Humans to Mars Will Cost About "Half a Trillion Dollars" and Life Support Roughly Two Billion Dollars

Harry W. Jones[1]
NASA Ames Research Center, Moffett Field, CA, 94035-0001

A recent estimate of the cost of the first human mission to Mars suggests that it could cost "half a trillion dollars." This estimate is consistent with most past estimates. A similar cost number can easily be derived using mass-cost estimating factors based on the International Space Station (ISS) and other experience. Using the same cost factors and life cycle cost estimating approach, the cost of the life support for the Mars mission could be two billion dollars or more. The cost to go to Mars is expected to be two or three times that of either Apollo, space shuttle, or ISS and could be as much as all three together.

Nomenclature

B	=	Billion
CxP	=	Constellation Program
DRA-5	=	Design Reference Architecture 5
GAO	=	Government Accountability Office
ISS	=	International Space Station
LCC	=	Life Cycle Cost
LEO	=	Low Earth Orbit
MT	=	Metric Ton
NRC	=	National Research Council
OIG	=	Office of Inspector General
SEI	=	Space Exploration Initiative
SSF	=	Space Station Freedom
VSE	=	Vision for Space Exploration

I. Introduction

THIS document gives some previously estimated costs for a human mission to Mars, cites the costs of earlier human missions such as Apollo and the International Space Station (ISS), and then derives an independent cost estimate using historical data. The cost of life support for the Mars mission is discussed.

II. Past estimates of Mars mission costs

Some of the previous estimates of the cost for a human mission to Mars are cited. They are largely consistent.

A. Sommerer's congressional testimony

John Sommerer chaired the Technical Panel of the National Research Council (NRC1) Committee on Human Spaceflight that prepared the report, "Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration." (National Research Council, 2014) On February 3, 2016, Dr. Sommerer testified to the Subcommittee on Space in their hearing on, "Charting a Course: Expert Perspectives on NASA's Human Exploration Proposals." Part of his prepared testimony was as follows:

> "To be explicit and to set the scale of the problem, the Technical Panel, aided by independent cost estimation contractors, and using an innovative process that respected the importance of development risks based on technical challenges, capability gaps, regulatory challenges, and programmatic factors, and the need to retain a reasonable operational tempo, concluded that the first crewed Mars landing might be possible 20-40 years from

[1] Systems Engineer, Bioengineering Branch, Mail Stop N239-8

now, after a cumulative expenditure of on the order of half a trillion dollars (constant FY2013 dollars)." (Sommerer, 2016)

B. Garver's public comment

Lori Garver, former Deputy NASA Administrator, discussed NASA progress and the current Mars approach in December, 2014. She said that we are at least 20 years from Mars and "The last estimates of human trips to Mars are around $500 billion dollars." (Hayes, 2014) Ms. Garver was apparently referring to the then recent 2014 report of the National Academy of Sciences.

C. National Research Council (NRC) report

The NASA Authorization Act of 2010 tasked the National Academy of Sciences to perform a human spaceflight study to review "the goals, core capabilities, and direction of human space flight." Costs for a Mars mission were assessed using the Design Reference Architecture 5 (DRA-5), which is a long surface stay conjunction mission. The NRC found that,

> "The scale of the government investment required to send humans to Mars is, to a rough order of magnitude, equivalent to:
>
> …
>
> • Two to four times the U.S. investment in the ISS, which amounted to roughly $150 billion, including launch costs." (National Research Council, 2014)

This means that the cost of a long stay human Mars mission is estimated at roughly $300 to $600 billion. The higher cost allows an earlier landing in 2033 but the more restricted budget will postpone it to past 2050. No detailed cost estimates were presented. The cost estimates are presented as uncertain, notional, and optimistic.

> "Projecting the cost of the development, production, and operations of the exploration elements required to land humans on Mars over the next several decades involved a high degree of uncertainty, so all cost assessments in this report are notional." And, '(T)he cost projections generated for this study are optimistic." (National Research Council, 2014)

D. Price's austere and minimal missions

Hoppy Price and his coauthors have described a scaled-back version of DRA-5. They find that, "By minimizing new technology, development risk could be low, with a program development cost and schedule similar to that of the ISS-about 18 years and $100 B." The cost includes launches but not the program or mission operations costs. Also, "(C)ost estimates provided here for the austere architecture are notional and draw heavily upon the cost estimates performed for DRA 5." (Price et al., 2009-6685) 100 billion dollars in 2009 would be 110 billion in 2015. (All conversions to 2015 dollars are from McMahon, 2014.)

After the NRC report, Price and different coauthors considered a three mission sequence including a four crew landing on Phobos, a two crew short-stay on Mars, and a four crew long stay surface mission. The current budget for human spaceflight is about $8 billion per year. (National Research Council, 2014) Price et al. present a figure showing that the Mars long stay mission would have a yearly cost approximately equal to the current human spaceflight budget over about 15 years, so the total cost in this second analysis would be about $120 billion. (Price et al., 2015)

E. The Vision for Space Exploration (VSE)

President G. W. Bush announced the Vision for Space Exploration (VSE) in 2004 but it was partially cancelled in 2010. The VSE, like the earlier Space Exploration Initiative (SEI), included robotic, moon, and Mars missions. NASA's 2004 budget projections, "based on long-term affordability," increased year by year from 3 billion to 5, 10, and finally to 15 or 18 billion dollars per year from 2004 to 2020. The total cost to 2020 amounted to roughly 130 billion dollars. Extending this annual cost rate for another 20 years to 2040 would add another 300 or 350 billion dollars. The overall total for VSE would then be 450 or 500 billion dollars. (Wikipedia, Vision for Space Exploration) 500 billion in 2004 would be 627 billion in 2015. (McMahon, 2014)

1. Charania on VSE costs

A. Charania examined VSE costs "in order to determine the validity of the trillion dollar figure often quoted in the media." (Charania, 2005) The trillion dollar estimate was apparently based on a misinterpretation of the costs of the earlier Space Exploration Initiative (SEI). (Day, 2004)

Charania estimated the Life Cycle Cost (LCC) of VSE as about 220 billion dollars from 2006 through 2025, but this did not include an actual first Mars mission. The costs included robotic precursors, launch systems, lunar landers, lunar outpost buildup but not surface activities, the Crew Exploration Vehicle, launch and mission operations, ISS support, space shuttle support, and Mars technology development. The costs for the last few years estimated rapidly ramp up to more than 25 billion dollars per year. Taking this rate out to 2040 would add 375 billion dollars more, for a total of about 600 billion dollars. (Charania, 2005)

Very roughly, the existing VSE cost estimates out to 2020 or 2025 seem to imply a cost of 250 or 300 billion dollars for Mars alone, mostly in future uncosted years. 300 billion in 2004 would be 376 billion in 2015.

2. Constellation costs

The Constellation Program (CxP) was developed to implement the VSE. Constellation was estimated by NASA to cost $230 billion in 2004 dollars out to 2025. (Wikipedia, Constellation Program) (GAO, 2009) The NASA estimate cited by GAO is nearly identical to Charania's estimate, and implies roughly the same 376 billion 2015 dollar cost for Mars.

F. Hunt and van Pelt on Mars Direct

Charles D. Hunt and Michel O. van Pelt compared NASA and ESA cost estimating methods. "As a non-sensitive, public domain reference case for human Mars projects, the "Mars Direct" concept was chosen." (Hunt and van Pelt, 2004) Robert Zubrin and others developed the influential Mars Direct concept in the early 1990's as a counter response to the Space Exploration Initiative. (Zubrin, 91-0328)

Hunt and van Pelt found that NASA used Apollo and space shuttle cost data while ESA used European cost data. They also found that the higher risk Mars direct approach "could cost less than the Apollo moon program." The NASA method cost estimate was 40 billion 2002 dollars, but it was clearly stated that the cost estimate might not be realistic. (Hunt and van Pelt, 2004) 40 billion in 2002 would be 53 billion in 2015.

G. Zubrin on Mars Direct

Hunt and van Pelt also considered Zubrin's cost estimates for Mars Direct. Zubrin's $22 billion in the early 1990's would be equivalent to about $32 billion in 2002 dollars, roughly consistent with their own estimates. (Hunt and van Pelt, 2004) The estimate would be 42 billion in 2015 dollars.

Zubrin had come to think that NASA's Space Exploration Initiative was basically a conglomeration of all possibly useful NASA exploration and technology programs, and that this added unnecessary complexity and cost. His Mars Direct proposal eliminated robotic and moon missions and technology development and added the innovative concept of deriving oxygen propellant for the return trip from the Martian atmosphere. (Wikipedia, Mars Direct)

H. Space Exploration Initiative (SEI)

President G. H. W. Bush initiated the Space Exploration Initiative (SEI) in mid-1989 and NASA made the detailed 90 Day Study of the proposed robotic, moon, and Mars missions. SEI would take 20 to 30 years and cost about 450 or 500 billion dollars. This astonishing cost, roughly 10 percent of the then current GDP, led to the rapid abandonment of SEI. (Wikipedia, Mars Direct) (Wikipedia, Space Exploration Initiative) (Dick, nd)

The total included much more than a single Mars mission.

> "By late 1989 … NASA had produced another cost estimate of $541 billion for 34 years of lunar and Mars operations, also roughly split in half. After this, the media often reported that the costs of Bush's plan were either $400-$500 billion, or $400-$550 billion. Often the press erroneously reported that these costs were for a single mission to Mars, rather than for thirty years or more of operating bases on *both* the Moon and Mars." (Day, 2004)
>
> The 500 billion dollar number for SEI in 1989 was "adjusted for inflation" to an exaggerated trillion dollar guess for the 2004 Vision for Space Exploration (VSE). (Day, 2004) The 541 billion dollar total in 1989 would be 824 billion in 2004 and 1,034 billion in 2015. The 270 half of 541 billion that applied to Mars would be 517 billion now.

I. Discussion of past Mars cost estimates

The more credible seeming estimates of the cost of a human mission to Mars are within the range of the recent NRC estimate, 300 to 600 billion current dollars. The lower number reflects a delayed schedule. Table 1 lists the past announced cost estimates for a Mars mission.

Table 1. Cost estimates for a first Mars mission in current dollars.

Source	Date of estimate	Cost, billions of current dollars
Sommerer	2016 (2013)	500
Garver	2014	500
NRC	2014	300 - 600
Price	2009, 2015	110, 120
VSE	2005	250 - 300
Hunt and van Pelt	2002	53
Zubrin	1991	42
SEI	1989	517

Zubrin's estimate, and the Hunt and van Pelt estimate they based on Zubrin's approach, are only ten percent of the more typical estimates. Price et al.'s estimates are based on austere and minimal missions that are designed to reduce cost and are only one-third or one-sixth of the larger estimates. The 300 to 600 billion estimates seem much more plausible but they are necessarily uncertain.

One problem with the publicly quoted costs is they may not distinguish between the cost of the first Mars mission and the cost of an extensive space program culminating in a Mars mission. SEI and VSE included advanced technology development, rockets and habitats, and robotic, moon, and Mars missions. Many space supporters believe that the best path to Mars includes some of these elements. Each program element has merits and interested advocates that strongly urge its inclusion. However, Price, Zubrin, and others believe we need a focused Apollo-like goal of getting to Mars as quickly, simply, directly, and cheaply as possible. They dismiss technology development and moon missions as unnecessary and costly distractions.

III. Cost estimates based on past human missions

In general, the best way to estimate costs is by direct analogy with the past costs of similar missions. Most of the estimates given here were made using cost estimation methods that are based on past mission data. NASA's human relevant human missions are the International Space Station (ISS), space shuttle, and Apollo.

A. International Space Station (ISS).

If you simply Google "ISS cost," the answer in big bold letters is "150 USD" from Wikipedia.

> "The ISS is arguably the most expensive single item ever constructed. In 2010 the cost was expected to be $150 billion. It includes NASA's budget of $58.7 billion (inflation unadjusted) for the station from 1985 to 2015 ($72.4 billion in 2010 dollars), Russia's $12 billion, Europe's $5 billion, Japan's $5 billion, Canada's $2 billion, and the cost of 36 shuttle flights to build the station; estimated at $1.4 billion each, or $50.4 billion total." (Wikipedia, International Space Station)

These numbers add up to 146.8 billion 2010 dollars or 160 billion 2015 dollars. The Washington Post on January 9, 2014, said, "To date, the International Space Station has cost as much as $160 billion." (Plumer, 2014)

1. Mars mass-based cost estimate

The NRC gives ISS and Mars mass values that allow a rough calculation of the cost of a Mars surface mission. The ISS has a mass of 420 metric tons (MT) in Low Earth Orbit (LEO). (NRC, 2014) A total current cost of 150 billion dollars for the 420 metric tons of ISS in LEO gives a cost of 0.36 billion dollars per metric ton. A Mars surface mission following DRA-5 would require 900 to 1,300 metric tons in LEO. (NRC, 2014) These 900 to 1,300 metric tons of a Mars surface mission would cost 320 to 460 billion dollars. These cost numbers are within the central range of the NRC and other more plausible estimates in Table 1.

2. OIG ISS cost check

NASA's Office of Inspector General (OIG) in 2014 calculated how much the US had spent on ISS, using GAO estimates for space shuttle launch costs and not including the costs of the international partners. The OIG calculated that the US spent approximately $75 billion on the ISS through 2013, $43.7 billion for construction and program costs plus $30.7 billion for 37 shuttle launches. However, some adjustments seem needed. Wikipedia gives the shuttle costs as 50.4 billion. The OIG notes that shuttle costs have been estimated as high as 1.5 billion per launch, which would give a shuttle cost of 56 billion, 25 billion higher. The international partners spent an additional 24 billion. The OIG cost also does not include the 11.2 billion spent on the US only Space Station Freedom from 1985 to 1993, before it was reconfigured as the ISS. 11.2 billion in 1993 would be 18 billion in 2015. These adjustments bring the original 75 billion up to 142 billion, much closer to the previous 150 billion. (Smith, 2014) (OIG, 2014)

3. GAO detailed ISS costs

In 1995 the GAO provided a detailed estimate of the NASA funding requirements for ISS. (GAO, 1995) The GAO cost estimate for the full planned ISS program is shown in Table 2 in billions of 2015 dollars.

Table 2. GAO ISS cost estimate in billions of 2015 dollars

Program element	2015 $B
SSF costs from 1985 through 1993	17.42
Planned development from 1994 to 2002 assembly complete	12.60
Operations, payloads, reserves, etc., from 1994 to 2002	17.11
Shuttle launch support to 2002	28.15
Operations/utilization 2003 to 2012	20.22
Shuttle launch support 2003 to 2012	50.85
ISS program total	146.33

NASA spent the equivalent of 17.42 billion 2015 dollars on Space Station Freedom (SSF) from 1985 to 1993. "When the International Space Station design was adopted, NASA estimated that about 75 percent of the previously prepared design work could be incorporated into the new configuration." (GAO, 1995) The ISS was to be developed from 1994 to 2002, when assembly was expected to be complete. During this time, the prime and other contracts would require 12.6 billion and operations, payloads, reserves and other activities 17.11 billion. The total development cost was 17.42 + 12.60 + 17.11 = 47.13 billion.

Shuttle launch support until assembly complete in 2002 would require 28.15 billion for 35 flights, 7 to MIR, 6 for research, and 22 for station assembly. Seven flights per year were planned at 738 million 2015 dollars per flight. After ISS assembly, ten years of operations and utilization would require 20.22 billion and continued shuttle flights at seven per year another 50.85 billion.

The total cost that the GAO estimated in 1995 is amazingly close to the current cost estimate, when converted into current dollars. But two adjustments to the GAO estimate are needed for correct comparison. The GAO number of shuttle flights is too high, but their cost is low by one-half. The GAO total shuttle cost here is 79 billion compared to the OIG 56 billion above, so GAO is 23 billion too high. The GAO 1995 estimated costs include only NASA's funding requirements and do not include the value of the international partners' contributions to the ISS, which is 24 billion. The GAO ISS program cost, adjusted for the international and actual shuttle costs, is 146 + 24 - 23 = 147 billion, still amazingly close to a round 150 billion.

The yearly operations costs are also amazingly similar to the 1995 GAO estimate. NASA spent $2.9 billion on the ISS program in 2013. $1.23 billion was spent on system operations and maintenance costs, such as hardware including Orbital Replacement Units (ORUs) and extra-vehicular activities (EVAs). 660 million was spent on research, labor and travel, and cargo and crew projects. (OIG, 2014) The total is 1.89 billion per year, very close to the 2.02 billion per year implied by the 20.22 billion over ten years in Table 2. The remaining 970 million spent in 2013 went for all crew and cargo transportation costs to ISS, with 370 million for crew. (OIG, 2014) This is roughly 10 billion over ten years, much lower than the 50.85 billion for shuttle transportation in Table 2. The shuttle is no longer flying and probably less mass at lower cost is being lifted to LEO than was expected in 1995.

4. Mars cost estimate based on detailed ISS costs

The detailed ISS costs can be used to make a more detailed estimate of the Mars mission cost. The Life Cycle Cost (LCC) of a mission can be computed as the sum of the hardware development cost, the hardware launch cost, and the operations cost including support and additional launch. The operations cost is usually estimated as some fraction of the development cost per unit time.

LCC = mass * development cost per unit mass + mass * launch cost per unit mass + mass * development cost per unit mass * time * operations cost per development cost unit per time unit

The detailed GAO ISS cost data can be used to determine the cost estimating factors. The ISS US hardware development cost is the sum of the first three amounts in Table 2, 47.1 billion. Per the GAO estimate, ISS was to be launched in seven shuttle missions, and the shuttle payload is 27.5 MT (Wikipedia, Space Shuttle), so the mass could be 193 MT. In fact, 26 shuttle missions have brought various hardware to ISS and the US mass is 121 MT in seven modules and 89 MT of structure and other elements, a similar total of 210 MT. (Wikipedia, Assembly of the International Space Station)

If the cost to develop 210 MT is 47.13 billion, the development cost per unit mass is 0.2244 $B/MT. If the cost to launch a shuttle is 1.5 billion and its payload is 27.5 MT, the launch cost per unit mass is 0.0545 $B/MT. If the total development cost is 47.13 billion and the operations cost is 1.89 billion per year not including launches, the operations cost per development cost unit per time unit is 0.04010 $B/MT-year. The shuttle launches to support ISS operations are not included since the Mars mission will not have operational support launches.

These three cost factors are sufficient to estimate Mars mission cost, but checking the ISS costs requires adjustments for shuttle costs and international partner costs. The cost estimates for ISS and Mars based on the GAO derived cost factors are shown in Table 3.

Table 3. ISS and Mars cost estimates using GAO derived cost factors.

	ISS	Mars low	Mars high
Hardware mass, MT	210	900	1300
Development cost per unit mass, $B/MT	0.2244	0.2244	0.2244
Development cost, $B	47	202	292
Launch cost per unit mass, $B/MT	0.0545	0.0545	0.0545
Launch cost, $B	11	49	71
Mission duration, years	10	3	3
Operations cost per development cost per year, $B/$B-year	0.0401	0.0401	0.0401
Operations cost, $B	19	24	35
ISS adjustments			
Shuttle total cost adjustment, $B	45		
International partners cost, $B	24		
Total, $B	146	275	398

The results of the more detailed cost estimating approach are as expected, for ISS and Mars. Since the GAO ISS numbers were used to derive the cost estimating factors, the ISS cost checks exactly. Two large ISS adjustments were required, amounting to half the total. The shuttle total cost was adjusted to the 56 billion dollars total previously computed, rather than separating out development and operations launches. The international partners cost was added.

The Mars costs for 900 and 1,300 MT are 275 and 398 billion dollars. A long stay Mars mission requires about three years, six to eight months out, eighteen or so on the surface, and six to eight months back. It is interesting that the cost factors and the three year Mars mission duration result in a cost breakdown of 73% development, 18% launch, and 9% operations. The GAO's planned ten year ISS mission had 32% development cost, 54% launch cost, and 14% operations cost, using the costs in Table 2.

ISS and space shuttle are or were continuing operational missions. Going to Mars could be a goal focused, fixed schedule project like Apollo.

B. Space shuttle

Space shuttle costs provide another way to estimate the hardware development cost and launch cost of space missions. What was the hardware development cost per metric ton for the space shuttle? The space shuttle has an empty weight of 78 MT. The payload to LEO was 27.5 MT and to ISS was 16 MT. (Wikipedia, Space Shuttle) The space shuttles cost roughly 2 billion dollars each in 1979, which is 6.5 billion in 2015 dollars. (Melina, 2011) The cost of building a space shuttle was 6.5/78 = 0.083 billion 2015 dollars per metric ton. This only 37% of the 0.2244 ISS hardware development cost per metric ton.

The last of the five shuttles was built in 1991 to replace Challenger. Endeavour cost roughly half as much as the first shuttles, $1.8 billion in 1987 dollars or 3.8 billion in 2015 dollars. (Melina, 2011) The fifth system's cost was lower because of the learning curve and because it used existing spare parts.

What was the launch cost per metric ton for the space shuttle? The total project cost is estimated as 209 billion in 2010 dollars, which is 227 billion in 2015 dollars. (Wikipedia, Space Shuttle) (Wall, 2011) There were 135 flights from 1981 to 2011. The cost per launch is 227/135 = 1.68 billion per launch. For a launch of 27.5 MT to LEO, the cost was 1.68/27.5 = 0.061 billion per MT. This is close to the 0.0545 used above for ISS launch, since similar space shuttle cost data was used.

C. Apollo

The Apollo program was done long ago in a different way than space shuttle and ISS, but its costs are interesting. Apollo was a huge crash program that consumed 0.8% of GDP at its peak year of 1966. The initial 1962 cost estimate was $20 billion. A January 1969 estimate, made when most of the work was done and the moon landing only six months away, was $23.9 billion. The final cost was stated as $25.4 billion in 1973. (Wikipedia, Apollo Program) Apollo thus cost about 205 billion in 2015 dollars.

What was the hardware development cost per metric ton for Apollo? The development of the Apollo spacecraft cost $7.95 billion per the 1969 estimate. (Wikipedia, Apollo Program) This is 51 billion in 2015 dollars. The Apollo spacecraft consisted of a combined Command/Service Module (CSM) and a Lunar Module (LM). (Wikipedia, Apollo spacecraft) The Apollo combined Command/Service Module (CSM) weighed 11.9 MT and 35 were built. (Wikipedia, Apollo Command/Service Module) The Lunar Module (LM) weighed 15.2 MT and 15 were built. (Wikipedia, Apollo Lunar Module) The built mass of Apollo spacecraft totaled 645 MT. The hardware development cost per metric ton for the Apollo spacecraft was 0.079 $B/MT. This compares to 0.083 $B/MT for space shuttle but is only 35% of the 0.2244 $B/MT for ISS. It seems likely that the space shuttle and Apollo hardware development costs per unit mass are lower because multiple systems were built.

What was the launch cost per metric ton for the Saturn V? The Saturn V program cost 6.4 billion in 1964-73 dollars, and $41.4 billion current dollars. The 13 launches cost 41.4/13 = 3.16 billion each. The Saturn V can launch 140 MT to LEO, so the Saturn V launch cost is 3.16/140 = 0.023 $B/MT. (Wikipedia, Saturn V) This Saturn V launch cost is less than half the above estimated space shuttle launch cost of 0.055 or 0.06 $B/MT.

1. Should the ISS-based Mars estimate be reduced based on space shuttle and Apollo costs?

The ISS-based estimate should not be reduced. The Apollo Saturn V launch cost per unit mass is less than half the shuttle launch cost, but the hardware launch cost is only 18% of the total Mars cost, so cutting it in half would reduce the total cost only by 9%. The space shuttle and Apollo hardware costs per unit mass are roughly only one third of the ISS cost. The ISS and its components had only a single production unit, while the space shuttle and Apollo produced multiple units, so their cost was lower due to learning curve effects that are not expected for a Mars mission. The ISS based estimate of roughly 300 or 400 billion agrees with the NRC, VSE, and SEI estimates that resulted from detailed professional analysis.

IV. Cost of life support

The cost of ISS life support is estimated as a guide to the cost of life support for Mars.

A. The cost of ISS life support

We first consider the mass of ISS life support and then apply the ISS mass cost factor. The masses of the ISS life support systems, their ORUs, and the total mass of the regenerative life support system are shown in Table 4.

Table 4. ISS ECLSS system, ORU, and total mass.

System	System mass, kg	ORU mass, kg	Mass of three spare ORUs, kg	Mass of one system and three spare ORUs, kg
Oxygen Generation System (OGS)	676	399	1,197	1,873
Carbon Dioxide Removal System (CDRA)	195	156	468	663
Carbon Dioxide Reduction System (CRS)	329	219	657	986
Urine Processor Assembly (UPA)	455	229	687	1,142
Urine Processor Assembly (UPA)	928	512	1,536	2,464
Totals	2,583	1,515	4,545	7,128

Typically ISS has one or two spares of each ORU on board. (Jones, 2016-109) It is assumed that a total of three spares of each ORU were procured. For a total life support mass of 7.1 MT, cost would be 7.1 * 0.2244 $B/MT = 1.6 billion dollars. Just the system itself, without spares would cost 0.58 billion dollars, and the system with one set of spares would be 0.92 billion.

A GAO report provides some direct life support cost information. As of 2011, NASA

> "plans to spend about $515 million procuring ISS spares to be used from 2010 through 2015 and about $384 million for spares to be used from 2016 through 2020." … (Fewer spares will be needed) "from 2016 through 2020 because NASA already purchased and pre-positioned spares aboard the ISS." … "(T)hrough 2015, NASA officials anticipate that the agency will spend about $288 million to procure spares for the Environmental Control and Life Support System." … "The total of $288 million includes $233 million NASA has budgeted to procure spares for the Regenerative ECLSS, which recycles liquid waste into potable water and oxygen. In terms of estimating the needed spares, the Regenerative ECLSS is the most high-risk functional system, as several of its ORUs are failing faster than originally anticipated." (GAO, 2011)

Of the $515 million to be spent for spares to be used from 2010 to 2015, $233 million or 45% is for regenerative life support spares. It seems likely that 45% of the $384 million for spares to be used from 2016 to 2020, or 174 million, is also for regenerative life support spares. The total for regenerative life support spares would then be about 407 million.

Of course, more spares will be procured for the ORUs with a higher failure probability, but actual failures are rare. Most spares are simply for insurance and will never be used or need to be replaced. It is typical to have one or two spare ORUs on board and another one or two on the ground. If we assume that the 407 million dollars is for two sets of regenerative life support spares massing 3.03 MT, then the cost of a full system with three sets of spare ORUs massing 7.1 MT would be 0.95 billion.

The launch and operations costs are additional components of the life cycle cost. The ISS life support equipment was launched on the shuttle, so the launch cost was 0.061 billion per MT. The system plus two sets of ORUs would mass 5.6 MT and its launch cost is 5.6 * 0.061 = 0.34 billion.

Operations cost for ISS is 0.0401 $B/MT-year, based on development cost and mission length. For a $1 billion development cost and an anticipated 15 year operational duration, the operations cost would be 1 * 15 * 0.0401 = 0.60 billion. The total cost of the ISS life support seems to be about 2 billion current dollars, one billion for hardware development, and one billion for launch and operations.

B. The cost of Mars life support

The cost of the Mars life support system could easily be the same or even more than that of the ISS system The ISS life support can provide for more than the three or four US crew on ISS, so it could be easily scaled down to one half the ISS size. On the other hand, a Mars mission will require two life support systems both able to support the full crew. One system will be for Mars transit, the trip from Earth to Mars and back in zero gravity. The other system will be for the surface of Mars. The Mars surface system may be a different design to take advantage of gravity, atmosphere, or surface materials. Having different transit and surface life support designs would increase the hardware development cost.

Another important difference between ISS and Mars is that Mars life support should have much higher reliability and maintainability than ISS life support. The ISS crew can receive oxygen and water from Earth or return to Earth if life support fails, but the Mars crew cannot. Higher reliability suggests that the number of spares should be larger.

Another important difference between ISS and Mars is that a Mars mission cannot receive spare parts from Earth as needed. All the spare parts must be launched to Mars and then either descend with the surface system or be sent back toward Earth with the transit system. The mass to be launched will be higher for Mars, especially if more spares are used for higher reliability. And the cost to send mass to the surface of Mars or on the round trip is much greater than the cost to launch mass to LEO.

1. Mars life support hardware development cost

Considering the ISS life support hardware development, a reasonable guess is that the Mars life support system, with two systems for transit and surface and three or more spares for each subsystem could mass 10 MT. To be conservative, assume the Mars hardware would mass 5 MT and cost 5 MT * 0.2244 $B/MT = 1.12 billion dollars to develop.

2. Mars life support launch cost

Still assuming that the Mars hardware masses 5 MT, the cost to launch it to LEO would be 5.0 * 0.061 = 0.31 billion. However, placing the life support mass on the surface of Mars or taking it on a round trip requires rockets, fuel, and landing systems that must also be launched to LEO.

A rocket's total-to-payload mass ratio or gear ratio is the ratio of the total payload, rocket, and propulsion mass needed in LEO to the final payload mass at the destination. The gear ratio for a full transit, from Earth to Mars and back to Earth, is 6.77. The gear ratio for material for a Mars lander is 3.77. (BVAD, 2004) The future gear ratio numbers are uncertain, since they depend on assumptions about future space transportation development.

Suppose that the 5 MT of life support hardware is half for transit and half for the surface. The required mass in LEO is then 2.5 * 6.77 + 2.5 * 3.77 = 26.4 MT. The total cost to launch the Mars life support to LEO would be 26.4 * 0.061 = 1.60 billion, greater than the development cost. This seems high because the shuttle launch cost basis seems high. Cutting it in half to correspond to the lower Saturn V cost would give 0.80 billion.

3. Mars life support operations cost

The Mars operations costs will be relatively smaller since the total mission duration is roughly 3 years, not 15 years as for ISS. The operations cost estimate is 0.0401 $B/$B-year, based on development cost and mission length. For a $1.1 billion development cost and a 3 year operational duration, the operations cost would be 1.1 * 3 * 0.0401 = 0.13 billion.

4. Total Mars life support cost

The estimated Mars costs are 1.12 billion dollars to develop, 0.80 to launch and 0.13 to operate, roughly 2 billion. This is the same as the previous result found for ISS. Since the mass data and cost estimating relationships were based on ISS, it was perhaps inevitable that the Mars cost estimate would be similar.

However, there are significant differences. The ISS cost estimate was 1.0 billion for development, 0.3 for launch, and 0.6 for operations. The Mars cost estimate was 1.1 billion for development, 0.8 for launch, and 0.1 for operations. The launch cost is much higher for Mars than for LEO, while the shorter duration of a Mars trip reduces operations costs.

The Mars cost is more likely to be higher than lower than 2 billion. The Mars mass, development cost, and launch costs were intentionally cut from the direct ISS analogs. If the mass had been left at 10 MT and the launch cost left at the ISS shuttle rate, the total cost estimate would have been 10 * 0.2244 + 10 * (6.77 + 3.77)/2 *0.061 + (10 * 0.2244) * 3 * 0.0401 = 6.7 billion. A lower cost would require lower system mass, lower development cost per unit mass, and lower launch cost per unit mass.

V. Can we afford "half a trillion dollars"?

The NRC report provides some comparisons:

> "The scale of the government investment required to send humans to Mars is, to a rough order of magnitude, equivalent to:
>
> • The cost of perhaps 75-150 "flagship class" robotic exploration spacecraft (assuming an average cost of $1 to $2 billion each).
>
> …
>
> • Two to four times the U.S. investment in the ISS, which amounted to roughly $150 billion, including launch costs." (National Research Council, 2014)

The Apollo program would cost 205 billion in current dollars, shuttle cost 227 billion, and ISS 150 billion. Mars will be two or three times as expensive as any one of the Apollo, space shuttle, or ISS programs. Mars could cost as much as any two or all three of these big US space projects.

"Half a trillion dollars" represents a major US government expenditure. It is similar to the cost of the Iraq and Afghanistan wars, the development of the F-35 jet fighter, or the homeland security budget since 9/11. The current federal budget is 3.8 trillion, 21% of the US GDP of 18 trillion.

A half trillion dollar Mars program would require 2.8% of the 2015 GDP. Carried out over 28 years, Mars would cost 0.1% of the 28 years' total GDP. Apollo cost 25 billion in then current dollars over ten years, 1962-1972. The GDP was about 860 billion in then current dollars, so Apollo cost about 2.9% of one current year's GDP. This is very close to the burn rate required for Mars, but the expenditure for Mars would be over a period nearly three times as long.

VI. Conclusion

The best and most realistic way to estimate project cost is by using comparisons to earlier similar projects. Professional cost estimating models use parametric cost estimating relationships, which relate cost to measurable cost drivers such as mass, number of systems produced, and technical difficulty.

The estimates produced by comparison to past projects are often disputed because, "Next time it will be different." Considering the well-known difficulties of space shuttle and ISS, it seems that we can easily do better.

We expect there will be fewer engineering mistakes, no emergency redesigns, no budget cuts, and less mismanagement and political conflict.

Engineering bottom-up estimates are often used as alternates to historical project cost comparisons, but they typically assume best case engineering, free of external impacts. Engineering estimates usually assume that the technical problems can be solved and that there will be no design errors and rework. The costs of integration, test, systems engineering, and management are underestimated or omitted. It is not easy to foresee conflicting goals, difficult customers, and inconsistent guidance. Engineering estimates that do not anticipate technical problems and political conflicts are wishful thinking.

Apollo was the most successful human space project, but it occurred because of early Soviet space dominance and a cold war crisis. Apollo's clear fixed goal and schedule, the Moon within the decade, provided unequalled drive and focus. Apollo was given sufficient resources to achieve its goal and had no need to cut or misrepresent its cost.

The space shuttle and ISS are different, conducted in a more normal environment of conflicting priorities and limited budgets, and achieving a more limited and less astonishing success. Mars will be a greater achievement than the moon, but it is not easy to plan and fund as if it was business as usual.

The assertion that a human Mars mission will cost about 500 billion dollars is well established and widely known. It was recomputed using very simple cost estimating. The point is that, if we work as we have in the past, the expected cost is "on the order of half a trillion dollars." It seems strange to estimate the extraordinary first human trip to Mars by assuming we will follow traditional development methods, but thinking that we can do much better could produce very over-optimistic cost estimates. We can hope but not plan that new ideas or new approaches can get humans to Mars for less than half a trillion dollars.

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