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Take Material to Space or Make It There?

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Introduction

Most human space missions are brief, and they take all the materials needed.

- However, the International Space Station recycles water and oxygen.
- It was assumed that Moon and Mars missions will recycle life support materials.

The "take or make" decision should be largely based on cost.

- Providing recycling equipment was cheapest for the space station.
- This is because the space shuttle launch costs were very high.
- And because the the space station mission is very long, about 25 years.

SpaceX has cut the launch cost by a factor of twenty-five to fifty.

- And currently planned missions are very brief, days or weeks.
- Material recycling or in situ production will not save cost for these missions.

Approach – analyze and compare costs

Taking life support requires providing the material, containers, and launch rockets.

Oxygen and water have negligible cost on Earth.

Taking them into space requires providing and launching containers.

In the past, the launch cost greatly exceeded the container cost.

But with the new lower launch costs, this is no longer true.

Making material in space requires developing and launching the production equipment.

The hardware development cost is usually much greater than its launch cost.

The hardware has continuing costs for operations and maintenance.

Making material saves cost only for higher launch cost and longer missions.

Cost models for taking or making material in space

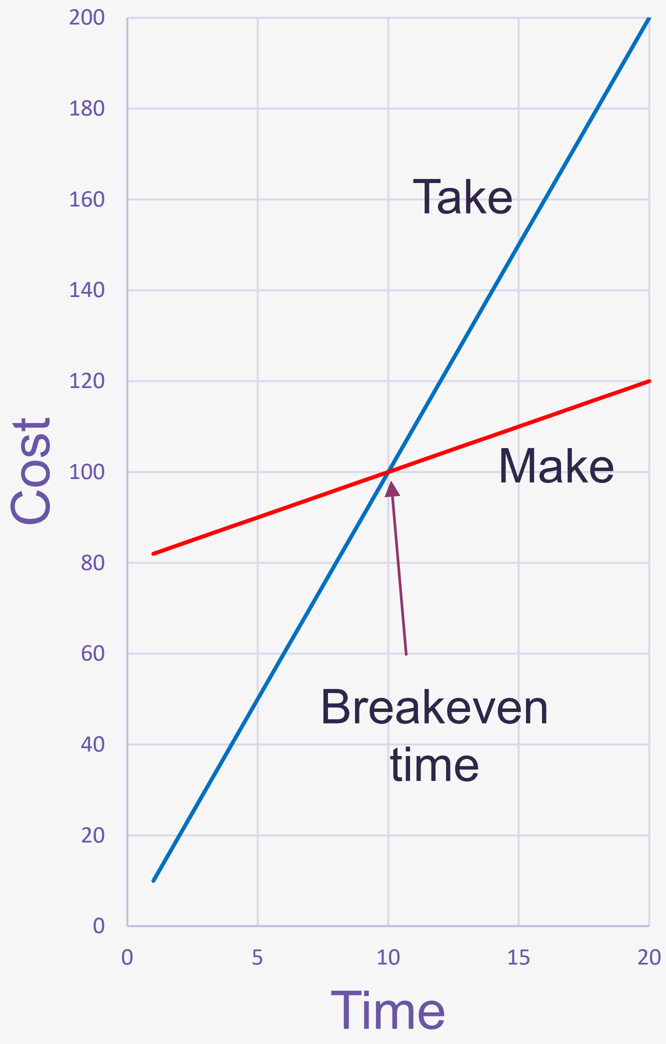
Cost to Take (t) = Container Cost(t) + [Life Support Mass(t) + Container Mass (t)] *Launch Cost

To take, the number of containers, the life support mass, and the container mass all increase with mission time.

Cost to Make (t) = Hardware Cost + Hardware Mass *Launch Cost + Operations Cost (t)

To make, the hardware cost and mass are fixed, but the operations cost increases with time.

The take-make breakeven point occurs when the costs are equal.



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Launch cost has dropped greatly

The cost per kilogram for shuttle launch to LEO was $1,990 million/27,500 kg = 72.3 $k/kg in current dollars.

The SpaceX Falcon 9 launches 22,800 kg to Low Earth Orbit (LEO) at a cost of 67 million dollars, for a launch cost is 2.94 $k/kg.

The SpaceX Falcon Heavy launches 63,800 kg to LEO at a cost of 97 million dollars, for a launch cost of $1.52 $k/kg.

- The space shuttle cost to LEO was roughly 25 to 50 times higher.
- More cuts to come?

Elon Musk has repeatedly estimated “Insanely Low Starship Launch Costs Of $10/kg.”

Hardware Development and Operations Costs

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 quantity, M is mass, S is the mission type, IOC is the year of initial operation capability, B is the design generation, and D adjusts for difficulty.

Based on ISS and the MOCM formula, the operations cost is estimated as 10% of the development cost per year.

Take or Recycle Water and Oxygen for the Space Station?

Take	Water	Oxygen		Make	Water	Oxygen
Material mass per container, kg	103	35.4		Material supply per year, kg	18,250	2,154
Container mass, kg	21.2	12.7		System mass, kg	476	113
Mass increase ratio	1.21	1.36		System cost, $k	410,711	70,113
Container cost, $k each	1,642	661		Operations cost, $/year	410,711	7,011
Container cost, $/kg material	15.94	18.67		Operations cost, $/kg	22.5	3.26
				Support mass per year, kg/year	476	11.3
Falcon launch cost, $k/kg	1.52	1.52		Falcon launch cost, $k/kg	1.52	1.52
				Falcon transportation cost, $k/year	724	17
Falcon transportation cost, $k/kg material	1.83	2.07		Falcon transportation cost, $k/kg material	0.04	0.01
Total Falcon cost to take, $k/kg	**17.8**	**20.7**		**Total Falcon cost to make, $k/kg**	**22.5**	**3.3**
Shuttle launch cost, $k/kg	72.3	72.3		Shuttle launch cost, $k/kg	72.3	72.3
				Shuttle transportation cost, $k/year	34,415	817
Shuttle transportation cost, $k/kg material	87.18	98.24		Shuttle transportation cost, $k/kg material	1.89	0.38
Total Shuttle cost to take, $k/kg	**103.1**	**116.9**		**Total Shuttle cost to make, $k/kg**	**24.4**	**3.6**

Which is better, to take or recycle water and oxygen?

Even with the new much lower Falcon Heavy launch cost, taking water to the space station (17.8 $k/kg) is not much cheaper than recycling it (22.5 $k/kg).

- Recycling costs 22.5 $k/kg of water recycled.
  - Shuttle launch cost is only 1.89 $k/kg of water recycled.
- The water tanks cost 15.94 $k/kg of water taken.
  - Falcon launch cost adds only 1.83 $k/kg of water taken.

At the shuttle launch cost of 72.3 $k/kg, taking water to the space station costs a total of 103.13 $k/kg.

- Recycling water was strongly favored at shuttle launch costs.

Recycling oxygen is still much cheaper than taking it in tanks, even at the lower Falcon Heavy launch cost.

- The oxygen recycling cost is 3.3 $k/kg, while the oxygen tank cost alone is 18.67 $k/kg of oxygen provided.
- Recycling oxygen still provides savings, but much less than at shuttle costs.

Take or recycle water and oxygen on a Moon mission?

The space station was launched in 1998.

The take or recycle decision depends largely on the continuing costs.

For a Moon mission, the crew size and mission duration affect the decision.

For recycling to save cost, the total masses of water and oxygen required over time must be large enough that the cost of taking them is greater than the cost of providing recycling equipment.

The recycling cost breakeven date decreases directly with the crew size,

Doubling crew size cuts the breakeven date in half.

The breakeven dates to take or recycle water and oxygen on a Moon mission are computed.

Moon versus space station

The cost per kg of payload for the Moon is much higher than for LEO.

The mass in LEO includes the rockets and fuel needed to put the payload on the Moon.

The launch cost for a Moon base would be 10.8 $k/kg.

This is the Falcon Heavy cost of 1.52 $/kg times a Moon LEO mass to payload mass ratio of 7.2.

The Moon base water and oxygen tanks are assumed the same as for the space station.

The Moon base water recycling and oxygen regeneration systems are assumed the same as for the space station.

The recycling hardware cost is a major factor in determining the cost breakeven date.

Make breakeven date for water and oxygen on a Moon base.

	Water	Oxygen
Cost of recycling system		
System cost, $k	410,711	70,113
System mass, kg	476	113
Falcon transportation cost, $k/kg	10.8	10.8
Falcon transportation cost, $k	5,141	1,220
Recycling system cost, $k	415,851	71,333
Water or oxygen production rate, kg/d	50	5.9
Crewmember use requirement, kg/CM-d	9.68	0.84
Crewmembers supported, CM	5.17	7.02
Recycling system cost per crewmember, $k/CM	**80,509**	**10,156**
Daily cost		
Yearly cost fraction	1.00	0.10
Daily cost, $k	1,125	19.21
Daily product, kg	50.00	5.90
Recycling cost per kilogram, $k/kg	**22.50**	**3.26**
Crewmember use requirement, kg/CM-d	9.68	0.84
Daily cost to recycle, $k/CM-d	217.85	2.73
Breakeven calculation		
Daily cost to take, $k/CM-d	280.40	28.01
Daily saving by recycling, $k/CM-d	62.56	25.27
Cost breakeven date, d	1,287	402

The recycling system cost per crewmember is computed.

The system cost and mass are as before.

The recycling cost per kilogram is computed.

It is very close to space station, because the Falcon transportation cost is much less than the system cost.

Daily cost to recycle is computed, $k/CM-d,

= Recycling cost per kilogram, $k/kg * Crewmember use requirement, kg/CM-d

Daily cost to take is computed, $k/CM-d,

= Material and container mass, kg/CM-d, * Transportation cost, $k/kg

Taking costs more than recycling on a daily operating basis.

Daily saving by recycling, $k/CM-d = Daily cost to take, $k/CM-d, - Daily cost to recycle, $k/CM-d

For recycling to save cost, the recycling system cost must be paid back by the daily cost savings.

The cost breakeven date, d, is computed

=Recycling system cost per crewmember, $k/CM/Daily saving recycling, $k/CM-d

Conclusions

The space station water recycling and oxygen generation systems saved significant cost because of the long mission duration and the high space shuttle launch costs.

“Make” rather than “take” would save little for a future space station because of the new much lower launch costs.

A Moon mission at current launch costs would have to continue for several years for recycling to save much cost.

Launch cost is now so low that it is not usually a deciding factor.

The “take or make” decision largely depends on mission duration.

For a short mission, less than a few years, probably “take.”

For a very long mission, many years, usually “make.”

For an intermediate mission duration, several years, “make” only if the mission duration is several times the cost breakeven date.

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