Towards a Common Basis of Comparison Across a Broad Trade Space of Mars Architecture Options

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Abstract— **As space travel and technology have continued to advance, there has long been interest in investigating ways to send humanity to Mars. Over the years, many studies have been performed looking at different concepts and trades for a human Mars mission. However, it is difficult for modern Mars studies to take advantage of findings in the past since it is often tedious and time-consuming to tap into this large body of work and reconcile differences in ground rules and assumptions. Currently, the Advanced Concepts Office (ACO) at NASA's Marshall Space Flight Center is working to recapture and re-baseline previous Mars studies to establish a broad basis of comparison for future Mars studies. This paper is the first step in this re-baselining work and establishes a plan to enumerate, synthesize, and evaluate previous Mars studies in a common framework.**

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1. INTRODUCTION

Humanity's fascination with Mars predates the advent of space access, but the coming-of-age of rocket propulsion in the mid-20th century provided the technological foundation for considering a human visit to the red planet. Werner von Braun's "The Mars Project," published in 1953, is acknowledged as the first integrated Mars mission architecture plan [1]; since then, the reformulation and refinement of Mars architectures and system concepts has been an ongoing activity, as continued study and planning for human Mars missions is necessary in order to incorporate evolving mission objectives, technology advancements, and the increasing body of knowledge regarding human factors and the various environments of space.

Historical Mars architecture studies represent an enormous body of work, but tapping into the findings and philosophies of these varied works entails a tedious and time-consuming individual effort. The unfortunate result of the widely scattered corpus of Mars architectures is that knowledge and understanding acquired in previous studies is not consistently and effectively brought to bear in the studies of today. The primary vehicle for bringing forward past learning is human recall, which both is imperfect and experiences significant attrition.

An effort is underway in the Advanced Concepts Office (ACO) at NASA's Marshall Space Flight Center to recapture and re-baseline previous architecture studies in order to establish a broad basis of comparison for future Mars architecture studies. Recapturing involves gathering and organizing data and documentation from previous efforts; re-baselining entails developing models capable of reproducing the original results, and then utilizing these models to implement a common set of ground rules and assumptions across the resulting trade space of Mars architecture options.

This paper will present the framing ACO is employing in performing this architecture meta-study. Included is a brief overview of previous survey efforts (Section 2); a discussion on the types of considerations that must be captured in order to assemble complete architecture concepts (Section 3); and a high-level approach that will be applied to not only capture descriptive models of alternative Mars architectures, but to build executable models as well (Section 4). It is expected that the completed basis of comparison results will be presented as a sequence of follow-on papers over the course of the next two years.

2. PAST MARS ARCHITECTURE STUDIES

Delving into the published literature on human Mars missions reveals a widely varying array of objectives, envisioned end-states, and means of achieving them. Numerous studies have been performed in the decades since von Braun formulated the first engineering solution for a human Mars mission. Each one, according to its scope, has contributed to the understanding and general body of knowledge regarding ways and means of accomplishing such a mission. "Flagship" studies such as NASA's Design Reference Architectures (DRA), visionary (though sometimes fanciful) mission concepts such as Inspiration Mars [2] or Mars One [3], and point designs formulated to showcase specific technologies or concepts of operation (conops) all take their place in this tapestry.

Efforts to capture and summarize the results of previous studies are not unprecedented. A review of "recent" human

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exploration studies covering the years 1988 to 1994 was first compiled by Drake in 1996 [4], and then later updated to include studies up to 1999 by Cooke in 2000. [5] These compilations were acknowledged as providing "a database of key trades and studies" and "knowledge of the benefits and payoffs of various technologies." However, the extent of the compilation consisted of a single chart per study reviewed, so querying the "database" for any technical details beyond the handful of bullets provided would entail a deep dive into the technical reports of the studies themselves. Similar reviews have occurred on other occasions as well [6], [7], with observations summarized at a similar level of detail.

The most comprehensive review of human Mars architectures to-date was published by the NASA History Division in 2001; *Humans to Mars: Fifty Years of Mission Planning, 1950-2000* provides a detailed narrative connecting the dots between the various phases NASA has been through over the course of multiple decades and administrations. [8] This publication, speaking from the perspective of an historian, provides an unparalleled view and understanding of the non-technical tides and currents that have influenced past preferences and decisions.

It is hoped that the results of this re-capturing and re-baselining effort will provide some small means of following a technical thread through the past evolution of Mars architectures. Though it will certainly proceed more slowly than a qualitative survey, the intent is to develop a true "database" which can be queried with respect to each of the critical constituents of a human Mars architecture.

3. Human Mars Architecture Considerations

It is common for human Mars studies to invest differing levels of detail into the various constituents of an end-to-end architecture. The extreme energy requirements of a roundtrip mission ensure that transportation considerations are always addressed; however, the design and conops of the Mars surface architecture is just as important to overall feasibility and viability as the transportation system design and conops. In order to establish a common basis of comparison across a wide array of architecture concepts, it will be necessary to identify a minimum acceptable definition in each of the areas discussed here.

Launch & Assembly

No matter what a Mars architecture looks like or how many elements it has, there will always be a decision on how to initially launch those elements into orbit. However, over the multiple decades in which human Mars architectures have been studied, the assumptions on launch and assembly have varied widely, resulting in significant differences in the overall architecture.

Launch Vehicle Capability & Availability—A first important assumption for this section of the mission is the following: what launch vehicles will be available to use? The performance, volume, reliability, launch cadence, and required development of the assumed launchers will have a significant impact on what types of Mars architectures are feasible. If, for example, it is assumed that an extremely capable launch vehicle will be available then the architecture can likely be completed with a few very large elements and a lower launch cadence. On the other hand, if it is assumed that there will only be smaller launch vehicles available based on current capabilities then the architecture may be more complex with many smaller elements, more launches, and a higher launch cadence. It may require more launches and complexity to use the smaller launch vehicles, but it may require huge development costs to develop a very high performance launch vehicle that is not currently available. Depending on the ground rules of a study, it may be more practical for the study to assume very large launch vehicles or it may be more practical to assume smaller launch vehicles.

Aggregation Orbit— Strongly tied to the available launch vehicles and element designs is how and where, if at all, aggregation of elements will occur after they are launched. If the in-space transportation stage is too large to be launched on a single vehicle, then it may have to be split up into multiple elements which are launched separately and then aggregated in orbit. These elements can all be launched into the same orbit and aggregate in that orbit, they can be launched into different orbits and move to an orbit for aggregation, they may not aggregate at all, etc. Whether the aggregation happens in LEO, HEO, or somewhere else, the elements may be exposed to radiation and MMOD risks depending on how long it takes to get all the elements into the orbit and to aggregate them. Depending on what launch vehicles are available, there will also be a tradeoff of how much mass the launch vehicle can get to the aggregation orbit versus how much ΔV the aggregated vehicle has to spend to get from the aggregation point to its destination.

In-Space Transportation

After getting into orbit, it is necessary to have a vehicle, or vehicles, which can transport the crew and any other mission elements between Earth and Mars.

Propulsion—One of the biggest trades for an in-space transportation stage is the type of main propulsion. Some of the more commonly traded options for a human Mars mission are chemical propulsion, electric propulsion, and nuclear thermal propulsion. These different propulsion options have tradeoffs with respect to development time/cost, efficiency, impulse, etc. Which type of propulsion is the best option will often depend on the goals and constraints of the human Mars architecture GR&A. With respect to the propulsion there are also trades with respect to the propellant, such as LH2 vs LCH4 for fuel. While LH2 allows for a higher specific impulse, LCH4 has a better packing density and could potentially be produced on the surface of Mars. Some chemical propulsion architectures may also look at storables, trading lower specific impulse with not needing a heavy cryo system.

Power—Tied to the propulsion is the power system, the main two trades being solar versus nuclear. Chemical propulsion concepts for a human Mars mission will generally always use solar power. For nuclear concepts, however, there is the option to use solar power or to use the nuclear reactor as a bimodal system, generating both power and thrust. Making the nuclear reactor bimodal may save mass by not needing a completely separate power system, but it may be limited in the power it can produce and will need cooling propellant to continually run.

Concept of Operations—Another important decision for the in-space transportation design is whether the mission conops will be an all-up vs split mission. A split up mission will have multiple trips between Earth and Mars, transporting any required cargo before sending the crew. An all-up mission has no pre-deployments. It is done with a large, all-in-one vehicle which brings the crew and required cargo. While the all-in one vehicle is very large and heavy, the in-space mission conops may be less complex and require less time to get everything in place. Other aspects of the conops, such as an aerocapture versus a propulsive capture at Mars, whether the mission is conjunction or opposition, to what Mars orbit the vehicle is going to, etc. will also impact the in-space transportation design.

In-Space Habitation

For a crewed mission to Mars, there will be functional requirements to maintain humans for an extended duration through deep space. Primary drivers in the design of an in-space habitat will be closely coupled with the desired number of crew and the transit time to and from Mars. Further coupling may occur depending on the physical form of the architecture. For example, a single stage vehicle from Earth departure to Earth return would have to support additional functions related to Mars descent and ascent. This may also be further coupled with surface architecture functions if the architecture intends to rely on this same single stage vehicle as the primary habitation element while on the surface. Obviously, this amount of coupling could be difficult to manage, which is typically the reason for decoupling the design into separate physical elements, such as an in-space habitat, surface habitat, etc., at the cost of increased architecture complexity.

Additionally, the micro gravity and radiation environments experienced during transit to and from Mars imply additional functions that an in-space habitation element may be required to accommodate based on design decisions. For instance, will the habitation element provide some form of induced gravitational environment to mitigate crew deconditioning during travel? Furthermore, there is the potential for coupling to the in-space transportation design. Certain propulsion systems may induce additional environments that may require mitigation for the safety of the crew, such as additional radiation protection from a nuclear-based propulsion system. Again these are just a few of the many detailed design decisions and possible coupling that may exist in the design of in-space habitation. Details such as hard vs inflatable structures, type of life support system, number and location of docking ports, specific radiation mitigation technologies are other design choices that me be made or derived based on a detailed analysis of a broad, integrated, architecture trade study.

Mars Descent & Ascent

Descent and ascent are crucial mission functions in evaluating any human Mars architecture concept. However, there are a plethora of design options from which to choose from in this regime, several of which are tightly coupled with many other key architecture design ground rules, assumptions, and design choices. One of the most critical design choices impacting descent and ascent is the desired landing site. This in itself is typically going to be greatly influenced by the desired campaign objectives, whether they be in the pursuit of scientific discovery and exploration, or for the purposes of human colonization, for example.

Assumptions regarding the physical form of the architecture will further expand the design choices that must be made. Typically, reducing the number of physical elements will reduce the overall mission conop complexity. For instance, assuming a single stage vehicle from Earth departure to Earth return will greatly simplify the overall mission conops, removing the need for several staging events, rendezvous and docking maneuvers, interface definitions, etc. However, this introduces significant design coupling due to the large number of functions that must be performed by an individual physical element. Allocating specific functions across several physical element(s), such as a dedicated descent and ascent elements, can help to break this coupling, at the cost of increased architecture complexity.

Several other key design choices will impact the descent and ascent function, such as propulsion system propellant type, and Mars entry, descent, and landing technologies. The selection of propellant is tightly coupled to the decision to make or bring propellant for subsequent phases of the mission, which will also have coupling to the surface architecture. High level architecture design choices will also be tightly coupled to the descent and ascent functions. For instance, number of crew to the surface, which will again not only have significant impact on the Mars surface architecture, will find coupling into the ascent systems. Another high level architecture design choice with significant coupling to descent functions is overall surface mission duration. Again, this choice will heavily influence the surface architecture, which in turn will result in a payload delivery requirement on for the descent function.

There is significantly more coupling of descent and ascent design to other key architecture design choices than has been discussed here. Planetary protection protocols, surface accessibility, descent and ascent trajectory assumptions, parking orbit selection, and launch vehicle selection, are examples of additional design decisions that will have impacts not only the descent and ascent phases, but throughout the architecture. It is clear that the design of Mars descent and ascent systems is not an independent process, but rather a highly integrated design task with coupling throughout the architecture.

Mars Surface Architecture

Much of the surface architecture design will be heavily influenced by the top level mission and campaign objective: exploration and discovery versus human colonization. These two top level objectives have significant impact on the design of the surface architecture, as well as nearly every facet of the architecture design. For instance, a goal of exploration and discovery may lead to a more nomadic approach, relying on much more independent, mobile surface assets that are separated by significant geographic distance, with shorter surface crew durations. Conversely, a goal of human colonization will likely be much more focused on a small geographic location, aiming to build and continually increase the amount of surface assets in the location, with the goal of supporting more and more humans with increasing surface mission durations over time. This will require more focus on surface support systems such as power, resource extraction, volatiles processing required for human survival, etc. This top level decision will likely impact subsequent architecture design choices related to surface architecture such as planetary protection protocol, number of supported crew, desired power system design, regenerative versus consumable life support, in-situ resource utilization, additional surface mobility platforms, etc. This will of course have further coupling to the in-space transportation and descent design in terms of payload mass delivered to the surface, and ultimately amount of mass launched from Earth and number of launches.

4. Re-Capturing and Re-Baselining Approach

As was discussed in Section 2, "meta" studies in the form of literature surveys provide an excellent opportunity to harvest findings and trends from the body of previous architecture trade studies. However, While the high-level observations from such analyses are typically consistent, it is often not possible to validate the outcomes of specific trades from study to study. This can be caused by a difference in technology assumptions or top-level conops, but some differences are difficult to reconcile because of incomplete documentation of the ground rules and assumptions (GR&A) used. Because report documents and presentations are often the only products retained after a study (along with an occasional spreadsheet), any accumulation of new GR&A or technology developments triggers the need for an all new study.

The objective of this effort is to go beyond merely reviewing past Mars studies and attempt to re-capture the proposed architectures as models. Though this represents a significant undertaking, the anticipated benefits are twofold (at least): First, by establishing a database of past Mars architecture models, "new" ideas on how a human Mars mission might be achieved can be subjected to a preliminary assessment that does not immediately trigger the need for a whole new architecture development. The quotation marks around the word new are important, because the diversity of means and ways that have been explored in the past is significant, and there are very few truly novel approaches with no precedent. The second benefit of this effort will be to demonstrate the execution of a model-based process from which the primary product is a configuration-controlled model of the Mars architecture rather than merely another final report document.

Enumeration

A unique architecture concept is generated by an enumeration process that flows through a trade space decomposition. While many studies treat this step implicitly, some make an effort to rationalize the particular scope of alternatives considered in the context of the broader trade space. This is often visualized in the form of a trade tree, particularly when multiple alternatives are being considered. Figure 1 shows a trade tree developed to map out the various human Mars architecture alternatives surveyed by Drake in 2007. [7]

While easy to read, trade trees are limited in the number of alternatives they can depict due to the exponential growth of the number of "leaves." This baselining effort aims to capture a wide variety of concepts from the literature, and so a traditional trade tree will likely be inadequate. An alternate method for depicting a trade space of alternatives is the morphological matrix. In this approach, each row in the "matrix" represents a specific choice or trade, with the available options captured as items in the row. In this approach, a single unique concept is assembled by selecting one option from each row in the matrix. An example is shown

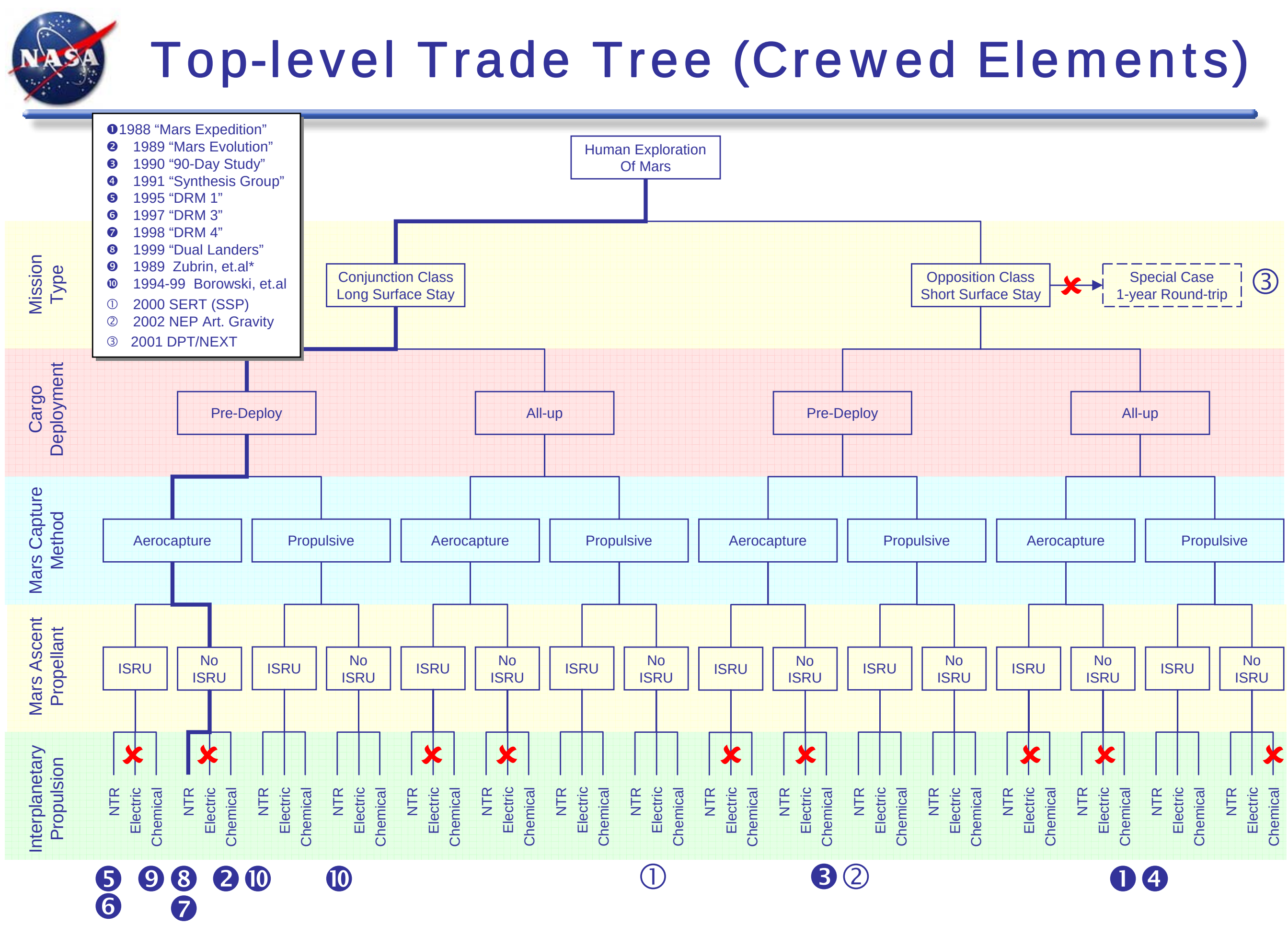

Figure 1. **Trade tree of Human Mars Architectures with overlay of studies reviewed by Drake. [7]**

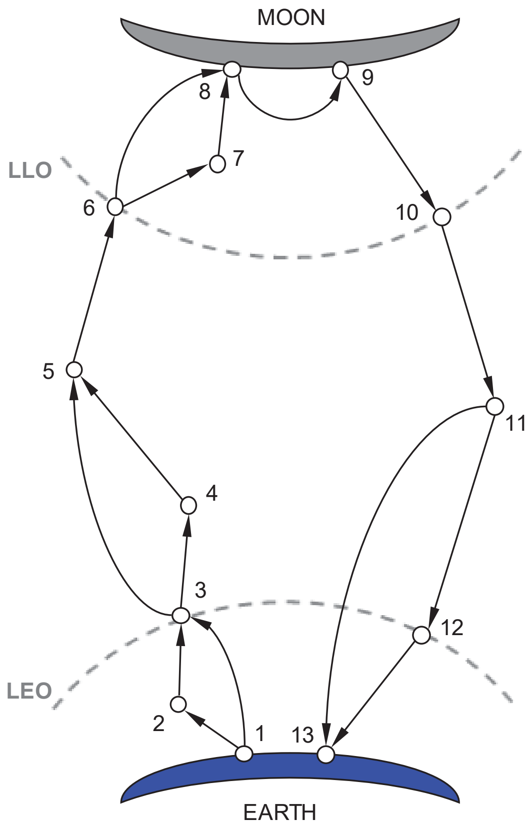

Figure 2. **Arney's depiction of a mission trade space as a graph. [10]**

in Table 1, which captures the same trade space as appears in Figure 1. This table is clearly not a "matrix," despite its name; however, it presents the same information as the trade tree in a much more compact manner.

Morph matrices, in turn, become cumbersome when employed in describing the mission trade space, as the availability of multiple "paths" requires either a multiplicity of matrix rows or recursive matrices. While still technically feasible, the ease of visualization for human interpretation suffers. A more suitable approach to communicating the multiple alternative paths present in the mission trade space is to use a graph. A variety of developments have demonstrated the graph-based approach, including Koo's Object-Process Networks [9], Arney's rule-based graph traversal algorithm [10], Iacobucci's Rapid Architecture Alternative Modeling (RAAM) [11], and Lafleur's application of Markov Decision Processes. [12] A simple example that demonstrates the utility of a graph approach to describing the mission trade space is provided in Figure 4.

For the approach taken in this study it is anticipated that a combination of morph matrix and graph methods may be used. The goal will be to develop a trade space mapping that encompasses all of the Mars architecture concepts surveyed; this mapping in turn will provide a means of generating new alternatives for consideration which may never have been formally explored.

Synthesis

Enumeration is descriptive in nature, and entirely suitable for cataloging results from the survey. However, the re-baselining portion of the study requires execution, not merely description. The goal of synthesis is to take the concepts described by the enumeration step and "synthesize" the various parts into an integrated whole. Sizing is often conflated with synthesis, and certainly synthesis involves sizing. However, sizing is an exercise in mass estimation and overall physical scaling, whereas synthesis requires trajectory, conops, launch cadence, and every other facet of the specified architecture to be harmonized.

Synthesis in such Pre-Phase A studies as human Mars architectures is often managed manually. Domain specific computational models are leveraged for propulsion, power, trajectory, and other engineering disciplines, but the integration itself is not completely formal and explicit. A variety of tools exist that are used as an aid in this process [13], [14], [15], [16], [17], and while each formulation differs on one point or another, several deficiencies can be observed in general that limit their utility for the type of broad study proposed in this paper. First, most of these tools are focused specifically on the sizing function of synthesis. As has already been stated, sizing is necessary but not sufficient for synthesis, as operational and logistics requirements do not all manifest directly in the sizing process. Second, most of these tools do not follow a truly object-oriented paradigm, and none implement a formal ontology in assembling architecture models. These factors do not appear as limitations in assembling models of individual architecture concepts; however,

The identified need for a more holistic synthesis has driven the development of the Dynamic Rocket Equation Tool (DYREQT), which provides a general capability for synthesis of space systems and system-of-systems architectures in the pre-conceptual and conceptual phases of design. While DYREQT's name implies a sizing and performance focus through its specific reference to the rocket equation, the formulation has matured since its original naming to encompass system-of-systems integration challenges where operations and logistics factor in more heavily. Rather than focusing on sizing, the primary aim of DYREQT is enabling flexible synthesis of any arbitrary architectures that may be described within DYREQT's ontology. Vehicle system architectures, conops, mission timelines/schedules, and trajectories are all explicitly integrated and converged in this model-based framework built on top of NASA's OpenMDAO software. [18] In doing this, DYREQT enables the rapid exploration and optimization of concepts subject to parametric requirements regardless of the high-/low-/mixed-/multi- fidelity nature of the disciplinary models used. [19]

For this re-baselining effort, the DYREQT framework will be used to ingest and synthesize the various Mars architecture concepts generated in the Enumeration phase. The architecture synthesis will proceed in two steps. First, the concepts will be modeled to the fullest extent possible given the documentation sources available. Some documentation is comprehensive and complete, but it unfortunately more common for important and necessary details to be left out, making it impossible to directly reproduce previous results. Where incomplete documentation is encountered the second step will consist of a reverse engineering and calibration effort to identify reasonable modeling assumptions that can fill the gaps identified.

Evaluation

There are several considerations of interest in evaluating human Mars architecture alternatives, including feasibility (i.e. "Will it close?"), viability (i.e. "Can it be accomplished

Table 1. Morph matrix depiction of Drake's Mars architecture trade space. [7]

Choice	*Option 1*	*Option 2*	*Option 3*
Mission Type	Long Stay	Short Stay	
Cargo Deployment	Pre-Deploy	All-Up	
Mars Capture Method	Aerocapture	Propulsive	
Mars Ascent Propellant	ISRU	No ISRU	
Interplanetary Propulsion	NTR	Electric	Chemical

with the available resources?"), and robustness (i.e. "How sensitive is the solution?"). These three concepts are stated here abstractly, but each plays a role in the evaluation of cost, schedule, safety and mission success, and performance. Establishing a value model within which to evaluate alternative architectures with respect to a system of Measures of Effectiveness (MoEs), Measures of Performance (MoPs), and Technical Performance Measures (TPMs) is a challenge, as it is critical that the value model capture all relevant dimensions in which the alternatives considered might differentiate themselves. Human Mars architecture studies always quantify some of these, but rarely are all addressed. While applying a common value model to architecture concepts not originally formulated in a common context will be challenging, it will be an important part of realizing the desired outcome of a common basis of comparison.

5. SUMMARY

Humanity has long been interested in exploring the red planet in person. Since even before mankind's missions to the Moon, there have been many studies looking at different concepts and trades for a crewed Mars mission. There is a large body of work of human Mars studies, but these studies often have different ground rules and assumptions, making it tedious and time-consuming for modern Mars studies to tap into this body of work and take advantage of findings from the past. The Advanced Concepts Office at NASA's Marshall Space Flight Center is currently working to recapture and re-baseline previous Mars studies to establish a broad basis of comparison for future Mars studies. This paper outlined a plan to enumerate, synthesize, and evaluate previous Mars studies in a common framework. This is the first step in ACO's re-baslining work and will be followed by additional papers completing the basis of comparison work.

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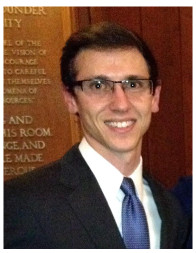

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