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EXTENSIONS OF NASA'S EXPLORATION ARCHITECTURE: PERFORMANCE CAPABILITIES AND MARKET ECONOMICS OF A LUNAR PROPELLANT PRODUCTION FACILITY

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Abstract

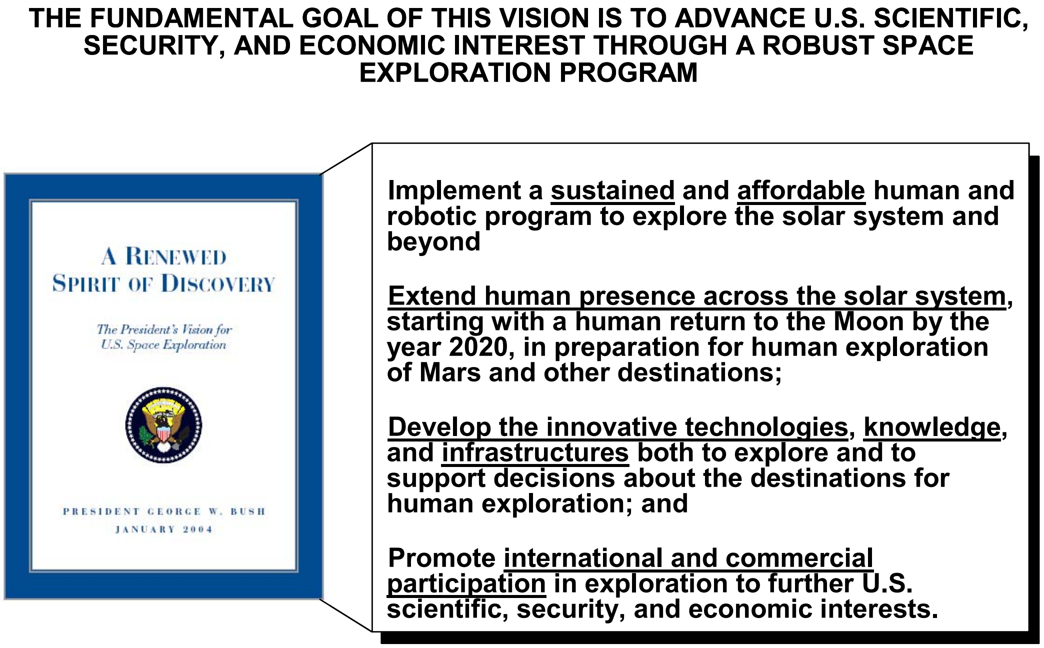
What are the parameters for a successful commercial company that can provide future products to a government customer interested in human exploration of the lunar surface? Multiple governments, specifically the United States of America, are interested in human exploration of cis-lunar space. These space exploration architectures could potentially utilize new commercial products (e.g. space hotels, propellant depots, orbital tourism). To analyze the characteristics of such markets, an economic analysis is performed of a lunar In-Situ Resource Utilization (ISRU) facility as if it was developed and operated by a commercial company providing propellant to a government customer. The ISRU facility is envisioned to be delivered by the government's transportation architecture. The facility is constrained to be less than 21 MT (the capability of a notional lunar lander as that designed by NASA's recent Exploration Systems Architecture Study) and assumed to be located near deposits of lunar polar ice. A conceptual design is presented for a notional ISRU plant capable of producing approximately 58 MT of propellant per year. Subsequently, both a deterministic and probabilistic economic analysis of a company's cash flow was performed. The deterministic delivered propellant price was $17,286/kg with a probabilistic mean of $19,913/kg (with a 90% certainty that price is less than or equal to $24,416/kg).

Nomenclature

CABAM	Cost and Business Analysis Module
ESAS	Exploration Systems Architecture Study
ISRU	In-Situ Resource Utilization
LCC	Life Cycle Cost
LEO	Low Earth Orbit
LSAM	Lunar Surface Access Module
NPV	Net Present Value
PPD-LS	Propellant Plant and Depot-Lunar Surface
VSE	Vision for Space Exploration
WACC	Weighted Average Cost of Capital

1. Introduction

One of the major components of the United States Vision for Space Exploration (VSE) [1,2] calls for a return to the moon with development of new lunar infrastructure to enable long term human habitation [Fig. 1]. The most detailed presentation of this future lunar architecture has been the Exploration Systems Architecture Study (ESAS), originating out of NASA Headquarters during the summer and late fall of 2005 [3]. The specifics of ESAS include a lunar return by 2018 with 4 astronauts initially staying for one week. This is accomplished through the development of multiple architecture elements including space shuttle derived crew and cargo launch vehicles, earth departure stage, Crew Exploration Vehicle (command module and service module), and Lunar Surface Access Module (or lunar lander). The Lunar Surface Access Module (LSAM) could have the capability to deliver crew in a two-stage configuration or cargo in a single stage



THE FUNDAMENTAL GOAL OF THIS VISION IS TO ADVANCE U.S. SCIENTIFIC, SECURITY, AND ECONOMIC INTEREST THROUGH A ROBUST SPACE EXPLORATION PROGRAM

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

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;

Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and

Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.

Fig. 1. United States of America Vision for Space Exploration (VSE) [2]

configuration. The ESAS architecture did not include specific details about the exact lunar infrastructure that would be enabled by the development of these elements. It may be the case that the United States will rely on international partners for assistance in the development of such infrastructure as NASA takes the responsibility for the transportation elements of lunar exploration. NASA is currently in the process of reviewing the ESAS architecture to obtain a more definitive architecture. Thus there may be changes to the longer term lead items such as the lunar lander and infrastructure with more definition of the near term elements such as the Crew Exploration Vehicle (CEV), Crew Launch Vehicle (CLV), and Cargo Launch Vehicle (CaLV).

2. Objective and Analysis Process

This analysis attempts to envision commercial components of a lunar infrastructure using the NASA ESAS as a guide. Specifically, this study examines the technical and economic capabilities of an In-Situ Resource Utilization (ISRU) facility that can be delivered by the lunar lander designed in the ESAS architecture.

One of the major goals of the United State Vision for Space Exploration (VSE) is the promotion of international participation and the commercialization of space [4,5,6]. Specific areas of involvement for the international community include the following [7]:

- Continue International Space Station cooperation refocused on human exploration
- Purchase of additional international partner transportation assets for the Space Station
- Coordination of lunar robotic pre-cursor missions
- Cooperate on variety of lunar surface systems (Habitats, Rovers, Power and logistics, Science and in-situ resource utilization equipment)
- Cooperation on Mars pre-cursor/science missions
- Preparation for joint human Mars missions

This study examines the commercialization goals in the context of lunar infrastructure, and specifically the extensions of the capabilities enabled by the LSAM as designed by the NASA ESAS. The process used for this study involved an international design team under the management of SpaceWorks Engineering, Inc. (SEI) of the United States. Shimizu Corporation (Japan) assisted in the technical sizing of the lunar In-Situ Resource Utilization (ISRU) facility while both CSP Japan, Inc. and SEI performed the subsequent economic analysis. The results shown here are part of a larger propellant economic study performed by the team.

The results shown here are only for the production of propellant on the lunar surface. Additional analyses were performed to determine requirements for propellant delivery to Low Earth Orbit (LEO) and the L-1 Earth-Moon location.

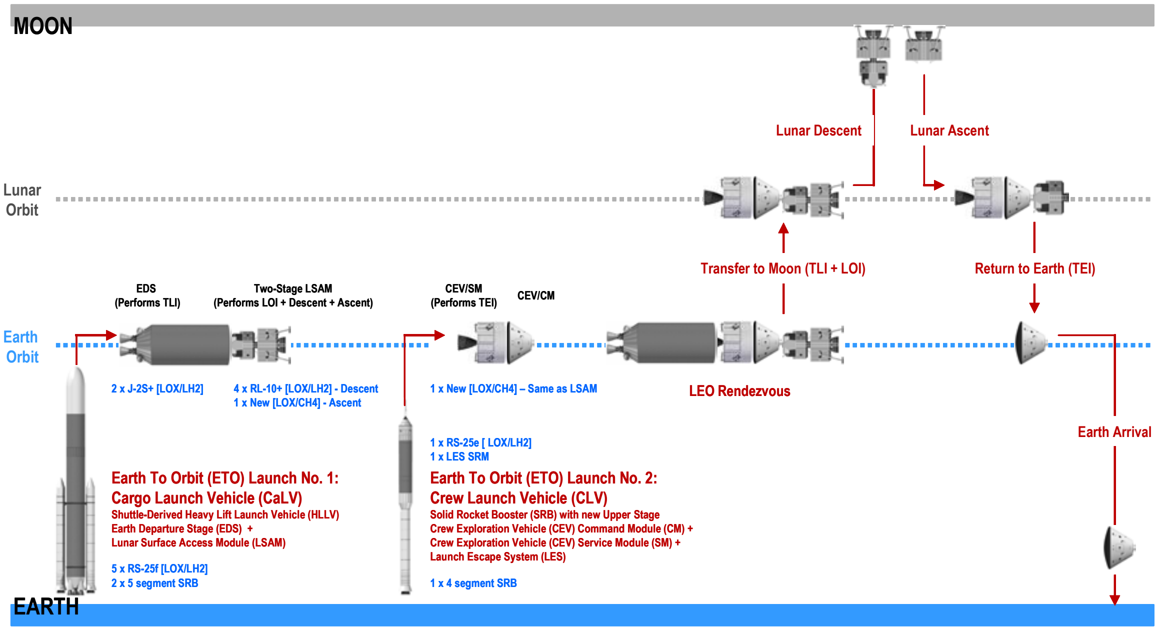
Shimizu Corporation of Japan was responsible for the sizing of the lunar ISRU plant given constraints on lunar surface mass that can be delivered by one lunar lander. CSP Japan was responsible for some initial economic analysis. SEI performed the economic analysis shown here including use of the Cost and Business Analysis Module (CABAM) model (financial analysis of the project) and ProbWorks Monte Carlo suite (for Monte Carlo simulation).

CABAM is an MS-Excel spreadsheet-based model that attempts to model both the demand and supply for space transportation and infrastructure services in the future. The demand takes the form of market assumptions (both near term and far-term) and the supply comes from user-defined systems that are placed into the model. CABAM takes inputs from various other disciplinary models to generate Life-Cycle-Cost (LCC) and economic metrics. One of the major assumptions inherent in CABAM is that the project is modeled as a commercial endeavor with capability to model debt, deprecation, taxation, cash flows, etc.

ProbWorks: Excel is a suite of uncertainty and sensitivity analysis tools for use within Microsoft Excel® for either Windows or Mac OS X. Each driver component has a particular benefit or utility to different classes of problems. The individual drivers in the current release are: Advanced Monte Carlo, Discrete Probability Optimal Matching Distribution (DPOMD), Pareto Sensitivity, and a Response Surface Equation (RSE) Generator. ProbWorks: Excel is a product of PiBlue Software, Inc.

3. Exploration Architecture

The specific human exploration architecture that is the foundation of this analysis is based upon an ESAS-like architecture [Fig. 2]. This includes an all-chemical propulsion solution using Space Shuttle derived Earth-to-orbit (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). Two ETO vehicle classes are used for this architecture. The



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

Fig. 2. Notional Representation of NASA ESAS Lunar Exploration Architecture (circa late 2005)

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 [8,9]. The HLLV includes a 5-segment Space Shuttle Solid Rocket Booster (SRB) and a new LOX/LH2 upperstage powered by one or more J-2s Saturn V derived engines. The “single-stick” launches the crew exploration vehicle and its propulsion system into LEO. An in-line 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 potentially the Lunar Orbit Insertion (LOI) delta-Vs. After inserting into LEO with the lunar lander as its payload, this stage has a 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 still being finalized but could consist of a two-stage mixed propellant design [Fig. 3]. The descent stage 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 could provide 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. This is one nominal scenario; the final lunar lander may have different characteristics.

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 Service Module (SM), 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 (maximum future expansion to 6) and is also capable of ISS crew delivery. The CEV could potentially be reusable.

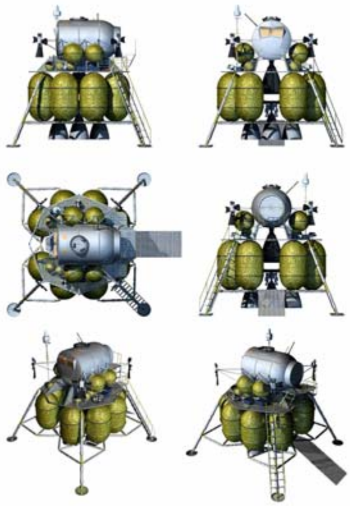


Fig. 3. Notional Representation of NASA ESAS Two-Stage Lunar Surface Access Module (LSAM) with Single Crew Cabin and Integral Airlock [3, 7]

Within the ESAS analysis, there was consideration for an outpost development strategy. The specific elements of this strategy are the following [7]:

- Power system and backbone of comm./nav are landed first
- Habitat, logistics, ISRU, and other surface infrastructure land and plug in to the power and communications./navigation systems established on the first flight
- An uncrewed, fueled ascent stage lands prior to the first crew’s arrival – allows for the presence of two fueled ascent stages during crewed rotations at the habitat
- During the course of designing the outpost, a number of design principles drove the selection of implementations
- Landed elements should not move unless absolutely necessary
- Autonomous activities (e.g. locomotion, payload manipulation) should only be performed if absolutely necessary
- Required crew operations for Outpost deployment should be limited and simple
- Landed elements should be delivered on common cargo descent stages
- Common functions (e.g. power distribution) should be performed by common means

- Logistics supply chain should require minimal crew time and robotic manipulation

These outpost strategies give justification for the analysis of an ISRU propellant plant that would assist in the development of sustainable lunar base. .

4. Lunar ISRU Production Facility

The basic concept presented here is an ISRU facility, referred to as the Propellant Plant and Depot-Lunar Surface (PPD-LS), on the lunar surface selling propellants (specifically LOX and LH2) to a government customer. The propellants are mined at the lunar poles with customer delivery at a depot located near the production facility. An assumption is made that there is accessible lunar polar water ice (one percent by weight water concentration in lunar regolith). At the PPD-LS (Lunar Surface), water is divided into oxygen and hydrogen by electrolysis, liquefied, and stored to serve fuels for various vehicles. The PPD-LS could potentially provide propellants for propulsions systems (lunar landers), fuel cells, etc.

The mass of the ISRU system delivered to the lunar surface is constrained to approximately twenty-one metric tons; the projected mass of the NASA designed lunar lander known as the Lunar Surface Access Module (LSAM). It is assumed that there are existing transportation elements (Earth-to-orbit and in-space) to deliver the LSAM to the lunar surface. In the scenario envisioned for this study, multiple crewed lunar surface excursions have already occurred and the development of a sustained presence on the surface has been initiated. Various candidate ISRU payloads are considered, differentiated by the availability of available constituents (lunar regolith or ice). Thus the candidate systems examined can produce oxygen and/or hydrogen.

Specific technologies that are deemed to be available for the PPD-LS include a bucket wheel excavator, water separation using heat from a nuclear power plant, and semi autonomous assembly of lunar facilities [10,11,12,13]. Figure 4 illustrates the components of the lunar PPD-LS. Table 1 gives the mass and dimensions of a conceptual PPD that could fit within a 21 MT constraint for an ESAS type lunar lander. This facility is sized to fit on the lander and arrive with no habitat. The propellant production rate is on average 20.0 kg/hour. If such a plant were operating continuously over a lunar 10 day period (approximating daylight operation) then that would equate to 4.8 MT/month or 57.6 MT/year of propellant.

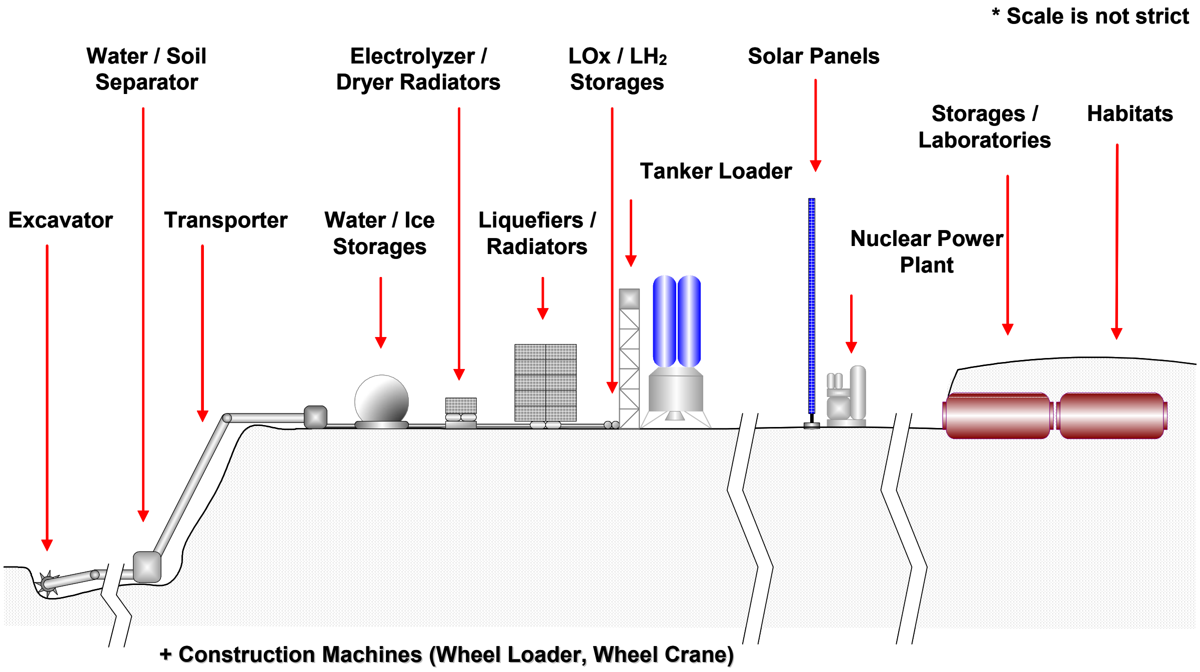


Fig. 4. Lunar Propellant Plant and Depot-Lunar Surface (PPD-LS) Components

Table 1. Lunar PPD Size for 21 MT Lunar Lander

Components	Size (stowed) [m]	Mass [MT]
Soil and Water Management		**15.03**
Excavator	2x0.1x0.1	1.00
Seperator	D0.6x3	0.80
Transporter	6x0.15x0.15	1.60
Water Storage	D2.0x1.7	1.43
WTM Loader	-----	-----
Wheel Loader	-----	-----
Wheel Crane	2.5x1.6x2	4.80
Nuclear Power Station	D8.6x2	5.40
PPD-LS		**5.91**
Electrolyzer	1x1x1	1.08
Dryer Radiators	3x3.1x0.05	0.04
Liquefiers LOX	0.6x0.7x1	0.13
Liquefiers LH2	0.5x1x1	0.42
Radiators LOX	5x3x0.1	0.21
Radiators LH2	5x3x0.3	0.58
Storage LOX	D1.6x2.1	1.23
Storage LH2	D1.6x4.3	2.15
Solar Panels	D8.6x0.45	0.07
Lunar Habitat Module	-----	-----
Lunar PPD Systems Total		**20.94**

5. Economics of Commercial Lunar ISRU facility

CABAM is used to model the life cycle cost and financial case of a company providing propellant services to a government customer on the surface of the moon. A deterministic analysis was initially performed. A probabilistic analysis was subsequently performed where distributions were placed on ISRU plant development/production costs, transportation costs, operations costs, and propellant production capability. This probabilistic analysis was performed for multiple Weighted Average Cost of Capital (WACC) values. WACC is a rate that is representative of the required return for a project. For this analysis the WACC is a proxy for the market risk premium.

The commercial company is assumed to be responsible of the development and construction of the ISRU plant but is not responsible for development of the transportation architecture to send the plant to the lunar surface. The commercial company is assumed to pay the transportation cost to the lunar surface to the government. The initial development of the PPD starts in 2014, with Initial Operating Capability (IOC) in 2022. For this analysis only one propellant plant is assumed to be

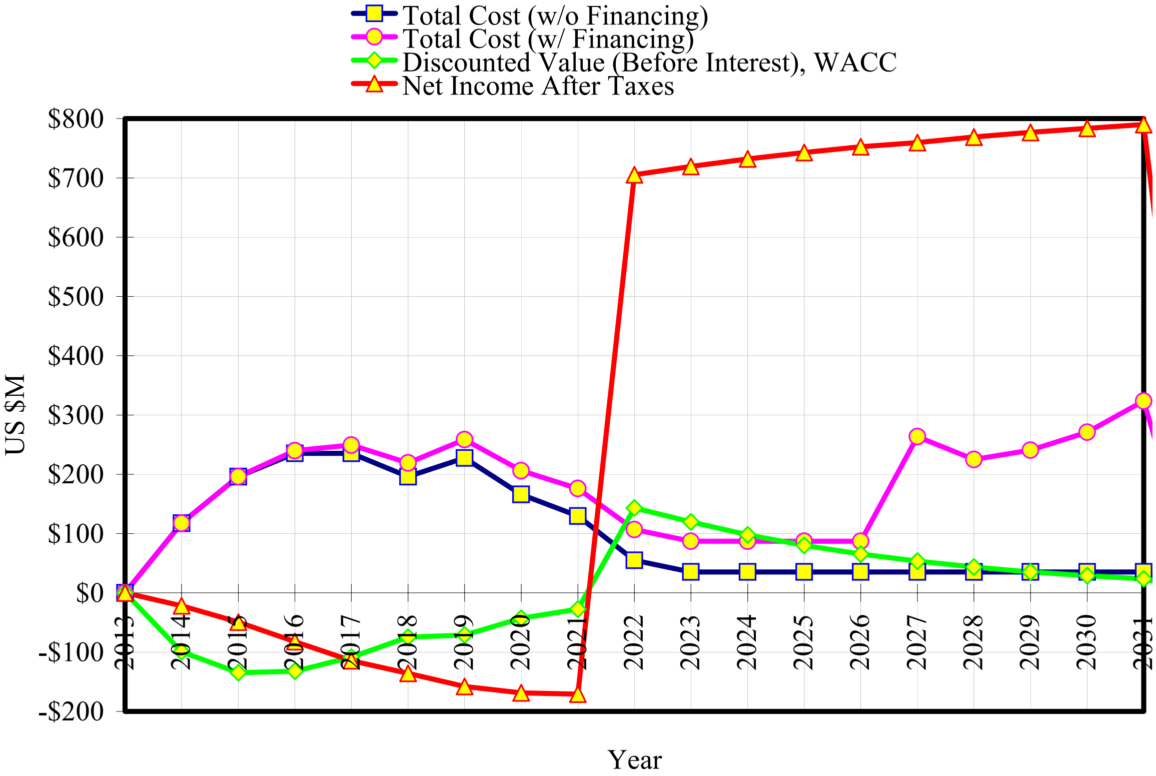


Fig. 5. Cash Flow for Deterministic Baseline Case (WACC = 21.7%, Price = $17,286/kg)

Table 2. Triangular Distributions for Various Uncertainty Parameters

Parameter	Deterministic/ Most Likely	Minimum	Maximum
DDT&E Cost [$M, FY2005]	**$930 M**	**-25%**	**+75%**
Nuclear Power Plant*	$195 M		
Excavation/Processing/Storage Facility Cost *	$578 M		
Mass of Excavation/Processing/Storage Facility*	$158 M		
Acquisition Cost [$M, FY2005]	**$310 M**	**-25%**	**+75%**
Nuclear Power Plant*	$65 M		
Excavation/Processing/Storage Facility Cost *	$193 M		
Mass of Excavation/Processing/Storage Facility*	$53 M		
Transportation Cost to Lunar Surface [$M, FY2005]	**$1,397 M**	**-10%**	**+25%**
Cargo Launch Vehicle (CaLV)**	$540 M		
Earth Departure Stage (EDS)***	$208 M		
Lunar Surface Access Module (LSAM)***	$649 M		
Mission Operations Cost [$M/year, FY2005]	**$30 M**	**-10%**	**+50%**
ISRU Propellant Production Capability [MT/year]*	**57.6**	**-20%**	**+5%**

Notes:
* - Source: Shimizu Corporation (75% development cost, 25% acquisition cost)
** - Source: Charania, A., "The Trillion Dollar Question: Anatomy of the Vision for Space Exploration Cost," AIAA-2005-6637, Space 2005, Long Beach, California, August 30 - September 1, 2005 [15].
*** - Source: Exploration Systems Architecture Study (ESAS) Draft Report, Section 12 [3].

operational. The commercial company has revenue-generating operations for 10 years.

Figure 5 shows the cash flow for such a commercial company. A baseline WACC was of 21.7% was arrived at using a traditional comparison amongst multiple industries, debt-equity assumptions, risk free rates, and market risk premiums. For the baseline case were WACC was equal to 21.7%, the price for propellant to a customer on the lunar surface was $17,286/kg.

The ProbWorks Monte Carlo suite was used to place distributions on various inputs to the model. Table 2 lists the specific values of the triangular distributions. One thousand Monte Carlo simulations were performed for each of eight WACC values. As shown in Figure 6, during each

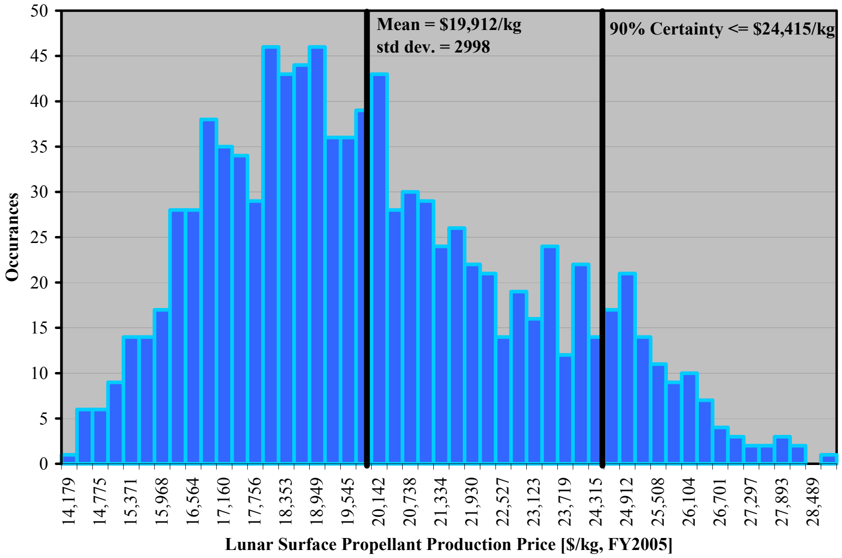
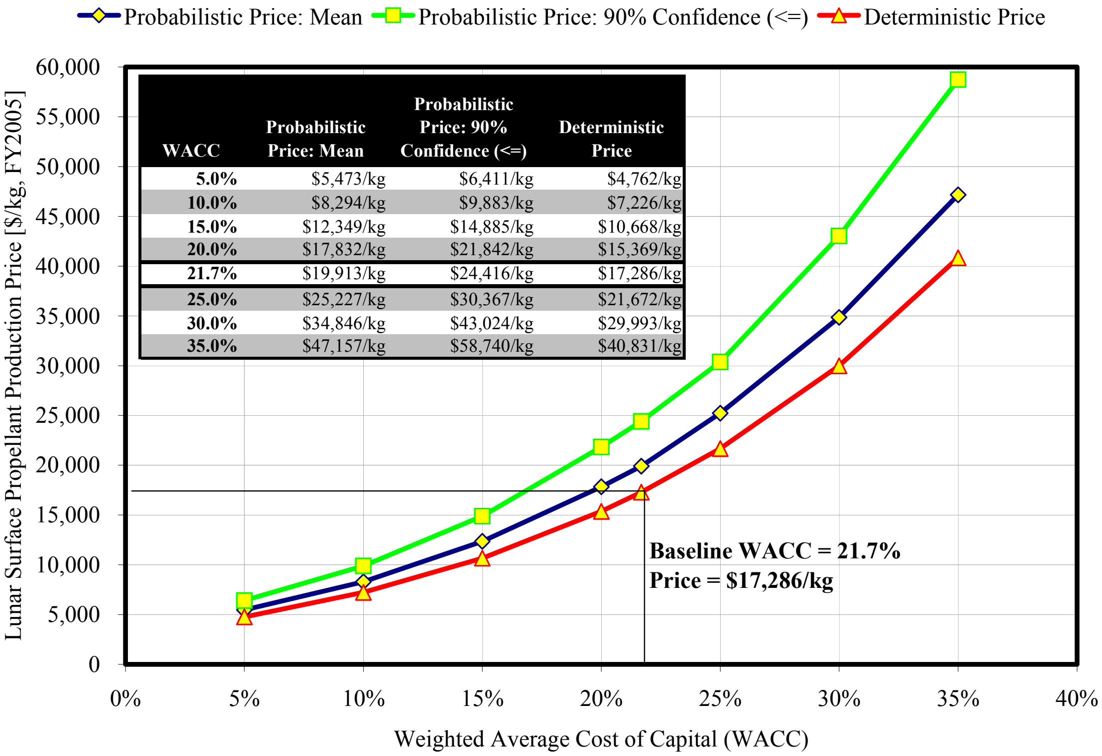


Fig. 6. Frequency Distribution of Propellant Price for Baseline Case (WACC = 21.7%) For 1,000 Monte Carlo Runs



WACC	Probabilistic Price: Mean	Probabilistic Price: 90% Confidence (<=)	Deterministic Price
5.0%	$5,473/kg	$6,411/kg	$4,762/kg
10.0%	$8,294/kg	$9,883/kg	$7,226/kg
15.0%	$12,349/kg	$14,885/kg	$10,668/kg
20.0%	$17,832/kg	$21,842/kg	$15,369/kg
21.7%	$19,913/kg	$24,416/kg	$17,286/kg
25.0%	$25,227/kg	$30,367/kg	$21,672/kg
30.0%	$34,846/kg	$43,024/kg	$29,993/kg
35.0%	$47,157/kg	$58,740/kg	$40,831/kg

Fig. 7. Delivered Propellant Price for Required Return Based Upon Weighted Average Cost of Capital (WACC) For 1,000 Monte Carlo Runs

of those simulations, the price was arrived at that made the Net Present Value (NPV) equal to zero. Figure 6 is the frequency distribution for one WACC value (the baseline case of 21.7%). The 90% certainty value is over $4,000/kg more than the mean with a slightly skewed output distribution.

Figure 7 shows the prices that need to be charged for various WACC values. The data shown is for the deterministic and probabilistic model simulations. Since most of the triangular distributions were skewed towards the maximum, the probabilistic (mean and 90% confidence) values are higher for each WACC value than the deterministic price. For the baseline WACC of 21.7%, the mean value was higher ($19,913/kg) than the deterministic value and 90% of the Monte Carlo output prices were less than $24,416/kg.

Given the cost and demand assumptions here, propellant prices have to be above $15,000 - 20,000/kg to achieve a NPV sufficient to initiate a project for a 21 MT lunar propellant production facility that produces about 58 MT of propellant per year.

6. Conclusions

This analysis has used the baseline ESAS lunar lander payload constraints to design an ISRU propellant production facility. Such a facility as designed here can produce about 58 MT of propellant per year and could achieve a return for a commercial company if prices were above $15,000-20,000/kg for propellant delivered at the lunar surface.

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