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Decision Analysis Methods Used to Make Appropriate Investments in Human Exploration Capabilities and Technologies

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NASA is transforming human spaceflight. The Agency is shifting from an exploration-based program with human activities in low Earth orbit (LEO) and targeted robotic missions in deep space to a more sustainable and integrated pioneering approach. Through pioneering, NASA seeks to address national goals to develop the capacity for people to work, learn, operate, live, and thrive safely beyond Earth for extended periods of time. However, pioneering space involves daunting technical challenges of transportation, maintaining health, and enabling crew productivity for long durations in remote, hostile, and alien environments. Prudent investments in capability and technology developments, based on mission need, are critical for enabling a campaign of human exploration missions. There are a wide variety of capabilities and technologies that could enable these missions, so it is a major challenge for NASA's Human Exploration and Operations Mission Directorate (HEOMD) to make knowledgeable portfolio decisions. It is critical for this pioneering initiative that these investment decisions are informed with a prioritization process that is robust and defensible. It is NASA's role to invest in targeted technologies and capabilities that would enable exploration missions even though specific requirements have not been identified. To inform these investments decisions, NASA's HEOMD has supported a variety of analysis activities that prioritize capabilities and technologies. These activities are often based on input from subject matter experts within the NASA community who understand the technical challenges of enabling human exploration missions. This paper will review a variety of processes and methods that NASA has used to prioritize and rank capabilities and technologies applicable to human space exploration. The paper will show the similarities in the various processes and showcase instances were customer specified priorities force modifications to the process. Specifically, this paper will describe the processes that the NASA Langley Research Center (LaRC) Technology Assessment and Integration Team (TAIT) has used for several years and how those processes have been customized to meet customer needs while staying robust and defensible. This paper will show how HEOMD uses these analyses results to assist with making informed portfolio investment decisions. The paper will also highlight which human exploration capabilities and technologies typically rank high regardless of the specific design reference mission. The paper will conclude by describing future capability and technology ranking activities that will continue to leverage subject matter experts (SME) input while also incorporating more model-based analysis.

CAPABILITY AND TECHNOLOGY INVESTMENT DECISIONS

NASA's need for informed capability and technology investment decisions

One of the roles of NASA's Human Exploration and Operations Mission Directorate (HEOMD) and Space Technology Mission Directorate is to invest in targeted technologies and capabilities that would enable human exploration missions. The identification of these technologies and capabilities is based on the missions, campaigns, destinations, architectures, elements, systems and subsystems that are needed to enable human exploration. Once all the technologies and capabilities are identified, NASA must make wise investment decisions to determine which ones to invest in the near term, which ones can be delayed, and which ones enable the mission as opposed to enhance the mission. These investment decisions must be made because NASA's capability and technology development budget will not allow for the development of all these capabilities and technologies simultaneously. Making these investment decisions can be difficult because of the many criteria included in enabling these systems. First, it is important to have requirements that drive the technologies. Many investment decisions need to be made early on in the conceptual phase, prior to standing up an official program. Since specific requirements aren't thoroughly derived at the conceptual level, it is difficult to determine in what to invest and the timing of those investments. Capability and technology development can still proceed without derived requirements as long as some performance metrics are identified. Performance metrics are determined by considering element functionality which is dependent on the mission architecture. During the conceptual phase, many architecture trade studies are undertaken to determine how changes in the architecture change the elements needed to enable the missions. Trade studies and system analysis also show how changes affect the exploration goals and objectives.

In theory, there could be a variety of systems that enable human exploration missions. Identification of these systems based on functional allocation could yield a variety of capabilities and technologies, thus making it difficult to clearly prioritize capabilities and technologies. While all of these trade studies are happening at various levels, technology and capability development organizations continue to invest and develop systems that the developers identify based on their understanding of the missions. Figure 1 shows a notional trade tree that could be used to determine functional capabilities and technologies.

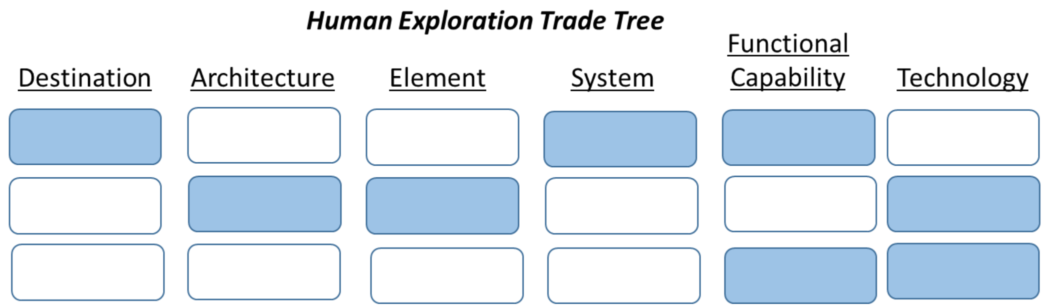

Figure 1. Human Exploration Trade Tree

Once specific exploration programs are officially stood up, then deep dive analysis can be performed and specific element requirements can be derived. NASA has several technology and capability development organizations that are investing resources on the early development and maturation of capabilities and technologies that could potentially enable exploration missions. These organizations develop portfolios that identify state of the art, beyond state of the art, and high risk game changing capability and technology development activities. Portfolio management is an important aspect for the technology and capability development organizations. In order to support the capability and technology development organizations and mission trade studies, NASA desires to inform these investment decisions.

CAPABILITY AND TECHNOLOGY ASSESSMENT AND INTEGRATION TEAM

NASA Langley Research Center's (LaRC) Technology Assessment and Integration Team (TAIT) was organized to develop a robust and defensible methodology and process to rank capabilities and technologies over a variety of disciplines. NASA mission directorate leadership is often asked to invest in technology development efforts based on a variety of drivers. Some of the drivers for these investments include:

- Investments based on which group of technologists or managers at the various NASA Research Centers or subcontractors who have the most political influence, have the best presentation to make their case, or have the most or last access to the decision maker(s)
- Investments based on maximizing continuity with current on-going research at the NASA Research Centers to ensure workforce stability and minimize complaints
- Investments of resources to the technology areas and groups of technologists at the various NASA Research Centers that have been perceived to have the best record of achieving results in the past

TAIT's customers were not satisfied with the results from the methods mentioned above and required a technology ranking methodology and process that was robust, defensible, traceable to architecture studies, repeatable and independent. The motivation for performing these decision making analysis activities include:

- Extremely tight HEOMD budgets require capability and technology insertion into architecture to reduce development and operating costs and ensure architecture closure and focus on near-term architecture benefits.
- Limited budgets require investments in capabilities and technologies with high probability of success, requiring methods of accurately quantifying development risk.
- Limited budgets require investments in technologies strongly linked to architecture requirements, requiring methods of accurately quantifying benefits.
- Limited budgets require accurate assessments of technology project costs.
- Many exploration design reference missions, architecture baseline designs and requirements are still evolving.

TAITs methodology incorporates a continuous requirements-driven process that begins at the conceptual stage of a program and continues through final design. Technology investment decisions are driven by benefit to the architecture through Figures of Merit (FOMs) linked to architecture requirements. This methodology is derived by requirements from architecture capability needs and provide traceability of technologies to architecture elements. This methodology includes cost and risk assessments where applicable. This methodology also allows for use of quantitative data and structured expert judgment for assessment. This methodology allows for integration of data and allows for identification of gaps and synergies. This methodology assesses an integrated portfolio by utilizing a technology portfolio tool or “calculator”, which examines sensitivities to assumptions and provides decision maker preferences. Lastly, this method provides independent, objective analysis of technologies, capabilities, performance metrics and requirements. The end goal for TAIT’s capability and technology ranking process is to provide defensible objective prioritization process for exploration based on non-biased solicited input from exploration systems SME’s and NASA leadership and decision makers.

TAIT CAPABILITY AND TECHNOLOGY PRIORITIZATION METHODOLOGY

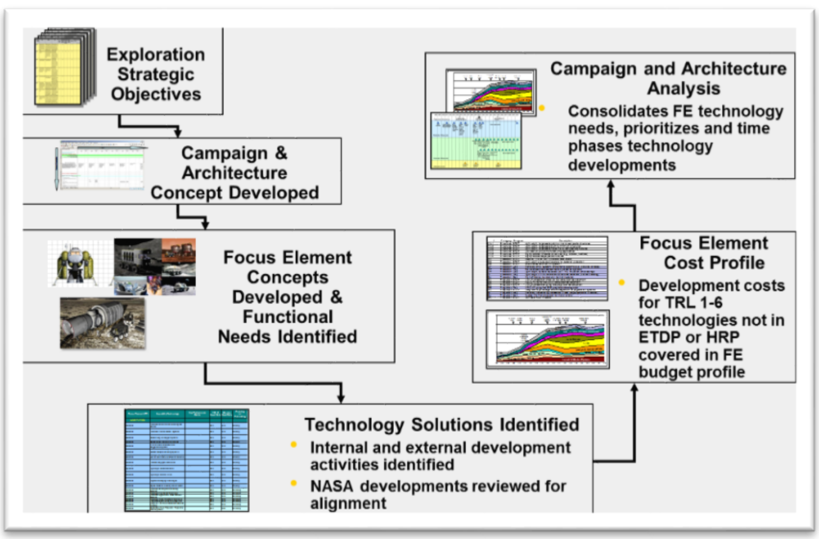

Figure 2. Top Level Methodology

Numerous technology prioritization methodologies are documented in the literature. Some heavily rely on subject matter data elicitation while others are thoroughly based on empirical analysis using quantitative data. Little literature exists that actually demonstrates the efficacy of any one methodology or approach, for every organization has differing levels of data quality and quantity. Thus any organization that performs technology prioritization can rarely adopt a published methodology without some degree of customization to their needs. The following describes the generalities of the approach used by TAIT in support of various customers and represents an informal combination of numerous methodologies documented by others.

The approach used in this framework incorporates the following characteristics:

- Make maximum use of quantitative data
- Include the ability to perform qualitative and quantitative evaluations

- Allow collaborative, real-time participation by experts and stakeholders
- Provide a method for weighting evaluation criteria
- Allow the evaluation of costs as well as benefits
- Allow the integrated evaluation of capabilities and technologies against multiple systems
- Include consideration of incompatibles or interaction between technologies
- Include the ability to assess uncertainty and quantify risk
- Allow the performance of sensitivity analysis and visualization of results
- Be easy to understand and explain
- Be systematic, repeatable, objective and open to scrutiny

During the final phase of the prioritization process, TAIT collects input from programmatic experts and NASA headquarters decision makers so they can assign weighting to each FOM. The mechanism used to perform the weighting is the Analytical Hierarchy Process (AHP). AHP is used to do a pairwise comparison of each FOM. TAIT also performs sensitivity analysis, which is done at all levels so the impact of the uncertainty in assumptions can be understood. The summary results are produced using FOM scoring, FOM weighting, and sensitivity analysis. If cost values are available TAIT has used this information to calculate return on investment (ROI) and cost and risk benefits. Figure 3 shows a graphical representation of TAIT's prioritization methodology.

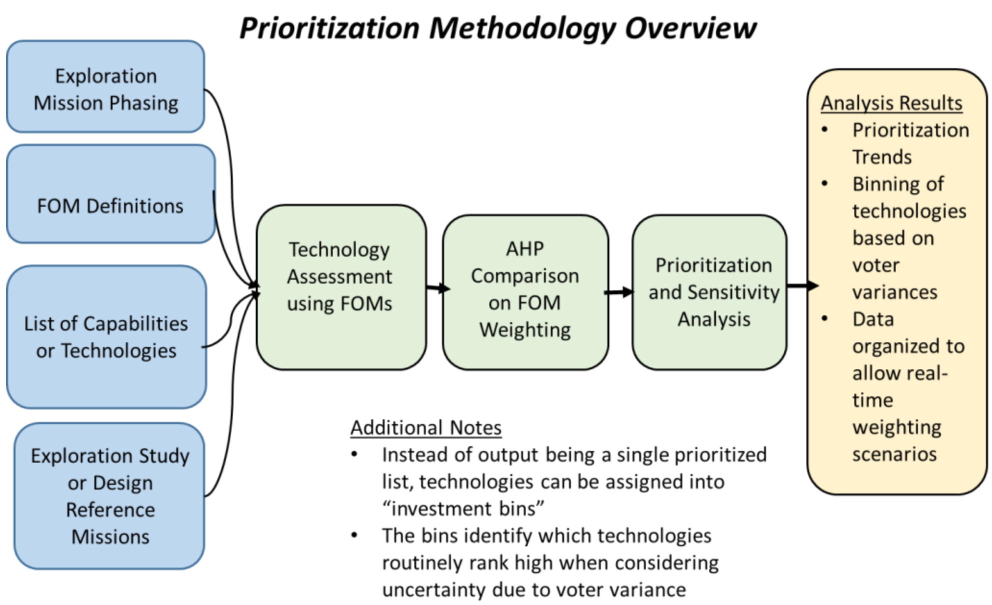

Figure 3. TAIT's Prioritization Methodology

ANALYSIS TYPES

Subjective Matter Expert Data Elicitation

The primary analysis method used by TAIT involves the use of subject matter experts (SME) voting processes combined with numerical consolidation and assessment. For instance, a set of FOMs are commonly used to gauge the impact that each technology could have to a given mission or architecture, with the actual technology-to-FOM values being based on SME voting. Voting can take place either in real-time in a workshop environment or could be solicited via email or other means. The benefit to this approach is that it compensates for lack of data. When used correctly it also rolls up various disparate voter preferences into a consolidated set of data that represents the voting pool's assessment of the data. Since technology data are usually sparse this approach is commonly used. The use of SME data elicitation can be fraught with challenges related to various biases that are often present. First, a significant amount of communication and coordination is required up front to ensure that all voters share a common understanding of nomenclature, FOM definitions, technology descriptions, and mission/architecture content. Some variability within voting results is expected, and actually wanted, but should be related to the various perspectives and opinions of the voters themselves. Additional variability due to misunderstanding of FOM definitions or other voting framework considerations is not wanted. Another type of bias is introduced when the voting population is not diverse enough to represent all potential perspectives. If the voting population is small and is largely drawn from a single organization or office, the voting preferences and opinions may be highly reflective of that organization's perspective. Another version of this bias is if all voters are drawn from a lower "technologist" level without proper representation of mission/architecture level systems thinkers and vice versa. An optimal voting population would be equally drawn from lower technology level experts and higher level systems thinkers, as well as from multiple organizations or offices.

Hybrid Approach

Because both subjective matter expert elicitations and model-based analysis have strengths and weaknesses, a third approach combines the best of both in an attempt to eliminate unwanted subjectivity while acknowledging the need for voter influence beyond empirical data from models. There are numerous ways to combine the two, but one approach that has been shown to work well is to provide model-based impact results, for use as guides, to the subject matter experts participating in FOM voting. This allows those voters to better understand the *potential* impacts that various technology options may have on systems and architectures, but provides them an opportunity to infuse their own expertise and knowledge that the models may not be appropriately capturing. For instance, voters may be aware of key political or senior level guidance constraints that were not captured by the modeling. If the model results were translated directly into FOM results this knowledge would not be captured. However, by allowing the voters the opportunity to vote on the FOMs themselves, with model results in hand, they could combine the objectivity provided by the models along with whatever additional considerations needed to be captured. TAIT used this hybrid approach during the Mars Entry, Descent and Landing Systems Analysis Study (Mars EDL SA). This study was sponsored by NASA's Office of Chief Engineer (OCE). Specifically TAIT was asked to perform technology prioritization and subsequently architectures prioritization of EDL system for a Mars Exploration-Class mission. Figure 4 shows how model-based analysis and subject matter expert elicitations can be used to prioritize technologies.

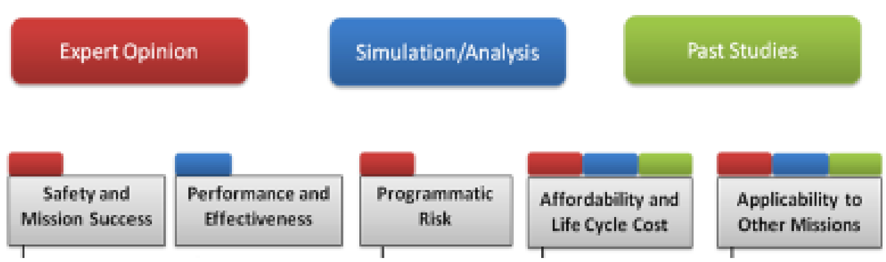

Figure 4. Hybrid Technology Assessment Approach

Model-Based Analysis

Model-based analysis leverages parametric analysis tools and capabilities to quantify the actual impact that various technologies have on potential systems and architectures. This is achieved by determining key performance parameters, or impact metrics, that each technology would have on each system(s) within an architecture. When the systems and architectures are then modeled parametrically, analysts can propagate the technology impacts throughout the model to understand the resulting impact on key FOMs. If uncertainties are known, various forms of probabilistic analyses can be used. The strength to this approach is that quantified insight can be garnered for the impact of each technology. This approach also introduces a sense of repeatability and objectivity to FOM scoring, for if uncertainty is limited the results should largely be dependent on the various algorithms within the model. If the modeling environment is broad in scope it may include cost and affordability assessments and loss of crew/loss of mission reliability analysis. These disciplines are often very subjective due to data paucity, so the objectivity provided by model-based analysis can be very useful. However, because data are very limited, particularly during conceptual design, model-based analysis can be a challenge. The additional confidence and sense of objectivity that model-based analysis provides should be tempered if initial data assumptions and knowledge are suspect. Models should be validated and verified to the extent possible, and even then may not properly account for various types of uncertainties that are simply due to the conceptual nature of early design. Even if all models are validated and consistently implemented, there are still some related limitations. First, there are numerous considerations that usually are not correctly captured using analysis models. For example, political ramifications and senior level guidance often trump other considerations. Secondly, an over reliance on model-based analysis may cause subject matter expertise to be discounted or overlooked. No results of any model should be used without consideration and review by the appropriate subject matter experts.

TYPES OF RESULTS

Depending on the quality and quantity of data used, prioritization results can take numerous forms. Traditionally, methodologies provide a ranked ordering of various technology candidates. This type of result is useful for understanding the actual ordering in which the various technology investments should be considered. This form of result is easy to understand and helpful to draw conclusions from. However, the quality of such a ranked ordering of results is only as good as the various data used as inputs. When using expert data elicitation, the results may only be based on a small set of subject matter experts available to support the voting processes. When using a model-based approach the input data may contain high levels of uncertainty. The danger lies in drawing any significant conclusions on a ranked ordering of results in these cases since a small change (voter addition/subtraction or modification of input assumption) could drastically impact the actual ordering. What may have been a top investment option may rapidly fall to a lesser attractive option when results are highly sensitive.

Two alternative approaches are available to address this challenge. If a ranked ordering of results is required based on customer needs, additional analysis should be performed to understand and visualize the various sensitivities to assumptions. For example, the following sensitivities and analyses could be considered (where warranted):

- Addition/removal of set(s) of voter results
- Varying emphasis on cost impacts when assessing benefit-to-costs
- Analysis of various FOM weighting scenarios
- Analysis of various SME weighting scenarios

Another alternative approach is to use a binning methodology to consolidate various results in a series of "bins" based on a combination of their overall score and some uncertainty metric associated with their overall score results. This approach allows customers to understand which groupings of investments could be more attractive than others without there being an actual ranked ordering. It is strongly suggested that this approach be used when initial input data sets are small and/or contain high uncertainty. This type of analysis also provides assessment using uncertainty bands. After binning the capabilities and technologies, a series of FOM weightings is applied to determine which capabilities or technologies typically end up in a particular bin and how the FOMs affect the results. Other analysis that can be performed on the data includes weighting of phases and filtering of FOMs and categories. This type of flexibility enables the customer to see a variety of scenarios without having to redo the FOM scoring or to reconvene the SMEs for additional data capture.

TECHNOLOGY PRIORITIZATION ACTIVITIES EXTERNAL TO TAIT

The National Research Council (NRC) of the National Academies performed a technology prioritization analysis on NASA's Office of Chief Technologist (OCT) technology area (TA) roadmaps. The OCT TA roadmaps encompassed all technology development efforts at NASA which included science, aeronautics and exploration. Thus the roadmaps were developed to show all technology investments at NASA and was much broader than solely prioritizing technologies and capabilities for NASA's exploration initiative. When the NRC performed their analysis, they had to consider NASA initiatives across mission directorates at a very top level. The review of the OCT technology roadmaps was two-fold. One aspect of the analysis involved comment and review from a broad public community via town-hall type meetings and input on a public website. The second aspect of the analysis involved prioritizing technology investments using SME panels. "Criteria were chosen to capture the potential benefits, breadth, and risk of the various technologies and were used as a guide by both the panels and the steering committee to determine the final prioritization of the technologies. The panels identified a number of challenges for each technology area that should be addressed for NASA to improve its capability to achieve its strategic goals. These top technical challenges were generated to assist in the prioritization of the level 3 technologies. The challenges were developed to identify the general needs NASA has within each technology area, whereas the technologies themselves address how those needs will be met. The individual panels were tasked with categorizing the individual level 3 technologies into high-, medium-, and low-priority groups. The panels generated a weighted decision matrix based on quality function deployment (QFD) techniques for each technology area. In this method, each criterion and sub-criterion was given a numerical weight by the steering committee. The steering committee based the criteria weighting on the importance of the criteria to meeting NASA's goals of technology advancement."[1] In summary, the NRC utilized subject matter expertise to evaluate and prioritize the OCT TA roadmaps and technologies. The NRC and TAIT both utilized SME assessment of technologies.

PRIORITIZED COMMON CAPABILITY AREAS

This section of the paper will illustrate which prioritized, common capability areas are critical and enable exploration missions. Table 1 shows which capability areas typically rank high regardless of exploration mission destination or other criteria. The table also shows which functional capability areas are sensitive to exploration mission destination. Table 1 also shows the various human exploration studies that have requested technology and capability prioritization analysis over several years.

Table 1. Technology Prioritization Activities and Functional Capabilities

Functional Capability	Capability Requirements Analysis and Integration (CRAI) 2003	Exploration Systems Architecture Study (ESAS) 2005	Constellation Technology Prioritization Process (CxTPP) 2008	National Research Council (NRC) Review of OCT TA's 2012	Human Spaceflight Architecture Team (HAT) 2012	Advanced Exploration System Division (AESD) Prioritized Technologies 2012	Evolvable Mars Campaign (EMC) Study 2014
Autonomous Systems and Avionics	◆	◆	◆		◆	◆	◆
Communication and Navigation	◆		◆		◆	◆	◆
Cryogenic Fluid Management	◆	◆	◆		◆	◆	
ECLSS	◆	◆	◆	◆	◆	◆	◆
EDL	◆			◆	◆	◆	◆
EVA	◆	◆	◆		◆	◆	◆
Fire Safety			◆			◆	◆
Human Research and Crew Health & Performance		◆	◆	◆	◆	◆	◆
ISRU		◆				◆	◆
Power and Energy Storage	◆	◆	◆	◆	◆	◆	◆
Propulsion	◆	◆	◆	◆	◆	◆	◆
Robotics	◆	◆	◆	◆	◆	◆	◆
Structures, Materials & Mechanisms	◆	◆	◆	◆	◆	◆	
Thermal		◆	◆		◆	◆	◆

CRAI prioritization activity - In 2003 – 2005 NASA organized an activity called "Capability Requirements Analysis and Integration (CRAI). The CRAI team was charted to identify and prioritize the capabilities and technologies that must be developed before the Nation's Space Vision can be attained. This team reported to the Space Architecture Team and assessed nine critical capability areas to accomplish this goal. An Independent Technology Assessment Team (ITAT) was formed to assess the data generated by the CRAI Team to prioritize capabilities and to identify capability gaps. Ten of the functional capabilities listed were prioritized and recommended for investment. **NASA's Exploration Systems Architecture Study (ESAS)** performed technology prioritization assessment in 2005. ESAS focused on lunar exploration. The objective of ESAS was to identify key technologies required to enable and significantly enhance the reference exploration systems and to prioritize near-term and far-term technology investments. [2] Eleven capability areas and 52 critical technologies were prioritized and recommended for investment. **Constellation Technology Prioritization Process (Cx TPP)** - NASA's Constellation program ran a technology prioritization activity called Cx TPP in 2008. The Cx TPP secured three separate independent organizations, one from NASA and two from industry, to perform a technology prioritization analysis on lunar exploration technologies. TAIT was the NASA organization that participated in this call for technology prioritization. Twelve capability areas and 86 critical technologies were identified for investment. **National Research Council (NRC) review of OCT TA's -** As stated previously in this paper the NRC also performed prioritization analysis on OCT's technology areas. The results from this assessment showed that eight level 2 technology areas were prioritized and identified for continued investment. NASA's **Human Spaceflight Architecture Team (HAT)** study performed prioritization activities in 2012. HAT's Technology Development (TechDev) team and TAIT performed this prioritization. Twelve functional capability areas and 68 critical technologies were prioritized and recommended for investment. During the same year NASA's HEOMD requested a consolidated list of critical technology development investments identified by key HEOMD organizations. The **Advanced Exploration Systems Division (AESD)** reviewed technology prioritization results from HAT TechDev and Exploration Systems Division (ESD). HAT and ESD performed technology prioritization analysis for architectures that would enable multiple design reference missions. The design reference missions include human exploration at the moon, near-Earth object (NEO), Mars Moons, and Mars surface. From this assessment AESD prioritized fifteen capability areas and 60 critical technologies that were recommended for investments. In 2014 the **Evolvable Mars Campaign (EMC) study** performed capability prioritization analysis that looked at multiple exploration destinations. TAIT performed this prioritization analysis. This prioritization analysis identified twelve capability areas and 32 performance gaps.

For the seven different prioritization activities shown in Table 1 specific functional capabilities were prioritized and identified as critical. The assessment of prioritized capability areas are described here.

- Environmental control and life support system (ECLSS), power and energy storage, propulsion and robotics functional capabilities were prioritized seven out of seven times as needed for human exploration. These capabilities were critical and needed regardless of exploration destination.
- Autonomous systems and avionics are grouped into one functional capability. Autonomous systems, extra-vehicular activity (EVA), Human Research or Crew Health and Performance, and structures, materials and mechanisms functional capabilities were prioritized six out of the seven times as needed for human exploration.
- Entry, descent, and landing (EDL) functional capability was prioritized five out of seven times as a critical need for human exploration. This capability area is critical for human Mars-class surface missions. Thermal, communication and navigation, and cryogenic fluid management functional capabilities were also prioritized five out of seven times as a critical need for human exploration. For the EMC study, cryogenic fluid management was included in the thermal functional capability.
- Fire safety functional capability was prioritized three out of seven times as needed for exploration. For a few studies, fire safety was included in the ECLSS capability area. Also, in-situ resource utilization (ISRU) functional capability was prioritized three out of seven times as needed for human exploration. The ISRU functional capability is a critical need for human Mars exploration.

FUTURE ACTIVITIES

Future capability and technology ranking activities will continue to leverage SME input while also incorporating more model-based analysis. As the capability and technology data potentially scale and become better defined, the interconnectivity of the data must be maintained. The data are hierarchical, have many dependencies across capability areas, and are also dependent upon the architecture. This type of data lends itself to a model-based engineering framework, where the hierarchy of the data can be dynamically modeled, dependencies can be linked and maintained, and the impacts of the architecture can be quickly assessed. Once the capability area data, along with the dependencies and architecture elements, are modeled in this framework, changes in the data or customer requests can be made quickly while maintaining the relationships. Implementing model-based engineering with the capability and technology data will make the data more responsive to changes, more scalable to new relationships, and more useful to the agency.

SUMMARY

There continues to be a need to prioritize capabilities and technologies that are critical and enable human exploration. Capability and technology development organizations need to justify their portfolios, and NASA exploration mission directorates need to determine which capabilities and technologies will enable human exploration. These organizations have a need to prioritize in order to make prudent investment decisions and to manage portfolios. Historically, the organizations that perform capability and technology prioritization analysis used subject matter experts to provide assessment and scoring. These organizations rely on decision makers to emphasize preferences based on policy and political knowledge. The specific outcomes from these prioritization activities are dependent on customer goals and objectives. This paper showed that, for human exploration technology prioritization activities spanning more than a decade, certain capability areas continue to rank high regardless of the exploration destination or mission emphasis while other capability areas are sensitive to the exploration destination. As NASA decision makers' requests for capability and technology prioritization analysis continue and as the data become more defined, the model-based engineering framework can be utilized to show interconnectivity between the capability areas and the exploration architecture.

Acronyms

AMO - Autonomous Mission Operations
AESD – Advanced Exploration Systems Division
CHP - Crew Health & Performance
Comm/Nav - Communications and Navigation
ECLSS - Environmental Control and Life Support System
EDL - Entry, Descent, and Landing
EDL SA - Mars Entry, Descent and Landing Systems Analysis Study
EMC - Evolvable Mars Campaign
ESD – Exploration Systems Division
EVA - Extravehicular Activity
FOM - Figure of Merit
HEOMD - Human Exploration and Operations Mission Directorate
ISRU - In-Situ Resource Utilization
NAC- NASA Advisory Council
NEO – Near Earth Object
NRC – National Research Council
OCE - Office of Chief Engineer
POC – Point of Contact
SME - Subject Matter Expert
SMT - System Maturation Team
SOA – State of the Art
STMD – Space Technology Mission Directorate

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