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ABSTRACT

This paper investigates a new method of measuring the affordability of aerospace technologies. First, a new bimodal NTR Mars mission architecture was defined. Starting with brainstorming on the different ways to get to Mars, several different trade studies were investigated, the results of which defined the architecture. A Reduced-Order Simulation for Evaluating Technologies and Transportation Architectures (ROSETTA) model has been created from this architecture. This model is an Excel workbook of interconnected worksheets that represented the different disciplines used in creating the architecture. Each worksheet is based on the results of higher fidelity codes such as the Program to Optimize Simulated Trajectories (POST) and the Aerodynamic Preliminary Analysis System (APAS). These results were then reduced to simpler, parametric relations, giving rise to the 'Reduced Order' in ROSETTA. The BNTR ROSETTA model is capable of rapidly resizing the Mars transfer vehicle and landers and estimating the key cost and mass metrics as the input technology assumptions change. Future technology assessment will be done probabilistically, by assigning a distribution to each input parameter that the technology affects, then running a Monte Carlo analysis in order to generate an output distribution for each metric. Benefit-to-cost ratios and top-level uncertainties can be determined from this data.

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INTRODUCTION

This research investigated two aspects of evaluating a manned mission to Mars based around using artificial gravity on a Bimodal Nuclear Thermal Rocket (BNTR), a class of NTR capable of producing both thrust for propulsion and electricity for power. The first aspect of the investigation was the architecture of the mission.

Once the architecture was finalized, it was simulated using a Reduced-Order Simulation for Evaluating Technologies and Transportation Architectures model (ROSETTA model). This model can subsequently be used to probabilistically assess the affordability, or 'bang for the buck', of a candidate technology to be applied to this architecture. NASA's Integrated Technology Assessment Center will use this model to rank order the different technologies and then recommend the best area to concentrate future research funding. [1]

The overall framework of the mission was similar to an Apollo-style program, potentially sending one scientific mission at every opportunity between 2010 and 2040 to study various different sites on Mars.

Similar missions using a BNTR have been proposed [2], but the general mission architecture did not allow for multi-mission use of the Mars transfer vehicle, mostly due to political concerns of bring a BNTR back to Earth orbit. To address this concern, once the reactor reached initial criticality the transfer vehicle was never recaptured into Earth orbit or brought below the nuclear-free altitude limit of 800 km.

Each mission consisted of a number of Mars Transfer Vehicles (MTVs). Each MTV was a self-sufficient vehicle capable of independently making the entire round trip. Each crew vehicle transported one lander capable of delivering 5 MT to the surface. Cargo carrying MTV's would carry as many landers as possible. Once safely on an interplanetary trajectory, the two vehicles carrying the crew were joined by a 200-meter long tether then spun at 1.0 RPM in order to simulate Mars gravity. On the return trip, the MTV pair was first spun up to simulate Mars gravity, then gradually increased to 3.0 RPM in order to simulate Earth gravity by the time the crew returned home.

MISSION ARCHITECTURE ANALYSIS

For the present GT study, various analyses and trade studies were conducted before finalizing a new architecture. Several issues considered included:

- Using In-Situ Resource Utilization (ISRU) on Mars to produce propellant for the lander versus bringing fuel from Earth.
- Microwave power beaming from the MTV, in order to further leverage the bimodal aspect of the BNTR versus bringing a second power station with the lander.
- Split-mission profile versus sending all vehicles at once; for a split-mission profile, the advantages of a Venus swing-by trajectory; and various possibilities for Earth and Mars orbital basing.

The morphological matrix of all possible options is given below in Table 1. Bolded options were the final selections.

Table 1: Architecture Morphological Matrix

Mars ascent propellant	**ISRU**	Carry with	
Surface Power	**Power beaming Orbital reactor**	Surface reactor	Solar arrays
Earth Orbit Basing	**LEO**	Lunar Orbit	Lagrange Point
Mars Orbit Basing	**LMO**	**AMO**	Highly elliptical
Cargo Transfer	**Split mission**	Dual mission	
Transfer Orbit	**Hohmann**	**Fast**	Planetary fly-by

ISRU Trade Study

This trade study was conducted as a top-level analysis of two separate propulsion systems for the lander vehicle. One used LOX/CH_4, using resources generated from the Martian atmosphere for the ascent propellant. The second system used LOX/LH_2, requiring both ascent and descent propellant to be brought from Earth.

The advantages of one system were the disadvantages of the other, and vice versa. The advantage of using LOX/CH_4 was the reduced IMLEO because it removed the necessity of carrying ascent and descent propellant down to the surface. Additionally, by not having to haul the ascent propellant down to the surface, the overall mass ratio is much lower for this vehicle, resulting in a much smaller, and hence less expensive, vehicle. The advantage of using a LOX/LH_2 system was the high I_{sp} of 460 seconds, compared to an I_{sp} of 380 seconds for the LOX/CH_4 system.

Table 2: ISRU Trade Study Results

	LOX/CH4	LOX/LH2
Delta V	5100 m/s	7600 m/s
Isp	380 s	460 s
MR	3.9279	5.3880
ς	0.7454	0.8144
λ	0.1300	0.1300
M cargo	5000 kg	5000 kg
M isru	378 kg	0 kg
M h2	1892 kg	0 kg
M pl	7271 kg	5000 kg
M init	50770 kg	78240 kg
M prop	37845 kg	63719 kg
M struct	5655 kg	9521 kg

The data and results of the trade study are given in Table 2. The ΔV used was based on data from a 3-DOF trajectory simulation (described later) The effective structural factor (λ) [3] used was a rough estimate for both the LOX/CH4 system and the LOX/LH2 system. Both systems were required to bring 5 MT of cargo to the surface. Additionally, the LOX/CH4 system had to bring the ISRU plant, estimated at 1% of the ascent propellant mass, and the seed hydrogen for the methane, estimated at 5% of the ascent propellant mass.

The LOX/CH4 system was selected based on the lower initial mass and lower structural mass.

Surface Power Analysis

Three options were identified to supply electrical power while on the surface: microwave power beaming from a MTV in Areosynchronous Mars Orbit (AMO) to rectennas on the surface; bringing a dedicated nuclear reactor; using solar cells. Of these three options, using solar cells was quickly discarded as impractical due to the reduced solar flux available at Mars and the possibility of obscuring sandstorms.

Advantages and disadvantages for both options were then identified. The advantages of microwave power beaming were the increased synergy with the BNTR already on the MTV and lower mass to take to the surface. The disadvantages were reliance on automated equipment in AMO and the additional mass of the transmitter on the MTV. The advantage of bringing a dedicated nuclear reactor was the reliability of having the system on the ground and available for maintenance. The disadvantage of bringing a dedicated reactor was the additional mass brought to the surface. The need for a back up power supply (a LOX/CH_4 fuel cell to increase synergy with the ISRU plant) was the same for both options (or any ground power system, for that matter). Thus, this requirement provided no advantage to either option.

When all the advantages and disadvantages were identified, the final selection was made using Analytic Hierarchy Process (AHP). [4] Both options were compared against each other in the categories of safety, feasibility, complexity, cost, and synergy. Based on this analysis, microwave power beaming was selected.

Orbital Basing Analysis

Several options were possible for both Earth and Mars orbital basing. When brainstorming for options for the Earth orbital basing, the possibility of extensive infrastructure in the Earth-Moon system was allowed. However, on further definition of the framework, that infrastructure could not be assumed to be available, leaving LEO basing as the only option.

Mars orbit basing was more flexible since any infrastructure at Mars would have to be supplied by the mission, no matter what scenario was considered. The decision was essentially where to leave the MTVs while the crew was on the surface. The main concern in making this decision was the amount of ΔV the lander would be required to provide, which essentially set the size of the lander. Selecting Low Mars Orbit (LMO) would minimize the lander ΔV but might preclude using the BNTR as a power satellite. Selecting AMO would maximize the lander ΔV, but would allow each MTV to act as a power satellite. The highly elliptical orbit was included as a possible compromise between the two.

After further review of the options, a different compromise was selected. Due to the excess power capability of one MTV (see the later section *Interplanetary Propulsion*), it was necessary to provide only one MTV as a power satellite. Thus a compromise of using both LMO and AMO was selected.

One of the cargo MTVs would carry enough extra propellant in order to first deliver its landers to LMO, burn to AMO and take up station as a power beaming satellite, burn a second time down to LMO, pick up the returning landers, and then burn for Earth. The remaining MTVs would go directly to LMO and stay there, to be more easily accessible from the surface, in case of emergency.

Interplanetary Trajectory Analysis

The options considered here essentially came down to using one large vehicle versus using a fleet of smaller vehicles. Because cost and complexity went up more than linearly with size, using one vehicle wasn't economical.

Once the field was narrowed down to using a fleet of smaller vehicles, using them flexibly in a split mission scenario (sending an automated cargo mission and a separate crew mission) was a more effective use of assets, particularly in light of the expected vast improvement in autonomous intelligence for the time frame in question.

The last remaining aspect of the interplanetary trajectory was the use of a gravity assist swing-by of Venus. Based on the greater ΔV requirement, the shortened length of the surface stay (30 days) and the only marginally better level of radiation exposure (52.0 rem vs. 58.4 rem), a direct trajectory was selected. [5]

Scenario Summary

Once the mission architecture analysis was complete, the two vehicle designs were integrated into the overall mission scenario.

The lander was designed around the crew mission. It was intended to take 5 MT of crew or payload to the surface from LMO, using a LOX/CH_4 propulsion system. Once on the surface, it generated all of its ascent propellant from an integral ISRU plant, while receiving electrical energy from a MTV stationed in AMO. When the surface stay was complete, the lander returned to LMO, rendezvousing with its MTV, and returned to Earth. The MTV was sized to carry one lander on a fast transfer orbit from Earth to Mars and back again. A complete cycle based around these designs is summarized below.

The cycle begins in one opportunity and continues into the next. In the first opportunity, the cargo mission will fly on a slow Hohmann orbit. Because the MTV was sized around the much larger ΔV required for a fast transfer, it will be able to carry multiple landers on a minimum ΔV orbit. However, depending on the total payload required, several MTV may be required on this part of the mission.

Once in LMO, the landers will undock and one MTV will shift its orbit to AMO to begin microwave power beaming. The landers will then descend to the surface and will immediately begin producing their ascent propellant. With the ascent propellant produced, the crew mission will be given the go-ahead to fly at the next opportunity.

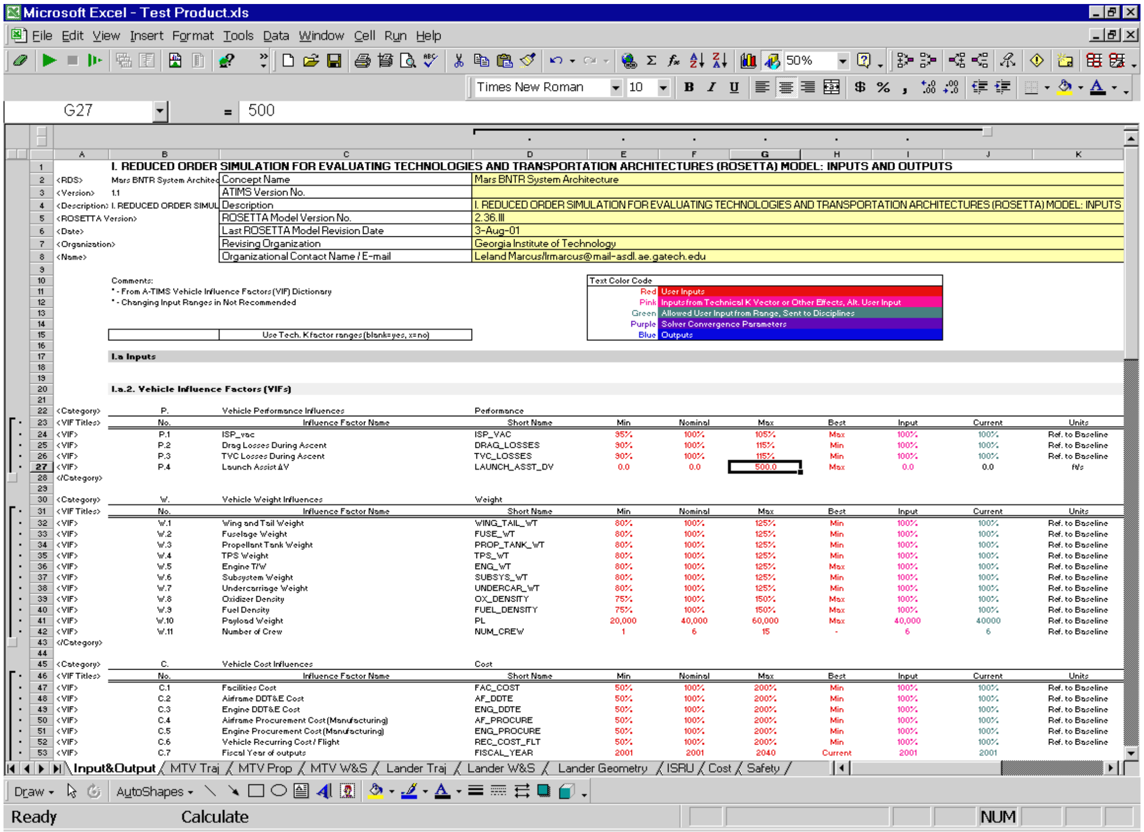
The crew mission will consist of two MTVs with their associated landers. On the trip to Mars, these two vehicles will be tethered together and spun to simulate Mars gravity. At Mars, the MTVs will stay in LMO and the landers will descend to meet with the cargo lander from the previous opportunity.

Also during the second opportunity, the cargo segment of the next mission will be sent to prepare the way at the next landing site. This overlap will continue as long as the architecture is in use.

After the surface stay is complete, all the landers will ascend to LMO and rendezvous with their respective MTVs, after the power satellite MTV descends to LMO. Again, the crew will fly on a fast trajectory while the cargo mission will fly on a Hohmann trajectory. When the MTVs return to Earth, they will enter a MEO rather than LEO, in order to keep the BNTR above 800 km altitude, and then the cycle will repeat.

ROSETTA MODEL DESCRIPTION

The ROSETTA model for this architecture was an Excel workbook composed of 10 different worksheets, each one covering a different discipline. Engineering disciplines were included for the MTV and the lander as well as a cost and safety worksheet for the entire architecture. A summary of each discipline is given, followed by an overview of the working of the entire model. An example of the Input & Output page is shown in Figure 1.



Microsoft Excel - Test Product.xls

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<Date>		Last ROSETTA Model Revision Date	3-Aug-01
<Organization>		Revising Organization	Georgia Institute of Technology
<Name>		Organizational Contact Name / E-mail	Leland Marcus/lrmarcus@mail-asdl.ae.gatech.edu

Comments:
* - From A-TIMS Vehicle Influence Factors (VIF) Dictionary
* - Changing Input Ranges in Not Recommended

Use Tech. K factor ranges (blank=yes, x=no)

Text Color Code	
Red	User Inputs
Pink	Inputs from Technical K Vector or Other Effects, Alt. User Input
Green	Allowed User Input from Range, Sent to Disciplines
Purple	Solver Convergence Parameters
Blue	Outputs

I.a Inputs

I.a.2. Vehicle Influence Factors (VIFs)

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Input&Output / MTV Traj / MTV Prop / MTV W&S / Lander Traj / Lander W&S / Lander Geometry / ISRU / Cost / Safety

Ready Calculate NUM

Fig. 1: Example Input and Output worksheet from ROSETTA model

MTV Propulsion

The MTV main propulsion consisted of a solid core bimodal nuclear thermal rocket with I_{sp} ~ 960-980 seconds and T/W_{earth} ~ 5-7. [6] The BNTR used an open-loop LH2 flow path to produce thrust and a closed-loop flow path through a Brayton power generation cycle to produce electricity. The secondary flow path for power generation, using a separate working fluid that never interacted with the propellant, was sized based on two separate considerations.

The first consideration was providing enough power for the ground station using microwave power beaming from AMO to a rectenna on the surface. The second consideration was providing enough cooling capacity for decay heat removal from the power history of a main propulsion burn. The cooling requirement to remove decay heat became the driving factor in sizing the power generation system.

When modeling the propulsion characteristics of the BNTR, the main input was the allowable chamber temperature. From this number, using the physical characteristics of hydrogen, the worksheet calculated c^* and chamber pressure. From these intermediate steps, the worksheet then calculated I_{sp} and mass flow rates as its main output. Thrust and power levels were handled parametrically rather than on a physical basis.

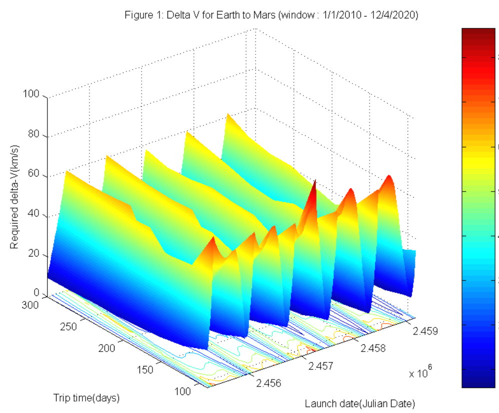

Fig. 2: ΔV versus Time of Flight and Departure Date for direct Earth to Mars

MTV Trajectory Analysis

Supporting interplanetary trajectory analyses were conducted using IPREP, a patched-conics analysis that determined the ΔV required for any given launch date and transit time. Fig. 2 shows the ΔV required for a direct Earth to Mars transit from 2010 to 2020. The synodic period of 26 months is shown by the time between peaks or valleys.

For the purposed of the model, this data was reduced to a table look up which gave the minimum ΔV for a specified Time of Flight and flight opportunity.

MTV Weights & Sizing

The MTV weight statement used Mass Estimating Relationships (MERs) to generate the mass required for each subsystem based on several different inputs, such as the payload (the lander) mass and the total ΔV required for a complete round trip.

Since there was very little historical data available for in-space vehicles, there could be high uncertainty in this sort of analysis. To account for that, many factors in this discipline were handled parametrically. When combined with the probabilistic approach of Monte Carlo analysis, this gave a good understanding of what the values need to be to succeed.

Lander Propulsion

As opposed to the MTV propulsion worksheet, the lander propulsion was analyzed more parametrically. However, analysis using SCORES, a web based rocket analysis tool [7], was conducted to determine the effective range for those parameters. For example, this analysis gave the suggested maximum and minimum values to use for I_{sp}.

Lander Aerodynamics & Trajectory

Aerodynamic data was calculated using APAS. This software package used a subsonic/supersonic panel code called UDP (Unified Distributed Panel), and a hypersonic code HABP (Hypersonic Arbitrary Body Program). Two different geometries were considered, a bi-conic VTVL vehicle and a lifting body vehicle. The bi-conic vehicle (see Fig. 3) was the preferred shape, mostly due to concerns about landing and take off using the lifting body shape.

A table of Martian atmospheric properties was used to calculate Reynolds numbers. These were matched to possible Mach numbers and altitudes (plausible trajectory). The atmospheric temperature and pressure values (from Martian data) were extracted along a representative trajectory and used to produce the aerodynamic characteristics (see Fig. 4).

Analysis of ascent and descent trajectories from the surface of Mars was conducted using POST, and used the aerodynamic data for the bi-conic shape. This required analysis of both the entry trajectory to determine required descent propellant as well as the necessary ascent propellant for the return trip to Low Mars Orbit (LMO).

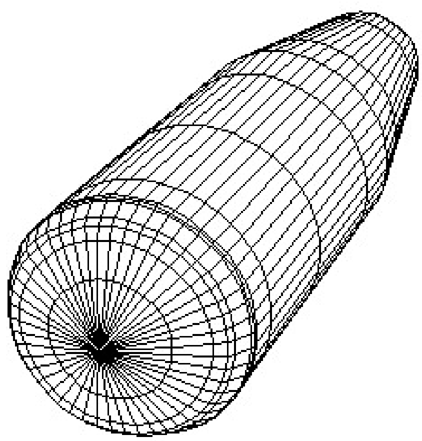

Fig. 3: Descent Profile of APAS Geometry

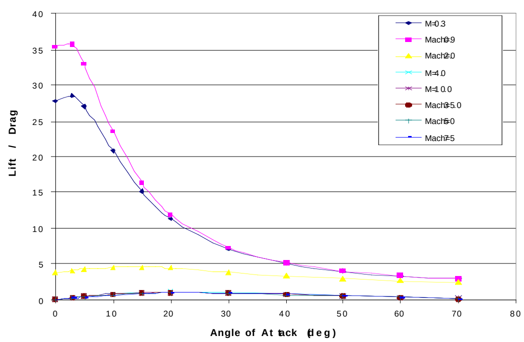

Fig. 4: Lift/Drag versus α

This analysis resulted in an estimate of the total required ΔV for both trajectories. The ascent ΔV of 3998 m/s was much greater than the descent ΔV of 1500 m/s, so the lander was sized around this number. The ascent ΔV was composed of 3443 m/s of ΔV_{Flight} and 555 m/s of $\Delta V_{Total\ Losses}$. These numbers were used as a table look-up for the Trajectory worksheet in the ROSETTA model.

Lander Weights & Sizing

The lander weight statement also used historical MERs. However, due to the greater historically database of launch vehicles and previous research conducted into a Mars Reusable Excursion Vehicle, there was a great deal more fidelity associated with this worksheet. The same future work to improve the in-space MERs will also improve this area.

Similar to the MTV Weights & Sizing, this sheet estimated the mass of the various lander subsystems based on a number of different architecture parameters, again such as the payload mass and the amount of ΔV required.

In-Situ Resource Utilization (ISRU)

The model of this system took the required propellant production and the time available for production then sized the ISRU plant, both mass and power, as an output. This information fed directly into the Lander Weights & Sizing worksheet.

Cost

Cost was estimated using the Design, Development, Test, & Engineering (DDT&E) and Theoretical First Unit (TFU) worksheet from CABAM. [8] This worksheet used historical Cost Estimating Relationships (CERs) based on sub-system weights to estimate the DDT&E cost and TFU cost for both the MTV and lander. Complexity factors were included in order to account the specific requirements of a human Mars mission. This information was then used to produce architecture level outputs, such as dollars per mission and dollars per kilogram to the surface.

Safety

A modified version of GT-Safety was used to determine what the probability of loss of mission, loss of vehicle, loss of crew and the casualty rate for ground and public personnel is for any given concept. In order to achieve this, a series of inputs were required that are both specific and general in nature.

The specific data that GT-Safety used dealt with items such as the propellant weight, the number of engines, the number of crew and the vehicle dimensions. The general data was more of a comparison of how the concept vehicle ranks compared to the baseline (Shuttle). This was in the form to indicated whether the concept vehicle was less complex when it comes to operations handling then the baseline, or whether the concept vehicle had a more advance Integrated Vehicle Health Monitoring System on board then the baseline.

Component-level safety data were input on a log scale where 3 equaled the baseline database; a value greater then 3 was better then the baseline and a value less then 3 was worse then the baseline. For the specific data, those values were either input from other worksheets in the ROSETTA model or were set values.

The combined inputs were then used to perform calculations in five areas: crew safety on the ground, crew safety in flight, TPS reliability, engine reliability and the overall reliability. The values from each of these areas are then used to calculate the overall safety results.

Sample Results

Table 3: Sample Results-Lander

	Nominal		Worst	
ΔV	5000	m/s	5200	m/s
Isp	380	s	360	s
ETO cost	2200	$/kg	11000	$/kg
M dry	21600	kg	26100	kg
M gross	108950	kg	146100	kg
DDT&E	3072	$M	3436	$M
TFU	678	$M	777	$M
Total Cost (1)	5825	$M	10588	$M
Cost/kg (1)	388.3	$k/kg	705.8	$k/kg
Total Cost (5)	8263	$M	27086	$M
Cost/kg (5)	110.2	$k/kg	361.2	$k/kg

Using the BNTR ROSETTA model, results can be generated quickly and over a range of different inputs. The example case given in Table 3 was for a quick comparison between two different lander designs, using two vehicle inputs and one economic input. The first case represented the nominal case for all inputs, while the second used the 'worst' allowable inputs over the pre-defined range, thus giving a good feel for the span of this particular design space.

Both sets of lander results were recalculated by the ROSETTA model in less than a minute using Excel's Solver, and generated the key cost and weight metrics for the lander segment of the scenario. Cost estimates per kg of payload delivered to the surface are shown for a single Mars mission scenario. Here, initial development costs (DDT&E) and acquisition costs are amortized over this one Mars mission. An average cost for a five mission case is also given.

FUTURE TECHNOLOGY ASSESSMENT APPROACH

With a ROSETTA model as the key recalculation mechanism, probabilistic risk and uncertainty assessments can be conducted using direct Monte Carlo methods. Using built-in iteration and Solver, these worksheets can very quickly produce a converged design of the entire architecture for a given set of inputs, and the key output metrics such as MTV weight, lander weight, cost, and safety can be extracted for that case.

The ways each technology affects the various inputs to the ROSETTA model are represented as k-factor modifiers for that technology. For each candidate technology, k-factors can be assigned a triangular distribution of values (e.g. a light weight materials technology might be given a k-factor for tank weight that reduces it by between 5-10%, with a most likely value of 8%.) Additionally, n-factors, distributions similar to k-factors, may be used to simulate the effect of internal simulation 'noise' or embedded uncertainties due to model error or incomplete knowledge of a given input.

Once the factors are assigned for each technology, a portfolio of technologies can be selected for evaluation. Several thousand runs can be conducted quickly using the Crystal Ball® add-in for Excel, making a ROSETTA model a central feature for technology evaluation process such as Georgia Tech's TIES [9]. TIES allows for rapid assessment of the benefit of both individual technologies and entire investment portfolios of multiple technologies. Application of TIES to the BNTR ROSETTA model remains to be future work.

CONCLUSIONS

A new human Mars mission architecture was proposed. Key features included the use of multiple MTV's powered by bimodal NTR propulsion, artificial gravity induced by rotating coupled vehicles during transit, ISRU for CH_4 production on the Martian surface, wireless power transmission for surface power, and reusable biconic Mars landers.

From the higher-fidelity trajectory, aerodynamic, cost, safety, and weights analyses performed in support of this study, a new fast-acting ROSETTA model was created. The spreadsheet-based ROSETTA model parametrically represented the entire architecture and was able to resize the required vehicles and determine new weights, costs, and safety metrics as the key input assumptions were varied. Future probabilistic technology assessment activities by both NASA's ITAC and Georgia Tech's Space Systems Design Lab will use the new BNTR ROSETTA model to evaluate portfolios of candidate technologies that might benefit a future human Mars mission.

ACKNOWLEDGEMENTS

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