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Moon Base Life Support Design Depends on Launch Cost, Crew Size, and Mission Duration

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Brief human space missions such as Apollo and shuttle used material storage for life support but a long mission such as space station uses a recycling life support system. The upcoming Moon visits will probably be brief with few crew at first but in the future there may be a long term or even permanent Moon base with a large crew. The initial life support system will probably use storage and resupply of materials from Earth, but it could be replaced later by recycling, especially if launch cost per kilogram is high. Moon base life support design is investigated considering requirements, performance, reliability, cost, and risk. The launch cost, crew size, and mission duration are variable parameters that affect the life support design choice. Greater launch cost, crew size, or mission duration all tend to make recycling more cost-effective than resupply.

Nomenclature

AMCM	=	Advanced Missions Cost Model
CDRA	=	Carbon Dioxide Removal Assembly
CM	=	Crewmember
COPV	=	Composite Overwrapped Pressure Vessel
CRS	=	Carbon Dioxide Reduction System
DDT&E	=	Design, Development, Test and Evaluation
IOC	=	Initial Operation Capability
ISS	=	International Space Station
LCC	=	Life Cycle Cost
LEO	=	Low Earth Orbit
LiOH	=	Lithium hydroxide
MADS	=	Maintenance and Analysis Data Set
MOCM	=	Mission Operations Cost Model
MTBF	=	Mean Time Before Failure
OGS	=	Oxygen Generator System
ORU	=	Orbital Replacement Unit
Pr(LOC)	=	Probability (loss of Crew)
UPA	=	Urine Processor Assembly
WPA	=	Water Processor Assembly

I. Introduction

THIS paper compares the life cycle cost of resupply and recycling life support systems for a Moon base. The costs include development, launch, and operations. The costs are for multi-unit resupply or recycling systems meeting the life support requirements for material quantities, reliability, and risk. Breakeven dates occur when the cost of recycling first becomes less than the cost of direct resupply, for different crew sizes and launch costs. The life support cost is estimated for different crew sizes and mission lengths.

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II. Moon base mission parameters and life support system requirements

The Moon base life support system design depends on mission parameters such as crew size and duration and also on life support requirements such as the mass of materials that must be supplied and the reliability and risk of the supply.

A. Moon base mission parameters

Many different Moon base missions are possible and the particular scenario influences the life support design. In this study the crew size and mission duration are variable parameters. The crew size will vary from 1 to 100 and the mission duration from 1 to 10,000 days.

Many options have been considered for the base location. Potential locations are classified as equatorial, mid-latitude, or polar. Polar locations are either north or south and equatorial and mid-latitude locations are either near side, far side, or close to the Earth terminator. An equatorial location has a 28 day solar cycle, with 14 days of darkness and extreme hot and cold. A polar location might be able to provide nearly continuous solar power and would allow much easier thermal control.[1] The location affects the cost of power and cooling, but this life support cost is not included in this study. The date of initial base operation is estimated at 2030.

B. Life support mass requirements

Table 1 shows the life support material requirements and waste products for a single crew member. The quantities are in kilograms per crewmember-day (kg/CM-d).

Table 1. Life support system mass requirements and resulting waste streams, kg/CM-d.

Crew requirements				Crew wastes			
Water supply		Oxygen and food		Waste water		Carbon dioxide	
		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						
Wash water	4.09			Respiration and perspiration condensate	2.28		
Shower water	2.73			Used wash and shower water	6.82		
Urine flush water	0.49			Urine and flush water	2.00		
Total water supply	9.68			Total waste water	11.10		
Total crew inputs			12.29	Total crew outputs			12.10

These requirements are based on early space station planning, except that clothes and dish washing have been eliminated.[2] [3] The waste water includes additional water provided in the food or produced from the food by crew metabolism. This added water allows recycling to have lower water recovery efficiency.

C. Life support reliability and risk requirements

Reliability and risk are two aspects of system failure that have different impacts and performance requirements. Reliability is simply the probability that equipment will operate correctly over the time expected. A failure can be ignorable, easily repairable, or fixable by using a spare. Or it can require extensive crew time for trouble shooting and repair. Higher reliability is desirable to reduce crew time, down time, and the mass of spares. It seems reasonable that extensive effort should be spent in improving reliability, planning maintenance and repair, and minimizing spares. However, the current reliability of resupply and recycling systems is adequate for a moon base. Improving reliability would be difficult and costly for recycling and is unnecessary for storage. Setting higher requirements for reliability would be unrealistic. Reliability has a major effect on crew time, down time, and spares logistics. They cannot be independently specified and designed for. The cost of spares is included in this study. The number of required spares is computed and the cost of developing all of them and of launching the expected failed number is included.

Risk is more important but easier to deal with. The most important risk is Probability of Loss of Crew, Pr(LOC). An unrepairable failure of oxygen supply, water supply, or carbon dioxide removal could cause Loss of Crew, but only if the crew had no options. A Moon base would probably have emergency stockpiles of materials and equipment. The crew could receive more material and equipment from Earth in a few days, or in the worst case could return to lunar orbit or Earth. The situation on a Moon base is much different than for a Mars base or Mars transit, and is more similar to the space station. This study will assume that the probability of an unrepairable failure of life support must be less than 1% per year, with no real need for a lower failure rate or specific limits on crew time, down time, or spares.

D. Other design criteria

Selecting the technology for a system design is a standard engineering exercise. The simplest way to compare technologies is to use a checklist containing the significant criteria. These include quantitative performance, reliability, and safety or risk, as discussed above, and other performance factors and costs. Performance factors include operational problems such as noise, microgravity sensitivity, contamination potential, maintainability, and crew time. These are qualitative and design dependent and can be considered in the final design choice using engineering judgement.

E. Cost

The inescapable design selection criterion is cost, which is a complex result of many engineering and management decisions. The essential cost is the Life Cycle Cost (LCC), which includes development, launch, and operations cost. The life support system design alternatives will be compared using LCC.

III. Life support system design alternatives

The two major alternative life support system designs are material resupply or recycling. Their implementation and cost factors are described.

A. Storage and resupply

Storage and resupply uses tanks and containers. Their mass is used in computing design and launch cost. 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.[4] The oxygen mass is 0.84 kg/CM-d and the oxygen tank mass is 0.30 kg/CM-d. A space station water tank weighs 21.2 kg and holds 103 kg of water, 0.21 tank mass per kg of water.[5] The water mass is 9.68 kg/CM-d and the water tank mass is 2.00 kg/CM-d.

Carbon dioxide is removed using lithium hydroxide (LiOH) in multiple canisters. 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/crewmember-day.[6] About 1.1 kg of LiOH is chemically required to remove the 1.0 kg of carbon dioxide per crewmember per day.[7] The International Space Station (ISS) LiOH canister provides about 1.5 kg/kg/crewmember-day of LiOH.[8] Estimating 1.3 kg/CM-d of LiOH, the canister contains 5.2 kg of LiOH and the canister mass is 0.45 kg/CM-d.

Table 2 lists the masses of the containers and the crewmember-days (CM-d) supplied for these current tanks and containers.

Table 2. Resupply masses and containers for oxygen, water, and LiOH.

		Current containers				Large containers			
Material	Supply mass, kg/CM-d	Contained supply mass, kg	Container only mass, kg	Filled container mass, kg	Container capacity crewmember-days, CM-d	Contained supply mass, kg	Container only mass, kg	Filled container mass, kg	Container crewmember-capacity days, CM-d
Oxygen	0.84	35.4	12.7	48.1	42.1	1,000	300	1,300	1,190
Water	9.68	103	21.2	124.2	10.6	1,000	300	1,300	103
LiOH	1.30	5.2	1.8	7.0	4.0	1,000	300	1,300	769

This study will consider up to 100 crewmembers for up to 10,000 days, one million CM-d, so larger size containers will also be considered for convenience in tracking and handling. The oxygen, water, and LiOH containers are assumed to hold 1,000 kg of material and mass 300 kg each. As a first approximation, changing the container size would not change the ratio of container to content mass, but using containers much larger than now flown would require new design and manufacturing approaches.

1. Resupply reliability

The tanks and containers used in space have high reliability. Composite overwrapped pressure vessels (COPVs) have been used to store oxygen in most spacecraft. The analysis of the accelerated life testing on a used NASA shuttle COPV tank found an estimated life of 350 years for the worst shuttle tank the testers could obtain. This would suggest the probability of a tank failure is about 1/350 = 0.0028 per year.[9] Water tanks can be expected to have better reliability since they use simpler technology and are not under pressure. The Apollo 13 experience showed that a LiOH container can actually be rebuilt in flight using cardboard and duct tape. It is hard to imagine an unrecoverable LiOH cannister failure. (Such very low probabilities of a container failure consider only their intrinsic failure modes. The probability of an accident causing a failure, due to an environmental impact or human error, can be significant.)

Suppose that smaller, shorter missions, up to 1,000 crewmember days, use the current containers. Fully supplying these missions will require 24 oxygen tanks, 95 water tanks, and 250 LiOH canisters. Suppose the failure rate of the tanks and canisters is 1/350 = 0.0028 per year. Without spares the overall probability of failure is high, but using one spare oxygen tank, two spare water tanks, and three spare LiOH containers decreases the failure probability to about 1% over one year. (This is an "r out of n" redundancy problem, since r out of the n total tanks must not fail. The failure probability is found using the binomial distribution.) Suppose that the larger, longer missions, up to 1,000,000 crewmember days, will use the large containers. Fully supplying these missions will require 840 large oxygen tanks, 9,709 large water tanks, and 1,300 large LiOH canisters. Using eight spare oxygen tanks, fifty spare water tanks, and eleven spare LiOH containers decreases the failure probability to about 0.1% over one year.

Because of the expected high reliability of tanks and canisters, the probability of an unrecoverable failure can be reduced to less than 1% per year by providing a relatively small number of spares. Shorter missions than one year would have a proportionally smaller probability of failure. Longer missions would be gradually resupplied over time, and would not have all supplies provided before the mission. A tank or canister failure could be compensated for by an additional delivery. Because the added cost of providing sufficient spare containers is negligible, the cost of providing and launching spares will not be considered in the resupply LCC.

B. Recycling

The ISS life support system contains atmosphere and water recycling processors. The Carbon Dioxide Removal Assembly (CDRA) is designed to allow the carbon dioxide to be vented to space or to be delivered to a Carbon Dioxide Reduction System (CRS). The electrolysis Oxygen Generator System (OGS) provides oxygen directly to the cabin atmosphere. Waste hygiene water and cabin condensate is stored and routed through the Water Processor Assembly (WPA) to the potable storage tank. Resupply water is usually passed through the WPA before use. Urine is pumped from the urinal to the Urine Processor Assembly (UPA) and the distillate is combined with other wastewater and sent to the WPA.[10] Table 3 lists the masses of the life support recycling system and the number of crewmembers supported by one system.

Table 3. Recycling system masses and number of crewmembers.

Acronym	System	Number of crewmembers supported	Total mass, kg	Average number of spares for one operating system	Redundancy
CDRA	Carbon Dioxide Removal Assembly	4	201	1.96	2.96
CRS	Carbon Dioxide Reduction System	4	18		
OGS	Oxygen Generator System	7	113	2.94	3.94
WPA	Water Processor Assembly	10	476	2.33	3.33
UPA	Urine Processor Assembly	8	128	3.12	4.12
			Average	2.59	3.59

The number of crewmembers supported and the system masses are from Carrasquillo, Reuter and Philistine,[5] except that the carbon dioxide reduction system is from Eckart[7] and ARC[11]. The average number of spares for one operating system and the redundancy factor are computed next.

1. Recycling reliability

The ISS maintenance approach uses spare subsystems, called Orbital Replacement Units, (ORU's). The ISS typically has on board one or two spares for each ORU. Even if an operating ORU has a 95% probability of working throughout the expected ISS mission duration, spares would be provided to give the required higher than 95% reliability. The spares are for insurance and rarely used.

The Mean Time Before Failure (MTBF) is the inverse of the failure rate of a component. ISS ORU's typically have MTBF's of tens or hundreds of thousands of hours. The MTBF's of the ISS ORU's that were estimated before flight experience are given in an early version of the ISS Maintenance & Analysis Data Set.[12] These have been used to calculate the number of spares required to achieve a probability of an unrepairable life support failure of less than 1% per year.

Calculating the number of spares for active recycling systems differs from that for storage tanks. Storage tanks are in use until they are emptied or fail, and have a constant failure rate until then. Any tank can fail any time. For recycling life support ORU's, the spares are kept in storage. Only one unit is operating and the off-line spares have a negligible failure rate. The probability of not having a needed spare using cold spares is given by the Poisson distribution.

The Poisson pdf gives the probability, for failure rate f = 1/MTBF, that there will be exactly n(t) = x failures in time t.

$$\text{Poisson pdf } [n(t) = x] = (N * f * t)^x \, e^{-f * t} / x! \tag{1}$$

The Poisson distribution's mean value, which is the expected number of failures during the mission of length L, is N L/MTBF, where N is the number of systems operating. The probability of n(t) or fewer failures is the summation of the Poisson pdf from x equals 0 to n(t). The Poisson distribution is in Excel and Excel worksheets have been developed to compute the number of spares for multi-unit systems.[13]

For a small crew, only a single unit of each recycling subsystem must be operated. The number of spares for each ORU can be found so that the total probability of not having a pare when one is needed is less than 1% per year. For most ORU's two or three spares are needed, but many need only one and a few four and even five. The mass weighted average number of spares for each system is shown in Table 3. No data was found for the CRS. The overall average ORU number of spares needed for a less than 1% probability per year of insufficient spares is 2.59. The overall system mass increase is a factor of 3.59, including the operating unit and 2.59 spares.

Providing spares at the full system level, CRDA, etc., would require many more spares than using ORU's, since a set of ORU's can replace many failures but a full system spare can repair only one. The OGS and CDRA would require four spares and the WPA and UPA six to achieve a probability of an unrepairable life support failure of less than 1% per year. In actual operation, a few ORU's have had much lower MTBF's and much higher failure rates than estimated in the MADS. They would require many more spares than estimated here.

For larger missions, more than one operating unit is needed. The maximum crew for the Moon base was assumed to be 100. Multiple recycling systems will be needed, up to 25 for the CDRA, which now has several systems on ISS. With multiple units operating, the number of spares per unit to achieve an unrepairable life support failure of less than 1% per year will be lower by nearly half. We will consider a crew of 30. Table 4 shows the numbers of each system and spares required.

Table 4. Number of recycling system masses and spares for 30 crewmembers.

Acronym	System	# crewmembers per system	Units for 30 crew	Number of spares	Units plus spares	Redundancy
CDRA	Carbon Dioxide Removal Assembly	4	8	4.73	12.73	1.59
CRS	Carbon Dioxide Reduction System	4	8			
OGS	Oxygen Generator System	7	5	5.27	10.27	2.05
WPA	Water Processor Assembly	10	3	3.21	6.21	2.07
UPA	Urine Processor Assembly	8	4	4.49	8.49	2.12
					Average	1.96

Except for the CDRA, the number of spares is slightly larger than the number of operating units. The average redundancy is 1.96, less than the average redundancy of 2.59 for a single operating unit. Table 5 shows the average redundancy for crews of 1, 3, 10, 30, and 100.

Table 5. The average redundancy for crews of 1, 3, 19, 30, and 100.

Crewmembers	1	3	10	30	100
Average redundancy	3.59	3.59	2.74	1.96	1.42
Logarithmic curve fit	3.85	3.28	2.65	2.08	1.46

The average redundancy for different numbers of crewmembers, Ncrew, can be approximated by a logarithmic curve, where LN is the natural logarithm.

$$\text{Average redundancy} = 3.85 - 0.52*\text{LN}(\text{Ncrew}) \quad (2)$$

The curve fit numbers are shown in Table 5. The logarithmic curve fit will be used to compute the recycling redundancy for a 1% probability of having sufficient spares for one year. The development cost will include the operating units and all spares. The launch cost will include the operating units and the expected number of spares used during the mission of length L, which is the Poisson distribution mean value, N L/MTBF. The operating cost will be proportional to the development cost of the constant number of operating units.

IV. Life support system development cost

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

$$\text{Cost} = 5.65 * 10^{-4}\, Q^{0.59}\, M^{0.66}\, 80.6^{S}\, (3.81 * 10^{-55})^{(1/(IOC-1900))}\, B^{-0.36}\, 1.57^{D} \quad (3)$$

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).[14] The 1999 to 2018 inflation correction will be applied.[15]

The AMCM is based on 260 government aerospace programs.[14] These include ships, aircraft, missiles and planetary and manned spacecraft.[16] The AMCM incorporates scaling according to quantity, Q, and mass, M.

V. Resupply development cost for a Moon base

Tables 6 and 7 show the AMCM parameters for resupply development cost for a Moon base. Table 6 gives values for the current containers and Table 7 for new design large containers.

Table 6. AMCM parameters for resupply using current containers.

Symbol	Parameter	LiOH canisters	Oxygen tanks	Water tanks
Q	Quantity	Ncrew*Mdays/4.0	Ncrew*Mdays/42.1	Ncrew*Mdays/10.6
M	Mass, lb	3.96	27.94	46.64
S	Specification	2.39	2.39	2.39
IOC	Initial Operational Capability	2030	2030	2030
B	Block	7	20	2
D	Difficulty	-3	-3	-3

Table 7. AMCM parameters for resupply using new large containers.

Symbol	Parameter	LiOH canisters	Oxygen tanks	Water tanks
Q	Quantity	Ncrew*Mdays /769	Ncrew*Mdays /1,190	Ncrew*Mdays /103
M	Mass, lb	440.00	660.00	440.00
S	Specification	2.39	2.39	2.39
IOC	Initial Operational Capability	2030	2030	2030
B	Block	1	1	1
D	Difficulty	-1.5	-1.5	-1.5

The quantity of containers needed increases directly with the product of the number of crewmembers and the mission length, Ncrew (CM) * Mdays (d), which gives the number of crewmember days for the mission. Table 2 gives the container capacity, Ccont (CM-d), which is the number of crewmember days provided by each container.

$$\text{Q resupply} = \text{Ncrew} * \text{Mdays} / \text{Ccont} \tag{4}$$

The empty container masses, M, that determine cost are given in kilograms in Table 2 but are converted into pounds in Tables 6 and 7. The specification, S, and the initial operation capability date, IOC, are the same for all life support systems considered here. The specification, S, is 2.39 for a planetary base. The IOC date was set to 2030

The block, B, or hardware generation varies. LiOH has been used 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.[2] The Shuttle had twenty-four internal gas pressure vessels, many of different design, 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.[9] 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.[2] The new large containers would be block 1, first generation.

The resupply difficulty was set to -3, very extremely easy, for the current well known technology of gas pressure tanks, water tanks, and material containers. The difficulty was set to -1.5 for the new design tanks, which would pose new challenges in obtaining material stock and developing tooling.

VI. Recycling development cost for a Moon base

Table 8 shows the AMCM parameters for recycling systems development cost for a Moon base.

Table 8. AMCM parameters for recycling systems development cost.

Symbol	Parameter	CDRA	CRS	OGS	WPA	UPA
Q	Quantity	Fn(Ncrew)]/4	Fn(Ncrew)]/4	Fn(Ncrew)]/7	Fn(Ncrew)]/10	Fn(Ncrew)]/8
M	Mass, lb	442	40	249	1,047	282
S	Specification	2.39	2.39	2.39	2.39	2.39
IOC	Initial Operational Capacity	2030	2030	2030	2030	2030
B	Block	2	2	2	2	2
D	Difficulty	0	0	0	0	0

The quantity of operating recycling systems needed increases directly with the number of crewmembers. Table 3 gives the system capacities in number of crewmembers.

$$\text{Q operating, recycling} = \text{Ncrew} / \text{system capacity in CM} \quad (5)$$

As shown in equation 2, the required recycling redundancy also depends on the number of crew members. The total quantity of operating units and spares for recycling systems is given by

$$\text{Q operating + spares} = \text{redundancy} * \text{Q operating} = [3.85 - 0.52*\text{LN(Ncrew)}]\ \text{Ncrew/system capacity} \quad (6)$$

This can be simplified for Table 8 entry.

$$\text{Q operating + spares} = \text{Fn(Ncrew)]/system capacity} \quad (7)$$

The system hardware masses, M, that determine cost are given in kilograms in Table 3 but are converted into pounds in Table 8. The specification, S, and the initial operation capability date, IOC, are the same for all life support systems considered here. The specification, S, is 2.39 for a planetary 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 space technology. The recycling development difficulty, D, was set to 0, average.

VII. Launch cost

Commercial rockets have greatly reduced the cost to launch to Low Earth Orbit (LEO). Launch to LEO is a small part of the total cost to emplace mass on the Moon.

A. The cost to launch to LEO has been reduced

The space shuttle carried 27,500 kg to LEO.[17] The initially planned space shuttle budget was 4 billion dollars per year for 10 launches, 400 million dollars per launch. Actual costs were higher due to a lower than planned launch rate of about four per year.[18] The real incremental cost per launch was 1.2 billion dollars, which is 1.7 billion in current dollars.[19] The cost per kilogram for shuttle launch to LEO was $1,700 M/27,500 kg = $62 k/kg in current dollars.[20]

The Falcon 9 launches 22,800 kg to LEO at a cost of 62 million dollars, so the launch cost is $2.7 k/kg. The Falcon Heavy launches 63,800 kg to LEO at a cost of 90 million dollars, for a launch cost is $1.4 k/kg.[21] The actual space shuttle cost was twenty-three or forty-four times higher in current dollars. The new low launch cost makes resupply and storage life support very much cheaper than before, which is more favorable to choosing resupply and storage life support over recycling.

B. The cost to emplace mass on the Moon is much higher

The moon base cost per kg of payload is much higher than for LEO. The mass that must be placed in LEO includes the rockets and propulsion mass needed to take a surface payload to the Moon. 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) divided by the payload mass. To send hardware from LEO to lunar orbit and then land it on the surface has a gear ratio of 6.6. A reasonable launch cost for a Moon base would be about 10,000 $/kg, based on the Falcon Heavy cost of 1,400 $/kg and a Moon base gear ratio of 6.6. A range of 1,000 $/kg to 100,000 $/kg will be considered.

The total mass of the resupply containers that must be launched is equal to the mass of the filled containers from Table 2 times the quantities of containers from Tables 6 and 7. The total mass of the recycling systems that must be launched is equal to the mass of the recycling systems from Table 3 times the quantities of operating units , Q operating, from equation 5 plus the expected number of failed units during a mission of length Mdays, which is the Poisson mean value, Q operating * Mdays/MTBF.

VIII. Operations cost

The space operations phase of most human missions has been short, but ISS and probably a future lunar surface base will operate for a decade or more. 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) or 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) or 10.4% of development cost per year, not including launch.[14] The JSC Mission Operations Cost Model (MOCM) estimates the operations cost per year as 10.9% of the total development and production cost.[22]

The resupply operating cost will be proportional to the container development cost, but the containers will be built, filled, launched, emptied, and discarded. Only a small portion of those used over the base mission duration will be in use at any one time. The operations cost will depend on the number of tanks and containers in actual service, estimated to be one year's supply. The resupply operations cost is set at 11% of the cost on one year's tanks and containers.

$$\text{Resupply operations cost} = 0.11 * \text{Cost one year's containers} \tag{7}$$

The recycling operating cost will be proportional to the development cost of the operating units, Q operating.

$$\text{Recycling operations cost} = 0.11 * \text{Cost of Q operating units} * \text{Mdays}/365 \tag{8}$$

IX. Life Cycle Cost for resupply and recycling for a Moon base

The three components of Life Cycle Cost are the development, launch and operations costs. These cost components have been determined above for resupply and recycling life support for a Moon base. The costs have three variable parameters, launch cost, crew size, and mission duration. The LCC is estimated for resupply and recycling over a range of launch costs, crew sizes, and mission durations. Recycling is more cost effective than resupply for higher launch cost, greater crew size, and longer mission duration. The breakeven mission duration, when recycling becomes less costly than resupply, is determined for different launch costs and crew sizes.

The LCC's were computed for different crew sizes and mission durations for different launch costs. The AMCM was used to estimate development costs for the three kinds of resupply containers and five different recycling systems, with the quantities of each depending on the crew size and mission durations. The recycling development cost included all operating units and spares needed to ensure high reliability. The total launch cost was computed for different launch costs per kilogram to the lunar surface using the masses of the filled containers or the recycling systems. Only the spares needed for expected recycling failures were included in launch cost. The operations cost was set at eleven percent per year of the development cost either of one year's containers or of all the recycling systems required.

Figure 1 shows the breakeven date between resupply and recycling for different numbers of crewmembers and different launch costs.

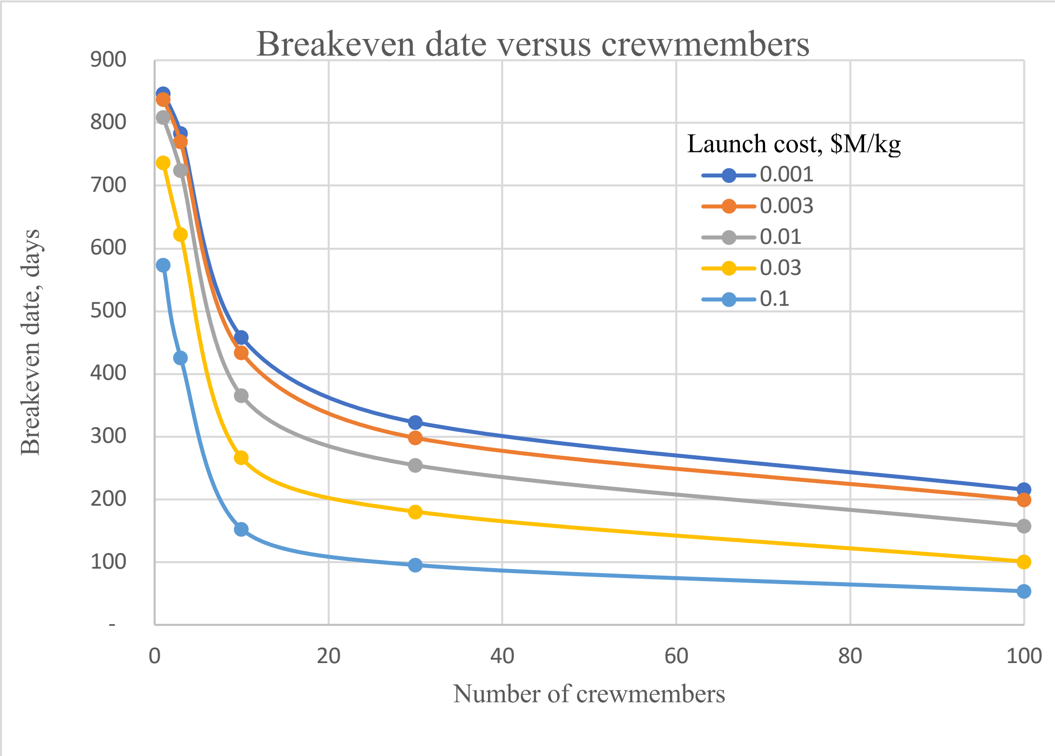

Figure 1. Breakeven date versus number of crewmembers for different launch costs.

The breakeven date ranges from about 400 to more than 800 days for a few crewmembers, dropping to about 50 to 200 days for 100 crewmembers. Curves are shown for lunar emplacement costs per kilogram varying from 0.001 $M/kg ($1 k/kg) to 0.1 $M/kg ($100 k/kg). The launch costs are for lunar surface emplacement, the cost to LEO times the gear ratio. The maximum launch cost increase reduces the breakeven date from 215 to 54 days for 100 crewmembers, a factor of four The effect of launch cost is directly shown in Figure 2, which gives breakeven date versus launch cost for different crew sizes.

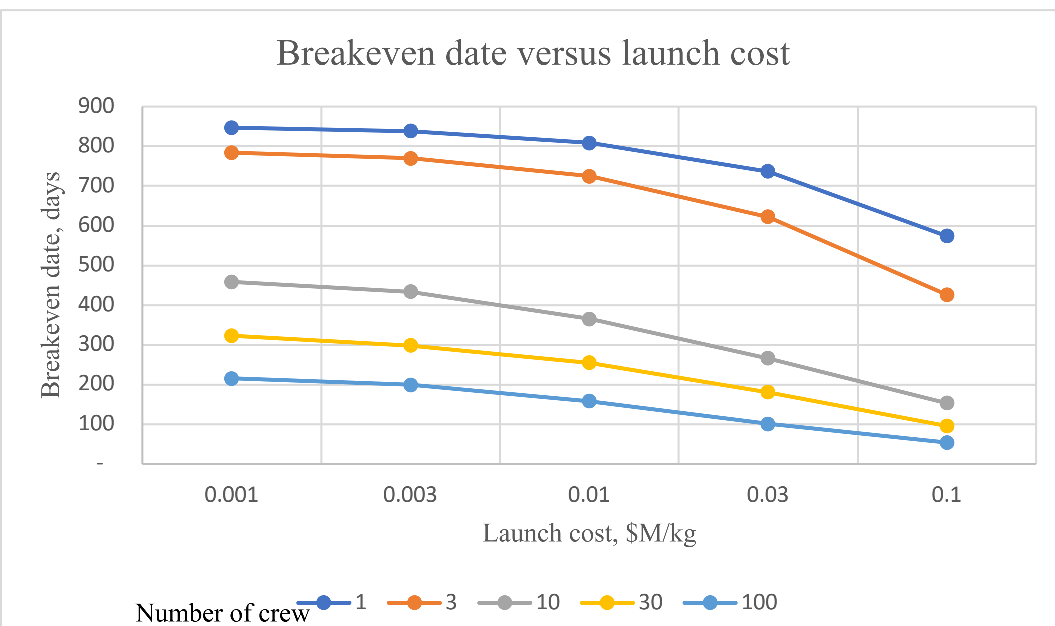

Figure 2. Breakeven date versus launch cost for different crew sizes.

Launch cost affects breakeven date less than crew size affects breakeven date. The crew sizes considered are 1, 3, 10, 30, and 100. For a launch cost of 0.1 $M/kg (100 k/kg), increasing crew size from 1 to 100 reduces the breakeven date from 574 to 54, a factor of more than 10.

Figure 3 shows the total life support cost versus mission length for a launch cost of 0.01 $M/kg (10 $k/kg).

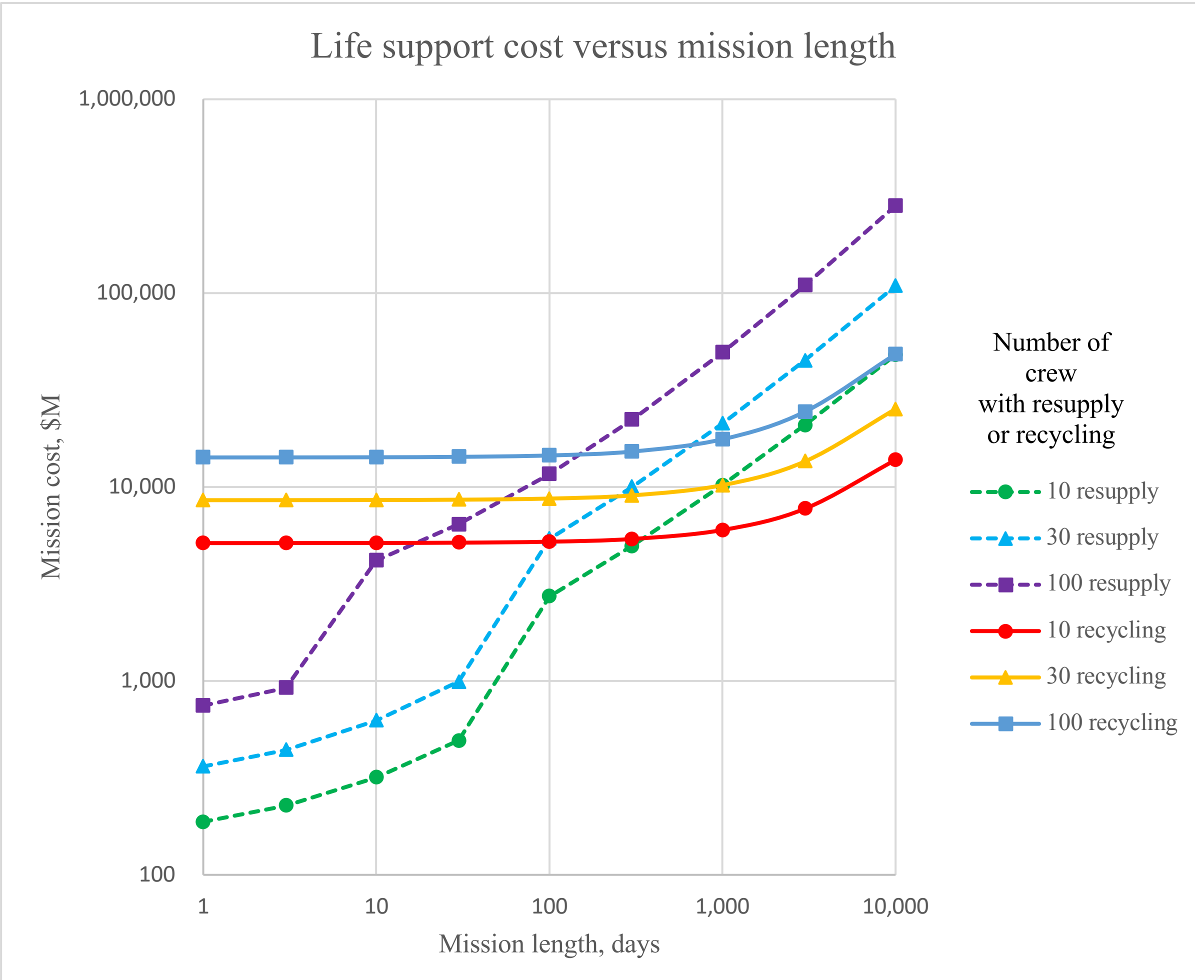

Figure 3. Life support cost versus mission length for a launch cost of 0.01 $M/kg ($10 k/kg).

Costs are given in 2019 $M. The costs are shown for crews of 10, 30, and 100. Resupply costs are shown dotted and recycling with solid lines. The mission length varies from 1 to 10,000 days. The breakeven dates for crews of 10, 30, and 100 are 365, 254, and 158 days respectively.

The recycling costs are nearly constant up to past 100 days, but then increase as the operating cost increases directly with mission duration. The resupply costs increase constantly with mission duration because the containers developed and material launched also increase directly with mission duration. The resupply development costs increase by a factor of 3.4 when the new design large containers are first used, which is when the number of crewmember-days first equals 1,000.

Typical life support estimated costs are about 10,000 $M, or 10 billion dollars. Resupply for small crews and short missions would cost less than 1 billion dollars, but recycling cost for large long missions could be several 10's of billions of dollars.

Figure 3 corresponds to a lunar surface emplacement cost of 0.01 $M/kg (10 k/kg). Higher launch costs move the resupply cost curves up and lower launch costs move them down. The recycling curves are essentially unchanged since launch cost is only a small part of recycling cost.

Two potential cost factors of recycling systems are not reflected here. First, it is assumed that the ORU MTBF's are well known, so that all failures can be repaired using the computed number of spares. The ISS experience has shown that a few ORU's can have unexpectedly high failure rates and low MTBF's so that the expected number of spares is far too few to repair all failures. Second, comparisons of systems using the total launch mass, which includes the mass of the power and cooling systems needed to support the recycling systems, find that the this total launch mass can be much higher than the recycling system mass alone. This suggests that including the allocated costs for power and cooling may significantly increase the total cost of recycling systems.

A. ISS life support life cycle cost check

An earlier paper estimated that the total cost of the ISS recycling life support system was roughly 2 billion dollars, one billion for hardware development, and one billion for launch and operations. This is a very uncertain estimate based on current spares procurement costs. This cost included 0.95 billion for development of one complete life support system and three sets of spares, 0.34 billion for shuttle launch of the system and two sets of spares at a launch cost of 61 $M/kg, and 0.60 billion for fifteen years of operation based on 10% per year of the 0.40 billion development cost of one system and one set of spares.[23]

A quick rough check can be made using Figure 3. The ISS life support cost is for 4 crew and 15 years or 5,475 days. In Figure 3, the recycling curve for 10 crew and about 6,000 days has a cost of about 10 billion dollars. Reducing this cost by the crew ratio of 4 to 10 suggests that a system for a crew of four might have a life cycle cost of 4 billion dollars, which is 2 times higher than the earlier ISS life support estimate of 2 billion dollars.

A directly computed check can be made using the life cycle cost estimation process used to generate Figure 3. For 4 crew and 5,475 days, the computed mission cost is 6.0 billion dollars, a factor of 3 times higher than the ISS life support estimate of 2 billion dollars.

The agreement between the different estimates is surprisingly good. Cost errors and uncertainties of a factor of 2 or 3 are common in large aerospace projects. A factor of 2 or 3 is small compared to the three orders of magnitude range of costs plotted in Figure 3. Because of the poor quality and uncertainties in cost estimates, cost estimates probably should not force a design decision unless the estimated cost difference is larger than a factor of 2 or 3.

X. Development, launch, and operations cost breakdown

Cost breakdowns versus duration are shown for resupply and recycling for 30 crew and 0.01 $M/kg launch cost. Figure 4 shows development, launch, and operations costs for resupply for missions of 3 to 300 days.

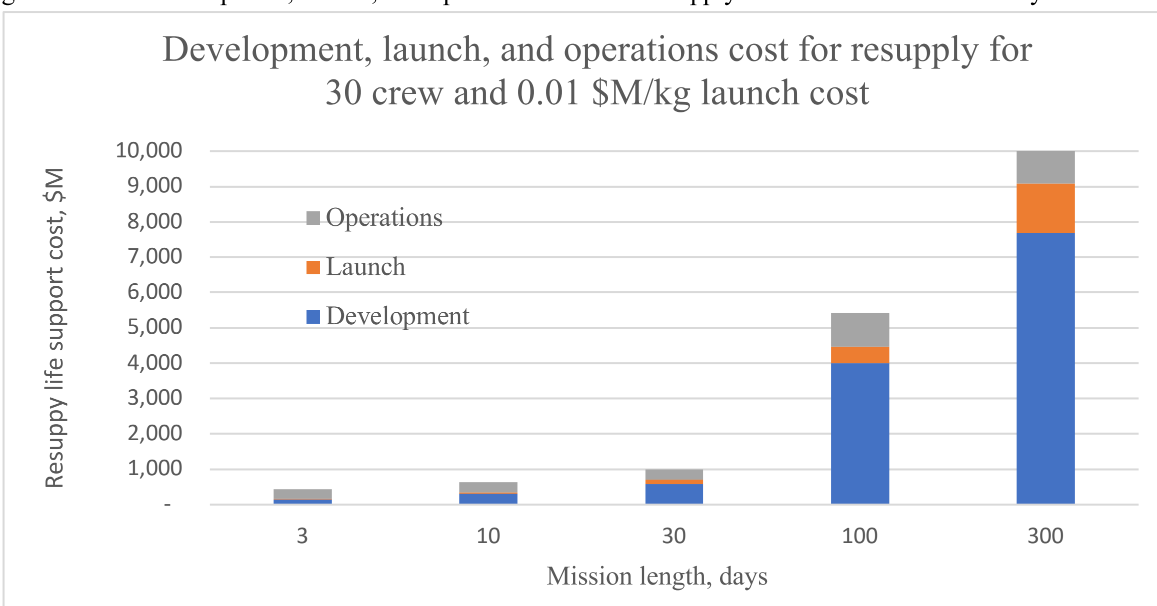

Figure 4. Cost breakdown for resupply for 30 crew and 0.01 $M/Kg launch cost

As shown earlier in Figure 3, total resupply cost increases very rapidly for missions longer than 300 days and recycling then usually saves cost. Storage tank development is always the largest resupply cost, even at 10,000 days (not shown). With 30 crewmembers, storage development cost is higher after 100 days because new larger more expensive containers are then used. The launch cost increases directly with mission length since it is proportional to the crew consumed mass. Interestingly, with the new much lower launch costs, launch cost is no longer the largest cost component for resupply. The operations cost does not increase as rapidly as the total development cost because it was assumed that only one year's supply of containers would be in simultaneous operational use.

Figure 5 shows development, launch, and operations costs for recycling for missions of 100 to 10,000 days.

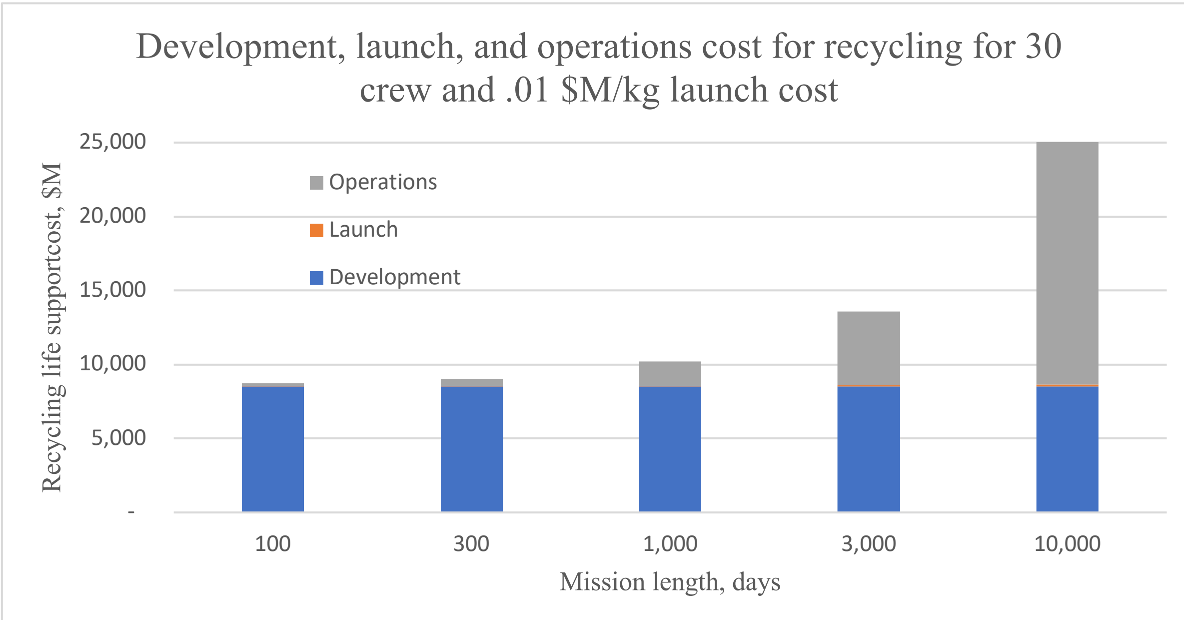

Figure 5. Cost breakdown for recycling for 30 crew and 0.01 $M/Kg launch cost

As shown earlier in Figure 3, total recycling cost stays nearly constant out to about 300 days. The fundamental recycling cost is for the development of the operating system and spares. This cost is constant for any length mission. The launch cost of recycling systems is very low because their mass is very low. Recycling was developed to save launch cost and does so. The operations cost is estimated at 11% per year of the development cost of the operating units, not including all spares. The operations cost increases directly with mission length. It equals the original development cost in about 5,000 days or 14 years.

XI. Conclusion

Resupply and recycling have often been compared and breakeven dates computed using launch mass. It is well known that recycling saves more mass for larger crews and longer missions. However, launch cost is only one component of life cycle cost and, with the recent significant decline in launch cost, it has become relatively small compared to development cost and even operations cost for multi-year missions.

This comparison of resupply and recycling includes the full life cycle cost for development, launch, and operations. Reliability and risk are considered and affect the costs through the number of spares that must be built and launched. The results for a lunar base suggest that crews larger than 10 and missions longer than a year are needed for recycling to save cost compared to resupply. The recycling cost savings can become very large for much larger crews and longer missions.

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