The Life Cycle Cost (LCC) of Life Support Recycling and Resupply

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Brief human space missions supply all the crew's water and oxygen from Earth. The multiyear International Space Station (ISS) program instead uses physicochemical life support systems to recycle water and oxygen. This paper compares the Life Cycle Cost (LCC) of recycling to the LCC of resupply for potential future long duration human space missions. Recycling systems have high initial development costs but relatively low duration-dependent support costs. This means that recycling is more cost effective for longer missions. Resupplying all the water and oxygen requires little initial development cost but has a much higher launch mass and launch cost. The cost of resupply increases as the mission duration increases. Resupply is therefore more cost effective than recycling for shorter missions. A recycling system pays for itself when the resupply LCC grows greater over time than the recycling LCC. The time when this occurs is called the recycling breakeven date. Recycling will cost very much less than resupply for long duration missions within the Earth-Moon system, such as a future space station or Moon base. But recycling would cost about the same as resupply for long duration deep space missions, such as a Mars trip. Because it is not possible to provide emergency supplies or quick return options on the way to Mars, more expensive redundant recycling systems will be needed.

Nomenclature

AMCM	=	Advanced Missions Cost Model
BED	=	Breakeven Date, days
D	=	Duration, days
DM	=	Dry Mass, kg
HDCF	=	Hardware Development Cost Factor, $M/kg
HDCR	=	Hardware Development Cost Rate, $M/day
ISS	=	International Space Station
LCC	=	Life Cycle Cost, $M
LEC	=	Launch and Emplacement Cost, $M/kg
LEO	=	Low Earth Orbit
LiOH	=	Lithium hydroxide
LMR	=	Logistics Mass Rate, kg/day
M	=	Mass, kg or lb
N	=	Number of crew
OCF	=	Operations Cost Factor, /day
Q	=	Quantity
RC	=	Recycle
RS	=	Resupply
T	=	Time, days
WM	=	Wet Mass, kg

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I. Introduction

THIS paper investigates and compares the Life Cycle Cost (LCC) of space life support systems that either recycle life support materials or resupply them from Earth. Equations for the LCC of life support are developed and the parameters driving the costs are identified. The LCC of recycling and resupply is estimated and compared for four potential future human missions; a future space station, a moon base, a Mars transit vehicle, and a Mars base.

II. Life Cycle Cost (LCC)

The LCC of a space system includes its development cost, its launch and emplacement cost, and its operations cost.

$$\text{LCC} = \text{development cost} + \text{launch and emplacement cost} + \text{operations cost} \tag{1}$$

The cost of developing a space system is usually assumed to be proportional to its Dry Mass (DM). The Hardware Development Cost Factor (HDCF) is the cost of developing hardware in dollars per kilogram ($/kg). If the system requires a total flight Dry Mass of DM kg, its hardware development cost is HDCF * DM $.

The system mass that must be launched and emplaced includes the hardware system Wet Mass (WM) and the logistic supplies including the spare parts and materials required to operate the system. The cost of the spare parts is included in the hardware development cost. The logistics materials mass is measured by the Logistics Mass Rate (LMR) in kg/day. The total logistics mass over a certain mission Time (T) is LMR * T kg.

The life support system mass has a cost for launch and emplacement. The total launched and emplaced system mass is the Wet Mass, WM, plus the time increasing logistics mass, WM + LMR * T. The cost to place a kilogram of hardware or materials at the mission location is the Launch and Emplacement Cost (LEC) in $/kg. The launch and emplacement cost is then (WM + LMR * T) * LEC $.

The system operations cost is usually assumed to be proportional the product of its development cost, HDCF * DM $, and the mission Time, T. The Operations Cost Factor (OCF) is the fraction of the total development cost spent on operations each year. The total mission operations cost is HDCF * DM * OCF *T.

The total LCC of a space life support system is then:

$$\text{LCC} = \text{HDCF} * \text{DM} + (\text{WM} + \text{LMR} * \text{T}) * \text{LEC} + \text{HDCF} * \text{DM} * \text{OCF} * \text{T} \tag{2}$$

LCC directly depends on fundamental parameters; the Hardware Development Cost Factor (HDCF), the hardware Dry Mass (DM) and Wet Mass (WM), the Logistics Mass Rate (LMR), the mission Time (T), the Launch and Emplacement Cost (LEC), and the Operations Cost Factor (OCF).

A. The Life Cycle Cost (LCC) of resupply and recycling systems

The LCC formulas and most parameters differ significantly between recycling and resupply life support systems. The parameters and cost elements for recycling will be indicated by #RC. The LCC for a recycling system is then:

$$\text{LCC\#RC} = \text{HDCF\#RC} * \text{DM\#RC} + (\text{WM\#RC} + \text{LMR\#RC} * \text{T}) * \text{LEC} + \text{HDCF\#RC} * \text{DM\#RC} * \text{OCF} * \text{T} \tag{3}$$

The mission Time (T), Launch and Emplacement Cost (LEC), and the Operations Cost Factor (OCF) are identical for recycling and resupply. A recycling system would have a high fixed initial mass and cost and a relatively low time dependant logistics mass. A resupply life support system provides water, oxygen, and carbon dioxide removal material in containers. Little material is needed for very brief missions. A resupply system would have essentially zero fixed initial mass and cost and a high time dependant logistics mass. The parameters and cost elements for resupply will be indicated by #RS. The LCC for a resupply system is then:

$$\text{LCC\#RS} = \text{HDCR\#RS} * \text{T} + \text{LMR\#RS} * \text{T} * \text{LEC} + \text{HDCR\#RS} * \text{T} * \text{OCF} * \text{T} \tag{4}$$

Equation 4 for LCC#RS still includes the three terms for development, launch and emplacement, and operations costs, but differs for equation 3 for LCC#RC. Resupply has no initial hardware dry mass. The first term includes the Hardware Development Cost Rate for resupply (HDCR#RS), which reflects how the cost of the dry mass of containers increases with time. The resupply development cost is HDCR#RS * T. Resupply has no initial wet mass to launch. The time dependant mass of containers and materials is included in the Logistics Mass Rate for resupply (LMR#RS). The operations cost is the resupply development cost, HDCR#RS * T, times the Operations Cost Factor multiplied by Time, OCF*T. Since the mass and development cost of containers increases with the mission time, and the operations cost increases with both the development cost and mission time, the operations cost for resupply increases as time squared. The mission Time (T), Launch and Emplacement Cost (LEC), and the Operations Cost Factor (OCF) are identical for recycling and resupply.

B. Recycling-resupply Breakeven Date (BED)

Resupply systems have near zero initial cost but high, time-increasing development, launch, and operations costs. Recycling systems have very high initial development cost and relatively low time increasing logistics costs. Resupply systems have low mass and cost for short missions and high mass and cost for long missions. Recycling systems have slowly increasing mass and cost with mission time. There is usually a breakeven mission date before which resupply has lower LCC and after which recycling has lower LCC. The breakeven date is a convenient way to compare resupply and recycling.

At the breakeven mission date, T = BED, and the LCC of recycling just equals the LCC of resupply. Beyond the LCC Breakeven Duration, BED, the large initial cost of recycling is more than paid for by the accumulating daily savings in resupply costs.

$$\text{LCC\#RC (T = BED)} = \text{LCC\#RS (T = BED)} \tag{5}$$

Simplified versions of the LCC in equations 3 and 4 aid analysis.

$$\text{LCC\#RC (T)} = \text{Constant LCC\#RC} + \text{T} * \text{Variable LCC\#RC} \tag{6}$$

$$\text{LCC\#RS (T)} = \text{T} * \text{Variable LCC\#RS} \tag{7}$$

To find BED,

$$\text{Constant LCC\#RC} + \text{BED} * \text{Variable LCC\#RC} = \text{BED} * \text{Variable LCC\#RS} \tag{8}$$

$$\text{BED} = \text{Constant LCC\#RC}/[\text{Variable LCC\#RS} - \text{Variable LCC\#RC}] \tag{9}$$

The breakeven date occurs when the constant LCC of recycling is just paid for by the accumulated daily LCC savings of recycling over resupply.

C. Approximate Breakeven Date (BED)

Rather than expand BED using the full detailed versions of equations 3 and 4, the usually less important parameters are set to zero to provide an approximate BED. The approximate BED is hoped to have useful-enough rough accuracy and to help call attention to the major cost drivers.

$$\text{Approximate BED} = (\text{HDCF\#RC} * \text{DM\#RC})/(\text{HDCR\#RS} + \text{LMR\#RS} * \text{LEC}) \tag{10}$$

In the approximate BED, all the recycling launch and emplacement costs and the operations costs have been set to zero. This is equivalent to setting the recycling Wet Mass (WM#RC) and Logistics Mass Rate (LMR#RC) and the Operations Cost Factor (OCF) all to zero. The hardware development cost is assumed to dominate the recycling costs. The resupply operations cost has also been set to zero. The time dependent hardware development and launch and emplacement costs are assumed to dominate resupply costs.

The exact BED is determined by setting the LCC#RC of equation 3 equal to the LCC#RS of equation 4. Later work shows that the approximate BED is between ½ and 2 times the exact BED.

D. Approximate Breakeven Date (BED) analysis

The approximate BED can be factored for analysis.

$$\text{Factored approximate BED} = (\text{DM\#RC}/\text{LMR\#RS}) * [\text{HDCF\#RC}/(\text{LEC} + \text{HDCR\#RS}/ \text{LMR\#RS})] \tag{11}$$

The first term in the factored approximate BED, DM#RC/LMR#RS, is the dry hardware mass of the recycling system divided by the daily amount of resupply logistics materials that would be saved by recycling. This first term is essentially the mass breakeven date, when the recycling hardware mass is paid for by the resupply mass saved. The larger the recycling system mass is compared to the daily mass savings, the more delayed is the recycling mass breakeven date. The greater the daily resupply logistics mass, the earlier will be the recycling breakeven date. A more accurate mass breakeven date would include neglected factors, the wet instead of the dry recycling mass, WM#RC for DM#RC, and the recycling Logistics Mass Rate, LMR#RC, would be subtracted from the resupply Logistics Mass Rate, LMR#RS.

The second term is the recycling Hardware Development Cost Factor, HDCF#RC, divided by the Launch and Emplacement Cost, LEC, plus the resupply Hardware Development Cost Rate, HDCR#RS, divided by the resupply Logistics Mass Rate, LMR#RS. The HDCF#RC numerator converts recycling mass to recycling cost. The LEC + HDCR#RS/ LMR#RS denominator converts resupply Logistics Mass Rate, LMR#RS to the sum of the resupply launch cost per day plus resupply hardware development cost per day. If the Hardware Development Cost Factor for recycling, HDCF#RC, is much greater than the resupply launch and emplacement cost, LMR#RS * LEC, the recycling cost breakeven date will be much later than the mass breakeven date. If the resupply Hardware Development Cost Rate, HDCR#RS, is large compared to the resupply launch and emplacement cost, LMR#RS * LEC, the recycling cost breakeven date will be further delayed.

E. Typical Breakeven Dates (BED's)

Typical values based on later results would be DM#RC = 100 to 300 kg per crewmember including redundant systems and LMR#RS = 10 kg per day per crewmember. The first term in equation 11, the mass breakeven date, DM#RC/LMR#RS, is then 10 to 30 days. The second term is the recycling Hardware Development Cost Factor, HDCF#RC, divided by the Launch and Emplacement Cost, LEC, plus the resupply Hardware Development Cost Rate, HDCR#RS, divided by the resupply Logistics Mass Rate, LMR#RS. It can also be about 10 to 30. The LCC breakeven date, BED, can then range from 100 to 900 days. This is shown in Figure 1.

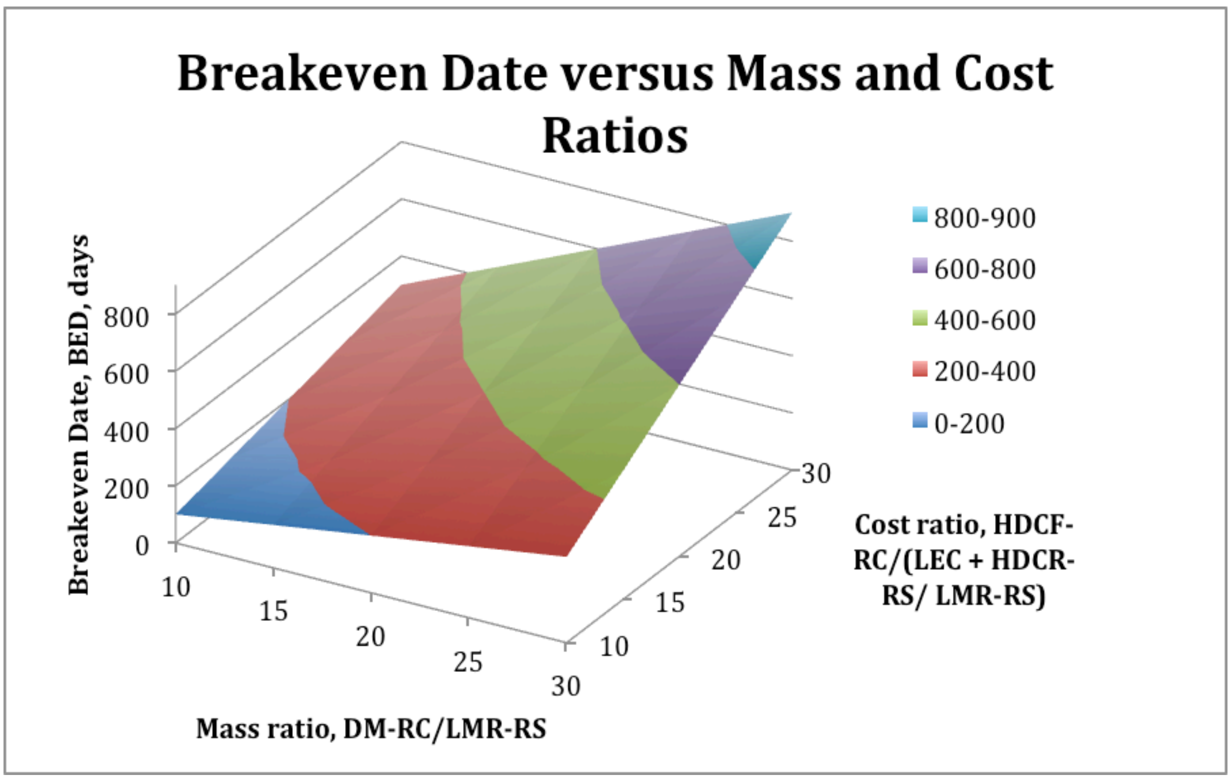

Figure 1. Breakeven date versus launch mass breakeven date and hardware/launch cost ratio.

The approximate cost Breakeven Date, BED, is shown on the BED axis of Figure 1. It is the product of the launch mass breakeven date, shown on the mass ratio axis and the cost ratio of total recycling hardware cost per kilogram to launch plus resupply hardware development cost per kilogram, shown on the cost ratio axis. LCC breakeven date is 10 to 30 times longer than the mass breakeven date.

F. Breakeven Date summary

The life cycle cost of a space hardware system consists of its development, launch and emplacement, and operations costs. Cost drivers include hardware dry mass, logistics mass, launch cost, operations costs, and mission length. Life support recycling systems have a high initial hardware development cost and relatively low logistics requirements, while resupply systems have a low mass for brief missions, but the mass increases rapidly with mission duration. Recycling saves cost when the accumulated cost over time of resupply would exceed that of recycling, which occurs at the recycling-resupply cost breakeven date. The cost breakeven date is approximately the cost of the recycling system divided by the sum of the daily increases in the resupply launch and development cost.

III. Life Cycle Cost (LCC) for a future space station, moon base, Mars transit, and Mars base

The LCC for life support recycling and resupply will be computed for a space station, moon base, Mars transit vehicle, and Mars base. The Life Cycle Cost (LCC) and its three components are shown in Table 1.

Table 1. Life Cycle Cost (LCC) components for a space station, moon base, Mars transit vehicle, and Mars base.

	Space station		Moon base		Mars transit		Mars base	
Mission duration, days	3,650		3,650		365		500	
	Recycling	Resupply	Recycling	Resupply	Recycling	Resupply	Recycling	Resupply
Hardware development cost, $M	151	1,020	492	3,412	700	321	2,978	1,646
Percent of LCC	47%	24%	46%	20%	81%	33%	86%	65%
Launch and emplacement cost, $M	7	2,084	31	9,874	83	626	44	629
Percent of LCC	2%	49%	3%	58%	10%	64%	1%	25%
Operations cost, $M	165	1,112	537	3,719	76	35	445	246
Percent of LCC	51%	26%	51%	22%	9%	4%	13%	10%
Life Cycle Cost, $M	323	4,217	1,060	17,005	859	982	3,467	2,521
Resupply LCC/ Recycling LCC	13.1		16.0		1.1		0.7	

The development costs, launch and emplacement costs, and operations costs are computed in the sections below. A fixed mission Duration, D, is used for to avoid using a time dependent equation for the resupply hardware mass and development cost. The life cycle cost components are given in Table 1 and in Figure 2.

For the 10 year long missions within the Earth-Moon system, the future space station and Moon base, life support using resupply costs 13 or 16 times as much as recycling. Launch and emplacement makes up half the cost of resupply and the hardware development and ten year operations cost are each about one quarter. Launch and emplacement cost is negligible for recycling, and the hardware development and ten year operations cost are each about half the total cost. All the cost components are much higher for resupply than recycling.

The cost components and relationships are different for the brief one-year Mars transit and 1 1/3 year Mars base. Triple redundant life support recycling is used for Mars, rather than the single string in the Earth-Moon system, and the difficulty was judged higher, so the recycling hardware development costs are five or six times higher for Mars. Hardware development cost is more than 80% of the Mars recycling LCC. For Mars, resupply is comparable to or slightly less costly than recycling. Resupply has significant costs for hardware development and launch and emplacement.

One significant implication is that, while recycling is far more cost effective than resupply for a space station or Moon base, resupply is clearly cost competitive for a Mars mission. Resupply life support for Mars would be much easier and faster to develop than recycling and is intrinsically simpler and more reliable. It is also notable that life support for a Moon base would be three times as costly as for a space station, and that life support cost for a full Mars mission, transit, base, and return, would be ten times higher than for a space station.

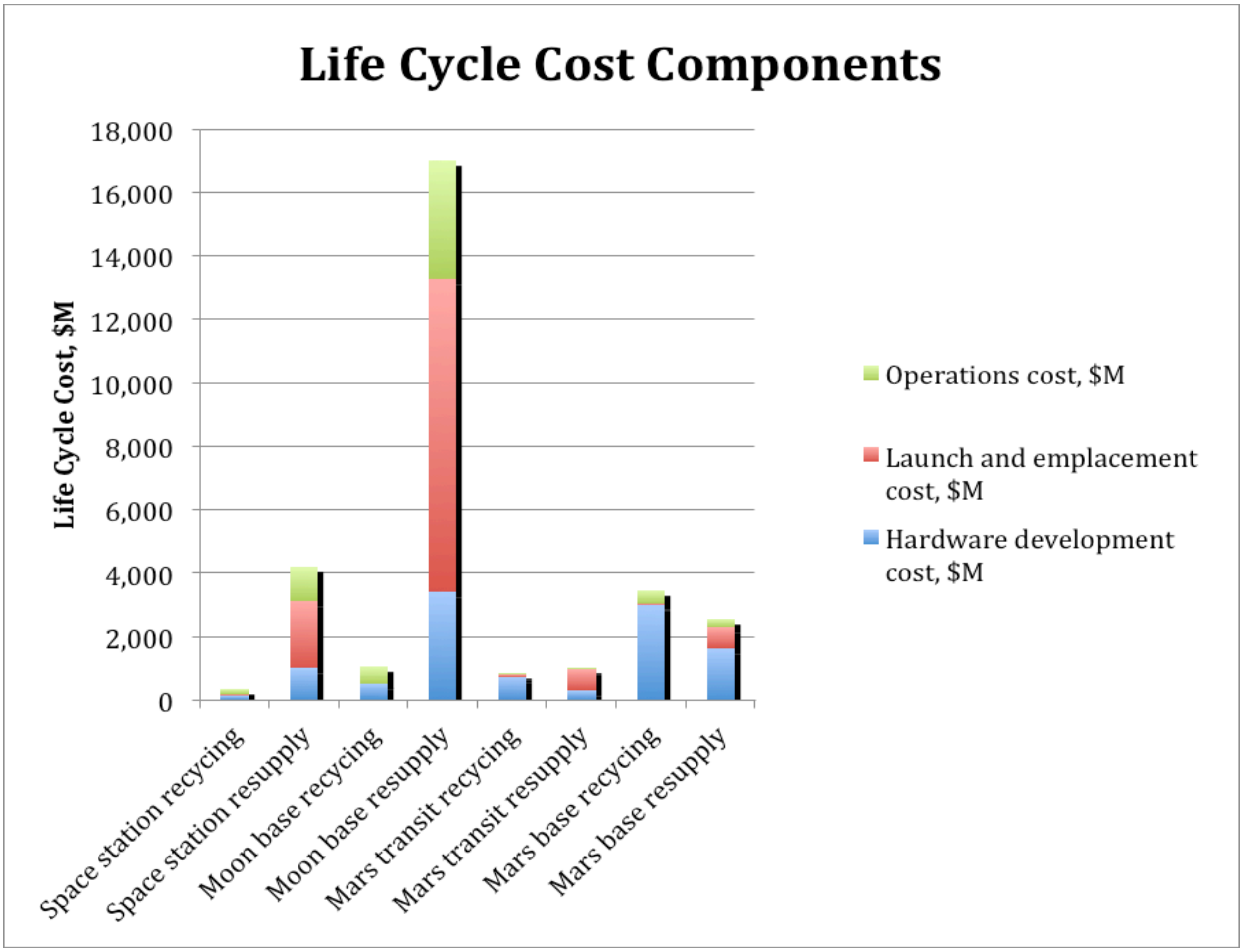

Figure 2. LCC components for a space station, moon base, Mars transit vehicle, and Mars base.

A. Hardware development costs

Hardware development costs can be estimated using the Advanced Missions Cost Model (AMCM). The AMCM is a single equation cost estimating relationship using mass, quantity, mission type, number of design generations, and technical difficulty to estimate the total system cost for design, development, test, evaluation, and production of multiple units.

1. The AMCM formula

The AMCM formula for the cost in millions of 1999 dollars is:

$$\text{Development and production cost} = \alpha\, Q^{\beta} M^{\Xi}\, {}^{\text{™}}{}^{S} \sum{}^{1/(IOC-1900)} B^{\varphi} \copyright^{D} \tag{12}$$

The Greek letter constants are:

$\alpha = 5.65 \times 10^{-4}$

® = 0.5941

$\in = 0.6604$

™ = 80.599

$\sum = 3.8085 \times 10^{-55}$

$\rangle = -0.3553$

© = 1.5691

Q is the total quantity of development and production units, M is the system dry mass in pounds, S specifies the type of mission (2.13 for human habitat, 2.46 for crewed planetary lander), IOC (Initial Operation Capability) is the first year of system operations, B is the hardware block or 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). (Guerra and Shishko 2000, pp. 946-7)

Table 2 shows the AMCM cost estimate parameters and results for a future space station, a moon base, a Mars transit vehicle, and a Mars base.

Table 2. AMCM cost estimates for a future space station, a moon base, a Mars transit vehicle, and a Mars base.

		Space station		Moon base		Mars transit		Mars base	
D	Mission duration, days	3,650		3,650		365		500	
AMCM parameter		Recycling	Resupply	Recycling	Resupply	Recycling	Resupply	Recycling	Resupply
Q	Quantity	1	1,825	1	1,216	3	122	3	167
M	Mass, lb	1,452	37.3	968	37.3	968	37.3	968	37.3
M	Mass, kg	660	37	440	37	440	37	440	37
S	Specification	2.13	2.13	2.46	2.46	2.13	2.13	2.46	2.46
IOC	Initial date	2030	2030	2030	2030	2030	2030	2030	2030
B	Block	2	1	2	1	1	1	1	1
D	Difficulty	-1	-3	-1	-3	1	-2	1	-2
	Hardware development cost, $M	151	1,020	492	3,412	700	321	2,978	1,646

The hardware development costs are produced directly by the AMCM. A fixed mission Duration, D, is used to avoid using a complicated time dependent equation for the resupply hardware mass and development cost. The future space station and moon base are assumed to have a mission duration, D, of 10 years or 3,650 days. The Mars transit is assumed to take one year, 365 days, for a round rip. The Mars base surface stay is assumed to be 500 days. Mass, M, is given in lb to conform with the AMCM formula and in kg for later use.

2. *The AMCM parameters*

The AMCM specification, S, is 2.13 for a manned habitat such as a space station and Mars transit vehicle. It is 2.46 for a planetary lander such as a moon or Mars base. The IOC date was set to 2030 for all missions. The hardware block, B, was set to 2, second generation, for a future space station and a moon base, assuming that they would be based on the ISS design. B was set to 1, new design, for the new long duration resupply system and for the higher reliability multiply redundant Mars transit and Mars base recycling systems.

For Mars transit and Mars base recycling, the difficulty, D, is estimated to be 1, above average. Recycling physical-chemical technology is not especially difficult in itself, but Mars presents requirements for high reliability and multiple diverse redundancy. The recycling difficulty was set to -1, less than average, for a future space station and moon base since emergency resupply or crew return are possible. The storage systems for resupply are much less difficult. The resupply difficulty was set to -3, extremely easy, for a future space station and moon base. The resupply difficulty was set to -2, easy, for Mars transit and a Mars base.

3. *Recycling system hardware mass, quantity, and logistics*

The recycling system mass is taken from the "Mars Design Example" in *Human Spaceflight: Mission Analysis and Design*. (Connelly) The Mars habitat-lander has six crew and uses recycling life support similar to the International Space Station (ISS). The proposed life support provides carbon dioxide removal using a 4-bed Molecular Sieve (4BMS), trace contaminant removal using a Trace Contaminant Control System (TCCS), oxygen generation using a water electrolysis Oxygen Generation Assembly (OGA), and wastewater and urine recycling using a Vapor Compression Distillation (VCD) system. (Doll and Eckart, pp. 554, 558) (Connelly, p. 998) The single string, six crew, and total redundant system mass of the habitat-lander life support is shown in Table 3.

Table 3. Habitat-lander life support masses.

Subsystem		Single string mass, kg/crewmember	Six crew mass, kg	Redundancy	Total mass, kg
4BMS	Carbon dioxide removal	30	180	3	540
TCCS	Trace contaminant removal	20	120	3	360
OGA	Carbon dioxide removal	35	210	3	630
VCD	Oxygen generation	25	150	2	300
	Totals	110	660		1,920

The life support reliability is improved for Mars by providing dual or triple redundant subsystems. In addition, about 1.5 kg per crewmember day of water is provided by the food and can be used to make up system losses and supplement oxygen generation. No spares or logistics supplies are included. The ISS also uses multifiltration water processing and Sabatier carbon dioxide reduction, which are not included in the habitat-lander design.

Table 4 shows the estimated Number of crew, N, system hardware dry Mass, M, per recycling life support unit, the Quantity, Q, of redundant units, the initial launched Dry Mass, DM, and the Logistics Mass Rate, LMR, for a future space station, a moon base, a Mars transit vehicle, and a Mars base.

Table 4. Number of crew, mass per unit, redundancy, Dry Mass, DM, and Logistics Mass Rate, LMR, for recycling life support.

Parameter		Space station	Moon base	Mars transit	Mars base
N	Number of crew	6	4	4	4
M	Mass per unit, kg	660	440	440	440
M	Mass per unit, lb	1,452	968	968	968
Q	Quantity	1	1	3	3
DM	Dry Mass, kg	660	440	1,320	1,320
LMR	Logistics Mass Rate, kg/day	0	0	0	0

The single string mass of 110 kg/crewmember is multiplied by the number of crew to obtain the recycling life support unit dry mass. The space station and moon base systems are single string, not redundant. The Mars systems have triple redundant subsystems including the VCD.

4. Resupply system hardware mass, quantity, and logistics

A resupply life support system provides oxygen and water using tanks. Carbon dioxide is removed using lithium hydroxide (LiOH) canisters and trace contaminants are removed by activated charcoal in the LiOH canisters. The resupply launch mass consists of oxygen, water, and LiOH, in their tanks and containers. However, only the tanks and containers, not the oxygen, water, and LiOH, must be designed. The hardware mass used in the AMCM cost estimating equation is the mass of the tanks and containers.

A summary of the crew oxygen, water, and lithium hydroxide (LiOH) resupply rates is given in Table 5, in kg per crewmember per day.

Table 5. Oxygen, water, and LiOH logistics mass resupply rates, kg/crewmember - day.

		Material	Tanks and containers
Oxygen		0.84	0.34
Drinking and food preparation water	2.38		
Urine flush water	0.50		
Wash water	1.29		
Total water		4.17	0.83
LiOH		1.40	0.35
Material and container subtotals		6.41	1.52
Materials plus tanks and containers			7.93
Added resupply module structure			1.59
Resupply full weight			9.52
Resupply dry weight			3.11

The logistics requirements are 7.93 kg per crewmember per day, for materials and containers without additional packaging for a resupply module. The material crew supply requirements are based on space station analysis, except that showers, dish washing, and most of the crew hygiene water have been eliminated. As noted for recycling, about 1.5 kg per crewmember day of water is provided in the food or by food metabolism. (Reed and Coulter) (Wieland)

The storage tank mass estimates are 0.4 kg of tankage per kg of oxygen (BVAD, 2004, p. 31) and 0.2 kg of tankage per kg of water (ILO, p. 99). About 2 kg of LiOH is required to remove the 1 kg of carbon dioxide per crewmember per day. (Eckart, p. 192) The shuttle LiOH canister weighs 7 kg and is rated at 4 crewmember-days, which gives 1.75 in kg per crewmember per day. The mass of the LiOH canister is estimated to be 20 percent of the total mass of the LiOH and container or 0.35 kg.

For ease in providing and handling resupply, the oxygen, water, and LiOH will be packaged together in a combined resupply module holding a twelve crewmember-day provision. An additional twenty percent mass, 0.2 kg per kg, 1.59 kg, is allowed for the resupply module structure. The twelve crewmember-day resupply module has a dry weight of 37.3 kg and a full weight of 114 kg.

The Logistics Mass Rate (LMR) including materials, containers, and module is 9.52 kg/day for one crew, 57.1 kg/day for six crew, and 38.1 kg/day for four crew. The twelve crewmember-day module dry mass M is 37.3 kg. The number of resupply modules produced for each mission depends on the crew size and mission duration. If the Number of crewmembers is N and the mission duration is D days, the quantity Q of resupply modules is Q = N * D /12. A filled or wet combined resupply module would be provided every second day on a future space station and every third day on a moon base, a Mars transit vehicle, or a Mars base. The Logistics Mass Rate is LMR = 9.52 N kg/day.

Table 6 shows the mission duration, number of crew, dry mass for one combined resupply module, quantity of modules, and Logistics Mass Rate (LMR) for a future space station, a moon base, a Mars transit vehicle, and a Mars base.

Table 6. Number of crew, dry mass per module, quantity of modules, and Logistics Mass Rate (LMR) for resupply life support.

Parameter		Space station	Moon base	Mars transit	Mars base
D	Mission duration, days	3,650	3,650	365	500
N	Number of crew	6	4	4	4
M	Dry mass per module, kg	37.3	37.3	37.3	37.3
M	Dry mass per module, lb	82.1	82.1	82.1	82.1
Q	Quantity of modules	1,825	1,216	122	167
LMR	Logistics Mass Rate, kg/day	57.1	38.1	38.1	38.1

The resupply module development and production cost will depend on the dry mass, M, and quantity, Q, of the combined resupply modules. Varying M and Q in the resupply module design has little effect on cost. The total dry resupply container mass, M * Q, largely determines the development cost since Q and M have similar exponents in the AMCM cost estimation equation.

B. Launch and emplacement (L&E) costs

The usual cost for launch to LEO is about $10 k/kg. (Wertz and Larson 1996, p. 125) A yearly Space Shuttle budget of 4 billion dollars for 10 planned launches of 16,000 kg to LEO corresponds to a cost of $25 k/kg. The Space X Falcon Heavy is expected to launch 53,000 kg to LEO at a cost of 85 million dollars, a cost of only $1.6 k/kg. (Space X, Falcon Heavy) Falcon Heavy cost estimates per launch have been higher, up to 135 million dollars, giving a higher cost of $2.5 k/kg to LEO. (Wikipedia, Falcon Heavy) An average historical cost for launch to LEO is $10 k/kg. The best case would be about $2.5 k/kg, and the worst case might be about $25 k/kg.

A rocket's stack-to-payload mass ratios or gear ratio is the ratio of the total payload, rocket, and propulsion mass needed in LEO to the final emplaced payload mass. (BVAD 2004) The gear ratios from the Life Support Baseline Values and Assumptions Document (BVAD) are given in Table 7. The (BVAD 2004) and (BVAD 2008) values differ somewhat.

Table 7. Gear ratios for a moon base, a Mars transit vehicle, and a Mars base.

	(BVAD 2004)	(BVAD 2008)	Average
Moon base	6.98	7.2	7.1
Mars transit, Earth-Mars	3.16	2.16	2.7
Mars transit, Earth-Mars-Earth	6.77	5.77	6.3
Mars transit, average	-	-	4.5
Mars base	3.77	2.77	3.3

All of the Mars transit resupply mass is launched to Mars but half of it is used before Mars is reached and is not accelerated back to Earth to complete the round trip. The average of the Earth-Mars and Earth-Mars-Earth gear ratios will be used to reflect that each gear ratio applies to half the Mars transit resupply.

Table 8. Launch and emplacement cost for a space station, a moon base, a Mars transit vehicle, and a Mars base.

	Space station		Moon base		Mars transit		Mars base	
Mission duration, days	3,650		3,650		365		500	
	Recycling	Resupply	Recycling	Resupply	Recycling	Resupply	Recycling	Resupply
Initial launch mass, kg	660	0	440	0	1,320	0	1,320	0
Logistics Mass Rate, kg/day	0	57.1	0	38.1	0	38.1	0	38.1
LEO launch cost rate $M/kg	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Gear ratio	1	1	7.1	7.1	6.3	4.5	3.3	3.3
Launch and emplacement cost rate, $M/kg	0.01	0.01	0.071	0.071	0.063	0.045	0.033	0.033
Launch and emplacement cost, $M	7	2,084	31	9,874	83	626	44	629

The initial launch mass of the recycling system should be the wet mass but only the dry mass of Table 4 is available. The recycling Logistics Mass Rate is zero. Resupply life support has negligible initial launch mass. The resupply Logistics Mass Rate for filled resupply modules is given in Table 6. The total launch mass is the initial mass plus the logistics mass for the full mission duration. The launch and emplacement cost rate is the LEO launch cost rate times the gear ratio.

C. Operations costs

The Johnson Space Center (JSC) developed the Mission Operations Cost Model (MOCM) to provide a quick rough order of magnitude cost estimate for spacecraft mission operations. The MOCM estimates manned spacecraft operations cost as 10.9% per year of the total development and production cost. (Jones 2003-01-2635) The Operations Cost Factor (OCF) is 0.109 per year or 0.000299 per day

Table 9. Operations cost for a space station, a moon base, a Mars transit vehicle, and a Mars base.

	Space station		Moon base		Mars transit		Mars base	
Mission duration, days	3,650		3,650		365		500	
	Recycling	Resupply	Recycling	Resupply	Recycling	Resupply	Recycling	Resupply
Hardware development cost, $M	151	1,020	492	3,412	700	321	2,978	1,646
Operations cost rate, $M/day	0.000299	0.000299	0.000299	0.000299	0.000299	0.000299	0.000299	0.000299
Operations cost, $M	165	1,112	537	3,719	76	35	445	246

IV. The recycling and resupply cost curves and Breakeven Date (BED) for the four missions

The formulas for recycling and resupply LCC that use the time variable, T, in equations 3 and 4, are modified to use the same descriptive terms as the tables above.

Recycling LCC(T) = Hardware development cost + (Initial launch mass + Logistics Mass Rate * T) * Launch and emplacement cost rate + Hardware development cost * Operations cost rate * T (13)

Resupply LCC(T) = Hardware development cost (T) + Logistics Mass Rate * T * Launch and emplacement cost rate + Hardware development cost (T) * Operations cost rate * T (14)

Since the numbers of resupply tanks and containers increase with mission time, the resupply hardware development cost also increases with time. The parameters from equations 13 and 14 that are used in the time variable Life Cycle Cost (LCC) computations are shown in Table 10.

Table 10. Time variable Life Cycle Cost (LCC) computations.

	Space station		Moon base		Mars transit		Mars base	
	Recycling	Resupply	Recycling	Resupply	Recycling	Resupply	Recycling	Resupply
Hardware development cost, $M	151	12 (T/2)^0.5941	492	50 (T/3)^0.5941	700	18 (T/3)^0.5941	2,978	79 (dT3)^0.5941
Initial launch mass, kg	660	0	440	0	1320	0	1320	0
Logistics Mass Rate, kg/day	0	57.1	0	38.1	0	38.1	0	38.1
Launch and emplacement cost rate, $M/kg	0.01	0.01	0.071	0.071	0.063	0.045	0.033	0.033
Operations cost rate, $M/day	0.000299	0.000299	0.000299	0.000299	0.000299	0.000299	0.000299	0.000299
Mission time, T, days	Life Cycle Cost, $M							
72			534	532				
85	161	163						
313					849	848		
365					860	972		
500							3,467	2,526
808							3,741	3,741
3,650	322	4,261	1,060	17,003				

The hardware development costs for recycling are as before. The time dependent hardware development costs for resupply were obtained by substituting Q = N * T /12, where N is the number of crew, in the AMCM development cost formula.

The recycling and resupply LCC can be computed for different mission times, T, as shown in the bottom section of Table 10. The Moon base Breakeven Date, BED, is 72 days and the future space station is 85 days, both much less than their ten year mission duration. The Mars transit BED is 313 days, a little short of the nominal 365 day round trip length. The Mars base BED is 808 days, significantly beyond the 500 day nominal mission length.

The purpose of developing the time dependent equations for recycling and resupply LCC was to plot LCC versus time and show the Breakeven Dates for the four missions. Equations 13 and 14 and the parameters of Table 10 are used to plot the LCC of recycling and resupply for a future space station, a moon base, a Mars transit vehicle, and a Mars base in Figures 3 through 6.

A. The cost curves and BED of recycling and resupply for a space station

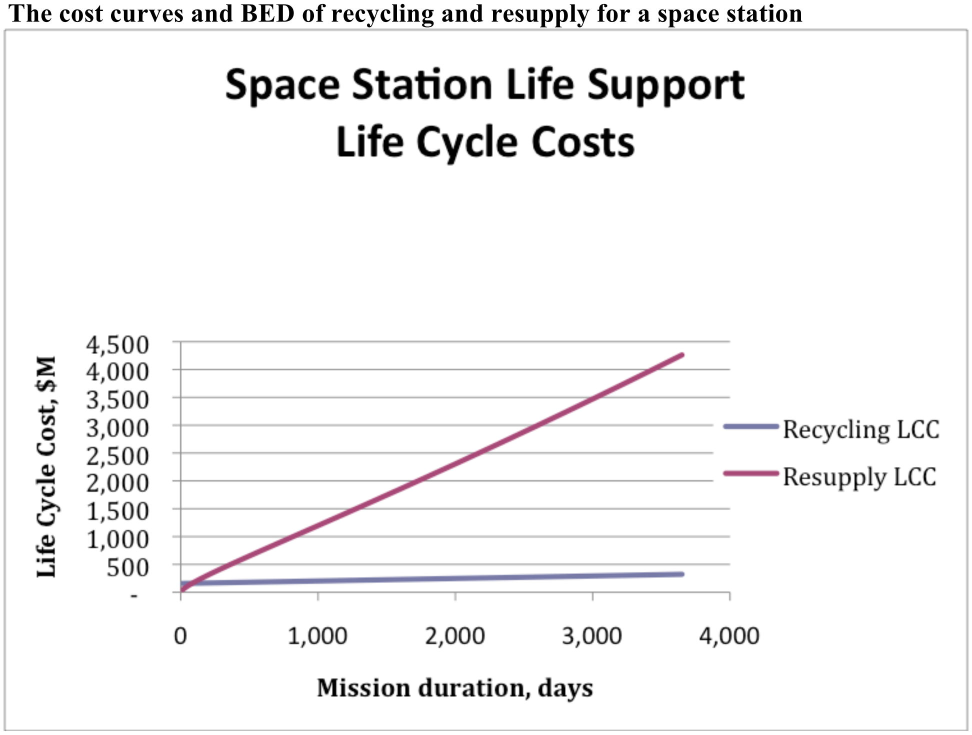

Figure 3. The LCC of recycling and resupply for a future space station.

The recycling and resupply LCC plots cross at the space station recycling breakeven date, 85 days. For a space station mission duration of ten years, 3,650 days, the LCC of recycling is estimated to be 323 $M and the cost of resupply to be 4,261 $M, 13 times higher.

B. The cost curves and BED of recycling and resupply for a moon base

Figure 4 shows the LCC of recycling and resupply for a moon base.

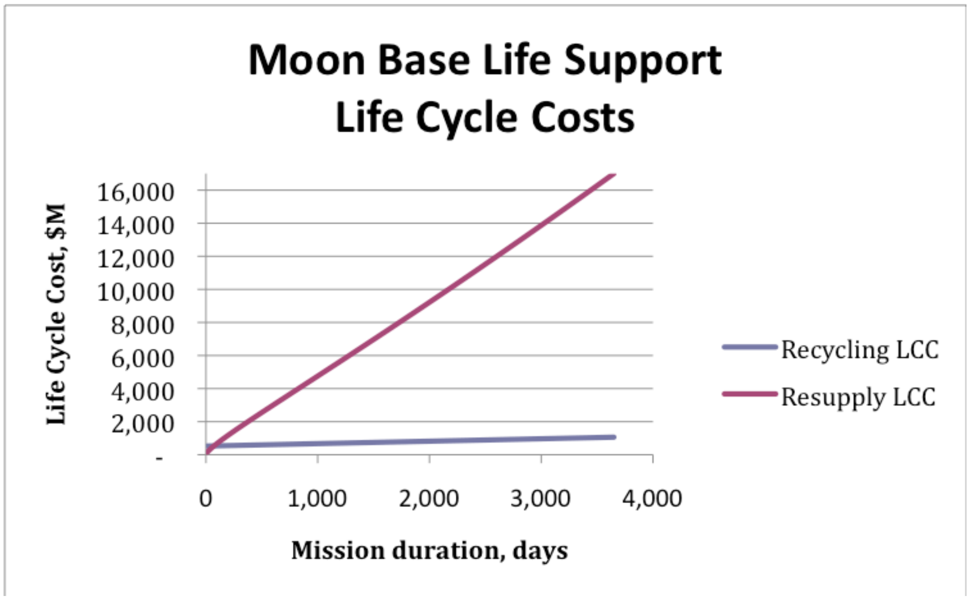

Figure 4. The LCC of recycling and resupply for a moon base.

The recycling and resupply LCC plots cross at the moon base recycling breakeven date, calculated to be 85 days. For a moon base mission duration of ten years, 3,650 days, the LCC of recycling is estimated to be 1,060 $M and the cost of resupply to be 17,003 $M, 16 times higher.

C. The cost curves and BED of recycling and resupply for a Mars transit vehicle

Figure 5 shows the LCC of recycling and resupply for a Mars transit vehicle.

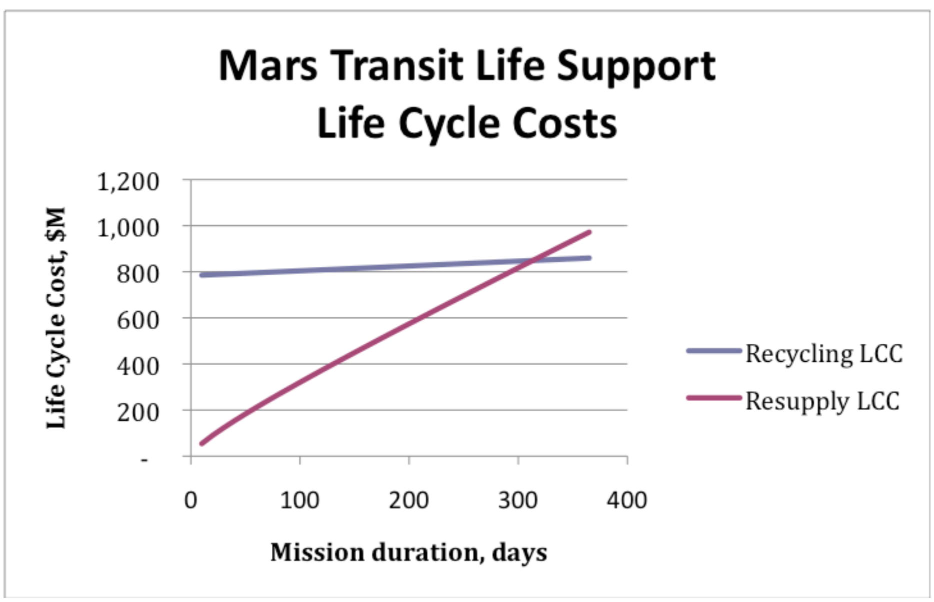

Figure 5. The LCC of recycling and resupply for a Mars transit vehicle.

The recycling and resupply LCC plots cross at the Mars transit vehicle recycling breakeven date, calculated to be 313 day, slightly shorter than the nominal mission duration of 365 days. For a Mars transit mission duration of 365 days, the LCC of recycling is estimated to be 860 $M and the cost of resupply to be 972 $M, 1.1 times higher.

D. The cost curves and BED of recycling and resupply for a Mars base

Figure 6 shows the LCC of recycling and resupply for a Mars base.

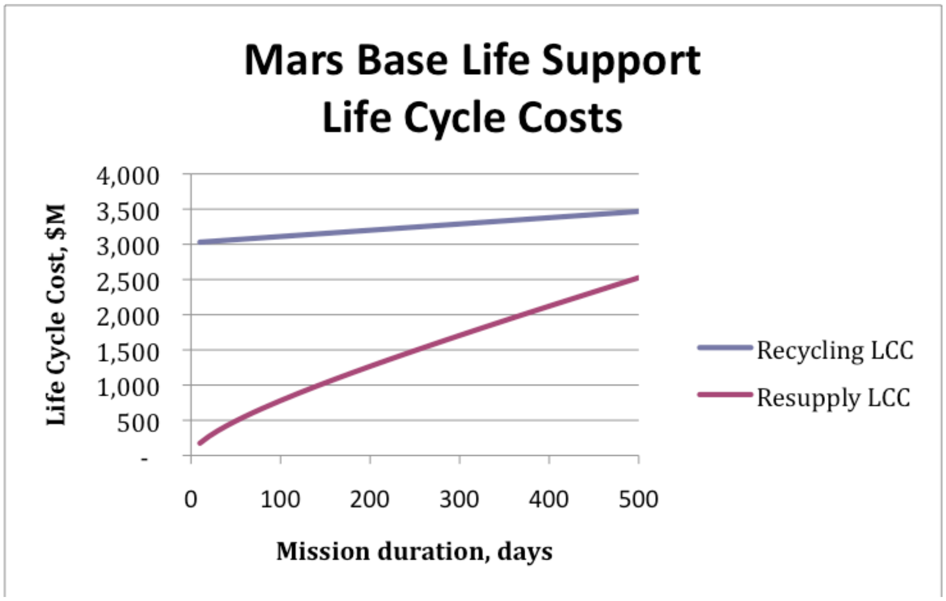

Figure 6. The LCC of recycling and resupply for a Mars base.

The recycling and resupply LCC plots do not cross during a nominal 500 day Mars stay. The Mars base recycling breakeven date is calculated to be 808 days, significantly beyond the mission duration. For a Mars base mission duration of 500 days, the LCC of recycling is estimated to be 3,467 $M and the cost of resupply to be 2,526 $M, 70 percent of the recycling cost.

E. The exact and approximate Breakeven Dates (BED's)

The exact breakeven dates for the four missions are shown in Table 10 and again in Table 11. The formula for the approximate breakeven date in equation 10 is modified to use parameters in the tables above.

Approximate BED = Recycling hardware development cost (D))/
(Resupply hardware development cost (D)/D + Resupply launch cost per day) (15)

In the approximate BED, the recycling and resupply hardware development costs are evaluated at the end of the nominal mission Duration, D. The resupply hardware development cost is divided by the mission Duration, D, to get the resupply hardware cost increase rate in $M per day. The resupply launch cost per day is the product of the resupply Logistics Mass Rate in kg per day and the Launch and Emplacement Cost in $M per kg.

Table 11 shows the exact and approximate Breakeven Dates (BED's) for recycling versus resupply for the four missions.

Table 11. Exact and approximate Breakeven Dates (BED's) for recycling versus resupply.

	Space station	Moon base	Mars transit	Mars base
Exact BED	85	72	313	808
Approximate BED	132	91	204	1,184
Approximate/exact ratio	1.56	1.26	0.65	1.47

The approximate BED's are roughly between two-thirds and one and a half times the exact BED's, a reasonable agreement for a rough approximation. The closeness of the approximation confirms that the major factors in the choice between recycling and resupply are the initial cost for developing recycling hardware and the daily cost increments for developing resupply hardware and launching resupply hardware and materials. Operations costs are high but not an independent discriminator since they reflect development cost and mission duration.

V. Conclusion

This paper compared the Life Cycle Cost (LCC) of life support recycling systems to the LCC of resupplying all materials from Earth. The major cost of recycling systems is usually their development cost but the operations cost will be equally high for a ten year mission. The major cost of resupply systems is usually their mass launch and emplacement cost but development and operations costs are significant.

Resupply is very much more expensive than recycling for a space station or Moon base. Why does resupply cost only about as much as recycling for Mars? There are two major reasons. Life support for Mars must be much more reliable than for space station or a Moon base and using triple redundant recycling systems for reliability effectively triples the recycling cost. The space station and Moon base missions were assumed to be ten years in duration, while the Mars transit and base are one year and one and one-third years, which cuts the resupply cost by roughly a factor of four (not ten due to the roughly square root increase of cost with quantity of resupply units). Lower launch and emplacement cost would make resupply more attractive for Mars, but even zero launch cost would not make resupply less expensive than recycling within the Earth-Moon system.

The feasibility of recycling for Mars will depend on the development work completed and operational experience obtained beforehand. It would be useful to gain much more experience in the Earth-Moon system before going to Mars. The best life support system for Mars could be a single thread recycling system coupled with either a full or survival level resupply system.

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