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The Recent Large Reduction in Space Launch Cost

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

The development of commercial launch systems has substantially reduced the cost of space launch. NASA's space shuttle had a cost of about $1.5 billion to launch 27,500 kg to Low Earth Orbit (LEO), $54,500/kg. SpaceX's Falcon 9 now advertises a cost of $62 million to launch 22,800 kg to LEO, $2,720/kg. Commercial launch has reduced the cost to LEO by a factor of 20. This will have a substantial impact on the space industry, military space, and NASA. Existing launch providers are reducing their costs and so are satellite developers. The military foresees an opportunity to rapidly replace compromised space assets that provided communications, weather, surveillance, and positioning. NASA supported the development of commercial space launch and NASA science anticipates lower cost missions, but human space flight planning seems unreactive. Specifically, it has been claimed that commercial spaceflight has not reduced the cost to provide cargo to the International Space Station (ISS). The key factor is that the space shuttle can provide cargo and crew to ISS while the Falcon 9 must also use the Dragon capsule, which adds cost and reduces payload. The cost of a Falcon 9 and Dragon capsule mission to ISS is about $140 million with a payload of 6,000 kg, $23,300/kg. The shuttle payload to ISS is less than to LEO, 16,050 kg, so its cost is also higher at $93,400/kg. The launch cost to ISS has been reduced by a factor of 4. Calculations that show commercial launch provides no cost reduction to ISS assume half the usually cited shuttle cost and allocate it to the actual delivered payload, about half the full capacity. In a split mission, with crew and pressurized cargo launched separately from hardware and materials, the higher Falcon 9 plus Dragon costs would apply only to a fraction of the launch mass. A 4 to 1 cost reduction saves most, 75%, of the total cost. A further reduction to 10 or 20 to 1 saves 90 or 95%, but this is only a small, 15 or 20%, portion of the original cost. The recently reduced space launch cost can be expected to substantially impact human space flight.

Nomenclature

DDT&E	=	Design, Development, Test and Evaluation
ISS	=	International Space Station
LEO	=	Low Earth Orbit
NAFCOM	=	NASA Air Force Cost Model

I. Introduction

THE cost of space launch dropped from very high levels in the first decade of the space age but then remained high for decades and was especially high for the space shuttle. In the most recent decade, commercial rocket development has reduced the typical space launch cost by a factor of 20 while NASA's launch cost to ISS has declined by a factor of 4.

This paper reviews the history of the reduction in space launch costs, considers the reasons for the decline, and discusses the implications for space users. Very high launch cost was long considered the major impediment to space exploration and exploitation. Many technical approaches were suggested to reduce launch cost but none succeeded until commercially motivated suppliers bypassed the problems long inhibiting government sponsored rocket builders. Surprisingly, launch vehicle reuse - the most anticipated method to cut cost - has not so far actually cut cost and probably contributed to very high shuttle launch cost. The decline in launch costs has removed a major barrier and is expected to increase exploration, exploitation, and human expansion in space. The commercial market, the military, and NASA have responded differently due to their different goals and methods. Rocket builders and

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

users are reacting to market signals by cutting prices, and the military sees an opportunity to increase security using space, but NASA seems slower to adapt.

II. The history of space launch costs

The mass that launch systems can deliver depends on the destination orbit. Launch systems are usually compared using the launch cost per kilogram to Low Earth Orbit (LEO). The cost for cargo to the International Space Station (ISS) is higher since the payload is lower because ISS is in a higher inclination orbit to accommodate Russian launch sites.

A. Launch cost per kilogram to Low Earth Orbit (LEO)

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

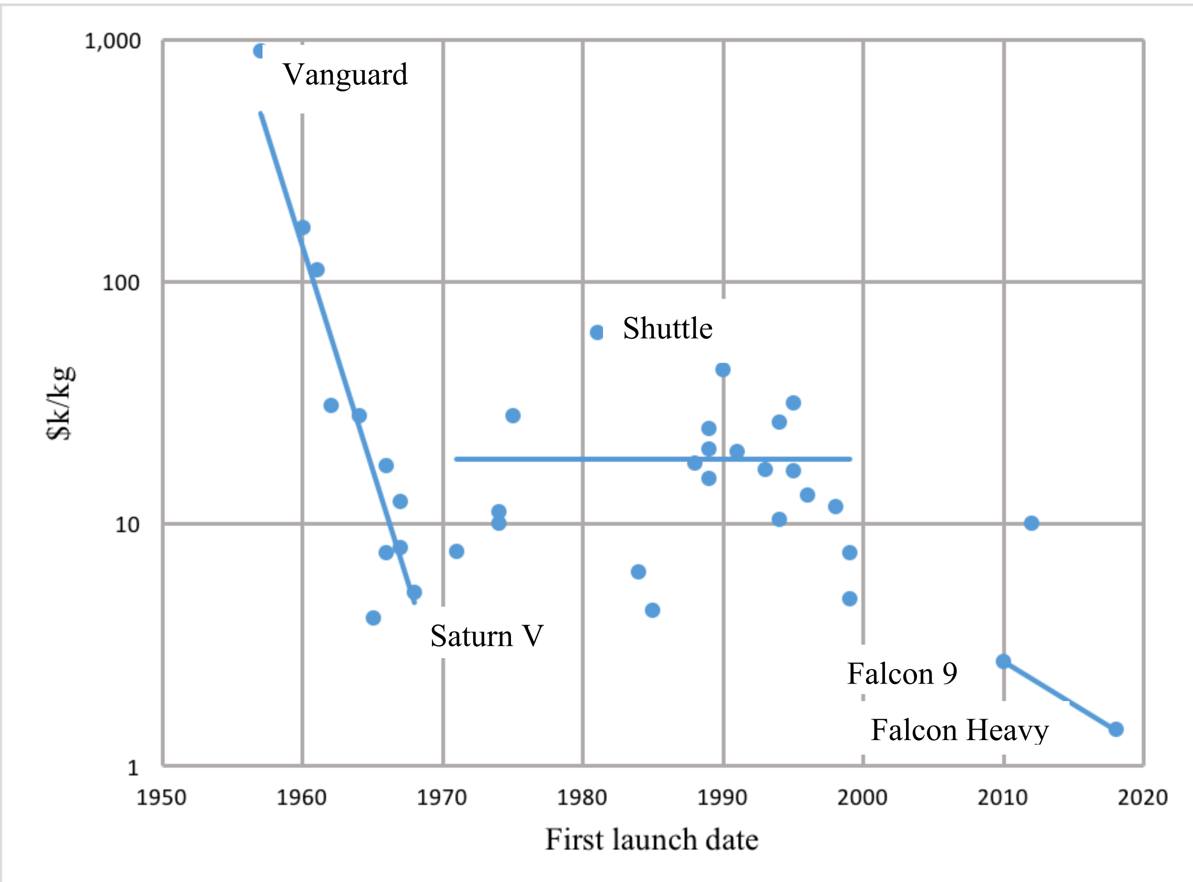

Figure 1. Launch cost per kilogram to LEO versus first launch date.

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

The average launch cost did not change much from 1970 to 2000, especially since many systems with initial flight before 2000 continue to be used. From 1970 to 2000 the average launch cost was $18.5 k/kg, with a typical range of $10 to $32 k/kg. Of the 22 systems initially launched from 1970 to 2000, only 7 have costs below $10 k/kg, and they are all Soviet or Chinese and their cost may be subsidized. Only 2 systems have costs above $32 k/kg, the shuttle at $61.7 k/kg and the small and costly Pegasus.

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

B. Launch cost per kilogram to the International Space Station (ISS)

Table 1 shows the launch cost of the space shuttle and Falcon 9 plus Dragon to the International Space Station (ISS). The numbers are taken from Appendix B:

Table 1. Total launch cost to ISS for space shuttle and Falcon 9 plus Dragon.

System	Shuttle	Falcon 9 plus Dragon
Total cost per launch, 2018 $M	1,697	150
kg to ISS	16,050	6,000
Total 2018 $k/kg	105.8	25

The Falcon 9 plus Dragon reduce the space shuttle cost to ISS by about a factor of 4. The cost reduction factor for cargo to ISS is much less than the reduction factor for LEO, but it is still a significant cost reduction.

III. The reasons for the decline in launch costs

The technical problems leading to high space launch costs have been identified and cures proposed, but the long delay until the recent reduction in launch costs suggests that cultural and institutional barriers have hindered implementing potential technical improvements. The next sections discuss the technical and institutional reasons for the decline in launch costs.

A. Technical causes and cures of very high space launch cost

After an initial decline at the beginning of the space age, Western launch costs have remained very high and relatively constant until recently. High launch costs have been "the greatest limiting factor to expanded space exploitation and exploration." (Wertz and Larson, 1996, pp. 115-7)

The technical causes of high launch cost have been assessed as follows:

1. Goal of maximum performance and minimum weight, originally from ballistic missiles
2. Higher cost of expendables versus reusables
3. High cost of human spaceflight
4. High cost of new technology, hardware, and software
5. Low failure tolerance and consequent intense design effort and detailed oversight
6. High system complexity, parts counts, and number of interfaces (Wertz and Larson, 1996, pp. 126-33)

Commercial launchers saved initial development cost by using missile designs, but missiles are designed for high performance, not minimum cost. Comparing rockets to aircraft, it seems that reusability is the obvious path to reducing costs, but the example of the space shuttle does not support this. Reusable rockets have higher development costs and reduced payload due to the need for landing fuel. The Falcon 9 is reusable and has been reused, but the projected cost savings remain in the future. Human spaceflight adds costs for life support, higher reliability, and man rating. Commercial and military payloads are expensive and there is low tolerance for failure. Development and production cost increases with system complexity. (Wertz and Larson, 1996, pp. 126-33)

The possible technical approaches to cut launch cost have been assessed as follows:

1. Simplify the vehicle configuration
2. Increase vehicle production and launch rates
3. Use industrial design and production methods (cultural change)
4. Optimize for minimum cost
5. Reduce the parts count
6. Increase simplicity and design margins
7. Reduce instrumentation
8. Design for production and operation (Wertz and Larson, 1996, pp. 147-53)

One study suggested that the record low cost of the Saturn V could be reduced by a factor of 5, to a cost similar to the Falcon Heavy. The Pegasus system achieved low development cost using a commercial off-the-shelf approach, but because of its small payload it had the second highest launch cost in recent decades. Wider design margins can accommodate weight growth without costly last minute weight reducing efforts, help avoid miniaturization, and allow redundancy rather than intensive design to increase reliability. (Wertz and Larson, 1996, pp. 148, 149, 154)

"To make significant reductions in launch costs, new 'clean sheet' launch systems must be developed. … institutional barriers within government and industry have prevented major inroads is cost reduction." (Wertz and Larson, 1996, p. 155) The long awaited large reduction in launch cost has now been achieved, but what were the "institutional barriers" that delayed this?

B. Institutional causes and cures of very high space launch cost

The high cost of ordinary launch vehicles, the higher cost of the space shuttle, and the success of SpaceX can all be explained by institutional causes.

Some of the institutional causes of high cost for ordinary launch vehicles were mentioned above, including military heritage, need for high reliability, and a non-industrial culture. The fundamental cause of the past high commercial launch cost seems to be lack of competition. The US launch industry has been a monopoly, the United Launch Alliance (ULA), and its main customer has been the US government, NASA and the military, which need high reliability and had little incentive to exert cost pressure. The ULA lost most of the commercial market to Russia and Arianespace which are also heavily subsidized by their governments. (Zimmerman, 2012)

The space shuttle had unique NASA cost drivers. About one-fourth of the shuttle operational costs went for "the general area of NASA center and program support, maintenance of capability, and product improvement." "Another major cost driver in Shuttle is launch operations costs. The fact that 10,000 contractors and 1,000 civil service are needed … is indicative of the lack of operational simplicity. This marching army plus mission operations and crew operations personnel make up one third of the overall shuttle operations costs. The low Shuttle flight rate not only makes for inefficient use of personnel and facilities, it distorts the cost per flight calculations because of high fixed costs." (Rutledge, 93-4063)

SpaceX has low costs largely because it is vertically integrated, with largely in-house development of the components of its rockets. It carries out all phases of the product lifecycle, including design, engineering, manufacturing, software, integration, testing, launch, and operations. Most activities have been in a single large facility. The competing ULA is a systems integrator and launch operator with hundreds of subcontractors that have dozens of facilities spread all over the country, which is a political necessity for a government funded jobs program. SpaceX designs for simplicity, for instance the Falcon 9 uses 9 identical engines. The Falcon Heavy effectively uses three Falcon 9's. Another key factor in SpaceX's low costs is its young, highly motivated workforce of top graduates willing to work significant unpaid overtime. SpaceX uses state of the art automated manufacturing equipment "previously unheard of in the space industry, where hand assembly of components is still the norm." (Greg, 2015)

In 2010, NASA compared SpaceX's cost to develop the Falcon 9 to the cost NASA's models predicted using the traditional cost-plus-fee method. Using the NASA-AF Cost Model (NAFCOM), NASA estimated that it would have cost NASA $1,383 million to develop these systems using traditional contracting. The estimated SpaceX cost was $443 million, a 68% reduction from the traditional approach. SpaceX attributed their cost efficiencies to a few key factors:

1. Smaller workforce
2. Use of in-house development
3. Fewer management layers and less infrastructure
4. Commercial development culture

The cost of Design, Development, Test and Evaluation (DDT&E) depends primarily on the size of the workforce needed. SpaceX estimates that subcontracting one dollar's worth of in-house work would cost three to five dollars due to subcontractor overhead and profit. The commercial development approach includes a firm fixed price versus cost plus, no oversight, fixed requirements, disciplined systems engineering, and fixed funding instead of annual budgeting. (NASA, 2011)

Perhaps the the key determinant of SpaceX's lower cost was that modern management allowed a highly effective engineering effort. "SpaceX's approach to rocket design, which stems from one core principle: Simplicity enables both reliability and low cost." All the Falcon 9 engines are identical where other rockets use two or three to gain performance at higher cost. The Falcon 9 avionics and controls are triple-redundant. Elon Musk, SpaceX's CEO, is also chief engineer and he claims. "I know my rocket inside out and backward." The frequent management - engineering conflict of goals and communications gap seem eliminated. SpaceX's organizational style is Silicon Valley, not NASA. "(T)he buzzwords of the business culture—lean manufacturing, vertical integration, flat management—are real and fundamental. … This really is the greatest innovation of SpaceX: It's bringing the standard practices of every other industry to space." (Chaikin, 2012)

C. Will space launch cost go lower?

There are many reasons to expect that space launch costs will go lower, even much lower. These include launch vehicle reuse, an expanded market due to lower cost, increased commercial competition, better management and engineering, and technical advances.

The reuse of rockets and entire launch vehicles has been considered important in reducing launch cost, but so far reuse has not led to lower cost. The space shuttle was extremely expensive, largely due to the high cost of refurbishing the shuttle between flights. The Falcon 9 was designed to be reused, at a significant increase in development cost, but so far it has been reused only a few times. Falcon 9 reuse may reduce costs by a factor of two. "SpaceX president Gwynne Shotwell told the Space Symposium conference that the cost of refurbishing the Falcon 9 rocket that originally flew the CRS-8 Space Station resupply mission last year for SES-10 was 'substantially less than half' what it would have cost to build a brand new one." (Morris, 2017)

Reuse might provide much more drastic cost reductions. Elon Musk believes that the new Raptor engine can achieve full reusability of all rocket stages and "a two order of magnitude reduction in the cost of spaceflight" to $10 per pound by 2025. (Wang, 2016)

General market and competitive effects could lead to further cost reduction. The lower cost of launch should lead to an increased number of space flights, which would lead to cost reduction due to the learning curve, to reliability growth due to failure mode discovery and repair, and would more quickly pay back the initial development cost and so justify more investment in launcher design. Previously the launch market belonged to a limited number of government supported entities possibly more concerned with military capability, launch reliability, national prestige, and creating jobs and economic stimulus than with reducing costs or developing new technology. The commercial rocket business has provided a different engineering-savvy business model that has greatly reduced costs. A growing more competitive market will tend to favor technology advances that cut cost and improve performance.

IV. The implications of the decline in launch costs

High launch costs have been considered the major barrier to further advances in space. Lower launch costs are expected to increase exploration, exploitation, and human expansion. The major customers for launch services are commercial satellites, the military, and NASA. The commercial market, the military, and civilian government are three different sectors of society, with different roles, goals, and characteristic approaches. The expected impact of lower costs has been different for commercial satellites, the military, and NASA.

A. The lower launch costs will affect missions, spacecraft design, and space business

High launch costs have affected all aspects of space planning. High launch costs have been the greatest factor limiting the number and reducing the scope of space missions. Reduced launch cost will directly allow more, bigger, better missions. (Wertz and Larson, 1996, p. 117)

High launch costs lead to high spacecraft costs through "intense pressure to make every kilogram of the spacecraft pack as much performance and capability as possible." (Wertz and Larson, 1996, p. 154) Space hardware must be very light and so it tends to be fragile, creating a problem during launch. Weight removal is difficult and requires extensive analysis and testing to ensure surviving launch. Reliable, tested and proven, standard, inexpensive off-the-shelf systems can not be used because of their weight. Using more mass allows increased design margins, use of redundancy, and operational robustness. (Wertz and Larson, 1996, p. 154) Reduced launch cost will directly allow heavier, more robust and reliable, and better performing spacecraft to be developed at lower cost.

Low cost commercial launch "will change our lives. The development of a robust space economy promises growth, astounding new products and services, amazing high-tech jobs and a quantum leap in our national security capabilities." "Launch cost has always been the primary constraint in the space business. If access to space weren't so expensive we'd have an astounding amount of entrepreneurial activity in Low Earth Orbit (LEO) and beyond. Space tourism, materials development, pharmaceutical research, power generation, communications, earth imaging and national security all have "killer apps" just waiting for reliable and affordable access to space." (Autry, 2017)

B. The commercial satellite market reaction to lower launch costs

Until the 2000's, communications satellites were the principal commercial launch market. The total number of commercial launches was roughly 25 to 35 per year until the Falcon 9 expanded the market and became the largest supplier, passing the Ariane 5. Communications satellites use a limited number of internationally allocated geosynchronous slots. The commercial satellite launch market is far from an open and competitive market, since most suppliers and customers have been government regulated and subsidized. Prices can be affected by political reasons.

In a restricted market, lower costs might not have much impact. None the less, "Satellite design and manufacturing is beginning to take advantage of these lower-cost options for space launch services." And, "(T)he satellite manufacturing industry may 'experience a shock similar to what the launcher industry is experiencing'" (Wikipedia, Space launch market competition) Ultimately, a commercial market tends to reduce costs and improve performance.

C. The military space reaction to lower launch costs

The military is eager to take advantage of lower launch costs, which provide a forceful and dramatic solution to vital current problems. The United States' military capabilities greatly depend on space assets, including communications, global positioning, weather, and surveillance satellites. Satellites are vulnerable to attack and difficult to hide or defend, so the ability to rapidly and cheaply replace them is very attractive. "Recent private sector developments in access to space could open the door for a new concept for airpower. If realized these capabilities could fundamentally change the USAF's power projection paradigm, while building new strategic options for the nation." (Air University, 2017, p. ii)

The Air University white paper explains the problem and proposed solution. "(O)ur current space architecture grows increasingly vulnerable." "Fast Space envisions sortie-on-demand launch capability, made possible through economically viable business cases, high launch rates, sustainably lower costs, rapid turn-around, and higher reliability." This provides "The ability to immediately deliver additional effects worldwide such as precision navigation and timing, electronic warfare, cyber effects, directed energy, kinetic attack, and rapid global transport of cargo and personnel." "In short, competition in space has returned. Space is congested and contested and our advantages in space can no longer be assured. The US military depends on space assets that are increasingly at risk of attack." (Air University, 2017, pp. 1, 2, 7) Low cost space launch provides the solution to urgent current military problems and could enable a new era of US military dominance through control of space.

The Air University report characterizes NASA's launch system efforts as directly leading to higher costs than a commercial approach. "A government agency, even a well-run agency, does not have the correct economic incentives to lower costs. NASA was not incentivized to eliminate the operational and labor costs that were part of the Shuttle system. Since NASA depends on political support, which is driven by the number of jobs in congressional districts, the opposite is true. America has proven over its history that private industry, properly incentivized in a pro-competition environment, is much more successful at lowering costs." "NASA chose the highest technical risk solution from among the three major X-33 bids, as they gave higher points to the bidders with the 'most new technology'… This is the exact opposite of how almost any commercial firm would have evaluated the process, as 'technical risk' is something to be eliminated and mitigated before taking a product or service to market." "The NAI had to make everybody happy, so it included a significant piece of work for all parties. The 'political process' required to achieve buy-in and consensus significantly increased the estimated price." (Air University, 2017, pp. A-2, 3)

D. The NASA manned space reaction to lower launch costs

Even though NASA has enabled and supported the development of commercial space launch, its success may compete with NASA's in-house rocket development and disrupt NASA's current vision of space exploration. NASA appears much less willing than some in the military to accept and exploit the new lower launch costs. This is especially true in life support, where the key choice is between direct supply of consumables with high launch mass versus recycling to reduce launch mass. Recycling was long thought thought to be necessary on all long human missions due to the historically very high launch cost per kilogram. Now resupply may be much cheaper as well as much more reliable than recycling. (Jones, 2017-87)

Some in NASA think the new lower launch costs are exaggerated or even nonexistent. In 2008, NASA signed a contract with SpaceX for 12 launches at a cost of $1.6 billion. NASA payload specialist and space station engineer Ravi Margasahayam, speaking as a private citizen, stated, "My cost per pound went up with these rockets. On the shuttle, it would be much less." "Margasahayam points out that, while the space shuttles were more expensive — a whopping $500 million per launch (or possibly $1.5 billion, according to one analysis we've seen) — each mission carried about 50,000 lbs. (plus seven astronauts!). That means each pound of cargo used to cost about $10,000 to ship on a shuttle." "For SpaceX - the cheapest of NASA's new carriers - dividing the cost of each launch ($133 million) by the cargo weight of its most recent resupply mission (5,000 lbs.) gives you about $27,000 per pound

($59.5 k/kg). But that's a high estimate. SpaceX told Tech Insider that its Dragon cargo spacecraft launched on a Falcon 9 rocket can carry up to 7,300 lbs." (Kramer and Mosher, 2016)

How do these numbers check? For space shuttle, the quoted article notes that Margasahayam's cost to launch was too low. (Kramer and Mosher, 2016) Using $1.5 billion rather than $500 million would increase his computed shuttle launch cost by a factor of three, to $30,000 per pound or $66 k/kg. And there is a further correction. The shuttle carried 27,500 kg (60,000 lb) to LEO, but only 16,050 kg (35,380 lb) to ISS. (Wikipedia, Space Shuttle) A better cost for shuttle launch to ISS is $1.5 billion/16,050 kg = $93.4 k/kg. And the SpaceX potential payload to ISS is 6,000 kg. (Spacex.com, 2018) (Wikipedia, SpaceX Dragon) 133 million/6,000 kg = $22.2 k/kg. This shows that SpaceX provides a cost reduction to ISS by a factor of 4. A more direct calculation in Appendix B gives a similar result.

The NASA engineer's casual analysis made two mistaken assumptions that favored shuttle over commercial launch. They may be derived from similar mistakes in an earlier NASA estimate provided to Congress. The space shuttle cost per pound to ISS was "Calculated assuming four missions per year with a capability to deliver 16 metric tons (35,264 pounds) to the space station at a total annual program cost of $3.0 Billion. $3,000,000,000 ÷ (4 flights × 35,264 pounds/flight) = $21,268 per pound." (U.S. House of Representatives, 2011, p. 5) This $21,268 per pound is equivalent to $46.8 k/kg and is too low by half because of the too low by half ($750 million) shuttle cost per launch. The NASA estimate supplied to the House for commercial resupply to ISS was $26.77 k/lb or $58.9 k/kg, which is similar to the cost for Falcon 9 of $59.5 k/kg computed above, which was based on the 2008 contract cost and actual rather than potential payload. Some comments were critical, such as "the numbers announced by this House report are garbage." (Zimmerman, 2011) Unlike the military, which embraced and emphasized the benefits of lower space launch cost, NASA has denied and clearly underestimated them.

E. Factors other than launch costs

The space shuttle had some capabilities that the Falcon 9 lacks. The Falcon 9 payload to ISS is much lower than shuttle due to the need for the Dragon capsule, even though the payloads to LEO are similar. The Falcon Heavy payload to LEO is more than twice the space shuttle's. (Spacex.com, 2018) The Falcon 9 and Dragon are expected to carry crew to the ISS, but the shuttle also could sustain a crew in orbit for weeks and had a large workspace in the payload bay. Both the space shuttle and Falcon 9 can return cargo to Earth.

The Falcon 9's cost to NASA is lower than shuttle's because Falcon 9 launch is a contracted service rather than supported by an in-house capability. Most Falcon 9 launches are commercial, so the cost of development and operations is spread over many launches per year. NASA shuttle management was well aware of this cost spreading effect and initially planned to have all US launches, commercial, military, and NASA science, use the shuttle. After Challenger, most space shuttle flights were restricted to building the ISS or where humans were needed, as in Hubble repair. The low flight rate of the space shuttle was a major factor in its high cost. (Rutledge, 93-4063)

V. Conclusion

The cost of space launch has been substantially reduced. This provides greatly expanded opportunities to exploit space for commercial users, the military, and NASA. The commercial competitive launch approach sponsored by NASA provided an unconstrained environment that allowed a focused management to cut costs using good engineering. Competition drives innovation and forces efficiency, cuts costs and creates new opportunities.

The commercial low launch cost opportunity, competing foreign space efforts, and a possible new military push into space suggest that NASA should plan for lower launch costs and try to increase the number and size of missions. The previous assumptions and design decisions made for the space station should be reconsidered, especially the use of recycling rather than resupply for life support. Further commercialization may be advantageous.

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

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

Table A1. Launch cost to LEO in current dollars.

System	First launch date	$k/kg	Reference
Ariane 44	1988	17.9	Wertz and Larson, 1996
Ariane 5G	1996	13.1	Futron, 2002
Athena 1	1995	31.7	Wertz and Larson, 1996
Athena 2	1995	16.6	Futron, 2002
Atlas IIA	1991	19.8	Wertz and Larson, 1996
Atlas-Centaur	1964	28.0	Koelle, 1991
Cosmos	1967	12.4	Futron, 2002
Delta 3910	1975	28.0	Koelle, 1991
Delta E	1960	167.8	Koelle, 1991
Delta II	1989	15.3	Futron, 2002
Delta III	1998	11.7	Koelle, 1991
Dnepr	1999	4.9	Futron, 2002
Falcon 9	2010	2.7	SpaceX.com, 2018
Falcon Heavy	2018	1.4	SpaceX.com, 2018
H-2	1994	26.4	Wertz and Larson, 1996
Kosmos	1967	8.0	Wikipedia, Comparison, 2018
Long March 2C	1974	10	Futron, 2002
Long March 2E	1971	7.7	Wertz and Larson, 1996
Long March 3B	1984	6.3	Futron, 2002
Pegasus XL	1990	43.5	Futron, 2002
Proton SL-13	1965	4.1	Wertz and Larson, 1996
Rockot	1994	10.4	Futron, 2002
Saturn V	1968	5.2	Williams, 2016
Saturn IB	1966	17.3	Koelle, 1991
Scout	1961	111.8	Koelle, 1991
Space shuttle	1981	61.7	Pielke and Byerly, 2011
Soyuz	1966	7.6	Futron, 2002
Start	1993	16.7	Futron, 2002
Taurus	1989	20.4	Wertz and Larson, 1996
Titan II	1962	31.0	Wertz and Larson, 1996
Titan IV	1989	24.7	Wertz and Larson, 1996
Titan-Centaur	1974	11.2	Koelle, 1991
Vanguard	1957	894.7	Koelle, 1991
Vega	2012	10.0	Wikipedia, Comparison, 2018
Zenit 2	1985	4.4	Futron, 2002
Zenit 3SL	1999	7.6	Futron, 2002

The costs were corrected from the reported basis years to current dollars using the Consumer Price Index (CPI). (CPI Inflation Calculator, 2018) The data of Table A1 are plotted in Figure 1 of the main text.

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

Table A2. Launch cost to LEO for Saturn V, space shuttle, Falcon 9, and Falcon Heavy.

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

These costs are used in Table A1. The cost reduction factor from shuttle to Falcon 9 is about 23.

Appendix B: Launch cost to to the International Space Station (ISS)

The space shuttle carried 27,500 kg to LEO but only 16,050 kg to ISS. (Wikipedia, Space Shuttle) The cost per kilogram for shuttle launch to ISS was $1,697 M/16,050 kg = $105.8 k/kg in current dollars using the shuttle cost from Table A2.

In 2008 NASA awarded a $1.6 billion to SpaceX for 12 cargo delivery flights to ISS. (Wikipedia, SpaceX Dragon) The cost per launch in current dollars is $1,792 million/12 = $149 M/launch. This cost is higher than the $62 M for a Falcon 9 launch because of the added requirement for the cargo-containing Dragon capsule. NASA awarded five more cargo-supply missions to SpaceX in late 2015, with an undisclosed cost estimated at $140 or 150 million per launch, $144 to 154 million in current dollars. (de Selding, 2016) The costs were corrected from the reported basis years to current dollars using the Consumer Price Index (CPI). (CPI Inflation Calculator, 2018) The average current cost estimate is about 150 million.

Each 2008 contract launch was required to carry 5,000 lbs (2,273 kg) to ISS, but the potential payload to ISS is much larger than the contract minimum, 6,000 kg. (Spacex.com, 2018) (Wikipedia, SpaceX Dragon) The cost for Falcon 9 and Dragon cargo to ISS is $150 M/6,000 kg = $25 k/kg, 24% of the shuttle cost to ISS and a reduction by a factor of 4.2. The cost reduction factor for cargo to ISS is much less than the reduction factor for LEO, but it is still a significant cost reduction.

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