Key Mars Architecture Decisions

Introduction

As noted in the 2022 Architecture Concept Review Systems Analysis of Architecture Drivers white paper, exploration architectures are heavily influenced by the order in which driving questions are answered. Decisions in one part of the architecture will ripple through other parts of the architecture and beyond, often in ways that are not intuitively obvious.

Making one key decision before fully understanding the cascading impacts of that decision across the end-to-end architecture can limit the architecture's flexibility or utility. The essential question is: of all the important decisions to be made, which should be decided first?

The practical utility of this approach is to understand which decisions lay in the critical path of others. To make good choices, it is critical to visualize and manage the complex web of interrelated decisions and their flow-down impacts. This approach allows for deliberate and informed progress.

Ensuring the flow-down impacts of far-reaching decisions are carefully traced, assessed, and weighed will help NASA make lasting decisions that have the most flexibility and value. This is a critical factor in the effort as once these and other priority decisions are made they have lasting impact on the architecture. Subsequent changes will be costly in both time and money given the long timelines for development of new human capabilities (5 to 15 years, similar to aircraft).

This white paper describes the initial set of human Mars decisions that the agency has identified as high-priority architectural drivers.

Mapping Key Architecture Decisions

A "key" architecture decision is defined as a decision whose outcome so profoundly influences the architecture that it requires very high-level review. For example, deciding how many crew members an architecture must accommodate influences virtually every aspect of the architecture. It requires high-level consideration and consensus between multiple programs and projects.

An example at the other end of the spectrum is deciding handrail color or style. Even though the decision may affect many elements, it is best categorized as an engineering decision that will not require the same level of scrutiny.

NASA architecture teams have developed a systems engineering-driven process to:

1. identify key architecture decisions needed,
2. determine relationships between decisions (including dependencies and flow-down impacts),
3. and develop a recommended logical order in which to make these decisions.

NASA is developing a model-based environment to manage this complex web of information. The process and rationale are described in the Exploration Systems Development Mission Directorate's Moon to Mars Architecture Definition Document, Section 2.3.1 Key Mars Architecture Decision Drivers.

To develop the catalog of key Mars architecture decisions, NASA subject matter experts have begun a bottom-up review of heritage Mars architecture studies. Analyzing decades of documents, these experts identified the most influential factors in designing the initial human exploration campaign for Mars.

Next, they began decomposing the agency's blueprint objectives for exploration using a top-down approach. This resulted in use cases and functions that can then be mapped to needed architecture decisions.

Together, these two approaches provided more thorough insight, simultaneously helping refine objectives, uses cases, and functions. The resulting initial analysis — which is still ongoing

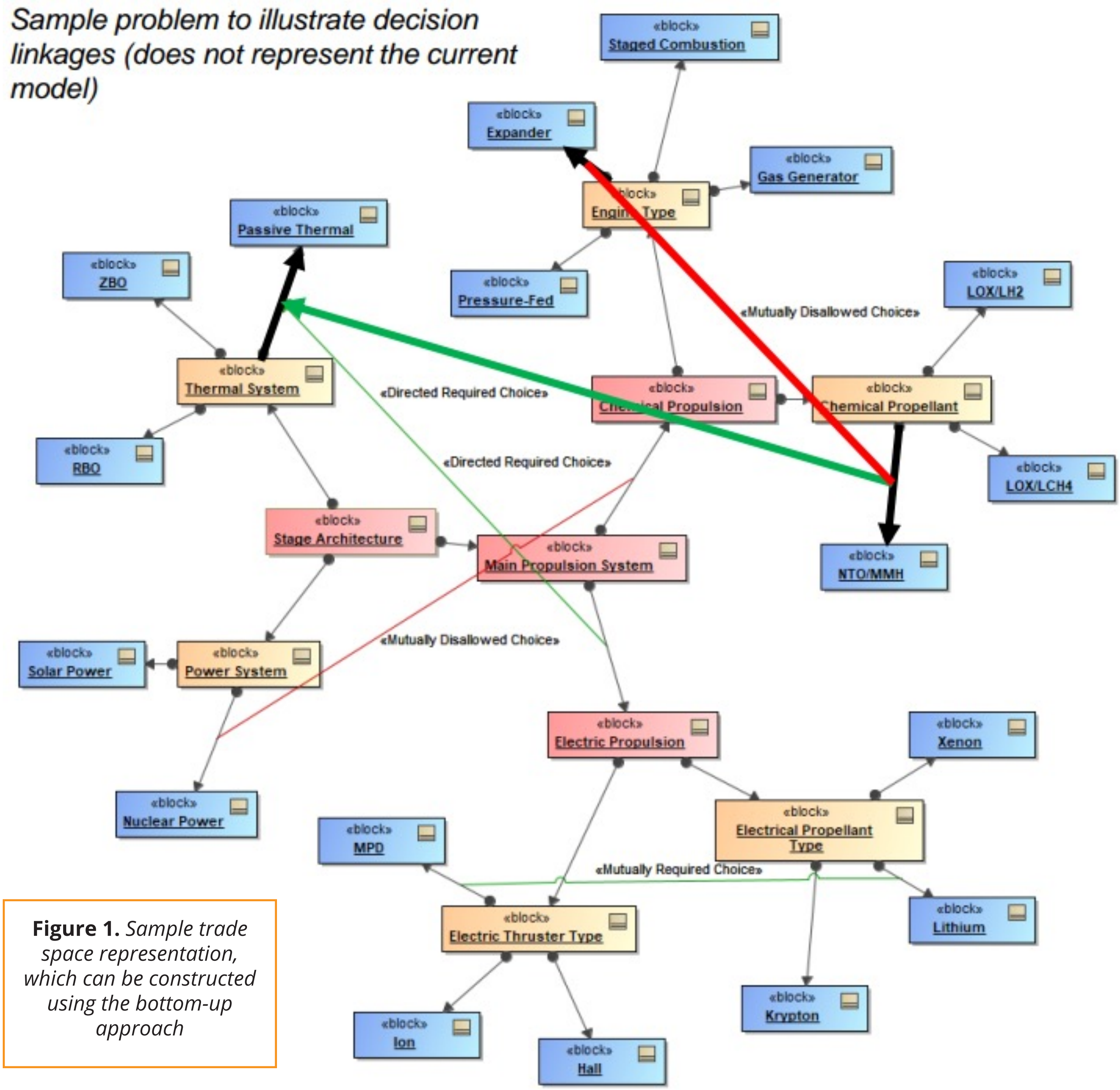

Figure 1. *Sample trade space representation, which can be constructed using the bottom-up approach*

— identified nearly 100 candidate key decisions for the Mars architecture, though the count was slightly reduced during subsequent agency-wide review and refinement.

As part of this effort, NASA also developed an initial model of architecture decision relationships. Through the frequency or dependency linkages illustrated in Figure 1, the agency extracted seven key decisions for priority analysis.

The seven decisions presented here represent NASA's initial focus for architecture integration efforts for an initial human exploration campaign for Mars. The complete model — including linkages to remaining lunar architecture decisions — continues to be developed and refined.

Seven Priority Human Mars Architecture Decisions

NASA's initial modeling effort isolated seven key human Mars architecture decisions, detailed below and shown in Figure 2. These are the recommended starting point for planning the initial human exploration campaign for Mars.

While the agency will prioritize these seven decisions first, analysis and mapping of the remaining catalog of key architecture decisions will continue in parallel. NASA

PRIORITY HUMAN MARS ARCHITECTURE DECISIONS

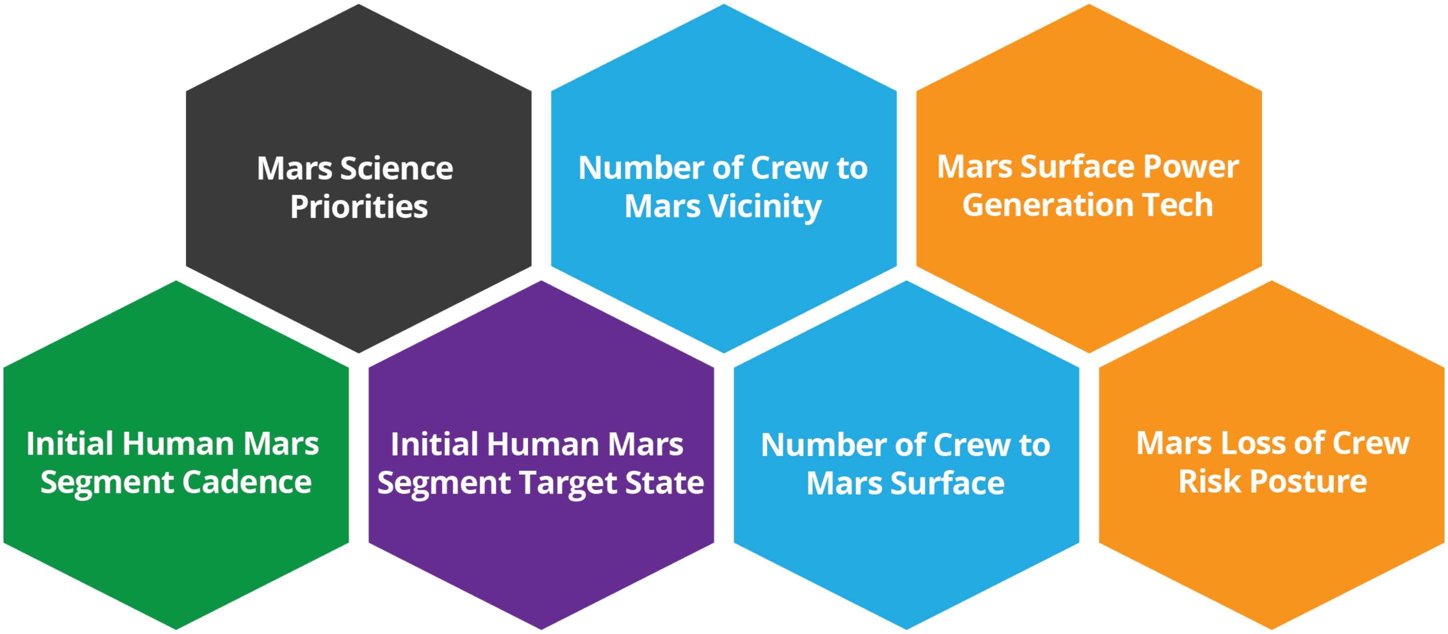

Figure 2. *Priority Human Mars Architecture Decisions*

will report progress and results at annual Architecture Concept Reviews and document them in yearly revisions to the Moon to Mars Architecture Definition Document.

Human Mars Mission Science Priorities

NASA's Moon to Mars strategy identifies science as one of three pillars upon which the agency's blueprint for sustained human exploration throughout the solar system is built. As a foundational aspiration, it can trigger the cycle of national capability and inspiration and build the value system of human exploration upon benefit to humanity. The blueprint identifies objectives in five different science disciplines:

- Lunar/planetary science
- Heliophysics science
- Human and biological science
- Physics/physical science
- Applied science

Accomplishing any portion of these objectives will require resources in virtually all aspects of the mission, including crew time, dedicated payload mass delivered to the surface, dedicated payload mass returned from the surface, communication throughput, and power. Arguably, the science conducted on the surface of Mars — at the farthest end of the human transportation and communications systems in consideration through the next decade — will have the greatest impact on the scope and scale of the architecture. Therefore, science priorities warrant the earliest possible attention.

Recent history demonstrates the importance of making this decision earlier rather than later. NASA's Artemis exploration campaign was directed to establish initial operations in the lunar South Pole region, with a focus on acquiring volatile resources thought to be found there. That limited focus may be incompatible with high-priority lunar science objectives uniquely addressed at other locations.

Establishing foundational science priorities built on broad input from the science community early in the architecture definition process may help mitigate disruption or delay to implementation of an initial human exploration campaign for Mars.

Initial Human Mars Segment Target State

A decision about the vision — or "target state" — for NASA's initial human exploration campaign for Mars is fundamental to developing an architecture that enables that vision. Architecture elements and concepts of operation will vary greatly depending on the desired end state.

For example, a series of focused science exploration missions to different landing sites would favor one architecture. Establishing a permanent, fixed base from which astronauts could conduct many surface missions supporting diverse and evolving exploration activities would favor a very different architecture.

Note that the scope of this key decision is limited to defining a vision for the initial Humans to Mars campaign segment. A separate decision will define subsequent human Mars campaign segments. The ideal end state for the vision is an architecture that meets NASA's highest priority objectives, with flexibility to expand to meet new needs or goals as they emerge.

Initial Human Mars Segment Mission Cadence

The initial state for human exploration of Mars will establish the "right" for "architecting from the right," but other questions remain:

- How many unique missions are necessary during the initial segment? (These could include robotic science, cargo delivery, or precursor demonstration missions.)
- Will there be crewed orbital or fly-by precursor missions to Mars, or will the first crewed mission land on the surface of the Red Planet?
- What additional resources are needed to balance the cadence of initial Mars missions with ongoing near-Earth and lunar surface operations?

Historically, human exploration spaceflight programs have established a campaign of test flights, demonstrations, and crewed missions that build up to a desired end state. Depictions of these gradual buildups can aid stakeholders in strategic planning and investment forecasting for the initial human exploration campaign for Mars.

Mars Loss of Crew Risk Posture

Robotic exploration projects typically establish a loss of mission risk posture, but human spaceflight programs must also develop an understanding of the overall loss of crew risk. Loss of crew risk posture is a useful guidepost in making risk-informed architecture decisions. For example, whether to prioritize technologies that enable faster round-trip human missions as one means to mitigate crew health and performance concerns.

As the architecture becomes more defined, a formal agency-level safety reporting threshold will be established for each design reference mission to achieve human rating certification. However, establishing a risk posture guidepost early in the architecture development process will help avoid disruptions and reworks during the later certification phase.

Number of Crew to Mars Surface per Mission

Crew complement is the most common study constraint across all architectures and elements. Crew complement selection has implications for habitable vehicle and element volume, life support system design, and crew support systems for health and performance (such as medical, exercise, and food systems). It also has ramifications for logistics needs (including science and mission utilization, food, clothing, medical supplies, etc.), which inform campaign launches and cadences.

Operationally, crew complement helps establish an upper limit for Mars entry, descent, landing, and ascent vehicle sizing (with flow-down impacts to ascent propellant management, including Mars surface infrastructure needs). It also helps establish a lower limit for crew availability to perform systems monitoring, maintenance and troubleshooting; science and utilization (particularly during surface extra-vehicular activities); and inspirational engagements with the public. The unique communications challenges at Mars — an environment where real-time communication with Earth is not possible — also have implications for task management and contingency responsiveness of a given crew complement during critical operations.

Number of Crew to Mars Vicinity per Mission

A companion to the Mars surface crew complement decision is deciding the total crew complement to Mars vicinity. This decision will have some similar considerations to defining crew complement to the surface, but also some unique constraint drivers.

The number of crew to the vicinity of the Red Planet will have implications for Earth ascent and descent, Mars transit vehicle habitable volume, crew support systems sizing, and logistics manifesting. This decision may also influence Mars capture and parking orbit operations, with flow-down implications for task management and contingency response. For example, in "split crew" architectures, some crew might remain in Mars orbit while others descend and work on the surface, changing the crew's physical availability to perform these functions.

Primary Mars Surface Power Generation Technology

The scope of human exploration on Mars will depend largely on the amount of energy available. That energy will power crew life support systems, support surface element keep-alive functions, and make, move, or maintain critical ascent vehicle propellants.

Solar energy has long been a reliable choice for in-space power applications. However, recent robotic science mission experience has brought solar power risks for Mars surface missions into sharper focus, particularly given the loss of crew risk if the surface power system were to fail during a human expedition with limited mission abort options.

This particular architecture decision is limited in scope to power generation technique. Power load sizing and distribution technology selections are cataloged as separate decisions, though interdependencies with those decisions must be factored into power generation decision analyses. The narrowing window of opportunity to infuse Mars-forward considerations into lunar surface power implementation decisions for Artemis make this a timely activity.

Future Work

During upcoming strategic analysis cycles, NASA architecture teams will continue to refine the modeling environment, assess various options within the solution space, and prioritize remaining decisions for the initial human exploration campaign for Mars. As the bottom-up and top-down identification processes continue, additional needed decisions may be identified. Linkages to decisions for lunar exploration campaign segments that have not yet been made will be developed, analyzed, and prioritized. This insight will enable an informed and methodical approach to address the needs of the multi-decadal vision that is the Moon to Mars Objectives.

Conclusions

Developing architectures to enable human exploration of the solar system will require hundreds of individual decisions by many different decision authorities across the agency. All of these decisions will be important, but there is a class of decisions that so profoundly influences the entire end-to-end architecture as to warrant the highest level of scrutiny. Ensuring the integrated impacts of far-reaching decisions are carefully traced, assessed, and weighed will help decision authorities make lasting decisions that are resistant to implementation delays, disruptions, or costly relitigation.

Through a methodical process, NASA has identified a set of seven Mars architecture decisions to start with. However, the agency will continue to define and map the full catalog of key decisions, reporting progress at annual Architecture Concept Reviews and updating the Architecture Definition Document with architecture decisions as they are made.

Key Take-Aways

The order in which key decisions are made heavily influences exploration architectures. Every decision is important, but not every decision can be first.

NASA endeavors to establish a logical order for decision making by modeling the decision trade space for human Mars exploration. This methodology will allow decision-makers to understand the integrated impacts of each individual decision on the overarching architecture.

Of the nearly 100 Mars architecture candidate decisions identified for analysis, NASA has identified seven key decisions to focus on first.

While Mars serves as a test case for this approach, lessons learned will inform future decision-making for the Moon and subsequent human exploration enterprises.

As architecture decisions are made, updates will be reflected in NASA’s Moon to Mars Architecture Definition Document.