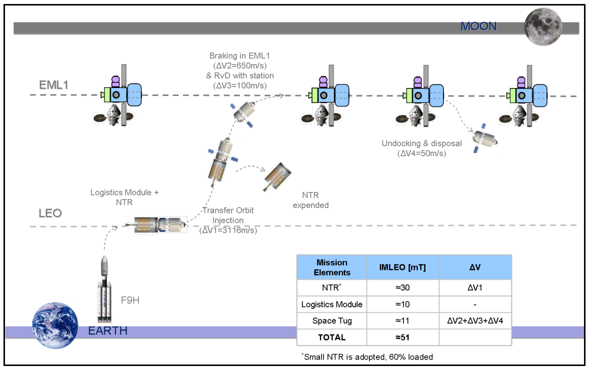

Fig. 9: Cis-Lunar Architecture – Logistics Mission

According to the mission architectures just described many new elements with respect to the previous exploration step (i.e. ISS) were identified as needed. In particular a minimum of ten different elements in total is needed, which are:

- Transportation Elements
  - Habitat-Service Module (1 unit)
  - CEV-Service Module (6 units)
  - CEV (6 units)
  - CPS (3 units)
  - Small NTR (10 units)
  - Space Tug (6 units)
- In Space Elements
  - Cis-lunar Habitat (1 unit)
  - Airlock (1 unit)
  - Logistics Module (6 units)
  - Robotic Arm (1 unit)

All these elements can further be classified as “New Project”, “Upgraded Versions” and “Already Used”. This allows easily visualizing and validating the approach adopted in the definition of the missions and of the whole scenario (some details are provided in the section *“HSE Scenario Elements Summary”*).

<u>HSE Scenario</u>

The process just described for the Cis-Lunar concept, was followed for all the 6 mission concepts. At the end, a large number of missions were included in the scenario and all the relative mission architectures were investigated, ending up with the overall set of elements needed to accomplish all the missions of the HSE scenario. For all the details about the other destinations please refer to [5].

It is worth noticing that the considerations about the elements came from the idea to have as much as possible a gradual “improvement” through the following destinations.

Summarizing all the results obtained for the various destinations the reference HSE scenario was built. It is shown in Figure 10, where all the missions are indicated along the temporal reference window.

The “star” envisaged in 2039 identifies the final human mission to Mars (NASA DRA 5.0).

In Figure 10 each destination area is divided in more rows, which refer to the different phases, part of the mission concept.

All the missions are indicated with a specific abbreviation and colour, to specifically identify them. In particular, the missions labelled with a green U are the unmanned missions for the delivery of the cargo, those labelled with a pink M are the crew exploration missions and those labelled with a yellow U are the unmanned logistics missions. Finally, already planned robotic missions are also included in the scenario.

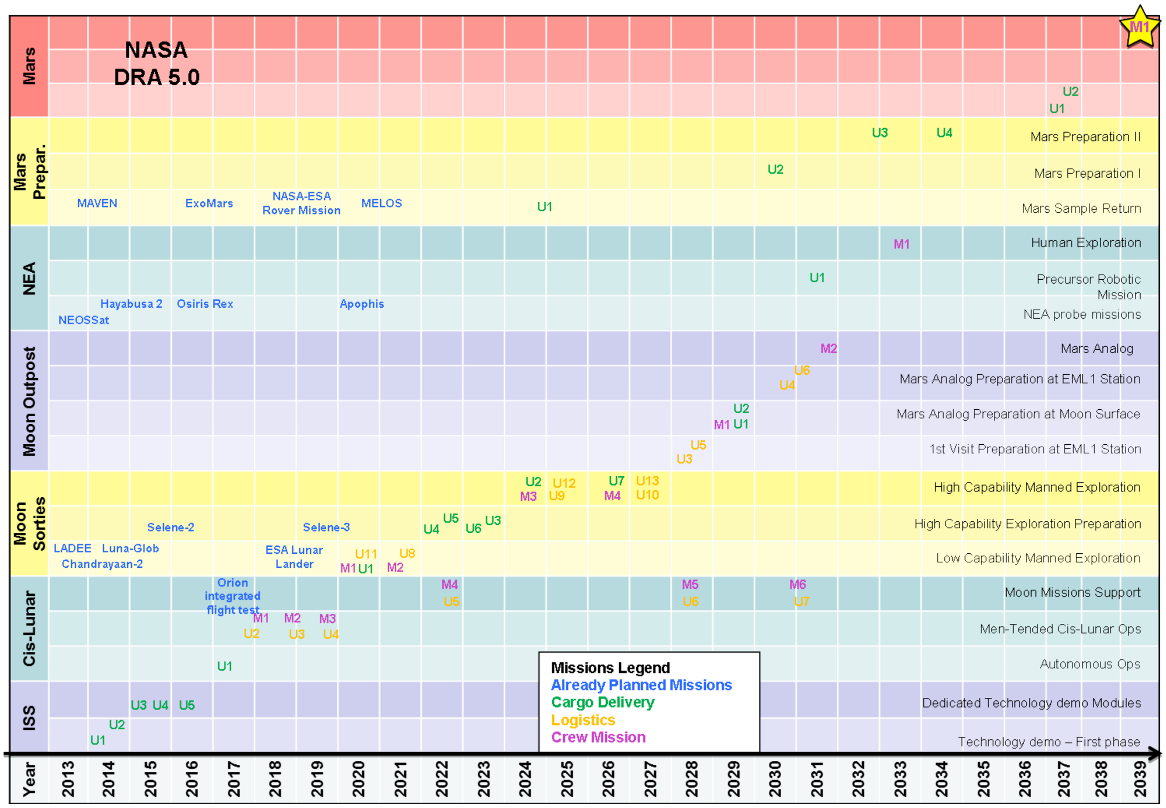

Fig. 10: Human Space Exploration Reference Scenario

<u>HSE Scenario Elements Summary</u>

As explained before, for each one of the missions included in the scenario, the relative architecture and concept of operations were analyzed, analogously to what described for the cis-lunar case [5]. Furthermore, an assessment of the needed elements derived from the architectures analysis. In the present paper, it is not possible to go into the details of each case. An overview of the obtained results is shown in Figure 11. The graph reports a pictorial summary of all the elements as needed through all the intermediate destinations.

The number reported next to every element image refers to the number of units needed at the specific destination. Moreover, a different colour is used to indicate that the element is a "New Project", an "Upgraded Version" or an "Already Used" element with respect to the previous step (red, yellow or green colour, respectively). It is worth underlining that the graph shall be read starting from the bottom, representing the first intermediate destination, i.e. ISS, up to the top, representing the last step, i.e. Mars Preparation.

From the graph it can be seen that there is a gradual improvement in the elements utilization.

For example, if consider the Nuclear Thermal Rocket element, the first element appearing the scenario is represented by a Demo at ISS. Then, there is a Small NTR ("Upgraded Version" with respect to the previous step) implemented in the cis-lunar concept and later the same small NTR is used in the Moon missions ("Already Used") and so on.

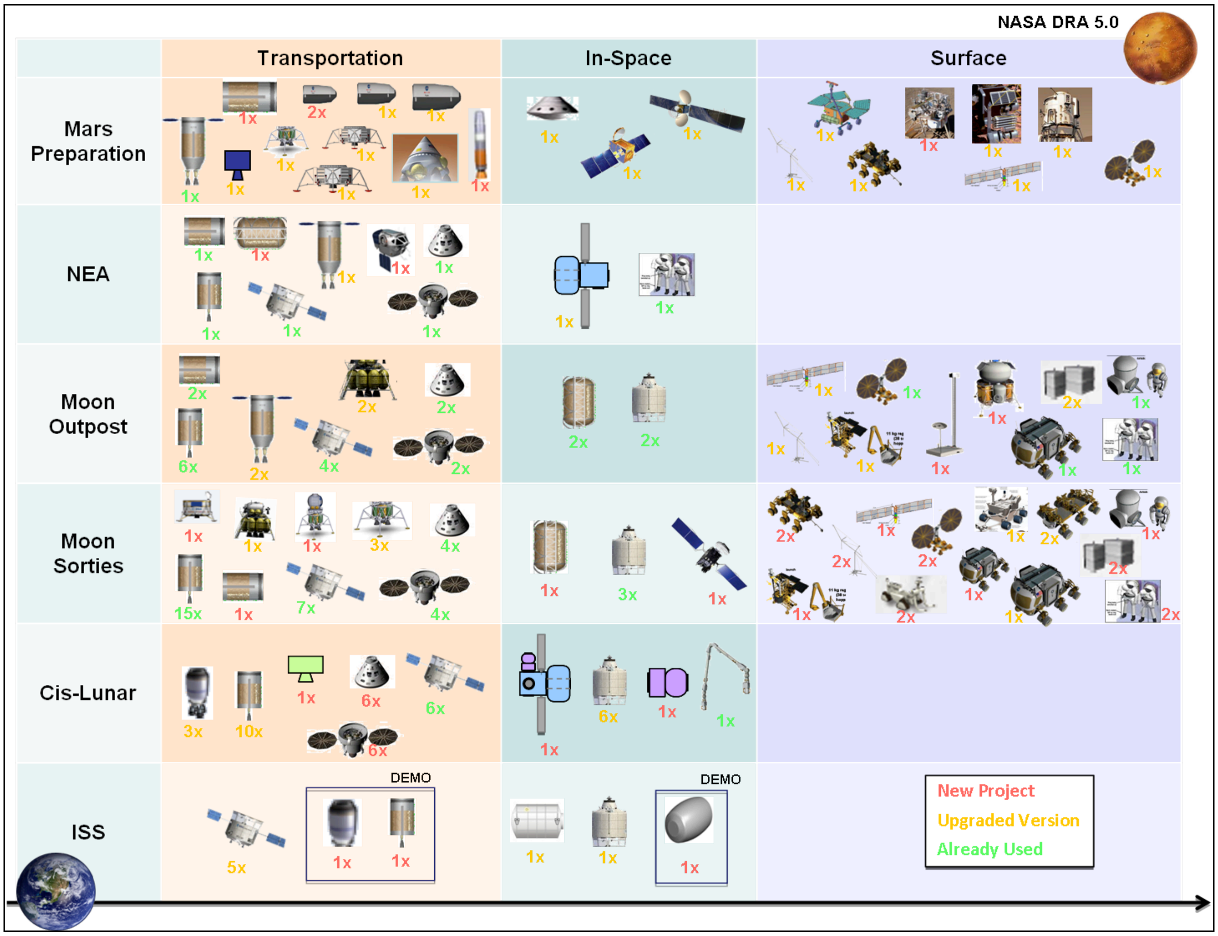

Fig. 11: HSE Scenario Elements Summary

III. HSE TECHNOLOGIES

The second part of the study was aimed at identifying the innovative and promising not yet fully space qualified technologies and determining their applicability on the elements of the proposed HSE Scenario.

III.I Technologies Identification

The technologies to be considered for the applicability analysis can be grouped into Technological Areas (TA), which can have a direct correspondence with the subsystems. In particular, within this study, eleven TAs were defined, including the most innovative, promising and not-yet qualified technologies applicable to the Human Space Exploration. They are listed hereafter:

- TA.1 Structures and Mechanisms
- TA.2 Power
- TA.3 Thermal
- TA.4 Robotics and Automation
- TA.5 Avionics
- TA.6 Communications
- TA.7 Attitude, GNC
- TA.8 Life Support
- TA.9 Propulsion
- TA.10 Environment, Humans and Safety
- TA.11 Atmospheric Descent and Landing

For each technological area, which was divided into relevant sub-areas, the most significant technologies were collected and described.

An example of this classification is reported in the table shown in Figure 12, which specifically refers to the “TA.1 Structures and Mechanisms”.

For this TA two sub-areas were considered, which are “Structures” and “Mechanisms”, and for them a certain number of technologies was identified.

Obviously this process was followed for all the 11 TA and at the end quite a large database was obtained, collecting the most innovative technologies to be considered for the HSE scenario elements.

Technological Sub-Area	Technologies	Name/Variants
1.1 Structures		
	Advanced Al Alloy Structures	Al-Li Alloy
		Al-Ti Alloy
		Al-Sc Alloy
	Other Metals Structures	Titanium
	Advanced Composite Structures	Al MMC
		Al Honeycomb
		Graphite epoxy resin
		Thermoplastic
	Open Cells Resin Foams Structures	BASF Melamine - Basotect
	Advanced Deployable Structures	Ultra-light Rigid
		Flexible
	Multifunctional Structures	Rigid
		Flexible
	Smart Nano-Structures	
	Flexible Pressurized Inflatable Structures	
	Boom & Modular Structures	
	Advanced Secondary/Tertiary Structures	Flexible Bags
	Aeroshell Hypersonic Structures	Rigid - Fix/Deployable
		Flexible - Deployable
	Structures Health Monitoring and Control Techniques	Self Healing Structures
		Advanced Techniques
1.2 Mechanisms		
Docking Mechanisms	In-space Docking Mechanisms	Unmanned Docking Sys
		IBDM/iLIDS/NDS
	Surface Docking Mechanisms	
Generic Mechanisms	Low-cyclic Deploying Mechanisms	
	Low-cyclic Extension Mechanisms	
	High cyclic Long Life Pointing Mechanisms	
	Low Speed Surface Deployment Mechanisms	
Specific Mechanisms	Sampling Mechanisms (Drilling, Collection)	
Separation	Advanced Pyrotechnique Separations	Low-shock
	Non-explosive Separation Mechanisms	
	Hot Structures Separations	

Fig. 12: Technologies List – TA.1 Structures and Mechanisms

III.II Technologies Mapping

Starting from the technologies database and the HSE scenario elements set, an "applicability analysis" was performed, which allowed determining the applicability of the technologies to each element class.

The elements were grouped into 16 classes and each of them has its specific technologies set. The 16 identified elements classes are:

- Nuclear Thermal Rocket
- Long Permanence Habitat (>2 months)
- Short Permanence Habitat (<2 months)
- Pressurized Modules
- Lander
- Surface Power
- Aeroshell
- Ascent Vehicle
- Earth Entry Vehicle
- Airlock and Suitports
- Space Tug
- Tank
- Surface Mobility - Rover
- ISRU
- Robotic Arm
- Communications Assets

The "applicability analysis" was carried out considering that, with respect to an element, a technology can be:

- required, if enabling or significantly impacting on the overall mission/architecture;
- applicable, if possible to be implemented, even if not strictly required;
- demo, if it can be implemented as a demo while being required for a following mission;
- not applicable, if not possible to be implemented.

An example of the "applicability analysis" results is provided in Figure 13 (for all the other classes please refer to [5]).

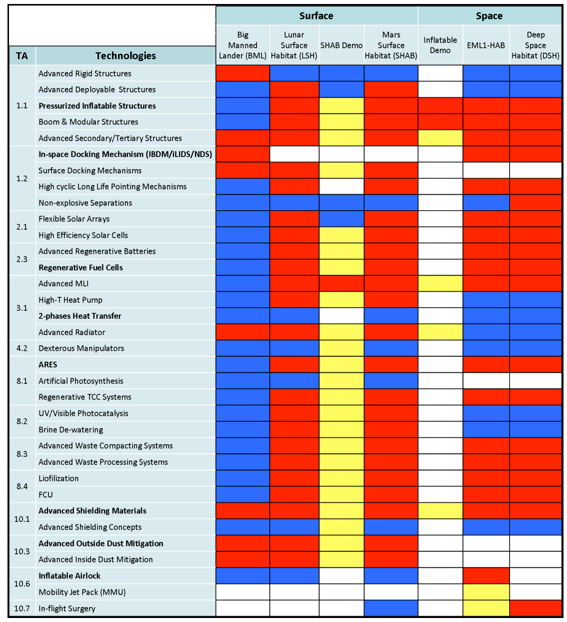

Fig. 13: Technologies Applicability on Elements – Long Permanence Habitat[§]

This matrix refers to the "Long Permanence Habitat" class of elements and, according to the colour of the cell, indicates if the listed technologies are required (red), applicable (blue), demo (yellow) or not applicable (white) on the various elements belonging to this class.

Starting from the matrices obtained for all the elements classes, a mapping of the required and applicable technologies through the various destinations was performed. Figures 14 and 15 show two tables summarizing the mapping for the "TA.1 Structures and Mechanisms", throughout the HSE scenario.

The table reported in Figure 14 refers to the required technologies; for each destination the number of elements requiring the specific technology is indicated, as well as the total number of elements on the whole scenario. Moreover the first time the technology is needed is specified, showing both the element on which and year when it is required.

§ For the deep space habitat a preliminary design analysis was performed, taking as reference the two previous studies [9], [10].

Required Technologies	HSE Destinations/Concepts							Total		
	ISS	CL	MS	MO	NEA	MP	Mars	#	1st Element	Year
In-Space Advanced Docking Mechanisms	2	4	5	4	5	3	7	30	ATV-like	2014
Advanced Secondary/Tertiary Structures		3	5	5	4		7	24	EML1-HAB	2017
Advanced Rigid Structures		1	3	2	1	5	5	17	CEV	2018
Advanced Pyrotechnique Separations		2	3	3	4	1	4	17	CEV	2018
Advanced Deployable Structures		1	2	4	1	2	4	14	CEV-SM	2018
High-cyclic Long Life Pointing Mechanism		1	1	2	3	1	3	11	EML1-HAB	2017
Low-cyclic Deploying Mechanisms			1	2	1	3	4	11	SolPS	2022
Non-Explosive Separation Mechanisms	1				1	2	5	9	PMM-like	2014/15
Boom & Modular Structures	1	2		1	1		3	8	Inflatable Demo	2015
Pressurized Inflatable Structures	1	2		1	1		3	8	Inflatable Demo	2015
Low-speed Surface Deploying Mechanism			2	1		3	1	7	1-ton lander	2022
Surface Docking Mechanisms			3	2			2	7	PR-Demo	2023
Sampling Mechanism			3	1				4	1-ton lander/SER	2022
Hot Structures Separations						3	1	4	Small Aeroshell	2024

Fig. 14: Technologies Mapping throughout HSE scenario destination – TA.1 Structures and Mechanisms

Similarly, the table in Figure 15 summarizes the number of elements in which the technologies can be applied throughout the different destinations. In the table, some of the most relevant elements (especially the first ones) are reported.

Applicable/DEMO Technologies	HSE Destinations/Concepts							Total
	ISS	CL	MS	MO	NEA	MP	Mars	#
In-Space Advanced Docking Mechanisms						MAV Demo		1
Advanced Secondary/Tertiary Structures	ATV-like, PMM-like, inflatable demo	LM	2	LM		SHAB Demo	1	9
Advanced Rigid Structures	ATV-like,PMM-like,NTR demo	6	17	12	8	14	13	73
Advanced Pyrotechnique Separations			Fuel Tank, LRS	2	1	8	1	14
Advanced Deployable Structures		EML1-HAB	5	1	1	9	3	20
High-cyclic Long Life Pointing Mechanism			1-ton lander, BML					2
Low-cyclic Deploying Mechanisms			3					3
Non-Explosive Separation Mechanisms	ATV-like	EML1-HAB	BML	LSH	Drop Tank	5	2	12
Boom & Modular Structures			5	2		4	3	14
Pressurized Inflatable Structures			5	2		1	2	10
Low-speed Surface Deploying Mechanism			SML, BML					2
Surface Docking Mechanisms						SHAB Demo		1
Sampling Mechanism			8-tons lander, precursor rover			2-tons lander		3
Hot Structures Separations								

Fig. 15: Technologies Mapping throughout HSE scenario destination – TA.1 Structures and Mechanisms

IV. CONCLUSIONS

The paper has presented the results obtained in the frame of the MITOR 2012 project, which was developed as collaboration between Politecnico di Torino and Massachusetts Institute of Technology (MIT).

The main focus of the paper was the description of the process that was followed and the methodologies adopted to define and analyze a reference scenario for the future Human Space Exploration.

The starting point for the present study was the reference human mission to Mars as defined by the NASA DRA 5.0. All the evaluations and major decisions were driven by the final objective to have a human mission to Mars by the end of 2030s.

Within the paper the adopted methodologies as well as some the obtained results have been discussed.

In order to progressively achieve the required capabilities through incremental steps to finally accomplish the human mission to Mars, a minimum of six intermediate destinations concepts were evaluated necessary to be included in a future HSE Scenario (2014-2037). Each concept, as it is defined, allows the demonstration of capabilities through correlated strategies, and common and evolutionary missions, architectures and elements.

Moreover, a list of innovative and promising, not yet space qualified technologies was identified that can be applied to different HSE scenario elements to accomplish needed functions at various extent.

The resulting mapping of the required technologies throughout the scenario destinations is a very important starting point to identify the most important technologies, necessary to move forward in the exploration of the solar system, and to understand on which technologies it is more necessary to invest.

Furthermore, the "applicability analysis" results give also a good picture of where the technologies are applicable and therefore where they can be tested prior to be implemented in the relevant mission.

V. LIST OF ACRONYMS

ATV – Automated Transfer Vehicle
BML – Big Manned Lander
CEV – Crew Exploration Vehicle
CL – Cis-Lunar
CPS – Cryogenic Propulsion Stage
DMS – Deimos
DRA – Design Reference Architecture
DRM – Design Reference Mission
DSH – Deep Space Habitat
EML – Earth-Moon Lagrangian point
EML1-HAB – Habitat in EML1
EVA – Extra Vehicular Activities
GER – Global Exploration Roadmap
GNC – Guidance Navigation and Control
HEO – High Earth Orbit
HSE – Human Space Exploration
IMLEO – Initial Mass in Low Earth Orbit
ISRU – In Situ Resources Utilization
ISS – International Space Station
LEO – Low Earth Orbit
LOX – Liquid Oxygen
LRS – Lunar Relay Satellite
LSH – Lunar Surface Habitat
MAV – Mars Ascent Vehicle
MEO – Medium Earth Orbit
MIT – Massachusetts Institute of Technology
MO – Moon Outpost
MOr – Mars Orbit
MP – Mars Preparation
MS – Moon Sortie
NEA – Near Earth Asteroid
NTR – Nuclear Thermal Rocket
PMM – Permanent Multipurpose Module
RvD – Rendezvous and Docking
SHAB – Surface Habitat (Mars)
SML – Small Manned Lander
TA – Technological Area

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