COMPETITION FOR A SUPER HEAVY LIFT LAUNCH VEHICLE

Gerald Black
Aerospace Engineer (retired, 40+ year career)
Currently Chair of the Ohio Chapter of the Mars Society
gblack@cinci.rr.com

ABSTRACT

Several new super heavy lift launch vehicles (SHLVs) are currently under development in the United States and elsewhere. SpaceX is developing the Falcon Heavy and an as yet unnamed rocket unofficially referred to as the BFR. Meanwhile, NASA is developing the Space Launch System, which comes in 3 different configurations. Russia and China also have programs underway. This document compares these launch vehicles and discusses the merits of each.

Currently NASA is putting all of its SHLV funding into the SLS, whereas SpaceX is funding the Falcon Heavy and the BFR on its own dime. An alternative strategy is proposed where NASA would conduct a competition to develop a super heavy lift vehicle and award fixed price contracts to the competition winner or winners.

INTRODUCTION

Launch vehicles can be classified according to payload capability. NASA uses a classification scheme that includes the following categories: sounding rocket (suborbital); small lift vehicle (up to 2000 kilograms (kg) of payload to low earth orbit (LEO)), medium lift vehicle (2000 kg to 20000 kg of payload to LEO), heavy lift vehicle (20000 kg to 50000 kg of payload to LEO), and super heavy lift vehicle (SHLV) (50000 kg or more of payload to LEO)[1].

There are no launch vehicles in operation today that fit this definition of SHLV, that is, being capable of launching 50,000 kg (about 110,000 pounds) or more of payload to LEO. Examples of SHLVs from the past include the Saturn V used for the Apollo program, Russia's ill-fated N1 launch vehicle, and Russia's Energia launch vehicle. No SHLV has flown since the final flight of the Energia launch vehicle that launched the Buran Space Shuttle into orbit in 1988. However, several new SHLVs are now under development due the resurgence of interest in human missions beyond low earth orbit.

Figure 1 shows the five SHLV launch vehicles currently under development in the United States, in order of increasing payload capability from left to right. First, there is SpaceX's Falcon Heavy, which is scheduled to have its first launch in the spring of 2016. This launch vehicle will have more than double the payload capability of any current launch vehicle, though with a payload capability of 53,000 kg to LEO it just barely satisfies the payload requirement for a SHLV. Next, three different configurations of the NASA's Space Launch System (SLS) are planned. Finally, SpaceX is developing a rocket that will have even more payload capability than any of the SLS versions. This rocket does not have an official name yet, but unofficially it's called the BFR, for Big Falcon Rocket (or Big F… Rocket). SpaceX has not released a picture of the BFR yet. The image in figure 1 is actually for an outdated 2010 concept called the Falcon XX. The BFR may or may not resemble this concept.

Other countries have also talked about plans for a SHLV, most notably Russia[2] and China with their Long March 9 launch vehicle[3]. Very little is known about the foreign plans, however, and it's hard to predict how vigorously these plans will be pursued.

This document primarily discusses the SHLVs being developed in the United States, namely the Falcon Heavy, the SLS and the BFR. The author is very much in favor of SHLV development, and the more payload capability these vehicles have the better (we'll discuss why later). Finally, the author will discuss changes in government policy that he believes would help promote SHLV development and reduce costs.

COMPARISON BETWEEN THE FALCON HEAVY, THE SLS AND THE BFR

The Falcon Heavy is derived from the Falcon 9 launch vehicle. The first stage of the Falcon Heavy consists of a center booster plus two side mounted boosters. The two side mounted boosters are identical to the first stage of the Falcon 9. The center booster is also the same as the first stage of the Falcon 9 except that the stage structure has been beefed up since it returns from a higher altitude and thus experiences higher loads during the recovery phase. The Falcon 9 and Falcon Heavy share the same second stage.

Just as they are planning to recover and reuse the first stage of the Falcon 9, SpaceX is planning to recover and reuse all three boosters that make up the first stage of the Falcon Heavy. Initially there was a plan to recover and reuse the second stage, but this plan has now been abandoned. Elon Musk (the CEO of SpaceX) has said that he thinks the company's resources can better be spent in other ways.

Three versions of the SLS are planned. The first version, Block 1, can launch 70,000 kg to LEO. The second version, the Block 1B, can launch 105,000 kg to LEO. The Block 1B version is the same as the Block 1 except that the original upper stage (the Interim Cryogenic Propulsion Stage) is replaced with a more powerful upper stage (the Exploration Upper Stage). Finally, the Block 2 version can launch 130,000 kg to LEO, matching the capability of the Saturn V used in the Apollo program, which could also launch 130,000 kg to LEO. The Block 2 version is the same as the Block 1B version, except that the side mounted boosters will be replaced with more powerful advanced side mounted boosters.

The SLS has a relatively low amount of innovation compared to the BFR. The Space Launch System is based primarily on Apollo and Space Shuttle era hardware and infrastructure. The RL10 engine used in the upper stage of the SLS even predates the Apollo program, having been designed mostly in the 1950s and having had its first flight in 1961. It is one of the most costly engines in its class[4].

Also, none of the components of the SLS will be reused. On the Space Shuttle program they reused the side mounted solid rocket boosters (as well as, of course, the Space Shuttle itself).

However, these boosters required extensive refurbishment, so the decision was made not to reuse them on the SLS.

By relying on proven components, the SLS represents a pathway to a SHLV that has very low technical risk. The program has thus far avoided major technical problems, such as the first stage vibration problem that plagued the Ares 1 launch vehicle and led to a large cost overrun that contributed to the cancellation of the Constellation program.

SpaceX, on the other hand, was only founded in 2002, so their hardware is very new, and they've also been very innovative. Most of the innovations that SpaceX has introduced are related to reducing costs, which has been the central focus of the company.

Although the payload capability of the SpaceX's BFR has not been revealed yet, it has been claimed that the BFR will have significantly more payload capability than any of the SLS versions. SpaceX has said that this rocket will be part of a "Mars Colonial Transporter" system, so in addition to the new rocket, this system would include a spacecraft that is claimed to be capable of landing 100 tons of cargo or 100 people on Mars[5]. That's a lot – much more than the SLS will be able to land on Mars. Thus, there has been speculation that orbital refueling might also be part of SpaceX's plans.

SpaceX hasn't released many details about the BFR yet, but they have revealed that both stages of the rocket would be powered by a new rocket engine named the Raptor that would use methane/LOX propellants. Also, the goal is to make both stages of the BFR reusable, thus making the vehicle fully reusable.

The innovations that SpaceX is pursuing on the BFR have low risk with the exception of making the vehicle fully reusable. The latter poses a sizeable technical challenge and comes with moderate to high risk. There is risk that SpaceX won't succeed in making the BFR fully reusable, or that so much refurbishment will be needed that reusability won't produce the hoped for cost savings. But there is also the promise of great reward if successful, since a fully reusable vehicle might lower costs by one or even two orders of magnitude (one tenth or even one hundredth) over what is possible with today's expendable launch vehicles.

On December 22, 2015 SpaceX succeeded for the first time in recovering the first stage of the Falcon 9 during an orbital launch. The first stage touched down on Landing Zone 1 at Cape Canaveral, and Elon Musk (the CEO of SpaceX) stated that it had no damage. This bodes well for the reusability of the first stage of the BFR, and lessons learned from the Falcon 9 will be applied to the BFR design. The author is optimistic that the goal of a fully reusable BFR will eventually be achieved.

Fortunately, reusability is not essential for the BFR to be a success. As will be shown later in this document, even if SpaceX fails totally in making the BFR reusable, the BFR will still cost more than an order of magnitude less than the SLS (that is, less than one tenth as much as the SLS).

In early 2015 Elon Musk said he hoped to reveal details of the Mars Colonial Transporter system (which includes the BFR) by the end of 2015. However, due to the Falcon 9 launch failure in June of 2015 the unveiling has been delayed till 2016.

Despite the many differences between the SLS and the BFR, the bottom line is that they will both work. The most significant difference between the two is the cost, and that will be discussed in detail in a later section.

PAYLOAD CAPABILITY AND INITIAL LAUNCH DATE

Table 1 shows the payload capabilities and initial launch dates for the planned SHLVs. For reference, the Saturn V used in the Apollo program could launch 130,000 kg to LEO.

References 2, 3, 6, 7 and 8 were the source for the payload and initial launch date for all launch vehicles in the table except the BFR. Since SpaceX has not released the payload capacity or initial launch date for the BFR, the author made his own estimates. The estimate of 150,000 to 200,000 kg payload capability for the BFR is simply based on statements by SpaceX that the launch vehicle will have significantly more payload capability than the SLS. SpaceX has been studying various BFR designs for several years and has initiated testing at Stennis Space Center of the injectors for the Raptor engine that will power the BFR[9]. Thus, an initial launch date of 2021 is possible provided that the effort is fully funded.

COST COMPARISON FOR THE FALCON HEAVY, THE SLS, AND THE BFR

Figure 2 is helpful in understanding some of the issues involved and in comparing the relative cost of the Falcon Heavy, the SLS and the BFR. Credit for this excellent figure goes to Georgia Tech and the National Institute of Aerospace. The author made two minor additions to the figure. The first addition was that the original figure lacked a label for the x axis, so the label "Payload to Low Earth Orbit (kg)" was added. The original figure also lacked inclusion of the BFR, so a data point was added giving the author's estimate of the cost and payload capability of the BFR.

The vertical axis of this figure gives the launch cost in dollars per kilogram of payload, assuming that the full payload capacity of the launch vehicle is utilized. The horizontal axis gives the launch vehicle payload capacity to LEO in kilograms.

For existing commercial launch vehicles (the diamonds in the figure) a clear trend emerges, as is shown by the curved line fitting the data points. Namely, launch costs go down as the payload capacity of the launch vehicle increases. There is some difference depending on the launch service provider (United Launch Alliance with the Atlas V and the Delta Heavy is more expensive than the others, while SpaceX with the Falcon 9 and the Falcon Heavy is less expensive), but the trend is clear.

This leads me to explain how the data point for the BFR that was added to the figure was estimated. The payload capability of the BFR hasn't been revealed yet, except for the claim that it will be significantly higher than any version of the SLS. The most capable version of the SLS (Block 2) can launch 130,000 kilograms to low earth orbit, so a reasonable guess for the payload capacity of the BFR would be somewhere in the 150,000 kg to 200,000 kg range. Since the horizontal axis of the figure only extends to 150,000 kg, I set the BFR payload to low earth orbit to 150,000 kilograms on the figure. For the launch cost (vertical axis), I took into account that the launch cost for the Falcon 9 is currently $4750/kg to launch 13,100 kg to low earth orbit[10], and the launch cost for the Falcon Heavy is $1700/kg to launch 53,000 kg to low earth orbit[10], which agrees well with our figure. These are the current launch costs without any reusability, and these costs would be expected to decrease if SpaceX is successful in reusing the first stage of the Falcon 9 and the three booster stages that comprise the first stage of the Falcon Heavy. The BFR, like the Falcon 9 and the Falcon Heavy will be a commercial launch vehicle. Noting the stated trend for commercial launch vehicles and extrapolating out to 150,000 kilograms, the launch cost for the BFR should be very roughly $1000/kg *assuming no reusability*. It's true that extrapolation can be hazardous and the cost could certainly differ from this estimate. However, unless the stated trend breaks down for very large payloads (which would be surprising), the cost of the BFR *assuming no reusability* should at least be less than the $1700/kg current cost of the Falcon Heavy.

Besides the commercial launch vehicles, there are three non-commercial launch vehicles on the figure for which the launch costs are much higher. These are the Space Shuttle, the SLS (the three points under the label HLLV) and the Saturn V. The primary reason that the launch costs are much higher for these vehicles is that, unlike the commercial launch vehicles, these programs utilized traditional cost-plus contracts and were subject to the strictest requirements of the Federal Acquisition Regulation. With government cost-plus contracts there is little or no incentive to reduce costs, whereas with commercial companies competing against one another there is tremendous incentive to reduce costs.

The three data points on the figure beneath the label HLLV (for Heavy Lift Launch Vehicle) require special explanation. These data points arose from a study by NASA's Human Exploration Framework Team (HEFT) circa 2011. They are for an outdated version of the SLS that was similar in design to the current SLS Block 1B version but which could only launch 100,000 kg to low earth orbit versus 105,000 kg for the SLS Block 1B[11]. Unfortunately, NASA has not published any more recent estimates of the operational costs of the SLS, so these are the best estimates available. The reason that there are three data points instead of one is that the launch cost for the SLS is highly sensitive to the launch rate, and the launch rate is currently unknown. The more launches of the SLS per year the lower the launch cost due to economies of scale. As is shown in the figure, if the SLS were to fly three times per year the cost would be $23,000 per kg, if it were to fly twice per year the cost would be $33,000 per kg, and if it were to fly only once every two years the cost would be $50,000 per kg.

Unfortunately, assuming that the current NASA budget increases just at the rate of inflation, NASA will only be able to afford an SLS launch once every two years. This is an issue not only because of the high launch cost, but it also raises a safety issue. Both the NASA Advisory Council and the Aerospace Safety Analysis Panel have warned that this launch rate is insufficient to maintain the competency of the launch crew[12 and 13]. Of course, this problem could be remedied with a substantial increase to NASA's budget. However, many knowledgeable people have been warning that such an increase is unlikely to occur.

The launch cost for the most powerful version of the SLS, the Block 2 version that can launch 130,000 kg to LEO, will most likely be less than that of the version of the SLS shown in the figure that can launch 100,000 kg to LEO. A rough estimate of the cost per kilogram of the Block 2 version can be obtained by assuming that the vehicle cost is the same and multiplying the costs of the SLS version in the figure by the factor 100,000/130,000 = .769. This results in cost estimates for the Block 2 version of the SLS of $17,692/kg if it were to fly three times per year, $25,385/kg if it were to fly twice per year, and $38,462/kg if it were to fly once every two years

We are now at the point where we can compare the operational costs of the Falcon Heavy, the SLS, and the BFR. The SLS costs for the most powerful Block 2 version will likely be between $17,692/kg (this assumes a substantial increase in the NASA budget allowing a launch rate of three times per year) and $38,462/kg (this assumes the current NASA budget adjusted for inflation, which only allows a launch rate of once every two years). This compares to the currently advertised cost of the Falcon Heavy of $1700/kg and the author's rough estimate of the BFR cost of $1000/kg. The cost of the Falcon Heavy will thus be at least an order of magnitude less than the cost of the SLS (that is, one tenth as much), and the cost of the BFR even less. This is assuming no reusability for the Falcon Heavy and the BFR. If SpaceX succeeds in its goal of making both stages of the BFR reusable the cost of the BFR could be two orders of magnitude less than the SLS (that is, a one hundredth as much).

Thus far we have only discussed the operational costs. What about the developmental costs for the SLS and the BFR? About $2 billion is being spent on development of the SLS every year. The General Accountability Office reported that NASA will have spent almost $12 billion on the Space Launch System through 2017[14]. NASA has not released an estimate of the total cost through the development of their most capable version (the Block 2 version) in spite of criticism from the GAO for not doing so[14]. However, outside estimates of the cost range between $30 billion and $40 billion. By contrast, Elon Musk stated that SpaceX could develop a SHLV that could launch 150,000 kg to LEO (20,000 kg more than the most capable version of the SLS) for $2.5 billion[15]. Thus, it appears likely that the developmental cost of the BFR would also be more than an order of magnitude less than the SLS.

WHY IS THE SLS SO EXPENSIVE?

It is evident that the difference in cost between the SLS and the commercial alternatives (Falcon Heavy and BFR) is *huge*. So why is the SLS so expensive? It's a combination of many factors. Unlike the commercial launch vehicles, the SLS is being developed under cost-plus contracts. With the cost-plus contracts, there is little or no incentive to reduce the costs. The SLS contracts are also subject to the strictest requirements of the Federal Acquisition Regulation. This results in thousands of documents[16], endless reviews, all major decisions must be approved by NASA, all costs must be itemized, and all this results in inefficiencies and excessive paperwork.

Another factor is the flat budgets (budgets that stay roughly the same each year instead of varying as needed) that result in slow, phased development with three major configurations instead of just one. As a result two different upper stage designs are being developed instead of just one, and likewise two different side mounted booster designs are being developed instead of just one. The flat budgets limit expenditures in any one year but greatly add to the total cost and greatly extend the development time.

Lack of meaningful competition has also contributed to the costs of the SLS. The NASA Authorization Act of 2010[17] that initiated development of the SLS specified that "the Administrator shall, to the extent practical utilize existing contracts, investments, workforce, industrial base, and capabilities from the Space Shuttle and Orion and Ares 1 projects". This language ensured that there would be no competition for most of the SLS contracts. Rather than establish an efficient program that would minimize costs, it seems that the primary purpose of this legislation was to preserve jobs in the states of the senators who crafted this legislation.

WHICH SHLV IS BEST FOR HUMAN MISSIONS BEYOND EARTH ORBIT?

The fact that the cost in $/kg of payload of the Falcon Heavy is at least an order of magnitude less than that of the SLS has caused many people to advocate using the Falcon Heavy for some or all missions beyond earth orbit instead of the SLS. A recent study[10] partially funded by NASA showed how using the Falcon Heavy, along with leveraging commercial capabilities and public-private partnerships, could greatly reduce the costs of a lunar base compared to using the SLS along with the traditional NASA cost-plus contracts. This study was certainly right regarding the cost saving advantages of leveraging commercial capabilities and public-private partnerships.

However, it is incorrect to conclude from the Falcon Heavy versus SLS comparison that a SHLV with a smaller payload capability is more cost effective than a SHLV with a larger one. This is the case for the Falcon Heavy and the SLS, but it is not true in general. The Falcon Heavy versus SLS comparison is distorted by the fact that the SLS was developed by the NASA bureaucracy without competition under cost-plus contracts, whereas the Falcon Heavy was developed by SpaceX without government funds and with huge incentive to contain the costs.

It turns out that SpaceX's BFR represents a greater potential to reduce costs than the Falcon Heavy for beyond earth orbit human missions. This is because, other things being equal, launch costs decrease as the payload capability of the launch vehicle increases (see the earlier discussion regarding figure 2). Thus, the BFR, with the greatest payload capability of any of the SHLVs under development, in all likelihood will have the lowest cost.

Besides having lower launch costs, there are other benefits that accrue by using a more capable launch vehicle. A larger payload shroud diameter enables larger payloads. Current launch vehicles have a max payload shroud diameter of 5 meters. The Falcon Heavy will also have a payload shroud diameter of 5 meters. However, the SLS will have a max payload shroud diameter of 10 meters, and the BFR payload shroud diameter will likely exceed 10 meters. Doubling the diameter results in 4 times the cross sectional area, which makes a world of difference. A habitation module for a crew of 4 requires a diameter of about 8 meters. This is beyond the capability of the Falcon Heavy to launch unless an inflatable module is used. Even using inflatable modules, a payload shroud diameter of only 5 meters would result in major headaches for the designers who would have to struggle to make all the needed components for a lunar base or a Mars mission fit inside.

Another benefit of launch vehicles with higher payload capacity is that fewer launches would be required. This improves the odds of mission success by reducing the possibility that a critical component would be lost due to a launch failure. It would also reduce or eliminate the need for orbital assembly. For example, the BFR could ease construction of a commercial space station to replace the International Space Station when its life ends. If we are ever to pursue such lofty goals as establishing settlements on the moon, Mars or elsewhere, then the very heavy payload capability of a vehicle like the BFR is needed do this most efficiently and affordably.

A CHANGE IN POLICY IS NEEDED

Currently 100% of the money NASA is spending to develop a SHLV is going to the SLS. However, the SLS program costs are out of control and the schedule has been slipping. With the current NASA budget the flight rate for the SLS will be so low that safety will be compromised. The BFR appears to be a much better choice both in terms of capability and affordability.

One problem with the current policy is that it may actually inhibit development of the BFR. While BFR development will cost a lot less than that of the SLS, it is still a large chunk of money. The problem is that NASA is the only customer needing a SHLV for the foreseeable future, and with NASA committed to the SLS, that destroys the business case for the BFR. Investors in SpaceX may be loath to invest in a product whose payoff is so far in the future as long as NASA remains committed to the SLS. Development of the BFR could be greatly accelerated if the program had access to NASA funding and expertise.

A change in policy is clearly needed to serve the best interests of our space program and the effort to advance humanity beyond low earth orbit.

COMPETITION TO DEVELOP A REUSABLE COMMERCIAL SHLV

The author believes that the large pot of money spent on the SLS would be better spent on developing a reusable commercial super heavy lift launch vehicle such as SpaceX's BFR. A competition to develop such a launch vehicle would best be modeled after the COTS (Commercial Orbital Transportation Services) program. The COTS program was not a government program but rather a public-private partnership. This program led to the highly successful commercial cargo and commercial crew programs for providing transportation to and from the International Space Station.

Instead of traditional cost-plus contracts, the COTS model relies on Space Act Agreements followed by fixed-price contracts. The Space Act Agreements are not binding contracts but rather payment for milestones achieved. During this phase of the competition, the competitors are free to make all design decisions. The competitors also contribute development money during this phase, which they do in the hope of winning future business. This contrasts with the cost-plus contracts where NASA pays the entire cost plus an additional payment for profit. Following the Space Act Agreements, fixed-price contracts are awarded to the competition winners. However, unlike the cost-plus contracts, detailed cost accounting is not required.

The commercial cargo program produced two new spacecraft and two new launch vehicles, namely the Dragon spacecraft and the Falcon 9 launch vehicle by SpaceX, and the Cygnus spacecraft and the Antares launch vehicle by Orbital Sciences Corporation (see figure 3). NASA conducted a study[18] and found that if it had developed the Falcon 9 and Dragon spacecraft under traditional cost-plus methods that it would have cost 8 times as much as it cost SpaceX.

The commercial crew program has also been highly successful. The winners of the fixed-price contracts were announced on September 16 of 2014. They were Boeing with their CST-100 capsule, and SpaceX with their Dragon 2 capsule (see figure 4). The cost of this program, including all the competitors combined, has been much less than for the Orion spacecraft, which is a program of approximately equal complexity but which is being developed using a traditional cost-plus contract.

By using the COTS model, both the commercial cargo and the commercial crew programs were able to fund two suppliers for less than one supplier would have cost had traditional cost-plus contracts been used. This experience strongly indicates that with a COTS type program we could afford two SHLV suppliers at less cost than we currently spend on the SLS. In fact, it makes good sense to have more than one SHLV supplier. If we have a moon base depending on supplies from earth, it would be smart to have more than one SHLV supplier in case of a launch vehicle failure.

Competitions are always good, since they accelerate progress and encourage innovation. Besides SpaceX, other companies would likely enter the competition. Blue Origin or United Launch Alliance might propose a SHLV utilizing Blue Origin's BE-4 engine, which is reusable and happens to be remarkably similar to the Raptor engine that SpaceX is planning for the BFR. ULA is already working on a new rocket that uses this engine named the Vulcan, which is meant to replace their Atlas V, Delta IV and Delta IV Heavy launch vehicles.

It is even possible that the SLS could be reborn as a commercial program rather than a government program, managed by a prime contractor such as Boeing, Lockheed Martin, or United Launch Alliance. In this way the SLS program might simply continue under a Space Act Agreement while it competes against the other competitors for a fixed price contract. This would force the SLS contractors to innovate, introduce reusability and make very substantial cost reductions in hope of winning a fixed price contract.

CONCLUSIONS

In judging the suitability of a SHLV for human missions beyond earth orbit, three parameters are of prime importance: 1) payload capability, 2) payload shroud diameter, and 3) costs ($/kg of payload). Based on these parameters we can rank the three SHLVs being developed in the United States (the BFR, the SLS, and the Falcon Heavy). Details regarding the BFR haven't been released yet, but from what has been revealed it is highly likely that that the BFR will come out on top in all 3 categories. In the near future details may be released confirming this assessment. Thus, it appears that the BFR is by far the best choice for human missions beyond earth orbit.

The SLS does have an advantage over the Falcon Heavy regarding payload capability and payload shroud diameter. This is of less importance for simple missions that require few launches such as missions to cislunar space. It is more important for demanding missions requiring many launches such as landing humans on Mars, where we want to avoid orbital assembly and the risk of losing a critical component due to a launch failure.

However, the real killer as far as the SLS is concerned is its cost. Assuming no reusability, the cost of the SLS is at least an order of magnitude higher (that's 10 times higher) than that of the Falcon Heavy and much more than an order of magnitude higher than the BFR. The Falcon Heavy will have a reusable first stage, the SLS will have no reusability, and the BFR is designed to be fully reusable (reusing both the first and second stages). Assuming that SpaceX succeeds in making the BFR fully reusable, the SLS may cost two orders of magnitude more than the BFR (that's 100 times as much). With NASA's current budget the SLS is just not affordable.

The SLS program should be terminated and replaced with a competition to develop a reusable commercial SHLV with a high payload capacity such as the BFR. This competition should be modeled after the highly successful COTS program.

REFERENCES

1. "Launch Vehicle", Wikipedia Encyclopedia, en.wikipedia.org/wiki/Launch_vehicle#By_size
2. "Russia Gives Green Light to Super-Heavy Rocket Project", April 24, 2014, sputniknews.com/russia/20140424/189348744/Russia-Gives-Green-Light-to-Super-Heavy-Rocket-Project.html
3. "China develops new rocket for manned moon mission: media", Dec. 8, 2014, www.spacedaily.com/reports/China_develops_new_rocket_for_manned_moon_mission_media_999.html
4. "RL10", Wikipedia Encyclopedia, en.wikipedia.org/wiki/RL10
5. "Mars Colonial Transporter", Wikipedia Encyclopedia, en.wikipedia.org/wiki/Mars_Colonial_Transporter
6. "First Falcon Heavy Launch Scheduled for Spring", Jeff Foust, Sept. 2, 2015, spacenews.com/first-falcon-heavy-launch-scheduled-for-spring/
7. "Space Launch System", Wikipedia Encyclopedia", en.wikipedia.org/wiki/Space_Launch_System
8. "NASA considers SLS launch sequence for human Mars missions in the 2030s", Chris Gebhardt, Sept. 24, 2015, www.nasaspaceflight.com/2015/09/nasa-considers-sls-launch-sequence-mars-missions-2030s/
9. "SpaceX's Gwynne Shotwell Talks Raptor, Falcon 9, CRS-2, Satellite Internet and More", Amy Svitak, aviationweek.com/blog/spacexs-gwynne-shotwell-talks-raptor-falcon-9-crs-2-satellite-internet-and-more
10. "Economic Assessment and Systems Analysis of an Evolvable Lunar Architecture that Leverages Commercial Space Capabilities and Public-Private-Partnerships", Charles Miller, Alan Wilhite, Dave Cheuvront, Rob Kelso, Howard McCurdy and Edgar Zapata, July 13, 2015, page 18, www.nss.org/docs/EvolvableLunarArchitecture.pdf

11. “Space Launch Report – Space Launch System Data Sheet”, Ed Kyle, 3-15-2015, www.spacelaunchreport.com/sls0.html
12. Smith, Marcia S., “Future of NASA’s Human Spaceflight Program Dominates NAC Meeting”, July 30, 2014, www.spacepolicyonline.com/news/future-of-nasas-human-spaceflight-program-dominates-nac-meeting
13. “Aerospace Safety Analysis Panel Annual Report for 2014”, page 23, oiir.hq.nasa.gov/asap/documents/2014_ASAP_Annual_Report.pdf
14. United States General Accountability Office report “Space Launch System”, July 2014, www.gao.gov/assets/670/664969.pdf
15. “The SLS: too expensive for exploration?”, by John Strickland, 11-28-2011, http://www.thespacereview.com/article/1979/1
16. “Working the paper trail – SLS team processing thousands of CDR documents”, Chris Bergen, 5-15-2015, www.nasaspaceflight.com/2015/05/sls-team-working-thousands-pages-cdr-documentation/
17. “NASA Authorization Act of 2010”, sections 302 and 304, www.congress.gov/111/plaws/publ267/PLAW-111publ267.pdf
18. NASA, “Commercial Market Assessment for Crew and Cargo Systems Pursuit to Section 403 of the NASA Authorization Act of 2010 (P.L. 111-267)”, April 27, 2011, http://www.nasa.gov/sites/default/files/files/Section403%28b%29CommercialMarketAssessmentReportFinal.pdf

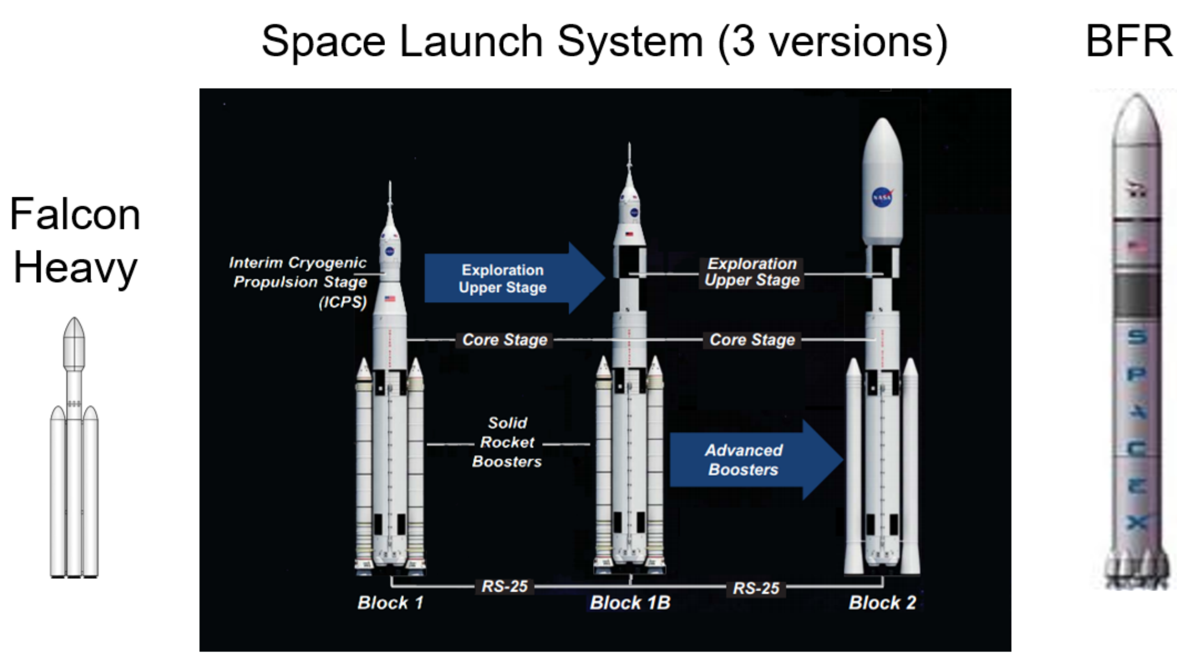

Figure 1. Super heavy lift vehicles under development by the United States. Images: NASA and SpaceX

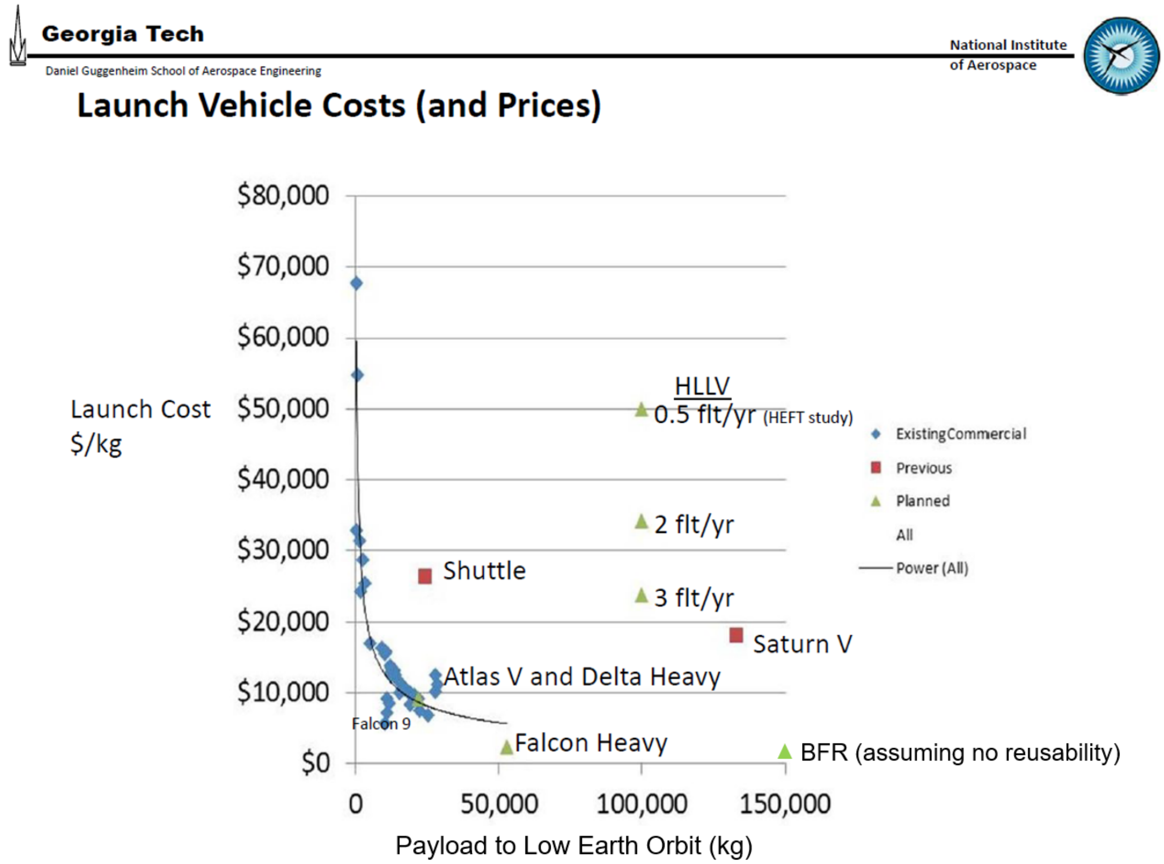

Figure 2. Credit: Georgia Tech and the National Institute of Aerospace. Minor additions by Gerald Black.

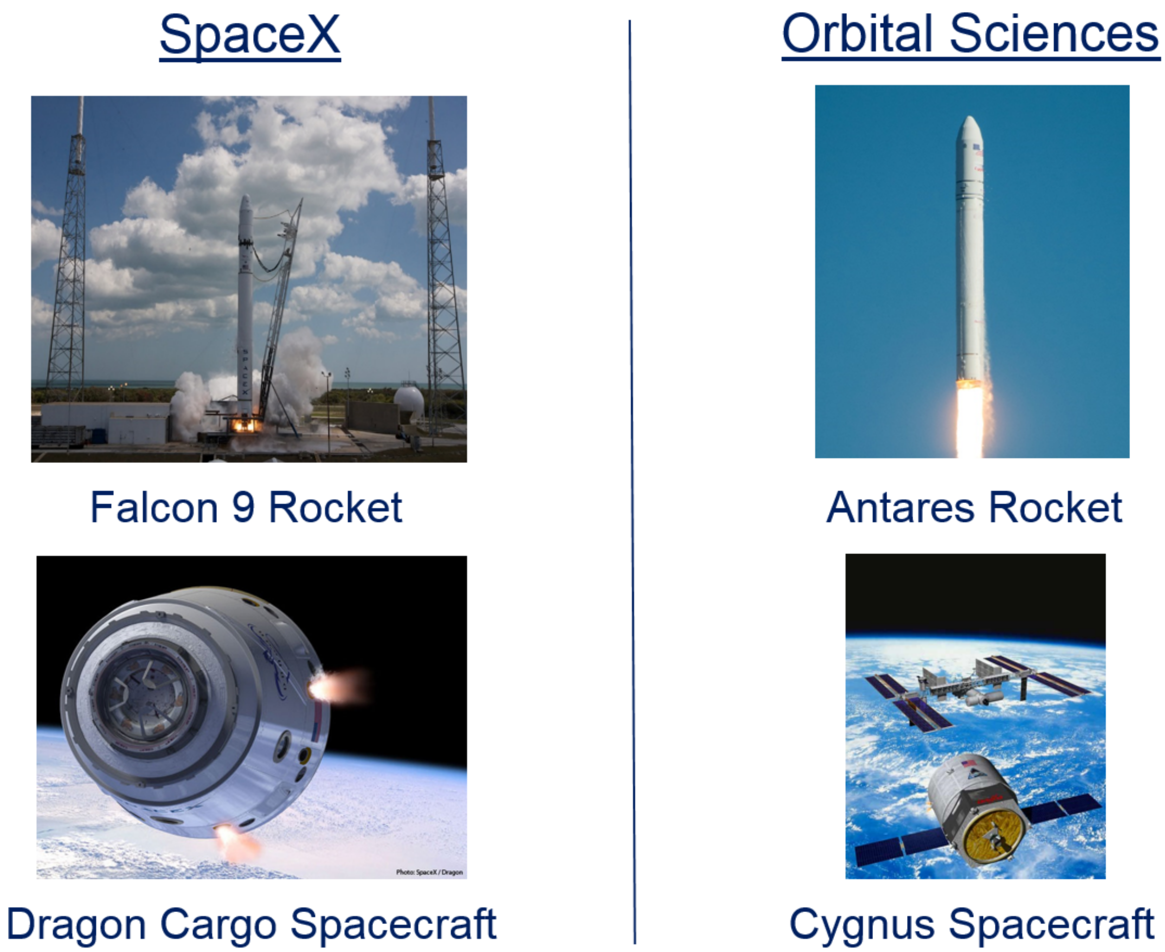

Figure 3. Commercial Cargo Program Suppliers. Images: SpaceX and Orbital Sciences Corp.

Figure 4. Commercial Crew Program Suppliers. Images: SpaceX and Boeing

Launch Vehicle	Origin	Payload to LEO (kg)	Initial Launch Date
Falcon Heavy	U.S., SpaceX	53,000[6]	Spring, 2016[6]
SLS Block 1	U.S., NASA	70,000[7]	2018[7]
SLS Block 1B	U.S., NASA	105,000[7]	2021[7]
SLS Block 2	U.S., NASA	130,000[7]	2028[8]
BFR (unofficial)	U.S., SpaceX	150,000 – 200,000	2021
Unnamed	Russia	Phase 1: 70,000 – 80,000[2] Phase 2: 100,000 – 120,000[2]	2030[2] After 2030[2]
Long March 9	China	130,000[3]	2028[3]

Table 1. Super heavy lift vehicle payload capability and initial launch date