The Impact of Lower Launch Cost on Space Life Support

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The development of commercial launch systems has substantially reduced the cost of space launch. NASA's Space Shuttle had a cost of about $1.5 billion to launch 27,500 kg to Low Earth Orbit (LEO), $54,500/kg. SpaceX's Falcon 9 now advertises a cost of $62 million to launch 22,800 kg to LEO, $2,720/kg. Space launch costs were very high for decades, typically about $20,000/kg, and it was understood that this high launch cost made it necessary for long human missions to recycle water and oxygen to reduce logistics mass. Short missions such as Apollo or Shuttle used stored and resupplied life support materials, but for a much longer mission such as the International Space Station (ISS), recycling saves logistics mass and reduces launch cost. The Life Cycle Cost (LCC) will be computed for resupply logistics and for a recycling system similar to that on the ISS. The LCC includes the costs of development, launch, and operations. The new low launch cost makes open loop life support much cheaper than before. Direct logistics resupply would be less costly than recycling for future human missions, such as a long term moon base, a Mars mission, or a future space station in LEO.

I. Nomenclature

AMCM = Advanced Missions Cost Model
BVAD = Baseline Values and Assumptions Document
CM = Crewmember
d = days
DDT&E = Design, Development, Test and Evaluation
ECLSS = Environmental Control and Life Support System
ESM = Equivalent System Mass
ISS = International Space Station
kg = kilograms
LCC = Life Cycle Cost
LEO = Low Earth Orbit
LiOH = Lithium hydroxide
MOCM = Mission Operations Cost Model
ULA = United Launch Alliance

II. Introduction

THE new low launch cost of commercial rocket systems changes the relative expense of open loop life support, which requires large supplies of water and oxygen, compared to recycling, which largely closes the water and oxygen loops to reduce the mass of logistics. The International Space Station (ISS) is a decades-long mission that uses recycling life support systems, but the much shorter Shuttle and Apollo missions used resupply. The cost of space launch dropped from very high levels in the first decade of the space age but then remained high for the next four decades. In the most recent decade, commercial rocket development has reduced the space launch cost by a factor of 10 or 20.

The more cost-effective life support system, resupply or recycling, is the one with the lower Life Cycle Cost (LCC) for the mission duration. The LCC includes the system development, launch, and operations costs. The development cost of recycling systems is much greater than the cost of resupply materials and tanks, but the launch cost of recycling systems is much lower than resupply materials due to their much lower mass. Since the operations cost of a system usually proportional to its development cost, it is also much higher for recycling systems than for

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resupply materials. The recent large reduction in launch costs tends to make resupply less expensive that recycling. With the new low launch costs, resupply will cost less than recycling similar to that on ISS for the potential future long duration multi-year missions, including a moon base, a Mars mission, or future space station.

The decline in launch costs has removed a major barrier to space. The progress of the human race has included increasing exploration and expansion based on improving transportation. Now globalization has encompassed the entire Earth. The new low cost of space launch will enable increased exploration and expansion in the Earth-moon space, extending into the solar system.

III. The history of space launch cost reduction

The mass that launch systems can deliver depends on the destination orbit. Launch systems are usually compared using the launch cost per kilogram to Low Earth Orbit (LEO). The cost to launch moon or Mars systems is much higher.

Figure 1 shows the launch cost per kilogram to LEO in current dollars for various launch systems plotted against the first system launch date. The data is taken from Table A1 in Appendix A. The usual approach is to compare launch costs per kilogram by dividing the total cost per flight by the maximum payload deliverable to LEO. Smaller payloads, payload accommodation systems, and payload volume limits can increase the launch cost per kilogram.

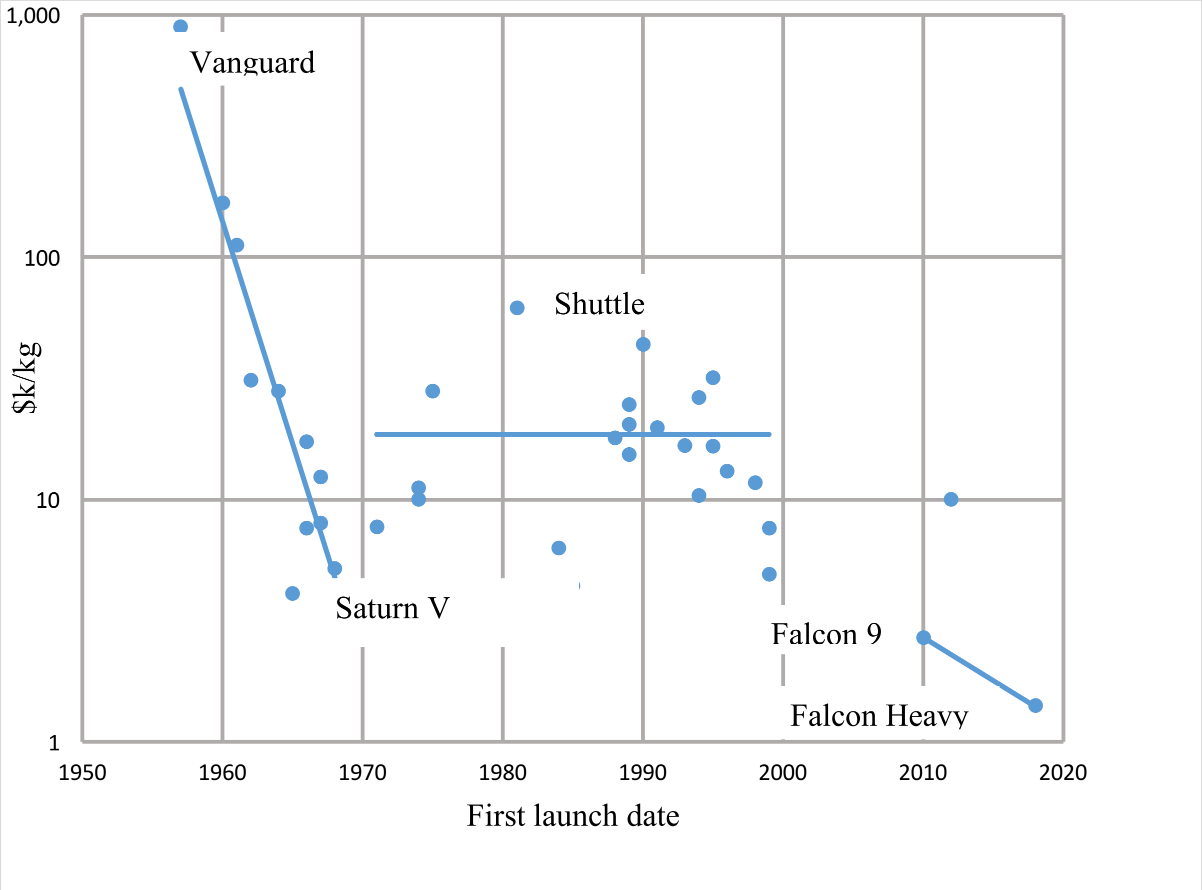

Figure 1. Launch cost per kilogram to LEO versus first system launch date.

The major impression given by Figure 1 is of two large initial and recent cost drops with a long intermediate period of more constant cost. Three early systems had launch costs to LEO above $100 k/kg, with Vanguard even approaching $1,000 k/kg. Vanguard was the first and by far most expensive launch system. Costs dropped rapidly to the Saturn V used for Apollo, to about $5 k/kg, which still is the lowest historical cost except for three Soviet systems and the two recent Falcons. Vanguard's launch cost was about 170 times that of the Saturn V.

The average launch cost did not change much from 1970 to 2000, especially since some systems with early initial flights continued to be used for decades. From 1970 to 2000 the average launch cost was $18.5 k/kg, with a typical range of $10 to $32 k/kg. Of the 22 systems initially launched from 1970 to 2000, only 7 have costs below $10 k/kg, and they are all Soviet or Chinese. Only two systems have costs above $32 k/kg, the Shuttle at $61.7 k/kg and the small and costly Pegasus.

A major drop in cost occurred in 2010 with the Falcon 9 at $2.7 k/kg. The Falcon Heavy reduces the cost to $1.4 k/kg. Shuttle's launch cost was about 20 times that of the Falcon 9 and about 40 times that of the Falcon Heavy. The average 1970 to 2000 launch cost of $18.5 k/kg is reduced by a factor of 7 for the Falcon 9 and and 13 for the Falcon Heavy. (The costs above and in Appendix A are in 2018 dollars. The unadjusted cost of Shuttle is used in the abstract.)

IV. The reasons for the decline in launch costs

What caused the long delay before the recent reduction in launch costs? "To make significant reductions in launch costs, new 'clean sheet' launch systems must be developed. … institutional barriers within government and industry have prevented major inroads is cost reduction."[1] The high cost of ordinary launch vehicles, the higher cost of the Space Shuttle, and the success of SpaceX can be explained by institutional causes.

Some of the institutional causes of high cost for ordinary launch vehicles were their military rocket heritage, the need for high reliability, and a non-industrial culture. The fundamental cause of the past high commercial launch cost seems to be lack of competition. The US launch industry has been a monopoly, the United Launch Alliance (ULA), and its main customer has been the US government, NASA and the military, which need high reliability and had little incentive to exert cost pressure. The ULA lost most of the commercial market to Russia and Arianespace, which are also heavily subsidized by their governments.[2]

The Space Shuttle had unique NASA cost drivers. About one-fourth of the Shuttle operational costs went for "the general area of NASA center and program support, maintenance of capability, and product improvement." "Another major cost driver in Shuttle is launch operations costs. The fact that 10,000 contractors and 1,000 civil service are needed … is indicative of the lack of operational simplicity. This marching army plus mission operations and crew operations personnel make up one third of the overall Shuttle operations costs. The low Shuttle flight rate not only makes for inefficient use of personnel and facilities, it distorts the cost per flight calculations because of high fixed costs."[3]

SpaceX has low costs partly because it is vertically integrated, with largely in-house development of the components of its rockets. It carries out all phases of the product lifecycle, including design, engineering, manufacturing, software, integration, testing, launch, and operations. Most activities have been in a single large facility. The competing ULA is a systems integrator and launch operator with hundreds of subcontractors that have dozens of facilities spread all over the country, which is a political necessity for a government funded jobs program. SpaceX designs for simplicity, for instance the Falcon 9 uses 9 identical engines. The Falcon Heavy effectively uses three Falcon 9's. Another key factor in SpaceX's low costs is its young, highly motivated workforce of top graduates willing to work significant unpaid overtime. SpaceX uses state of the art automated manufacturing equipment "previously unheard of in the space industry, where hand assembly of components is still the norm."[4]

Perhaps the the key determinant of SpaceX's lower cost was that innovative management established a highly effective modern engineering effort. "SpaceX's approach to rocket design, which stems from one core principle: Simplicity enables both reliability and low cost."[5] The frequent management-engineering conflict of goals and communications gap seem eliminated. SpaceX's organizational style is Silicon Valley, not NASA. "(T)he buzzwords of the business culture—lean manufacturing, vertical integration, flat management—are real and fundamental. … This really is the greatest innovation of SpaceX: It's bringing the standard practices of every other industry to space."[5]

V. Will space launch cost go lower?

Launch cost will probably go lower for several reasons. SpaceX has demonstrated rocket recovery and reuse, which may provide additional cost savings of 30 to 50 percent.[6] The expected increasing number of launches will reduce the amount of past development and current operating costs that are charged to each launch. The number of competitors providing rocket launch has increased and more are considering entry.

The reuse of rockets and entire launch vehicles has been considered important in reducing launch cost, but so far reuse has not actually led to lower cost. The Space Shuttle was extremely expensive, largely due to the high cost of refurbishing the Shuttle between flights. The Falcon 9 was designed to be reused, at a significant increase in development cost, but so far it has been reused only a few times. Falcon 9 reuse may reduce costs by a factor of two. "SpaceX president Gwynne Shotwell told the Space Symposium conference that the cost of refurbishing the Falcon 9 rocket … was 'substantially less than half' what it would have cost to build a brand new one."[6]

Reuse might provide much more drastic cost reductions. Elon Musk believes that the new Raptor engine can achieve full reusability of all rocket stages and “a two order of magnitude reduction in the cost of spaceflight” to $10 per pound by 2025.[7]

The lower cost of launch should lead to an increased number of space flights, which would lead to cost reduction due to the learning curve, to reliability growth due to failure mode discovery and repair, and would more quickly pay back the initial development cost. Previously the launch market belonged to a limited number of government supported entities possibly more concerned with military capability, launch reliability, national prestige, and creating jobs and economic stimulus than with reducing costs or developing new technology. The commercial rocket business has provided a different engineering-savvy business model that has greatly reduced costs. A growing more competitive market will tend to favor technology advances that cut cost and improve performance. There was one US launch company, ULA, in 2006, three more now, SpaceX, Orbital ATK, and Blue Origin, and possibly a dozen total by 2020. One author sees a potential speculative bubble in space launch. Boom and bust has frequently occurred in the history of transportation. Airlines, railroads, and canals have been over-developed and lost investor’s capital, even while providing great economic benefits to the nation.[8]

VI. The future impact of lower launch cost

Lower launch cost will produce changes that will increase with time and are ultimately unpredictable. Launch cost is only one of many factors influencing space mission planning. Since launch cost has been reduced, overall mission costs will be lower and more launches can be expected, but in the short term most things will generally remain the same. The same commercial, civil government, and military customers will carry out the same kinds of missions, use the same infrastructure, and launch familiar systems.

However, space operations have changed significantly, with Falcon 9 and Falcon Heavy rockets landing on ocean platforms and some being recovered and reused. In the future, higher mass, less reliable, less capable, higher risk, and less expensive payloads can be launched. Higher risk technical and commercial experiments can be made. The missions, payloads, and operations infrastructure can adjust to use more space launches and less development and operations effort. If launch is cheaper, available, and reliable, there will be less need to have replacement satellites or space station spares stored on orbit, since they can be launched when needed. Just-in-time supply and delivery chains can be designed. The logistics inventory and supply chain can be optimized for cost-effectiveness.

For the ISS, less costly, high capacity, more reliable transportation would allow fewer spares to be kept on board. For future mission life support systems, this improved transportation would favor more direct supply of water, oxygen, and other materials and less recycling. Less costly, more flexible, and more reliable transportation can be substituted for stockpiling contingency reserves, for recycling materials, and for using local resources. Cargo with much lower value per kilogram can be delivered. The ability to launch on demand will lead to more flexible scientific, commercial, and military missions.

In the long term, basic innovations can change everything beyond our ability to predict. This has repeatedly occurred in the history of transportation, with the successive development of sailing ships, canals, steamships, railroads, automobiles, and aircraft. Human life has completely changed and we are now in the era of globalization. Significant services are now provided from Earth orbit. Lower space launch cost will enable future human expansion in space. National prestige, military necessity, and commercial opportunity all provide goals and motivation, but the result will probably be surprising.

VII. Lower launch cost impact on life support logistics

Open loop systems resupply water and oxygen in tanks for crew use and provide disposable lithium hydroxide (LiOH) in canisters to remove carbon dioxide. Short human space missions such as Apollo and Shuttle have used open loop life support, but the long duration ISS recycles water and oxygen and removes carbon dioxide with a regenerative molecular sieve. The ISS regenerative and recycling life support systems have significantly reduced the total launch mass needed for life support.

It has usually been assumed that future life support systems for long duration missions would be similar to the ISS ECLSS (Environmental Control and Life Support System). The ISS ECLSS has lower than expected reliability, leading to a requirement for two or three onboard spare Orbital Replacement Units (ORUs). Recycling needs significant improvements in performance, reliability, and other factors for future missions. And, since the development cost of recycling systems is much higher than the cost of tanks and canisters, the relative cost savings of recycling are much less than the launch mass savings. Resupply is flight proven, highly reliable, and has very low development cost. If another space station was built in LEO, resupply life support could be much cheaper than the current recycling systems. The mission most favorable to recycling would be a long term lunar base, since the resupply mass would be large, the proximity to Earth would reduce the need for high recycling reliability and spares, and the launch cost would be much higher than for LEO due to the need for lunar transit and descent propulsion systems. For a long term lunar base, the new low launch costs make resupply cheaper than recycling systems similar to ISS life support.

VIII. Life support cost analysis approach

The analysis of the cost of life support considers the crew life support mass requirements, alternate life support systems approaches, and required spares.

A. Life support materials mass

Table1 shows the crew life support material requirements and the waste produced. The quantities are in kilograms per crewmember-day (kg/CM-d).

Table 1. Minimum life support system requirements and resulting waste streams.

Crew requirements	kg/CM-d	kg/CM-d	Crew wastes	kg/CM-d	kg/CM-d
Crew oxygen		0.84	Carbon dioxide		1.00
Food solids		0.62			
Food water content		1.15			
Food preparation water	0.75				
Drinking water	1.62		Respiration and perspiration condensate	2.28	
Urine flush water	0.5		Urine and flush water	2.00	
Wash water	1.29		Used wash water	1.29	
Water supply		4.16	Waste water		5.57
Total crew inputs		6.77	Total crew outputs		6.57

These minimum requirements are based on space station analysis, except that showers, dish washing, and most crew hygiene water have been eliminated.[26] The waste streams include carbon dioxide and additional water produced from food by the crew metabolism.

B. Life support systems approaches - resupply and recycling

The two fundamentally different approaches to providing life support are resupply and recycling.

1. Resupply systems

A life support system using only initial supply and storage would provide oxygen, food, and water from storage. Carbon dioxide would be removed using lithium hydroxide (LiOH). The oxygen and water are provided in multiple tanks. About 0.4 kg of tank mass is required per kg of oxygen.[9] A space qualified oxygen tank weighs 12.7 kg and contains 35.4 kg of oxygen. 0.36 kg tank mass per kg of oxygen.[10] Using the 0.36 ratio, the total of oxygen and tanks is 1.14 kg/CM-d.

About 0.2 kg of tank mass is required per kg of water.[11] A Shuttle water tank weighs 21.2 kg and holds 103 kg of water.[12] Using the 0.2 ratio, the total of water and tanks is 4.99 kg/CM-d.

LiOH is provided in multiple canisters. About 1.1 kg of LiOH is chemically required to remove the 1.0 kg of carbon dioxide per crewmember per day.[13] The ISS LiOH canister provides about 1.5 kg/CM-d of LiOH.[14] The filled Shuttle LiOH canister weighed 7 kg and was rated at 4 crewmember-days, so the required resupply mass of LiOH plus canister is 1.75 kg/CM-d.[15] The mass of the canister alone is estimated to be about 20 percent of the 7 kg or 1.4 kg. The LiOH canister use rate is 0.35 kg/CM-d.

Table 2 summarizes the life support resupply masses.

Table 2. Resupply masses of oxygen, water, and LiOH.

Material	Material mass, kg/CM-d	Container, kg/CM-d	Totals, kg/CM-d
Oxygen	0.84	0.30	1.14
Water	4.16	0.83	4.99
LiOH	1.40	0.35	1.75
Totals	6.50	1.88	7.88

2. *Recycling systems*

The ISS ECLSS is shown in Figure 2.

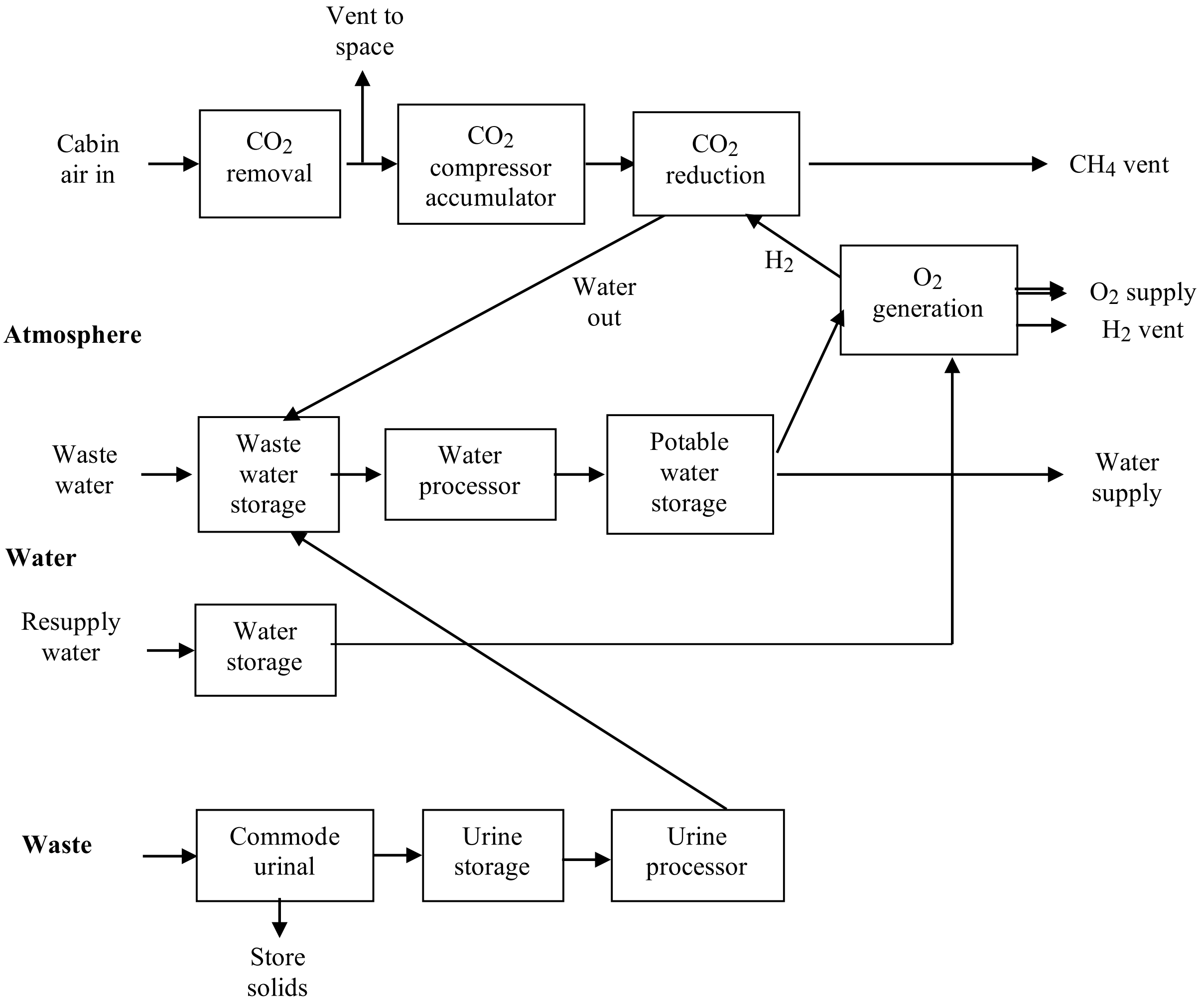

Figure 2. The ISS life support system.

The ISS life support system contains atmosphere, water, and waste recycling processors. The four bed molecular sieve carbon dioxide removal system is designed to allow the carbon dioxide to be vented to space or to be delivered to the Sabatier carbon dioxide reduction system. The electrolysis oxygen generator provides oxygen directly to the cabin atmosphere. The hydrogen can be vented overboard or used for carbon dioxide reduction.

Waste hygiene water and cabin condensate is stored and routed through the potable water processor to a potable storage tank. Resupply water delivered by Progress or other resupply vehicles is usually run through the water processor before potable use. Urine is pumped from the urinal to the urine processor and the distillate is combined with other wastewater. The commode bags and compacts feces. Solid wastes and feces are usually loaded into Progress and burned up during Earth reentry.[16] [17] [18] Table 3 lists the life support recycling system masses.

Table 3. Recycling system masses per crewmember.

System	# crewmembers	Total mass, kg	Mass/CM, kg/CM
Carbon dioxide removal	4	201	50.3
Carbon dioxide reduction	4	18	4.5
Oxygen generation	7	113	16.1
Water filtration	10	476	47.6
Urine processing	8	128	16.0

The number of crewmembers supported and system masses are from Carrasquillo, Reuter, and Philistine,[12] except that the carbon dioxide reduction is from Eckart[13] and ARC[19].

3. *Sustaining systems and the Equivalent System Mass*

For initial analysis, life support systems are frequently compared using the system hardware mass. The hardware mass has been expanded into Equivalent System Mass (ESM), which includes the mass of the hardware, its spare parts and operating materials, and adds the mass of the power and cooling systems required to sustain the system and the structural mass required to provided the enclosed pressurized volume to house the system. The ESM approach provides a more accurate assessment of the required launch mass and its impact on launch cost.

However, the cost of the sustaining power, cooling, and structure will not be included here in the LCC of recycling life support. It seems reasonable that the power, cooling, and structure would be provided by the spacecraft, and that any additional costs to sustain life support would be relatively small and would not be charged to life support or considered a factor in design decisions. But the ESM of the power, cooling, and structure can easily be several times the mass of the hardware itself, largely due to high power requirements for carbon dioxide removal and oxygen generation. This would increase the recycling launch cost proportionately.

Neglecting the cost of the power, cooling, and structure need for recycling life support favors recycling over resupply. These costs should be included if recycling has significant launch cost, which is not the case in this analysis.

C. Reliability and spares

The resupply containers and the recycling systems will be provided with spares. The number of spares is estimated to provide less than a 0.001 probability of failure on a Mars mission. A moon base or future space station will be given the same level of spares, although lower reliability and fewer spares would be acceptable.

1. *Resupply system spares*

It is assumed that the resupply tanks and containers for all missions will be provided with 10% spares. The requirement for spares on a Mars mission is most compelling, since providing additional life support materials or having the crew return are not possible. Typical conjunction class Mars missions have outbound and return transit times of 200 to 250 days each and Mars surface stays of 400 to 550 days.[20] The total transit time that recycling life support would operate is 400 to 500 days, interrupted by a quiescent period of 400 to 550 days if all the crew is on the surface.

Using the estimated reliability of existing tanks, the number of required spare oxygen tanks for Mars needed for less than a 0.001 probability of an oxygen shortage on a Mars transit mission was 10%.[21] Water tanks and LiOH containers are expected to have similar or better reliability, not being under pressure. A moon base or a future space station would consume oxygen, water, and LiOH as needed, and so would only need actually failed containers to be replaced. The 10% spares to be provided would be used to establish a contingency storage.

2. *Recycling system spares*

It is assumed that the recycling systems for all missions will be provided with three sets of spare ORU's. Again, the requirement for spares on a Mars mission is most compelling, since providing more spare parts or emergency life support materials, or having the crew return are not possible. The number of spare ORU's for Mars was calculated as that needed for less than a 0.001 probability of having all units fail during the mission using the initially estimated failure data. The number of spares needed was usually 3 or 4 for each ORU, with an average of 3.5. The same computation made using the actual flight failure rates indicated a dozen or more spares would be needed for four unexpectedly failure prone ORU's, raising the average number needed to more than 5 spare ORU's.[22] The problem

ORU's would be expected to be redesigned and demonstrated before a Mars mission, and if so, only a more normal number of 3 or 4 spares would be needed.

A moon base or a future space station would not need to have three sets of spare ORU's always available, since providing life support materials or having the crew return temporarily to Earth are always possible. However, these missions could extend for decades or longer, and it would be reasonable to develop a set of spares at the same time as the initial systems and to launch them before they are needed. The ISS ECLSS has many on-board ORUs that are not expected to be used, but are there to provide confidence that nearly all failures can be repaired.

IX. Life Cycle Cost (LCC) analysis

LCC includes all the costs incurred during the three phases of a space mission: development, launch and emplacement, and operations.

A. Development cost

Development cost includes DDT&E (Design, Development, Test, and Engineering) and hardware production. Development cost can be estimated using the Advanced Missions Cost Model (AMCM). The model is a single equation using mass, quantity, mission type, number of design generations, and technical difficulty to estimate the total cost for DDT&E and production.

The AMCM formula for the cost of DDT&E and production in millions of 1999 dollars is:

$$\text{Cost} = 5.65 * 10^{-4}\ Q^{0.59}\ M^{0.66}\ 80.6^{S}\ (3.81 * 10^{-55})^{(1/(IOC-1900))}\ B^{-0.36}\ 1.57^{D}$$

Q is the total quantity of development and production units, M is the system dry mass in pounds, S is the specification according to the type of mission (2.13 for human habitat, 2.39 for planetary base, 2.46 for crewed planetary lander), IOC is the year of initial operation capability, B is the block or hardware design generation (1 for new design, 2 for second generation), and D is the estimated difficulty (0 for average, 2.5 for extremely difficult, and -2.5 for extremely easy).[23]

B. Launch cost

LCC will be computed using the launch cost for specific missions and also for a wide range of launch costs. The launch costs per kg of payload are much higher for moon or Mars missions than for LEO. The mass that must be placed in LEO includes the rockets and propulsion mass to take a surface payload to the moon or Mars or to take a round trip payload to the moon or Mars and back to Earth. A rocket's stack-to-payload mass ratio or gear ratio is the total mass needed in LEO (payload mass plus rocket mass plus propulsion mass) to the emplaced payload mass. To send a system from LEO to Mars and let it be aero-captured into Mars orbit has a gear ratio of 3.6. Mars landing would be by parachute, not propulsive. To take a system out of Mars orbit and sent it back toward Earth and be aero-captured has a gear ratio of 3.4. Assuming that aero-capture has no propulsion cost, the gear ratio of Mars orbit round trip payload is 3.6 * 3.4 = 12.2. To descend from Mars orbit to the surface has a gear ratio of 1.3, so from LEO to Mars surface has a gear ratio of 3.6 * 1.3 = 4.7. To send a system from LEO to moon orbit and return it from moon orbit for direct reentry to Earth has a gear ratio of 4.8. To take a system from LEO to moon orbit, enter moon orbit, and descend to the surface has a gear ratio of 6.7.[24] Assuming that the future cost of launch to LEO will be from $100 to 100,000/kg, the emplaced cost for future LEO, moon, and Mars launches could range up to $1,000,000/kg.

C. Operations cost

The operations phase of most human space missions has been short, but ISS and possibly a future lunar surface base will operate for more than a decade. Future operations costs are usually estimated as a percentage of the development cost per year. For the Shuttle, the ten year operations costs were 58% of the total cost, so that the yearly operations cost was 0.58/0.42 * 10 = 13.8% of development cost per year. In an estimate for ISS, the ten year operations costs were 51% of the total cost, so that the yearly operations cost was 0.51/0.49 * 10 = 10.4% of development cost per year, not including launch.[23] The JSC Mission Operations Cost Model (MOCM) estimates the operations cost as a percentage of the total development and production cost of the spacecraft. For manned spacecraft, the estimated operations cost per year is 10.9% of the total development and production cost.[25] It is apparent that if the mission is longer than ten years, the total operations cost will be larger than the system development cost.

X. Resupply life cycle cost for a ten-year moon base

Table 4 shows the full Life Cycle Cost (LCC) computation for resupply for a moon base. It shows the hardware development, launch, operations, and total costs for the LIOH resupply containers, oxygen tanks, and water tanks on a ten-year lunar surface mission. The cost is in million dollars per crewmember, $M/CM.

Table 4. LCC for resupply for a ten-year lunar surface base.

Mission duration, years				10	Totals, $M	%
AMCM parameter		LiOH canisters	Oxygen tanks	Water tanks		
Q	Quantity	913	87	147		
M	Container mass, lb	3.1	27.9	46.6		
M	Container mass, kg	1.4	12.7	21.2		
S	Specification	2.39	2.39	2.39		
IOC	Initial date	2030	2030	2030		
B	Block	7	20	2		
D	Difficulty	-3	-3	-3		
	Hardware development cost, $M/CM	122	88	385		
Total development cost, 1999 M dollars				595		
Inflation factor, 1999 to 2018				1.52		
Total development cost, 2018 M dollars					**905**	**75**
Filled container mass each, kg		7.0	48.1	124.2		
Filled container mass total, kg		6,388	4,166	18,309		
Total launch mass, kg				28,863		
Launch cost, $/kg				10,000		
Total launch cost, $M					**289**	**24**
Operations cost, $M					**9**	**1**
Life Cycle Cost, $M					**1,203**	

The resupply hardware development costs are produced directly by the AMCM in 1999 dollars. The AMCM quantity, Q, mass, M, and block, B, differ for the three types of resupply. The quantities, Q, are obtained by dividing the mission length in days by the number of crew-days supply in each container. The empty container masses, M, were given above. The specification, S, initial operation capability date, IOC, and difficulty, D, are the same for the three types of resupply. The specification, S, is 2.39 for a moon base. The IOC date was set to 2030. The resupply storage systems have all been flight proven. The resupply difficulty was set to -3, very extremely easy, for the future moon base. This is below the prescribed AMCM minimum of -2.5, but -3 seems more appropriate because of the very extremely easy technology of gas pressure tanks, water tanks, and material containers.

LiOH has been primary on all human missions except Skylab and ISS, so counting Mercury, Gemini, Apollo transit and lander, Shuttle, and spacelab, the block, B, is estimated at 7.[26] The Shuttle had twenty-four internal gas pressure vessels, many of different designs, but the technology has been improved. The ISS has thirteen different types of on-board pressure vessels, some in multiple copies. Orbital ATK has produced 20 different pressure vessels for space use.[21] The oxygen tank block, B, is estimated at 20. Water tanks have been used on all human missions but designs have changed. The block, B, is estimated at 2, assuming a second generation ISS design.[26]

The hardware development costs include all the LiOH canisters and oxygen and water tanks for a ten-year mission. The 1999 to 2018 inflation correction has been applied.[27]

Launch cost is computed based on launch mass. The filled container masses were given above. The launch cost is set at 10,000 $/kg, based on the Falcon 9 cost of 1,400 $/kg and the lunar surface gear ratio of 6.7. (1,400 * 6.7 = 9,380.)

The operations cost is estimated at 10% of the average development cost of one year's containers. For continually operating systems, the operations cost is about 10% of the entire development cost. With intermittent resupply, containers will be built and discarded throughout the mission, so the number on hand and being maintained is far less than the total produced.

The total estimated cost for resupply life support for a ten-year moon base is about 1.2 billion dollars per crewmember. Development cost accounts for 75%, launch cost for 30%, and operations cost for 1%

XI. Recycling life cycle cost for a ten-year moon base

Table 5 shows the full Life Cycle Cost (LCC) computation for resupply for a moon base. It shows the hardware development, launch, operations, and total costs for the recycling systems; carbon dioxide removal, carbon dioxide reduction, oxygen generation, water filtration, and urine processing for a ten-year lunar surface mission. The cost is in million dollars per crewmember, $M/CM.

Table 5. LCC for recycling for a ten-year lunar surface base.

Mission duration, years						10	Totals, $M	%
AMCM parameter		carbon dioxide removal	carbon dioxide reduction	oxygen generation	water filtration	urine processing		
Q	Quantity	4	4	4	4	4		
M	Hardware mass, lb	110.7	9.9	35.4	104.7	35.2		
M	Hardware mass, kg	50.3	4.5	16.1	47.6	16.0		
S	Specification	2.39	2.39	2.39	2.39	2.39		
IOC	Initial date	2030	2030	2030	2030	2030		
B	Block	2	2	2	2	2		
D	Difficulty	1	1	1	1	1		
	Hardware development cost, $M/CM	485	99	229	468	228		
Total development cost, 1999 M dollars						1,507		
Inflation factor, 1999 to 2018						1.52		
Total development cost, 2018 M dollars							**2,291**	**50**
Total hardware mass each, kg		201.2	18	64.4	190.4	64		
Total launch mass, kg						538		
Launch cost, $/kg						10,000		
Total launch cost, $M							**5**	**0**
Operations cost, $M							**2,291**	**50**
Life Cycle Cost, $M							**4,588**	

The recycling hardware development costs are produced directly by the AMCM in 1999 dollars. The recycling system hardware mass per crewmember, M, is obtained from Table 3. The quantity, Q, specification, S, initial operation capability date, IOC, block, B, and difficulty, D, are the same for all the recycling systems. The quantity, Q, is 4 for the operating system and 3 spares. The specification, S, is 2.39 for a moon base. The IOC date was set to 2030. The hardware block, B, was set to 2, second generation, assuming that the systems would be based on the ISS designs Recycling physical-chemical technology is not especially difficult. The recycling difficulty was set to 1, more than average, for a future moon base.

As for resupply, the launch cost is $10,000/kg, based on the Falcon 9 and the moon gear ratio. The operations cost is estimated at 10% of the entire development cost, so ten years operations cost is equal to the development cost. The total estimated cost for recycling life support for a ten-year moon base is about 4.6 billion dollars per crewmember. Development cost accounts for 50% and operations cost also for 50%, since the operations cost is 10% of the development cost over ten years. Launch cost is negligible.

XII. Comparing the Life Cycle Cost of recycling and resupply

As seen by comparing Tables 4 and 5 for a ten-year lunar surface mission, the cost of recycling at about 1.2 $B is about 3.8 times higher than resupply at about 4.6 $B. For both resupply and recycling, the development cost is significant at 75 and 50%, but the remaining cost is nearly all launch for resupply and nearly all operations for recycling.

Recycling saves more cost relative to resupply for longer missions and higher launch cost. A long duration moon base was selected as the detailed example because it provides a better opportunity for recycling to save cost than other potential future missions. However, for recycling to save cost cost compared to resupply for a moon base, the mission duration would have to be more than 20 years and the emplaced launch cost more than $100,000/kg.

Figure 3 shows the mission launch cost per kilogram and the duration for several missions.

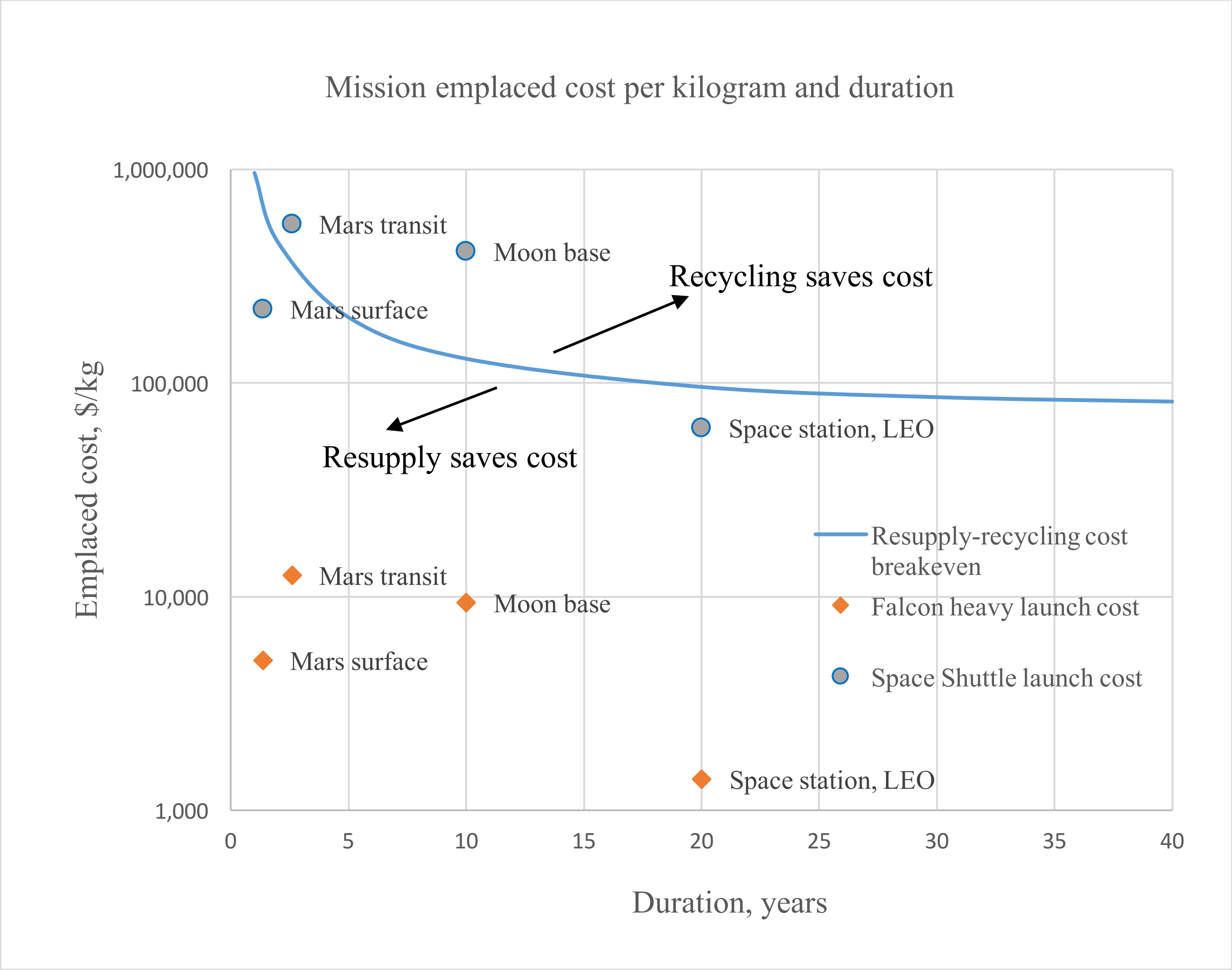

Figure 3. Mission launch cost per kilogram and mission duration and resupply-recycling cost breakeven.

The ten-year moon base has a launch cost of about $10,000/kg, based on Falcon 9. However, the Shuttle-based launch cost for a moon base would be about $400,000/kg. Recycling saves significant cost using the Shuttle launch cost to LEO. Above the solid blue line, at higher launch cost and higher duration, recycling saves cost.

Below the solid blue line, resupply saves cost. Recycling for a twenty-year space station in LEO would not save cost at the Falcon 9 launch cost to LEO of $1,400/kg and not even at the Space Shuttle cost of $61,700/kg. Even on a very much longer mission in LEO, recycling would not save cost.

Using recycling on a Mars transit, most of the hardware must make the round trip. For resupply, the supplies used outbound would have a lower launch cost, since they do not have be returned to Earth. The Mars transit emplaced launch cost for resupply is shown in Figure 3. Since the resupply-recycling cost breakeven curve assumes equal launch cost for resupply and recycling, the recycling saving is less than indicated by the distance to the breakeven curve. A Mars surface mission has a lower gear ratio and shorter duration than a Mars transit, and recycling does not save cost even at the larger Space Shuttle launch cost. At the current Falcon 9 launch cost to LEO, resupply is significantly less costly than recycling for a space station, moon, or Mars.

XIII. Conclusion

The new low launch cost makes open loop life support much cheaper than before. Open loop systems resupply water and oxygen in tanks for crew use and provide disposable lithium hydroxide (LiOH) in canisters to remove carbon dioxide. Short human space missions such as Apollo and Shuttle have used open loop life support, but the long duration International Space Station (ISS) recycles water and oxygen and removes carbon dioxide with a regenerative molecular sieve. These ISS regenerative and recycling life support systems have significantly reduced the total launch mass needed for life support. But, since the development cost of recycling systems is much higher than the cost of tanks and canisters, the relative cost savings have been much less than the launch mass savings. The Life Cycle Cost (LCC) includes development, launch, and operations. If another space station was built in Low Earth Orbit (LEO), resupply life support would be much cheaper than the current recycling systems. The mission most favorable to recycling would be a long term lunar base, since the resupply mass would be large, the proximity to Earth could reduce the need for high recycling reliability and spares, and the launch cost would be much higher than for LEO due to the need for lunar transit and descent propulsion systems. For a ten-year lunar base, the new low launch costs make resupply cheaper than recycling systems similar to ISS life support.

Appendix A: Launch cost to Low Earth Orbit (LEO)

Table A1 shows the first launch date and the launch cost to LEO in current dollars for many historical rocket systems. Most of the data was obtained from past compilations, but the Saturn V, Space Shuttle, Falcon 9, and Falcon Heavy launch costs are calculated below.

Table A1. Launch cost to LEO in current dollars.

System	First launch date	$k/kg	Reference	#
Ariane 44	1988	17.9	Wertz and Larson, 1996	1
Ariane 5G	1996	13.1	Futron, 2002	28
Athena 1	1995	31.7	Wertz and Larson, 1996	1
Athena 2	1995	16.6	Futron, 2002[28]	28
Atlas IIA	1991	19.8	Wertz and Larson, 1996	1
Atlas-Centaur	1964	28.0	Koelle, 1991[29]	29
Cosmos	1967	12.4	Futron, 2002	28
Delta 3910	1975	28.0	Koelle, 1991	29
Delta E	1960	167.8	Koelle, 1991	29
Delta II	1989	15.3	Futron, 2002	28
Delta III	1998	11.7	Koelle, 1991	29
Dnepr	1999	4.9	Futron, 2002	28
Falcon 9	2010	2.7	SpaceX.com, 2018	
Falcon Heavy	2018	1.4	SpaceX.com, 2018[30]	30
H-2	1994	26.4	Wertz and Larson, 1996	1
Kosmos	1967	8.0	Wikipedia, Comparison, 2018[31]	31
Long March 2C	1974	10	Futron, 2002	28
Long March 2E	1971	7.7	Wertz and Larson, 1996	1
Long March 3B	1984	6.3	Futron, 2002	28
Pegasus XL	1990	43.5	Futron, 2002	28
Proton SL-13	1965	4.1	Wertz and Larson, 1996	1
Rockot	1994	10.4	Futron, 2002	28
Saturn V	1968	5.2	Williams, 2016[32]	32
Saturn IB	1966	17.3	Koelle, 1991	29
Scout	1961	111.8	Koelle, 1991	29
Space Shuttle	1981	61.7	Pielke and Byerly, 2011[33]	33
Soyuz	1966	7.6	Futron, 2002	28
Start	1993	16.7	Futron, 2002	28
Taurus	1989	20.4	Wertz and Larson, 1996	1
Titan II	1962	31.0	Wertz and Larson, 1996	1
Titan IV	1989	24.7	Wertz and Larson, 1996	1
Titan-Centaur	1974	11.2	Koelle, 1991	29

Vanguard	1957	894.7	Koelle, 1991	29
Vega	2012	10.0	Wikipedia, Comparison, 2018	31
Zenit 2	1985	4.4	Futron, 2002	28
Zenit 3SL	1999	7.6	Futron, 2002	28

The costs were corrected from the reported basis years to current dollars using the Consumer Price Index (CPI).[27] The data of Table A1 are plotted in Figure 1 of the main text.

Table A2 shows the computation of the launch cost per kilogram to LEO in current dollars for the Saturn V, Space Shuttle, Falcon 9, and Falcon Heavy.

Table A2. Launch cost to LEO for Saturn V, Space Shuttle, Falcon 9, and Falcon Heavy.

System	Saturn V	Shuttle	Falcon 9	Falcon Heavy
kg to LEO	140,000	27,500	22,800	63,800
Cost per launch, 2018 $M	728	1,697	62	90
2018 $k/kg	5.20	61.72	2.72	1.41
Reference	Williams, 2016[32]	Pielke and Byerly, 2011[33]	SpaceX.com, 2018[30]	SpaceX.com, 2018[30]

These costs are used in Table A1. The cost reduction factor from Shuttle to Falcon 9 is about 23 and to Falcon Heavy is about 44.

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