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COORDINATED ANALYSIS OF TECHNOLOGY DEVELOPMENT INTERESTS FOR THE GLOBAL EXPLORATION ROADMAP: THE GER TECHNOLOGY DEVELOPMENT MAP

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The International Space Exploration Coordination Group (ISECG) is continuing its dialogue and coordination on global human and robotic exploration activities, articulated in the Global Exploration Roadmap (GER). The international dialogue has intensified since the GER's initial release in 2011. A second iteration highlighting further details and progress on the international effort has been published in August 2013.

One major aspect of near-term coordination is the collection and analysis of technology development efforts supporting the implementation of the GER in order to leverage investments of individual ISECG agencies. Over the course of the last year, the Technology Assessment Team (TAT) has shared information on agency technology development interests and priorities as well as respective investment plans related to exploration. The inputs of the participating ISECG space agencies are integrated in a data repository, whereby the individual technology development activities and plans are categorized using the NASA Space Technology Roadmaps Technology Area Breakdown Structure (TABS) and mapped to the elements and capabilities identified in the GER mission scenario. The resulting product—the GER Technology Development Map (GTDM)—is unique in providing a detailed picture of technology developments across the space exploration community. It combines in a systematic fashion technology development entries of several participating ISECG space agencies. The GTDM allows the analysis of this data set from many different angles, providing valuable insights into overlapping areas and investment gaps for both individual agencies and the global ISECG teams. This allows identifying potential challenges for the GER implementation as well as innovative competition or new collaboration opportunities. The TAT analysis thus yields a more robust architecture and enables a more complete and coordinated approach to the implementation of the GER.

This paper highlights the progress made since the first iteration of the GER, provides insights into the data repository and complements the TAT's contribution to the latest release of the GER. A global analysis of the data, based on evolving detailed inputs to the GTDM, is presented.

I. INTRODUCTION

The International Space Exploration Coordination Group (ISECG) was established by 14 space agencies to advance the Global Exploration Strategy by providing a forum where interested agencies can share their objectives and plans, and explore concepts that make use of synergies. The ISECG is committed to the development of products that enable participating agencies to take concrete steps toward partnerships that reflect a globally coordinated exploration effort.[1]

In the development of the Global Exploration Roadmap (GER), the Exploration Roadmap Working Group formed a Technology Assessment Team (TAT) of agency experts to provide a coordinated analysis of technology development interests for exploration. The principal goal of the TAT is to facilitate leveraging investments in technology development efforts of individual ISECG agencies supporting implementation of the GER.

The participating space agencies agree that no single agency has the resources to invest robustly in all of these technologies. Therefore, appropriately leveraging global investments in technology development and demonstration is expected not only to enable but also to accelerate the availability of critical capabilities. However, technology development is a competitive area and agencies want to identify where they should focus their investments to maximize their contribution potential while ensuring that they play a critical and visible part in the exploration endeavour.

Within the TAT, agencies shared information on their technology development interests and priorities as well as respective investment plans related to the implementation of the GER. The inputs of the participating ISECG space agencies are integrated in a data repository, whereby the individual technology development activities are categorized by Technology Areas and mapped to the elements and capabilities identified in the ISECG Mission Scenario. The result—the GER Technology Development Map (GTDM)—becomes thereby a unique product combining in a systematic fashion technology development entries of several participating ISECG space agencies.

The GTDM allows the analysis of this data set from many different angles. Individual agencies can identify gaps as well as overlapping areas. While the former could indicate areas that need further attention for the implementation of the GER, the latter could spur innovative competition, identify new collaboration opportunities, yield a more robust architecture, and enable a more coordinated approach to its implementation. The GTDM is unique in providing such a detailed picture of technology development across the space exploration community and could contribute to more sophisticated and strategic approaches to program management and system engineering in space exploration.

Based on the initial release of the GER in 2011, the TAT presented an introduction of its work and preliminary findings at multiple conferences in the last year. Since then, the international dialogue has been continued and intensified in order to properly capture the stakeholder and community feedback to the GER as well as to reflect the progress in programmatic planning around the world. This process resulted in an update and consolidation of the GER towards the driving goal of human exploration of Mars. The 2013 release of the GER includes a single reference mission scenario – evolved from the two potential pathways "Asteroid Next" and "Moon Next" – that describes the importance of a stepwise evolution of critical capabilities, which are necessary for executing increasingly complex missions to multiple destinations. Since the GER focuses on incremental steps and near-/mid-term activities, it contains limited Mars architecture details, so the GTDM utilizes NASA's "Human Exploration of Mars Design Reference Architecture 5.0"[2] as a preliminary reference for GER technology development needs for anticipated human Mars mission elements.

This paper reflects the changes in the GER and highlights the progress made since 2011. It provides insights into the data repository itself and complements the TAT's contribution to the latest release of the GER. A global analysis of the data, based on evolving detailed inputs to the GTDM, is presented.

II. THE GER TECHNOLOGY DEVELOPMENT MAP

To facilitate the dialogue among the agencies on technology development, the inputs to the GTDM have been categorized based on the Technology Areas developed by NASA's Office of the Chief Technologist[3] and the following terminology has been adopted within the TAT:

- *Capability:* Set of abilities required to achieve mission objectives based on specific performance requirements, e.g., Launch X tons to LEO, transit to Mars, precise descent and landing, surface or atmospheric sample acquisition.
- *System:* A single technology or a combination of multiple technologies with specifications that provides or contributes to a set of capabilities. A system can satisfy more than one capability requirement, e.g., Atlas 5, Delta 4, Arianne 5, Soyuz, sample acquisition robot, gas sample acquisition device.
- *Technology:* A technology is a piece of hardware and/or software that provides one or

more functionalities, e.g., vision system, manipulator.

- *Technology Development:* R&D activity advancing the Technology Readiness Level (typically to TRL 6) such that the technology can be handed over to the flight program, e.g., to enable start of design, development, test, and evaluation (DDT&E) cycle. It thereby addresses the gap between existing and required technologies, e.g., development and validation of open and closed-loop Environmental Control and Life Support Systems (ECLSS), including Atmosphere Revitalization, Water Recovery, Waste Management and Crew Accommodations, focused at improving reliability and reducing logistics over the state of the art.

Each of the participating TAT agencies provided GTDM technology development entries derived from their applicable agency technology portfolios that support the GER scenario. Although the TAT attempted to standardize the GTDM data entries, the individual inputs of the participating ISECG space agencies are guided by varying constraints and assumptions[4].

The GTDM contains currently 368 technology development entries reflecting the technology development portfolios in support of the GER of eight ISECG participating agencies.

The GTDM data entries include content such as detailed descriptions, performance characteristics, applicability to the ISECG Mission Scenario related elements/capabilities and destinations, see Table 1. In addition the GTDM identifies technology demonstration and/or verifications applicability to field analogues, the ISS, and early exploration missions. An example of an individual GTDM technology development entry is shown in Figure 1.

The GTDM was initially created and maintained in a spreadsheet format, and although useful in capturing the individual agency data sets, the spreadsheet capabilities were limited in ease of data entry, data sorting, analysis, and report outputs. The current version of the GTDM is now hosted within a relational database providing all of the data entry, sorting, analysis, and enhanced reporting capabilities of a modern relational database. In addition, a planned server-based tool will allow all registered users log-on access to the latest version of the data ensuring timely and accurate information sharing, while read/write privileges ensure proper database configuration management (including a revision history log).

The GTDM data can be assessed at an individual agency level, at a combined ISECG participating agency level, or any combination of specific agency inquiries. Data can also be easily custom formatted and exported using the relational database tools via common electronic media standards (i.e. PDF files, spreadsheets, etc.). Some of the standard reports currently provided by the GTDM include:

1) ISECG GTDM Critical Technology Development Needs Summary;
2) ISECG TAT Investment Gap Technology Needs;
3) Agencies per Technology Need (Select number of Agencies);
4) Single Agency Technology Plans (Select Agency);
5) NASA TABS Categorization of Technology Developments by Agency;
6) GER Critical Technology Needs and Related Partner Investment Plans.

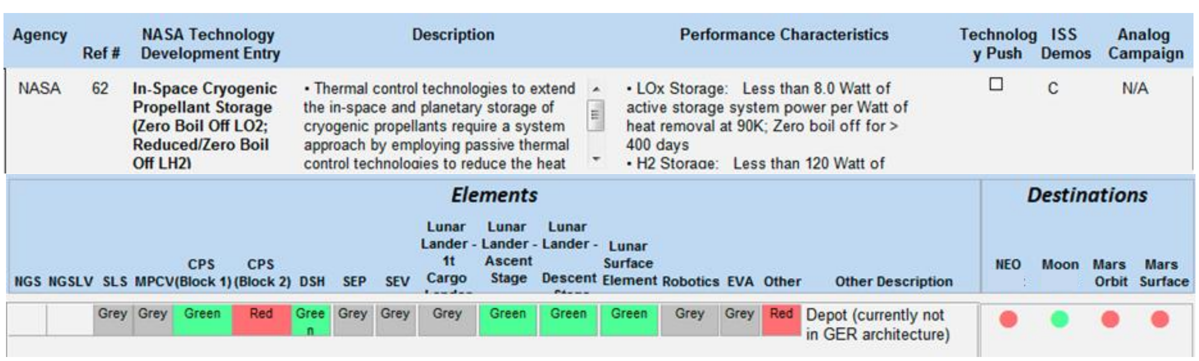

Fig. 1: GTDM Technology Development Entry (Example).

GTDM Data Field Entry	Description	Notes/Example
Entry #	Entry number	001-XXX (agency unique)
Agency	Agency submitting this technology development entry	e.g. CSA, ESA, DLR, NASA
TA (Technology Area)	Technology Area based on NASA's Office of the Chief Technologist (OCT) definitions (TA01-TA14)	TA01 (Launch Propulsion Systems) … TA14 (Thermal Mgmt Systems)
Sub & Sub-Sub TA	Sub & Sub-Sub-Technology Area as defined in the TA OCT's definitions	i.e. TA X.Y & TA X.Y.Z
Title	Indicating the title (short name) describing the technology development	
Description	Providing more details on the technology development efforts and why technology development is required	
Performance characteristics/objective of technology development	Details on what advancements beyond the currents state-of-the-art is required, including metrics where know/applicable	
Applicability of the elements/capabilities	Mapping of the applicability of the technology development entry against the ISECG GER portfolio of identified elements/capabilities (listed in Section III)	Color coding used to show agency identified technology development strength of applicability to the element/capability: *Green*: highly applicable *Yellow*: could be applicable *Red*: identified as critical by NASA *Blue*: may be needed but architecture trades are not complete *Grey*: not applicable Empty: not assessed
Applicability of the scenario/destinations	Mapping of the applicability of the technology development entry against the ISECG GER scenario/destinations (e.g. NEO, Moon, Mars Orbit, Mars Surface)	Color coding used to show agency identified technology development strength of applicability to the scenario/destinations: (same as above)
ISS technology demonstrations	Applicability of the technology development entry for ISS demonstration	P: identified/planned for ISS demonstration C: candidate for ISS demonstration N: otherwise
Analogue Campaign	Applicability of the technology development entry for analogue and/or field demonstration	AC Applicable: analogue campaign is applicable N/A: not applicable
Technology Push	If technology development entry has no direct technology pull applicability to element/capability, or scenario/destinations, then is considered a technology push	Y: technology not required by any mission scenario N: otherwise
Comments	Additional data field for any general or special notes applicable to the technology development entry	
Investment Plan/Level	Used for high-level qualitative analysis of agency investment and/or planning	High/Primary Investment Planning Med/Secondary Investment Planning Low/No Investment Planning N/A - not applicable
Critical Need Applicability	Used for linking entries to identified critical technology needs	Check box (if applicable)
Key Words	Used for enhanced search capability within the database	
Point Of Contact (POC)	Individual responsible for GTDM entry information	
Agency Unique Fields	Individual agency defined special purpose fields (i.e. agency specific)	

Table 1: GTDM Relational Database Record Contents.

TA	Technology Area Title	CNES	CSA	DLR	ESA	JAXA	NASA	Roscosmos	UKSA
1.0	Launch Propulsion Systems								
1.1	Solid Rocket Propulsion Systems								
1.2	Liquid Rocket Propulsion Systems			●		●	●	●	
1.3	Air Breathing Propulsion Systems								●
1.4	Ancillary Propulsion Systems					●	●		
1.5	Unconventional/Other Propulsion Systems								
2.0	In-Space Propulsion Technologies								
2.1	Chemical Propulsion			●	●	●	●	●	●
2.2	Non-Chemical Propulsion				●	●	●	●	
2.3	Advanced (TRL <3) Propulsion Technologies								
2.4	Supporting Technologies	●					●	●	
3.0	Space Power and Energy Storage								
3.1	Power Generation	●			●	●	●	●	●
3.2	Energy Storage			●	●	●	●		●
3.3	Power Management and Distribution						●	●	●
3.4	Cross Cutting Technology						●		
4.0	Robotics, Tele-Robotics and Autonomous Systems								
4.1	Sensing & Perception		●	●		●	●	●	●
4.2	Mobility		●	●		●	●	●	
4.3	Manipulation	●	●	●	●	●	●	●	●
4.4	Human-Systems Integration		●		●	●	●	●	●
4.5	Autonomy	●	●	●	●	●	●	●	●
4.6	Autonomous Rendezvous and Docking	●	●	●	●	●	●	●	●
4.7	RTA Systems Engineering		●	●			●		●
5.0	Communications and Navigation								
5.1	Optical Comm. And Navigation			●	●			●	
5.2	Radio Frequency Communications					●			●
5.3	Internetworking		●						
5.4	Position, Navigation, and Timing		●		●	●	●	●	
5.5	Integrated Technologies	●					●	●	
5.6	Revolutionary Concepts							●	
6.0	Human Health, Life Support & Habitation Systems								
6.1	Environmental Control Life Support & Habitation Systems			●	●	●	●	●	
6.2	Extravehicular Activity Systems					●	●	●	
6.3	Human Health and Performance	●	●		●	●	●	●	●
6.4	Environmental Monitoring and Safety				●	●	●	●	
6.5	Radiation		●	●	●	●	●	●	●
7.0	Human Exploration Destination Systems								
7.1	In-Situ Resource Utilization		●	●	●	●	●	●	●
7.2	Sustainability & Supportability			●	●		●		
7.3	Advanced Human Mobility Systems		●		●	●	●		
7.4	Advanced Habitat Systems				●		●		
7.5	Mission Operations & Safety		●	●	●		●	●	●
7.6	Cross-Cutting Systems		●		●	●	●		●
8.0	Science Instruments, Observatories & Sensor Systems								
8.1	Science Instruments		●	●					●
8.2	Observations				●				
8.3	Sensor Systems		●	●				●	●
9.0	Entry, Descent and Landing Systems								
9.1	Aeroassist & Entry			●	●	●	●	●	
9.2	Descent			●		●	●		
9.3	Landing			●	●	●	●	●	
9.4	Vehicle Systems Technology	●		●	●	●	●		●
10.0	Nanotechnology (not assessed)								
11.0	Modeling, Simulation, IT & Processing								
11.1	Computing		●	●	●		●		
11.2	Modeling		●				●		
11.3	Simulation							●	
11.4	Information Processing		●				●		●
12.0	Materials, Structures, Mech Systems and Manufacturing								
12.1	Materials		●	●			●	●	
12.2	Structures		●			●	●	●	
12.3	Mechanical Systems		●		●		●	●	
12.4	Manufacturing			●	●		●		
12.5	Cross-Cutting								
13.0	Ground and Launch Systems Processing								
13.1	Technologies to Optimize the Operational Life-Cycle						●		
13.2	Environmental and Green Technologies						●		
13.3	Technologies to Increase Reliability and Mission Availability						●	●	
13.4	Technologies to Improve Mission Safety/Mission Risk						●		
14.0	Thermal Management Systems								
14.1	Cryogenic Systems					●	●		
14.2	Thermal Control Systems			●	●	●	●	●	
14.3	Thermal Protection Systems			●	●	●	●	●	

Table 2: Categorization of GER Applicable Technology Developments by Agency (sub-TA Level).

This GTDM capability builds upon the already unique consolidation of the ISECG participating agency data entries into a single shared database by now further adding a powerful set of tools useful for a wide range of analysis in the areas such as better identification of technology prioritization and investment planning, potential technology development partnerships and cooperation, better fidelity technology roadmap development, and other useful applications.

As an example, Table 2 shows a report of "NASA TABS Categorization of Technology Developments by Agency", specifically at the sub-TA Level, i.e., X.Y TABS (Technology Area Breakdown Structure) Level. This particular report highlights the GTDM technology developments in which agencies have identified interest in technology development consistent in supporting the GER. A 'dot' indicates that particular agency has one or more technology development entries in the database that are applicable to the associated sub-TA. For example, all agencies have identified numerous investments in TA 4.0–Robotics, Tele-Robotics & Autonomous Systems. In contrast, only two agencies are investing in TA 7.4–Advanced Habitat Systems. The latter suggests limited opportunity for multi-agency collaboration, while the former indicates many possible opportunities over a broad range of shared interests. At the same time, low agency activity may pose programmatic risk to the development, particularly for critical elements. Note that there are no agency entries associated with TA10 (Nanotechnology). This does not imply that there are no individual agency investments in nanotechnology, rather that there has not been an identified technology pull associated with the GER or nanotechnology solutions are being pursued in other technology areas such as TA 3.2 Energy Storage.

III. ANALYSIS OF TECHNOLOGY DEVELOPMENT PRIORITIES AND CRITICAL TECHNOLOGY NEEDS

The ISECG Mission Scenario, included in the recently presented new version of the Global Exploration Roadmap, provides an integrated stepwise approach to human and robotic exploration. In particular, it identifies a set of missions in the lunar vicinity and on the lunar surface that advance readiness for human Mars missions after 2030. The long-term human exploration strategy (1) initially exploits the ISS activity to enhance future exploration missions via technology development and validation, human health research and operations simulations, (2) targets beyond-LEO destinations envisioning the early deployment in the lunar vicinity of an Evolvable Deep Space Habitat capable of sustaining the human presence and advancing deep space exploration capabilities, and (3) takes advantage of the flexibility assured by the lunar vicinity orbiting infrastructure to envision a human lunar surface return within 2030 as an essential step in preparation for human Mars. In parallel, robotic missions will be carried out to demonstrate deep space capabilities (i.e., a small near-Earth asteroid redirection mission), to fill strategic knowledge gaps (i.e., RESOLVE, SELENE-2, Luna 28/29), and to validate deep space operations (i.e., Lunar Vicinity Human Asteroid Exploration, Human-Assisted Sample Return, MSR).

The ISECG Mission Scenario highlights a set of new elements and capabilities considered key for the successful achievement of the exploration goals:

- ROSCOSMOS Next Generation Space Launch Vehicle,
- ROSCOSMOS Next Generation Spacecraft
- NASA MPCV (Orion),
- NASA Space Launch System (SLS),
- Cryogenic Propulsion Stage (CPS),
- Evolvable Deep Space Habitat (eDSH),
- Advanced In-Space Propulsion,
- Cargo Logistics Delivery Systems,
- Small Cargo Lander,
- Crewed Lunar Lander Descent Module,
- Crewed Lunar Lander Ascent Module,
- Lunar Surface Elements,
- Servicing Support Systems.

Also, it provides a clear missions timeline that permits the identification of the technology/capability requested readiness times. The comparison of the ISECG Mission Scenario with the GER Technology Development Map (GTDM), resulted in the identification of technology development priorities and critical technology needs (enabling technologies essential to the success of the GER Mission Scenario) as well as of eventual development technology gaps or overlapping areas.

The applicability of the GTDM technology developments to the different elements introduced by the ISECG Mission Scenario is shown in Table 3, where:

- Complete applicability is indicated by a green dot (●),
- A technology completely applicable and considered critical for the element development is indicated by a red triangle (Δ),
- Partial applicability is indicated by a yellow circle (○),
- Lack of applicability is indicated by a white cell.

Even if the GTDM analysis has been performed up to a sub-sub TA level (as described in Table 1), for ease of readability, Table 4 shows only the applicability of the GTDM technologies to the ISECG Mission Scenario elements at sub-TA level. To develop Table 4, the mentioned applicability has been assessed for all the identified technology developments within a sub-Technology Area and the following process has been adopted:

In case one technology resulted as critical for the element development, the entire sub-technology area has been considered critical (red triangle). If not,

1) In case one technology resulted applicable, the entire sub-technology area has been considered applicable (green dot). If not,
2) In case one technology resulted partially applicable, the entire sub-technology area has been considered partially applicable (yellow circle).

For example, within sub-TA 12.2, the following technology developments have been identified:

- Lightweight and Efficient Structures and Materials
- Structures and Materials for Inflatable Modules
- Debris Protection Structures

All of them are applicable to the "Anticipated Human Mars Mission Elements" but the "Structures and Materials for Inflatable Modules" is also considered critical, so it is the entire sub-TA.

Sustainable missions to Mars, including exploration of intermediate destinations as described in the GER Mission Scenario, will require certain technologies that have been identified as critical needs. While there is no comprehensive list of technology requirements to implement all the GER elements/capabilities coming from any ISECG working group, NASA has provided a needs driven analysis of the GER capabilities and identified the most complete list of critical technologies through their Human Spaceflight Architecture Team assessment. This subset of GTDM technology developments identified as critical technology needs applicable to the GER Mission Scenario is summarized below:

<u>In-Space Propulsion Technologies (TA02)</u>

- LOX/Liquid Methane Cryogenic Propulsion System (Mars Lander)
- Advanced In-Space Cryogenic Propellant Storage & Liquid Acquisition
- Electric Propulsion & Power Processing
- Nuclear Thermal Propulsion (NTP) Engine

<u>Space Power & Energy Storage (TA03)</u>

- High Strength & Autonomously Deployable In-Space Solar Arrays
- Fission Power for Electric Propulsion & Surface Missions
- Regenerative Fuel Cells
- High Specific Energy & Long Life Batteries

<u>Robotics, Tele-robotics & Autonomous Systems (TA04)</u>

- Telerobotic control of robotic systems with time delay
- Robotic Systems Working Side-by-Side with Suited Crew
- Autonomous Vehicle, Crew, and Mission Ground Control Automation Systems
- Automated/Autonomous Rendezvous and Docking & Target Relative Navigation

<u>Communication & Navigation (TA05)</u>

- High Data Rate Forward & Reverse Link Communications
- High-rate, Adaptive, Internetworked Proximity Communications
- In-Space Timing and Navigation for Autonomy

<u>Life Support & Habitation Systems (TA06)</u>

- Closed-Loop & High Reliability Life Support Systems
- Fire Prevention, Detection & Suppression (reduced Pressure)
- EVA Deep Space Suits, including Lunar & Mars environment
- Advanced EVA Mobility (Suit Port)

<u>Long Duration Human Health (TA06)</u>

- Spaceflight Medical Care, Behavioral Health and Performance
- Microgravity Biomedical Counter-Measures
- Human Factors and Habitability
- Space Radiation Protection/Shielding

<u>Human Exploration Destination Systems (TA07)</u>

- Anchoring Techniques & EVA Tools for Micro-G Surface Operations (NEO)
- Surface Mobility
- Lunar & Mars ISRU (In-Situ Resource Utilization)
- Dust Mitigation

<u>Entry, Descent, & Landing Systems (TA09)</u>

- Entry, Descent, and Landing (EDL) – Mars Exploration Class Missions
- Precision Landing & Hazard Avoidance

<u>Thermal Management Systems (TA14)</u>

- Low Temperature Mechanisms (Lunar poles)
- Robust Ablative Heat Shield - Thermal Protection Systems (Mars & Lunar reentry velocities)

Each GTDM technology development entry has identified ISS technology demonstration and analogue campaign applicability. The ISS microgravity space environment provides a unique test-bed capability for testing GER critical technologies. In that regard, sharing of the ISECG GTDM technology portfolio with the ISS working groups is being coordinated to ensure best utilization planning for future ISS experiments and technology demonstration missions. Likewise, the GTDM has been shared with the ISECG analogues community for potential lab and field technology demonstration planning in support of the GER.

Technology Area	Sub-Technology Area	Next Generation Spacecraft	Next Generation Space Launch Vehicle	Space Launch System	MPCV	Cryogenic Propulsion Stage	Evolvable Deep Space Habitat	Cargo Logistics Delivery Systems	Advanced In-Space Propulsion	Small Cargo Lander	Crewed Lunar Lander Ascent Module	Crewed Lunar Lander Descent Module	Lunar Surface Elements	Servicing Support Systems	Anticip. Human Mars Mission Elements
1 Launch Propulsion Systems	1.2 Liquid Rocket Propulsion Systems		●	●		●				●	●				●
2 In-Space Propulsion Technologies	2.1 Chemical Propulsion	○			●	●	○	●	Δ	●	●	●			Δ
	2.2 Non-Chemical Propulsion						●	●	Δ				○		Δ
	2.4 Supporting Technologies					Δ	●	●			●	●	○		Δ
3 Space Power and Energy Storage	3.1 Power Generation	○			●	Δ	●	○	Δ	●	●	●	●	○	Δ
	3.2 Energy Storage	○			●	●	●	●	●	●	●	○	Δ	●	●
4 Robotics, Tele-Robotics and Autonomous Systems	4.1 Sensing & Perception	●			●	○	●	●		●	○	●	●	●	●
	4.2 Mobility												●	●	●
	4.3 Manipulation	●			●		●		○	●		○	●	●	●
	4.4 Human-Systems Integration	●			●		●			●	●	●	●	●	Δ
	4.5 Autonomy	●	●	●	●	Δ	Δ	●	●	●	●	●	Δ	●	Δ
	4.6 Autonomous Rendezvous and Docking	●			●	●	●	●	●	●	●	○	●	●	●
	4.7 RTA Systems Engineering			●	●	●	●	●	●	●	●	●	●	●	●
5 Communications and Navigation	5.1 Optical Comm. And Navigation	●			●		●	●	●	○	○		●	○	●
	5.2 Radio Frequency Communications				○		○	○		○	○	○	○		○
	5.4 Position, Navigation, and Timing	●	○	●	Δ	●	●	●		●	Δ	Δ	●	●	●
	5.5 Integrated Technologies				Δ	●	Δ	●		●	●	●	●		Δ
6 Human Health, Life Support & Habitation Systems	6.1 ECLS & Habitation Systems	●			●		Δ	○			●	●	Δ		Δ
	6.2 Extravehicular Activity Systems				●		○				●		Δ		Δ
	6.3 Human Health and Performance	●			●		Δ				●	●	●		Δ
	6.4 Environmental Monitoring and Safety	●			●		Δ	●			Δ	○	Δ		Δ
	6.5 Radiation	●			●		Δ	●		●	●	●	Δ		Δ
7 Human Exploration Destination Systems	7.1 In-Situ Resource Utilization												●		Δ
	7.2 Sustainability & Supportability				○		●				○		○		●
	7.3 Advanced Human Mobility Systems						●				●		Δ		Δ
	7.4 Advanced Habitat Systems						○						○		○
	7.5 Mission Operations & Safety	●			●		●				●		●		●
	7.6 Cross-Cutting Systems				○						●		Δ	●	Δ
8 Science Instruments, Observatories & Sensor Systems	8.1 Science Instruments				○		○			○	○	○	●		●
	8.3 Sensor Systems												●	●	●
9 Entry, Descent and Landing Systems	9.1 Aeroassist & Entry	●			●									○	Δ
	9.2 Descent				○					○		○			○
	9.3 Landing									●	○	●			Δ
	9.4 Vehicle Systems Technology									●		●		○	●
11 Modeling, Simulation, Information Technology and Processing	11.1 Computing									●	○	●	○	○	○
	11.2 Modeling			●	●	●	●	●	●	●	●	●	●	●	●
	11.3 Simulation	○			○		○			○	○	○	●	●	●
12 Materials, Structures, Mechanical Systems and Manufacturing	12.1 Materials	○			○		●		○	○	○	○	●		●
	12.2 Structures	●	●	●	●	●	●	●	●	●	●	●	●	●	Δ
	12.3 Mechanical Systems	●			●	●	●	●	●	●	●	●	●	●	●
	12.4 Manufacturing	○			○		●						●		●
13 Ground and Launch Systems Processing	13.1 Technologies to Optimize the Operational Life-Cycle			●		●									
	13.3 Technologies to Increase Reliability and Mission Availability	○		○											
14 Thermal Management Systems	14.1 Cryogenic Systems					Δ	●			○	●	●	●		Δ
	14.2 Thermal Control Systems	●			●	●	●	●	●	●	●	●	Δ		●
	14.3 Thermal Protection Systems	●	○	○										○	Δ

Table 3: GTDM technology developments applicability to ISECG Mission Scenario key elements.

ISECG/TAT Critical Technology Needs			Scenarios / Destinations				Applicable Partner Technology Areas							
Title / Description	ISS Tech Demo	Analog Campaign	Asteroid	Moon	NASA DRA 5.0 Mars Orbit	NASA DRA 5.0 Mars Surface	CNES	CSA	DLR	ESA	JAXA	NASA	Roscosmos	UKSA
Nuclear Thermal Propulsion (NTP) Engine • Nuclear thermal propulsion (NTP) was identified by NASA's DRM 5.0 as required for economical transport of crew to Mars because it provides the high thrust and high specific impulse needed to significantly reduce launch mass for the heavy payloads identified. The NTP system would also reduce the cost of transits to the Moon, E-M L1, NEOs, and orbital missions to Mars and its moons. The NTP system consists of two principal components. The first component is the primary NTP stage that includes the nuclear thermal rocket engines, RCS, avionics, auxiliary power, long duration CFM for the LH2 propellant and docking capability. The second component is an integrated saddle truss and LH2 drop tank assembly connecting the NTP stage to the mission payload that provides additional propellant storage for a wide range of mission and payload needs. • NTP has strong synergy with chemical rocket hardware and can use the same LH2 tanks in the launch vehicle. It can be developed in a timely manner at reasonable cost and can service both NEOs and Mars with same vehicle components helping to reduce overall cost.	↓	↓	● (blue)		● (blue)	● (blue)						Nuclear Thermal Propulsion (NTP) Engine	Nuclear propulsio engine	
Automated/Autonomous Rendezvous & Docking, Proximity Operations, and Target Relative Navigation • Maturation of subsystem technologies (relative navigation sensors, GN&C flight software, system managers, and mechanisms) to accomplish autonomous rendezvous and proximity operations for various in-space destinations such as satellite servicing and NEA exploration. The benefit of this technology development is to improve human safety, improve mission performance and flexibility by enabling autonomous rendezvous and proximity operations interactions with complex or uncontrolled planetary bodies. The U.S. space industry have yet to develop and demonstrate a robust Automated/Autonomous Rendezvous and Docking (AR&D) capability suite that can be confidently utilized on human spaceflight and robotic vehicles over a variety of design reference missions.	→	↑	● (red)	● (red)	● (red)	● (red)	PRISMA Studies of a Active Debris Removal Mission	Docking and berthing mechanisms (Robotic Servicing Mobility rovers (Rovers) Planetary rover navigation, hazard avoidance and mapping (Optics) Robotic arms (Robotic Servicing Sample handling equipment (Planetary Drilling Scientific rovers (Rovers) Situational awareness systems (Robotic Servicing) Utility rovers (Rovers)	Mobile Asteroid Surface Scout (MASCOT)	Advanced GNC fo autonomous RVD Advanced Robotic Orbital Servicing for active debris removal (ADR) GNC for un-cooperative target Vision-based sensors	Sensing and Control [On-orbit Docking] Crew Intervention Control [Autonomous and Crew Operation]	Anchoring Techniques & EVA Tools for u-G Surface Operation Crew Autonomy beyond LEO Automated/Autonomous Rendezvous & Docking, Proximity Operations, and Target Relative Navigation Telerobotic contro of robotic systems with time delay Surface Mobility	Autonomous Rendezvous and Docking, Proximity Operations	Autonomous Guidance and Control Adjustable Autonomy
Long Duration Spaceflight Medical Care • Strong evidence from spaceflight and analogs indicate that medical conditions of different complexity, severity, and emergency will inevitably occur during long-term Exploration missions. Long duration missions (>1 year) increase the risk of serious medical conditions due to limited options for return to Earth, no resupply, highly limited mass, volume and some communication delays. Plans for medical care consider the most likely medical conditions, their operational and health consequences and the resources needed for treatment. Plans for the medical system seek to minimize the probability of mission failure or loss of crew. • HRP's Integrated Medical Model (IMM) simulates medical events during space flight missions and estimates the impact of these events on crew health and mission success. A three-crew, 386 day, asteroid mission simulation with 28, 2-crew EVAs suggests an optimized medical kit having a mass of 62 kilograms and a volume of 0.15 m3. (These figures do not include all of the medical equipment needed for diagnosis). IMM is best used to make relative comparison between different missions or sets of resources, but the estimated probability of evacuation for this scenario is 9.8% and the probability of loss of crew is 2.8%. Risks on this order of magnitude warrant active mitigation. • The medical system must monitor and treat crewmembers during the mission. The requirements for the medical system are impacted by mission duration; number of EVAs; age and gender of the crew; and crew medical expertise •The return of biological samples is required to assess human system response to the mission in order to efficiently mitigate risks in future missions. •Technologies will be tested on ISS and in flight analog environments	↑	↑	● (red)	● (green)	● (red)	● (red)	Cardiolab Cardiospace, Cardiomed	Computer Simulation and Modelling (Radiation Mitigation) Intelligent diagnostic system (Advanced Crew Medical Systems) Lab-on-a-chip diagnostic system (Advanced Crew Medical Systems) Medical simulation systems (Advanced Crew Medical Systems) Radiation Biology (Radiation Mitigation) Radiation Measurement (metrology) (Radiation Mitigation) Remote patient monitoring system (Advanced Crew Medical Systems)		Crew Health Monitoring	Human Health[Space Medical] Space Medical [Space Medical]	Long Duration Spaceflight Medic Care Microgravity Biomedical Counter-Measures for Long Duration Spaceflight Microgravity Biomedical Counter-Measures - Optimized Exercis Equipment	Autonomous medical diagnostic systems and technologies Medical Diagnosis/Prognos and control in long-duration spaceflight Microgravity systems - measures for Long Duration Spaceflight	Intracranial blood pressure monitoring Gravity suit

LEGENDS

ISS TECHNOLOGY DEMONSTRATIONS
- ↑ ISS demonstrations are identified/planned
- → Candidate for ISS demonstrations
- ↓ Not a candidate for ISS demonstratons

ANALOG CAMPAIGN
- ↑ Technology is applicable to analog campaigns (AC Applicabl
- <Blank> Insufficient info to specify add'l categories (TBD)
- ↓ Not applicable to analog campaigns" (N/A)

DESTINATIONS
- ● (red) Technology development has been identified as critical by NASA as interpreted for this element/capability
- ● (blue) Technology development may be needed but architecture trades are not complete
- ● (green) Identified technology development entry is highly applicable to this element/capability
- ● (yellow) Identified technology development entry could be applicable to this element/capability

Partner Technology Area Applicability
- (dark green) High
- (green) Medium
- (light green) Low
- (white) Applicability data not available

Table 4: GER Critical Technology Needs and Investments (Examples).

IV. GLOBAL ANALYSIS OF CRITICAL TECHNOLOGY NEEDS AND INVESTMENTS

Each agency's technology development activities closely related to the identified critical technology needs have also been extracted from the GTDM. These planned activities stemming from the individual agency's portfolios of technology developments, along with the respective agency's investment plan for achieving the applicable objectives, provides a high-level analysis tool for showing potential advancement towards closure of the respective technology needs. This mapping of technology investments with respect to the critical needs is particularly helpful for advancement of the GER in two ways: firstly, it allows for the identification of technology development gaps, i.e., technologies where the current portfolio of activities from the participating agencies is unlikely to meet the required performance in the timeframe envisioned in the GER scenario. Those areas have to be subject to further assessment by the agencies to close the development gap. Secondly, the mapping highlights areas of common interest of several participating agencies. It encourages detailed technical discussion, where collaborative efforts can leverage individual investments or where dissimilar redundancy can increase robustness of the overall architecture.

For example in Table 4, Nuclear Thermal Propulsion has been identified as a candidate critical need for the asteroid and Mars destinations. Currently only NASA and Roscosmos have identified Nuclear Thermal Propulsion (TA 2.2.3) technology development in their respective investment portfolios. Subsequently, the prioritization of this particular technology should warrant significant investment if it's to be achieved in support of the GER roadmap.

Preliminary analysis of the critical technology needs has identified areas that only one agency has stated investment plans (i.e. NASA):

- Fire Prevention, Detection & Suppression (reduced pressure),
- Suit Port.

Another example from Table 4 is Autonomous Rendezvous & Docking, required for all destinations. However in this case, all of the GTDM participating partners have identified multiple activities with investment plans relating to supporting this particular critical need. This would be an area of potential international partnerships to avoid overlap of technology development, or also to re-prioritize internal agency investment planning into other technology needs where partner investment depth is not as deep (e.g. Long-Duration Spaceflight Behavioural Health and Performance).

A preliminary analysis of the critical technology needs has identified several areas where a majority of participating agencies have stated investment plans (i.e. six or more agencies):

- Automated/Autonomous Rendezvous & Docking, Proximity Operations, and Target Relative Navigation,
- Telerobotic control of robotic systems with time delay,
- Robots Working Side-by-Side with Suited Crew,
- Precision Landing & Hazard Avoidance,
- Long Duration Spaceflight Medical Care,
- Microgravity Biomedical Counter-Measures for Long Duration Spaceflight,
- Space Radiation Protection,
- Surface Mobility.

Although no single tool can thoroughly and completely assess the ISECG community's complete technology portfolio, the GTDM has provided an initial ability to evaluate identified critical needs mapped to investment planning for the individual agencies. And as with any high level analysis tool, follow up discussions with the specific agency technology developers will provide the actual required level of detail for making informed decisions for both the ISECG and the individual agencies.

V. GLOBAL ANALYSIS OF AREAS FOR COORDINATION

One of the global analyses using the GDTM is the areas analysis for coordination to identify the domains for collaboration among the agencies. If an agency wants to find a partner to develop the technologies, the GTDM provides insight into potential future collaborations. With this insight, the ISECG can facilitate interaction between the specific expertise at each agency to assist in determining if collaboration is possible and advantageous to each agency.

By bringing these potential collaborations to light, the ISECG hopes to help prevent agencies from unintentional duplicating efforts and thus reduce development costs and accelerate timelines. The scheme works very well if looking for collaboration opportunities across the multi-agency community because an agency may easily find other agencies that are interested in the same technology development areas to start directly sharing the detailed information among the agencies. Several areas have been identified as the developing areas where multiple agencies can start inventing as shown in Section IV.

Collaboration can occur at any point in the life-cycle of the technology's advancement (e.g., concept development, system/mission component development, mission execution). For example, an agency may wish to remain autonomous until their technology reaches TRL 5. At this point the agency would be willing to begin collaboration with other agencies to assist in progressing the technology further.

The GTDM can be utilized within an agency internally to find the partner agency for collaboration on particular areas. The GTDM could be utilized externally among the agencies to decide the areas based on the priorities of the agency's interest. In general, even with the GTDM, effort is required to find the partner within the allowable time limit. The ISECG hopes that GTDM can facilitate the interaction among the agencies to start the actual collaboration for the technology development.

With ESA being a collaboration of twenty member nations we have a strong example of how and why collaboration works. Future collaborations can be between ESA and other non-European agencies as well as between individual European nations and non-European nations.

VI. CONCLUSIONS

This paper presents the work and findings of a dedicated Technology Assessment Team chartered by the Exploration Roadmap Working Group of the ISECG. This work informed and complemented the development of the Global Exploration Roadmap, while it demonstrated an inherent value to the participating agencies in its own right. Through the development of the GER Technology Development Map (GTDM), the agency experts shared unprecedented detail on their respective agency's technology development activities and plans, advancing the common understanding of relevant technologies and systems for future human and robotic exploration. Today, the GTDM is a comprehensive relational database holding inputs from eight space agencies and providing individual and common analysis capability.

The analysis has focused on the relation of the agencies' technology activities to the ISECG Global Exploration Roadmap mission scenario and its elements. The GTDM indicates the applicability of the technology developments to the GER elements and identifies critical technology needs for their implementation. It therefore demonstrates the efforts of agencies to advance the coordinated steps towards human and robotic exploration of the Moon, near-Earth asteroids and Mars. By combining this information with individual priorities and investments of agencies, the GTDM provides essential information for the ISECG on the feasibility of the conceptual elements and capabilities as well as for the participating agencies on their planning for potential roles in a coordinated global exploration scenario. It facilitates the identification of areas where further coordination can benefit agencies with overlapping technology investments, areas where dissimilar redundancy can increase the robustness of exploration capabilities, and gaps where additional investments might be beneficial or required for sustainable exploration missions.

Findings from the global analysis described in this paper include the overview of international exploration technology development efforts, the mapping of agencies technology development activities to GER mission scenario elements, a list of critical technology needs for future GER implementation, listings of areas of common interest for future coordination and of areas of limited activity that require further attention.

The contents and capabilities of the GTDM are unique in providing such a detailed picture of technology development across the international exploration community. Participating agencies have expressed the wish to maintain and further develop the GTDM database within the ISECG, acknowledging its capabilities for sharing technology development information and for analysis as well as its value for individual agency planning for coordinated future space exploration.

[1] http://www.globalspaceexploration.org/
[2] http://www.nasa.gov/pdf/373665main_NASA-SP-2009-566.pdf
[3] http://www.nasa.gov/pdf/501317main_STR-Overview-Final_rev3.pdf
[4] GLEX-2012.09.3.1x12269 Assessment of Technology Developments for the ISECG Global Exploration Roadmap