Parametric Cost Analysis of Refueling Options in Cislunar Space

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Over the next several years NASA intends to develop and maintain a sustained human presence in cislunar space and on the surface of the Moon. The sustained lunar presence will then serve as a steppingstone for human missions to Mars. To propel the spacecraft taking humans and cargo to and from the lunar surface and to and from Mars will require on the order of hundreds of tons of propellant. Single-use refueling elements (expendable tankers) may be more cost-effective for smaller campaigns, but as the propellant demand grows, so does the potential for a cost benefit from reusable tankers. The cost of two different architectures for delivering propellant to cislunar space was estimated and compared. The first architecture relies on expendable tankers for propellant delivery while the second architecture reuses every element, including launch vehicle stages. The study determined that if the cost of reusing refueling tankers is consistent with the current state of the art, the expendable refueling architecture is more cost effective. However, refinements of the methods used to estimate launch and tanker reuse costs are needed to provide more precise estimates of the breakeven point.

Nomenclature

CBE	=	Current Best Estimate
CDF	=	Cumulative Distribution Function
CER	=	Cost Estimating Relationship
CI	=	Confidence Interval
CH4	=	Methane
ConOps	=	Concept of Operations
CT	=	Cargo Tanks
Delta-V	=	Delta in velocity, change in velocity
EDL	=	Entry, Descent, and Landing
EXAMINE	=	Exploration Architecture Model for the IN-space and Earth-to-orbit modeling
HLS	=	Human Lander System
IVF	=	Integrated vehicle fluids
LEO	=	Low Earth Orbit
LOX	=	Liquid Oxygen
LV	=	Launch Vehicle
λ	=	Reusable cislunar tanker ratio of propellant mass flow in vs. out during LEO top off operations
MEL	=	Master Equipment List
MPE	=	Main Propulsion Engine
MPS	=	Main Propulsion System
MT	=	Main Tanks
NRHO	=	Near Rectilinear Halo Orbit
PDF	=	Probability Distribution Function
RCS	=	Reaction Control System
RCE	=	Reaction Control Engine
RCT	=	Reaction Control Tanks
SEER-H	=	System Estimation and Evaluation of Resources-Hardware
t	=	Metric Ton
SPE	=	Secondary Propulsion Engine

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SPS	=	Secondary Propulsion System
ST	=	Secondary Tanks
TCS	=	Thermal Control System
TPS	=	Thermal Protection System
WSB	=	Weak Stability Boundary
ZBO	=	Zero Boiloff

I. Introduction

ONE of the greatest hurdles to space exploration is cost. Even the simplest of spacecraft typically cost hundreds of millions of dollars and are typically only used once. Refueling vehicles on-orbit has long been proposed as a strategy to extend mission lifetimes and thus lower the cost of spaceflight [1–3]. Over the last several decades, tremendous progress has been made in the technical aspects of orbital refueling and the operational aspects of reusing spacecraft. Many foresee a reduction in the cost barriers to accessing space as space vehicle refueling and reuse continue to mature. Even with said cost reductions, it is expected that meeting NASA's lunar and Mars exploration objectives will require spending tens of billions of dollars on propellant resupply. Despite this significant expense, there is (to the author's knowledge) no recent literature comparing the cost of different propellant resupply strategies. There is, however, increasing interest in the field of reusable spacecraft. SpaceX, Blue Origin, and Relativity Space are developing fully-reusable orbital launch vehicles (called Starship[4], Project Jarvis[5], and Terran R[6] respectively) to enable frequent, inexpensive access to space. Though spacecraft reuse is frequently touted as a way to drastically reduce the cost of spacecraft, this sector is still emerging and difficult to predict. Yet, it would still be prudent to ask: under what circumstances would reusable propellant tankers be a more affordable propellant resupply service than expendable tankers? Given there are virtually infinite architectural variations that could be considered, this research limited the scope to the two extremes of propellant resupply philosophies—on one end of the spectrum, every element (tankers and Launch Vehicle (LV) stages) was reused, and on the other end, every element was used only once. The total cost for full-reuse was compared to a fully-expendable baseline for variable propellant demand levels, propellant types, reuse assumptions, and tanker size.

II. Concept of Operations

Two reference architectures, depicted in Figure 1, were conceptualized to compare their costs:

1) A fully-expendable architecture: Commercially-launched, identical tankers are delivered directly to a customer resupply node by an expendable LV. Tankers refuel the customer spacecraft with all of their transferable propellant, then perform a disposal maneuver. Tankers are manufactured and launched until the customer demand is met.
2) A fully-reusable architecture: Multiple nearly-identical tankers (common development, but their minor distinctions are explained in II) are launched to Low Earth Orbit (LEO) by reusable 1st stages. Each subsequent tanker (called the LEO tankers) docks with the first tanker (called the cislunar tanker), transfer a portion of their propellant, then use what propellant remains to perform Entry, Descent, and Landing (EDL) for reuse. All LEO tankers are recovered, inspected, repaired if necessary, and flown again until the cislunar tanker is completely refueled. Once full, the cislunar tanker departs LEO for the customer resupply node. Once at the node, the cislunar tanker refuels a customer spacecraft with a portion of its onboard propellant. Next, the cislunar tanker uses its remaining propellant for Trans-Earth Injection (TEI) followed by EDL. Once landed, inspection, re-certification, transfer to the launch pad, and refueling occur before the next mission.

Once all propellant resupply missions are complete, the customer spacecraft can continue on its mission or embark on a new mission. Both architectures assumed Near-Rectilinear Halo Orbit (NRHO) was the customer resupply node. This Earth-Moon L2 southern halo orbit was selected because its stability offers low station keeping, on the order of 10 m/s per year, and it has a much higher characteristic energy than LEO—offering reusable lunar landers and Mars transit vehicles alike easy access to propellant resuppsly[7]. NRHO is also out of range of the most significant thermal effects from Earth and the Moon's albedo[8]. This reduces propellant boiloff challenges.

A. Propulsion Systems

Commercial LVs were assumed to deliver expendable tankers to a Weak Stability Boundary (WSB) transfer to NRHO. This WSB transfer offers opportunities for ballistic or near-ballistic insertion each lunar cycle, thus forgoing the need for a large, costly tanker main propulsion system (MPS). With Reaction Control System (RCS) thrusters, the

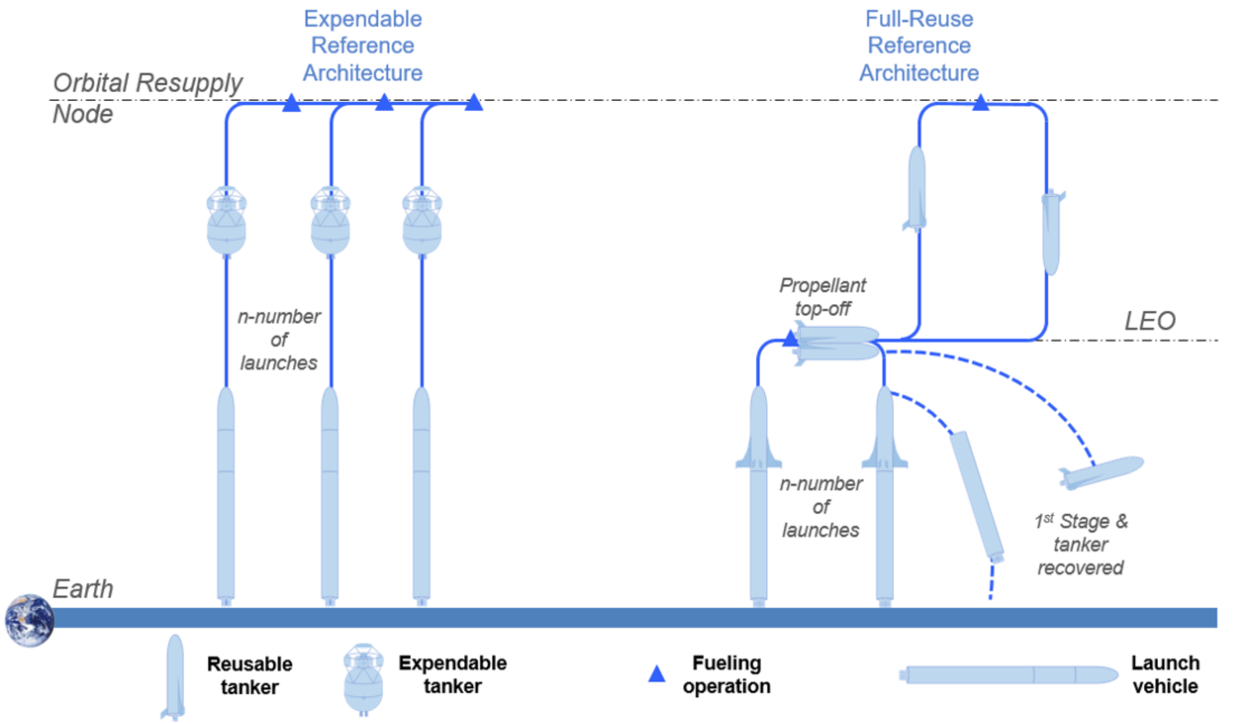


Fig. 1 Fully expendable architecture vs. fully reusable architecture

expendable tankers performed the ΔV burns specified in Table 1. Architecture 2, on the other hand, involved full-reuse of elements and stages Thus, the tanker must function as its own LV 2^{nd} stage for LEO insertion, and therefore requiring a vacuum-optimized secondary propulsion engine(s) (SPE). The main propulsion engine(s) (MPE) provides thrust vectoring, retro-propulsion, and a terminal landing burn. The number of engines varied with tanker size in order to provide a sufficient thrust-to-weight ratio. Crossfeed of propellant from Main Tanks (MT) to SPE and Secondary Tanks (ST) to MPE was assumed and sized in the parametric model accordingly (The purpose and distinctions between MT and ST are explained in II.C). Both MPE(s) and SPE(s) were assumed to be turbopump-fed. All ΔV burns for the entire mission after reaching a circular LEO parking orbit are shown in Table 1.

Expendable tankers had a dedicated RCS system using helium pressure-fed nitrogen tetroxide + monomethylhydrazine (NTO/MMH). Reusable tankers stored main and secondary propellant boiloff in accumulators which supplied pressure-fed gaseous propellant to the Reaction Control Engines (RCEs). Both low and high-thrust RCEs were sized on tankers in each of the architectures.

B. Thermal Management

There were two consequences of the reusable tanker performing final ascent to LEO:

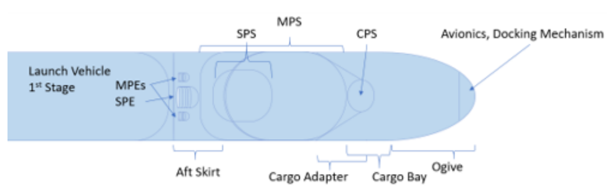
1) an aggressive stage mass fraction was highly favorable, even necessary for smaller tankers to close the reusable architecture. Tankers had to be "bare-bones" in order to avoid unfairly hindering smaller tankers, especially LOX/CH4-propelled tankers (due to lower specific impulse) from being able to deliver payload to LEO.
2) Multi-layer insulation (MLI) was not an option to insulate cryogens stored in the MT, without a way to shroud the delicate mylar layers from acoustic and aerodynamic loads (the additional shroud mass could not be justified for LEO tankers, but could be traded for the cislunar tankers in the future).

To keep the reusable tanker lightweight, no active cryocooling was assumed. Instead, boiloff was mitigated through several techniques to passively reduce and utilize boiloff before it was vented including: frequent launches to quickly top off the cislunar tankers (the consequences of this assumption are discussed in II.D), transferring from LEO to TLI on a 5-day Hohmann transfer to cut months off each leg of the transit, keeping the vehicle aligned nose-to-sun, and pointing the high-emissivity heat shield tiles on the tanker's broad side to deep space (the required attitude adjustments were assumed to be captured by the station keeping in 1), and the common bulkhead separating fuel and oxidizer was assumed

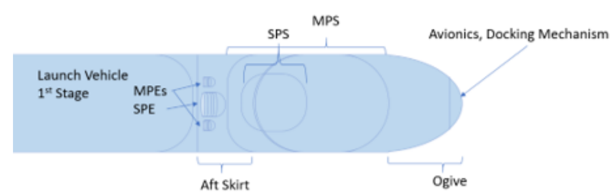
Table 1 Comparison of ΔV budgets for fully expendable and fully reusable architectures

	1. Fully Expendable		2. Fully Reusable	
Maneuver	**Performing Elements**	**ΔV (m/s)**	**Performing Elements**	**ΔV (m/s)**
Earth ascent	1st stage, 2nd stage	9,100	1st stage, cislunar tanker	9,100
LEO Circularlization	1st stage, 2nd stage	100	Cislunar tanker	100
Station keeping	-	-	Cislunar tanker	0.27 / day
AR&D	-	-	Cislunar tanker	10 (passive)
TLI	2nd Stage	3,200	Cislunar tanker	3,200
Phasing and TCM	Tanker	45	Cislunar tanker	45
NRHO insertion	Tanker	45	Cislunar tanker	450
Station keeping	Tanker	10 / year	Cislunar tanker	10 / year
Two docking attempts	Tanker	90 (active)	Cislunar tanker	10 (passive)
Disposal after refueling	Tanker	15	-	-
TEI	-	-	Cislunar tanker	450
EOI	-	-	Cislunar tanker	0 (direct entry)
EDL	-	-	Cislunar tanker	225

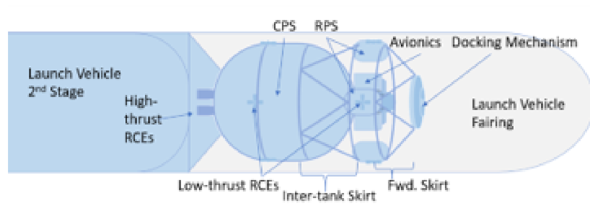
to be double-walled with the gap at vacuum to prevent propellants from causing each other to boiloff or freeze. These tactics reduce boiloff by reducing delivery time and net heat leak. Integrated Vehicle Fluids (IVF) utilize remaining boiloff for RCS and onboard power. IVF, a capability that has undergone significant early-phase development [9], first assumes boiloff is stored in accumulators. This high-pressure propellant vapor is then used for both gaseous RCS burns and primary onboard power generation via an internal combustion engine. Autogenous pressurant gas was assumed for all propulsion systems. After the TLI burn, the MTs were assumed to be empty (remaining ullage could either be vented or captured in the accumulators). The propellant for the remainder of the mission was assumed to be contained within recessed, common-bulkhead subtanks called the ST. With the MT tank wall acting like a sun shade, and the significantly lower surface area of the ST, heat leak to the propellant was reduced to radiation and conduction from MT to ST—another boiloff mitigation. Figure 2 depicts the functional layout of each tanker from which the parametric model was based upon.



(a) Reusable Cislunar Tanker



(b) Reusable LEO Tanker



(c) Expendable Tanker

Fig. 2 Functional layouts

Since the expendable tankers have no main propulsion and thus rely on a WSB trajectory taking anywhere from 90-120 days, cryogenic propellants require active cooling to mitigate boiloff. 100 Wt lift, 90 K cryocoolers with broad area cooling were assumed to provide Zero BoilOff (ZBO) for liquid oxygen and liquid methane while providing reduced boiloff for liquid hydrogen. No cryocoolers were included for non-cryogenic propellants. All expendable tankers included single-loop heat rejection with deployable radiators. As with other subsystems, thermal management scaled parametrically with tanker size except cryocoolers, which changed in quantity with tanker size.

C. Propellant Management

The delivery of four different propellant combinations was explored for each architecture. Bi-propellants like LOX/H2 and oxygen-methane (LOX/CH4) present an opportunity for commonality with the reusable tanker MT. If the customer needed bi-propellant, a common propellant tank stored both customer and secondary propellant and fed both the propulsion system and propellant transfer system. Xenon (Xe) and Krypton (Kr), however, necessitate distinct propellant storage for propulsion and customer cargo since these mono-propellants generate insufficient thrust for tanker Earth-ascent burns. Thus, reusable tankers included a cargo bay for integrating Kr or Xe customer tanks (CTs) and transfer systems. Although this analysis solely focused on propellant delivery, the cargo bay could also be used to integrate non-propellant payloads, such as cargo for reusable lunar landers. Expendable tankers do not require a cargo bay since they are launched in a fairing, though cargo could be fitted to the tankers with an adapter if there was enough volume in the payload fairing. Aluminum alloy was the material assumed for all large tanks such as the MT and ST. Carbon composite was only assumed for accumulators, pressurant, RCS, and mono-propellant tanks.

LEO tankers are assumed identical to the cislunar tankers aside from a few minor distinctions: they do not include a CT, customer transfer system, cargo bay, or cargo adapter. Since all other subsystems and components are identical between the two tanker variants, they are assumed to share the same development costs. These minor distinctions do have major implications on the architecture. LEO tankers only transfer main and secondary propellant (main and secondary propellant types are always the same, just stored in the MT and ST respectively) to the cislunar tanker. Due to this simplifying assumption, cislunar tankers delivering Xe or Kr were assumed to depart LEO with the minimum MT fill fraction necessary to return themselves to Earth—anything higher would be for nothing (this implicitly assumes that if a customer wants Xe or Kr, they do not want LOX/CH4 or LOX/H2, which of course does not have to be the case). Conversely, cislunar tankers delivering LOX/H2 and LOX/CH4 are assumed to depart LEO with completely full MTs. This distinction means cislunar tankers delivering LOX/H2 and LOX/CH4 require more LEO tankers per cislunar mission to fully tank up, but fewer overall cislunar missions because any excess LOX/H2 or LOX/CH4 can be transferred to the customer at the node.

Propellant transfer systems for each tanker also functioned differently due to differences in each architecture's Concept of Operations (ConOps). Expendable tankers required solar arrays on the order of kilowatts to power their cryocoolers. To take advantage of this power abundance, electric pumps were assumed for customer propellant transfer. Given the high number of LEO top off launches each reusable tanker requires, the time constraints due to boiloff, and the fact that reusable tankers do not require high power generation for other purposes, pressure-fed transfer was assumed. Accumulators were sized to provide autogenous pressurant for propulsion and propellant transfer.

D. Launch

Some simplifying assumptions were made regarding the reusable architecture's LV 1st stage. For the sake of relevance to current launch industry trends, the propellant combination LOX/RP-1 was assumed. The specific impulse and Propellant Mass Fraction (PMF) were assumed constant, while 1st stage diameter varied as a function of 1st stage mass. In reality, specific impulse and PMF vary with altitude and stage size respectively, but were considered negligible in this circumstance. Similar assumptions were made for the 2nd stage, used in the expendable architecture only, except the propellant combination was LOX/H2 for this stage. More assumptions in Table 2. The LV stage outer diameter was sized discretely (5 7, 9 m, and so on) based on the tanker size to allow enough payload volume for expendable tankers, and to maintain a reasonable length/diameter ratio for reusable tankers.

Reusable tankers were assumed to launch just frequently enough to keep $\lambda < 0.1$, where λ is the ratio of mass flow out of the system over mass flow into the system:

$$\lambda = (\dot{m}_{Boiloff} + \dot{m}_{Stationkeeping})/\dot{m}_{Delivered} \quad (1)$$

A lower launch cadence puts more strain on the operations schedule, which is why the maximum feasible launch cadence was assumed, and varied with tanker size. This assumption permitted larger tankers with lower boiloff rates to take advantage of the more relaxed schedule, while still allowing smaller tanker architectures to close.

E. Entry, Descent, and Landing

In contrast to the expendable architecture, the reusable 1st stage must reserve 10% of its total usable propellant for retropropulsion and landing burns. This significantly reduces the payload mass to LEO, thus increasing the number of launches required for each cislunar propellant resupply mission.

As already mentioned, unlike the expendable tanker, both the reusable cislunar and LEO tankers require a Thermal Protection System (TPS). As the name would suggest, LEO tankers perform Entry, Descent, and Landing (EDL) from LEO, but must be ready for reuse with minimal down time to inspect and refurbish or replace the heat shield. Cislunar tankers were assumed to perform direct entry from a lunar distance. This would require a much higher temperature tolerance TPS which might require more time to refurbish between flights than the LEO tankers. This could be acceptable if a second cislunar tanker was ready to go since the time between cislunar tanker missions is much greater than that of the LEO tankers, even if LEO tankers alternate between their topoff missions. Ablative heat shields, although highly effective at heat transport and potentially reusable for several missions, would eventually need extensive refurbishment or replacement. Non-ablative heat shields such as the Space Shuttle's ceramic tiles can be just as troublesome for reuse: infamous for their fragility, the thermal tiles also required nearly two man-years of labor for every single flight [10]. As a baseline, non-ablative, generic TPS was assumed. This option should be subject to TPS material, vehicle, and entry velocity trades, but such trades are outside the scope of this work.

Unlike expendable tankers, the reusable tankers also required landing gear in order to be reused. For simplicity, 2.5% of the tanker inert mass was allocated to the landing gear.

Table 2 ConOps Assumptions

	Expendable Architecture	Reusable Architecture
Launch Cadence	14 days	1-6 days (Boiloff rate dependent)
Customer resupply node	NRHO	NRHO
Topoff node	-	LEO (200 km circular)
Cislunar transfer type	WSB (Slow)	Hohmann (Fast)
Return method	-	LEO aerocapture
No. of reuses	0	100, but maintenance costs incurred for each flight

III. Tools, Methods, and Assumptions

This section describes the tools, methods and assumptions used in this work. First, the tool Exploration Architecture Model for the IN-space and Earth-to-orbit modeling (EXAMINE) was used to size all the tankers and LV stages. Next, the parametric cost estimating tool System Estimation and Evaluation of Resources-Hardware (SEER-H) was used to estimate the cost of the development and production of each of the tankers. Since this work analyzes several hundred design variations of tankers, a Python script was written to automatically translate the output from EXAMINE into SEER command files. Finally, to model the cost of LVs and reusing spacecraft, several overarching assumptions were made. The following subsections provide a detailed description of the tools and major assumptions used in this work.

A. Exploration Architecture Model for the IN-space and Earth-to-orbit modeling (EXAMINE)

Exploration Architecture Model for the IN-space and Earth-to-orbit modeling (EXAMINE) is an Excel-based tool for sizing spacecraft and LVs[11]. EXAMINE is often used to make high-level architecture trades for pre-phase A systems analysis. The tool offers a rapid way to make relative comparisons between many design options and parametric data to understand trade space sensitivities. Subsystem mass data from EXAMINE can also be used as an input for high-level cost assessments in pre-phase A.

In this work, EXAMINE was used to generate a Master Equipment List (MEL) of all components in each tanker. The cost of the components in each subsystem were then modeled in SEER-H. Some examples of these components include: fuel tank structure, fuel tank spray on foam insulation, MPS fuel feed systems, helium pressurization storage system, solar arrays, radiators, etc. One of the primary inputs to EXAMINE is Delta-V, which determined the propellant and propellant tank sizing required by the tankers.

For a given delivered propellant mass, a corresponding expendable and reusable tanker were sized. The transferable propellant was then scaled to drive a sizing sensitivity. Unlike the expendable architecture which uses an expendable 1st stage, 2nd stage, and payload fairing, the reusable architecture recovers the 1st stage, and the tanker is used as the 2nd stage which does not require a fairing. However, the 1st stage required some propellant (10% of total usable assumed) for recovery, which reduced the delivered payload to LEO. The reusable tanker also required propellant for trans-Earth injection from the resupply node. The reusable tanker could also use propulsive LEO insertion, but direct entry was assumed since a TPS is already required for LEO tankers to de-orbit—this strategy allows ground-based maintenance between cislunar resupply missions. Thus, the reusable architecture must procure multiple launches per resupply mission to topoff the reusable tanker—this was the only feasible way for the reusable tanker to have enough delta-v to reach the resupply node and come back to Earth for reuse. The reusable architecture consisted of a small fleet of reusable tankers (four were assumed) whereas the expendable architecture produced a new tanker each mission. The LV stages scaled accordingly as tanker gross mass increased. Level of propellant demand was explored to determine when the return on investment occurred for full-reuse, if at all.

B. System Estimation and Evaluation of Resources-Hardware (SEER-H)

System Estimation and Evaluation of Resources-Hardware (SEER-H), or simply SEER, is a commercial parametric cost estimating tool developed by Galorath Inc.* It is one of the standard tools used by NASA to estimate the costs of space missions for early planning or proposal phases. Galorath performed an internal validation study of SEER where it was used to predict the costs of 15 NASA space science missions. Galorath found that SEER's mean error in predicting mission cost was -1% with a standard deviation of 19%[12]. NASA performed an independent validation study of SEER and other parametric cost estimating tools in an attempt to verify Galorath's results[13, 14]. The NASA SEER validation study reported that point estimates modeled in SEER had an average error of 25%, median error of -0.3% and a standard deviation of 43%. The analysis of SEER's uncertainty quantification capabilities found that 75% of the cases studied fell within SEER's 80% confidence interval.†

The backbone of SEER is its proprietary Cost Estimating Relationships (CERs) and associated database of cost history. To model the cost of a spacecraft in SEER, the user inputs "work elements" which correspond to different components of the spacecraft. For each "work element" the user chooses an "application" which sets the majority of the inputs for SEER's CERs. SEER's database contains hundreds of mechanical/structural "applications" for spacecraft components; examples include payload adapter, separation mechanism, space propulsion component, aerodynamic control surface, spacecraft antenna – dish, spacecraft harness, gimbal mechanism, etc. Mechanical/structural "applications" in SEER are modeled using mass, material composition, complexity of form, complexity of fit, construction process, amount of new design, design replication, certification level, and a number of other inputs. Electronic components are modeled using the number of printed circuit boards, number of discrete components per board, number of integrated circuits per board, clock speed, number of pins, percent new design, and a number of other inputs. If the user knows all these inputs, they can potentially improve the accuracy of the estimate by inputting them into SEER. Otherwise, SEER will estimate the inputs using its database and the electronic "application" input by the user. If a spacecraft component does not have a matching "application" in SEER, the user can select an analogous technology and alter the inputs.

For every input in SEER the user defines a "least," "likely," and "most" value corresponding to an optimistic, most likely, and pessimistic assumption for the input. Mass modeling in the present work assumed the "least" value was 95% of the Current Best Estimate (CBE), the "likely" value was the CBE plus the Mass Growth Allowance (MGA) and the "most" input was 30% more than the "likely" input. These assumptions are a slight variation on those recommended in Galorath's SEER Space Guidance document[15]. The SEER Space Guidance recommends that the "likely" estimate be equal to the CBE, however, the NASA validation study recommends the "likely" estimate be 95% of the CBE to include the possibility that the spacecraft design will be less massive than the CBE which occurred in 3% of the cases studied by the validation study[13]. The American Institute of Aeronautics and Astronautics (AIAA) American National Standard Mass Properties Control for Space Systems recommends that space missions carry a 30% total margin (including the Mass Growth Allowance (MGA) and mass margin) prior to Authority to Proceed (ATP) [16]. SEER models uncertainty by assigning each "work element" a distribution of possible costs in addition to a median cost. The least/likely/most

*Reference to or appearance of any specific commercial products, processes, or services by trade name, trademark, manufacturer, or otherwise does not constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or NASA.

†SEER outputs project costs at probability levels in intervals of 10%. Thus 80% confidence intervals must be used as opposed to the more common 95% confidence interval.

inputs for each work element correspond to the lower bound, mode, and upper bound of a beta distribution. By default, SEER uses the median value of each beta distribution as the input to its CERs. To model uncertainty SEER can also output a Cumulative Distribution Function (CDF), however, SEER only outputs the CDF in 10% increments from 10-90%. However, this study does not include an uncertainty analysis.

SEER-H estimates all the costs associated with the development and production of the tanker hardware. This includes system-level costs such as: system engineering, integration assembly and test, program management, and safety and mission assurance. It also includes component-level costs such as requirements capture, design analysis, simulation, layout, verification, prototypes, spares, engineering test, integration, documentation, project engineering, systems engineering, tooling, material, fabrication, integration and assembly, production support, sustaining engineering, and tooling maintenance. SEER-H does not estimate the cost of software, of ground support equipment, propellant, or operations. How these costs were modeled will be discussed in the following sections.

C. Reuse Cost Assumptions

Normally, the cost of reusing a vehicle is determined by estimating the number of flights each component of the vehicle can be safely used before needing to be repaired or replaced. The cost of the component and cost of labor to replace the component is then estimated to provide an estimate of the average cost of maintenance per flight. Such an approach, however, requires data on the life of components, and the cost of repairing or replacing them. Currently, reusable spacecraft are an area of rapid innovation by a number of private aerospace companies. Because of proprietary restrictions and the fact that the cost of reuse appears to be rapidly changing, the authors of this work chose a different approach than the traditional cost estimate of the maintenance/reuse of tankers. Instead, the authors used general simplified assumptions based on publicly available information. The authors acknowledge that these assumptions will produce imprecise cost estimates, but should be useful in estimating upper and lower bounds of the reuse cost.

Since a sufficient data set to perform a traditional reuse cost estimate is not available, the authors instead sought to bound the estimate with two polar assumptions; the first representing the current State-of-the-Art (SOA) in spacecraft reuse, and the second an Extremely Optimistic (EO) view of spacecraft reuse. The SOA case is based off of the purported claim that the cost to recover and refurbish a used Falcon 9 rocket 1st stage was less than 10% of the cost to build the 1st stage [17]. Thus, each flight of the reusable tanker was assumed to cost 10% of its production cost. The EO assumption represents a potential future capability and is based on data from today's commercial airlines. According to the U.S. Department of Transportation's Bureau of Transportation Statistics, fuel costs represent 15-20% of airline expenses. Thus, the EO assumption is that the cost of each flight after development and production costs have been paid will be five times the cost of the CH_4/LOX or H_2/LOX used to propel the cislunar/LEO tankers (i.e. the cost of the fuel is 20% of the reuse cost). For reference, the cost of CH_4/LOX or H_2/LOX propellant per reusable tanker launch was 0.02-0.05% of the production cost of the tanker. Meaning the EO assumption was that 0.1-0.25% of the production cost is paid for each flight, and the EO assumption assumes the reuse cost is 40-100 times less than the SOA assumption. While it is extremely unlikely that reusable spacecraft will operate on the economy of scale of commercial airlines, the EO assumption does provide a reasonable lower bound for the reuse cost.

The cost of H_2 and LOX was estimated by adjusting the price NASA paid for these propellants under the Space Shuttle program for inflation. The 2021 cost of liquid CH_4 was obtained from the U.S. Energy Information Administration's website. Finally the cost of Xe and Kr propellants were taken from a paper comparing propellant options for high-power hall thrusters and adjusted for inflation[18]

D. Launch Vehicle Cost Assumptions (preliminary)

This work was primarily focused on developing the EXAMINE models for and estimating the cost of the tankers. The LV costs presented in this work are preliminary rough estimates. A detailed analysis of LV cost will follow in future work.

The expendable architecture assumed that there exists a commercial LV capable of launching the tankers on a TLI orbit. Currently, the largest heavy-lift commercial LV, the Falcon Heavy, can only send 15.3 t to a TLI orbit. However, the gross mass of the expendable tankers modeled in this work ranges from 8-90 t (See Fig. 4c). Thus, the vast majority of expendable tankers presented in this study will not able to be launched by existing LVs. Therefore, an estimate of the cost of a super-heavy-lift LV was needed. It was assumed that a private company would develop the super-heavy-lift LV to fill the demand for the dozens of launches required by the expendable tanker architecture. To model the cost of procuring these launches, a cost estimating relationship was developed by fitting available data on LV costs and capabilities to a power series model. The commercial LV data and associated cost estimating relationship is shown in

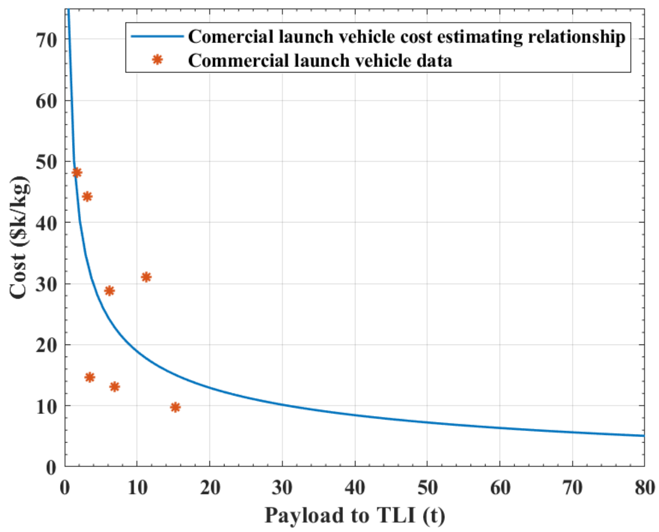


Fig. 3 Cost estimating relationship for a future super-heavy-lift commercial LV

Fig. 3. The x-axis displays the payload a commercial LV is capable of sending to TLI orbit and the y-axis displays the cost of the associated LVs in thousands of dollars per kg of payload. The data was fit to a function of the form

$$y = ax^b + c \tag{2}$$

where y is the cost in thousands of dollars per kg delivered to TLI, x is the payload the LV can send to TLI in a single launch. a, b, and c are the coefficients of the power function that are determined by the fitting algorithm. In this cost estimating relationship, while the cost per launch goes up (not depicted), the cost per kg of payload delivered to cislunar space goes down. Note that in this case, payload refers to the payload of the LV, i.e. the gross mass of the expendable tanker.

The cost estimating relationship in Fig. 3 extends far beyond the data set which was used to build the CER. Such a large extrapolation beyond the data set likely does not accurately estimate the cost of a future super-heavy-lift LV, but it does provide an order of magnitude estimate of the associated cost.

To estimate the cost of the reusable 1^{st} stage, a different approach was used. The mass and performance characteristics of the reusable 1^{st} stage were modeled in EXAMINE, however, a full EXAMINE model including a master equipment list has not been completed yet. To obtain an initial estimate of the development, production, and reuse, costs of the 1^{st} stage, it was assumed that the cost per kilogram is identical to the tanker stage. Thus, by multiplying the cost per kg by the mass of the boost stage, an order of magnitude estimate of the cost is obtained.

IV. Results

The costs presented in this work are divided into seven categories: development cost, production cost, reuse cost, propellant cost, tanker cost, launch cost, and total cost. Development cost includes all costs associated with the design, development, testing, and evaluation of the refueling tankers including building and testing prototypes. Production cost includes all the costs associated with constructing the refueling tanker units and preparing them for their initial flight. Reuse cost is the cost of refurbishing and refueling a tanker after it has flown. Since the expendable tankers are used only once, they do not incur a reuse cost. Propellant cost is the cost of the payload propellant of Xe, Kr, H2/LOX, or CH4/LOX, and additionally for the reusable tankers, the cost of the H2/LOX, or CH4/LOX used to propel the tanker to/from Cislunar space. Tanker cost is the sum of all the costs directly related to the tanker. That is the sum of the development, production, reuse, and propellant cost. For the expendable tankers launch cost is the cost of procuring a commercial LV to launch it on a TLI trajectory; the launch cost for the reusable tankers is the cost of the reusable 1^{st} stage booster. The total cost is simply the sum of the development, production, reuse, propellant, and launch costs. All costs presented in this work have been normalized unless otherwise noted. The normalization constant is the average of the development cost of all of the expendable tankers.

A. Expendable Architecture Costs

This subsection presents the costs associated with the expendable architecture. The results for the expendable architecture are summarized in Fig. 4. Figure 4a shows the cost of developing the expendable tanker spacecraft for all cases. Note that all costs presented in Fig. 4 are normalized to the average of the development cost of all the expendable tankers presented in Fig. 4a. Since Xe, and Kr, are very dense fuels, the tanks required to store them are significantly smaller than those used to store similar quantities of H2, CH4 and O2. As a result, the Xe, and Kr, tankers were significantly smaller and less expensive to develop. H2, the least-dense fuel, requires the largest fuel tanks and therefore was the most expensive. In addition, CH4, H2, and O2 all required a significantly larger and more technologically complex TCS than Xe and Kr.

A similar trend is shown in Fig. 4b which shows the first unit production cost of the expendable tankers. The first unit production cost is the cost of building the first expendable tanker to fly on a mission delivering propellant to cislunar space. The production cost of each unit decreases as more units are built. As additional tanker flight units are produced, the workers building the hardware gain experience, work more efficiently, and thus, the production cost decreases. In SEER, this is modeled using Wright's Cumulative Average Model given by Eq. 3.

$$P_n = P_i N^b \tag{3}$$

The term P_i is the first unit production cost, N is the total number of units produced, P_n is the total cost to produce the N units, and b is a scaling factor between 0 and 1 that determines how much the cost is reduced for each additional unit produced. In SEER, each component has its own b value determined by SEER's proprietary database and algorithms.

In Fig. 4c the gross mass of each tanker is plotted on the y-axis while the x-axis displays the transferable propellant per tanker. Figure 4d is similar but the y-axis shows the gear ratio of each tanker. In this work gear ratio is defined as the fraction of the gross mass that is deliverable propellant. The gear ratios range from 0.44 to 0.85 meaning 44-85% of the mass of the total mass being delivered to cislunar space is propellant. Figure 4d also illustrates that larger tankers carrying more propellant are generally more mass efficient.

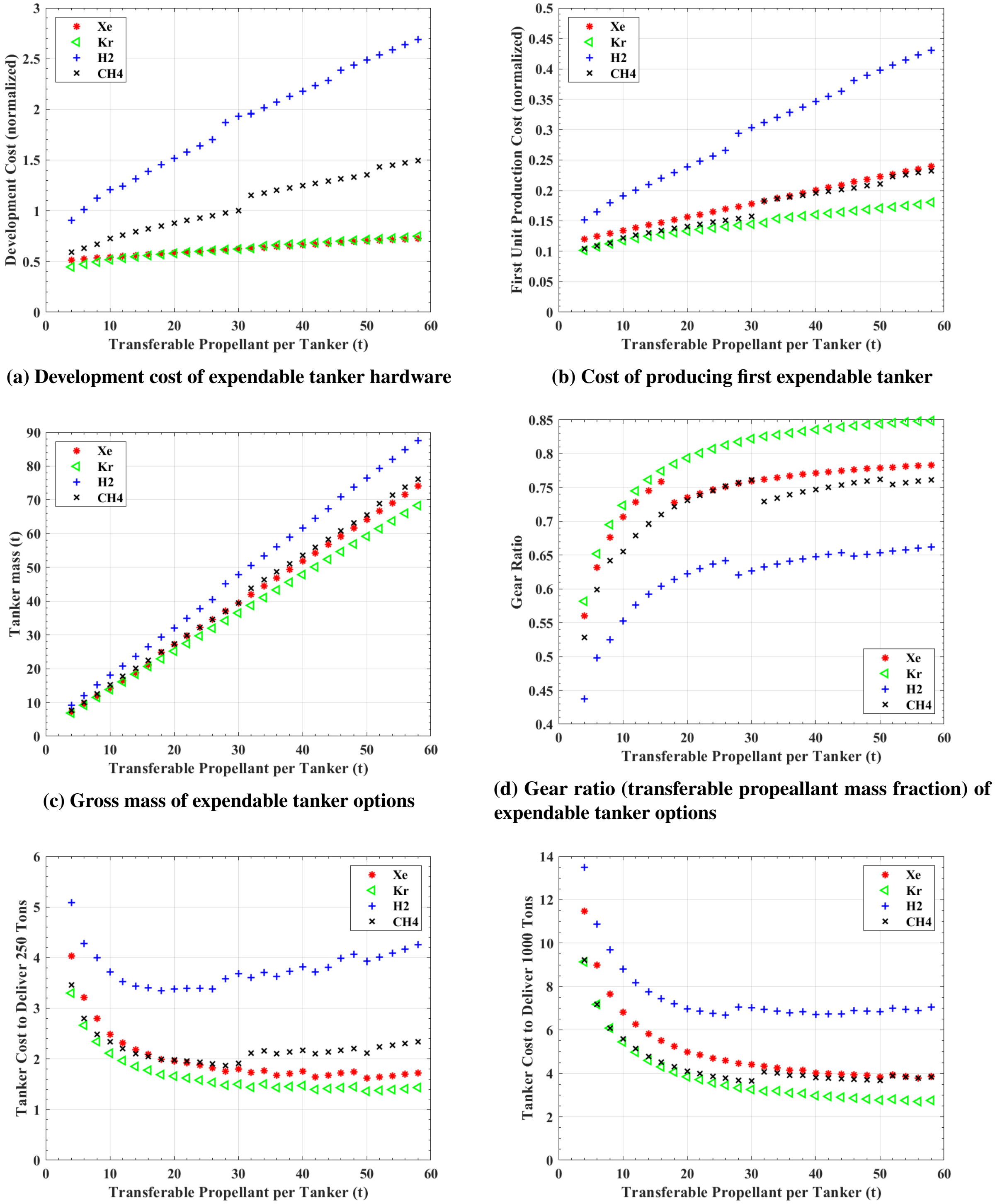
Figures 4e and 4f show the tanker costs to deliver 250 t and 1,000 t of propellant respectively. The tanker cost is the sum of the development cost, production cost of all flight units, and the cost of the propellant delivered. Tanker cost does not include the cost of the commercial LV which delivers the tanker to cislunar space. Figures 4e and 4f illustrate that, for tankers delivering Xe or Kr, in general, building larger tankers and reducing the number of flights reduced the tanker cost. However, for tankers delivering H2 or CH4, as the size of the tanker increased, the cost of a campaign of missions initially decreased, then increased. For example, when delivering 250 t of H2 to cislunar space, the minimum cost tankers delivering 18 t each were the minimum cost option. Increasing the size of the tankers beyond 18 t of transferable propellant would decrease the total number of flight units, but increase the tanker cost due to increased development cost and per tanker production cost. In this case, the added savings from building many smaller lower cost tankers outweighs the cost of building a small number of more expensive tankers. When the total propellant demand increased to 1,000 t, it becomes more cost-effective to build larger tankers. Figure 4f shows the minimum tanker cost option for delivering H2. Note that as the total propellant need increased, the minimal-cost tanker size also increased.

However, tanker costs are not the only consideration. For this architecture to be successful, it required a LV capable of sending the tanker on a TLI orbit. LV costs are discussed more thoroughly in Sec. IV.C.

B. Reusable Architecture: Properties, Development Cost, and Production Cost

This subsection presents the costs associated with the reusable tanker architecture. The results for the reusable tanker architecture are summarized in Figs 5 and 6. This work analyzed nearly 300 design variations on the reusable architecture including tankers delivering Xe, Kr, CH4/LOX, and H2/LOX. Each tanker used either CH4/LOX or H2/LOX for both its MPS (liquid) and RCS (gaseous). There were six main propellant options: Xe delivered via CH4/LOX, Xe delivered via H2/LOX, Kr delivered via CH4/LOX, Kr delivered via H2/LOX, CH4/LOX delivered via CH4/LOX, and H2/LOX delivered via H2/LOX. For each of these propellant options there were between 45-50 design variations. The design variations of the tankers ranged in transferable propellant capacity from 2-320 tons, and diameters ranged from 5-15 m as shown in Fig. 5a.

As mentioned in Sec. II, first, the cislunar tanker was launched to LEO. Upon arrival, its MT was nearly empty other than the customer propellant (which only required a separate tank for dissimilar MPS and customer propellant types). The cislunar tanker then required several refueling flights shown in Fig. 5b. The required number of refueling flights varied widely from 4-44. Note that the number of refueling flights is simply the number of LEO tanker flights to top off the cislunar tanker before it departs for NRHO, not the total flights to deliver a given amount of propellant. For example,



(a) Development cost of expendable tanker hardware

(b) Cost of producing first expendable tanker

(c) Gross mass of expendable tanker options

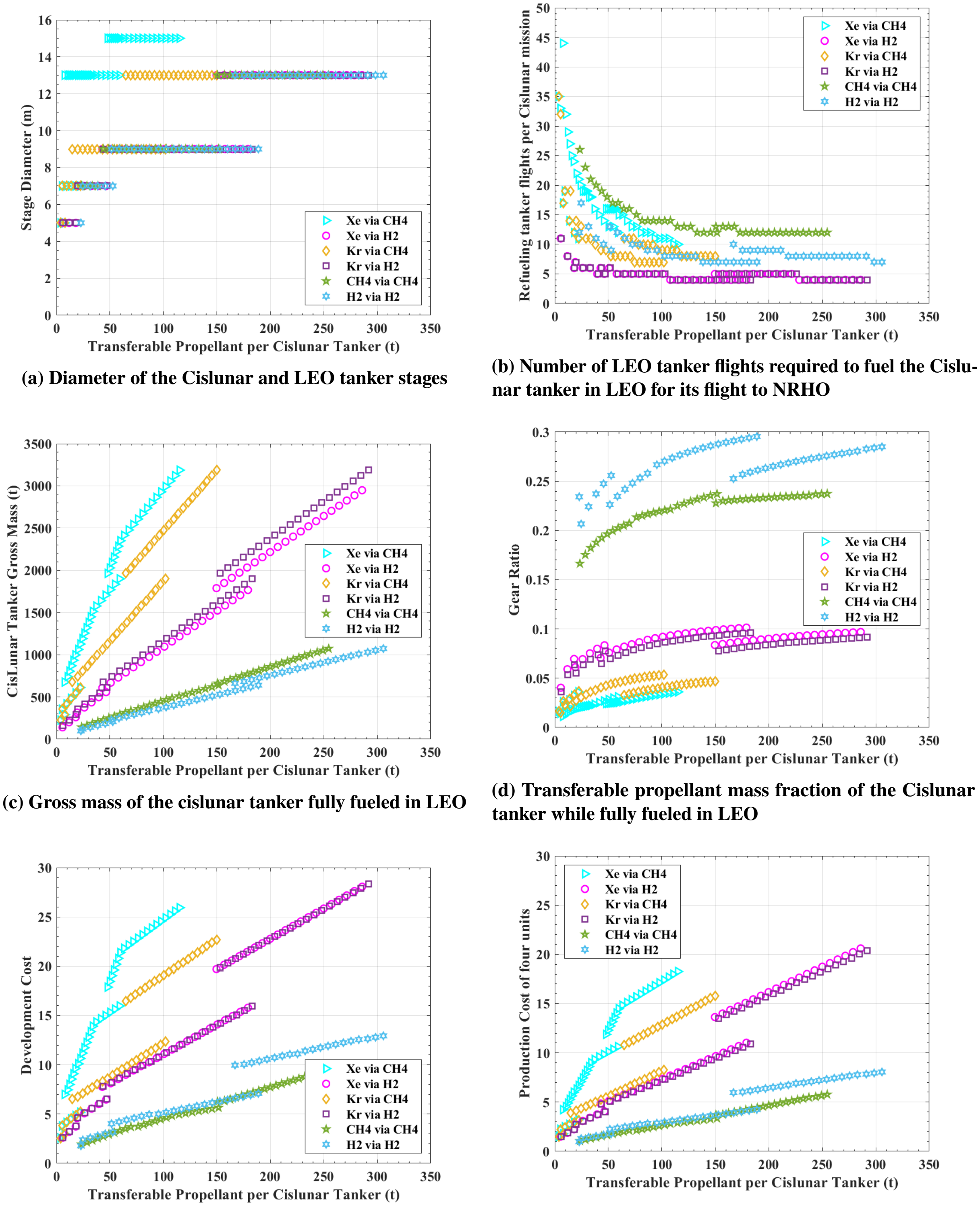
(d) Gear ratio (transferable propeallant mass fraction) of expendable tanker options

(e) Cost of building appropriate number of tankers to deliver 250 t of propellant to Cislunar space

(f) Cost of building appropriate number of tankers to deliver 1,000 t of propellant to Cislunar space

Fig. 4 Expendable tanker architecture

if the goal is to deliver 1,000 t of Xe propellant to cislunar space via H2/LOX, and the cislunar tanker is designed to carry 100 t of Xe, 10 cislunar tanker flights would be required. However, according to Fig. 5b, for the 100 t Xe via H2



(a) Diameter of the Cislunar and LEO tanker stages

(b) Number of LEO tanker flights required to fuel the Cislunar tanker in LEO for its flight to NRHO

(c) Gross mass of the cislunar tanker fully fueled in LEO

(d) Transferable propellant mass fraction of the Cislunar tanker while fully fueled in LEO

(e) Development cost of reusable tanker hardware

(f) Production cost of one cislunar tanker and three LEO tankers

Fig. 5 Reusable architecture attributes and cost

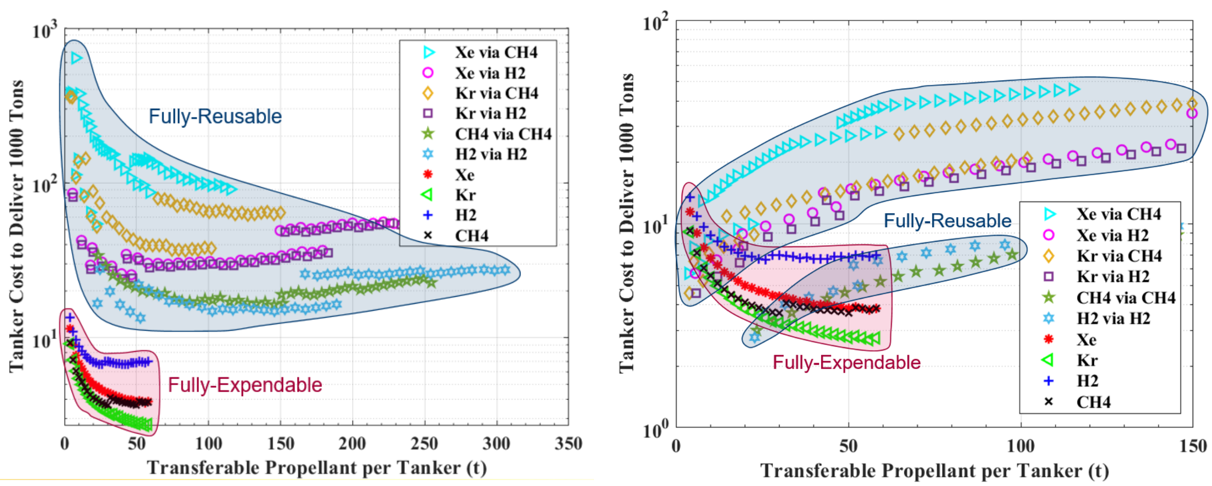
case, five refueling tankers were needed for each cislunar flight. This means to complete the 10 cislunar flights the cislunar tanker would need to be launched a total of 10 times and the LEO tankers would need to be launched 50 times, a total of 60 launches to deliver 1,000 t! Continuing to reference Fig. 5b, note that because of the high specific impulse of H2/LOX, the tankers delivering propellant via H2/LOX required a smaller mass of H2/LOX and therefore could be fueled for the trip to NRHO with fewer refueling flights. Thus, in terms of the number of refueling flights required, designs using H2/LOX have an advantage over those that use CH4/LOX.

Figure 5c shows the gross mass of the cislunar tanker when fully-fueled in LEO and ready to depart for NRHO. The gross masses of the respective LEO tankers are nearly identical. Note the gross masses ranged from 100 t to a gargantuan 3,250 t. For reference, the fully-fueled Saturn V rocket was 2,800 t gross. Figure 5d presents the gear ratio of each tanker design. In this case the gear ratio is defined as the fraction of the cislunar tanker that is transferable propellant when the tanker is fully fueled in LEO. Note that the tanker designs delivering CH4/LOX and H2/LOX have significantly lower gross masses in Fig. 5c and significantly higher gear ratios in Fig. 5d, both with respect to transferable propellant per cislunar tanker. There are several reasons for this, mainly, the arbitrary constraint that Xe and Kr tanks were launched full instead of being partially full and topped off in LEO. This revision, if implemented, would mean the Xe and Kr tankers could take advantage of departing LEO with full MTs instead of partially empty ones, thus raising their gear ratios and lowering their required gross mass to deliver a given payload (under the original assumptions, if the Xe and Kr tankers departed LEO with full MTs, they would arrive with the same Xe or Kr mass, but excess LOX/H2 or LOX/CH4 without an assumed customer for it, thus the extra launches to fully fuel it were unnecessary). Since tankers delivering Xe and Kr were the only kind constrained by their payload to LEO, they had to be sized larger than the LOX/H2 and LOX/CH4 tankers by a factor of three (for a given 1st stage mass), which likely also detracted from their gear ratio.

Figure 5e shows that the estimated development cost of the reusable tankers ranges from 1.8-28.3. Recall that the normalization constant used is the average of the development cost of the expendable architecture. Meaning that the development costs associated with the reusable tankers are from 1.8 to 28.3 times as costly as the development costs of the average expendable tanker. Figure 5f shows the cost of producing the reusable cislunar tanker and the three reusable LEO tankers. While the costs are significantly higher than the expendable tanker costs shown in Fig. 4b, the cost presented in Fig. 5f are non-recurring, while the expendable tanker cost is incurred for each flight according to Eq. 3.

The key to determining whether a reusable or expendable architecture is more cost-effective is in determining the cost of refurbishing a previously used tanker and returning it to flight. Comparing Figs. 5 and 4, it is clear that designing a tanker large enough that it can deliver its payload propellant and still have enough propellant to return to Earth incurs a significant performance hit. A reusable architecture will only be viable if the cost of returning the vehicle to service after each use is low enough to offset the much larger development cost.

Figure 6 compares the reusable architectures' tanker costs with that of the expendable architectures' tanker costs for a campaign delivering 1,000 t of propellant to NRHO. Recall that for the reusable architecture the tanker cost includes



(a) Cost to deliver 1,000 t of propellant, state-of-the-art reuse assumptions.

(b) Cost to deliver 1,000 t of propellant, extremely-optimistic reuse assumptions.

Fig. 6 Reusable tanker costs with SOA and EO assumptions compared with expendable tanker costs.

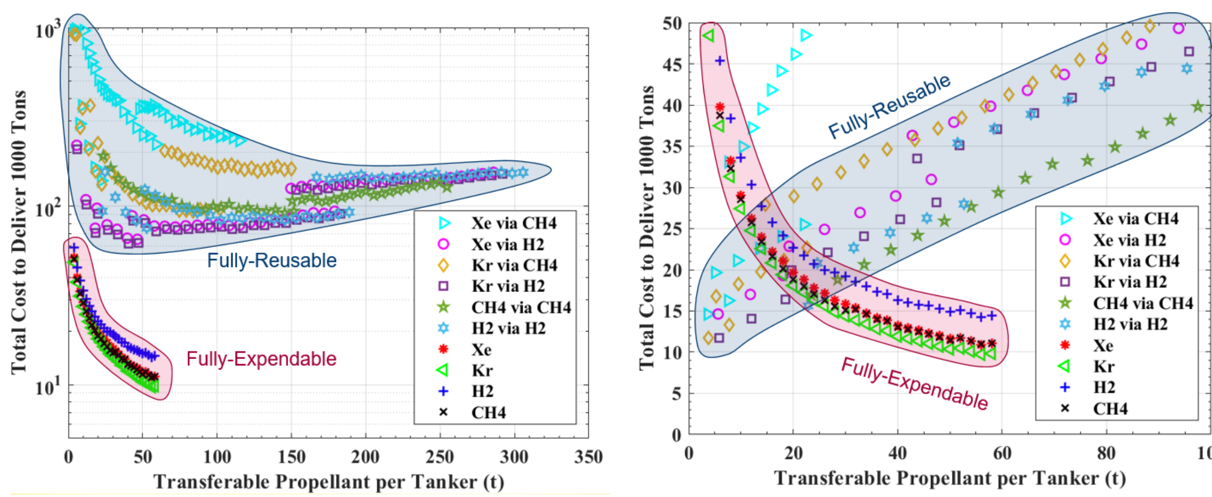
the cost of development, production, reuse, and propellant. Figure 6a displays the reusable architecture costs with SOA assumptions while Fig. 6b displays the reusable architecture costs with EO assumptions. Recall that the SOA assumption is that the cost of reusing a tanker is 10% of its production cost, while the EO assumption is that the reuse cost is five times the cost of the propellant used by the tankers to get to and from their destinations. Note that in both figures the y-axis is displayed on a log scale. Using the SOA reuse assumptions, the reusable architecture costs are typically an order of magnitude greater than the expendable architectures. However, when using the EO assumptions, there are some reuse cases that offer significant cost savings. In particular, the H2 via H2 case sized to deliver 25 t of propellant per tanker is about half the cost of the equivalent expendable tankers delivering H2/LOX.

The State-of-the-Art (SOA) turnaround time for reusing a spacecraft is frequently changing, but 27 days is believed to be the current record for LV stages that do not reach orbital velocities[19]. If tankers are assumed to be "rapidly reusable", meaning a turnaround time of 2-12 days, then two LEO tankers can be used multiple times per cislunar tanker mission on alternating launch windows. (Without rapid reuse, LEO tanker resupply missions would not be able to keep pace with propellant boiloff in the cislunar tanker). This would imply orbital, "super-heavy-lift" vehicles with turnaround times a factor of two faster than the SOA for "heavy-lift" LV stages that do not reach orbital velocities. This would also imply orbital, heavy-lift LV stages with turnaround times up to a factor of 14 faster than the SOA for heavy-lift LV stages that do not reach orbital velocities. The total life cycle number of missions per tanker depends on the total propellant demand and number of launches required. The median anticipated number of reuses per tanker was 100 for a campaign delivering 1,000 t of propellant total. This would imply each orbital-class vehicle can be reused an order of magnitude more than the current record, 10 reuses, by a sub-orbital velocity LV stage[20]. Thus, only four reusable tankers must actually be produced per propellant resupply campaign: one cislunar tanker, two LEO tankers which alternate topping off the cislunar tanker, and a reserve tanker in case a tanker experiences a failure and either cannot be recovered or must undergo lengthy repairs.

C. Total Architecture Cost (Preliminary Estimates)

This subsection compares the total cost of the expendable and reusable architectures. The total cost includes the cost of development, production of all flight units, reuse, propellant, and launch costs using the assumptions outlined in Sec. III.D.

Figure 7 compares the total cost to deliver 1,000 t of propellant. Figure 7a compares the cost of the expendable tanker options with the reusable tanker options using SOA reuse assumptions. Note y-axis is on a log scale and the reusable tanker options are roughly an order of magnitude more costly than the expendable options. Figure 7b compares the total costs of the expendable tankers with the total costs of the reusable tankers plotted on a linear scale. Note that in



(a) Total cost to deliver 1,000 t of propellant plotted on a log scale, reusable cases using SOA assumptions

(b) Total cost to deliver 1,000 t of propellant plotted on a linear scale, reusable cases using EO assumptions

Fig. 7 Total cost of delivering 1,000 t of propellant to NRHO including cost of development, production, reuse, propellant and launch services.

Fig. 7b the range on both the x and y axes has been reduced to allow for a better view of the region of interest where the reusable tanker cost breaks even with the expendable tanker cost. As a result, many of the more costly reusable cases are omitted from Fig. 7b

V. Discussion

Launch cadence for expendable tankers was arbitrary since time required to deliver propellant was assumed not affected by launch cadence, and active cryocooling provided negligible or zero boiloff. LOX/CH4 had zero boiloff, and H2 was reduced boiloff. The total H2 fuel boiloff was always 1% of the total customer propellant mass or less, even for transit times lasting months.

Since reusable tankers did not have active cryocooling, LEO tankers had to launch frequently enough to outpace boiloff as they tanked up the cislunar tankers. Their boiloff rates (for cryogenic customer, main, and secondary propellant) were on the order of 0.1 %kg/day for LOX/LCH4 and 1%kg/day for LH2. This was consistent with flight data from LV 2^{nd} stages[21]. Higher boiloff rates for the smallest tankers drove the launch cadence as low as 1 day just to keep λ<0.1. The largest tanker architectures were able to tolerate up to a 6-day launch cadence and keep their λ<0.05. Launch cadences no greater than 6 days only imply a given LEO tanker unit launches every 12 days, which is better than the SOA by roughly a two. This is potentially feasible for an early-generation reusable orbital vehicle, but future work should verify the boiloff modeling is not too conservative and consider trading sub-cooled propellant transfer or active cryocooling to further reduce boiloff. Propellant used for station keeping in LEO was found to be negligible: close to three orders of magnitude lower than boiloff.

As tanker gross mass increased, the gear ratio increased, and the number of tankers needed to meet a given propellant demand decreased. This is primarily why cost is reduced for increasing expendable tanker size. Expendable tankers can also attain higher gear ratios because they did not need Earth return propellant. Expendable tankers also tended to favor less expensive unit production costs. Since Kr and Xe are high density, their storage tanks were several factors smaller (by mass and volume) than the cryogenic propellant tanks. This efficiency resulted in cheaper production costs for Kr and Xe. Despite this, LOX/CH4 ended up less expensive than Xe when the cost of producing the propellant was included. Reusable Xe and Kr tankers did not out-perform their LOX/H2 and LOX/CH4 counterparts, as previously explained by the constraint on only topping off main propellant in LEO. Clearly, this assumption should be revisited in order to analyze launching Xe and Kr tanks partially empty, then using LEO tankers to fill them.

As propellant demand increased, the development cost became more trivial compared to production and operation costs. For higher demand, expendable tankers started to see significant cost savings from mass production. The reusable architecture did not benefit from mass production since only four tanker units were necessary, but the production cost of reusable tankers became more trivial compared to operation costs for sufficiently high propellant demand.

Interestingly, H2 was a much more expensive propellant commodity than CH4, but was the least-expensive propellant choice evaluated for reusable delivery. The affordability of Kr relative to the others was not surprising given Kr is high density, storable at a non-cryogenic temperatures, does not require an oxidizer, and is relatively inexpensive compared to Xe.

Architectures with full element reuse must take a performance hit to enable the recovery of LV stages and the reuse of tankers, and thus tend to require up to an order of magnitude more launches in a resupply campaign compared to expendable tankers. This is primarily why reusable tankers were favorable in the situation where the reuse costs were extremely optimistic. However, the break-even point was highly dependent on the architecture and cost assumptions. With SOA reuse costs, the reusable architecture assessed was inherently more expensive than the expendable architecture, independent of propellant demand level.

VI. Conclusions and Future Work

When using assumptions consistent with the current SOA in spacecraft reuse cost, the fully-expendable architecture was more affordable than the fully-reusable one. However, for sufficiently high propellant demand and extremely optimistic assumptions about the cost of reusing tankers, the fully-reusable architecture was found to be less expensive than the fully-expendable architecture. However, certain circumstances could favor partially-reusable architectures over even the best expendable and reusable architectures. Partial reuse was not evaluated, but is an important area to investigate in the future.

Although the fully-reusable tanker architecture using SOA reuse assumptions did not break even with the fully-expendable counterpart, it is possible there are different fully-reusable architectures out there that do break-even. The two architectures in this work can be thought of as baselines from which future trade studies can reveal more about the major drivers affecting cost. The reuse cost was one of the largest contributors to the total cost and yet it was also the most uncertain cost. While this work provided upper and lower bounds for the reuse cost the range of those bounds is extensive.

Launch costs are another one of the key cost drivers, yet the model used to approximate these costs was lower fidelity than the parametric tanker models. Instead of relying on the sparsely available public data for launch costs, we can model LVs in EXAMINE, then pass the output into SEER using the same methodology as the tankers. This would allow us to take advantage of SEER's extensive historical databases, thus increasing the fidelity of the LV cost estimates. The TPS assumptions also significantly influence the reusable tanker results. More information is needed to determine how many reuses the TPS can withstand, and how frequently they can be re-flown. Topping off the reusable tankers in High Earth Orbit (HEO) instead of LEO may also prove advantageous. Although the reusable tankers do not require active cryocooling, this could be traded in addition to different passive cryofluid management (CFM) techniques. Likewise, expendable tankers could potentially benefit from fast transfers with passive CFM. Finally, changing delivery nodes from NRHO to different orbits will likely also influence results.

The goal of this work was to answer the question: "What level of propellant needs to be delivered to cislunar space for a fully-reusable architecture to be more cost-effective than a fully-expendable architecture?" That question can not be answered without knowing more about the cost of operating, repairing, and reusing spacecraft. A more appropriate research question would be: "How low does the reuse cost need to be for a fully-reusable architecture to be more cost-effective than a fully-expendable architecture when delivering a certain level of propellant to cislunar space?" Re-framing the analysis performed in this work to answer the second question and eliminating the oversimplified assumptions is of high priority for future work.

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