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ECONOMIC ANALYSIS OF A LUNAR IN-SITU RESOURCE UTILIZATION (ISRU) PROPELLANT SERVICES MARKET

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ABSTRACT

Lunar In-Situ Resource Utilization (ISRU) capabilities may potentially enable a new market for supply of propellants, oxygen, and other consumables of value both to NASA (in support of exploration efforts) and to commercial customers (complementing new in-space businesses). For this preliminary examination, an economic analysis was performed of a company that produces propellant and oxygen on the Moon. Three business case studies of such a company were explored: (Case 1) sale of propellant and oxygen on the lunar surface, (Case 2) sale of propellant to a government customer in Low Lunar Orbit (LLO), and (Case 3) sale of propellant to a commercial customer in GEO. The imagined propellant company's period of operations coincides with planned NASA lunar missions; from 2022 to 2031. Economic analysis was performed using spreadsheet-based models built upon SEI's Cost and Business Analysis Module (CABAM) tool. Credible estimates of future vehicles necessary to provide services in this market (e.g. a vehicle to transfer propellant from the lunar surface to customers in LLO) were conceptually sized using SEI's StageSizer tool. The PiBlue Software ProbWorks suite of Excel plug-in tools was used to examine uncertainty through probabilistic analysis. Results of this study include quantitative costs and benefits associated with a company offering these services. The price per kilogram that a company must charge for consumables produced through ISRU in order to be an economically viable business concern was determined. Information useful for considering the potential role for ISRU services in NASA's Moon and Mars exploration architecture is also presented in this study.

NOMENCLATURE

CABAM	Cost and Business Analysis Module
CER	Cost Estimating Relationship
DDT&E	Design, Development, Testing, and Evaluation
EDS	Earth Departure Stage
ESAS	Exploration Systems Architecture Study
ETO	Earth-To-Orbit
GEO	Geosynchronous Earth Orbit
ISS	International Space Station
ISRU	In-Situ Resource Utilization
NESC	Nodal Economic Space Commerce
NPV	Net Present Value
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LLO	Low Lunar Orbit
LOX	Liquid Oxygen
LS	Lunar Surface
LTV	Lunar Tanker Vehicle
MT	Metric Tons
OTV	Orbital Transfer Vehicle
SEI	SpaceWorks Engineering, Inc.
TLI	Trans-Lunar Injection

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INTRODUCTION

Overview

One of the most often expressed reasons for human exploration is commercial market enablement and expansion. This economic rationale can take many forms including Earth-To-Orbit (ETO) launch services (crew and cargo), space tourism and hotels, propellant depots, telecommunications, and resource utilization. Human cis-lunar space exploration architectures could potentially utilize such new commercial products and services to lower the cost of exploration as well as enable related capabilities.

Human exploration of the Moon is currently of great interest to the world's space agencies. As these exploration plans mature, commercial opportunities may present themselves. What would future commercial endeavors utilizing the Moon consist of? What products could be produced and what price points would exist that make companies financially viable?

This study examines a specific potential area of such commercialization, lunar In-Situ Resource Utilization (ISRU). ISRU is a term that refers to the use of local raw materials for some constructive purpose (construction, propellant production, providing breathable atmosphere, etc.)[1]. An economic analysis was performed of a commercially operated lunar ISRU facility that produces rocket propellants and oxygen using water extracted from the lunar soil. This study assumed the commercial company develops the ISRU plant, pays for NASA's future space transportation assets to deliver such a payload to the lunar surface, and privately develops assets for orbital delivery (if delivering propellant beyond the lunar surface). The price at which the company must sell its products in order to achieve a particular return on investment is determined for a variety of scenarios taking into account design performance, development and acquisition costs, and required financing costs.

PROCESS

Case Studies

Three major case studies are investigated, differentiated by the location of propellant delivery. For each case study it is assumed the propellant is produced on the lunar surface and then delivered to a location (lunar surface, Low Lunar Orbit, Earth orbit). Figure 1 illustrates these possible paths of propellant delivery and potential synergy with NASA's human lunar exploration architecture. Delivery of propellant to low lunar orbit or GEO is accomplished by new vehicles referred to as a Lunar Tanker Vehicle (LTV) and Orbital Transfer Vehicle OTV) respectively.

Case study 1 focuses on Lunar Surface (LS) propellant delivery. Variants from this case study include the following:

1A) Sale of propellant (LOX/LH2) on the lunar surface
1B) Sale of propellant and oxygen on the lunar surface

Case study 2 focuses on Low Lunar Orbit (LLO) propellant delivery. Variants from this case study include the following:

2A) Sale of propellant to a government customer in LLO
2B) Sale of propellant to a government customer in LLO and sale of oxygen on the lunar surface
2C) Sale of propellant to a government customer in LLO, sale of oxygen on the lunar surface, and sale of propellant on the Lunar surface

For case studies 1 and 2, both the minimum cost to the company and price charged for propellant and oxygen products were determined. The minimum cost per kg of product (as opposed to the price) is the result when financing costs and required return on investment are zero. In this situation, only the costs of development, acquisition, and inflation are incurred by the commercial company.

Case study 3 consists of Geosynchronous Earth Orbit (GEO) propellant delivery. Variants from this case study include the following:

3A) Sale of propellant to a commercial customer in GEO
3B) Sale of propellant to a commercial customer in GEO and sale of oxygen on the lunar surface
3C) Sale of propellant to a commercial customer in GEO, sale of oxygen on the lunar surface, and sale of propellant on the lunar surface

General Study Assumptions

The Exploration Systems Architecture Study (ESAS) of November 2005 was used as the resource for all NASA Lunar exploration activities in order to have a static, well documented, and readily available reference human lunar architecture[2]. Data and lunar surface payload delivery capabilities were utilized from the publicly available ESAS study in order to determine the possible size of the lunar propellant production factory. It is acknowledged that the current NASA human lunar architecture design has changed from that of the referenced ESAS results. The impact of these changes will need to be considered further in future works

The ISRU plant system design, specifications, and capabilities were provided by CSP, Japan Inc. and Shimizu Corporation[3]. They were asked to provide a notional ISRU plant design detailing possible propellant production performance and mass.

The commercial company is assumed to be responsible for 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 United States government. Initial development starts in 2014, with Initial Operating Capability (IOC) in 2022. Figure 2 illustrates a notional program development roadmap, with assumptions about NASA exploration timelines (circa mid-2006). It was assumed that NASA would attempt its human lunar landing in the latter part of the next decade (2017-2018). A commercial ISRU plant operator would most likely wait until the government has already embarked on its lunar surface plans. Thus, development and assembly of the plant is assumed to occur in the years when the government is attempting its first landing. The initial propellant facility is delivered first in the 2021/2022 timeframe, with a LTV tanker following one year later. Only one propellant plant is assumed to be operational, and the commercial company has revenue-generating operations for 10 years.

Modeling Process

Three main tools were used to perform this assessment. An economics tool was employed for business case analysis, an engineering design tool was used to size the lunar tanker vehicle (LTV) and orbital transfer vehicle (OTV), and a statistical engineering tool was used to perform probabilistic analysis.

The economics tool is the Cost and Business Analysis Module (CABAM), a SpaceWorks Engineering, Inc. (SEI) internally developed Microsoft Excel model[4]. CABAM determines the cash flows and other financial measures of success for a hypothetical company given programmatic, cost, and market demand inputs. Program definition inputs include operated assets, production rates, and program duration. Revenues are calculated using this information along with nonrecurring, recurring, and financing cost inputs.

The engineering design tool is StageSizer, also an SEI internally developed Microsoft Excel tool. StageSizer is a conceptual level weights and sizing tool intended for the design and analysis of in-space stages including launch vehicle upperstages, cis-lunar transfer stages, lunar ascent and descent stages, etc. The tool is based on a combination of historical mass estimating relationships, physics-based equations, and empirical data. The general inputs into the model are mission and subsystem-level parameters that are used to size a particular stage. The output of the StageSizer tool is a multi-level weight breakdown statement that details the contributions of subsystems, margin, propellants, payload, etc., to the total gross weight of the stage.

The statistical engineering tool is ProbWorks, a Microsoft Excel plug-in developed by SEI's partner corporation, Pi Blue Software[5]. ProbWorks is a suite of uncertainty and sensitivity analysis tools including Advanced Monte Carlo, Discrete Probability Optimal Matching Distribution, Pareto Sensitivity, and Response Surface Equation generator. The probabilistic capabilities in the ProbWorks: Excel tools are useful when trying to minimize the computational expense for Monte Carlo simulations, ranking the influence of input variables, and design space approximation through Response Surface Methodologies.

SUPPLY: ISRU PROPELLANT COMPANY

The commercial company envisioned to provide propellant production and delivery for this study is assumed to own several assets to accomplish this task. However, the company is assumed to leverage government and existing commercial developments in the construction and delivery of company assets.

The commercial company will purchase delivery services from Earth to Low Lunar Obit from the U.S. Government (NASA).

NASA's Ares V Cargo Launch Vehicle (CaLV) will provide Earth-To-Orbit (ETO) launch of all commercial company elements. The Earth Departure Stage (EDS) of the Ares V will provide the Trans-Lunar Injection (TLI) burn for all elements. The ISRU plant was sized to fit on a NASA lunar cargo lander as described in the ESAS report, and is transported to the Lunar Surface from LLO by this lander[2]. The cargo lander has the capability to deliver 21 MT to the lunar surface as described in the ESAS report:

> The ESAS team recommends the deployment of a lunar outpost using the "incremental build" approach. Along with the crew, the [crew] lander can deliver 500 kg of payload to the surface, and up to 2,200 kg of additional payload if the maximum landed capacity is utilized. This capability opens the possibility of deploying an outpost incrementally by accumulating components delivered by sortie missions to a common location. This approach is more demanding than one that delivers larger cargo elements. In particular, the habitat, power system, pressurized rovers, and some resource utilization equipment will be challenging to divide and deploy in component pieces. The alternative to this incremental approach is to develop a dedicated cargo lander that can deliver large payloads of up to 21 MT[2].

The reusable Lunar Tanker Vehicle (LTV) performs transfer of propellant from the Lunar Surface to LLO and back. To minimize development cost, The LTV is derived from the NASA crew Lunar Surface Access Module (LSAM) descent stage (shown in Fig. 3). The Reusable Orbital Tanker Vehicle (OTV) performs transfer of propellant from LLO to GEO. The OTV is assumed to be derived from a Lockheed Martin Atlas V Centaur III stage. A Space Exploration Technologies (SpaceX) Falcon V or similar vehicle provides ETO launch of the OTV.

ISRU Facility

The 21 MT payload capability of the NASA ESAS cargo lander constrains the mass of the ISRU facility. It was assumed that there is accessible water ice in the lunar regolith at a concentration of one percent by weight. Multiple assumptions have been made with regard to technological capability of ISRU facility components. ISRU technologies deemed available by the time of this enterprise include: bucket wheel excavators, water separation by heating method, nuclear power plant for plant heat source, and assembly of lunar facilities by semi-autonomous system. Fig. 4 shows the notional elements required for such a plant (not to scale). Table 1 gives a top-level mass estimate for the ISRU plant, totaling less than the 21 MT payload constraint. Given the input material is water, the output products of the facility are oxygen and hydrogen. Their production rate is on average 20.0 kg/hour (each output). If such a plant were operating continuously over a lunar 12 day period (daylight operation) then that would equate to 5.8 MT/month or 69.1 MT/year of processed water. With a mixture ratio by mass of 8:1 oxygen to hydrogen in water, 49.4 MT/year of propellant (LOX/LH2 at a mixture ratio of 5.5:1) and 19.7 MT/year of additional oxygen can be produced. Thus the amount of output material is more than that potentially required for rocket propulsion systems, with the excess product being oxygen. The sizing and capabilities of the plant were developed by CSP, Japan, Inc. and the Space & Robot System Group of the Institute of Technology of Shimizu Corporation, both located in Tokyo, Japan[3]. Shimizu Corporation and CSP, Japan, Inc. both have a history of advanced space concept design and analysis ranging from studies on space hotels to developing simulated lunar regolith.

Lunar Tanker Vehicle (LTV)

As shown in Fig. 5, a reusable Lunar Tanker Vehicle (LTV) performs transfer of propellant from the Lunar Surface to LLO and back. It is assumed 1,860 m/s of Delta-V is required for a one-way transfer. The LOX/LH2 propellant system has an Oxidizer/Fuel (O/F) mixture ratio of 5.5:1. The LTV is derived from a NASA ESAS LSAM with the LSAM ascent stage replaced by tanks to store the propellant for sale to customers in LLO. The LTV is capable of delivering 22,000 kg propellant from the Lunar Surface to LLO and returning. The LTV burns 25,100 kg propellant while performing the delivery mission (equivalent to the propellant capacity of the baseline ESAS LSAM descent stage upon which the LTV is based). Sizing the LTV to these capacities yields an amount of propellant delivered to LLO by the LTV sufficient to fuel two NASA LSAM descent stages prior to descent to the surface.

Orbital Transfer Vehicle (OTV)

As shown in Fig. 6, a reusable Orbital Tanker Vehicle (OTV) is used to perform transfer of propellants from LLO to GEO and back. It is assumed to provide 2,050 m/s of Delta-V required for a one-way transfer. The LOX/LH2 propellant has an O/F mixture ratio of 5.5:1. The OTV is assumed to be derived from similar stages such as the Lockheed Martin Atlas V Centaur III stage [REF]. The resulting OTV is capable of delivering 450 kg of LOX/LH2 propellant from LLO to GEO (for sale to the GEO customer) and returning using 11,800 kg of propellant for the transfers. Compared with a standard Single Engine Centaur (SEC) upper stage as used on the Atlas V launch vehicle, this Centaur-derived transfer stage has the same overall diameter (10 ft), but is considerably shorter due to the removal of the barrel sections of the main propellant tanks. Only the tank domes are retained in the OTV configuration. The transfer stage has a 20% larger energy storage capacity than a standard Centaur. In addition, the transfer stage incorporates photovoltaic solar panels to enable recharging the main batteries. Compared with a standard SEC upperstage, the transfer stage has an enhanced avionics package. In addition to the standard SEC avionics suite, the transfer stage adds a parabolic antenna, redundant command and control systems, redundant star tracker systems, and redundant Ku-band transponders. The transfer stage main propellant tanks and main propulsion system are modified to enable autogenous repressurization. The standard SEC helium pressurization system is removed from the stage. A passive docking system has been added to the transfer stage to facilitate docking with the customer spacecraft or satellite in GEO. For the purpose of calculating cryogenic propellant boil-off, it was assumed that the transfer stage may have to wait in GEO for up to 10 days prior to initiating a burn to return to LLO. The rates of boil-off were assumed to be 0.75% per day for the LH2, and 0.25% per day for the LOX.

Cost to Supply

Development, acquisition, transportation, and operations costs were calculated for each of the various case studies. Case study 1 did not require the use of the LTV or OTV, case study 2 required an LTV, and case study 3 required both an LTV and OTV. Analogies, Cost Estimating Relationships (CERs), and direct research were the source of the various cost estimates presented here[2,6,7]. Table 2 shows the cost assumptions for all elements. Development costs are nominally above \$1B for all cases, with acquisition costs between \$300M to \$1B. Transportation costs are a very large component of overall cost, almost always as much as development cost. A notional mission operations cost is used for all cases. Both deterministic and probabilistic runs of the economic models were performed. One of the main components of the uncertainty was assumed to be the cost elements. Thus distributions were paced upon all the major cost categories. Table 2 has the various distributions (same percentages for all case studies). There is a larger distribution on development and acquisition cost versus transportation cost due to the higher level of confidence in the design and analysis of the transportation elements versus the ISRU elements.

DEMAND: GOVERNMENT LLO AND COMMERCIAL GEO CUSTOMERS

Case Studies

Various demand scenarios were considered involving delivery of output propellant to various locations (lunar surface, low lunar orbit, and GEO), and to either government or commercial customers. Table 3 lists the various case studies that were performed. For each case study, the final delivery location of the product, as well as quantity demanded, is given. The highest level of demand originates from the lunar surface.

Demand for propellant in case 1 (delivery to the lunar surface) is equal to the production capacity of the ISRU plant, which is 49.4 MT per year. This demand could originate from the U.S. government (NASA) or other international governments for the purpose of fueling lunar landers. Additional demand could originate from commercial companies wishing to purchase propellant on the lunar surface in support of lunar tourism, mining, or other entrepreneurial activities. The price for propellant on the lunar surface provides a useful comparison point to the price for propellant in LLO.

The primary demand for propellant in case 2 (delivery to low lunar orbit) is equal to the demand the amount required by two reference NASA ESAS lunar landers to descend from LLO to the lunar surface, which is estimated to be 21 MT per year. In the years 2022 through 2031, it is anticipated that

NASA will conduct two or more expeditions to the Moon per year. It is assumed that each descent requires a Delta-V of 1860 m/s, which results in 10,500 kg of propellant. In case 2C, there is a secondary demand for propellant on the lunar surface equivalent to the remaining supply produced by the ISRU facility after satisfying the 21 MT per year LLO demand.

Demand for propellant in case 3 is based upon assumptions about future Geostationary (GEO) spacecraft requirements. Propellant is one limiting factors of geostationary satellite lifetime. United Nations policies require that at the end of their operational life, geostationary spacecraft must be placed in a disposal orbit with a perigee at least 300 km above the geostationary orbit. Geostationary satellites must use a portion of their station-keeping propellant to transfer to this disposal orbit. This portion of station-keeping propellant can represent as much as six months of station-keeping propellant, thereby shortening the actual life of the satellite by six months of its design life. A market may exist to provide services to transfer satellites from GEO to a disposal orbit. Such a tugging mission would extend the life of an average GEO communications satellite by almost six months. If the fee for a tugging mission is less than the expected revenue for this period of operation, a demand for these services can be expected. Market statistics show that on average, about 15 satellites per year will need boosting to a disposal orbit[8]. A satellite tug could operate from a near-GEO orbit and transfer to and from GEO where necessary total Delta-V from GEO to a disposal orbit and back is roughly 14 m/s. With these assumptions, the total annual propellant requirement is small, on the order of 450 kg per year to transfer 15 satellites. Refueling this satellite tug from the Earth would require launching fuel from the Earth's surface to GEO, a very costly effort. Refueling this satellite tug from a different platform, however, could make it economically feasible. This satellite tug could therefore potentially be a customer of a Moon-based propellant provider.

ECONOMIC ANALYSIS

Methodology Overview

The economic analysis methodology was based upon determining the price required to achieve a desired financial return. The analysis varied the price per kg that the propellant-production company must charge for its products in order to achieve a Net Present Value (NPV) of zero. NPV is an indicator of financial success, and is calculated as the sum of all future cash flows discounted to their present values. Cash flows are discounted by Weighted Average Cost of Capital (WACC), a measure of the cost of capital which takes into account the debt and equity financing structure of the company. An NPV of zero indicates that the company has broken even on its investment after financing charges to investors have been met. Sweeps of WACC were performed to investigate the sensitivity of the results to the cost of financing. WACC is the average of the costs of debt and equity sources of financing, each of which is weighted according to its respective use in the given situation. A firm's WACC is the overall required return on the firm as a whole and, as such, it is often used internally by company directors to determine the economic feasibility of expansionary opportunities and mergers[9]. The baseline WACC for this study is 21.7 % based on a debt to equity ratio of three, equity beta of comparable industries (Aerospace, Air Transport, E-Commerce), tax rate of 30%, average nominal interest rate of 7.5%, inflation of 2.1%, and risk-free rate of 4%. Probabilistic simulation of each case involved 1000 Monte Carlo runs with triangular distributions on the cost variables as previously defined.

Results and Conclusions

Table 4 shows the main deterministic results from this analysis for all cases. Performing the economic analysis for a commercial company providing propellant (LOX/LH2) derived from lunar ice yields the following deterministic results (at 22.7% Weighted Average Cost of Capital):

1A) Sale to a government or commercial customer on the Lunar Surface: $26,845/kg
2A) Delivery to LLO to fuel two government customer LSAM descent stages: $133,947/kg
3A) Delivery to GEO to fuel a commercial customer satellite tug: $7,053,265/kg

Figures 7 and 8 show the cash flows for the hypothetical lunar ISRU company, examining both cost, value, and net income. After several years of negative cash flow due to development (and associated debt/equity financing), positive net income is achieved after operation in 2022. The sale of excess oxygen extracted from water during propellant production (Cases 1B, 2B, 2C, 3B, 3C) results in a modest reduction of propellant price.

Table 4 shows both the minimum cost and price for producing propellant and secondary oxygen. The minimum cost values include only inflation and do not include the cost of financing or a financial return on investment to the company. For the assumptions of this analysis, the price is approximately four times the minimum cost of production. The price includes financial return, debt interest financing, and all costs (development, acquisition, transportation, and operations).

Figure 9 shows a comparison of Cases 1 and 2. The price per kilogram for propellant delivered to LLO is roughly 5 times the price of propellant purchased on the lunar surface. This difference in price is a direct result of costs for delivery of propellants to LLO. Development costs for the case of delivery to LLO (Case 2), including development of a Lunar Transfer Vehicle derived from an ESAS LSAM descent stage, are more than twice the development costs for the case of propellant on the lunar surface. Transportation costs from the Earth to the Moon are double that of the lunar surface case due to the need to transport the Lunar Transfer Vehicle as well as the ISRU production plant. The Lunar Transfer Vehicle must use 25 MT of propellant to deliver 21 MT of propellant for sale in LLO.

Figure 10 illustrates the sensitivity of price to development and Earth-to-Moon transportation costs for Case 2A, where propellant is delivered to low lunar orbit. The price for delivery of propellant to LLO is fairly insensitive to lunar transportation costs, but sensitive to tanker vehicle development costs. If transport of elements to the moon were free, output prices could be reduced by approximately 19%. If the LTV tanker development was free, prices could be reduced by approximately 40%.

The price per kilogram for delivery of propellant from the lunar surface to a GEO satellite tug customer does not provide an attractive alternative as compared to launch from Earth. The price per kg to send propellant from the lunar surface to GEO is extremely prohibitive (over 7 million dollars a kg). The authors acknowledge that alternative architectures and delivery technologies may provide a lower price solution, but the results of this study indicate a significant challenge in competing with propellants delivered from Earth.

Probabilistic simulation in all cases resulted in higher mean price per kilogram than deterministic analysis due to distributions on cost variables skewed toward higher cost. Figures 11 and 12 show the probability distribution of price for Case 1A, Figures 13 and 14 show the probability distribution of price for Case 2A. The mean price for Case 1A is \$30,470/kg, and for Case 2A the mean propellant price is \$152,906/kg. These probabilistic prices are approximately 14% more than the deterministic prices. Figures 12 and 14 show the sensitivity of the price (both deterministic and probabilistic) to WACC. For case 1A, even with a very low WACC of 10%, indicative of a lower risk investment, the propellant price is around \$15,000/kg. For Case 2A, with a WACC of 10%, the propellant price is around \$60-75,000/kg.

FUTURE WORK

There is additional follow-on analysis work that can contribute to a better understanding of the true potential of ISRU, and could compare it with other propellant delivery options. Multiple assumptions were made for this analysis that could be reexamined. These include assumptions about schedule, development time, reuse of the LTV and OTV (currently unlimited over the 10 year project lifetime, limited lifetimes would only increase prices), propellant transport and transfer from lunar surface factory to LTV, cost estimates, WACC assumptions, etc. There is also additional work that could be performed to couple an ISRU performance model to the above economic analysis tools. These performance models could develop parametric relationships between ISRU plant mass and production capability. There is an overall comparison that needs to be performed of lunar ISRU versus propellant delivery from Earth. What is the line-in-the-sand that ISRU plants have to meet in order to be cost (and price) competitive with simple propellant delivery from Earth (potentially using LEO or GEO propellant depots)? There are other areas of NASA's human lunar exploration architecture where ISRU may provide benefit. These include oxygen for surface habitats, water for human consumption, and fuel cell reactants. Future studies could also examine the potential for smaller ISRU plants that could potentially be transported to the lunar surface as cargo aboard a sortie lander rather than a dedicated cargo lander (6 MT or less). Another analysis could study the feasibility, price per kilogram, and business case for a company producing propellants via lunar

ISRU to support refueling a spacecraft bound for Mars. Still another analysis could examine the business case for selling propellant in LLO to a space tourism company providing circum-lunar adventures.

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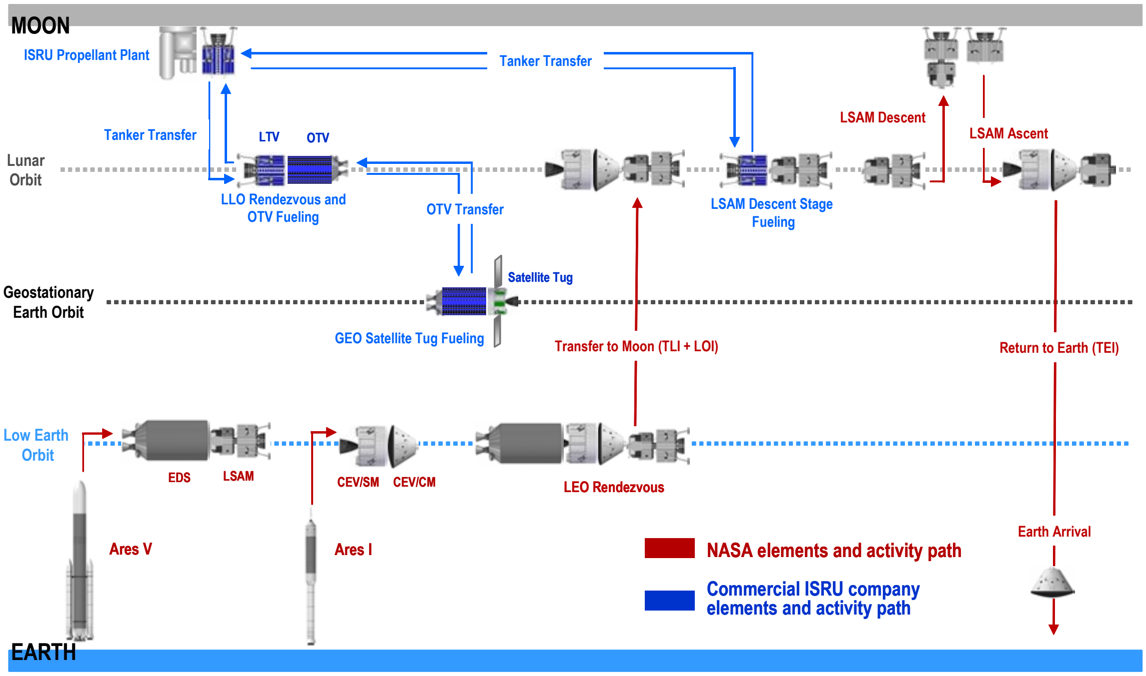


Note: Notional representation of lunar exploration architecture. Architecture elements may not be to scale.

Figure 1. Commercial ISRU Company and NASA Exploration Architecture

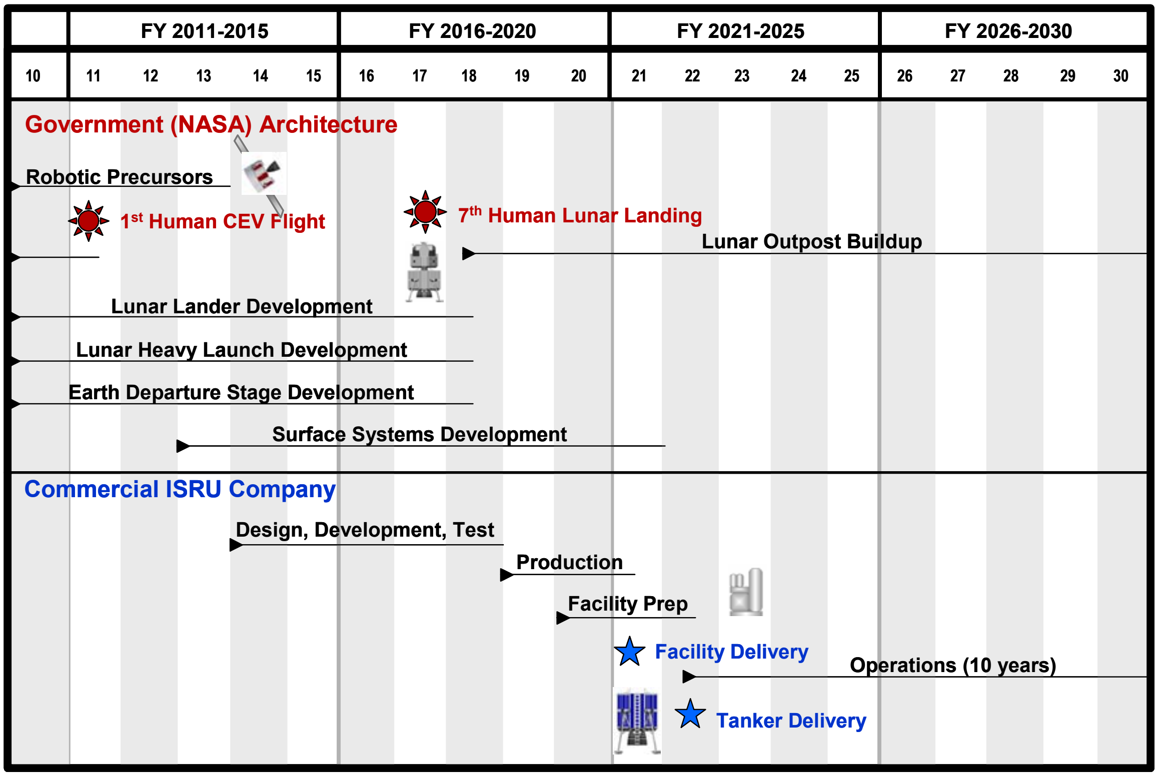


Figure 2. Commercial ISRU Plan Program Development Roadmap

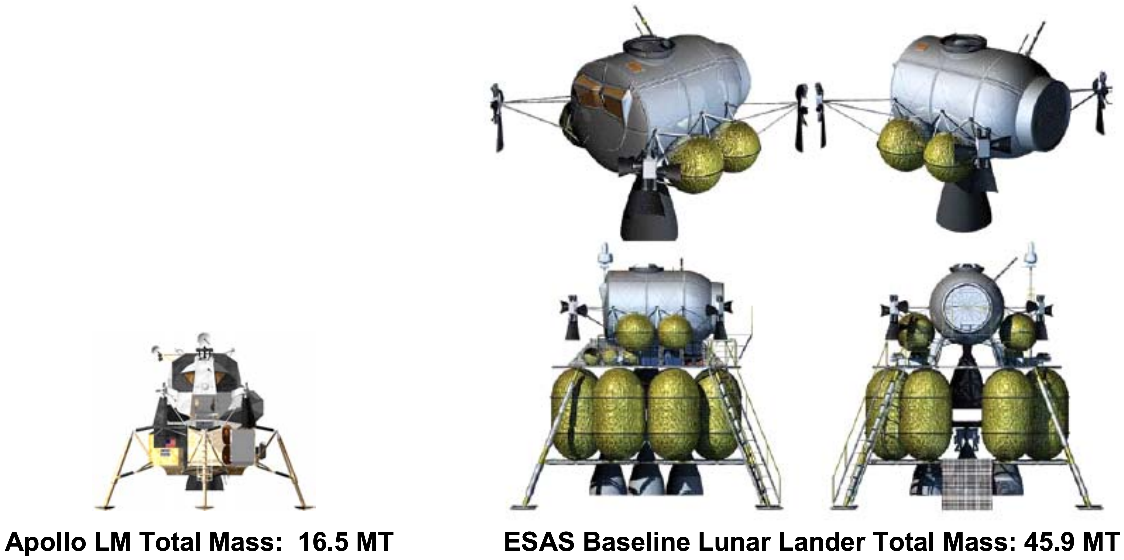
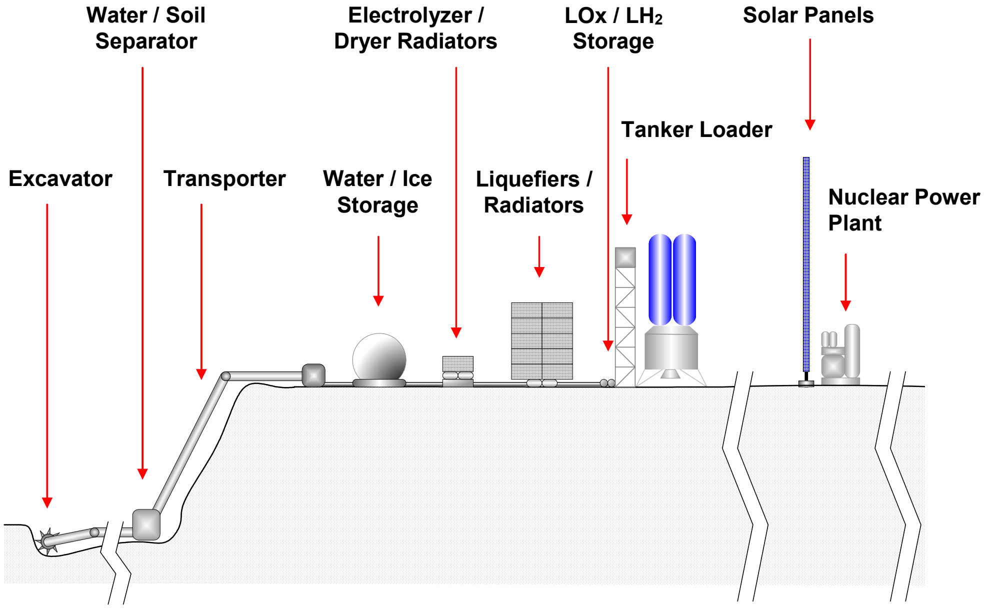


Figure 3. ESAS Lunar Lander Development Leveraged by Commercial ISRU Company



Credit: Shimizu Corporation
*Elements shown are not to scale, but represent those that are included in the plant landed by the lunar cargo lander

Figure 4. Notional Elements of a Lunar ISRU Plant and Storage Depot

Table 1. Lunar ISRU Plant Size for 21 MT Lunar Lander

Components	Size (stowed) [m]	Mass [MT]
Excavator	2x0.1x0.1	1.00
Separator	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
Power and Transport Sub-Total		**15.03**
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	-----	-----
Soil and Water Management Sub-Total		**5.91**
Lunar ISRU Plant Systems Total		**20.94**

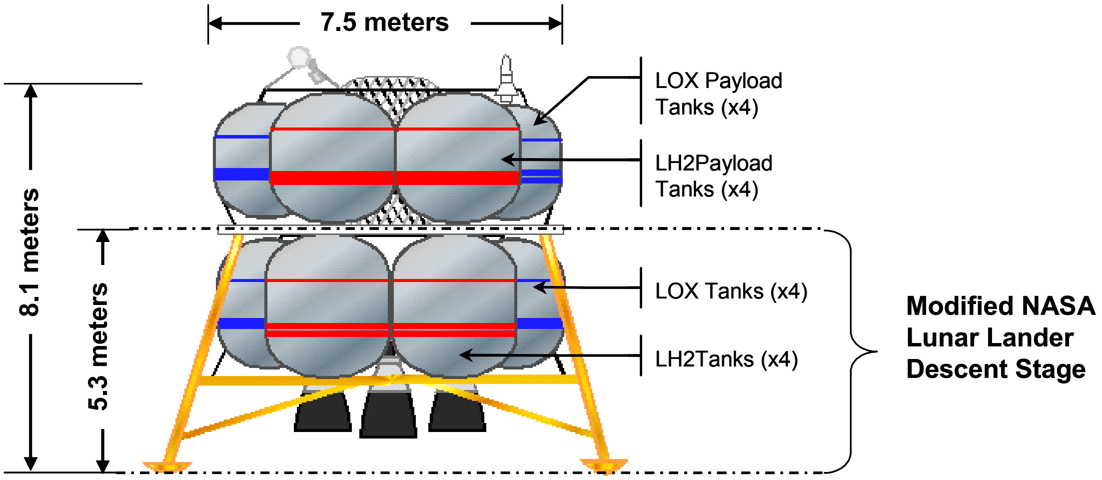


Figure 5. Lunar Tanker Vehicle (LTV) Operated by Commercial Company

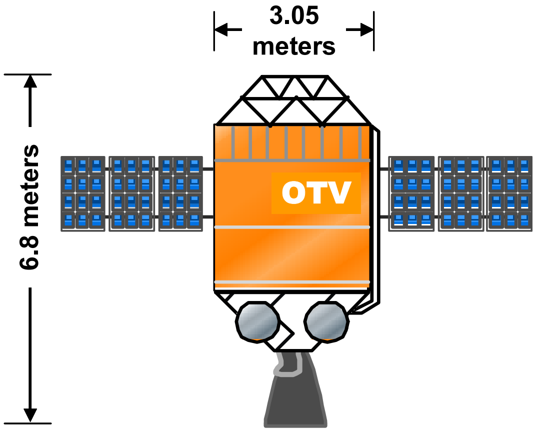


Figure 6. Orbital Transfer Vehicle (OTV) Operated by Commercial Company

Table 2. Monte Carlo Simulation: Triangular Distributions for Various Cost Uncertainty Parameters

	Deterministic/ Most Likely			Minimum	Maximum
Parameter	**Case 1: Lunar Surface**	**Case 2: LLO**	**Case 3: GEO**	**All Cases**	**All Cases**
DDT&E Cost [$M, FY2006]	**$957 M**	**$ 2,157 M**	**$ 2,557 M**	**-25%**	**+75%**
Nuclear Power Plant*	$200 M	$200 M	$200 M		
Excavation/Processing/Storage Facility Cost*	$595 M	$595 M	$595 M		
Mass of Excavation/Processing/Storage Facility*	$162 M	$162 M	$162 M		
Lunar Tanker Vehicle**	-	$1,200 M	$1,200 M		
Orbital Tanker Vehicle**	-	-	$400 M		
Acquisition Cost [$M, FY2006]	**$319 M**	**$ 1,019 M**	**$ 1,044 M**	**-25%**	**+75%**
Nuclear Power Plant*	$67 M	$67 M	$67 M		
Excavation/Processing/Storage Facility Cost*	$198 M	$198 M	$198 M		
Mass of Excavation/Processing/Storage Facility*	$54 M	$54 M	$54 M		
Lunar Tanker Vehicle**	-	$700 M	$700 M		
Orbital Tanker Vehicle**	-	-	$25 M		
Transportation Cost to Lunar Surface [$M, FY2006]	**$1,445 M**	**$2,220 M**	**$2,240 M**	**-10%**	**+25%**
Cargo Launch Vehicle (CaLV)***	$560 M	$1,120 M	$1,120 M		
Earth Departure Stage (EDS)****	$215 M	$430 M	$430 M		
Lunar Surface Access Module (LSAM)****	$670 M	$670 M	$670 M		
Falcon V or similar launch of OTV	-	-	$20 M		
Mission Operations Cost [$M/year, FY2006]	**$35 M**	**$35 M**	**$35 M**	**-10%**	**+50%**

Notes:
United States Dollars FY2006 unless otherwise noted
* - Source: Shimizu Corporation (75% development cost, 25% acquisition cost)
** - Source: SEI internal cost estimates derived from previous work; development cost to the commercial company is for modification of existing stages, not for complete development of a new vehicle
*** - 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[7].
**** - Source: Exploration Systems Architecture Study (ESAS) Draft Report, Section 12[6].

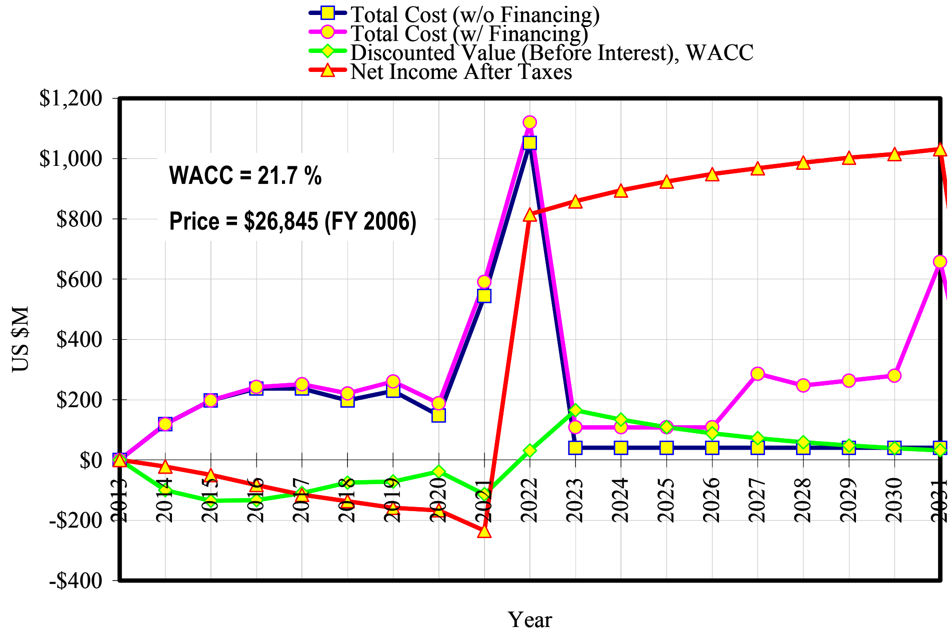
Table 3. ISRU Propellant Market Case Studies

Case #	Product(s)	Demand	Case Description
1A*	Propellant on Lunar Surface	49.4 MT/yr	The commercial provider of ISRU propellant sells its maximum production capacity each year to government and/or commercial buyers on the Lunar surface.
1B	Propellant on Lunar Surface Oxygen on Lunar Surface	49.4 MT/yr 19.7 MT/yr	Case 1A plus excess oxygen produced is sold to government and/or commercial buyers on the Lunar surface.
2A*	Propellant to LLO	21.0 MT/yr	The commercial provider of ISRU propellant delivers and sells only the amount of propellant demanded by a government customer in LLO.
2B	Propellant to LLO Oxygen on Lunar Surface	21.0 MT/yr 22.5 MT/yr	Case 2A plus excess oxygen produced is sold to government and/or commercial buyers on the Lunar surface.
2C	Propellant to LLO Oxygen on Lunar Surface Propellant on Lunar Surface	21.0 MT/yr 19.7 MT/yr 3.3 MT/yr	Case 2B plus excess propellant not demanded by the government is sold to a government and/or commercial customer on the Lunar surface.
3A	Propellant to GEO	0.45 MT/yr	The commercial provider of ISRU propellant delivers and sells only the amount of propellant demanded by a commercial satellite tug operator in GEO.
3B	Propellant to GEO Oxygen on Lunar Surface	0.45 MT/yr 51.2 MT/yr	Case 3A plus excess oxygen produced is sold to government and/or commercial buyers on the Lunar surface.
3C	Propellant to GEO Oxygen on Lunar Surface Propellant on Lunar Surface	0.45 MT/yr 19.7 MT/yr 37.2 MT/yr	Case 3B plus excess propellant not demanded by the GEO satellite tug operator is sold to a government and/or commercial customer on the Lunar surface.

*Probabilistic results presented for Case 1A and Case 2A

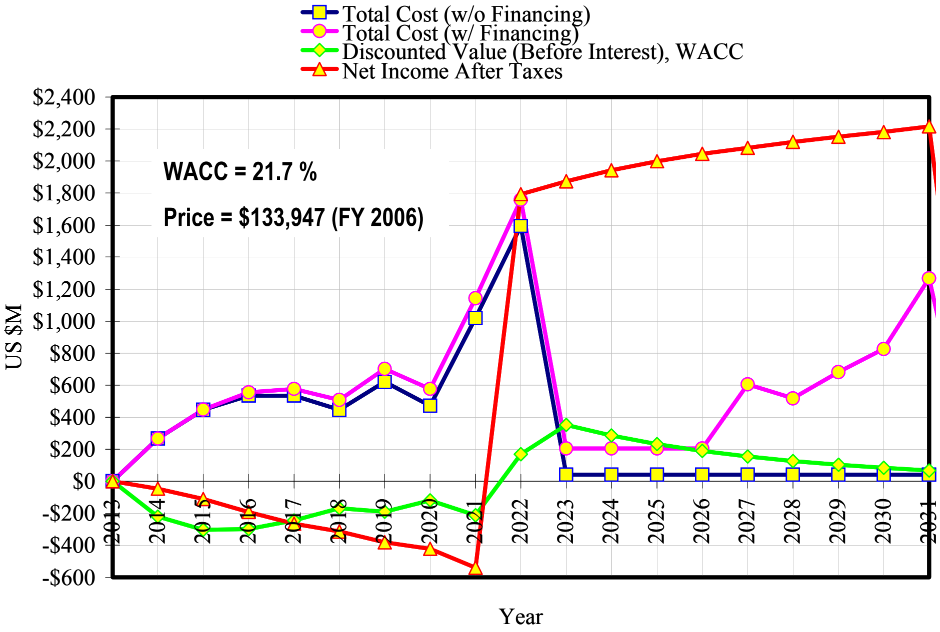
Table 4. Deterministic Price for ISRU Products, All Cases (WACC = 21.7%)

Case	Point of Sale of Product(s)	Price for Propellant for WACC = 21.7% {For Only Cost with Inflation}	Price for Excess Oxygen on Lunar Surface for WACC = 21.7% {For Only Cost with Inflation}	Price for Excess Propellant on Lunar Surface for WACC = 21.7% {For Only Cost With Inflation}
1A	Propellant on Lunar Surface	$26,845 per kg {$7,327 per kg}	-	-
1B	Propellant on Lunar Surface Oxygen on Lunar Surface	$25,571 per kg {$6,979 per kg}	$3,196 per kg {$872 per kg}	-
2A	Propellant to LLO	$133,947 per kg	-	-
2B	Propellant to LLO Oxygen on Lunar Surface	$126,243 per kg {$31,056 per kg}	$7,188 per kg {$1,768 per kg}	-
2C	Propellant to LLO Oxygen on Lunar Surface Propellant on Lunar Surface	$119,019 per kg {$29,279 per kg}	$6,777 per kg {$1,667 per kg}	$54,216 per kg {$13,337 per kg}
3A	Propellant to GEO	$7,053,265 per kg	-	-
3B	Propellant to GEO Oxygen on Lunar Surface	$4,632,347 per kg	$21,294 per kg	-
3C	Propellant to GEO Oxygen on Lunar Surface Propellant on Lunar Surface	$1,663,560 per kg	$7,647 per kg	$61,175 per kg



The deterministic price for propellant on the Lunar Surface is $26,845 per kilogram in order for the company to break even in terms of NPV with a required rate of return (WACC) of 21.7%

Figure 7. Cash Flows for Case 1A (Propellant on Lunar Surface)



The deterministic price for propellant in LLO to a government customer is $133,947 per kilogram in order for the company to break even in terms of NPV with a required rate of return (WACC) of 21.7%

Figure 8. Cash Flows for Case 2A (Propellant in LLO, Government Customer)

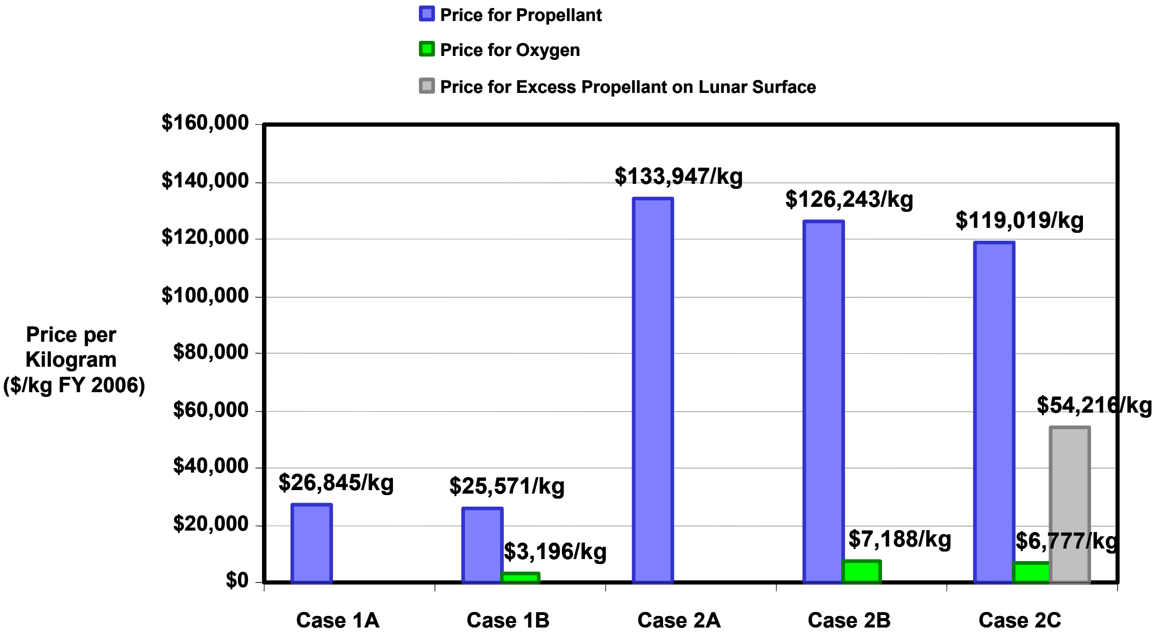


Figure 9. Deterministic Price / kg for Case 1 (Lunar Surface) and Case 2 (LLO, Gov't Customer)

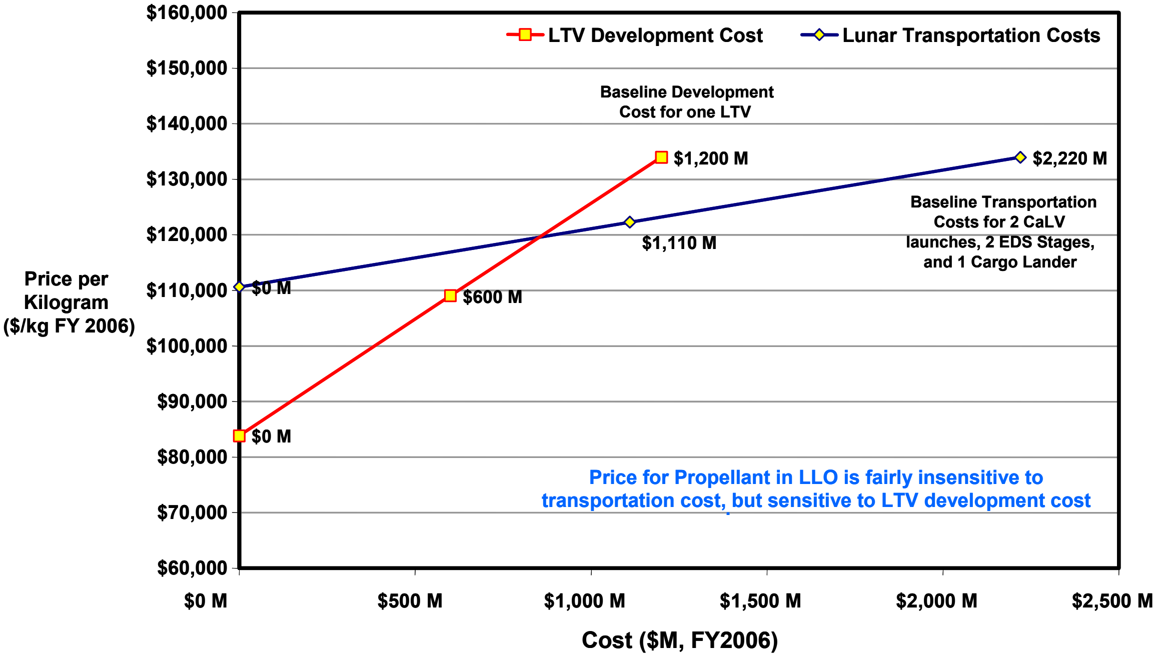
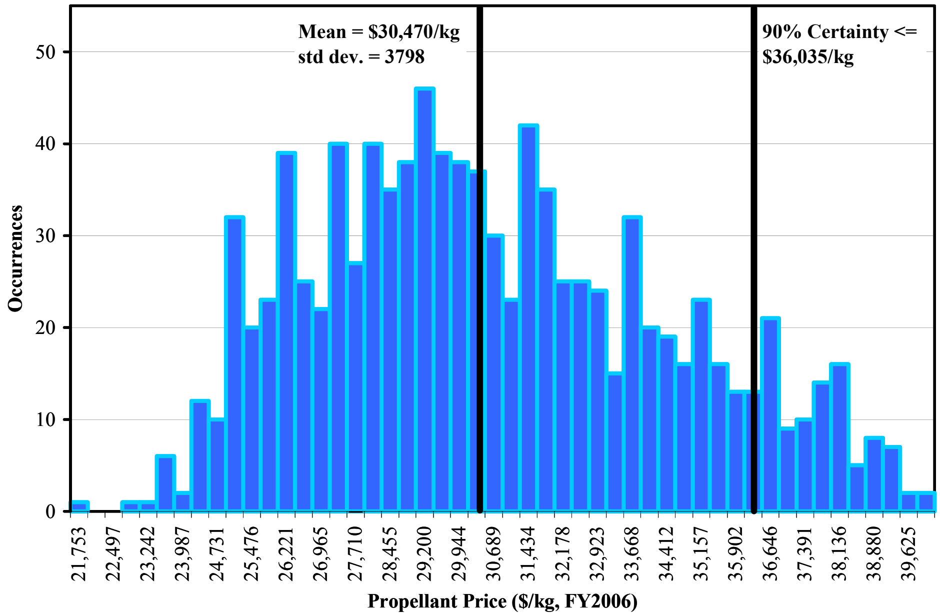
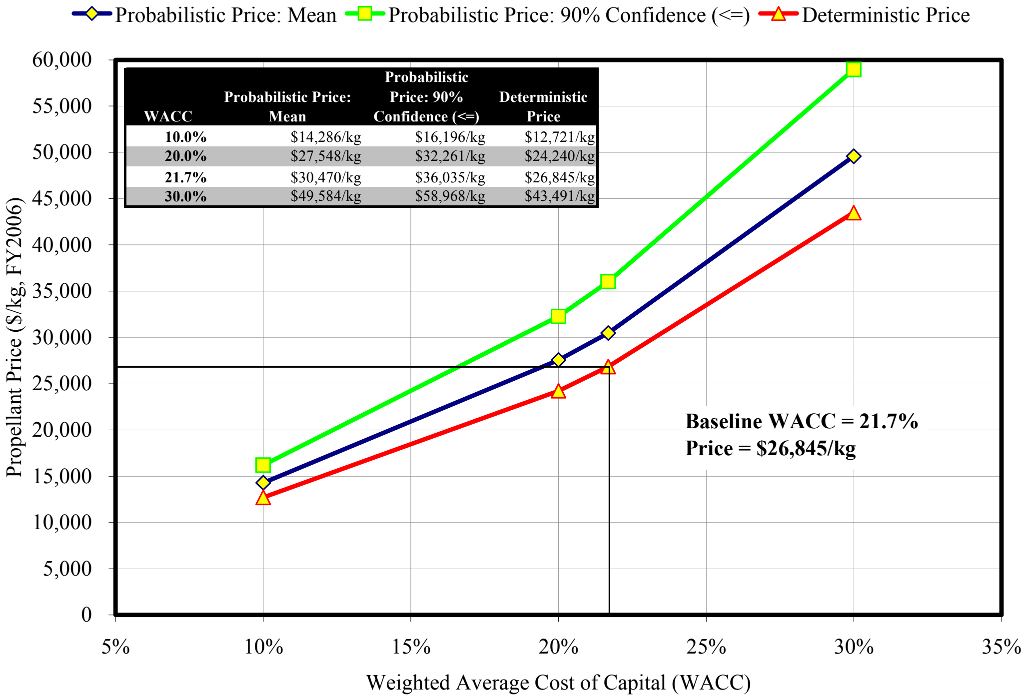


Figure 10. Case 2A (Propellant in LLO, Government Customer): Propellant Price Sensitivity to Costs



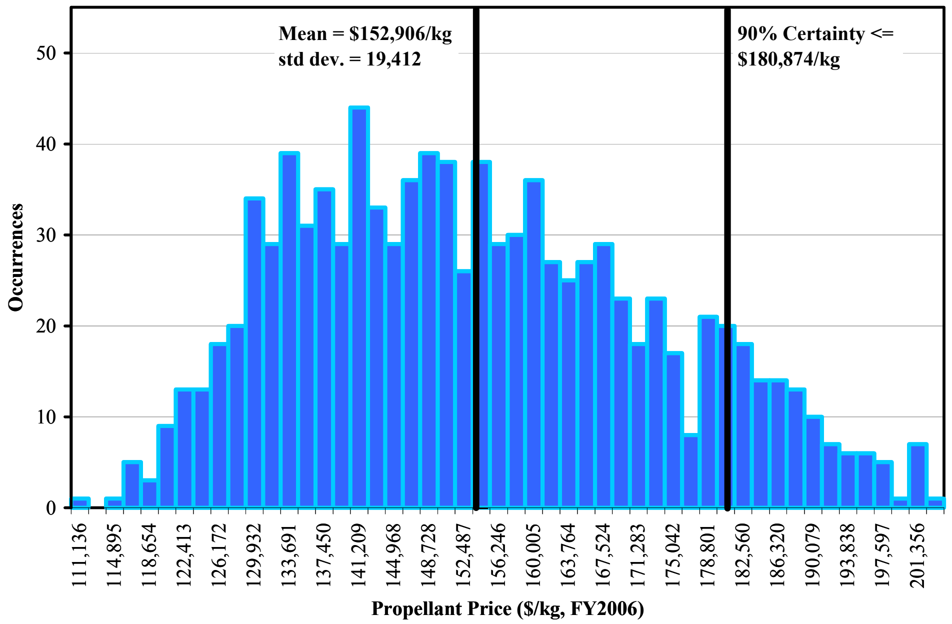
The probabilistic mean price for propellant on the Lunar Surface is $30,470 per kilogram in order for the company to break even in terms of NPV with a required rate of return (WACC) of 21.7%

Figure 11. Histogram of Price for Case 1A (Propellant on Lunar Surface)



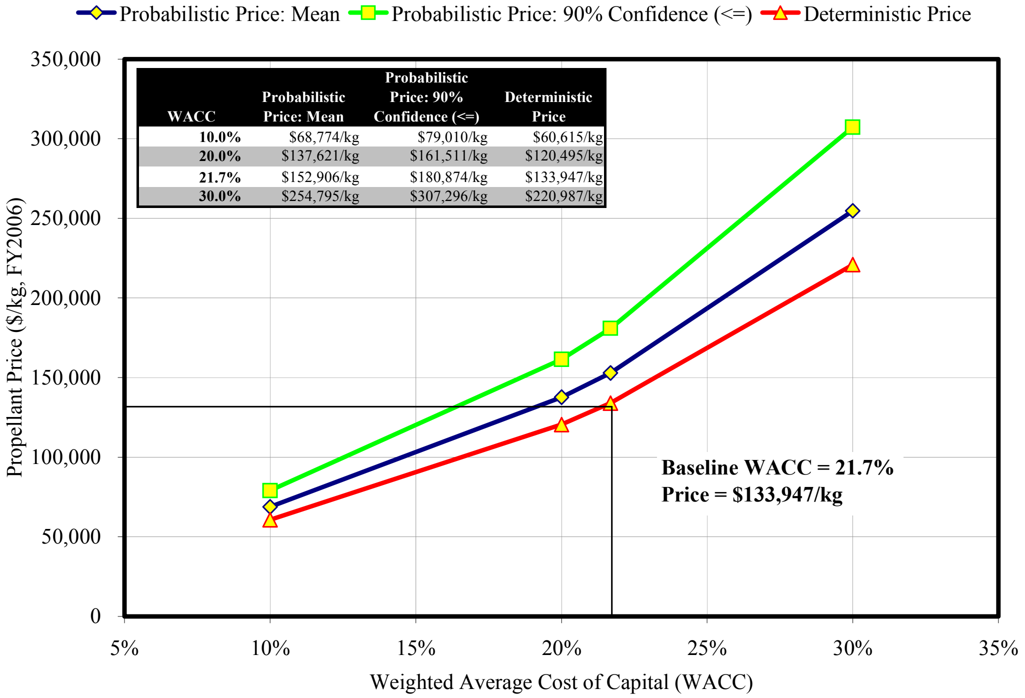
WACC	Probabilistic Price: Mean	Probabilistic Price: 90% Confidence (<=)	Deterministic Price
10.0%	$14,286/kg	$16,196/kg	$12,721/kg
20.0%	$27,548/kg	$32,261/kg	$24,240/kg
21.7%	$30,470/kg	$36,035/kg	$26,845/kg
30.0%	$49,584/kg	$58,968/kg	$43,491/kg

Figure 12. Case 1A (Propellant on Lunar Surface): Price for Required Return



The probabilistic mean price for propellant in LLO to a government customer is $152,906 per kilogram in order for the company to break even in terms of NPV with a required rate of return (WACC) of 21.7%

Figure 13. Histogram of Price for Case 2A (Propellant in LLO, Government Customer)



WACC	Probabilistic Price: Mean	Probabilistic Price: 90% Confidence (<=)	Deterministic Price
10.0%	$68,774/kg	$79,010/kg	$60,615/kg
20.0%	$137,621/kg	$161,511/kg	$120,495/kg
21.7%	$152,906/kg	$180,874/kg	$133,947/kg
30.0%	$254,795/kg	$307,296/kg	$220,987/kg

Figure 14. Case 2A (Propellant in LLO, Gov't Customer): Price for Required Return