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The Trillion Dollar Question: Anatomy of the Vision for Space Exploration Cost

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One of the key goals of the National Vision for Space Exploration as implemented by NASA's Exploration Systems Mission Directorate is affordability. The ultimate cost for such exploration is based upon various design approaches, projected demand, and technology. Multiple pronouncements have been made as to the cost for implementing this Vision. These assessments have relied on very broad analogies to past programs yielding perhaps questionable cost estimates. Deterministic and probabilistic level life cycle estimates are provided of the Vision for Space Exploration in order to determine the validity of the trillion dollar figure often quoted in the media. A sample lunar exploration architecture and development timeline are presented. The estimate presented here is not meant to be a complete and final judgment on the cost of the VSE. That will require a more detailed analysis using the actual architecture scenario resulting from NASA studies. But, a rational first approach was used in this examination to elevate the debate and provide clarity through a more rigorous cost estimate of lunar exploration, from cost guessing to cost estimation.

Nomenclature

CER = cost estimating relationship
CEV = crew exploration vehicle
DDT&E = design, development, testing, and evaluation
ERS = earth return stage
ESAS = Exploration Systems Architecture Study
ESMD = Exploration Systems Mission Directorate
ETO = earth-to-orbit
HLLV = heavy lift launch vehicle
IMLEO = initial mass in low earth orbit
ISS = International Space Station
LCC = life cycle cost
LEO = low earth orbit
MSAT = mission scenario analysis tool
NAFCOM = NASA/Air-Force cost model
SRB = solid rocket booster
TFU = theoretical first unit
VSE = Vision for Space Exploration

I. Introduction

Within the United States government, the major focus of human exploration of space has been on the Vision for Space Exploration (VSE) announced by President George W. Bush on January 14, 2004. As stated in the VSE: "The fundamental goal of this vision is to advance U.S. scientific, security, and economic interest through a robust space exploration program."[1] The VSE has four major objectives:

1) Implement a sustained and affordable human and robotic program to explore the solar system and beyond.

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2) Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations.
3) Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration.
4) Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.

In general, the United States Vision for Space Exploration is to be a full-scale human return to the Moon program with a Mars follow-on. However, given both limited public budgets for space exploration and all too common cost overruns for large government programs, there is need to maintain credible cost estimates to assure an affordable space program.

As of this paper, the NASA Headquarters Office of Program Analysis and Evaluation is engaged in a 60-90 Exploration Systems Architecture Study (ESAS) to examine many of the larger questions associated with the implementation of the VSE. This study will provide the analytical support for a number of key near-term decisions for NASA, the White House, and Congress and is expected to be released in late summer/fall of 2005. The focus areas of the study include:

1) Complete assessment of the top-level Crew Exploration Vehicle (CEV) requirements and plans to enable the CEV to provide crew transport to the ISS and to accelerate the development of the CEV and crew launch system to reduce the gap between Shuttle retirement and CEV IOC [initial operating capability].
2) Definition of top-level requirements and configurations for crew and cargo launch systems to support the lunar and Mars exploration programs.
3) Development of a reference lunar exploration architecture concept to support sustained human and robotic lunar exploration operations.
4) Identification of key technologies required to enable and significantly enhance these reference exploration systems and reprioritization of near-term and far-term technology investments.

The ESAS is seen to have large impact as it will be the new NASA Administrator's plan for the architecture components required to implement the VSE.

Unofficial sources have revealed that the study will advocate a large government-led effort in going back to the moon, with the commercial industry (and specifically the emerging commercial community) supporting the crew and cargo logistics support of the International Space Station (ISS)[2]. The study is thought to advocate development of a new U.S. government-derived, large payload space launch capability to replace the Space Shuttle, most likely a Shuttle-derived launch vehicle. The in-space human transportation component of the lunar exploration architecture, or CEV, will most likely be a capsule or lifting body carried to orbit on an expendable rocket booster, most likely a solid rocket booster with a new upper stage. One major aspect of the VSE is clear: the Space Shuttle is unlikely to fly again after 2010 with a crew in its current configuration. The Space Shuttle's main mission between now and 2010 will be to service the ISS.

II. The Appearance of the Trillion Dollar Estimate

After the announcement of the new National Vision for Space Exploration, there were attempts to quantify the implementation cost. In this quest, the media picked up various round number estimates for this cost, notably one trillion dollars and used it repeatedly. There are multiple online articles dealing with the history and evolution of this cost. These articles show the thought process of some estimators in arriving at a trillion dollar estimate. As stated by Dwayne Day in a very complete assessment of this initial estimate[3]:

> The $1 trillion cost estimate is wrong. It is based upon a completely inaccurate reading of historical data and deeply flawed mathematics. But the problems are worse than this. Not only was an inaccurate number repeated endlessly by the media without confirmation, but the flawed calculations were repeated again and again by various people with their own agendas. Reporters also appear to have ignored or evaded obvious weaknesses with the original source of the information, preferring to repeat an inaccurate number that they saw repeated endlessly rather than seek out better information. The story of the $1 trillion cost estimate raises some troubling questions about how modern journalism is conducted… Another unfortunate lesson here is that although NASA has little credibility when it comes to cost estimates, neither does the press. There is certainly tremendous irony

in the fact that reporters who are so skeptical of NASA cost estimates are themselves prone to wild exaggeration and inability to apply simple inflation adjustments.

The appearance of this round number may come from an estimate in 1989 during the administration of President George H.W. Bush of the then proposed Space Exploration Initiative (SEI). Generally the output cost for this project was around half-a trillion dollars for a multi-decade mission to the moon and Mars. These initial estimates seem to have been picked up and inflated with additional margin and then reported in multiple media outlets as the cost for the VSE.

III. Developing a New Cost Estimate

For this examination, a top level cost estimate is provided of the Vision for Space Exploration in order to better understand the true nature of this project and the validity of the oft-quoted trillion dollar estimate. This estimate is developed using historical analogies, external cost estimates, and specific Cost Estimating Relationships (CERs). The estimate includes the cost of robotic precursors, hardware development/acquisition, launch development, operations costs (launch and mission operations), ISS support, Space Shuttle support, and Mars-related technology development. The cost estimate is presented up to and including fiscal year 2025. It is posited here that forecasting beyond this time frame may be unwise given the inherent uncertainty in program stability. Thus the cost estimate here only extends to the development of a lunar outpost and initial development of Mars technologies. The publicly available information for the ESAS is used as the starting point of this lunar exploration architecture.

A. Exploration Architecture

Various lunar exploration architectures are under consideration by NASA’s ESAS. Shortly a baseline exploration solution will be announced by government officials; however at the writing of this paper no such architecture has been released. Therefore, a representative, best guess lunar exploration architecture scenario was used as the basis of the cost estimate presented here. Development, acquisition, and recurring costs are estimated for the various architecture components. The development and mission schedule is based upon a presentation given by NASA’s Special Assistant to the Administrator Chris Shank at the 6th annual Return to the Moon Conference (22 July 2005, Las Vegas, NV)[4].

A lunar architecture design is generated using the Mission Scenario Analysis Tool (MSAT)[5]. Mass estimate outputs from this architecture design process are used to estimate the development and acquisition costs. Figure 1 shows a notional illustration of the lunar exploration architecture. For this assessment the first crewed lunar landing in the twenty-first century (seventh overall in human history) is planned for 2018, with subsequent missions every year from then forward until 2025, for a total of 21 missions over this 8 year period. The number of missions is assumed to steadily increase over the years, from one mission in the first year to four in the last year. This increase is representative of a phased development process with additional surface elements to develop the lunar outpost along with coordinated technology development for Mars follow-on activities.

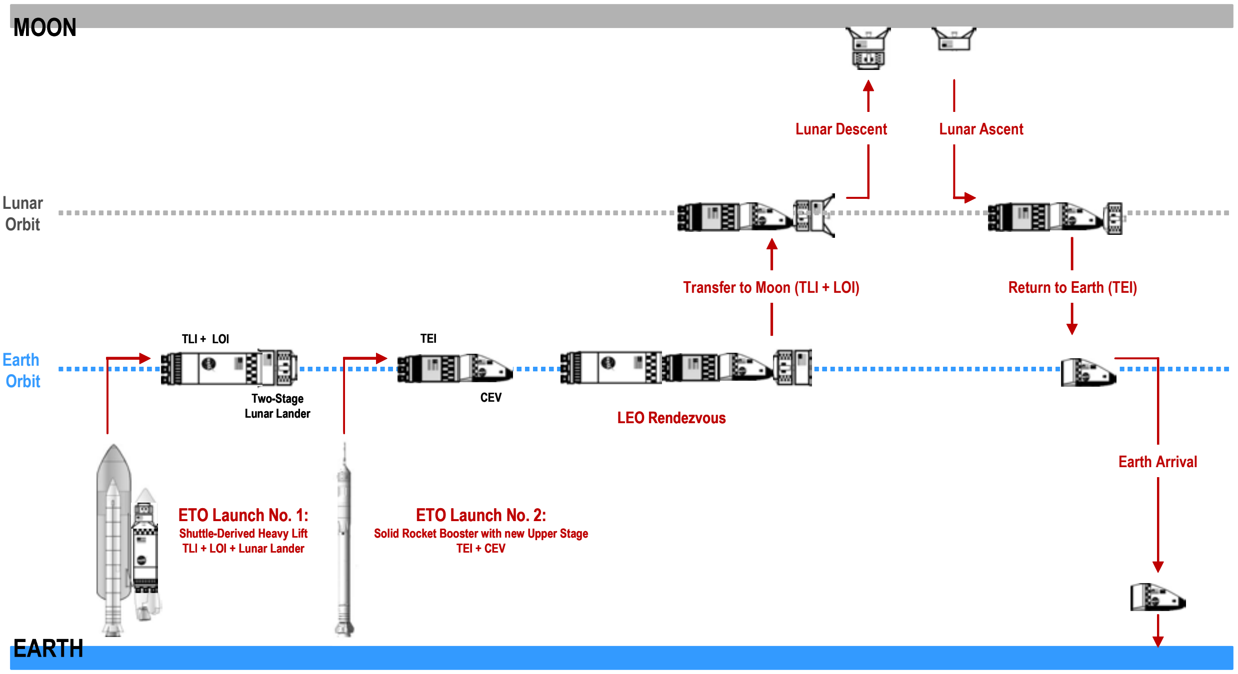
The specific architecture chosen for this analysis is an all-chemical propulsion solution using Space Shuttle derived ETO launch vehicles. Earth orbit rendezvous is required on the outbound leg of the mission since the crew is launched to Low Earth Orbit (LEO) separately from most of the other in-space elements. Also, this architecture assumes lunar orbit rendezvous both before and after surface exploration because the crew’s Earth return vehicle remains in Low Lunar Orbit (LLO). Specific lunar surface activities were not modeled as a part of this effort.

Two ETO vehicle classes are used for this architecture. The first is a “single-stick” two-stage launch vehicle for crew and the second is a 2½-stage shuttle derived Heavy Lift Launch Vehicle (HLLV) for lunar cargo. The HLLV includes a 5-segment Space Shuttle Solid Rocket Booster (SRB) and a new LOX/LH2 upperstage powered by one or more Space Shuttle Main Engines (SSMEs). The “single-stick” launches the crew exploration vehicle and its propulsion system into LEO. A side-mount shuttle derived HLLV is considered for this architecture. Each uses Shuttle SRBs and External Tank (ET) technologies and utilizes the Earth Departure Stage for LEO insertion. The HLLVs are responsible for launching all the in-space stages, except the CEV, in LEO.

The Earth Departure Stage (EDS) is the upperstage of the shuttle derived HLLVs and provides both the LEO insertion delta-V and the Trans-Lunar Injection (TLI) and Lunar Orbit Insertion (LOI) delta-Vs. After inserting into LEO with the lunar lander as its payload, this LOX/LH2 stage rendezvous with the CEV and then delivers all the in-space stages to low lunar orbit. After inserting into Low Lunar Orbit (LLO) the EDS is discarded and is not reused.

The lunar lander used for this architecture is a two-stage mixed propellant design. The descent stage is a non-reusable vehicle using LOX/LH2 propellants. It provides the lunar descent delta-V and aids the ascent stage in providing both consumables and power to the crew during their surface stay. The lunar ascent stage using LOX/CH4 propellants and provides a surface habitat for the crew for the one-week lunar surface mission. The ascent stage is designed to provide most of the power, life-support, and consumables needed by the crew. After the surface mission is complete the descent stage remains on the lunar surface, while the ascent stage returns to crew to LLO and rendezvous with the waiting CEV.

The crew is transported from the Earth's surface to LLO and back in the crew exploration vehicle (CEV). The CEV is assumed to be a capsule design similar but more capable than the Apollo-era command module. The CEV system consists of two stages, the capsule which houses the crew, and a power and propulsion module. The power and propulsion module, referred to as the Earth Return Stage (ERS), provides the Trans-Earth Injection (TEI) delta-V required to return the CEV from LLO to the Earth. The CEV is sized for a crew of 4 and is also capable of ISS crew delivery. Any CEV used for an exploration mission in this assessment is considered expendable.



Note: Notional representation of lunar exploration architecture. Architecture elements may not be in scale.

Figure 1. Human Lunar Conceptual Mission Architecture

B. Process

Given the uncertainty inherent in the early stages of such a program, a probabilistic cost estimate is developed for the various components of a lunar exploration architecture consistent with the Vision for Space Exploration (see Table 1). Triangular uncertainty distributions were placed on baseline costs and a Monte Carlo simulation was performed for twenty-five thousand runs. Various cost methodologies were used to arrive at the estimate presented here. For some portions of the architecture, the NASA/Air-Force Cost Model (NAFCOM) 2004 was used to estimate the Design, Development, Testing, and Evaluation (DDT&E) and Theoretical first unit (TFU) costs. Results from the MSAT physical sizing process were input into NAFCOM for the Earth Departure Stage (EDS), lunar lander, and Earth Return Stage (ERS). Other costs for other program elements such as the CEV, ETO launch vehicles, Space Shuttle support, ISS support, surface system, facilities, and operations (launch and mission) are developed from reference reports and historical experience/expert judgment. Mars development costs are set at a pre-determined amount for technology/systems development and do no include actual architecture development. Architecture element costs and their sources are shown in Table 1. These costs are inflated to then year dollars in the in the final Life Cycle Cost (LCC) calculation. A learning curve is applied for any multiple units acquired or for any additional learning on list the assumptions related to the costs of various elements in the architecture. A just-in-time production process is assumed for the CEV, EDS, lunar lander, and ERS.

Table 1. Elements of VSE-Based Exploration Architecture Cost Estimate

Mission	Start Year	End Year	Note (Most Likely Costs)
Robotic Precursors	2006	2015	US$300M per mission, one mission per year, based upon Discovery-class mission cost
Space Shuttle	2006	2010	US$250M additional return to flight cost after STS 114 US$3.5B for annual operational cost for 4 mission per year
International Space Station (ISS) Support[6]	2006	2015	US$1.4B per year ISS support costs, based upon GAO Estimate
Crew Exploration Vehicle (CEV)	2006	2011	US$5.0B DDT&E cost, US$1.5B TFU cost, 85% learning curve
Crew Launch	2006	2011	US$2.5B DDT&E cost, US$280M[7] TFU cost, 97% learning curve
Lunar Lander	2011	2018	US$3.6B DDT&E cost*, US$334.5M TFU cost*, 85% learning curve
Lunar Heavy Launch	2011	2018	US$6.0B DDT&E cost, US$540M[7] TFU cost, 97% learning curve
Earth Departure Stage (EDS)	2011	2018	US$2.0B DDT&E cost*, US$170.4M TFU cost*, 85% learning curve
Earth Return Stage (ERS)	2011	2018	US$1.5B DDT&E cost*, US$110M TFU cost*, 85% learning curve
Surface Systems	2011	2020	US$5.0B DDT&E cost, US$400M TFU cost, 85% learning curve 2019-2021: 1 surface package per year 2022-2023: 2 surface packages per year 2024-2025: 3 surface packages per year
Lunar Outpost Buildup	2018	2025	2018: 1 mission per year 2019-2021: 2 missions per year 2022-2023: 3 missions per year 2024-2025: 4 missions per year
Launch Operation Facilities for CEV Launch	2007	2011 (Dev. Ends), 2025	US$500M DDT&E cost, US$25M per CEV launch
Launch Operations Facilities for Lunar Heavy Launch	2012	2018 (Dev. Ends), 2025	US$3.0B DDT&E cost, US$20M per Lunar Heavy launch
Mission Operations Facilities: Development and Operations	2010	2018 (Dev. Ends), 2025	US$250M DDT&E cost US$417M per each mission per year (30% of ISS annual operations costs) US$125M per each surface package per year (10% of ISS annual operations costs)
Mars Development[8]	2020	2025	US$39.4B, based upon previous NASA MSFC cost estimate for Mars development comparing Mars Direct and Apollo

Note: Unless otherwise stated, costs as in US$FY2005, *NAFCOM 2004 based cost estimate

Table 2 shows the uncertainty distributions used for the Monte Carlo simulation. Expert judgment was used to arrive at the various distributions. Costs for more unique architecture elements had wider distributions. Thus the uncertainty distributions for the lunar lander or surface systems are very wide (from $3.5B to $5.0B and from $3.0B to $8.0B respectively) and skewed towards the upper end of the distribution (a more conservative approach).

Table 2. Input Cost Uncertainties

Factor	Minimum	Most Likely	Maximum
Robotic Precursors	US$300M	US$300M	US$400M
Crew Exploration Vehicle (CEV)			
DDT&E	US$4.5B	US$5.0B	US$6.5B
TFU	US$1.0B	US$1.5B	US$2.0B
Crew Launch			
DDT&E	US$1.5B	US$2.5B	US$3.0B
TFU/Initial Recurring Cost	US$280M	US$280M	US$350M
Lunar Lander			
DDT&E	US$3.5B	US$3.6B	US$5.0B
TFU	US$300M	US$334.5M	US$500M
Lunar Heavy Launch			
DDT&E	US$4.5B	US$6.0B	US$6.5B
TFU/Initial Recurring Cost	US$500M	US$540M	US$650M
Earth Departure Stage (EDS)			
DDT&E	US$1.5B	US$2.0B	US$2.5B
TFU	US$500M	US$170.4M	US$200M
Earth Return Stage (ERS)			
DDT&E	US$1.2B	US$1.5B	US$2.0B
TFU	US$100M	US$110M	US$150M
Surface Systems			
DDT&E	US$3B	US$5.0B	US$8B
TFU	US$100M	US$400M	US$600M
Launch Operation Facilities: CEV Launch			
DDT&E	US$400M	US$500M	US$800M
Initial Recurring Cost	US$20M	US$25M	US$40M
Launch Operations Facilities: Lunar Heavy Launch			
DDT&E	US$2B	US$3.0B	US$5B
Initial Recurring Cost	US$20M	US$20M	US$30M
Mission Operations Facilities: Development and Operations			
DDT&E	US$200M	US$250M	US$400M
Mission Ops Cost – Main (% of ISS Ops Cost)	10%	30%	35%
Mission Ops Cost – Surface Systems (% of ISS Ops Cost)	5%	10%	15%
Mars Development	US$25.0B	US$39.4B	US$50.0B

Note: Unless otherwise stated, costs as in US$FY2005

C. Deterministic Life Cycle Cost Results

After accounting for the various architecture elements, the deterministic total LCC (as seen in Table 3) from 2006 until 2025 for the VSE is estimated to be US$215.4B in then year dollars (US$159.0B in FY2005). This estimate is based upon the multiple assumptions described in previous sections. This estimate is relatively complete in that it accounts for the all the major components that would be required in the ESMD enterprise at NASA related to exploration (see Figure 2). About one-fifth of the cost is related to vehicle acquisition. For these assumptions, just over 10% of the total LCC is associated with CEV crew and Shuttle-derived heavy cargo launch. Total development for Mars is over 25% of the total LCC. As seen in Figure 3, a large investment is required during the initial years in the program for development of the CEV and crew launch system. After this period, development of the heavy lunar launch vehicle, in-space stages, and lunar lander can proceed. In the out years, as the lunar outpost is developed and more missions are attempted on a yearly basis, annual pogrom costs escalate as preparation begins for the Mars expeditions.

Table 3. Deterministic Life Cycle Cost Estimate for VSE-Based Exploration Architecture (2006-2025).

Cost Item	Cost (Then-Year)	Percentage of Total LCC (Undiscounted)
Total Robotic Missions	$3,369M	2%
Total Element Development Cost	$30,753M	14%
Total Launch Cost	$22,453M	10%
Total Acquisition Cost	$45,412M	21%
Total Facilities Development	$4,336M	2%
Total Recurring Launch Operations	$1,356M	1%
Total Mission Operations Costs	$15,497M	7%
Total ISS Support Cost	$15,606M	7%
Total Space Shuttle	$18,903M	9%
Total Mars Development	$57,708M	27%
Total Life Cycle Cost (Undiscounted)	**$215,395M**	100%
Total Life Cycle Cost (Discounted)	**$159,053M**	74%

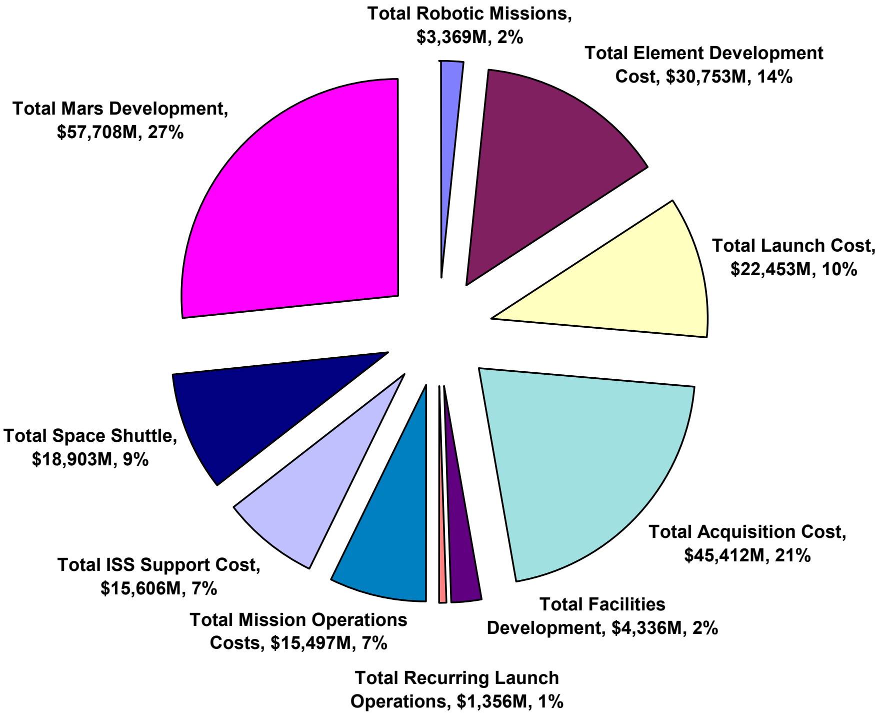


Figure 2. Deterministic Life Cycle Cost Breakout for VSE-Based Exploration Architecture (2006-2025)

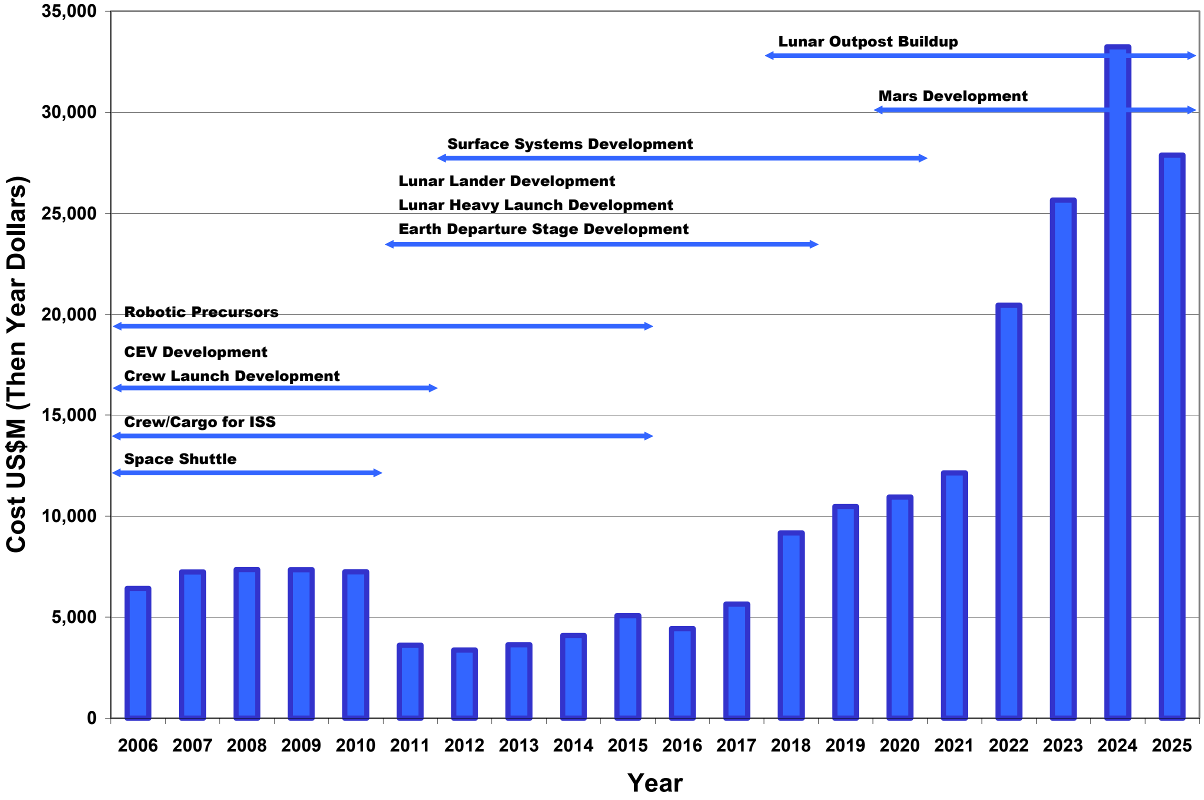


Figure 3. Deterministic Annual Costs for Selected VSE-Based Exploration Architecture (2006-2025)

D. Probabilistic Life Cycle Cost Results

As shown in Table 4 and Figure 4, given the input distributions for twenty-five thousand Monte Carlo simulations, there is a ninety percent certainty that the LCC from 2006 until 2025 is equal to or less than US$227.0B in then year dollars (US$167.2B in FY2005). Even with some assumptions of the uncertain future costs of individual architecture elements, the probabilistic LCC is only approximately five percent higher than the deterministic value given in the previous section. The effect of the large investment in Mars-related technologies in the post 2020 timeframe may be obscuring the costs for the direct lunar related exploration elements.

Table 4. Probabilistic Life Cycle Cost Estimate for VSE-Based Exploration Architecture (2006-2025).

Output Parameter (for 25,000 Monte Carlo Simulations)	Total Life Cycle Cost (Undiscounted)	Total Life Cycle Cost (Discounted)
Mean	215,165.26	159,165.15
Std. Dev.	9,225.20	6,259.70
Skewness	-0.0866	-0.0819
Kurtosis	2.6969	2.7121
Certainty Value (90%)	226,968.41	167,155.93

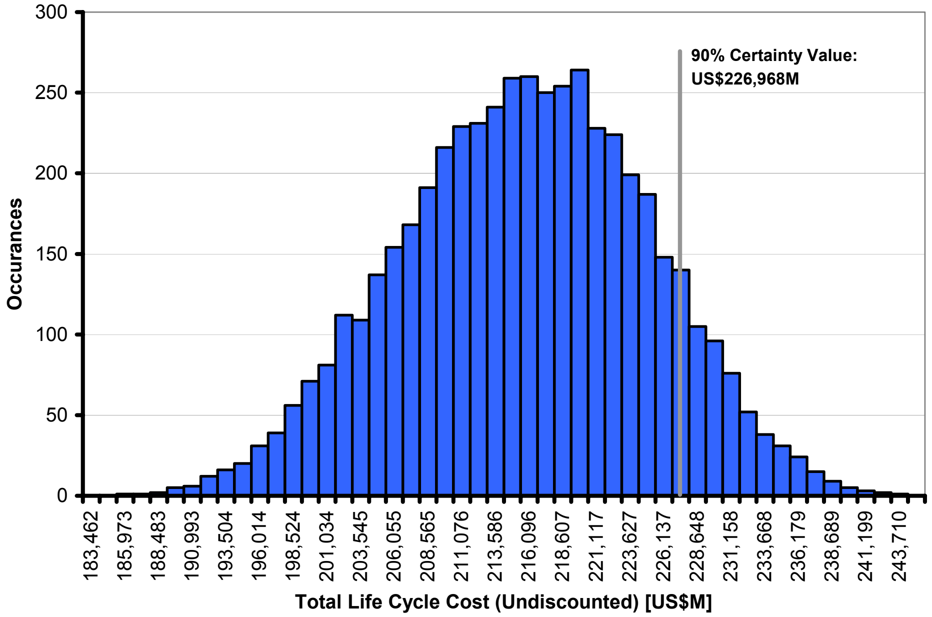


Figure 4. Output Distribution for Undiscounted Total Life Cycle Cost (2006-2025)

IV. Conclusions

The one trillion dollar estimate for implementing the Vision for Space Exploration, as provided by multiple sources, is not a credible estimate. Taking a more thorough estimation approach one can arrive at a life cycle cost of around US$215B (US$227B probabilistically) for the program years of 2006 through 2025. This is for a converged lunar architecture with Shuttle-derived heavy lift launch vehicles, lunar landers, in-space stages, Crew Exploration Vehicle, and initial cost for Mars development. Previous estimates have used rough analogies of historical cost estimates of previous programs and then doubled the resultant amount to arrive at estimates such as one trillion dollars. As a simple counterpoint to these large estimates, consider NASA's total life cycle budget as a government entity from 1958-2005. This amount, if added together and inflated to fiscal year 2005, would approach $700B. Thus the projected estimates of a trillion dollars for the VSE would be more than the cumulative NASA budget. It is only with the very unusual circumstance of extremely high mission rates and extreme program restarts could this exaggerated level of funding ever be envisioned to occur. The estimate presented here is not meant to be a complete and final judgment on the cost of the VSE. That will require a more detailed analysis using the actual architecture scenario resulting from the ESAS activity. But, a rational first approach was used in this examination to elevate the debate and provide clarity through a more rigorous cost estimate of lunar exploration, from cost guessing to cost estimation.

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