CAPITALISM IN SPACE

Private Enterprise and Competition Reshape the Global Aerospace Launch Industry

Robert Zimmerman

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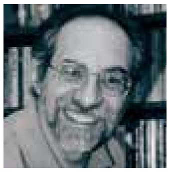
About the Author



ROBERT ZIMMERMAN is an award-winning independent science journalist and historian who has written four books and innumerable articles on science, engineering, and the history of space exploration and technology for *Science, Air & Space, Sky & Telescope, Astronomy, The Wall Street Journal, USA Today,* and a host of other publications. He also reports on space, science, and culture on his website, http://behindtheblack.com. He does not work for any aerospace company and has never received any money from NASA for his reporting.

His books include *Leaving Earth: Space Stations, Rival Superpowers, and the Quest for Interplanetary Travel* (Joseph Henry Press), which won the American Astronautical Society's Eugene M. Emme Astronautical Literature Award in 2003 as that year's best space history for the general public. He also has written *Genesis: The Story of Apollo 8* (Mountain Lake Press) and *The Universe in a Mirror: The Saga of the Hubble Space Telescope and the Visionaries Who Built It* (Princeton University Press). In 2000 he was co-winner of the David N. Schramm Award, given by the High Energy Astrophysics Division of the American Astronomical Society for Science Journalism, for his essay in *The Sciences,* "There She Blows," on the 35-year-old astronomical mystery of gamma ray bursts.

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The views expressed in this report are those of the author alone, and he is solely responsible for any errors in fact, analysis, or omission.

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Apollo 15 commander Dave Scott salutes the American flag on the Moon.
(National Aeronautics and Space Administration [NASA])

Introduction

It is essential for any nation that wishes to thrive and compete on the world stage to have a successful and flourishing aerospace industry, centered on the capability of putting humans and payloads into space affordably and frequently. This is a bipartisan position held by elected officials from both American political parties since the Soviet launch of the Sputnik satellite in 1957.

The reasons for this are straightforward:

- **Military strength:** For strategic reasons, the military must have the capability of launching satellites into orbit for the purpose of surveillance and reconnaissance. In addition, the country's missile technology must be state-of-the-art to make this data gathering as effective as possible. A healthy aerospace industry is the only way to achieve both.
- **Natural resources:** The resources in space – raw materials from asteroids and the planets as well as energy from the Sun – are there for the taking. Other nations are striving to obtain those resources and the wealth those assets will provide for their citizens. Without direct access to those resources, American society will have less opportunity for growth and prosperity, and the country will eventually fall behind as a major power.
- **Economic growth:** A thriving aerospace industry helps fuel the U.S. economy. It develops cutting-edge technology in fields such as computer design, materials research, and miniaturization that drives innovation and invention in every other field.
- **National prestige:** Even if the previous three reasons did not exist, the prestige of the United States requires that we remain competitive in the increasingly global race to explore and settle the solar system. If the United States doesn't compete in this effort, future generations of Americans will be left behind as China, Russia, Europe, India, and an increasing number of other nations establish operations in space and permanent colonies on the Moon, Mars, and the asteroids.

All of these goals require a prosperous U.S. aerospace industry, which in turn requires above all a viable space-launch industry, capable of placing payloads, both unmanned and manned, into orbit cheaply and efficiently.

Unfortunately, since the beginning of the 21st century the U.S. government has struggled to create and maintain a viable launch industry. Even as the government terminated the Space Shuttle program, with its ability to place and return humans and large cargoes to and from orbit, NASA's many repeated efforts since the mid-1980s to generate a replacement have come up empty.[1]

In addition, in the 1990s the Department of Defense instituted a new program, the Evolved Expendable Launch Vehicle (EELV), to guarantee itself launch services that – though successful in procuring those services – have done so at a very high cost, so high, in fact, that the expense now significantly limits the military's future options for maintaining its access to, and assets in, space.

Even as the federal government struggled with this problem, a fledgling crop of new American private launch companies have emerged in the past decade, funded initially by the vast profits produced by the newly born internet industry. These new companies have not been motivated by national prestige, military strength, or any of the traditional national political goals of the federal government. Instead, these private entities have been driven by profit, competition, and in some cases the ideas of the visionary individuals running the companies, resulting in some remarkable success, achieved with relatively little money and in an astonishingly short period of time.

An artist's concept of the X-33, one of many government efforts since the 1980s to replace the Space Shuttle, all of which failed. For more information, see endnote 1. (NASA)

Because of these differing approaches – the government on one hand and the private sector on the other – policymakers have an opportunity to compare both and use that knowledge to create the most successful American space effort possible.

This report provides a historical look at what has happened in the American space industry as well as the international launch market since the turn of the century, focusing for comparison on the launch cost for the various new rockets and spacecraft being developed by the private sector and the government. Cost always has been one of the most important limiting factors in every nation's space effort since the day the Soviet Union launched Sputnik in 1957. NASA listed lowering the cost to orbit as the number one reason for building the Space Shuttle. It is the reason the U.S. Air Force instituted the EELV program in the late 1990s. It has been the focus of Space Exploration Technologies Inc. (commonly known as SpaceX) from its founding, illustrated by the significantly lower prices the company charges for its commercial launches. Today, lowering cost is the number one consideration of many established space agencies and private rocket companies, resulting in a reinvigorated launch industry, more vibrant than anything since the 1960s space race.

Should future administrations leverage the lessons being learned now in private industry and make wise choices, the rest of the 21st century could see the entire solar system settled, with much of that exploration done by Americans, spending significantly less money than it has since the end of the 1960s space race.

The Falcon 9 first stage sits intact after completing the first-ever vertical barge landing on April 8, 2016, during the launch of a Dragon capsule to the International Space Station. (SpaceX)

Determining the Best Policy for Obtaining Access to Space

The central focus of this paper is a comparison between the two approaches to maintain and expand American access to space that NASA and the federal government have followed since the mid-2000s.

NASA's effort to build its own heavy-lift rocket for propelling humans to the Moon and beyond was specifically driven by the political vision of presidents and Congress. The program began under President George W. Bush with Constellation program and its Ares 1 and Ares 5 rockets and the Orion manned spacecraft. It then underwent significant modifications following the election of President Barack Obama, who attempted to cancel the program in 2010 before Congress stepped in to mandate its continuance. At that point the Constellation/Ares program was superseded by the Space Launch System (SLS) while work continued on the accompanying Orion spacecraft.

Alternatively, in NASA's commercial space program the space agency – and the broader federal government, including the Department of Defense – is merely a customer buying privately built rockets and capsules from an array of competing private companies including SpaceX, Boeing, Orbital ATK, and the United Launch Alliance (ULA). For cargo, SpaceX uses its Falcon 9 rocket to launch its Dragon capsule, while Orbital ATK uses either its Antares rocket or ULA's Atlas 5 rocket to launch its Cygnus freighter. For future human-crewed flights to the International Space Station (ISS), SpaceX will provide an upgraded Dragon capsule mated with the Falcon 9, and Boeing will provide its new Starliner Crew Space Transportation vehicle on a ULA Atlas 5.

For many reasons, it can be argued that a comparison of these two approaches is unfair. At first glance, the requirements for each seem significantly different. Both Ares 5 and SLS are heavy-lift rockets, comparable to the Saturn 5, and designed to lift into orbit payloads that exceed 70 tons. The rockets used by SpaceX, Orbital ATK, and Boeing to lift their crew and cargo and crew capsules into low Earth orbit are much less powerful, generally lifting less than 20 tons. None are capable of sending spacecraft beyond Earth orbit, as the SLS can.

Similarly, the Orion capsule has more demanding specifications. Operational assessments by Lockheed Martin suggest that it is capable of functioning successfully in space for at least 1,000 days; can travel, at a minimum, to and from Mars; and has sufficient micrometeorite and radiation protection for such travel.[2] The cargo and crew capsules of SpaceX, Orbital ATK, Boeing, and Sierra

Nevada do not have to meet such formidable requirements. They must merely reach low Earth orbit, which is far below the Van Allen radiation belts and means they will not face the solar and cosmic radiation storms of deep space and thus do not require heavy shielding. They also are not required to maintain reliable function in free flight for longer than a few days.

A closer look at these programs, however, reveals that the differences are not as significant as they first appear and that the capsules are quite similar. While Lockheed Martin believes Orion can operate attached to a larger Deep Space Habitat across a 1,000 day Earth-to-Mars mission profile, the capsules being built now for the first two SLS missions (the focus of this report) follow NASA's earlier and less stringent design requirements for manned independent operations in space for only 21 days, unmanned independent operations for six months, and docked operations to the ISS or a Deep Space Habitat for seven months.[3] The manned variant of SpaceX's Dragon as well as Boeing's Starliner are being built with minimum requirements allowing for manned independent operations in space for at least 2.5 days and docked operations to the ISS for seven months.[4] All three capsules are being built with the modern, highly reliable designs used routinely by communications satellites and planetary probes that are capable of operating for decades in deep space. The Orion spacecraft can carry four astronauts. The manned Dragon and Starliner are being designed to carry as many as seven.[5]

Though the Orion capsules being built will have more radiation shielding than either Dragon or Starliner, they are not completely shielded, and their shielding is insufficient for interplanetary flight.[6]

Essentially, the private capsules and the Orion capsules, as currently built, are ascent/descent capsules, primarily designed to bring humans up and down from the Earth's surface. When humans eventually travel beyond Earth orbit, none of these capsules, including Orion, will be sufficient. All are too small for interplanetary travel and their capabilities are inadequate. No crew of four can live in such a small capsule for the many months required to travel to and from Mars. Any interplanetary manned flight will require a much larger vessel, similar in scale to a Mir or International Space Station.[7] Orion, like Dragon and Starliner, will essentially be used as the ferry to go back and forth from Earth. Setting aside any future requirement that Orion will someday be built to maintain structural and operational integrity across a 1,000-day mission profile, Orion at its core is not much different than Dragon or Starliner. That NASA has imposed more stringent requirements on Lockheed Martin for building Orion does not change the fact that the product NASA is getting now will essentially perform similarly to crew capsules being designed and built by private space companies. Hence, an assessment of cost and development time for the two different manned capsule programs is reasonable.

The comparison between the Ares/SLS rockets and the rockets used by private space companies is valid as well. Though SLS is far more powerful and capable than any privately built rocket, it is being built, like the private rockets, to provide NASA access to space. Rather than state a mission requirement and allow the private sector to compete to create a capability by evolving current technologies in new configurations, NASA, in a very traditional governmental approach, has chosen to create Ares/SLS, without basis, as a big rocket.

The question here is whether that development is giving NASA access to space. It is not easy to build a heavy-lift rocket. As a result, SLS has cost a great deal of money and experienced many delays, during which no spacecraft has flown and the agency has obtained no access to space. Meanwhile, the privately built rockets and capsules are launching repeatedly, albeit with some notable failures. Their lower cost might limit their initial capability, but their multiple launches (and failures) have allowed their parent companies to innovate and improve. From this knowledge comes the ability to upgrade their rockets, as SpaceX is doing with its Falcon 9 and Falcon Heavy, so that the company can ultimately match the capabilities of SLS. More importantly, during this development time private rockets and capsules are flying, thus giving NASA the access to space that SLS is not capable yet of providing.

Hence, a comparison of these different rocket systems is useful as a process for exploring alternative approaches to space flight. Which line of attack is producing the results needed by both NASA and the nation? While both approaches are designed with the intent to provide the United States access to space, they are being executed with radically different methods in terms of technology and cost structure. Since the fundamental point of this paper is to reveal which policy best serves the national interests of the United States, a comparison of these two approaches is appropriate.

SpaceX Introduces Competition to the Rocket Industry

On December 4, 2003, Elon Musk stood on the National Mall in Washington, D.C., before a mockup of his proposed Falcon 1 rocket. His goal that day was to officially "unveil" it to the world. His plan, as he stated in his speech, was that the rocket and SpaceX, the company he had founded to build it, would transform how rockets were conceived, designed, constructed, and sold. "The history of launch vehicle development has not been very successful; there really hasn't been a success, if you define success as making a significant difference, a meaningful difference, in cost or reliability," Musk noted. "We have a shot with SpaceX, I think, for the first time in a long time."[8]

Musk was speaking not only about the Falcon 1 rocket, which he had designed to put small payloads into orbit at a starting price of approximately $6 million and was now available for all to see, but also about his proposed Falcon 5 rocket, which would bundle five engines in its first stage, to launch larger payloads for only $12 million. Falcon 1 would be in direct competition with Orbital Sciences' Pegasus rocket, which cost approximately $30 million per launch, or five times as much, while the Falcon 5 would compete with Boeing's Delta 2, which then cost about $60 million per launch, also five times more.

In 2003 these promises seemed both unrealistic and grandiose. For decades the launch industry had been moribund, with little new development and no cost reduction. Rockets were, as a rule, expensive, used once and then thrown away. No company in the industry seemed interested in producing new designs or new approaches that would be cheaper or reusable. When asked, industry experts routinely explained that such cost reductions or innovations were either not possible, or would actually harm the industry. As recently as December 2015 Stephane Israel, the head of Arianespace, reiterated his doubts about reusability and innovation in rocket design. "We prefer not to innovate too much when we make each launch," he noted. "The more you change, the more you take risks." Rather than gamble on new, more efficient designs that might fail, these companies focused on doing the same thing the same way, over and over again.[9]

Moreover, the number of launch companies remained small, and none seemed interested in competing aggressively against each other. The companies in the United States generally sold their rockets to NASA and the Air Force, while Arianespace and Russia focused on sales both to the commercial market and their own governments. Each had its niche market, and was content to glide along, leaving things as they were, without change. The lack of competition resulted in the price for launching a payload into space remaining very high, ranging from $30 million for the smallest payloads to almost a half a billion dollars for the largest, with the average cost for a typical commercial payload ranging somewhere between $100 to $225 million, depending on its size or intended orbit.

Before Elon Musk became a rocket builder, he had made his fortune as one of the creators of PayPal. After the company was purchased by eBay in 2002, Musk found himself with lots of cash and plenty of time to pursue personal interests. These included an interest in exploring space and getting to Mars. He decided he would pay for the first privately built Mars science probe. He soon discovered, however, that while he could easily afford to build the probe, the cost of launching it was beyond even his considerable resources.

Then he had an idea. Why not build his own rocket, do it for less than everyone else, make money while doing so, and then use that rocket to launch his own payloads, using his profits to pay for the effort?[10] He was not naïve about the challenge. As Musk admitted to the audience during the Falcon 1 unveiling, "The history of [commercial] launch vehicle development has not been very successful." In fact, the only previous commercial rocket funded entirely by private sources, the Conastoga, never successfully reached orbit. After one successful suborbital flight in 1982, followed by a launch failure of a redesigned version in 1995, the company folded.[11]

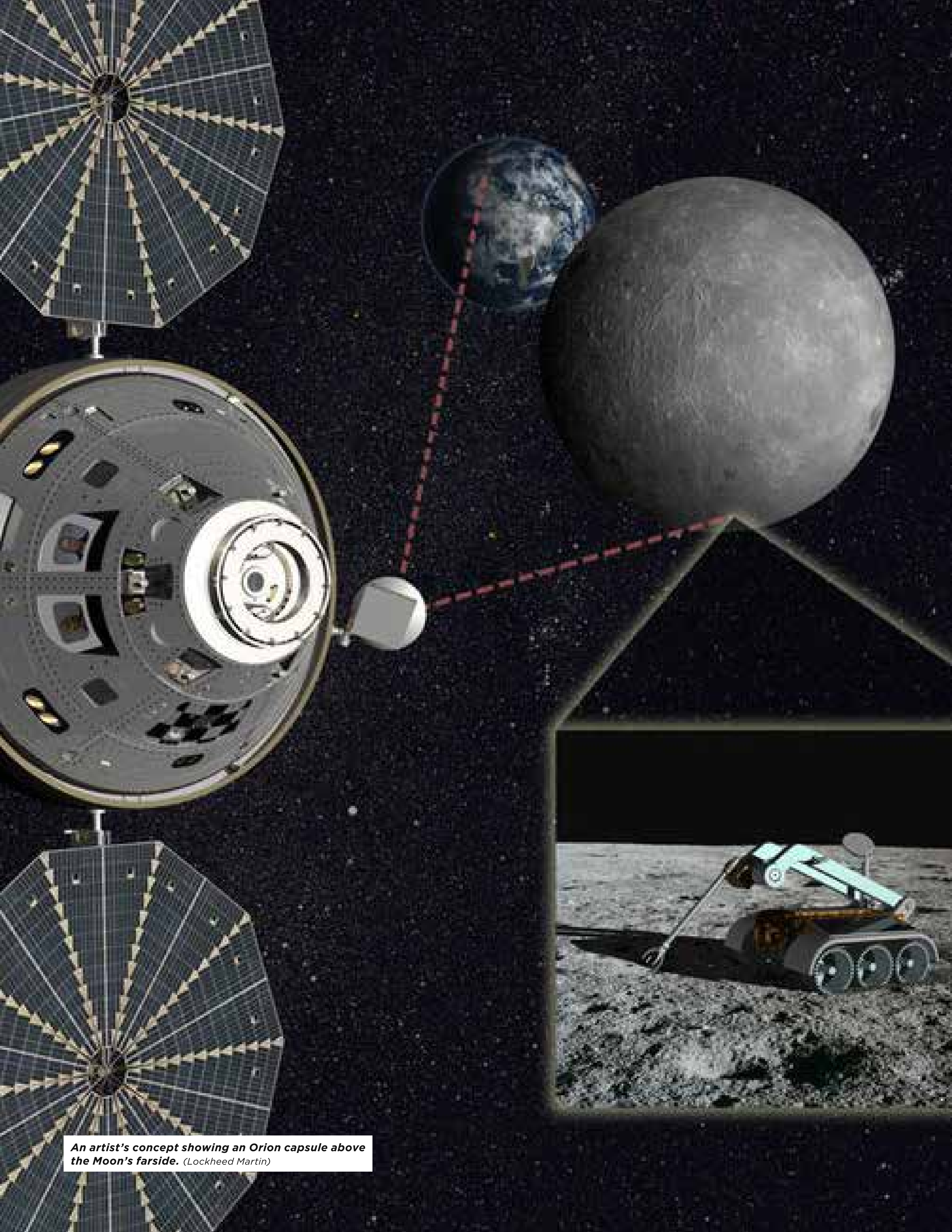
SpaceX's development of the Falcon 1 rocket and its Merlin rocket engine was no easier. The first launch, on March 24, 2006, failed 25 seconds after takeoff. The second launch, on March 21, 2007, failed as the second stage shut down prematurely. The third launch, on August 3, 2008, again failed, this time because the first-stage engine continued to fire after separation, causing it to collide with the second stage and payload. With his funds running low, Musk realized that if the next launch failed, the entire company would have had to fold.[12] Fortunately, the fourth launch was a success, placing a dummy test payload into orbit on September 28, 2008. This was followed by the last Falcon 1 flight, on July 14, 2009, in which SpaceX orbited its first commercial payload, a Malaysian Earth observation and technology research satellite.[13]

By this time SpaceX had evolved beyond the Falcon 1 as well as its plans to build the Falcon 5 with its bundle of five Merlin engines in the first stage. Instead the

An early Falcon 9 rocket awaits launch in October 2012. Note the square arrangement of the nine Merlin engines, later changed to a circular pattern. Note also the lack of landing legs, which were added later. (SpaceX)

company moved to the Falcon 9, using a bundle of *nine* Merlin engines for the first stage. Far more powerful, the rocket's bigger thrust allowed SpaceX to lift large payloads into geosynchronous orbit, enabling it to compete with every other major commercial launch company in the world. Moreover, SpaceX intended to keep the price low, undercutting its competition. For each Falcon 9 launch, SpaceX proposed to charge only $60 million. The Russians, whose $90 million price for a comparable launch with their Proton rocket was considered one of the lowest on the market, blanched. As noted in 2012 by Frank McKenna, president of International Launch Services (ILS), the Russian subsidiary that managed its commercial launches, "SpaceX is, on average, just under 50 percent less expensive than ILS, Arianespace of France, and other established launch service providers."[14]

SpaceX quickly signed up a large number of customers, even though the company was barely half a decade old. By 2012, only two years after SpaceX's first successful Falcon 9 test flight, the company possessed launch contracts with private satellite companies valued at more than $1 billion.[15] SpaceX's biggest new customer, however, was not a private company; it was NASA. Before describing how it became a customer of SpaceX, however, it is first necessary to outline the space agency's own efforts to build and launch a manned spacecraft to replace the space shuttle and make possible missions beyond Earth orbit. It was this effort that led NASA management to hire private companies to service the ISS rather than doing it themselves.



An artist's concept showing an Orion capsule above the Moon's farside. *(Lockheed Martin)*

The Space Launch System and Orion

On January 14, 2004, in a Kennedy-like speech at NASA headquarters, President George W. Bush committed the nation to yet another long-term space program. His proposal: replace the space shuttle with something he dubbed the Crew Exploration Vehicle (CEV) and then use it to begin the ongoing exploration of the solar system by returning to the Moon in the next decade. Bush's CEV eventually became the Orion capsule.

Two and half years later, on August 31, 2006, NASA announced the award of a contract to Lockheed Martin, valued at up to $8.15 billion, to build an unspecified number of Orion capsules through 2019.[16] The contract was divided into pieces. About half the funds, $3.9 billion, would be used to build the first two test capsules, one a manned capsule and one an unmanned cargo vessel for bringing cargo to the ISS. This contract was to be completed by September 2013. The second half of the contract, valued at $4.25 billion and running through 2019, would cover the cost of building additional spacecraft for later flights, though at the time of award the actual number of capsules was left an open question.

Ten years later, the Orion project has not kept pace with its original program goals.

As of May 2016, the prime contractor had built three engineering prototypes, used for ground testing, plus one flight-test capsule that was launched into space by a Delta 4 rocket in a two-orbit test flight on December 5, 2014. Two additional flight capsules are presently being readied, one for the first unmanned test flight of the Space Launch System (SLS) rocket, currently scheduled for 2018, and the second for the first manned flight, currently scheduled for 2021. None of these capsules are being built to bring cargo to the International Space Station, as originally announced.

The first Orion test capsule to fly in space sits in the Launch Abort System Facility at the Kennedy Space Center in Florida following a December 5, 2014, two-orbit 3,600-mile-high test flight on a United Launch Alliance (ULA) Delta 4 Heavy rocket. (NASA)

In addition, in the years since President Bush first announced the program, the total cost of Orion has grown far beyond the initial $8.15 billion contract awarded to Lockheed Martin. To be fair, most of the increase has nothing to do with the prime contractor or its building practices, but with changes to the program mandated by changing administrations and Congressional requirements. It is therefore necessary to look at the total amount appropriated annually by Congress to determine the cost of a project like Orion. Table 1 shows Orion's annual budget appropriations since the start of the program.

Since the first manned flight is not presently scheduled until 2021, these appropriations do not show the project's entire cost. By leveraging Orion's average yearly budget from 2005 until the present, it is reasonable to assume that Orion's future annual budgets after 2017 will continue to be approximately $1 billion per year, only slight less than NASA's own budget forecasts of $1.1 billion per year for Orion through 2021.[30] We therefore can extrapolate that Orion will cost, at a minimum, $4 billion more before that first manned flight, bringing the program's total cost to build three Orion flight capsules to be approximately $18 billion.

TABLE 1

YEAR	AMOUNT APPROPRIATED
2005	$0.422 billion[17]
2006	$0.750 billion[18]
2007	$0.890 billion[19]
2008	$0.950 billion[20]
2009	$1.100 billion[21]
2010	$1.220 billion[22]
2011	$1.200 billion[23]
2012	$1.200 billion[24]
2013	$1.197 billion[25]
2014	$1.197 billion[26]
2015	$1.194 billion[27]
2016	$1.270 billion[28]
2017	$1.300 billion[29]
Total	**$13.890 billion**

However, these numbers still do not provide the full picture, as they only represent the cost of the *capsule*, and do not include the costs for the rocket that will launch Orion.

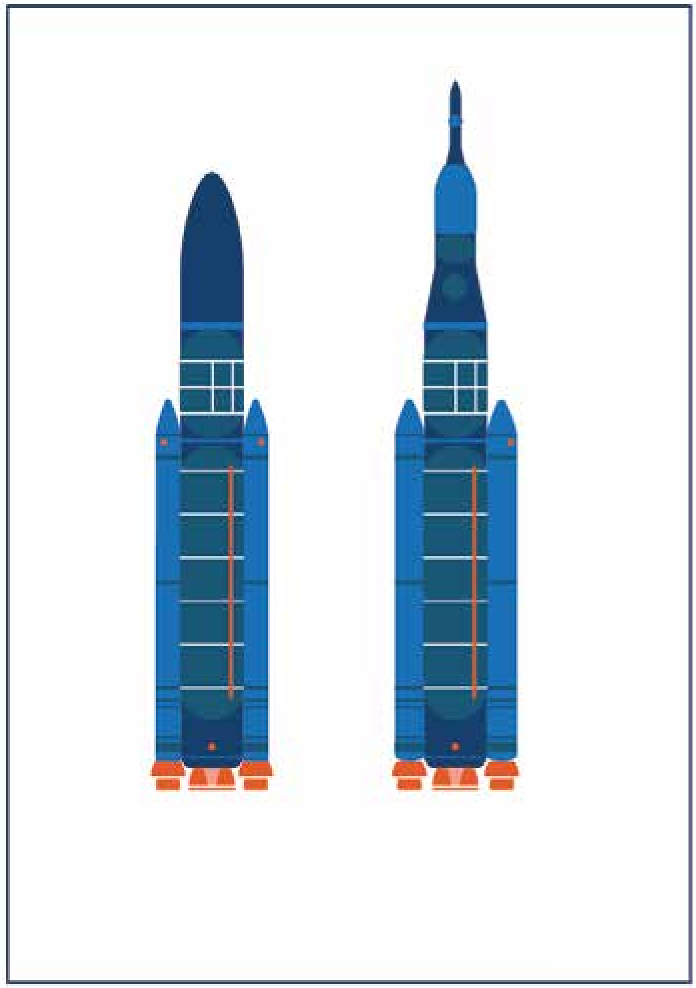
Initially that rocket was to be designated, depending on final mission profile, either the Ares 1 or the Ares 5 within the Bush administration's Constellation program. These two rockets were intended to be modern equivalents of the 1960s Saturn 1B and Saturn 5 rockets, capable of putting 27 and 137 tons into orbit respectively.[31] When the Constellation program was canceled by President Barack Obama in 2010, Congress mandated that NASA continue an equivalent program, using legacy shuttle components. Constellation morphed into the Space Launch System (SLS), a change that caused significant difficulties for the contractors involved while driving up costs. Nonetheless, because many components of SLS include components from Ares, and because both Ares and SLS were designed to put Orion capsules in orbit, it is not unreasonable to include both program's costs to assess the total cost of building the launch system for Orion. Table 2 shows the annual appropriations for both Ares and SLS since President Bush's initial 2004 announcement.

TABLE 2

YEAR	AMOUNT APPROPRIATED
2005	--------------[32]
2006	$0.367 billion[33]
2007	$1.210 billion[34]
2008	$1.220 billion[35]
2009	$1.040 billion[36]
2010	$1.660 billion[37]
2011	$1.800 billion[38]
2012	$1.860 billion[39]
2013	$1.857 billion[40]
2014	$1.918 billion[41]
2015	$2.051 billion[42]
2016	$2.000 billion[43]
2017	$2.000 billion[44]
Total	**$18.983 billion**

Since the first manned launch is not scheduled until 2021 at the earliest, these appropriated numbers, like the Orion capsule's development, do not entail the entire cost of the program. Even though yearly appropriations have been higher in recent years, it is fair to use the average amount appropriated per year for Ares/SLS, $1.5 billion, and assume that future annual SLS budgets will be at this more conservative number. This number also matches well with NASA's own budget forecasts.[45] Based on this, SLS can be estimated to cost at least $6 billion more (assuming that first manned Orion flight occurs four years hence in 2021), making the cost for NASA to build and launch two SLS rockets approximately $25 billion. Adding the Orion project's estimated price tag of $18 billion to that of Ares/SLS, $25 billion, we expect it will cost the taxpayer approximately $43 billion to build two SLS rockets, three Orion engineering test capsules, and the three Orion flight capsules.[46]

These budget numbers do not include any additional Orion/SLS rockets or capsules, nor do they include the service module Orion needs for its stated primary mission of flying beyond low Earth orbit. The



NASA's planned configurations of the Space Launch System, as of October 2015. (NASA/Adapted by CNAS)

European Space Agency and its prime contractor, Airbus, have agreed to build two service modules in exchange for participation in the ISS, but that agreement only covers the first two flights.[47] For later flights, additional money will have to be allocated to build more service modules.[48]

There is one very important additional detail: As noted earlier, the appropriated totals for Orion and Ares/SLS are far higher than the amounts NASA has awarded to the private contractors that are actually building SLS and Orion. Lockheed Martin received a contract for $8.15 billion to build the first two Orion flight capsules, plus some additional test capsules. Assuming that this contract has not been augmented with changes that have raised its total price (a likely scenario), this $8.15 billion is less than half of the total $18 billion that NASA will spend by the time the first manned Orion capsule flies in 2021. The additional

$10 billion, approximately 56 percent of the total cost of the project, probably covers NASA's administrative and overhead costs (some of which was caused by the change from Ares to SLS imposed by changing administrations and Congress) as well as other infrastructure expenses not directly tied to the construction of the capsules themselves.

Similarly, of the $25 billion NASA will spend to build Ares/SLS, only a portion is assigned to the contracts NASA awarded to private companies, first to build Ares and then to build SLS. NASA issued several different contracts for Ares, with the following constituting the largest and most important awards:

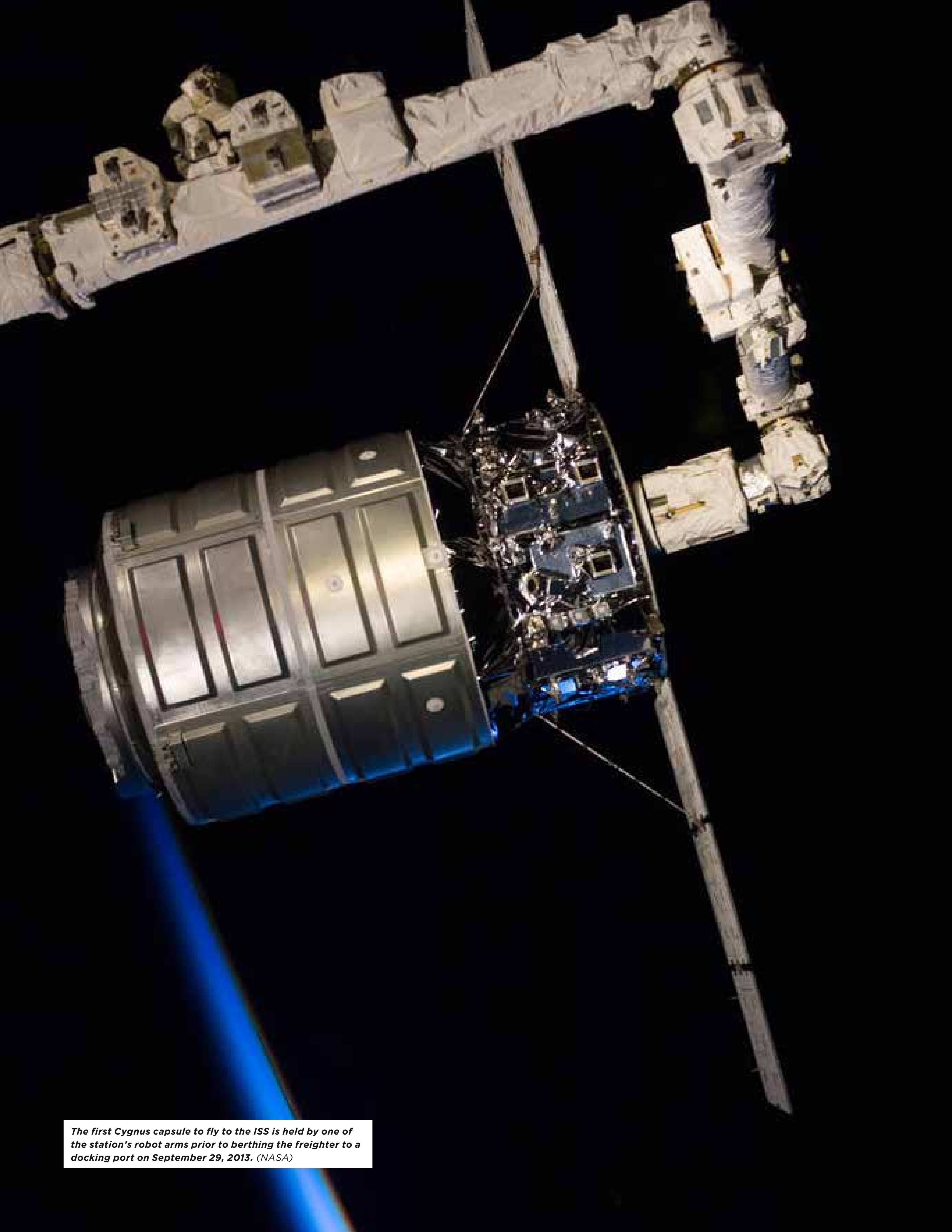
- Alliant Techsystems (ATK) received a contract for $1.8 billion to build the main stage of the Ares 1 rocket.
- Pratt and Whitney Rocketdyne was awarded a $1.2 billion contract to build the Ares 1 and Ares 5 upper stage engines.
- Boeing was awarded two contracts, $514.7 million to build the upper stage of Ares 1, and $799 million to design and install the avionics for Ares 1.[49]

Then, after the cancellation of Ares and four years of discussions to work out the new SLS design, on July 3, 2014, NASA announced the award of a new $2.8 billion contract to Boeing to build the avionics and the first stage for two SLS rockets through 2020. Other components of SLS, its solid rocket strap-on boosters and upper stage, appear to be using the Ares contract work already awarded to ATK (now Orbital ATK) and Pratt and Whitney Rocketdyne (now Aerojet Rocketdyne).[50]

Thus, of the entire $25 billion budgeted for both Ares and SLS, only about $7 billion appears to have been awarded to the private sector. Again, assuming that these contracts were not augmented by changes that increased their total (which is likely), the remaining $18 billion, about 72 percent of the program's total cost, probably covers NASA's administrative and overhead costs (some caused by the change from Ares to SLS imposed by changing administrations and Congress) as well as other infrastructure expenses not directly tied to the construction of the rockets.

The high overhead costs for Orion (56 percent) and Ares/SLS (72 percent) help explain why NASA and Congress have found it so difficult to afford future projects in space. This explanation gains more strength upon reviewing the relatively small overhead costs for NASA's commercial space program.

An artist's concept of the European Space Agency's service module, attached to the Orion capsule. (NASA)



The first Cygnus capsule to fly to the ISS is held by one of the station's robot arms prior to berthing the freighter to a docking port on September 29, 2013. *(NASA)*

Contracting Out Cargo and Crew to Private Companies

Having established a cost-structure baseline for SLS and Orion, it is now possible to discuss NASA management's decision to hire private companies such as SpaceX, Orbital ATK, and Boeing to provide cargo and crew ferrying service to the space station.

In 2006, shortly before Lockheed Martin first was awarded its Orion contract and SpaceX had begun its effort, NASA managers began looking for an alternative method for getting crew and cargo to the ISS. The shuttle's retirement was scheduled in four years and, unless management came up with new method of launching cargo and crew, they would have no way to man and supply the space station, other than depending on Russia's Soyuz rocket along with Soyuz and Progress capsules.

Before the Orion contract was even awarded, NASA managers understood that Orion was not the answer. Though it was initially supposed to have the ability to dock with the ISS, Orion was specifically designed for missions beyond Earth orbit, with all the necessary shielding and redundancies those mission profiles required. Such necessary design requirements rendered Orion and its rocket far too expensive and complex to provide freighter service to the ISS. According to estimates made in 2006, they expected both to cost several billion per year, and take almost a decade to develop, expectations that have since been proven correct. Managers therefore concluded that using Orion and SLS as a resupply freighter for the ISS was impractical.[51]

For this reason, NASA issued a request for proposals for a less expensive method for getting supplies to the ISS. Six different companies submitted proposals for a variety of different rockets and spacecraft, all focused not on doing deep space exploration of the solar system but on making a profit by inexpensively hauling cargo into orbit. On August 18, 2006, less than five months after SpaceX's first Falcon 1 launch failure (and only two weeks before the award of Lockheed Martin's Orion contract), NASA made contract awards to two of these companies, SpaceX and Rocketplane Kistler, requiring them to do test flights to the ISS to demonstrate that they could build the rocket and cargo vessels necessary to provide supplies to the station.

SpaceX's contract was for $278 million, and included the first test flight of the Falcon 9 rocket, the first test flight of a Dragon cargo capsule on a Falcon 9 rocket, and the first flight of a Dragon to berth with the ISS. Rocketplane Kistler was to get $207 million to complete construction and a demonstration flight to the ISS of its K-1 reusable rocket and cargo capsule.[52] Both companies were required to fly their demo missions to the ISS by 2009. NASA then would offer a second ISS supply-shipping contract competition open to the entire industry (though obviously favoring these two companies should they succeed in their demo missions).

The 2006 agreements were fundamentally different than the typical contracts the space agency had been using for decades. Traditionally, NASA's contracts were written under the government's Federal Acquisition Regulation (FAR). FAR contracts require suppliers to be supervised closely, while also requiring them to document carefully how they met all federal regulations. These requirements not only necessitated a great deal of complex paperwork, they also required a larger labor force for both the contractor and NASA, resulting in routinely higher costs and longer development time. Furthermore, NASA's FAR contracts, especially the ones for large projects such as SLS and Orion, were usually cost-plus, a frequently used government contract where the government pays the actual cost, plus an agreed-to percentage to cover the company's profit. Overages, should they occur, are covered by the government. FAR requirements and the cost-plus contract that traditionally go with them partly explains NASA's high costs for both Orion and Ares/SLS.[53]

To speed the cargo program and reduce its cost, NASA instead chose to use Space Act Agreements (SAAs), a much simpler and more streamlined contracting system. Instead of having NASA control and dictate every step

> **NASA issued a request for proposals for a less expensive method for getting supplies to the International Space Shuttle. Six different companies submitted proposals for a variety of different rockets and spacecraft, all focused not on doing deep space exploration of the solar system but on making a profit by inexpensively hauling cargo into orbit.**

of the design, construction, and operation of the rockets and capsules, the SAA agreements with SpaceX and Rocketplane Kistler left decisions largely to the companies, with ownership and control of the rockets and capsules remaining with each company. Furthermore, though the agreements provided both companies with funds, that money would be doled out in stages, as each company met a series of milestones. In addition, the funds provided by NASA were intentionally insufficient, requiring both companies either to obtain outside financing or to commit some of their own finances for development and construction. Finally, the contracts were fixed-price, not cost-plus, another type of government contract previously used by NASA for small projects. With fixed-price, if either company went over budget or experienced delays, it had to absorb the extra cost itself. It could not come to NASA for additional funds.[54]

When these contracts were awarded, SpaceX only had managed one failed launch of Falcon 1. Rocketplane Kistler was even further behind. Its K-1 rocket remained unfinished and unflown. In fact, Rocketplane Kistler never got off the ground, because the company was unable to obtain the financing required to meet its initial contract milestones. In October 2007 NASA canceled its agreement and put the remaining $170 million not already spent up for bid. In February 2008 the agency awarded a new SAA contract to Orbital Sciences to build its Antares rocket and Cygnus capsule.[55] Meanwhile, development at SpaceX moved forward, getting a Falcon 1 dummy payload into orbit in September 2008.

At this point, the Bush administration was nearing its end. Even though the original demonstration contracts with SpaceX and Orbital Sciences had not been completed, with neither company having flown its rockets, and both expecting to not meet that 2009 deadline for their demonstration flight to the ISS, on December 23, 2008, only two months after that first Falcon 1 flight and only days before the end of the Bush administration, NASA managers awarded the two companies full cargo contracts to supply the ISS. SpaceX's contract was for $1.6 billion to fly 12 Dragon cargo flights, while Orbital got $1.9 billion for 8 flights. Because of pressure from Congress, however, these contracts were awarded under the traditional FAR guidelines rather than as SAA agreements. Though this change raised the cost of the new contracts as well as increased development time lines somewhat, NASA appears to have streamlined the process considerably. In addition, rather than issue these FAR contracts as cost-plus, as NASA traditionally has done, the agency made them fixed-price, with payments to be made in stages on the completion of milestones.

The comments made by NASA's space operations chief Bill Gerstenmaier at the press conference to announce the contract awards were telling. "We don't have a backup *per se* in terms of cargo resupply," he said. "We really need these guys to deliver. We're committing to them to go deliver." With the shuttle retiring, the launch of SLS/Orion at least five years away (as predicted in 2010), and with its cost much too high to provide regular service to the ISS, these two commercial companies remained the only alternatives available to NASA, other than the Russian Progress and Soyuz capsules. Furthermore, with the election of Barack Obama in November 2008, it was unclear what the policy on space would be once his administration took over in early 2009. Awarding the contracts in the fall of 2008 avoided further delays as the new administration assessed the situation. The contracts presented a fait accompli to the new administration as it arrived.[56]

Development of Falcon 9 followed quickly, even if it lagged behind the predicted schedule. Engines tests of the Falcon 9's first stage had been ongoing, including a full mission-length static burn of all of the first stage's nine engines on November 22, 2008, only a month before contract award.[57] After additional tests of the rocket's second stage, the first launch was successfully completed on June 4, 2010, placing a dummy Dragon test capsule into orbit.[58]

On December 8, 2010, the first Dragon capsule to berth with the ISS splashed down and was recovered in the Pacific. It is seen here on a barge on its way back to shore. (SpaceX)

Dragon's development moved as swiftly. Design work began in 2005 as part of the company's initial proposal to NASA. Actual construction began in August 2006 after contract award, with Dragon's first flight taking place four years later, on the second launch of the Falcon 9 rocket on December 8, 2010. After completing two orbits of Earth, Dragon fired its thrusters and splashed down in the Pacific, where it was recovered successfully.[59] This flight was then followed by SpaceX's first demonstration flight to the ISS in May 2012, with Dragon being successfully captured and berthed to the ISS using the station's robot arm. It remained in this configuration for a week before returning to Earth for splashdown and recovery in the Pacific.[60] From concept to flight, SpaceX had been able to get both Dragon and Falcon 9 built and launched to the ISS in about seven years.

Orbital Sciences, meanwhile, was playing catch-up. After only five years of development, the first test flight of its Antares rocket took place on April 21, 2013, successfully putting a dummy Cygnus payload into orbit.[61] Six months later, on September 18, 2013, the first Cygnus capsule was launched to the ISS, and after berthing with the station it completed its mission one month later, undocking and then de-orbiting to burn up over the ocean.[62]

Since contract award, both companies have successfully launched a total of 16 capsules, including the demonstration flights. Through December 2016, SpaceX has successfully launched and recovered ten capsules, with the loss of an eleventh due to a first launch failure of a Falcon 9 rocket in June 2015. Orbital ATK (a company merger in 2014 changed its name) has successfully launched six capsules, with the loss of a seventh in October 2014 when an old Russian engine in the first stage of its Antares rocket failed.[63]

The Antares failure illustrated the flexibility of the private sector. Faced with a contractual commitment to launch a certain tonnage to the ISS within a certain timeframe, Orbital ATK improvised while it redesigned its Antares rocket, signing a deal with the United Launch Alliance (ULA) to use Atlas 5 rockets for the next two Cygnus cargo launches. These launched successfully in December 2015 and March 2016, followed by the successful launch of the redesigned Antares rocket in October 2016.

Because of the success of these cargo contracts, NASA followed up in September 2014 by awarding two companies contracts for ferrying humans up and down from the ISS. Like the cargo contracts, the two crew contracts are intended to provide the agency with redundancy while leaving most of the design work to the companies themselves. The contracts again were streamlined fixed-price FAR arrangements requiring milestone achievements before payments were made.[64]

Once again SpaceX's bid was successful, as its now proven Dragon capsule had been designed initially to carry humans, and thus needed relatively little upgrade to make it man-rated. Its contract was for $2.6 billion. Boeing picked up the other contract with a capsule it calls Starliner. Because the development of Starliner had barely begun, Boeing's contract provided them more money, $4.2 billion. The contracts for both companies tasked them to fly one manned test flight, followed by as few as two and as many as six manned missions to the ISS.[65]

In January 2016 NASA then issued a second round of cargo contracts, this time picking SpaceX and Orbital ATK again, but also adding Sierra Nevada with its proposed Dream Chaser reusable mini-shuttle. The cargo contracts required each company to fly at least six flights to the ISS for a total of 18 flights, at a total cost of $14 billion. How NASA will divide up the contract money depends on how the companies deliver and the number of flights they each end up flying. The contracts also allowed NASA the flexibility to procure additional flights from the three companies, if necessary.[66]

An artist's concept of Sierra Nevada's Dream Chaser mini-shuttle in orbit. A disposable rear cargo module has just separated. While the shuttle will return with cargo to Earth for reuse, the cargo module will burn up in the atmosphere. (Sierra Nevada Corporation)

Costing Out the Commercial Alternative

As with Orion and SLS, determining the total cost of the commercial program cannot be done merely by looking at the contracts that NASA has awarded. NASA has its fixed overhead costs for this program as well, though these costs are significantly smaller. To determine the total cost, Table 3 shows the annual appropriations Congress has given NASA's commercial space program since its inception late in the Bush administration.

Unlike SLS and Orion, these appropriations appear to match more closely with the amount of money NASA awarded in the commercial contracts themselves. For example, NASA's original SAA contracts to SpaceX, Rocketplane Kistler, and Orbital Science equaled $485 million total. According to the table above, from 2007 to 2011, when those demonstration contracts were ongoing, Congress appropriated $735 million for the program. Thus NASA's overhead and administrative costs for obtaining two demonstration flights to the ISS was relatively small compared with Orion/SLS, about $250 million or about 34 percent of the cost.[78]

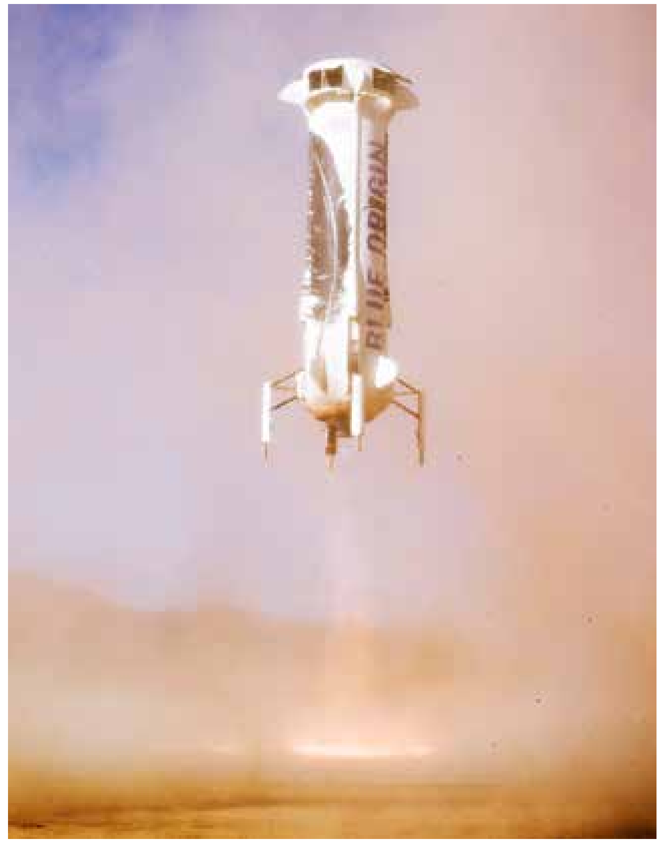
The first operational cargo contracts to SpaceX and Orbital ATK equaled $3.5 billion, while the first crew contracts to SpaceX and Boeing equaled $6.8 billion, for a total of $10.3 billion. Because these contracts either have not been completed or are barely begun, it is difficult to separate their costs from the total amount appropriated in order to estimate NASA's overhead. Even so, the following rough look at the numbers again suggests that the overhead for commercial cargo/crew since 2011 is far less than SLS/Orion.

TABLE 3

YEAR	AMOUNT APPROPRIATED
2007	$0.121 billion[67]
2008	$0.160 billion[68]
2009	$0.153 billion[69]
2010	$0.039 billion[70]
2011	$0.262 billion *(end of demonstration contracts)*
2011	$0.300 billion[71] *(beginning of operational contracts)*
2012	$0.406 billion[72]
2013	$0.525 billion[73]
2014	$0.696 billion[74]
2015	$0.805 billion[75]
2016	$1.000 billion[76]
2017	$1.180 billion[77]
Total	**$5.647 billion**

From 2011 to 2017, Congress appropriated NASA $4.874 billion total for the operational commercial crew/cargo program. Though the average appropriations per year during this time period is slightly less than $700 million per year, let us assume that for the next seven years, which takes us through the presently planned end of the ISS, Congress will give this program generous appropriations, similar to the $1 billion per year appropriated in 2016 and which the Senate appears ready to appropriate in 2017.[79] Adding this $7 billion to the $4.874 already appropriated gives us a total of $11.874 billion for commercial cargo/crew. This total, just under $12 billion, is only $1.7 billion more than the $10.3 billion awarded for all of the crew/cargo contracts, and translates to only 14 percent for NASA overhead, labor, and administrative costs.

Obviously, these rough calculations are not accurate, but they are not unreasonable and suggest that NASA's overhead for commercial space is relatively small. Unlike SLS and Orion, where the cost of the contracts is augmented by unexpected political mandates as well as the much larger carrying cost of the space agency's labor force – an army of employees who must be paid year in and year out whether SLS or Orion is ever launched – most of the cost for commercial crew is being spent by the private companies themselves on the actual rockets and spacecraft.



Blue Origin's New Shepard booster module successfully lands vertically during its second test flight. (Blue Origin)

Renewed Competition in the Private Launch Sector

The success of both SpaceX and Orbital ATK in building and launching their Dragon and Cygnus capsules did not merely provide NASA with a new way to launch cargo and humans into space; it has changed the entire commercial launch industry. As noted previously, the prices charged by the already existing launch companies had been high and unchanged for many years. To understand why SpaceX's arrival was so effective in transforming that industry, it is necessary to look closely at the history that led up to SpaceX's arrival.

Shortly after the loss of the space shuttle Challenger in January 1986, the Reagan administration made a major policy decision, changing the rules on how American commercial satellites would be launched. Beforehand, in an effort to make the shuttle cost effective, the federal government had insisted that all U.S. commercial satellites be launched by the shuttle. Thus, from 1982 to 1986 the private American launch industry practically died from a lack of any domestic business.

After Challenger, the Reagan administration changed that policy by ruling the shuttle no longer could launch commercial satellites. Instead, private launch companies would pick up the slack, with the hope that this would spark competition – and a rebirth of the American aerospace industry.

One new U.S. launch company, Orbital Sciences, did form in the late 1980s. It first developed the air-launched Pegasus rocket, launched from the bottom of an L1011 wide-body plane. Unlike other commercial rockets, Pegasus was aimed at the small satellite (or "smallsat") market, that is, satellites weighing less than 1,000 pounds. When it placed its first satellite in orbit in 1990, Orbital Sciences then priced each Pegasus launch at around $11 million. By the 2000s it was estimated a launch would cost around $30 million, though in 2012 and 2013 the company was paid $36 and $40 million respectively by NASA for two different science launches.[80]

Orbital Sciences also developed the Taurus and Minotaur rockets. Minotaur, initially an Air Force–funded project, used surplus ICBM solid-rocket motors and was aimed at putting slightly larger smallsats – ranging from 1,300 to 3,800 pounds – into orbit. The average cost per launch initially was expected to be just under $30 million.[81] The Taurus rocket, developed in the mid-1990s to launch even larger payloads, had a mixed launch record, with three failures out of nine launches, falling out of favor as a launch vehicle, regardless of price. At this time its production essentially has been abandoned.[82]

Unfortunately, Orbital Sciences, like Boeing and Lockheed Martin, did not succeed in gaining a large part of the commercial market share in the 1990s. These existing American rocket companies centered most of their effort on launching government payloads, for the military, NASA, and NOAA, which paid high prices and generally were not interested reducing costs. As a result, these companies made little effort to drop their prices enough to compete for market share, a fact illustrated by the increase in price charged by Orbital Sciences for its Pegasus rocket, which began at $11 million but by the 2010s had risen to $35 million.[83]

Instead, it was the European and Russian launch companies that ended up dominating the commercial launch market following the 1986 Reagan decision. At the time, the European Space Agency (ESA), under the management of its Arianespace commercial division, had developed its own rocket, dubbed Ariane, which was designed to obtain as much market share as possible. After going through several design upgrades, the Ariane 5 entered the market in 2000 with its first commercial launch. By 2004 it had 50 percent of the launch industry's market share and held that dominant position for the next dozen years, until SpaceX appeared with its Falcon 9.[84] During this time period a typical Ariane 5 launch would put two satellites into orbit at a cost of approximately $200 million, or about $100 million per satellite. Though the per-satellite price could be higher or lower depending on the eventual orbit and the weight of the two payloads, this price best represents the average fee charged by Arianespace for putting a typical communications satellite into geosynchronous orbit.[85]

Simultaneously, the fall of the Soviet Union and the lure of Western capital caused the Russians to form a partnership in 1995 with the U.S. company Lockheed Martin. The result of their pairing, International Launch Services (ILS), offered either the Russian Proton or Lockheed Martin's Atlas 5 as a launch vehicle. Over time, however, most of ILS's business migrated to the Proton. Russia's lower labor costs allowed them to charge significantly less than Lockheed Martin, and in 2006 the American company pulled out of the partnership, with the Russians eventually purchasing its share so that ILS is now solely owned by Russia.[86] The price for a typical Proton launch during this time period was generally about $90 million. As with Ariane 5, the cost per launch varied up or down, depending on payload and the eventual target orbit.[87]

Meanwhile, as Lockheed Martin pulled out of ILS it formed a new partnership, this time with its chief launch competitor Boeing and its Delta family of rockets. In the early 2000s the U.S. Air Force had decided it didn't have enough business to keep the rocket divisions of both companies solvent. If it allowed them to compete for contracts it was believed that either they both would be unable to make a profit, or one eventually would go out of business. Neither possibility was acceptable to the Air Force. National security required at least one launch company, and defense strategy demanded the military have at least two, to provide redundancy. Hence the Air Force and the two companies made a deal under the Air Force's Evolved Expendable Launch Vehicle (EELV) program.

EELV began in the late 1990s as an Air Force program to develop inexpensive new rockets for military launches. By the mid-2000s, the program had evolved into a three-way arrangement between the Air Force, Boeing, and Lockheed Martin. In 2005 the two private companies formed a partnership dubbed the United Launch Alliance (ULA), which signed a launch agreement with the Air Force. This arrangement, set to run through 2019, paid ULA about $1 billion per year to keep it in business (later reduced to $800 million). In addition, the Air Force made a block buy of 36 rocket cores to be used for up to 28 launches, at a cost of $11 billion. Depending on payload and the orbital requirements, the Air Force would choose either Lockheed Martin's Atlas 5 or some variant in Boeing's Delta rocket family for each launch, though the goal was to split the launches 50-50.[88] Based on this deal, the Air Force's cost for a ULA launch has been estimated as ranging from $100 to $460 million, depending on the source. ULA publicly states that Air Force launch costs average about $225 million per flight.[89]

The price to buy a commercial launch from ULA's two rockets also appears to be comparable. Based on two launches for NASA in 2010 and 2013, the Atlas 5 launch price was $124 million and $187 million. Meanwhile, the Delta 4 costs ranged from $141–350 million, depending on the rocket's configuration.[90]

Of course, these four companies – Arianespace, ILS (Russia), ULA, and Orbital Science – do not comprise the entire launch industry. By the time SpaceX completed its first successful Falcon 9 launch in 2010, however, these companies were essentially the only vendors capable of putting large American commercial payloads in orbit. China, for example, had the rockets to compete for this market, but legal restrictions passed by Congress due to security concerns prevented most private satellite companies from using their rockets. Japan had a launcher, but its high cost made it uncompetitive, while India's rocket only could launch smaller satellites and thus was not a major player.

The high launch costs charged by these companies, as well as their seeming inability to reduce these costs, had a generally negative effect on the commercial launch industry at the turn of the 21st century. In 1999 there were 76 commercial launches, pulling in $2.3 billion in revenue. By 2003, when Elon Musk unveiled his Falcon 1 mockup in Washington, the number of commercial launches had plummeted to only 18, with revenues falling to $1.2 billion, a decline that helped prompt the Air Force to forge its EELV bulk-buy deal with ULA.[91] Essentially, the launch industry had priced itself out of the market. Just as Musk had discovered that he couldn't afford to buy its very expensive rockets to send his private science probe to Mars, the satellite industry at the time was struggling and failing to cope with these high costs as well.

The SpaceX price list for each of its rockets, as of June 15, 2016. (SpaceX)

Thus, it is not surprising that SpaceX's $60 million Falcon 9 launch price forced a significant reshaping of the launch industry, a reshaping that has been magnified by SpaceX's effort to recover and reuse the Falcon 9's first stage.

Initially, SpaceX had tried to recover the stages by using parachutes and then hauling the stages from the ocean. This didn't work, as the salt water damaged the engines too much. Then, in September 2011 Musk announced that SpaceX was to going to attempt to recover a first stage by landing it vertically after launch. If the expensive engines and stages could be refurbished and reused rather than thrown away, Musk estimated he could drop SpaceX's launch price by 30–50 percent.

Since its initial announcement, SpaceX has pursued this effort aggressively. The company developed a test stage, dubbed Grasshopper, which used one Merlin engine to lift the stage from the launchpad as much as several thousand feet, hover, and then land gently where it started. SpaceX followed this with similar test flights of a Falcon 9 first stage, climbing 3,000 feet before returning to the launchpad intact. Since then the company has taken advantage of almost every Falcon 9 launch to test this engineering. Four times SpaceX tried to land the first stage on a large barge out in the ocean, and four times it failed. Then on December 21, 2015, the company tried to do it on land and succeeded, and followed up this success with the first successful barge landing on April 8, 2016, followed by two even more difficult barge landings on May 5, 2016, and May 27, 2016.[92]

SpaceX then announced that, based on the data obtained from the first recovered first stage, the launch price using a reused Falcon 9 first stage will be about $40 million, a 33 percent reduction from SpaceX's previously unbeatable launch prices. If all goes well, the company hopes to reuse one of these first stages on a commercial launch in early 2017.[93]

Nor has SpaceX limited its competitive effort just to rocket reusability. It also has competed in court, attacking the bulk-buy Air Force/ULA EELV deal, saying that it was restrictive, anti-competitive, and overpriced. Even though the military's more stringent technical requirements would increase costs, SpaceX still insisted it could launch comparable payloads for significantly less than the $225 million estimated figure provided by ULA. As Musk himself said in testimony to Congress in 2014, "As a country, we've generally decided competition and the free market is a good thing and monopolies are not good, and it's interesting to note that from the point from which Boeing and Lockheed's launch business merged, the point which they stopped being competitors,

On September 1, 2016 a Falcon 9 rocket with a commercial payload exploded on the launchpad during a prelaunch dress rehearsal of the countdown. This failure and the ensuing investigation canceled all of SpaceX's planned launches in 2016. (USLaunchReport.com)

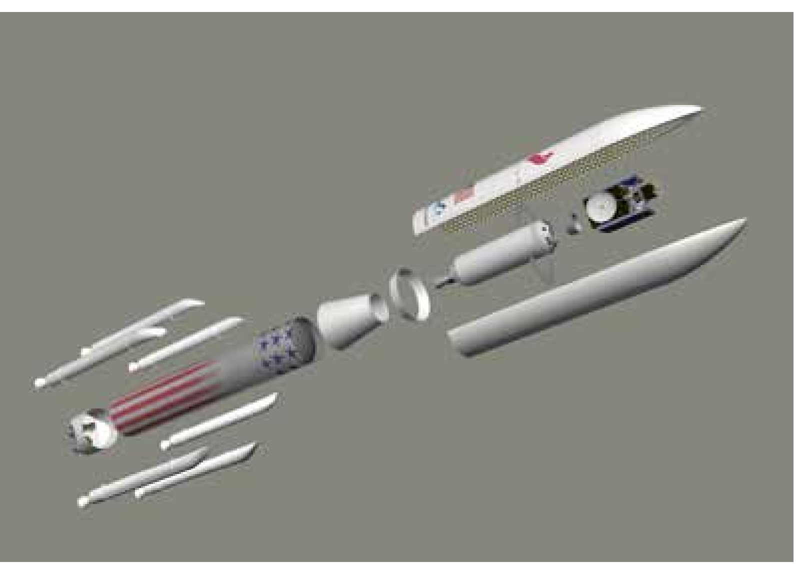
the costs doubled since then. I think the reality is, when competition is introduced . . . the cost to the U.S. taxpayer will drop substantially."[94]

ULA officials have countered Musk's arguments by pointing out the perfect launch record of the Atlas 5 compared to SpaceX's Falcon 9, which has had two failures since June 2015. The launch delays caused by the second of these failures, the September 1 Falcon 9 launchpad explosion, caused SpaceX to lose at least one commercial customer, Inmarsat, who switched launch vehicles because they could no longer afford any further delays.[95] The Air Force's requirements are no different. When it has to launch a billion dollar satellite, it needs to know that the launch will succeed. ULA's higher pricers were the premium charged for the company's guarantee that its launches would be successful.

Nonetheless, SpaceX subsequently was certified to compete for Air Force contracts and so far has been awarded one contract, thus breaking the ULA monopoly. As promised by Musk, SpaceX's price for this launch, $82.7 million, is significantly less than the average $225 million price that ULA has been charging. [96]

Faced with SpaceX's price and competitive pressure, launch companies that in the past had insisted that it was impossible to lower costs have discovered that lower prices are possible. For example, Arianespace and the European Space Agency (ESA), in trying to hold onto their market share, cut the launch prices in 2014 on the Ariane 5 rocket.[97] More importantly, ESA has instituted a major restructuring in how its next-generation rocket, Ariane 6, will be built, owned, and flown. Under the old arrangement, Ariane 5 was built by Arianespace, under the auspices of ESA, with the intent of spreading the work to as many of that organization's member countries as possible, even if that wide distribution raised costs. The system even included delicate negotiations between those member countries during the design phase of Ariane 5 to make sure the rocket design included components from the entire ESA. It is partly for this reason that during its entire operational lifespan Ariane 5 never made a profit, even though it captured more than 50 percent of the launch market. ESA repeatedly had to issue supplementary payments to Arianespace so the company would break even.[98]

For Ariane 6, however, the lead European aerospace contractors Airbus and Safran, which had built Ariane 5 for Arianespace, rejected the previous multinational arrangement. Instead, they formed a 50-50 joint venture, dubbed Airbus Safran Launchers (ASL), and insisted they be allowed to buy France's 35 percent equity in Arianespace so that ASL, not ESA's bureaucracy, obtained majority control of the operation. They further surprised ESA with their own rocket proposal for Ariane 6, which reduced the number of subcontractors, consolidated operations, and lowered costs.[99] ESA, realizing they could not match SpaceX's launch price under the old system, agreed. The deal had ASL buy France's 35 percent share in Arianespace so that Airbus Safran owned 74 percent. ESA then awarded the company a €2.4 billion contract to develop Ariane 6 and have it operational by 2020. Though the rocket will not be reusable, ASL hopes that its more efficient design, costing 40–50 percent less than Ariane 5, would allow them to charge about $77 million per satellite and therefore compete effectively with SpaceX.[100]



An expanded view of ULA's Vulcan rocket, showing its six-booster configuration. (United Launch Alliance (ULA))

Similarly, ULA has moved to match SpaceX – first, by beginning to phase out the Delta 4 family of rockets, since these rockets were very expensive to assemble and launch and thus could not compete effectively in the new launch market.[101] Second, ULA announced plans to develop a new rocket, dubbed Vulcan, to eventually replace the Atlas 5. Like SpaceX, to save money and lower Vulcan's cost, ULA is going to attempt to recover its first-stage engines. Unlike the Falcon 9, the first stage would not land vertically and intact. Instead, the engines, the stage's most expensive component, would separate from the stage, descend using a heatshield and parachutes, and then be snatched from the air by a helicopter. The engines will then be incorporated into a new first stage. ULA thus hopes that Vulcan will lower costs to about $100 million per launch.[102]

Russia meanwhile has addressed the competitive threat posed by SpaceX by retreating to its Soviet-era roots. The Putin administration has consolidated the entire Russian aerospace industry into a single corporation managed by the central government. It also has established a national ten-year plan, beginning in 2016, with a focus on serving internal needs rather than maintaining its international launch market share or reducing its costs.[103] Russia will slowly shift to a new family of rockets, dubbed Angara, that began development in the early 2000s and is expected to take at least another five years before becoming operational. Though the concept of Angara – a standardized modular design that can launch a range of payload sizes – has the potential to reduce costs, Russia's centralized bureaucracy also has designed the rocket much as ESA designed Ariane 5, with the workload distributed widely within Russia in order to maintain as many jobs as possible. Angara's long-term ability to compete on the international market therefore will depend on whether Russian labor costs continue to remain below that of other countries.[104]

Whether these new rockets can compete remains an open question. Even with these changes both Ariane 6 and Vulcan appear to be more expensive per launch than SpaceX's $60 million expendable Falcon 9[105], with predicted launch prices of $77 and $100 million respectively. Once SpaceX begins reusing its first stages, further reducing the rocket's launch price, these new rockets will be hard-pressed to remain competitive. Their challenge will be heightened even further with the introduction of SpaceX's Falcon Heavy, able to put more than twice as much payload into orbit with a projected launch price of only $90 million.[106]

SpaceX's effort to cut costs has had additional ramifications beyond these established players. The lower prices have made it possible for more satellite and rocket companies to enter the market, with the new launch companies all aiming to beat SpaceX at its own game by doing innovative engineering that will lower launch costs even further.

Of these companies, Blue Origin likely leads the way, though it is probably several years from launching its own orbital rocket. In terms of cutting-edge rocket engineering, however, Blue Origin is matching SpaceX quite closely. Not only has it, like SpaceX, successfully landed a rocket stage vertically, it already has reused that stage four times in later launches. These launches were for a suborbital spacecraft called New Shepard, aimed at the suborbital tourism market. Blue Origin, which is owned and financed by Amazon.com founder Jeff Bezos, plans to do the first manned flight tests of this reusable spacecraft/propulsion module beginning in 2017.

Eventually the company intends to scale up New Shepard's design so that they can compete in the orbital launch market. As part of this plan, they are developing a rocket engine that ULA is considering using in its new Vulcan rocket. That engine, like the Merlin engine that SpaceX uses in Falcon 9, is intended as the foundation for its orbital rocket entry.[107]

Also poised to enter the launch market is Vulcan Aerospace, a company that plans to build Stratolaunch, the biggest airplane ever, to act as the first stage of an air-launched rocket. Financed by internet billionaire Paul Allen, the company's goal, like SpaceX, is to lower the cost of getting payloads to orbit.[108]

Another company on the horizon is Rocket Lab. It is developing a small rocket dubbed Electron, aimed for the small-satellite market that Orbital ATK's Pegasus originally was aimed at and that SpaceX's Falcon 1 abandoned. Also targeting that same smallsat market is Virgin Galactic, which is developing LauncherOne, similar to Orbital ATK's Pegasus and Vulcan Aerospace's Stratolaunch in that it will be launched from the belly of an airplane. Both Rocket Lab and Virgin Galactic have launch contracts, but neither has as yet flown.[109]

Then there are the international competitors. India has been trying for more than a decade to develop a much larger rocket in order to compete with Falcon 9, Ariane 5, and Proton, and on September 8, 2016 successfully completed that rocket's first commercial launch. Japan has said several times that it is developing rockets that cost less, though commercial satellite companies so far have not flocked to buy its product.

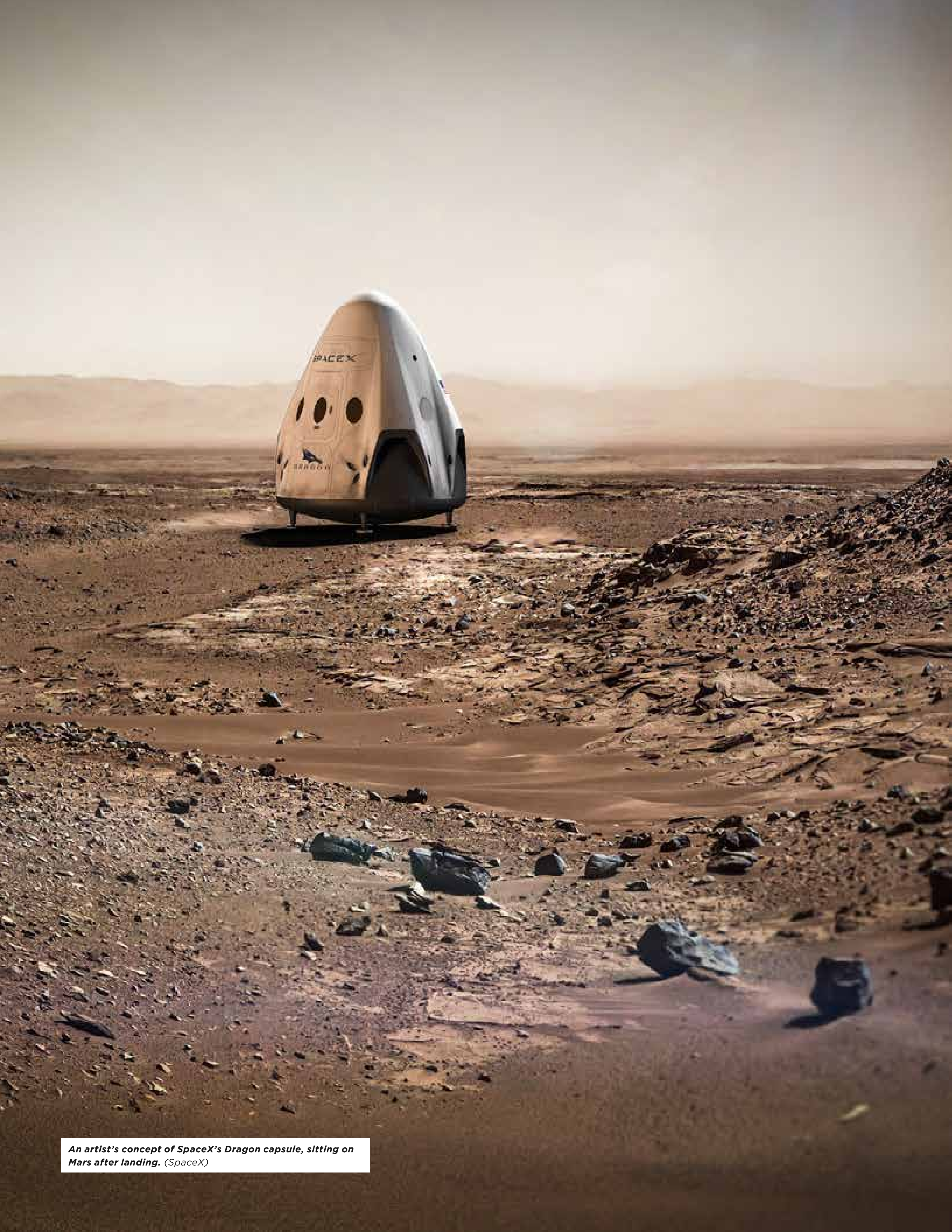
This list is only partial. It is important to remember that in a competitive free market there is no guarantee that any of these companies will succeed. Like Rocketplane Kistler, one or several of these efforts, both private or public, could fall by the wayside, either because of a launch failure or because of the simple inability to get sufficient investment capital. What is important is that there are now a lot of new, aggressive, and creative launch companies, all vying for market share and profits. While some surely will fail, many surely will succeed. The result will be a bigger launch industry, capable of putting more tonnage in orbit for significantly less.

This larger launch industry will allow NASA and the U.S. military to accomplish much more for far less. It also will infuse new life into the commercial aerospace industry. Satellite companies that in the past couldn't get funded because they had no affordable launch capability and because their proposals were radical or risky now will become practical and profitable.

One recent example illustrates this process quite clearly. The company OneWeb has proposed a constellation of 900 small satellites to provide worldwide internet access. They needed to raise $1.7 billion to finance this constellation, and had planned three rounds of fundraising. Their first round had raised about $500 million. After their second round in late 2016 raised $1.2 billion, they had no need for the third round.[110]

The ease in which this significant investment capital was raised is likely connected to the reshaping and reenergization of the launch industry in the last few years by increased competition, as described above.[111] The resurgent launch industry shows that OneWeb's 900 satellite constellation will have a way to get into orbit at an affordable cost, which in turn made it easier for the company to obtain substantial investment capital.

Each feeds on the other. An increased customer base fuels a larger, more innovative launch industry able to charge less per launch, which in turn encourages more new satellite companies. The cycle then repeats, becoming a catalyst for creating new wealth and greater capabilities to the United States.



An artist's concept of SpaceX's Dragon capsule, sitting on Mars after landing. *(SpaceX)*

Some Conclusions

Having outlined the significant effects on the launch industry caused by SpaceX's efforts to innovate and lower costs, as well as having carefully documented the costs and development times for NASA's two-pronged effort to replace the Space Shuttle, it now will be possible to summarize and compare these two approaches in order to get a better idea of what has worked and what has not.

This comparison, between the development of the Orion capsule and SLS under NASA's traditional contract and design policies versus the Dragon/Cygnus development, as shown in Table 4, is striking, and reveals that the old way of doing business is simply not a viable approach for the U.S. government to create a thriving space launch industry.

Lockheed Martin in 2006 was awarded the contract to build Orion for $8.15 billion. The company now expects to have completed three flight capsules (two of which are unmanned test vehicles) by 2021. When we add in the cost to build Ares/SLS as well as all NASA's carrying costs, the total outlay to build and launch these three capsules equals about $43 billion. From conception to first operational flight will take about 15 years, assuming that first manned Orion flight occurs in 2021.

SpaceX conceived Dragon in 2005, flew the first capsule in 2010, and as of December 2016, had successfully flown 10 total, nine to the ISS. Total contract cost was just under $1.9 billion, and that price will pay for 13 capsules and rockets total. From conception to first operational flight took seven years. Orbital ATK in turn began design work on Cygnus and Antares in 2007, flew the first capsule in 2013, and as of December 2016, had flown six capsules successfully to the ISS. Total contract cost was just over $2 billion, which will pay for the launch of nine capsules and rockets total. From conception to first operational flight took about five years. Adding to the SpaceX and Orbital ATK operational contracts an overhead cost of 34 percent (based on my estimate of the overhead for the initial demonstration contracts), as well as the $735 million for those development contracts, results in a total estimated cost of $5.4 billion for the first round of cargo contracts.

The differences between these two programs are stark and profound. Even when we include the additional costs and development times for the second round of cargo contracts as well as the commercial manned spacecraft as shown in Table 5, Orion/SLS is still far more expensive, is taking far longer to build, and is producing far less.

Why have the private space efforts been able to do so much more in so much less time for so much less? Though a certain percentage of the difference can be attributed to the program change from Ares to SLS as well as SLS/Orion's bigger size and more challenging goals (manned interplanetary travel versus Earth orbit crew and cargo flights to the ISS), these differences cannot explain it all.

Consider, for example, the Apollo capsule and the Saturn 1B and 5's rockets from the 1960s. Though they had similar design goals as SLS, it took only nine years from the first design work for the Saturn 5's engines in 1958 to the rocket's first test flight in 1967. Construction actually took even less time, less than five years, since the contracts both for capsule and rockets were not awarded until the 1962–63 time frame. And though the total cost for the Apollo program, estimated to be $151 billion in

TABLE 4

	FLIGHT CAPSULES	ROCKETS	DEVELOPMENT TIME	COST
ORION/SLS	3	2	15 years	$43 billion
COMMERCIAL CARGO & CREW	22	22	5–7 years	$5.4 billion

TABLE 5

	MANNED AND UNMANNED FLIGHT CAPSULES	ROCKETS	DEVELOPMENT TIME	COST
ORION/SLS	3	2	15 years	$43 billion
COMMERCIAL CARGO & CREW	42	42	5–9 years	$12 billion

2010 dollars, was significantly higher than what has been spent for Ares/SLS/Orion, this 1960s cost included all of the capsules, service modules, and rockets for the entire program of missions to the Moon, not just two rockets and three flight capsules (lacking service modules). The cost also included all the required infrastructure (VAB, launchpads, communications, mission control, etc.) that still exists, much of which SLS hopes to use.[112]

Furthermore, in the 1960s no one had ever built this kind of rocket or capsule. One would think that the time to build SLS/Orion would be far less than Saturn/Apollo because NASA has so much more experience today. Instead, SLS/Orion is taking much longer, with costs that appear not significantly less.

Finally, the recent announcement that SpaceX is planning to send an unmanned Dragon capsule to Mars by 2018 suggests again that the engineering differences between Orion and Dragon might not be as much as NASA has tried to suggest. Though Orion is larger and heavier with some additional radiation shielding for interplanetary travel, its primary function, like Dragon, is still an ascent/descent capsule for bringing humans safely up and down from Earth orbit. For any interplanetary mission, both Orion and Dragon are insufficient. As noted earlier, they are simply too small to provide the living quarters required for any crew on a six-month to two-year mission to Mars or beyond.

In addition, SpaceX's own heavy-lift rocket, the Falcon Heavy, suggests it is possible to build a heavy-lift rocket for much less money and far less time than it has taken NASA to build SLS. Falcon Heavy, about two-thirds as powerful as the first two SLS rockets, began development in 2008, with its first test flight scheduled for the second quarter of 2017 (as of December 2016). Though the rocket has not yet launched and its actual costs not yet determined, SpaceX has said that it plans to charge its customers only $90 million per launch, suggesting that the rocket's development cost is not much more than the Falcon 9, and far, far less than SLS.[113]

Other factors must therefore explain why SLS/Orion has been so difficult to build and has been so expensive, compared to Falcon 9/Dragon, Antares/Cygnus, and Saturn/Apollo. These factors are listed below, followed by recommendations on what the government should do to take advantage of them.

Just as the Homestead Act of 1862 encouraged westward expansion and settlement, government policies today could incentivize the private sector in the exploration of space.
(National Archives)

Policy Recommendations

1. Restore Ownership

The rockets and capsules built by SpaceX and Orbital ATK are not owned by NASA, nor are they designed solely to serve NASA's needs. Instead, the companies own them, and have designed them to have value both to NASA as well as other customers. This in turn requires the companies to keep the cost down so that all their customers can afford the product. Ownership also allows the companies to sell their product widely and make profits from it, regardless of whether NASA buys it. For example, Falcon 9's design was aimed specifically for the commercial communications satellite market. Though it can haul cargo and crew capsules to the ISS, its design makes it affordable and useful to many other satellite companies. Thus, SpaceX can make money from it, which in turn lowers NASA's cost.

Similarly, Dragon and Starliner are being designed not just to serve NASA but also a wider customer base. Boeing, for example, has signed an agreement with Bigelow Aerospace to use Starliner to provide cargo and passenger service to Bigelow's privately built space stations, which it hopes to launch by 2020.[114] SpaceX and Sierra Nevada meanwhile have offered their Dragon and Dream Chaser manned spacecraft to other countries as an inexpensive way to develop a space program. Instead of building their own rockets and spacecraft from scratch, Third World nations can buy these affordable American spacecraft and rockets and do science research in space, quickly and for relatively little money.

In contrast, though Lockheed Martin purportedly owns Orion, it has had no control over the capsule's concept or overall design. Instead, that control belongs to NASA, which has justified it to Congress and the public as a vehicle for sending humans beyond Earth orbit, to the Moon, to the asteroids, and even to Mars. To achieve NASA's goals, the agency has required Orion to meet these ambitious expectations. The result has been higher costs, and a very expensive spacecraft that is not practical for Lockheed Martin to sell to other customers. For example, the original heat shield for the spacecraft initially was based on the heat shield design used by the Apollo capsules of the 1960s. NASA figured it would save money to use this older design, since that heat shield design already had been proven successful during actual flights returning from beyond Earth orbit at the high speeds and temperatures such flight paths produce. Unfortunately, even before the first Orion test flight, it was discovered that this design did not scale up well for the larger Orion capsule. The surface of the Orion heat shield ended up too uneven. The old design also proved far too expensive to make, as it required too much manual labor to inject by hand the heat shield's ablative material into a honeycomb pattern of more than 330,000 individual cells. Similarly, NASA's interplanetary requirements for Orion has forced Lockheed Martin to give the spacecraft more radiation shielding (even if insufficient for interplanetary flights) than carried by the Dragon or Starliner capsules, further raising its development and operational costs.[115]

The ownership situation with Boeing's SLS rocket is even more tilted in the government's favor. NASA designed it solely for deep space missions and then handed out contracts piecemeal to different companies to build the rocket's different components. The rocket therefore essentially belongs to NASA, whose goals – exploring space – have nothing to do with reducing cost or obtaining profit. Even if NASA were interested in marketing it to the commercial market, which it is not, the cost for a single SLS is many times more expensive than the most costly ULA launch (priced at $460 million). No satellite company can afford it. NASA and the companies building SLS's components thus have only one customer, the government, and the only way they can hope to make money on it is to charge the government a lot to build it.

The hodge-podge of contractors involved in building SLS. Adapted from 2012 NASA PowerPoint presentation. (NASA)

Recommendation: The government should leave the design work and ownership of the product to the private sector. The private companies know best how to build their own products to maximize performance while lowering cost, especially because it is in their own self-interest to do this well, as a unreliable rocket will not attract many customers. NASA engineers and administrators in turn might be very skilled, but their priorities tend to focus on management and regulation. If NASA or the Air Force require a service they should request it from the private market, becoming a customer like everyone else. This will result in increased competition and performance at a lower cost.

2. Simplify Design and Construction

Because SpaceX and Orbital ATK are entirely in charge of construction, they have the ability to keep their design and manufacturing processes simple and efficient. For example, SpaceX built one rocket engine, the Merlin, and then used it on every stage of its Falcon 9 and Falcon Heavy. This reduced development time and costs while simplifying the manufacturing process. Similarly, rather than design a whole new first stage for its heavy-lift rocket, SpaceX decided to simply strap three Falcon 9 first stages together, a much simpler design solution that saved them millions.

With SLS and Orion, however, Congress imposed mandates that forced NASA to distribute the work to as many contractors as possible (similar to what ESA forced Arianespace to do with Ariane 5). SLS's first stage (built by Boeing) uses engines different from its second stage (built by Aerojet Rocketdyne). SLS also will use a third design for its solid rocket strap on boosters (built by Orbital ATK). This hodge-podge of contractors does nothing to improve the rocket, and everything to increase its cost and lengthen its development time.

Recommendation: Allow NASA and the Air Force to pick the most effective design built by the most efficient companies, even if this means that many established aerospace companies could very well lose their business with the government because they can't build cheaply. In the end, however, the nation, and its elected officials, will benefit, as the government will acquire more for less. The renewed competition for space contracts, unhampered by congressional mandates, also will encourage innovation and cost reduction, resulting in better rockets and spacecraft that can be useful not only to the government, but to many in the private sector.

3. Streamline Cost-Conscious Fixed-Price Contracts

The fixed-price contracts used by NASA for the commercial cargo/crew program (which were also the predominant contract used by NASA in the 1960s) not only put a ceiling on NASA's costs, they also created an incentive for the private companies to keep their costs low and build more efficiently. NASA and Congress further emphasized this desire to keep costs low by requiring the companies in the initial development contracts to invest some of their own money. Moreover, by paying SpaceX and Orbital ATK in increments only after reaching certain milestones, the fixed-price contracts encouraged work to be done quickly and as close to the planned schedule as possible. Also, the use of streamlined SAA/FAR agreements instead of the more complex FAR contracts reduced the costs to both NASA and the contractors while speeding up construction time.

In comparison, the cost-plus contracts that NASA is using for SLS and Orion have been the equivalent of blank checks to the private contractors. The companies actually benefit if costs go up, construction gets delayed, or NASA requests changes. Thus, even after a decade of work and significant budget increases, we are still years from the first manned launch, with many issues suggesting that further delays are imminent.[116]

Recommendation: Abandon the use of cost-plus contracts. They first were introduced in the early years of the space program, when the technology was very uncertain and companies demanded some cushion in case the needs of the engineering were beyond their financial capabilities. More than a half century later, this cushion is now unnecessary. Even with the most daring and radical designs, such as SpaceX's reusable first stage, the engineering is well within the resources of any U.S. company the government might consider hiring.

Recommendation: Even with the use of fixed-price contracts, the government should not entirely underwrite the development of new designs, but instead insist that the companies invest some of their own capital. If private companies are to own the product, making money by selling it to customers outside the government, then they also should help pay for its development. Moreover, more money does not necessarily translate into more success. Congress, NASA, and the Air Force should keep a tight rein on the purse strings, a policy that will effectively encourage the private sector to lower costs and work more efficiently.

Recommendation: Congress should allow NASA and the Air Force to simplify their contracting regulations. The success of the SAA agreements, creating capsules and rockets for significantly less money in significantly less time, demonstrated that the complex supervision and added regulations of the FAR contracts are mostly unneeded and actually interfere with the ability of the government to accomplish what it needs to accomplish.

4. Keep Overhead Low

The difference in cost between commercial cargo/crew and SLS/Orion can be attributed mostly to the different amounts of money NASA budgeted for each program's administration, overhead, and labor costs, within NASA. In the case of commercial cargo/crew, NASA left the ownership, design, and construction entirely up to the private companies, devoting almost no agency resources to the projects. The capsules and rockets still got built, but it was the private companies that did it, and the cost to the government was significantly reduced.

With SLS/Orion, however, NASA allocated significant agency resources, both labor and facilities, to design and construction. Yet NASA still had to award large contracts to private companies to get the rockets and capsules actually built. The result was a gigantic budget for NASA administration and operations that more than doubled the overall cost of the projects. In a sense, the government paid twice for Orion and SLS, once when the agency labor force designed and then supervised the project's construction, and then again when the agency hired private companies to do the work.

Dragon/Falcon 9 and Cygnus/Antares, however, demonstrated there is no need for that additional NASA design and supervision and the labor force that goes with it. The private sector has proven that it will respond to public and private demand and will do so quickly and for a reasonable price.

Recommendation: Congress must use its oversight power to direct NASA and the Air Force to eliminate or significantly reduce their overhead and labor forces, especially in the area of manned space. If most of this work is done by the private companies, there is no justification for the taxpayer to pay salaries for a large standing army of government workers who do little more than administration. In many cases, this recommendation should cause the elimination of a number of NASA centers and facilities.

While many NASA programs – the agency's planetary and astronomical programs, for example – are necessary and do excellent work, the history outlined in this paper suggests that much of the manned space program and the launch industry would be better served if they were handled almost entirely by a competitive private sector. It is in these areas that Congress should consider major reductions at NASA, even as it carefully provides sufficient funds for new manned and science projects in orbit and beyond. In fact, not only would this change in policy allow the government to do more for less in its manned program, a significant portion of the savings from these reductions then could be applied effectively to NASA's planetary, astronomical, and Earth resources programs, allowing them to do more.

5. Expand Competition

The striking competition in the private launch market, spurred by SpaceX's innovation and lower costs, illuminates a path for invigorating the aerospace industry, both for the private sector and the government.

SpaceX entered the aerospace market with one goal: lower the price so that it could compete aggressively for market share. That effort has succeeded. In response, the older, already established companies have become more competitive, or have indicated by non-action that they will fall by the wayside. The result is a revitalized launch industry. A tertiary effect has been the creation of *additional* new launch companies, able to gain investment capital and enter the market, thus completing the economic cycle and increasing the competition and further lowering prices.

NASA encouraged this process with its second round of commercial cargo contracts, awarding contracts to three companies – SpaceX, Orbital ATK, and Sierra Nevada – but left itself the freedom to decide later how many cargo launches from each company the agency would buy. If any company has problems or delays, NASA simply will send its business to the other two. The result: a heightened sense of competition, encouraging faster schedules and lower costs.

Recommendation: Expand competition. Assuming the government accepts the above recommendations, it then should award the work to multiple companies in order to increase competition as well as provide redundancy to the government. The history of those cargo contracts showed that it can actually cost the government less to award contracts for the same service to more than one company, as long as those contracts are streamlined, fixed-price, and leave the design to the private company.

An artist's concept of SpaceX's Falcon Heavy rocket during launch. (SpaceX)

A Final Point

A close look at these recommendations will reveal one common thread. Each is focused on shifting power and regulatory authority away from the federal government and increasing the freedom of American companies to act as they see fit to meet the demands of the market. The key word that defines this common thread is freedom, a fundamental principle that has been aspired to since the nation's founding.

Political leaders from both parties have made the concept a central core tenet of American policy. Democrat John Kennedy stated that his commitment to go to the Moon was a "stand for freedom" in the Cold War. Republican Ronald Reagan proposed "Freedom" as the name for the new space station, and viewed it as a platform for promoting private enterprise in space.

Freedom is actually a very simple idea. Give people and companies the freedom to act, in a competitive environment that encourages intelligent and wise action, and they will respond intelligently and wisely.

The United States' history proves that freedom can work. It is time that it prove it again, in space.

Endnotes

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2. This assessment is not a NASA requirement, but was made by Lockheed Martin itself, as noted in Congressional testimony by Wanda Sigur, Vice President and General Manager. "With our own investment, we have conducted studies that verified Orion's Mars re-entry capability and verified our design meets life limit requirements on all parts of the spacecraft required to support multi-year (1,000 day) missions." See Wanda Sigur, Vice President and General Manager, Statement to the Committee on Science, Space, & Technology, U.S. House of Representatives, May 18, 2016, "Space Subcommittee Hearing - Next Steps to Mars: Deep Space Habitats," https://science.house.gov/legislation/hearings/space-subcommittee-hearing-next-steps-mars-deep-space-habitats;William Gerstenmaier, "Exploration Strategy Update to NASA Advisory Council" (Washington, DC, March 31, 2016), https://www.nasa.gov/sites/default/files/atoms/files/gerst_april_2015.pdf; and Pedro Lopez Jr. et al, "Logistics Needs for Potential Deep Space Mission Scenarios Post Asteroid Redirect Crewed Mission," paper presented at 2015 IEEE Aerospace Conference, March 7–14, 2015, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150003005.pdf.

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6. Robert Zimmerman, "The Lie that is Orion," Behind the Black, July 27, 2016, http://behindtheblack.com/behind-the-black/essays-and-commentaries/the-lie-that-is-orion/. A review of NASA documents describing Orion at the space agency's official Orion website shows that the focus of Orion is similar to the private manned capsules, that of an ascent/descent capsule, with few fundamental differences. See "Orion Overview, NASA, https://www.nasa.gov/exploration/systems/orion/about/index.html, especially the Orion NASA, Spacecraft Overview, NASA Facts, http://www.nasa.gov/sites/default/files/617409main_orion_overview_fs_33012.pdf, which describes Orion's systems for launch, abort, and re-entry but says little about its capabilities for traveling beyond Earth orbit. The only exception, Orion Radiation, suggests that while Orion has more radiation shielding, the spacecraft itself is not completely shielded. See "Types of Radiation, NASA,http://www.nasa.gov/sites/default/files/np-2014-03-001-jsc-orion_radiation_handout.pdf, which states, "Orion will use the mass that is already on board to protect its crew by creating a temporary shelter in the aft bay of the spacecraft, which is the inside portion closest to the heat shield. This location minimizes the amount of equipment to move around while maximizing the amount of material that can be placed between the crew and the outside environment." For any mission to Mars lasting a year or more, this approach is inadequate.

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34. Senate, *Departments of Commerce and Justice, Science, and related agencies appropriations bill, 2007*, 119.

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36. Public Law 111-8, *Omnibus Appropriations Act, 2009*, 355.

37. Senate, *Departments of Commerce and Justice, and Science, and related agencies Appropriations Bill, 2010*, 117; House of Representatives, *Commerce, Justice, Science, and related agencies Appropriations Bill, 2010*, 139; and House of Representatives, *Departments of Transportation and House and Urban Development, and related agencies Appropriations Act, 2010*, 755–756. The budget report by the Senate appropriations committee, *Departments of Commerce and Justice, and Science, and related agencies Appropriations Bill, 2010*, recommended $2.16 billion for Ares. The budget report by the House appropriations committee, *Commerce, Justice, Science, and related agencies Appropriations Bill, 2010*, recommended $1.66 billion for Ares. The final conference report for 2010 Omnibus Budget, *Departments of Transportation and House and Urban Development, and related agencies Appropriations Act, 2010*, did not list separate line items for either Orion or Ares. Instead, the budget allocated $3.466 billion, the amount requested by the administration, expecting later budget requests to clarify how much would be spent for each program. For purposes of this discussion I am using the lower House proposal.

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70. Senate, *Departments of Commerce and Justice, and Science, and related agencies Appropriations Bill, 2010*, 117; and House of Representatives, *Departments of Transportation and House and Urban Development, and related agencies Appropriations Act, 2010*, 755–756.

71. Senate, *Departments of Commerce and Justice, and Science, and related agencies appropriations bill, 2011,* Report 111-229, 111th Congress, 2nd sess., 123-124, https://www.congress.gov/111/crpt/srpt229/CRPT-111srpt229.pdf; and Public Law 112-10, *Department of Defense and Full-Year Continuing Appropriations Act, 2011*, 86-87. I have divided the 2011 appropriation to show first the original demonstration cargo contract appropriation followed by the first operational contract appropriation. The final continuing resolution, *Department of Defense and Full-Year Continuing Appropriations Act, 2011*, does not mention any specific appropriations for commercial space. The numbers here come from the Senate report above, whose overall numbers match closely with the final budget numbers.

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1152 15th Street, NW Suite 950 Washington, DC 20005
t. **202.457.9400** | f. **202.457.9401** | **info@cnas.org** | **cnas.org**

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