Risk Based Precursor Design
Supporting a Crewed Mars Mission

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Abstract: The optimization of an integrated space exploration campaign requires balancing of multiple parameters including performance, cost, schedule and risk. This is particularly true of ambitious human exploration missions involving engineering elements and logistics of the scale that will be required for a crewed Mars mission. A clear definition of the campaign objective and an understanding of the design space with respect to these interdependent parameters are required to focus development activities. Objective-free trade studies may generate insights that are only indirectly useful, and real progress towards programmatic decisions and commitments can only be made if these trade studies are tied to the integrated analysis of the end objective. The use of a risk based design methodology where long term exploration campaign objectives flow down in the form of near term project requirements will be discussed here using a crewed mission to Mars as the high-level exploration campaign objective. The methodology involves identifying critical path (flagship) technologies required to support a Mars mission. Technology Readiness Levels (TRL) based uncertainty and reliability growth models, represent a means of assessing test and precursor effectiveness in terms of achieving the mission objective.

Keywords: Risk, crewed Mars mission, precursor program

1. INTRODUCTION

A crewed mission to Mars would be the culmination of one of the largest engineering undertakings of mankind in modern times. This would require technological maturity, engineering expertise, and organizational infrastructure of the kind that must be cultivated through decades of experience in operating space systems. Crewed missions to Mars would need to tackle unique challenges in logistics, operations and environments at scales that have not been encountered before. Some capabilities, such as the ability to perform Entry, Descent and Landing (EDL) of large masses on Mars, maintaining propellants on orbit for long periods at the right condition, generating propellants using *in situ* resources and operating life support systems over long durations of time, have few (if any) precedents in the existing engineering heritage at the scales that will be required. In order to demonstrate feasibility and acquire the requisite experience on all these fronts, precursor missions that simulate many of the conditions of an actual crewed mission are called for. Different aspects of the technology required may be at varying degrees of Technological Readiness Level (TRL) at the initiation of development activities, and the ease with which TRL can be advanced to the extent that there is an acceptable level of confidence in launching a full fledged campaign to Mars with a reasonable expectation of success, may vary with the type of technology as well.

The Mars Exploration Program Analysis Group (MEPAG) has looked into precursor programs extensively. When discussing risk they note that for a human mission all types of risks would eventually be analyzed using systematic, quantitative risk analysis methods, however this would require a specific engineering implementation [1]. Using the output of the Mars Design Reference Mission (DRM) 5.0 [2] as this engineering implementation, this paper describes a methodology that involves a systematic, quantitative risk analysis approach applied to the development and assessment

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of possible precursor program and mission implementations. These precursor initiatives would take the form of requirements of more near term missions such as crewed International Space Station (ISS) experience, crewed Lunar Base buildup, Lunar Robotic Missions, robotic missions to Mars, as well as programs for terrestrial based test programs for developmental technologies.

2. THE NEED FOR PRECURSOR MISSIONS

2.1 Using Precursor Missions to Gain Experience

By performing a mission analysis, an initial definition of the elements of hardware and the corresponding performance can be established to define the design space. Once this minimum set of required systems is described, the design space must be analyzed in iterative fashion, attempting to balance the different parameters to establish engineering requirements for a Mars mission with a high expectation of mission success.

Having established the need to develop and test technology in intermediate steps prior to the actual mission, engineering inevitably finds itself confronting the reality of investment and costs [3] required to do this. In the face of this, a practical observation might be that it is not possible to develop all required technologies to the 'plateau' level of reliability by the date of planned initiation of the mission. A cost constrained paradigm that considers the relative risks in terms of their impact on the mission schedule can be used to identify the most critical development areas which need to be attacked earlier, to best address the technical risks in the years leading to the commencement of the actual program. In addressing technological maturity under the constraints, it becomes necessary to plan the development of new technologies in parallel and not sequentially, in order to make incremental progress on all of the key systems. A natural means of achieving this type of development, and additionally, understanding interactive phenomena and developing organizational capability to launch and manage complex missions, is to design precursor missions of increasingly challenging objectives that pave the way for a crewed Mars mission.

Taking a cue from past programs, such as the Apollo program [4], the use of comprehensive or "all-up" test missions that test a number of operational aspects in the actual environments may be designed to provide rich information on the engineering systems and also to develop engineering capability to operate logistics of a challenging crewed mission, which requires the assembly and transportation of space systems that may be larger and more complex than the International Space Station (ISS). In addition to using these precursor missions to acquire experience, they should be designed to accomplish other objectives which take the form of intermediate goals. This type of mission has been emphasized in the recent work of Augustine et al [5] as a 'flexible path' approach to Mars.

2.2 Planning Precursor Missions within the Context of Mission Objectives and Heritage

In designing precursor missions it is important to identify and emphasize work on those technologies that are prerequisites for a range of future potential missions. For instance, irrespective of whether the destination for a future mission is an asteroid, the Moon or Mars, a heavy lift launch capability may be called for, in order to get large payloads in Low Earth Orbit (LEO). Consequently, it may be prudent to invest resources in developing in this area early in the development period leading to the date of commencement of an actual campaign on Mars. Some areas, such as Mars EDL requires practical demonstration of physical parameters in order to improve the determination of design parameters for environments that cannot be tested in terrestrial conditions.

It is necessary to take into account existing resources that can be used to test certain capabilities. For instance, the ISS may be used to test life support system capabilities for a crewed Mars transit or performing operations such as on orbit propellant transfer. Science mission payloads to Mars can be planned to fly onboard transportation systems that are very similar to what would be necessary for a crewed mission. In designing precursor missions, an essential factor to consider would be balance between the experiences gained towards a crewed Mars mission, and investment required to tackle problems relevant to the precursor mission but not directly relevant to the crewed mission. For instance, the Moon may be an interesting destination for a precursor mission. However, in planning such a mission within the context of the ultimate goal of getting to Mars, with due consideration to the budget limitations, it may be essential to limit the number of missions to the Moon such that adequate experience is gained on aspects directly applicable to a Mars mission (e.g. heavy lift launch vehicle, surface power sources) while keeping the cost for subsystems that do not have direct applicability to Mars at a minimum.

3. RISK BASED PRECURSOR MISSION DESIGN

A risk based design approach to precursor mission design would begin by developing an understanding of the key risk drivers impacting the campaign objective, in this case a crewed mission to Mars and back. The risks involved are characterized by means of analysis- the present paper considers a reference mission from NASA's Mars DRM 5.0 to help demonstrate how the defined risk drivers can be addressed during the requirements definition of 'critical path' projects. Once the risk drivers have been defined, experts must work to identify key milestones that each precursor mission must achieve and develop the corresponding campaign options. Once these options are defined, risk analyses will be conducted to investigate different aspects and metrics including hardware development risk, probability of loss of mission or crew risk (LOM or LOC), and cost risks including competing in-agency objectives and sensitivity to assumptions concerning partnering. Once these options are defined and analyzed from a risk perspective they will be evaluated with respect to their level to which they satisfy progress towards the ultimate objective. If there is difficulty in defining a specific objective, a suite of studies can be conducted to explore the design space to identify the meaningful success criteria (e.g. initial presence, long term base, exploration of multiple sites).

As seen in Figure 2, the proposed methodology starts with identifying critical path technologies required to support a Mars mission. This analysis assumes that no 'game changing' technologies are available, that is technologies that would completely change the design space such as interplanetary propulsion systems that could overcome Mars transfer window limitations. Potentially, analysis can be used to identify the areas where a game changing or revolutionary concept can provide any improvement to the capability to achieve the end objective by means of sensitivity analysis and studying bounding cases. Once key technologies are identified, Technology Readiness Level (TRL) based schedule uncertainty models and Reliability Growth Models are combined to assess test and precursor mission effectiveness and help determine if schedule goals are realistic and what technology maturity levels will be prior to the initiation of the Mars mission launch campaign. These models can be used to probe sensitivities of the expected date of successfully accomplishing a mission to different testing and precursor mission program options.

Science return and technological advancement are two elements that need to be examined to determine the value added to the program by a proposed mission. It is important to balance the requirements that derive from the engineering capability aspects and the exploration needs. A precursor program that is completely optimized to generate information that helps achieve a super-objective, such as a crewed Mars mission, would place all of the focus on technological advancement. However, because the duration of these technology development programs spans decades, it would neither be realistic, nor wise from a science or public engagement perspective, to design such a development program that focuses solely on developing technology for the long-term objective. Hence, a precursor mission must be designed by balancing science return and technological advancement. A successful precursor program will incorporate multiple critical path technologies into a single mission that also has stand-alone merit from both a science and public engagement perspective. These missions could likely take the form of large-scale robotic missions or crewed missions to a Lunar or deep space destination.

Taking advantage of precursor tests that can be carried out as a part of the lunar, near earth object mission architecture or the ISS missions will offer invaluable reliability growth for Mars technologies. Potential technologies to benefit from a test program during Lunar or ISS missions include but are not limited to: hardware reliability & reparability, fission surface power, launch vehicle reliability, EDL technologies, lander propulsion system, ground processing infrastructure, advanced power, habitation, and closed-loop life support systems. Each of these developmental technologies required to complete a Mars mission will have to be addressed through testing or precursor missions. The milestones identified for each campaign option will be aligned with the precursor programs designed for each of these technology or operational elements. In addition to shaping crewed exploration priorities to align with a Mars mission, robotic missions can also provide a fertile test bed for required developmental technologies. Examples of items that can be leveraged for a Mars Robotic Program include pinpoint landing, autonomous approach navigation, automated in-orbit rendezvous and capture, small-scale Mars ascent, and continuous communications infrastructure (as part of sample return and other missions).

Figure 1: Notional Precursor Design Vision, with Intermediate Milestones

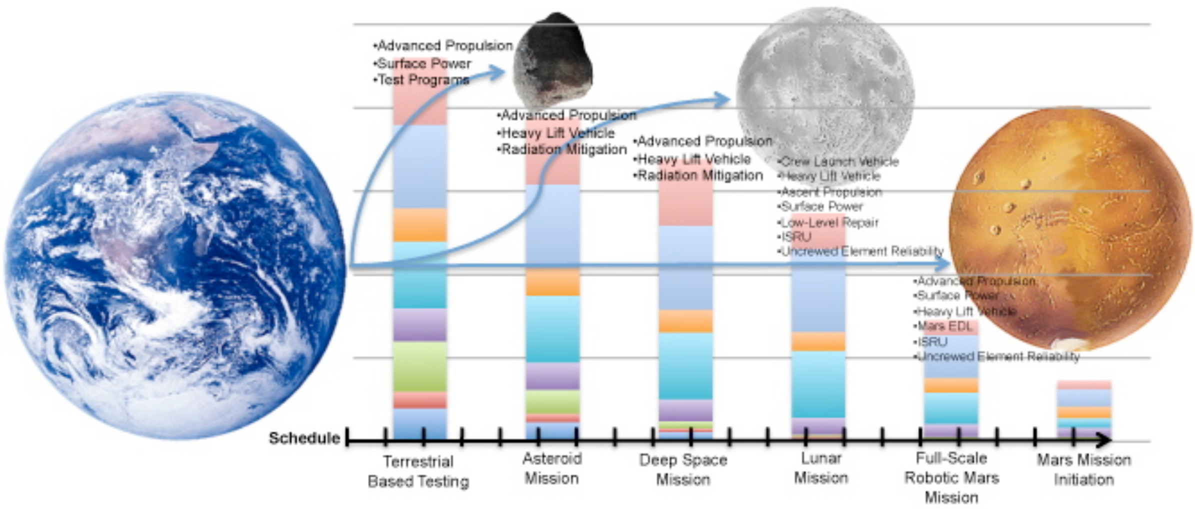
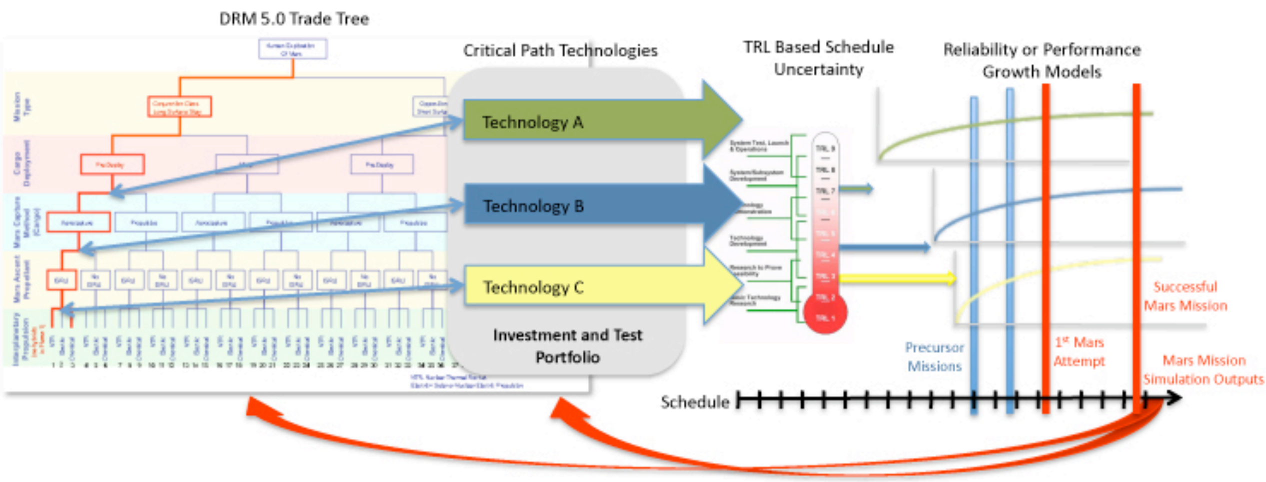


Figure 2: Mars Mission Precursor Design Methodology



3. MARS ARCHITECTURE LEVEL TRADE STUDIES

3.1 Flexible Path and Objective Optimization

A truly flexible path space exploration program follows the concept that multiple end-state objectives are carried through the program as long as possible. A degree of modularity must be built into the program whereby near-term missions can be re-designated. This allows for as much programmatic flexibility as possible. Technologies supporting these various objectives are developed in parallel with resources being shared by each competing 'hobby shop.' If done incorrectly this can lead to a program architecture that is inherently sub optimally designed to meet *any one* of those objectives. The ideal flexible path architecture would be one in which all work towards the primary objective, in this case a human mission to Mars, and which weights the stepping stone projects in terms of their value towards achieving the end objective. Suitable requirements and mechanisms would have to be established to ensure that there is direct correlation of mission experience on the precursor missions and ultimate mission objective. The advantage of the flexible path is that while the single objective timeline may become longer, intermediate milestones can be crafted to cater to important science and exploration needs, providing public engagement as missions of interest in their own right along the way to Mars.

During the design of these intermediate milestone missions, which are intended to mature critical path technologies, it is important to balance the merit of the milestone missions against the progress towards the primary objective, Mars. If a Lunar Outpost is determined to be a valuable milestone mission that could mature Mars mission critical path technologies it would be important to balance funding and schedule spent on the Lunar Outpost mission against impacts on the first crewed Mars mission timeline to ensure progress towards this primary objective is not eroded without increasing the likelihood of mission success.

3.2 Architecture Trade Tree

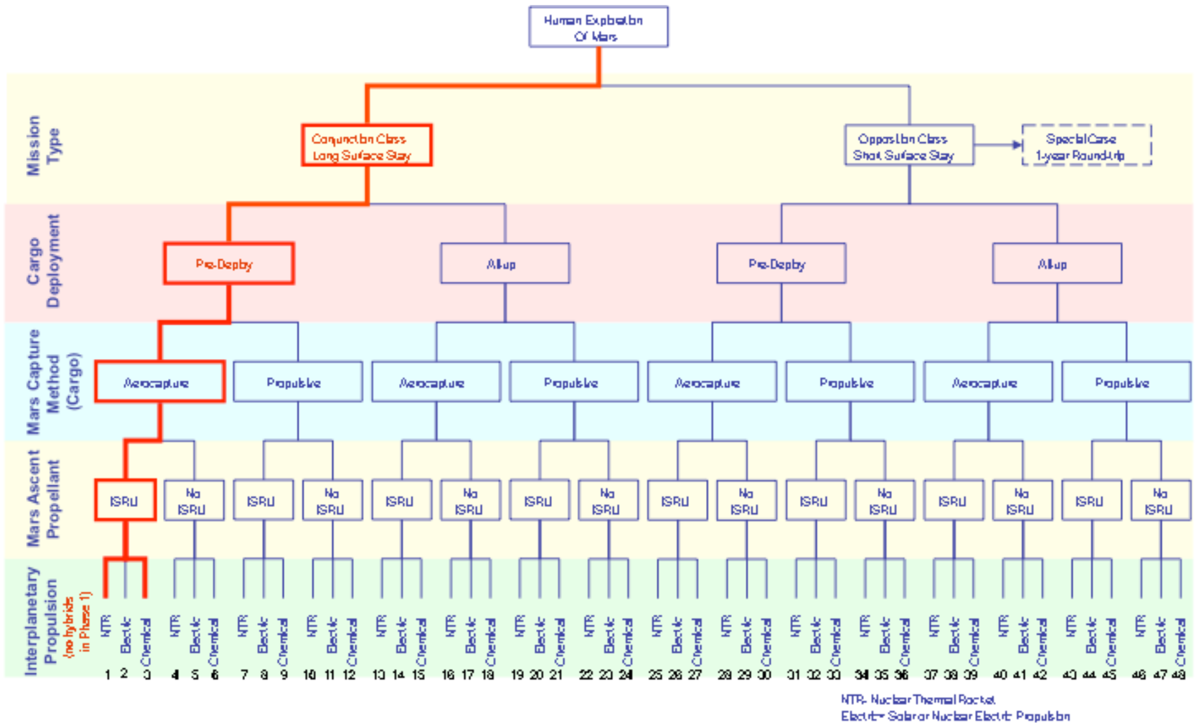
Mars DRM 5.0 used a trade tree to assess key mission design and technology decisions. The trade tree, shown in Figure 3, was considered options for combinations of mission type, cargo deployment, Mars orbit capture method, Mars ascent propellant, and interplanetary propulsion. Many of these key trades hinge on the development of critical path technologies. To address these critical path technologies the study also conducted preliminary precursor studies [6] to highlight technologies that needed to be matured. The approach described here proposes a method to help design the missions and test development programs designed to mature these technologies. These critical path technologies would need to be compiled into an Investment and Testing Portfolio. Once there, the Mars Mission Precursor Design Approach described would be applied to them combining both the TRL, Schedule Risk Assessment, and the Reliability Growth Models described below.

3.3 Investment and Testing Portfolio

The following is a sample list of technologies that need to be developed to successfully embark on a crewed mission to Mars:

1. Mars Entry, Descent, and Landing
2. Surface Power
3. Nuclear Thermal Propulsion
4. Chemical Propulsion
5. Life Support Systems
6. In Situ Resource Utilization (ISRU)
7. Low-Gravity Threat Mitigation
8. Ground Processing
9. Mars Surface Mobility
10. Mars Subsurface Access
11. Telecommunications
12. Cryogenic Fluid Management
13. Planetary Protection

Figure 3: Mars Architecture Study Trade Tree, Mars DRM 5.0, NASA



4. APPLYING A RISK INFORMED PRECURSOR AND TEST DESIGN PARADIGM

4.1 Modeling Technological Readiness Level (TRL)

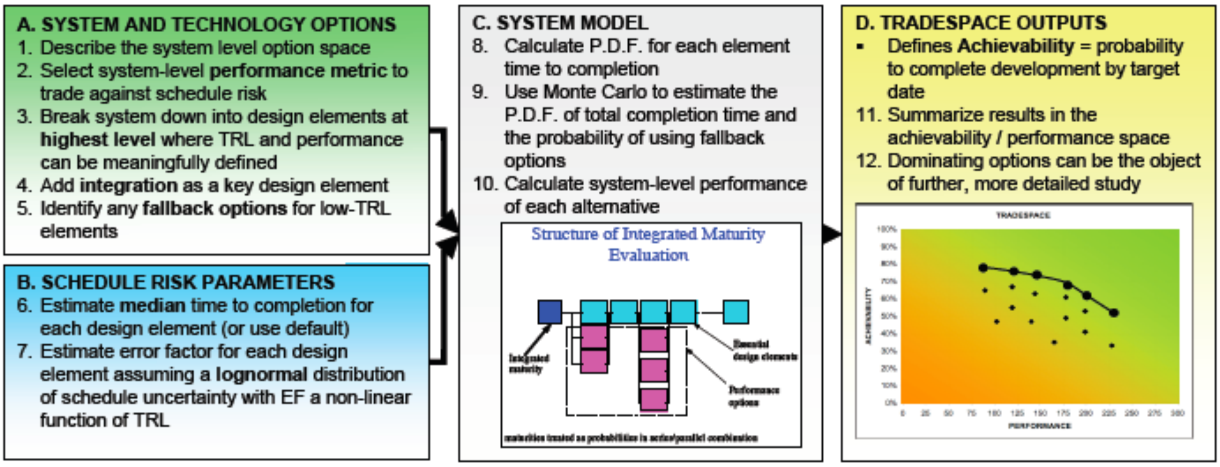
A top-down, systematic approach offers a number of advantages over the alternatives just described. While the modeling logic can appear extremely close or even identical to the previous examples, the key difference is in the application approach: a top-down, systematic analysis that maintains its focus on the ultimate study goals (accurate relative conclusions, capture of all schedule uncertainty differentiators) at every step along the way. This approach is not new. It has been applied with success on projects as varied as DoE radiographic technologies [7] and ROPOT (NASA Ames reusable launch vehicle, RLV options study) [8].

The proposed model [9], applicable to all types of systems and project phases, consists in building a simple, top-down model where system-level integration is recognized as an important performance and schedule risk driver, and where schedule uncertainties follow a lognormal distribution that is a function only of TRL level. A combination of expert elicitation and analytical models can be used to arrive at descriptions and confidence in different technologies or solutions. Such TRL models can be used to inform the prioritization of the development programs for critical technologies en route Mars. Figure 4 depicts the methodology flow for the analysis approach considered.

4.2 Reliability Growth Model

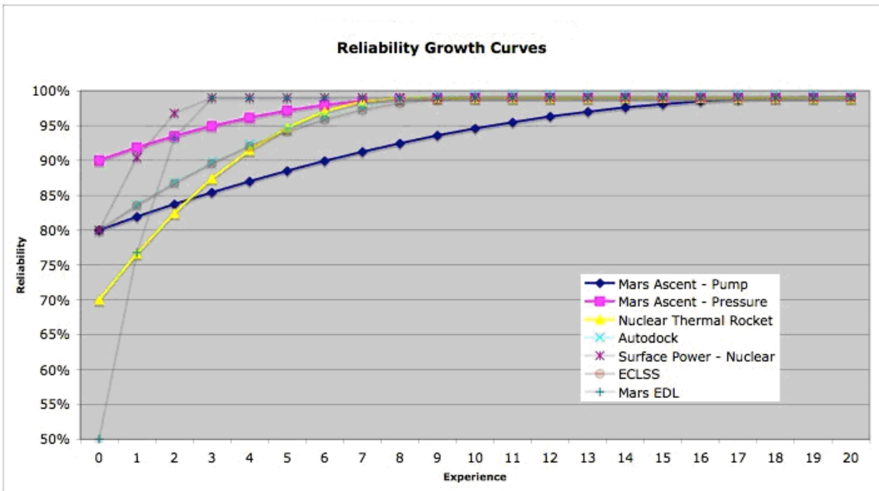
The immaturity of the developmental technologies needed to complete a Mars mission will have to be addressed through testing or precursor missions. Through demonstrations and experience, a reliability growth will occur as flaws are uncovered during testing and removed from the design.

Figure 4: Top-Down TRL Risk Analysis Approach



Due to time constraints, a maturity model designed to model propulsion systems and developed during the Exploration Systems Architecture Study (ESAS) [10] was used to model all of these developmental technologies. The reliability curves in Figure 5 show experience necessary to mature these technologies across their reliability ranges. These curves correspond with the bars that were used to represent a range of anticipated reliabilities for each technology.

Figure 5: Notional developmental technology reliability growth curves

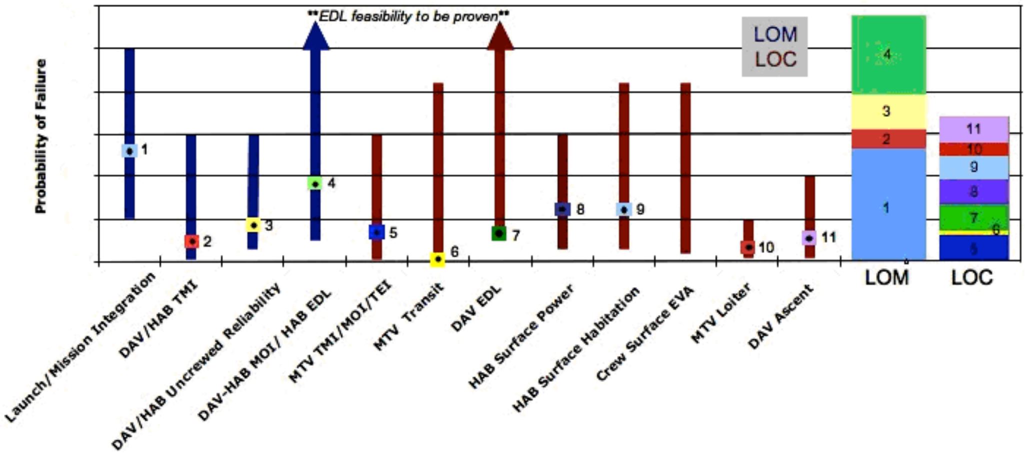


The maturity model used during this analysis to model developmental technology's reliability growth needs to be adjusted for each technology through discussions with experts. This initial model was developed to support the Exploration Systems Architecture Study [10] trade studies and was intended to model propulsion systems and may differ in character for varying technologies. Once these reliability curves are modified for each technology, costing and precursor analyses should be performed based on overall risk buy-down for the mission architecture. A detailed maturity growth model would allow potential risk buy-down to be quantified for each technology and provide decision makers with the information required to allocate the most impact on the probability of mission success.

6. INVESTMENT AND TESTING PORTFOLIO TRACKING

The anticipated reliability range of a subset of Mars Architecture risk driver ranges is shown in Figure 6. The range of the potential probability of failure is represented below using bars for risk driving elements. The tic marks on each bar represent the nominal failure probability assumed during trade studies. Investments and further analyses in the way of precursor activities, reliability growth implications, sparing/modularity capabilities, and ISS / Lunar synergies will determine where the actual element reliability falls within the given range. While these results provide high level insights, further analyses are expected to directly tie cost and reliability improvement programs with their risk mitigation impacts for elements and mission architectures.

Figure 6: Mission Risk Driver Ranges



The top Mars Architecture technology risk drivers are described below along with potential risk mitigation / precursor strategies shown in Table 1. The notional risk ranges have been correlated with risk mitigation and precursor activities proposed in the *Mars Architecture Study: Precursor Activity Report* [11]. These identified risks must be examined and tracked carefully as the architecture design and development progresses. In order to reach an acceptable level of risk for the overall Mars architecture a thorough risk reduction effort must be made across all technologies. Vigilance will be needed throughout the program to assure that other risks remain low. The bars are roughly arranged in the order of the mission events.

Launch / Mission Integration. The required level of mass to Low Earth Orbit in the necessary launch window makes the launch and integration stage of a Mars mission very difficult. With current ground processing and delay history, the required 10+ launches within the Mars launch window will require investments to lower the probability of failure for the mission. The number of launches (and launch vehicle reliability) limits the improvement that can be achieved.

Trans Mars Injection (TMI)/Mars Orbit Insertion (MOI)/Trans Earth Injection (TEI) Burns. The lack of experience the Nuclear Thermal Propulsion system has will make it a risk driver for a mission to Mars. Extensive testing and potential Lunar, or other synergies need to be further analyzed to provide opportunities to mature the propulsion system to an acceptable level.

Mars EDL. Extreme uncertainty concerning how to design the Mars entry, descent, and landing system makes it a major risk driver for a human Mars mission. The United States has successfully landed five robotic systems on the surface of Mars, all of which had landed mass below 600 kg (0.6 metric tons). A human Mars mission requires a simultaneous two order of magnitude increase in landed mass capability, four order of magnitude increase in landed accuracy, and an entry, descent and landing operations sequence that may need to be completed in a lower density (higher surface elevation) environment.

Crewed / Equipment Reliability. The duration of a mission to Mars makes both crewed and uncrewed time on systems a large risk driver. Current technology and design philosophies create an unacceptable level of risk when applied to a Mars mission. With no resupply capability, methodologies concerning sparing, levels of modularity, and scavenging need to be thoroughly explored in order to design systems capable of sustaining a crew for the duration of such an extreme mission. Mission phases will require dramatic improvements in equipment reliability since there is a limit to the mass available for redundancy and sparing.

Table 1: Mission Risk Drivers with Potential Risk Mitigation Techniques,

Risk Element	Basis	Mitigation/Precursors
TMI/MOI/TEI Burns Nuclear Thermal Propulsion	Existing Study, and Adapted ESAS Maturity Models	Develop NTP engine and test on Earth before flight test (2-3 demo engines) Lunar NTP flight test (demo NTP engines for lunar transfer stage) At least 1/10-scale uncrewed Mars mission Full-scale Mars cargo mission
Life Support Systems	ISS/Shuttle Equipment Reliability Redundancy Assumptions	Develop Repair Concepts Earth-based technology development and field tests Operational experience on the lunar surface Robotic (partial scale?) demonstration on Mars surface
Entry, Descent and Landing	Notional Concepts, Mars EDL Experience	Current precursor program accounts for an appropriate subscale system level test at Mars. Flight tests of TPS entry at Earth At least 1/10-scale precursor flight at Mars Full-scale cargo mission at Mars may provide certification for human landing
Mars Ascent Vehicle	ESAS Maturity Models	Most of development testing in vacuum and high-altitude chambers on Earth for engines and cryogenic fluid management Flight test of ascent system in LEO Common System with Lunar Lander
In Situ Resource Utilization	Notional Maturity Estimate	Subscale feasibility demo package missions to demonstrate the CO2 option (H2)-based O2 production) one or more robotic Mars prospecting missions.
Surface Power	Notional Maturity Estimate	Earth-based technology development and field tests Operational experience on the lunar surface Robotic (partial scale?) demonstration on Mars surface
Uncrewed Elements (Repair not an option)	ISS/Shuttle Equipment Reliability Redundancy Assumptions, Notional Improvement	Modularizaton Reliability Improvement Programs Operational experience on ISS Operational Experience on Lunar Surface Robotic Experience

	Estimates	

7. EVALUATING THE BENEFIT OF PRECURSOR MISSIONS

In determining the number and sequence of precursor missions to be flown, it is important to understand the technology drivers within the context of the ultimate objectives and the mission accomplishment parameters. To enable this, a Monte Carlo based mission model was developed to assess mission success probabilities given various levels of initial mission experience on critical path technologies. The risk estimates used were notional, but allowed to analysts to run sensitivities to various levels of precursor mission experience. Putney et al [3] show the output of some of the bounding cases of cumulative mission success probabilities across successive attempts. A key observation is the extent to which initial experience influences the delay in program schedule.

The schedule delay model can be used to develop an understanding of the probabilistic distribution of end dates for a round trip crewed mission to Mars. Once this is used to determine a target mission opportunity, the breakdown of risk contributors (Loss of Mission, Loss of Crew) is studied to determine the risk driving elements or systems at different initial conditions of experience level. The understanding gained from the use of TRL uncertainty models can be used to iteratively study the impacts to schedule when applied to the delay model.

Every proposed precursor program must be designed in the context of the crewed program and should ideally have a tangible requirement that ties aspects of the mission to the ultimate objective. In evaluating precursor missions on the basis of expenditure, the extent to which the actual operational environments need to be replicated must be considered. In order for technologies to buy their way on to a flight mission, it is essential that they be amply tested on Earth first to characterize system operational and failure behavior to the best possible extent. For instance, to test certain aspects of life support systems, experiments on Earth can provide a great deal of information on how to design closed loop systems with high mean time between failures. Using the TRL development forecasting models, it is essential to prioritize the development and testing of those components that have greater design lead times and uncertainty associated with operation. Precursor missions should be designed around these technologies in order to focus the development of necessary elements which more or less, ‘make or break’ the campaign strategy.

A test should incorporate as many aspects of the ultimate mission as is feasible. This is similar to the concept of “all-up” testing employed during the Apollo program. For instance, the use of ISRU for propellant generation and the FSPS to power this and other life support systems on Mars may be determined to be the large uncertainty driver and hence the key determinant of the feasibility of sending humans to Mars. These systems can be designed and tested on Earth, compliant with launcher considerations (design to accommodate cargo in modular masses and volumes). Science and robotic missions to Mars in the development years preceding the crewed campaign must be designed to test the characteristic EDL conditions, and environmental parameters determined from these missions can be utilized to develop a feasible design for larger payloads. Eventually, a mission can be flown that utilizes propulsion concepts that will be needed for a human mission, tests the EDL and autonomous deployment and operation of the ISRU and FSPS systems. The in situ resources generated can be used to demonstrate operability of certain systems for the duration of a crewed mission, and ultimately, prepare scientific samples for return to Earth. This type of end to end mission that employs most of the elements of the crewed mission, without endangering an actual crew and perhaps allowing some of the attendant safety requirements to be relaxed to test the tolerance of systems to extremes, can provide a wealth of knowledge on systems in addition to being challenging to engineering and providing opportunities for science payloads that can ‘go along for the ride.’

Designers invariably resort to heritage-informed designs. In addition to searching for lessons learned in existing heritage, it is important to structure future missions in a manner that allows for more experience to be gained. For instance, components of Mars EDL technologies can be tested across multiple smaller missions that serve the additional purpose of performing science activities. In flowing down mission requirements to these precursor missions, it is important that the additional cost involved that does not directly 'buy' experience that is applicable to the Mars human EDL be minimized. Rather than consider 'science' type robotic missions as completely independent of the 'human exploration' type missions, it may be advantageous to craft robotic missions that test most of the technologies that will be required for the human mission.

8. CONCLUSIONS

The risk based design methodology of how long term exploration campaign objectives should flow down in the form of near term project requirements explained here provides a possible framework for technology precursor design activities. The appropriate balance between buying down risk for long term objectives against creating meaningful near term milestones is an imperative balance in establishing a sustainable program spanning decades. Additionally, embedding precursor decisions and TRL development programs in such a framework provides the evidence required for project managers to accept the risk and use these critical path technologies on milestone missions in order to help mature the technologies. It is only with the perspective of what technologies are required for long term objectives and what precursors are required to mature those technologies, that critical path technologies will be incorporated into precursor missions in an optimized, meaningful way.

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