Flexibility for in-Space Propulsion Technology Investment

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ESD.71 Engineering Systems Analysis for Design
Application Portfolio

Executive Summary

This project looks at options for investment for in-space propulsion technology development for human space exploration. Only two propulsion types are considered: Solar Electric Propulsion (SEP) and a Chemical Propulsion Stage (CPS). A simulation is built around cost data and mission profiles included in a presentation from NASA. These include precursor flights that sufficiently raise the Technology Readiness Level (TRL) of each technology for use in human spaceflight. The current mission campaign is designed for a Near-Earth Asteroid (NEA) with the intention of creating technological readiness for Mars missions. While SEP and CPS will be required for Mars missions, the intermediate goal may be executed with CPS alone.

The simulation includes uncertainty in the success of precursor flight demonstrations. This uncertainty demonstrates the real possibility that SEP is not actually available for the NEA mission. A scheme is proposed to maximize technology development cost effectiveness, while ensuring technology is available for the human exploration missions. Given the uncertainty of successful flights, flexibility of a put option is included to delay development of SEP given insufficient TRL at set decision points. By creating a measure of effectiveness that rewards successful technology investment and including flexibility to revert to only CPS, total expected cost can be reduced. More importantly, the mean expected cost effectiveness is increased by over 35%. Suggested next steps include defining uncertainty of the costs and including more alternative propulsion technologies.

Contents

Background

This project is focused on investment for in-space propulsion technology development for human space exploration. That refers to the engines that will take people from Earth orbit to space exploration destinations (the engines do not operate in Earth's atmosphere). For the purposes of this assignment only two propulsion types will be considered: Solar Electric Propulsion (SEP) and a Chemical Propulsion Stage (CPS).

In-Space Propulsion

SEP- shown below involves very large solar arrays to collect energy. Propulsion is achieved by an electric engine which is an order of magnitude more fuel efficient[1] than chemical propulsion. While electric thrusters and solar arrays are not new technologies, developing them at sufficiently large sizes has not yet been demonstrated. Since the solar energy available at any given time (and location) limits the thrust of the engine, SEP systems have very low thrust despite their high efficiency. The thrust level influences time-of-flight to a destination. For most cargo, this does not matter much, however for transferring crew (people) it leads to transit times that are logistically infeasible due to extra mass of consumables and radiation shielding required. The result is that SEP cannot be the only in-space propulsion technology for space exploration with humans.

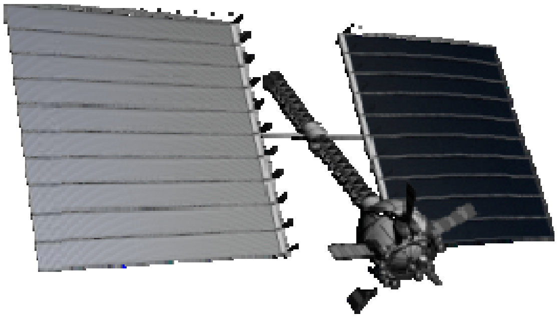

Figure 1 Solar Electric Propulsion

In general CPS (shown below) is chemical rockets. Liquid fuel and oxidizer combine to create expanding gasses that are channeled through a nozzle to create thrust. Almost every rocket in existence so far has been a chemical rocket. While they are not as efficient as electric engines, they can provide very high thrust and are not dependent on solar energy. CPS technology for in-space systems has much more heritage than SEP. It is however important to note that some technology development is still required as no one has stored high-performing chemical propellants in space for any significant amount of time yet. That sort of storage would be required for these missions because sometimes the propulsion stage is launched into space more than a year before it is actually used. (For example the propulsion that is required to return astronauts from the destination must be carried for the duration of the trip).

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[1] For rocket engines an "efficiency" parameter is usually calculated as specific impulse (I_{sp}). This is more precisely a measure of impulse delivered per unit mass (or weight) of propellant for a given engine. In broad terms it is a measure of fuel efficiency.

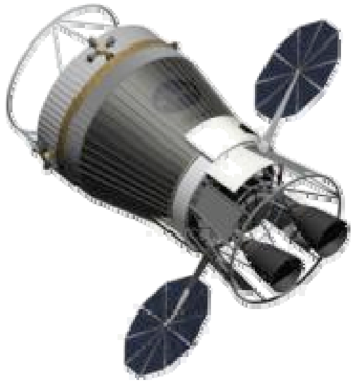

Figure 2 Chemical Propulsion Stage

Exploration Destination

Since the end of the Apollo program, the goals for human spaceflight in the U.S. have been debated. The last few decades have focused on the International Space Station in low-Earth orbit. The Constellation Program which was officially cancelled in the Spring of 2010 focused on returning astronauts to the Moon and setting up a long duration lunar outpost. Selecting the destination for space exploration is just as much a question of politics as of science.

The two primary exploration destinations currently being considered by NASA are Near-Earth Asteroids (NEA) and Mars. As explained by President Obama in a speech at the Kennedy Space Center on April 15, 2010, the stated goal for human space exploration is to eventually go to Mars. However due to mission complexity, cost, and risk the decision has been made that the next destination for people should be a NEA.

While the infrastructure to send a human mission to a NEA is incredibly complex, only the two in-space propulsion alternatives described below are considered for this exercise:

Alternative 1: A combination of SEP and CPS are used to transport crew and cargo to the NEA.

Alternative 2: Only CPS is used to transport crew and cargo to the NEA.

It is important to note that for the NEA mission using only CPS is a possibility. For the Mars mission in the future, it will be logistically infeasible to use only CPS and SEP will be required.

Setup for Analysis

A NASA presentation is available that includes details on possible “Design Reference Missions.” That means they’ve planned what they believe the development and operations required to complete a NEA mission will be considering realistic NASA funding limitations, technology availability, and so on.

In terms of SEP and CPS it lays out the flagship technology demonstration missions that will be required to prove the technologies are available and reliable to use for the actual mission. While only two SEP and 2 CPS are required for the NEA mission in the 2029 timeframe, there will be 4 initial CPS flights and 3 initial SEP flights before that time. The purpose of these missions is to gain experience with the technology to prove its flight-readiness.

This documentation includes detailed cost breakdowns for each subsystem from 2010 through the end of the NEA mission in 2031. To limit the scope of this exercise, the costs given are taken as assumptions. In future analysis it will be important to evaluate and include uncertainty on the costing in simulation as appropriate.

This analysis is supposed to look at propulsion technology investment. Costs can be measured by the cost data described above. However it is important to have a metric by which benefits of the investment can be evaluated. To do this, Technology Readiness Level (TRL) will be used. TRL is a (mostly) objective scale from 1 to 9 used to evaluate the maturity of a given technology. A TRL of 1 is little more than a theoretical idea and a TRL of 9 indicates the technology has been proven in operation. TRL definition varies by government agency. Below are the NASA-defined TRL used for this exercise.

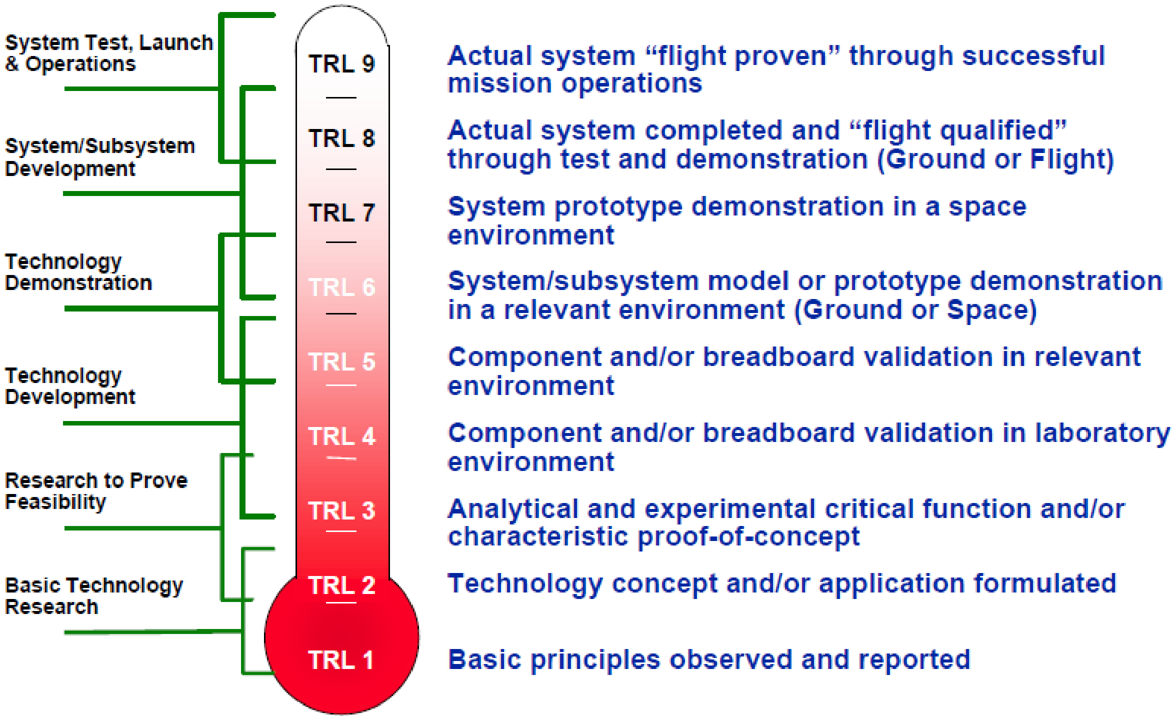

Figure 3 NASA Technology Readiness Levels

It is assumed that SEP currently has a TRL of 6. SEP engines have flown in space, but not at the size range required for human exploration. CPS is assumed to currently have a TRL of 7. The engines have flown frequently in space, but the storage of propellants has not been fully demonstrated. (There have been easier-to-store propellants stored or propellants on orbit for shorter duration).

The Model

The timeline shown below is from the referenced NASA presentation. The red box shows the CPS and SEP flights being considered. The dashed blue box indicates the flights required for the mission itself- all other flights are precursors that are effectively used to raise the TRL of a given technology.

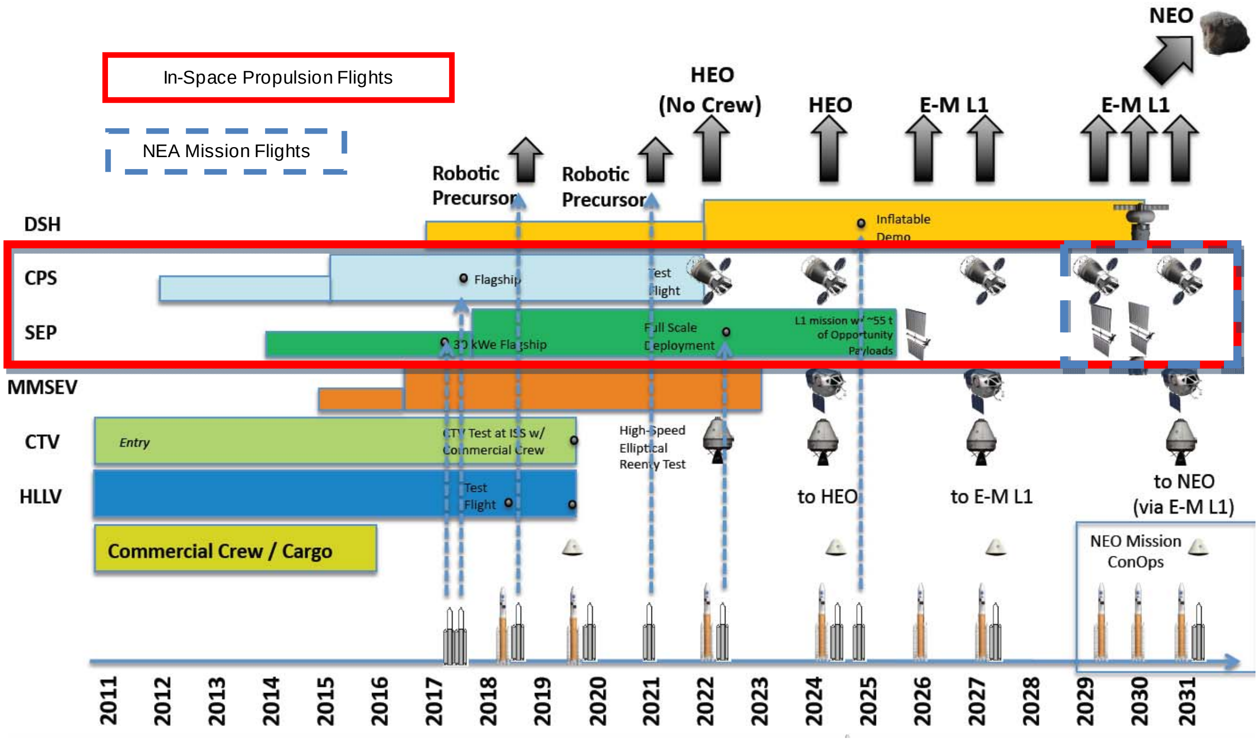

Figure 4 NEA mission development and operations timeline

For each precursor flight, it is expected that the TRL is increased by 1. The table below shows the expected TRL due to successful precursor flights. Actual NEA mission flights are highlighted in yellow.

Flight #	SEP Flight Year	CPS Flight Year	SEP Expected TRL	CPS Expected TRL
0	(initial state)		6	7
1	2017	2017	7	8
2	2022	2022	8	9
3	2026	2024	9	9
4	2029	2027	9	9
5	2030	2029	9	9
6	-	2031	9	9

Table 1 TRL based on precursor flights

Introducing Uncertainty

If the information in table 1 is taken as deterministically true, SEP will have a TRL of 9 by its 3rd flight in 2026 and CPS will have a TRL of 9 by its 2nd flight in 2022. However in reality deployment of new propulsion systems has a lot of uncertainty. There are many ways in which these complex spacecraft can fail (only some of those ways result in explosions).

For this simulation it is assumed that each CPS or SEP flight has some probability of success. If the flight is successful, then the TRL is increased by 1 as expected. However if the flight fails, the TRL remains the same. This is a good approximation of what actually happens because in mission failures while a lot is learned about the system, operators often lose flight data or the ability to test the design as originally intended. As such the TRL will not advance after a flight failure but it is never reduced.

An even 50/50 chance ($p=0.5$) is used to determine if each flight is a success or failure. While in reality the probability distribution may not be so simple, or the mean probability may be higher or lower, this can be updated in the future based on historical data of testing early flight systems in space. Meanwhile the 50/50 chance of success represents the high risk associated with flying new technologies in space.

The figure below shows the deterministic case simulation against a sample simulation with uncertainty tracking total TRL over time where $TRL_{Total} = TRL_{SEP} + TRL_{CPS}$. It is important to note that this is one case of the 10,000 simulations run in total where the success of each flight has been determined randomly according to the previously described distribution. This measurement of TRL over time is a proxy for benefits gained from technology investment. As with expected value in general, more is better. This shows how important it is to consider uncertainty. In this simulation the deterministic (no uncertainty) model reaches a TRL_{Total} of 18 in 2026. In this situation, it is assumed that every flight is successful (as the reference literature suggests) so the TRL increases with each flight opportunity. However in the simulation considering uncertainty, when the NEA mission must be executed in 2029, the Total TRL is only at 16. This is due to several failed flights resulting from the 50/50 chance of success for each flight (and each failed flight not increasing the TRL level). This indicates that either one or both technologies are not ready for human spaceflight by the required 2029 timeframe.

The $p=0.5$ for successful flights results in some flights failing. For this one simulation (shown in figure 5) the flight successes are summarized in the table below.

Are flights successful?		
	SEP Flights	**CPS Flights**
Flight 1	NO	YES
Flight 2	NO	NO
Flight 3	YES	NO
Flight 4	YES	NO
Flight 5	NO	NO
Flight 6	-	NO

Table 2 Sample Simulation Flight Successes and Failures

These flight successes and failures result in a lower expected TRL_{Total} than if there were no uncertainty at all. This is illustrated in figure 5 below.

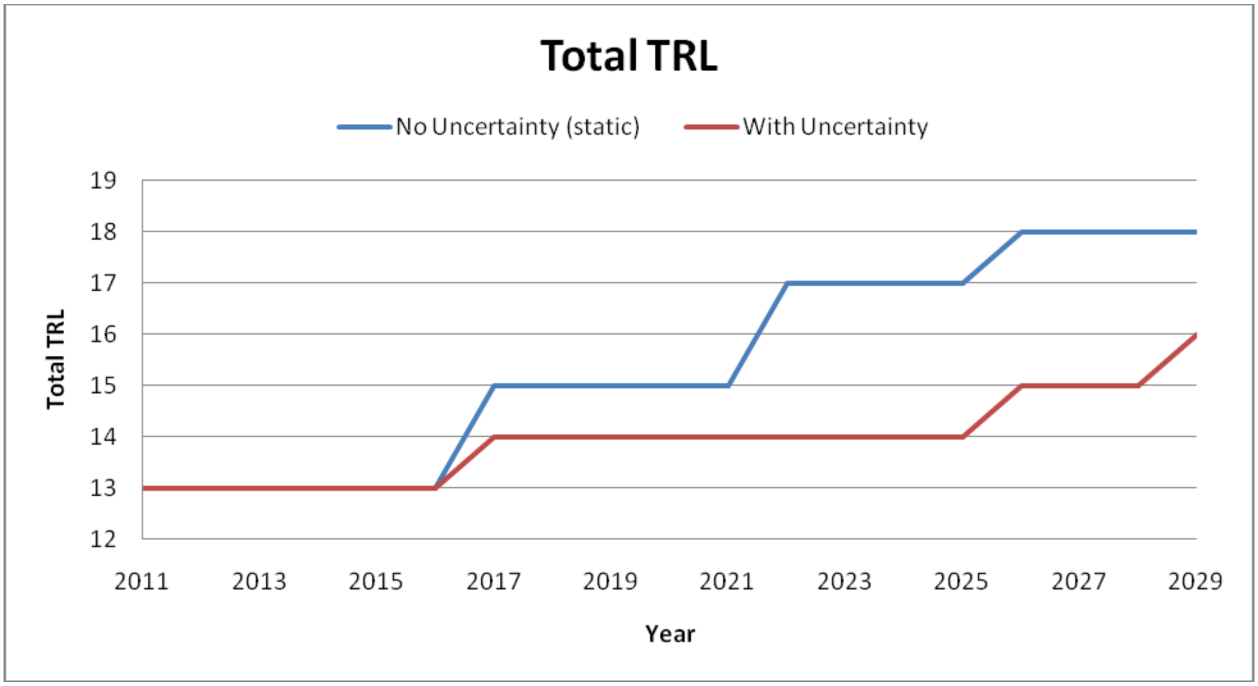

Figure 5 Total TRL over time with and without uncertainty

Measure of Effectiveness

After simulating all flights with some probability of success, there will be a total TRL for both propulsion technologies at the end of the simulation in 2031. In the case that all flights fail, the total TRL remains 13 (6 for SEP + 7 for CPS). In the case that both technologies reach 9, the total TRL will be 18. Either way, the amount of TRL increase can be measured and compared to the costs spent. A measure of effectiveness metric is calculated that is the change (increase) in TRL per unit cost.

$$Cost\ Effectiveness = \frac{TRL_{SEP\ Final} + TRL_{CPS\ Final} - TRL_{SEP\ Initial} - TRL_{CPS\ Initial}}{Cumulative\ Cost}$$

The units of this cost effectiveness metric are $\frac{\Delta TRL}{billion\ \$}$. This is a measure of the improvement in technology gained by investing money in technology development.

Setting up the Baseline Case

Having created a measure of effectiveness, the baseline case can be run. This is the simulation of $\frac{\Delta TRL}{billion\ \$}$ over time. Eventually this simulation and others with decision rules will be simulated 10,000 times to analyze their behavior. For these statistics only the cost effectiveness at the end of the project (in 2031) will be considered. However to explain exactly how the baseline simulation works, there is test data included below for the evolution of cost effectiveness over time.

The table below shows some sample data (only up to 2023) to show exactly how the simulation is implemented and the Cost Effectiveness is calculated. For the purposes of this exercise the costs are all accepted without uncertainties. The TRLs begin at 6 and 7 for SEP and CPS respectively. They increase in the event of a successful flight. Then the Cost Effectiveness is calculated according to the previously described equation.

Table 3 Simulation sample data

Baseline w/ Uncertainty, NO Decision Rules							**FLIGHT 1**
	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
SEP Cost	$ -	$ -	$ -	$ 56	$ 115	$ 177	$ 161
CPS Cost	$ -	$ 86	$ 233	$ 347	$ 507	$ 594	$ 419
SEP TRL	6	6	6	6	6	6	6
CPS TRL	7	7	7	7	7	7	7
Total TRL	13	13	13	13	13	13	13
Cum. SEP cost	$ -	$ -	$ -	$ 56	$ 171	$ 348	$ 509
Cum. CPS cost	$ -	$ 86	$ 319	$ 666	$ 1,173	$ 1,767	$ 2,186
Total Cum. Cost	$ -	$ 86	$ 319	$ 722	$ 1,344	$ 2,115	$ 2,695
Cost Effectiveness (dTRL/billion$)	-	0.000	0.000	0.000	0.000	0.000	0.000

					FLIGHT 2		
…	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**…**
…	$ 342	$ 976	$ 1,640	$ 1,663	$ 1,815	$ 1,819	…
…	$ 432	$ 472	$ 473	$ 267	$ 84	$ 87	…
…	6	6	6	6	7	7	…
…	7	7	7	7	8	8	…
…	13	13	13	13	15	15	…
…	$ 851	$ 1,827	$ 3,467	$ 5,130	$ 6,945	$ 8,764	…
…	$ 2,618	$ 3,090	$ 3,563	$ 3,830	$ 3,914	$ 4,001	…
…	$ 3,469	$ 4,917	$ 7,030	$ 8,960	$ 10,859	$ 12,765	…
…	0.000	0.000	0.000	0.000	0.184	0.157	…

Note that in this simulation the first flights are in 2017. However *both* these missions have failed (in this sample simulation) as the TRLs remain the same until the second flights of CPS and SEP in 2022. As a result the cost effectiveness (ΔTRL/billion $) remains 0.000 until the time successful flights are achieved in 2022.

Deterministic vs Uncertain Baseline Case

Having now developed a model that could calculate cost effectiveness and include uncertainty on the success of missions, a simulation is run to compare against the deterministic model where all flights are unrealistically assumed to be successful. The figure below shows the cost effectiveness for a sample simulation. In this trial the final cost effectiveness in 2029 is 0.16 ΔTRL/billion $. This is significantly less than the predicted outcome of 0.27 ΔTRL/billion $ with the deterministic model. Again this highlights the importance of considering uncertainty on the success of flights when considering the expected value or in this case cost effectiveness.

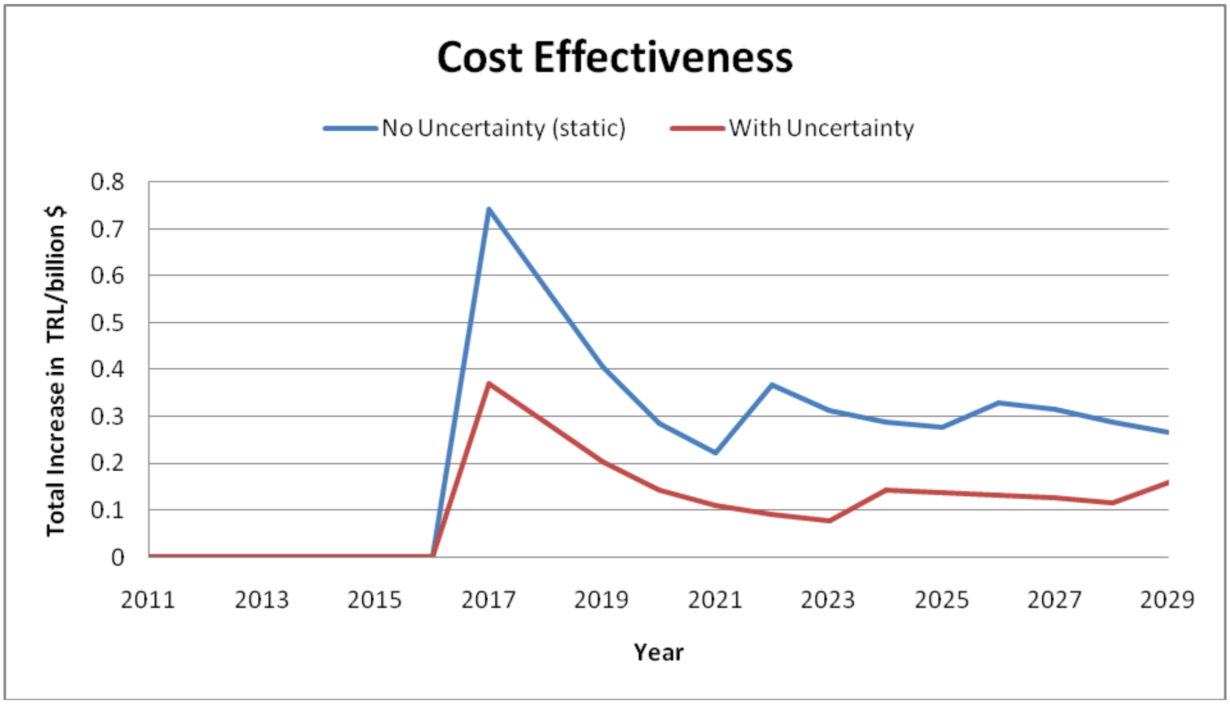

Figure 6 Cost effectiveness over time with and without uncertainty

The basic strategy is to invest in both technologies so that even if not used for the NEA mission, SEP becomes available in the future- or at least has a higher TRL and is closer to being available. This is a worthy goal because of the necessity for SEP when considering Mars missions. If the NEA mission were the penultimate exploration goal, using only CPS would be the less expensive alternative and SEP would be dominated in the trade space. The return function of Cost Effectiveness therefore seeks to maximize overall increase in TRL per dollar while ensuring that there is a feasible alternative to execute the NEA mission. Maximizing technology readiness rather than minimizing cost can also be seen as a form of flexibility given the uncertainty of mission goals. If the NEA mission is cancelled partway through development to focus on going to Mars directly (just as the Constellation program was recently cancelled) a strategy that favors TRL increase will greatly reduce the downside to that occurring. However investing in only the cheapest propulsion for the near term goal now may prove to be a waste if the goal is changed and in-space propulsion technology development must begin from scratch again several years from now.

Decision Rules

The baseline simulation proceeds with the planned investments in SEP and CPS regardless of demonstration flight failure and success. Even if the TRL of SEP is insufficient for human spaceflight, the spending on SEP flights continues in the baseline simulation. The decision rules will add the flexibility to abandon SEP. (Abandon is used for the scope of this model. In reality the idea is that it is a temporary shutdown that can re-open once the goal of the NEA mission is achieved. However this model does not currently extend beyond that point in time). This flexibility to abandon is a "Put Option."

As described in the previous section the general strategy is to invest in both SEP and CPS. However it is not logical to spend money on increasing the TRL of SEP when trying to achieve the specific mid-term goal of the NEA mission if SEP will definitely not be ready in time for the actual mission. That is to say if the TRL of SEP before 2029 (the mission) is below 8, it should be (temporarily) abandoned and the alternative of using only CPS will be used. That is because below this TRL, SEP is too risky to include in the actual NEA mission. In this case it won't be ready for the crewed mission to the NEA anyway. Then investment in SEP can be shutdown until after the NEA mission when it can be reopened and become useful again in the preparation for technology for Mars missions.

Two decision rules have been implemented at specific points in time:

> Decision rule #1: If the first SEP flight fails, shut down. If it succeeds, this brings SEP from TRL 6 to 7. One of the next 2 SEP flights must then succeed to proceed to the NEA mission including SEP (SEP reaching TRL 8), otherwise shutdown SEP and continue with CPS only.
>
> Decision rule #2: One of the first two SEP flights must succeed. Only one or the other may fail. This will make SEP at least a TRL 7 (could be 8). However the next flight must then succeed to achieve TRL 8 (or 9) before the NEA mission. If not, then shut down SEP and continue with CPS only.

Both decision rules implemented ensure that if SEP is included in the NEA mission it has at least a TRL of 8. Otherwise the costs of continuing with SEP are put off until after this interim goal (reaching a NEA) is achieved. When the "Abandon SEP" condition is triggered, the cost of SEP becomes 0 for further time periods and the TRL is not increased. There is no more opportunity to increase TRL before the NEA mission, but the cost burden is also removed. The model is set to run 10,000 times picking new flight successes and failures at random for each trial and then results are aggregated to get reliable statistics for the three options- No Flexibility, Decision Rule #1 (DR1), and Decision Rule #2 (DR2).

Results

Cost

While the ultimate metric being sought to maximize is Cost Effectiveness, it is worthwhile to note how the total cost distributions come out for each of the three options. The cost alone says nothing about the actual benefits of technology investment. It only reflects how the costs can change when the flexibility to shutdown SEP operations is available. The figure below shows this. Looking at only cost the baseline with no flexibility appears the same as the deterministic case with no uncertainty since the SEP flights are always paid for in both cases.

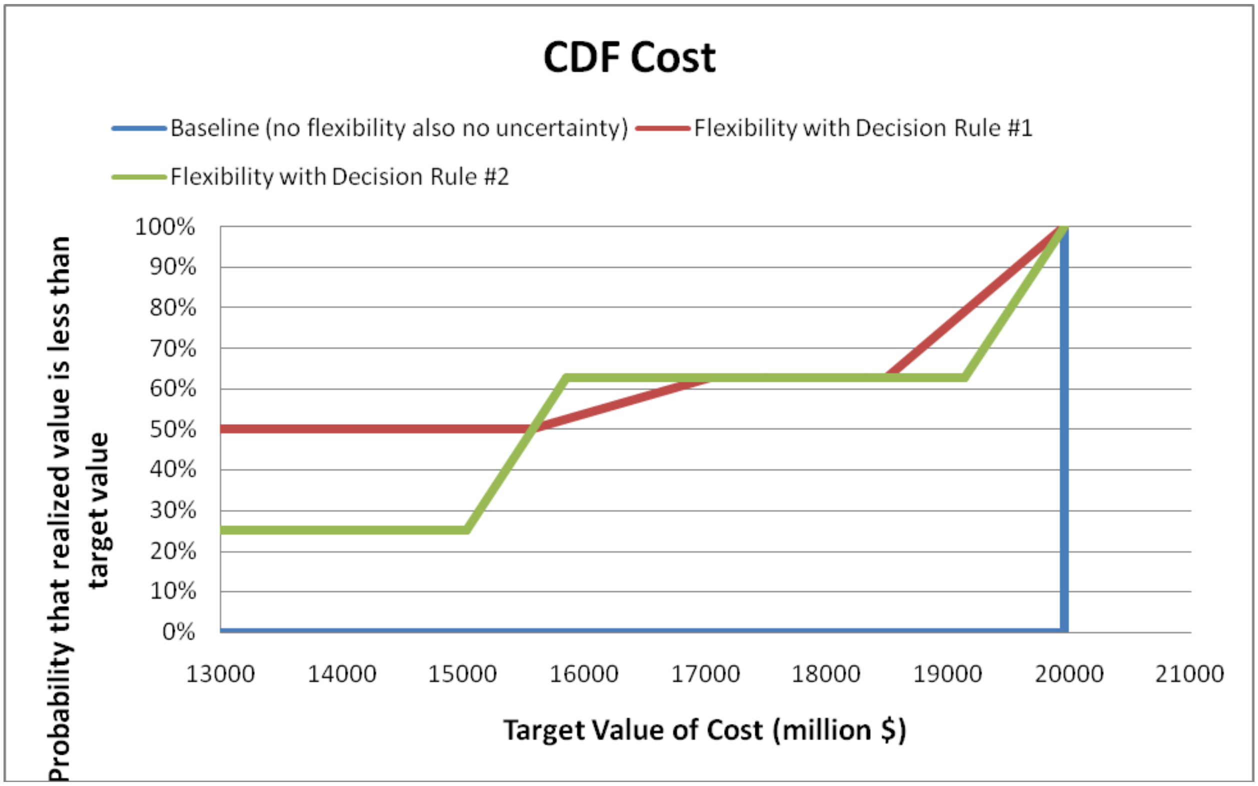

Figure 7 CDF Total Project Cost

Since this simulation only goes through the NEA mission, it makes sense that both the flexible options should generally cost less than the baseline rigid option which always funds SEP through the entire timeline. This is because when the put option is enabled, the SEP costs go away. Both these options dominate the baseline option in terms of cost alone. Between the two decision rules, #1 provides a higher probability of being below $15 billion. However between decision rules #1 and #2, neither option is completely dominated here based on the CDF alone. The mean cost values for the 3 options show a more clear ranking.

Option	Mean Cost (million $)
No flexibility	$19961
Decision Rule #1 (DR1)	$12139
Decision Rule #2 (DR2)	$16276

Table 4 Mean Cost by Option

Both flexible options offer significantly reduced costs over the Baseline. Decision Rule #1 has a further reduced mean Cost from Decision Rule #2.

It is important to note that these reduced costs from the put option reflect modeling the flexibility to “abandon” SEP. If missions continue on to Mars as expected, the cost of completing development of

SEP will return at a later time. There are several advantages to delaying this expenditure but the entire program costs may not improve quite so dramatically when future missions are considered. This analysis is limited to flights through 2031.

Cost Effectiveness

Since this simulation does not include all potential future projects, the cost effectiveness of technology development is really the important output. This is the metric to measure the value of technology preparedness returned. The table below shows the mean result of cost effectiveness for 10,000 iterations of the simulation. While DR1 provides significant increase in mean cost effectiveness and DR2 barely changes the mean (slight decrease) this information alone describes very little about what is actually occurring. The mean cost data is included again. The mean cost effectiveness shows that while the overall preference for DR1 remains the same, when looking at cost DR2 is no longer below the baseline.

Option	Mean Cost Effectiveness (ΔTRL/billion $)	Mean Cost (million $)
Deterministic (no uncertainty)	0.250	$19961
No flexibility	0.208	$19961
Decision Rule #1 (DR1)	0.288	$12139
Decision Rule #2 (DR2)	0.206	$16276

Table 5 Mean Cost Effectiveness by Option

The Probability Density Function (PDF) of the three options shows the general differences of the options. In the figure below it is clear that with no flexibility there is mostly one result (around 0.24 ΔTRL/billion $) and sometimes a bit less (around 0.14 ΔTRL/billion $). DR1 was able to greatly increase the upside capturing values at around 0.36 ΔTRL/billion $ without significantly changing the lower end. It is also clear here where DR2 increases the lower end significantly around 0.14 and marginally at around 0.04 ΔTRL/billion $. It is clear immediately that DR1 is the only option that significantly increases the available upside of cost effectiveness over the (unrealistic) deterministic case.

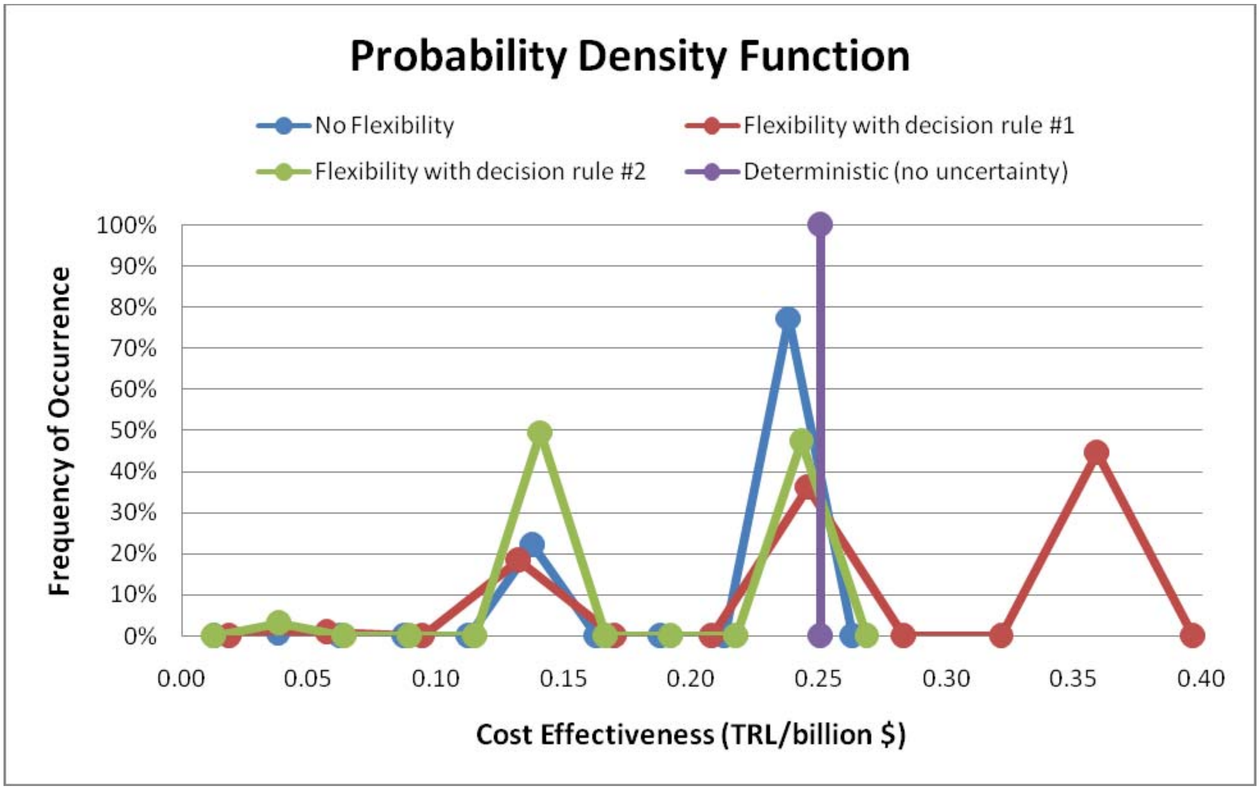

Figure 8 PDF 3 Options

Looking at the CDF shown in Figure 9 below highlights other subtleties. Overall DR1 almost completely dominates the baseline and DR2 options. The other two options are mostly dominated (except between approximately 0.11 and 0.14 ΔTRL/billion$ where DR1 is the worst option by a very small margin. The VARG curve also highlights another subtlety. While we know the mean cost effectiveness was slightly decreased with DR2, it is not definitively worse than the baseline case without flexibility. Unfortunately it did increase the “downside,” but in the CDF it can be seen that there is a slight increase in the upside above a target of about 0.23 ΔTRL/billion$. While this would probably not justify the increased risk overall, a serious risk-seeker may be attracted to this possibility as compared to just the baseline with no flexibility. As always the ‘best’ strategy depends on the behavior and risk value function of a specific decision maker, but in general the DR1 will yield the best results. Again it is clear in the CDF that DR1 is the only option to provide significant opportunities for value increase in the upper end over the deterministic case.

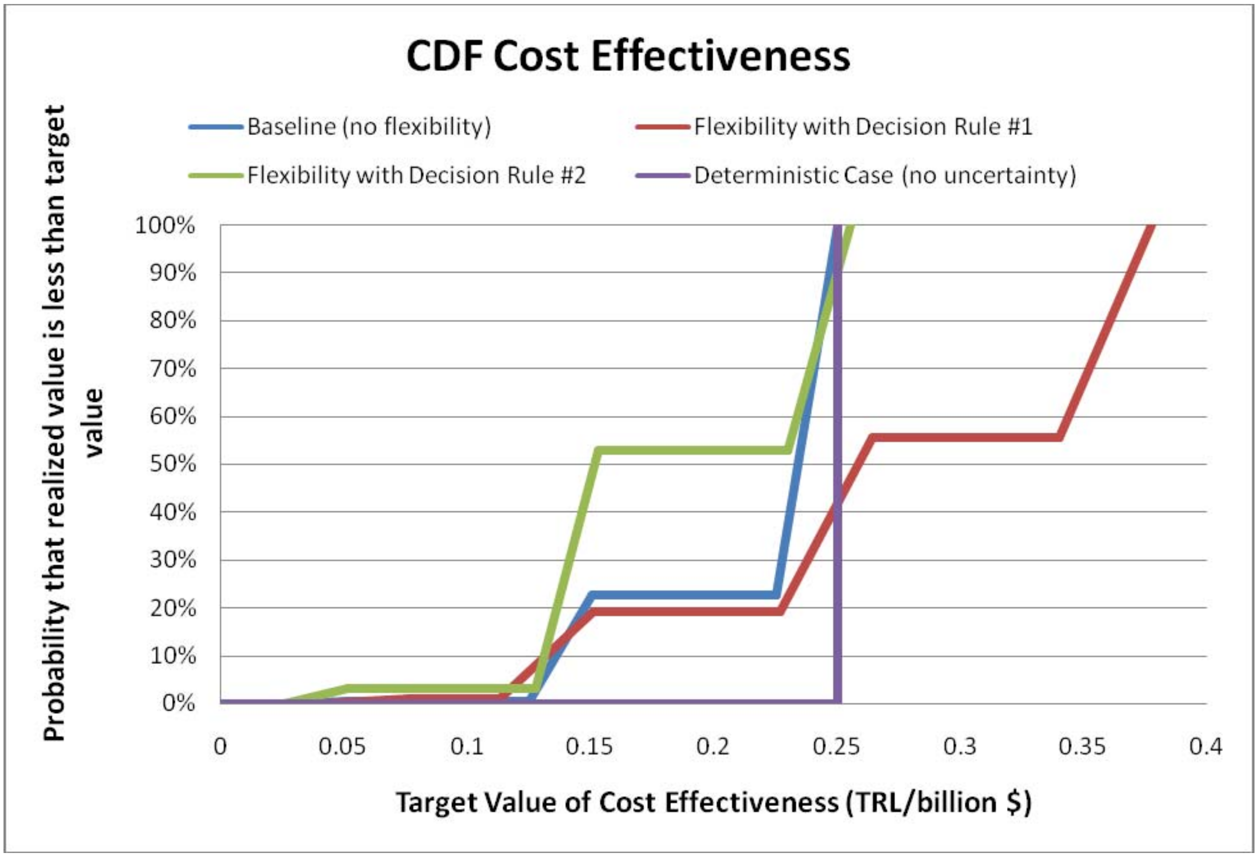

Figure 9 CDF 3 Options

To allow for a more simplified ranking we can look at just the P_5 and P_{95} values of each distribution as shown in the table below. When we do this DR2 appears to provide slightly more value than the Baseline with no flexibility and DR1 shows a very significant increase in value. DR2 has a 4% increase in P_{95} over the baseline while DR1 has a 52% increase in P_{95}.

(ΔTRL/billion$)	P5	P95
Baseline	0.10	0.25
DR1	0.19	0.38
DR2	0.13	0.26

Table 6 P5 and P95 values for all 3 options

This table contains less information than the Cumulative Distribution Functions above, but it is a simple and practical way to compare different options. Looking at the CDF and P_5 and P_{95} values, DR2 is almost always the preferred option.

When is SEP used?

Finally it is interesting to look at how often SEP is actually used for the NEA mission according to the 3 options. For the baseline option, SEP spending continues no matter what, but in reality if the TRL is less than 8, it will not be used for the mission. For the two options with decision rules, SEP is used if it is never abandoned. Through the 10,000 simulation iterations, whether or not SEP is actually flown is tracked and the cumulative results are shown in figure 10 below.

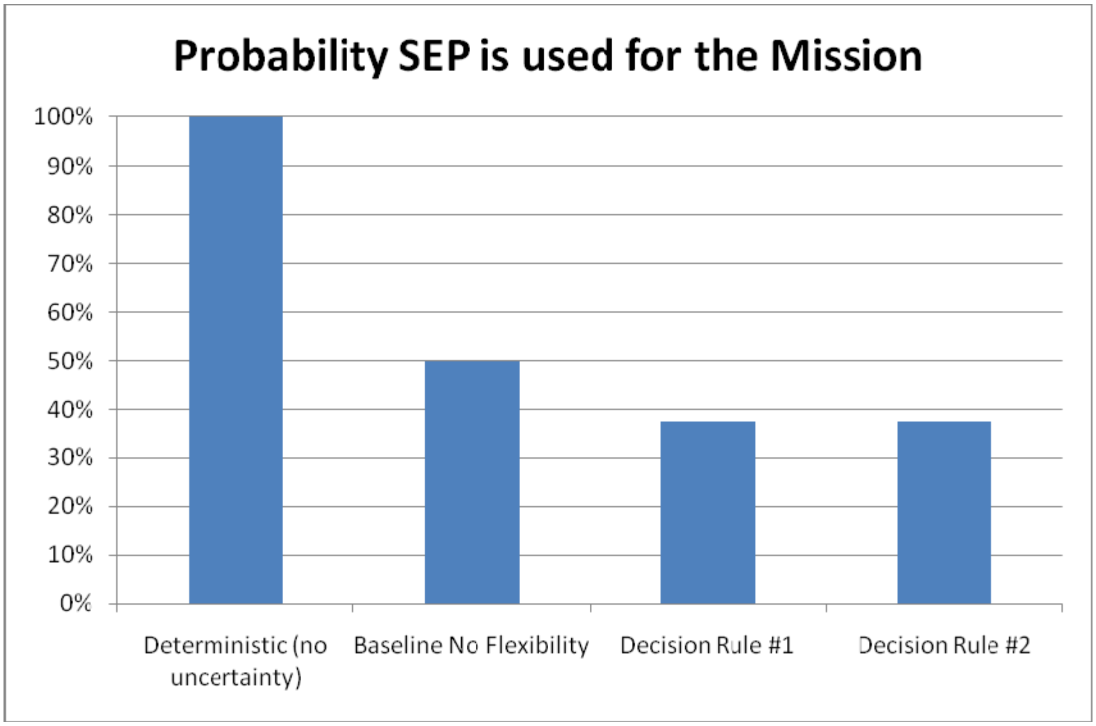

Figure 10 How often is SEP actually used for the mission?

SEP is not used as often for the actual mission when the flexibility to abandon is included. This is because the return function of cost effectiveness rewards effective technology development but does not require that SEP is flown for this mission. CPS is inherently less expensive for this mission. Overall value is created by advancing SEP and possibly including it in the NEA architecture. Designing in the flexibility to revert to only CPS is therefore very powerful and results in higher cost effectiveness even if it also results in reduced chances of actually flying SEP to the NEA. This really highlights the power of both understanding uncertainty and including flexibility afterwards. For the 50% of cases where SEP is not flown in the baseline case, SEP is still being funded. This indicates a lot of money is being spent on technology that is in no way contributing to the immediate goal. The included flexibility with DR1 and DR2 allows for a delay in this technology investment until it can be more useful.

Sensitivity

The only uncertain variables considered in the current model are the probabilities of a successful or failed flight for SEP or CPS. The current analysis used p=0.5 for both these uncertainties. A sensitivity analysis was performed by varying both the probability of SEP and CPS having successful flights from 0.25 to 0.75. The analysis shown in figure 11 demonstrates that the assumption of p=0.5 does not disrupt the trends of the general results. While in general the cost effectiveness is sensitive to the probabilities as expected, the ordinal trends of the options do not significantly change. In general the baseline without flexibility and DR2 provide similar mean cost effectiveness while DR1 provides the highest mean cost effectiveness. As the probability of SEP being successful increases, the advantage of DR1 is diminished because the put option is not enabled as frequently. Likewise when the probability of successful SEP flights decreases, DR1's value increases as the put option is enabled more frequently and the downside is limited.

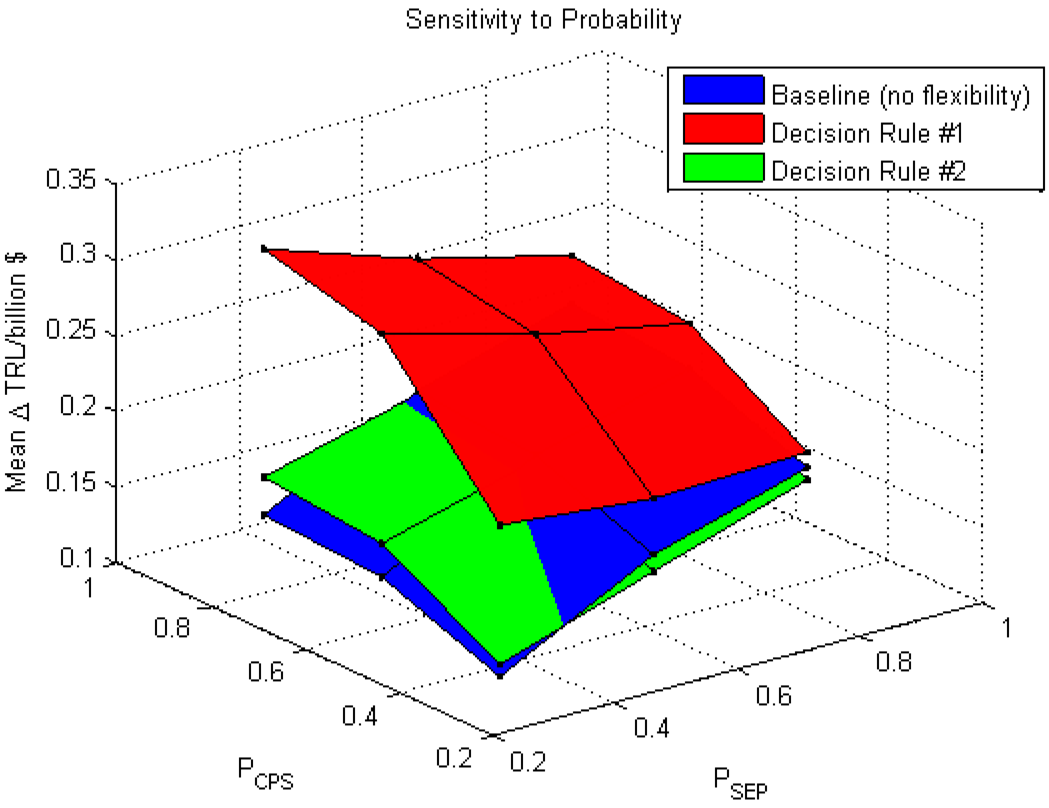

Figure 11 Sensitivity to Probability of Success

There are entire other aspects to the simulation that must be tested for sensitivity. The first is the cost data. These were assumed according to reference data, however there should probably be significant uncertainty included in the numbers.

Conclusion

Overall, it is possible to measure how effectively technology can be developed. The NEA mission can be done cheaper if SEP is not considered at all, but this does not allow for uncertainty in mission destinations or help to prepare for development of future missions. That is why it makes sense to optimize (in context of this simple model) ΔTRL/ $ rather than just minimizing cost to a certain objective. In fact this becomes a proxy for measuring the effectiveness of developing new technology capability. Maximizing this function will yield flexibility in the long run, because there will be more technology alternatives from which mission designers can choose. Specifically it opens up the possibility of getting a head start on preparation for Mars missions.

For this model due to the few quantized stages where decisions could be made, there were not very many permutations of logical ways to form “abandon SEP” decision rules. However sensitivity to different decision rules can be easily studied with simulation by changing the rule and comparing outputs. In this formulation of the problem DR1 provides the highest expected cost effectiveness of technology development.. In fact there may be many more options to consider beyond shutting down SEP. One of them would be to re-open the line of SEP research after accomplishing other tasks for which SEP is not critical. Other propulsive alternatives could be included to create other options that include Nuclear Thermal Propulsion or combinations of repurposed existing chemical rockets that do not require technology development.

Lessons Learned

Considering flexibility in design and calculating the expected value when including flexibility is extremely important. Flexibility creates value because in the real world things are uncertain. While a NASA design reference mission team may consider uncertainty in the energy required to reach a NEA or the energy density available from solar panels, they should really be considering bigger questions such as, “what if the destination changes?” Several times now, the entire direction of NASA’s human spaceflight program has made massive programmatic shifts due to new policy priorities and failure to meet milestones. Unfortunately in most of these events very little technology or capability that has been successfully completed carries over to the new program because it is not useful and there has been little flexibility considered in changing programmatic goals. In particular for these large programs, I think flexibility is not considered because it seems “wasteful” to build systems that may not be used. However this reflects the problem of complete denial of reality. We know from all the previously cancelled programs that national space policy changes and huge programmatic shifts occur with some regularity. Designing flexibility for these occasions could not only save billions in taxpayer dollars, but allow progress in human spaceflight to continue with more regularity than in the past.

While the model setup here is relatively simple it achieves something very important. Rather than just minimizing cost, it aims to increase technology capability. This inherently penalizes plans that do not create new capability and only use existing technology. It is true that if every technology of a human spaceflight mission architecture were new, risk aggregation would be a serious problem. However creating a measure of effectiveness based on TRL can be used to make sure that current mission planning is in fact preparatory for the greater goal of Mars missions as stated in current policy. If this sort of value of expected technology capability is applied to certain components in the human spaceflight architecture, it could help to design an architecture that is robust to changes in exploration goals. Even if exploration goals do not change, it may reduce cost by creating modular components that can be reused for different mission types within a program.

Appendix A: Sample Data

Deterministic, No Uncertainty				SEP flight						
				CPS flight			SEP FLIGHT 1			
	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
SEP Cost	$ -	$ -	$ -	$ 56	$ 115	$ 177	$ 161	$ 342	$ 976	$ 1,640
CPS Cost	$ -	$ 86	$ 233	$ 347	$ 507	$ 594	$ 419	$ 432	$ 472	$ 473
SEP TRL	6	6	6	6	6	6	7	7	7	7
CPS TRL	7	7	7	7	7	7	8	8	8	8
Total TRL	13	13	13	13	13	13	15	15	15	15
Cumulative SEP cost	$ -	$ -	$ -	$ 56	$ 171	$ 348	$ 509	$ 851	$ 1,827	$ 3,467
Cumulative CPS cost	$ -	$ 86	$ 319	$ 666	$ 1,173	$ 1,767	$ 2,186	$ 2,618	$ 3,090	$ 3,563
Total Cumulative Cost	$ -	$ 86	$ 319	$ 722	$ 1,344	$ 2,115	$ 2,695	$ 3,469	$ 4,917	$ 7,030
Cost Effectiveness (dTRL/billior	#DIV/0!	0	0	0	0	0	0.742115028	0.576535025	0.406752085	0.284495021

Baseline w/ Uncertainty, NO Decision Rules							SEP FLIGHT 1			
Simulation	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
SEP Cost (static)	$ -	$ -	$ -	$ 56	$ 115	$ 177	$ 161	$ 342	$ 976	$ 1,640
CPS Cost (static)	$ -	$ 86	$ 233	$ 347	$ 507	$ 594	$ 419	$ 432	$ 472	$ 473
SEP TRL	6	6	6	6	6	6	6	6	6	6
CPS TRL	7	7	7	7	7	7	7	7	7	7
Total TRL	13	13	13	13	13	13	13	13	13	13
Cumulative SEP cost	$ -	$ -	$ -	$ 56	$ 171	$ 348	$ 509	$ 851	$ 1,827	$ 3,467
Cumulative CPS cost	$ -	$ 86	$ 319	$ 666	$ 1,173	$ 1,767	$ 2,186	$ 2,618	$ 3,090	$ 3,563
Total Cumulative Cost	$ -	$ 86	$ 319	$ 722	$ 1,344	$ 2,115	$ 2,695	$ 3,469	$ 4,917	$ 7,030
Cost Effectiveness (dTRL/billior	#DIV/0!	0	0	0	0	0	0	0	0	0

Decision Rule #1							SEP FLIGHT 1			
Simulation	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
SEP Cost (static)	$ -	$ -	$ -	$ 56	$ 115	$ 177	$ 161	$ -	$ -	$ -
CPS Cost (static)	$ -	$ 86	$ 233	$ 347	$ 507	$ 594	$ 419	$ 432	$ 472	$ 473
SEP TRL	6	6	6	6	6	6	6	6	6	6
CPS TRL	7	7	7	7	7	7	7	7	7	7
ABANDON?							ABANDON			
Total TRL	13	13	13	13	13	13	13	13	13	13
Cumulative SEP cost	$ -	$ -	$ -	$ 56	$ 171	$ 348	$ 509	$ 509	$ 509	$ 509
Cumulative CPS cost	$ -	$ 86	$ 319	$ 666	$ 1,173	$ 1,767	$ 2,186	$ 2,618	$ 3,090	$ 3,563
Total Cumulative Cost	$ -	$ 86	$ 319	$ 722	$ 1,344	$ 2,115	$ 2,695	$ 3,127	$ 3,599	$ 4,072
Cost Effectiveness (dTRL/billior	#DIV/0!	0	0	0	0	0	0	0	0	0

Decision Rule #2							SEP FLIGHT 1			
Simulation	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
SEP Cost (static)	$ -	$ -	$ -	$ 56	$ 115	$ 177	$ 161	$ 342	$ 976	$ 1,640
CPS Cost (static)	$ -	$ 86	$ 233	$ 347	$ 507	$ 594	$ 419	$ 432	$ 472	$ 473
SEP TRL	6	6	6	6	6	6	6	6	6	6
CPS TRL	7	7	7	7	7	7	7	7	7	7
ABANDON?										
Total TRL	13	13	13	13	13	13	13	13	13	13
Cumulative SEP cost	$ -	$ -	$ -	$ 56	$ 171	$ 348	$ 509	$ 851	$ 1,827	$ 3,467
Cumulative CPS cost	$ -	$ 86	$ 319	$ 666	$ 1,173	$ 1,767	$ 2,186	$ 2,618	$ 3,090	$ 3,563
Total Cumulative Cost	$ -	$ 86	$ 319	$ 722	$ 1,344	$ 2,115	$ 2,695	$ 3,469	$ 4,917	$ 7,030
Cost Effectiveness (dTRL/billior	#DIV/0!	0	0	0	0	0	0	0	0	0

	SEP FLIGHT 2				SEP FLIGHT 3			SEP FLIGHT 4	SEP FLIGHT 5	
2021	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**
$ 1,663	$ 1,815	$ 1,819	$ 1,026	$ 458	$ 616	$ 633	$ 1,300	$ 1,335	$ 685	$ 358
$ 267	$ 84	$ 87	$ 89	$ 92	$ 94	$ 97	$ 99	$ 102	$ 105	$ 107
7	8	8	8	8	9	9	9	9	9	9
8	9	9	9	9	9	9	9	9	9	9
15	17	17	17	17	18	18	18	18	18	18
$ 5,130	$ 6,945	$ 8,764	$ 9,790	$ 10,248	$ 10,864	$ 11,497	$ 12,797	$ 14,132	$ 14,817	$ 15,175
$ 3,830	$ 3,914	$ 4,001	$ 4,090	$ 4,182	$ 4,276	$ 4,373	$ 4,472	$ 4,574	$ 4,679	$ 4,786
$ 8,960	$ 10,859	$ 12,765	$ 13,880	$ 14,430	$ 15,140	$ 15,870	$ 17,269	$ 18,706	$ 19,496	$ 19,961
0.223214286	0.368358044	0.313356835	0.288184438	0.277200277	0.330250991	0.315059861	0.289536163	0.267293916	0.256462864	0.250488452

	SEP FLIGHT 2				SEP FLIGHT 3			SEP FLIGHT 4	SEP FLIGHT 5	
2021	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**
$ 1,663	$ 1,815	$ 1,819	$ 1,026	$ 458	$ 616	$ 633	$ 1,300	$ 1,335	$ 685	$ 358
$ 267	$ 84	$ 87	$ 89	$ 92	$ 94	$ 97	$ 99	$ 102	$ 105	$ 107
6	7	7	7	7	8	8	8	8	8	8
7	8	8	8	8	8	9	9	9	9	9
13	15	15	15	15	16	17	17	17	17	17
$ 5,130	$ 6,945	$ 8,764	$ 9,790	$ 10,248	$ 10,864	$ 11,497	$ 12,797	$ 14,132	$ 14,817	$ 15,175
$ 3,830	$ 3,914	$ 4,001	$ 4,090	$ 4,182	$ 4,276	$ 4,373	$ 4,472	$ 4,574	$ 4,679	$ 4,786
$ 8,960	$ 10,859	$ 12,765	$ 13,880	$ 14,430	$ 15,140	$ 15,870	$ 17,269	$ 18,706	$ 19,496	$ 19,961
0	0.184179022	0.156678418	0.144092219	0.138600139	0.198150594	0.252047889	0.23162893	0.213835133	0.205170291	0.200390762

	SEP FLIGHT 2				SEP FLIGHT 3			SEP FLIGHT 4	SEP FLIGHT 5	
2021	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ 267	$ 84	$ 87	$ 89	$ 92	$ 94	$ 97	$ 99	$ 102	$ 105	$ 107
6	6	6	6	6	6	6	6	6	6	6
7	8	8	8	8	8	9	9	9	9	9
					ABANDON					
13	14	14	14	14	14	15	15	15	15	15
$ 509	$ 509	$ 509	$ 509	$ 509	$ 509	$ 509	$ 509	$ 509	$ 509	$ 509
$ 3,830	$ 3,914	$ 4,001	$ 4,090	$ 4,182	$ 4,276	$ 4,373	$ 4,472	$ 4,574	$ 4,679	$ 4,786
$ 4,339	$ 4,423	$ 4,510	$ 4,599	$ 4,691	$ 4,785	$ 4,882	$ 4,981	$ 5,083	$ 5,188	$ 5,295
0	0.226090889	0.22172949	0.217438574	0.213174163	0.208986416	0.409668169	0.401525798	0.393468424	0.385505012	0.377714825

	SEP FLIGHT 2				SEP FLIGHT 3			SEP FLIGHT 4	SEP FLIGHT 5	
2021	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**
$ 1,663	$ 1,815	$ 1,819	$ 1,026	$ 458	$ 616	$ 633	$ 1,300	$ 1,335	$ 685	$ 358
$ 267	$ 84	$ 87	$ 89	$ 92	$ 94	$ 97	$ 99	$ 102	$ 105	$ 107
6	7	7	7	7	8	8	8	8	8	8
7	8	8	8	8	8	9	9	9	9	9
	CONTINUE				CONTINUE					
13	15	15	15	15	16	17	17	17	17	17
$ 5,130	$ 6,945	$ 8,764	$ 9,790	$ 10,248	$ 10,864	$ 11,497	$ 12,797	$ 14,132	$ 14,817	$ 15,175
$ 3,830	$ 3,914	$ 4,001	$ 4,090	$ 4,182	$ 4,276	$ 4,373	$ 4,472	$ 4,574	$ 4,679	$ 4,786
$ 8,960	$ 10,859	$ 12,765	$ 13,880	$ 14,430	$ 15,140	$ 15,870	$ 17,269	$ 18,706	$ 19,496	$ 19,961
0	0.184179022	0.156678418	0.144092219	0.138600139	0.198150594	0.252047889	0.23162893	0.213835133	0.205170291	0.200390762

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