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ASSESSMENT OF TECHNOLOGY DEVELOPMENTS FOR THE ISECG GLOBAL EXPLORATION ROADMAP

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As the International Space Exploration Coordination Group (ISECG) exploration scenarios mature, the Technology Assessment Team (TAT) of the Exploration Roadmap Working Group (ERWG) is striving to create opportunities for agency cooperation in the area of technology development while recognizing the autonomy of agencies related to such investment decisions, and the need for each agency to find promising technologies in the global exploration effort. The TAT is currently preparing additional levels of analysis of technology development activities for the next release of the GER. The goal for this next step is improving the coherence and level of detail of the collected inputs by adding high-level performance characteristics and identifying the applicability to exploration scenarios. This is achieved through a mapping process of the individual technology development activities to the specific elements and capabilities of the ISECG design reference missions. As a result, individual agencies can identify gaps as well as overlapping areas that could spur innovative competition and yield a more robust architecture. Joint activities, on the other hand, can create partnership opportunities not only related to technology demonstration missions or platforms but also to the usage of unique ground facilities or capabilities.

I. INTRODUCTION

As part of ISECG's Exploration Roadmap Working Group (ERWG), the goal of the Technology Assessment Team (TAT) is to facilitate leveraging investments in technology development efforts of individual ISECG agencies. While preparing the Global Exploration Roadmap* (GER), and under the lead of the TAT, agencies have already begun sharing information on their technology development investment areas and priorities. The GER already features in its current version a high-level categorization of the technology development input of participating agencies, providing a general overview of the applicable challenges.

As the ISECG exploration scenarios mature, the TAT is preparing additional levels of analysis for the next release of the GER. The goal for this next step is improving the coherence and level of detail of the collected inputs by adding high-level performance characteristics and identifying the applicability to exploration scenarios. This is achieved through a mapping process of the individual technology development activities to the specific elements and capabilities of the ISECG design reference missions. As a result, individual agencies can identify gaps as well as overlapping areas that could spur innovative competition and yield a more robust architecture. Joint activities, on the other hand, can create partnership opportunities not only related to technology demonstration missions or platforms but also to the usage of unique ground facilities or capabilities. The overall goal is to create opportunities for cooperation while recognizing agency autonomy in investment decisions and for allowing each agency to find promising technologies in the global exploration effort.

This paper provides a work-in-progress overview of the ISECG technology assessment activity targeting a consolidated contribution to the next iteration of the GER.

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*http://www.globalspaceexploration.org/c/document_library/get_file?uuid=bd0428e8-9163-4483-976f-57208dc6507f&groupId=10812

II. BACKGROUND

The individual inputs of the participating ISECG space agencies to the GER Technology Development Map (GTDM) are guided by varying constraints and assumptions. To better understand the GTDM, the mapping process and the preliminary findings, it is important to understand those individual considerations as they are expressed below.

CNES

The principles that CNES considered when providing inputs to the GTDM are the following:

- focus on innovative exploration technologies;
- identify priorities on robotic technologies for both scientific and exploration missions;
- investigate technologies with potentialities for space and Earth applications.

The list of technologies provided by CNES is not exhaustive. Additional activities are performed in many areas.

CSA

Canada's vision is to make full use of the International Space Station and to contribute science and develop technologies for the exploration of the solar system, with Moon and Mars being prime destinations. These contributions will include scientific instruments, space robotics, artificial vision, mobility systems, and human space flights.

The CSA's Space Exploration Branch will concentrate its technology development efforts on Canadian space exploration signature technologies that have high potential for terrestrial applications.

A signature technology is a Canadian product or product line for which Canada is or has the potential to become a world leader and that is usable for multiple space missions. A signature technology can be either well established or emerging. Established technologies are those that have flown successfully on missions and for which there is good potential in the future. Emerging technologies respond to the future needs of multiple potential missions and are important contributions for those missions. They are areas in which Canada attempts to become a world leader through dedicated technology development.

The technology development activities identified in CSA's GER Technology Development Map result from a breakdown of CSA space exploration signature technologies related to the GER. Other unrelated technology development activities are not included.

DLR

The DLR technology inputs summarize ongoing and planned activities within DLR with relevance to robotic and human exploration. Part of the activities are initiated and financed by the DLR Space Administration and run by industry or academia, others include in-house technology activities at various DLR research institutes. All activities aim at preparing and developing technologies as well as the German industry, academia and institutions for future participation to ESA and international missions. They shall mature and enhance existing expertise within Germany in selected technology areas and in a stepwise approach from making best use of existing assets such as the ISS through advanced automated and robotic activities. As such, the DLR activities to a wide extent have to be regarded as complementary to ESA technology activities.

The selected portfolio of technologies was identified in a top-down approach with a certain prioritization of technology areas, but does not claim to be comprehensive of all exploration-related activities within DLR. In addition to directly applicable technologies for the GER elements, DLR activities also include potential technologies for some science instruments as well as for facilities for ground demonstration and verification of exploration technologies

ESA

In view of contributing to future exploration missions, ESA is investing in a wide range of technologies, spreading from the short-term ISS-related to the beyond-LEO-exploration enabling ones.

In selecting the different research areas, the Agency pursues different objectives:

- sustain current and enable future human and robotic exploration beyond-LEO by means of relevant technology advancements in different strategic areas;
- stimulate the growth of the European innovation infrastructure through the development of new technological solutions in essential space exploration domains ;
- mature breakthrough solutions combining R&D activities and system development initiatives;
- contributing to the creation of high-tech jobs and know-how.

The ESA provided data set, highly consistent with the GER enabling technologies, is an overview of the ESA Technology Roadmap for Space Exploration. This input summarizes the current developments and the on-going preparatory activities (studies, breadboarding and early developments) across the Agency from which future capabilities will be derived.

JAXA

JAXA has developed and maintain the JAXA technology roadmap which covers all related technologies required for the practical space application within ten years by envisioning the future missions around twenty years later. The technology roadmap is not a firm plan, and it is different from the mission roadmap which reflects actual planned activities.

The listed technology development items relevant to the human space exploration have been selected from the current JAXA technology roadmap by taking the followings into account.

- To promote the technology innovation and development to play the leading and critical roles in the international space exploration.
- To promote R&D of the key technologies for human transportation systems, and human space exploration.
- To demonstrate new technologies related to the human using ISS/JEM, and accumulate technology and knowledge for future human exploration activities.
- To acquire the technology step by step by performing robotic exploration initially and by enabling human exploration eventually.

NASA

The NASA technology development data set input provided to ISECG/TAT was directly based on the Human Space Flight Architecture Team (HAT) Technology Development Team (TechDev) Cycle 2011-C data products[1]. The HAT Capability Driven Framework includes elements and Design Reference Missions (DRM's) that closely align with the GER elements and scenarios, and subsequently NASA's list of critically required technologies were appropriate for inclusion into the TAT GTDM.

The methodology used by the HAT TechDev Team to derive the technology development portfolio provided an architecture driven assessment (i.e., "technology pull") of technology advancement needs across the spectrum of review cycle trade-studies associated with the flight elements and destination DRMs. The HAT TechDev Team integrated inputs from the HAT element & destination leads, engineering & systems disciplines, and technology developers (e.g. Programs within NASA's Office of the Chief Technologist, and the Human Research Program).

The portfolio summary of all of the HAT TechDev data was captured in the HAT Technology Development Summary Report, along with individual mapping to the Cycle 2011-C elements and destination DRMs driving requirements ("technology pulls"). Each Technology Development entry represents a summary view of information related to a specific advancement of technology beyond the current State-Of-the-Art (SOA).

Users and beneficiaries of the HAT TechDev data products include:

- Technology developers prioritization (e.g. OCT roadmaps, Advance Exploration Systems projects)
- ISS technology demonstration inputs into utilization planning (e.g. IEWG actions)
- National Research Council (i.e. inputs into the OCT Roadmap review)
- NASA technology inputs for the ISECG/TAT GTDM (the focus of this paper/discussion)

Note: Only technology development that is required to enable human space flight was addressed. Therefore, technologies that can provide only enhanced capabilities (not enabling) and technologies applicable to TA08 "Science, Instruments, Observatories and Sensor Systems" technologies were not addressed at this time.

III. DEFINITIONS

To facilitate the discussions among the agencies on technology development, 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 3 tons, 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, Ariane 5, Soyuz, Sample acquisition robot, Gas sample acquisition device.
- *Technology*: A technology is a piece of hardware or software that provides one or more functionalities, e.g., vision system, manipulator.
- *Technology Development:* R&D activity advancing the TRL (typically to 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.

[1] Mercer, C. et al., "Critical Technology Determination For Human Space Flight". May 2012. GLEX-2012.09.3.3x12551

IV. TECHNOLOGY CATEGORIZATION

The various agencies technology development inputs have been categorized based on the Technology Areas developed by NASA's Office of the Chief Technologist[2]. In addition to the OCT reference, brief descriptions are provided below of those 14 Technology Areas (TA's), including (as sub-bullets) examples of some potential specific technology development activities that are consistent with the GER mission scenarios.

TA01 Launch Propulsion Systems: Earth to LEO Launch Propulsion Systems (Space Access). Enhance existing solid or liquid propulsion technologies by lower development and operations costs, improved performance, availability and increased capability.

- Heavy Lift Propulsion Technology (Oxygen-Rich Staged Combustion)

TA02 In-Space Propulsion Technologies: Advancements in conventional and exotic propulsion to improve thrust performance levels, increase payload mass and reliability, and lower mass, volume, operational costs, and system complexity for primary propulsion, reaction control, station keeping, precision pointing, and orbital maneuvering.

- Electrical Processing & Power Processing for Space Electrical Propulsion (SEP)
- High-Thrust Storable Propellant: for interplanetary missions (cryo propellant storage)

TA03 Space Power and Energy Storage: Improvements to lower mass and volume, improve efficiency, enable wide temperature operational range and extreme radiation environment for space photovoltaic systems, fuel cells, and other electrical energy generation, distribution, and storage technologies.

- Regenerative Fuel Cell and Energy Storage Systems
- Autonomously Deployable 10-100kW In-Space Arrays (for SEP)
- High Specific Energy Battery
- Regenerative Fuel Cells

TA04 Robotics, Tele-Robotics, and Autonomous Systems: Improvements in mobility, sensing and perception, manipulation, human-system interfaces, system autonomy. Advancing and standardizing interfaces for autonomous rendezvous and docking capabilities to facilitate complex in-space assembly tasks.

- Autonomous navigation and mobility support systems for surface robots
- Manipulators and Servicing Technologies
- Autonomous Rendezvous and Proximity Operations

TA05 Communication and Navigation: Technology advancements to enable higher forward & return link communication data rates, improved navigation precision, minimizing latency, reduced mass, power, volume and life-cycle costs.

- High Rate, Adaptive, Internetworked Proximity Communications
- In-Space Timing and Navigation for Autonomy

TA06 Human Health, Life Support, and Habitation Systems: Improvements in reliability, maintainability, reduced mass and volume, advancements in biomedical counter-measures, and self-sufficiency with minimal logistics needs for long duration spaceflight missions. Advancements in space radiation research, including advanced detection and shielding technologies.

- Radiation Prediction, Monitoring, and Protection Technologies
- Deep Space Suit (Beyond LEO, Surface-Moon, and Surface-Mars)
- High Reliability Life Support Systems
- Remote Health Monitoring, Telediagnostic and Telemedicine

TA07 Human Exploration Destination Systems: Technology advancements with In-Situ Resource Utilization (ISRU) for fuel production, O2, and other resources, improved mobility systems including surface, off-surface and Extravehicular Activity (EVA) and Extravehicular Robotics (EVR), advanced habitat systems, and advancements in sustainability & supportability technologies.

- ISRU Mars – Methane fuel production
- Dust Mitigation
- Crew Surface Mobility

TA08 Science, Instruments, Observatories and Sensor Systems: Technologies to advance current state-of-the-art for remote sensing instruments/sensors for scientific instruments, advanced scientific observatories, and In-Situ instruments/sensors of planetary samples.

- Planetary Protection and Astrobiology
- Orbital Optical and Radar Instruments for Surface and Atmospheric Characterization

TA09 Entry, Descent, and Landing Systems: Human-class capabilities for Mars entry, descent, and

[2] http://www.nasa.gov/pdf/501317main_STR-Overview-Final_rev3.pdf

landing; low mass high velocity Thermal Protection Systems (TPS), atmospheric drag devices, deep-throttling engines, landing gear, advanced sensing, aero-breaking, aero-capture, etc. Soft precision landing capability, e.g., for Moon and NEA's.

- EDL for Mars Exploration Class Missions
- Precision Landing and Hazard Avoidance

TA10 Nanotechnology: New advanced materials for reducing vehicle & structural mass, improved functionality and durability, and unique new capabilities such as enhanced power generation & storage, nano-propellants for propulsion, and nano-filtration for improved astronaut heath management.

Due to the capability-driven and utilization-based assessment for GER scenarios, no nanotechnology inputs have been brought forward by the participating agencies at this stage. However, this does not exclude relevant fundamental research is pursued, but simply that it is currently not directly attributed to exploration activities.

TA11 Modeling, Simulation, Information Technology and Processing: Advancements in technologies associated with flight & ground computing, integrated s/w and h/w modeling systems, physics based models, simulation and information processing.

- Test and Verification Environments for Robotic Systems
- Advanced Software Development/Tools

TA12 Materials, Structures, Mechanical Systems & Manufacturing: Technology advancements for lightweight structures providing radiation protection, multifunctional structural design and innovative manufacturing. New technologies for reducing design, manufacturing, certification and life-cycle costs.

- Debris Protection
- Mechanisms for Long Duration, Deep Space Missions
- High Strength Lightweight Materials

TA13 Ground and Launch Systems Processing: Technologies to optimize the life-cycle operational costs, increase reliability and mission availability, improve mission safety, reduce mission risk, reducing environmental impacts (i.e. green technologies).

The current assessment focused mainly on the space segment of the exploration roadmap, therefore only limited inputs have been collected with respect to ground processing activities.

TA14 Thermal Management Systems: Technology advancement for cryogenic systems performance & efficiency, effective thermal control systems for heat acquisition/transport/rejection, and increase robustness and reduce maintenance for thermal protection systems.

- Thermal Control High Efficient Radiator (two-phase coolant)
- In-Space Cryo Propellant Storage (Zero-Boil Off)
- Robust Ablative Heat Shield for Lunar & Beyond Lunar Return Velocities

V. GTDM DATA STRUCTURE

The basis for the GTDM is a data repository containing the agencies' technology development activities given the assumptions of Section II. The entries in the data repository contain the following information:

- #: Entry number
- Agency: agency submitting this technology development entry
- TA: Technology Area based on NASA's Office of the Chief Technologist (OCT) definitions; Note: each technology development should be broken down to a level that it can be assigned to a single TA; if multiple TAs are applicable to a technology development, it should be assigned to the primary TA
- Sub-TA: Sub-Technology Area as defined in the TA list sheet of this document (inspired by OCT's definition of sub-TAs)
- 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 metric where know/applicable
- Applicability of the elements/capabilities and, if possible, technology development needs
    - *Green*: agency identified technology development entry is highly applicable to this element/capability
    - *Yellow*: agency identified technology development entry could be applicable to this element/capability
    - *Red*: technology development has been identified as critical by NASA as interpreted for the for this element/capability
    - *Blue*: technology development may be needed but architecture trades are not complete

  - *Grey*: technology development is not applicable for this element/capability
  - Empty: not assessed
- Destinations: Mars orbit: Indicate technology development applicability to the Mars orbit as destination. (The color coding for applicability is the same as for the previous item.)
- Destinations: Mars surface: Indicate technology development applicability to the Mars surface as destination. (The color coding for applicability is the same as for the previous item.)
- ISS technology demonstrations
  - P: identified/planned for ISS demonstration
  - C: candidate for ISS demonstration
  - N: otherwise
- Technology push
  - Y: technology not required by any mission scenario
  - N: otherwise
- Comments

The following GER mission scenario elements and capabilities are currently considered in the GTDM:

- ROSCOSMOS Next Generation Spacecraft
- ROSCOSMOS Next Generation Space Launch Vehicle (NGSLV)
- NASA Space Launch System (SLS)
- NASA Multi-Purpose Crew Vehicle (MPCV)
- Cryogenic Propulsion Stage (CPS)
- Deep Space Habitat (DSH)
- Advanced In-Space Propulsion
- Space Exploration Vehicle (SEV)
- Lunar Lander - 1t Cargo
- Lunar Lander Descent Module
- Lunar Lander Ascent Module
- Lunar Surface Elements
- In-Space Robotics
- EVA

As an example, a snapshot of a subsection of the GTDM is shown in Figure 2. The overall TAT process can be summarized as per Figure 3.

VI. PRELIMINARY FINDINGS

The current version of the GTDM contains over 250 technology development data entries from six space agencies. It has to be noted that the provided entries, while already categorized along the TAs, are not yet all defined at the same level of scope and detail, which creates quite a challenge to analyze the GTDM and draw solid conclusions. Furthermore, the current version of the GTDM did not utilize the OCT X.Y sub-TA classification, but rather a TAT proprietary numbering system that was implemented for use with the first generation of the developed analysis tools. In addition, a sub TA category of "Other" was used within some TA's to provide a catch-all for some entries; unfortunately this limited good correlation for the tools and analysis. Note: the TAT plans to standardize to the new OCT TA classification scheme upon its official release by NASA, and subsequently will update the tools to better utilize the data for better mapping correlation and analysis.

All the findings presented below are preliminary. While one agency might have identified a technology development activity in great detail, others might not yet have broken down their entries to the same level and their correct accounting at all corresponding sub-TAs. It should be noted as well that there is no complete list of technology requirements to implement all the GER elements/capabilities coming from any ISECG working group. It can however be assumed that NASA has identified the most complete list of critical technologies through their HAT exercise.

Hence, the technology development inputs to the GTDM are:

- needs driven based on GER elements/capabilities for NASA entries and
- portfolio/capability driven or by the desire to contribute for other agencies.

Figure 1 provides an overview of technology development activities by sub-TA[3] identified under the assumptions given in Section II. This figure gives a first impression of which agencies are investing in common technology areas. For example, several agencies invest in 4.3 Autonomous Rendezvous and Docking. In contrast, only one agency is investing in 6.7 Fire Detection and Suppression. The latter indicates little opportunity for collaboration, while the former indicates many possible opportunities. At the same time, low activity may pose programmatic risk to the development, particularly for critical elements.

Figure 4 highlights the technology developments (categorized per sub-TA) that NASA has identified as required to implement that specific element/capability and that no other agencies are investing in. In other words, if NASA is not pursuing this activity, that element is at risk. For example, NASA has identified the sub-TA Fire detection and suppression as required for the Deep Space Habitat DSH. However, no other agency has identified any related

[3] Please note that the currently used sub-TAs are not fully aligned with the NASA OCT subcategories.

technology development applicable for that element/capability[4].

Figure 5 displays the number of identified technology development activities per element/capability. The yellow color indicates that only one activity has been identified. For the green colored fields, the darker the color the more activities are identified, applicable to two and more. For instance entry 6.1 Human Health has multiple activities associated with Lunar Surface Element (dark color), while for 4.2 Autonomy associated with the MPCV has only a moderate number identified (lighter color). From this chart one can expect that the darker the color (and hence the more activities identified), the larger the potential for collaboration on technology developments for that element/capability.

Although the current stage of this information gathering and analysis activity indicates some interesting opportunities related to interagency collaboration, the reader should more focus on the GTDM framework and possibilities for analysis than these preliminary findings.

The GTDM can also be compared to the NRC[5] report, which defines three Technology Objectives, with the first 2 objectives most directly related to the GER:

- Technology Objective A: *Extend and sustain human activities beyond low Earth orbit.* Technologies to enable humans to survive long voyages throughout the solar system, get to their chosen destination, work effectively, and return safely; and
- Technology Objective B: *Explore the evolution of the solar system and the potential for life elsewhere*. Technologies that enable humans and robots to perform in-situ measurements on Earth (astrobiology) and on other planetary bodies.
- Technology Objective C: *Expand our understanding of Earth and the universe in which we live.* Technologies for remote measurements from platforms that orbit or fly by Earth and other planetary bodies, and from other in-space and ground-based observatories

[4] This conclusion is preliminary since agencies have only provided selected, prioritized inputs of their activities. However, it is a useful finding for further assessment.

[5] The Steering Committee for NASA Technology Roadmaps; National Research Council of the National Academies identifies in its report entitled NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space, 2012.

SubTA	CNES	CSA	DLR	ESA	JAXA	NASA
1.1 Liquid	○	○	●	○	●	●
1.2 LAS	○	○	○	○	●	○
1.3 Solid	●	○	○	○	○	○
1.4 Other	●	○	○	○	○	○
2.1 Chemical	●	○	●	●	●	●
2.2 Electric	●	○	○	●	●	●
2.3 Cryo-Prop	●	○	○	●	●	●
2.4 Nuclear	○	○	○	○	○	●
2.5 Other	○	○	○	○	○	○
3.1 RFC	○	○	●	●	●	●
3.2 Batteries	○	○	○	●	●	●
3.3 Solar	○	○	○	●	●	●
3.4 Nuclear	●	○	○	●	○	●
3.5 Other	○	○	○	○	○	○
4.1 Manipulators	○	●	●	●	●	○
4.2 Autonomy	●	●	●	●	●	●
4.3 AR&D	●	●	●	●	●	●
4.4 Sensors	○	●	●	●	●	○
4.5 Mobility	○	●	●	○	●	○
4.6 Human Interaction	○	○	○	●	●	●
4.7 Other	○	○	●	○	●	○
5.1 Nav	○	●	○	●	●	●
5.2 Comm	●	○	●	●	●	●
5.3 Other	●	○	○	○	○	●
6.1 Health	●	●	○	○	●	●
6.2 ECLSS	○	○	●	●	●	●
6.3 Radiation	○	●	●	○	●	●
6.4 EVA	○	○	○	○	●	●
6.5 Habitation	○	○	○	○	●	●
6.6 Environmental Monitoring	●	○	○	●	○	●
6.7 Fire	○	○	○	○	○	●
6.8 Other	○	○	○	○	○	○
7.1 Mobility	○	●	○	●	●	●
7.2 ISRU	○	●	●	●	●	●
7.3 Dust	○	○	○	○	●	●
7.4 Other	○	○	●	○	○	●
8.1 Science Package	●	●	●	●	○	○
8.2 Other	●	○	●	○	○	○
9.1 Entry	●	○	●	●	●	○
9.2 Descent	●	○	●	○	●	○
9.3 Landing	○	○	●	●	●	●
9.4 Other	○	○	○	●	○	●
11.1 All	●	○	●	○	○	●
12.1 Materials	○	●	●	○	●	○
12.2 Structures	○	○	○	○	○	○
12.3 Mechanisms	○	○	○	●	○	●
12.4 Other	○	○	○	●	○	●
13.1 Ground Comm	○	○	●	○	○	○
13.2 Other	○	○	○	○	○	●
14.1 TPS	●	○	●	●	●	●
14.2 Thermal Control	○	○	●	●	●	●
14.3 Other	○	○	○	○	○	○

Figure 1: Overview of technology development activities by Sub-TA (filled circles represent technical areas supported by each agency).

That report identifies a number of priority technologies for each of those objectives. Table 1 shows the mapping of the technology development activities of the individual participating agencies identified in the GTDM against those "Final Prioritization of Top Priority Technologies" for Objectives A and B. The NRC's "16 Top Priority Technologies" list is a subset of the identified 83 "High Priority" technologies, provided to NASA as a recommended prioritized list based on a near-term 5-year horizon and anticipated budget funding level. Note: 12 of the NRC's "16 Top Priority Technologies" are applicable to the GER and shown in Table 1 (Note: the remaining 4 Top Priority Technologies are largely applicable to science sensor & instrumentation systems).

A preliminary analysis of the current GTDM dataset shows that all those top technologies have associated development activities identified by multiple agencies, with the exception of Nuclear Thermal Propulsion and Fission Power Generation, which is only identified by NASA.

NRC Final Prioritization of the Top Technologies for Objective A+B	Technology development activity identified					
	CNES	CSA	DLR	ESA	JAXA	NASA
Radiation Mitigation for Human Spaceflight (X.1)		x	x	x	x	x
Long-Duration Crew Health (6.3.2)	x	x		x	x	x
ECLSS (X.3)			x	x	x	x
GN&C (X.4)		x	x	x	x	x
(Nuclear) Thermal Propulsion (2.2.3)						x
Lightweight & Multifunctional Materials & Structures (X.2)		x	x	x	x	x
Fission Power Generation (3.1.5)						x
EDL TPS (X.5)	x		x	x	x	x
Solar Power Generation (Photovoltaic and Thermal) (3.1.3)				x	x	x
Electric Propulsion (2.2.1)	x			x	x	x
In-Situ Instruments and Sensors (8.3.3)		x	x	x		x
Extreme Terrain Mobility (4.2.1)		x	x	x	x	x

Table 1: GTDM mapping to NRC Top Technical Priorities.

VII. CONCLUSIONS

From the work carried out to date we conclude the following:

- The development of a repository of technology development activities can be very helpful to identify opportunities for collaboration and hopefully leverage investments that advance critical exploration technologies.
- The quality of the analysis of the repository depends strongly on the consistent level of breakdown of the data entries.
- The TAT itself is an excellent forum for agencies to share their technology development roadmaps and investment priorities and to start a dialog on coordination and cooperation opportunities in order to leverage investments.

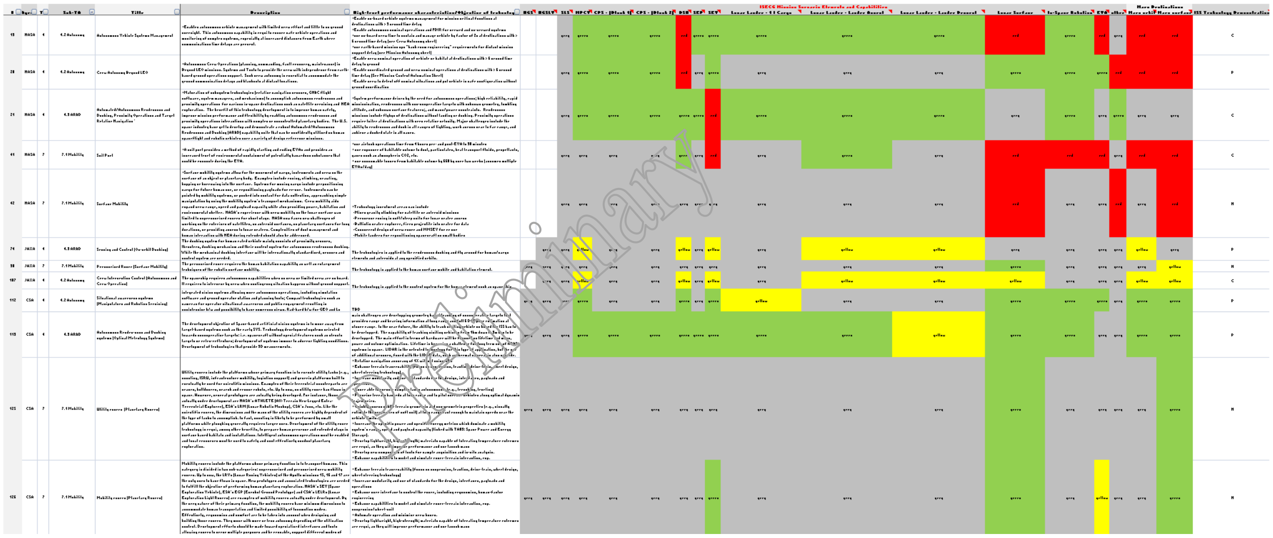


Figure 2: Snapshot of subsection of the GTDM.

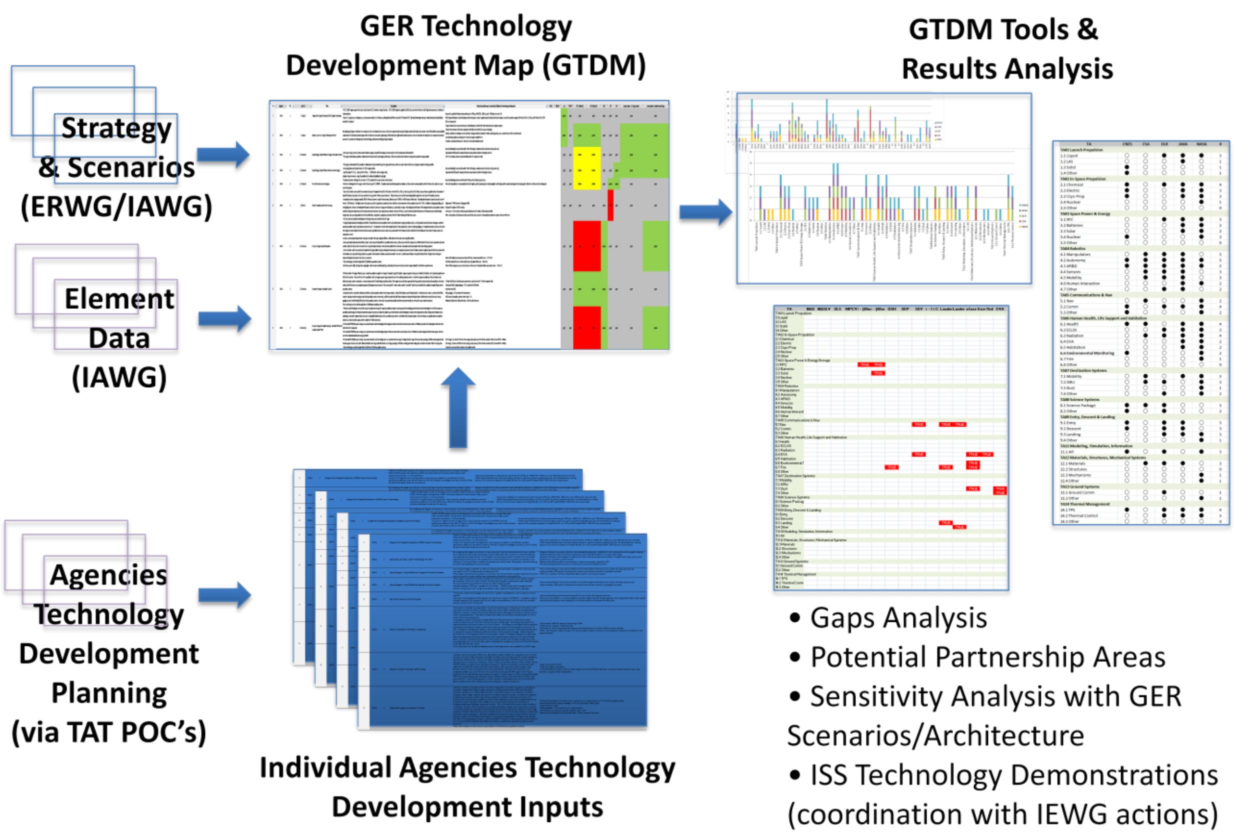
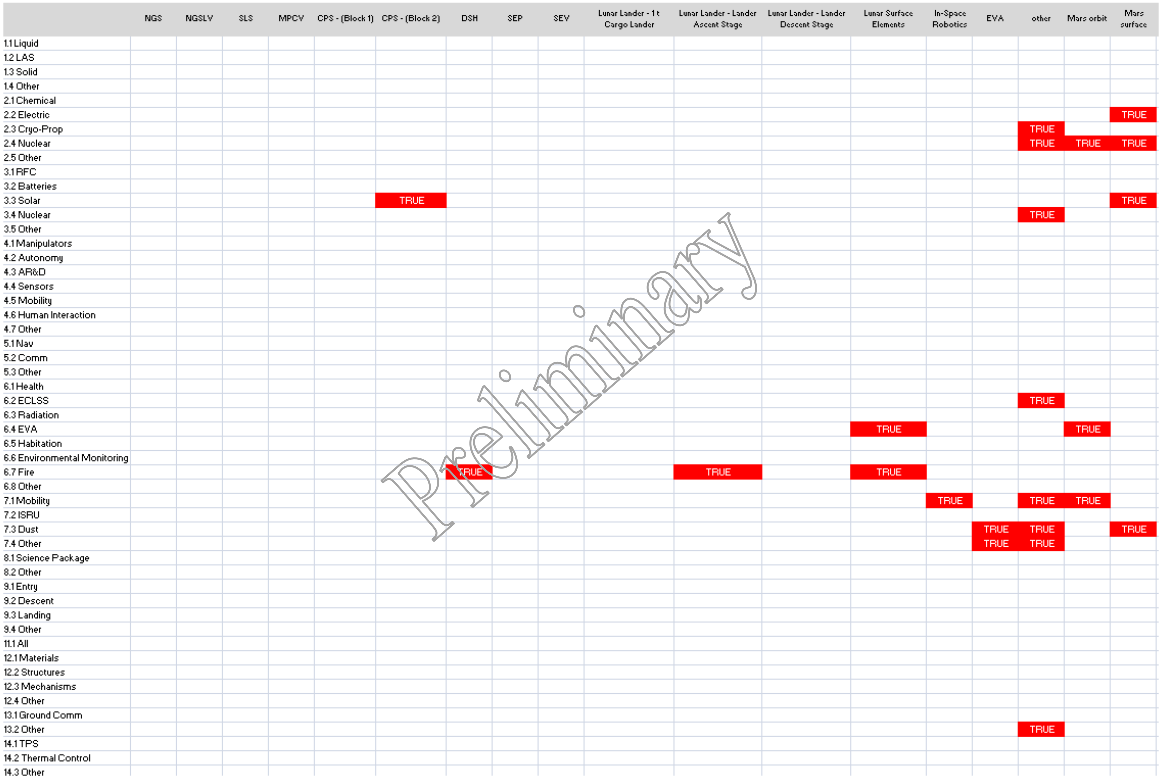


Figure 3: TAT Technology Development Data Capture & Analysis Process.



	NGS	NGSLV	SLS	MPCV	CPS - (Block 1)	CPS - (Block 2)	DSH	SEP	SEV	Lunar Lander - 1t Cargo Lander	Lunar Lander - Lander Ascent Stage	Lunar Lander - Lander Descent Stage	Lunar Surface Elements	In-Space Robotics	EVA	other	Mars orbit	Mars surface
1.1 Liquid																		
1.2 LAS																		
1.3 Solid																		
1.4 Other																		
2.1 Chemical																		
2.2 Electric																		TRUE
2.3 Cryo-Prop																TRUE		
2.4 Nuclear																TRUE	TRUE	TRUE
2.5 Other																		
3.1 RFC																		
3.2 Batteries																		
3.3 Solar						TRUE												TRUE
3.4 Nuclear																TRUE		
3.5 Other																		
4.1 Manipulators																		
4.2 Autonomy																		
4.3 AR&D																		
4.4 Sensors																		
4.5 Mobility																		
4.6 Human Interaction																		
4.7 Other																		
5.1 Nav																		
5.2 Comm																		
5.3 Other																		
6.1 Health																		
6.2 ECLSS																TRUE		
6.3 Radiation																		
6.4 EVA													TRUE				TRUE	
6.5 Habitation																		
6.6 Environmental Monitoring																		
6.7 Fire							TRUE				TRUE		TRUE					
6.8 Other																		
7.1 Mobility														TRUE		TRUE	TRUE	
7.2 ISRU																		
7.3 Dust															TRUE	TRUE		TRUE
7.4 Other															TRUE	TRUE		
8.1 Science Package																		
8.2 Other																		
9.1 Entry																		
9.2 Descent																		
9.3 Landing																		
9.4 Other																		
11.1 All																		
12.1 Materials																		
12.2 Structures																		
12.3 Mechanisms																		
12.4 Other																		
13.1 Ground Comm																		
13.2 Other																TRUE		
14.1 TPS																		
14.2 Thermal Control																		
14.3 Other																		

Figure 4: Critical technologies identified by NASA, but no other agency investing in.

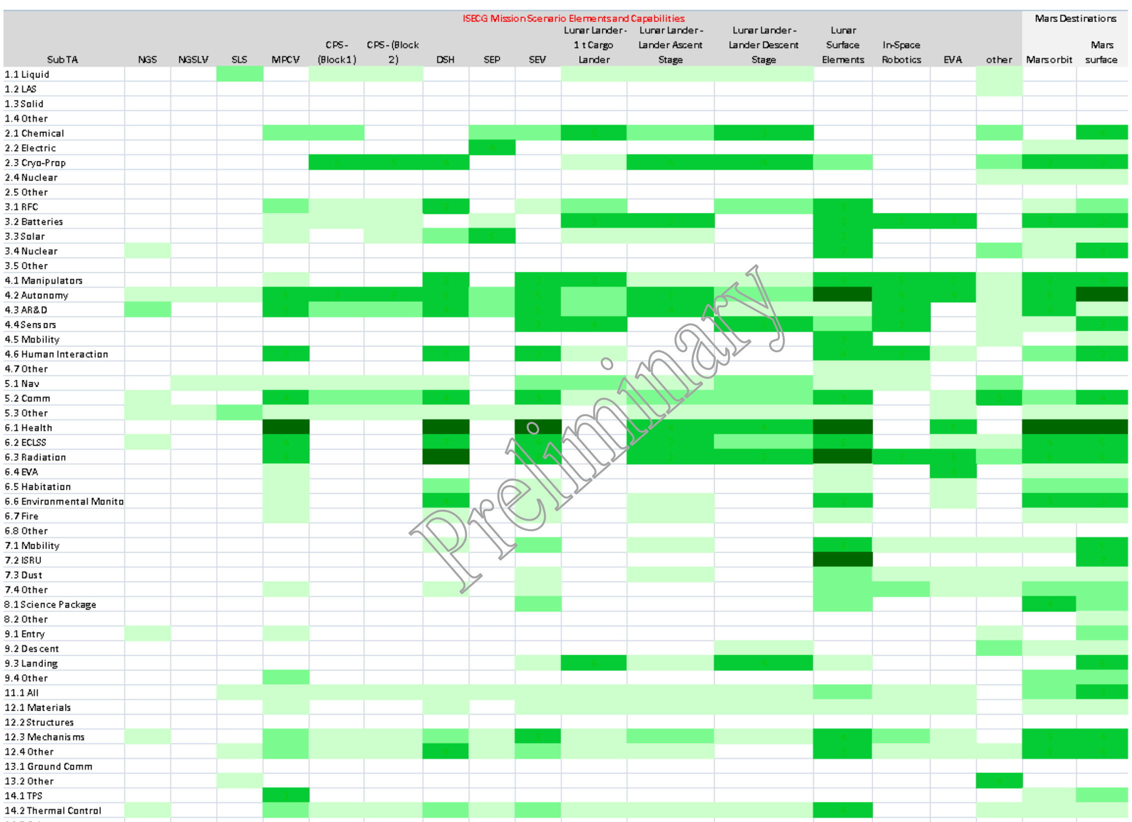


Figure 5: Number of technology development activities per sub-TA and element/capability
(Note: darker color represents more technology development activity identified).

APPENDIX A: ACRONYMS

CNES	Centre National d'Etudes Spatiales
CPS	Cyro Propulsion Stage
CSA	Canadian Space Agency
DDT&E	Design, Development, Test and Evaluation
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt e.V.)
DRM	Design Reference Mission
DSH	Deep Space Habitat
ECLSS	Environmental Control and Life Support System
EDL	Entry, Descent, Landing
ERWG	Exploration Roadmap Working Group
ESA	European Space Agency
EVA	Extravehicular Activity
EVR	Extravehicular Robotics
GER	Global Exploration Roadmap
GTDM	GER Technology Development Roadmap
HAT	Human Space Flight Architecture Team
HRP	NASA's Human Research Program
HSF	Human Space Flight
IAWG	International Architecture Working Group
IEWG	ISS Experts Working Group
ISECG	International Space Exploration Coordination Group
ISRU	In-Situ Resource Utilization
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JEM	Japanese Experiment Module
LEO	Low Earth Orbit
MPCV	Multipurpose Crew Vehicle (NASA)
NASA	National Aeronautics and Space Administration
NEA	Near Earth Asteroid
NEO	Near Earth Object
NGSLV	Next Generation Space Launch Vehicle (ROSCOSMOS)
NRC	National Research Council
NTP	Nuclear Thermal Propulsion
OCT	NASA's Office of the Chief Technologist
PDR	Preliminary Design Review
R&D	Research & Development
REM	Robotics and EVA Module
SEP	Solar Electric Propulsion stage
SEV	Space Exploration Vehicle
SLS	Space Launch System (NASA)
SOA	State of the Art
TA	Technical Area
TAT	Technology Assessment Team
TBD	To Be Determined
TRL	Technology Readiness Level
TPS	Thermal Protection System