Ending Apolloism

Removing The Mental Roadblocks That Continue To Confine Us To Low Earth Orbit

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Introduction

Project Apollo was arguably the greatest technical achievement in human history. But in terms of opening up the solar system to humanity, it was a magnificent disaster.

Since the last man walked on the moon in 1972, hundreds of billions of current-year dollars have been spent on NASA human spaceflight, with little currently to show for it other than a space station with a handful of crew that we share with Europe, Japan and Russia, and for which we are currently reliant on the Russians to access.

For decades, NASA's human spaceflight program has been more jobs program than space program. The latest, and most blatant and egregious phenomenon of a NASA program created primarily for the sake of the jobs it provides is the Space Launch System aka the Senate Launch System (and, to a lesser extent, the Orion Crew Capsule). Proponents of these programs claim that it is not possible to get humans to Mars, or beyond low earth orbit at all, without them. But most independent analyses (and at least one internal NASA study) indicate that not only are they unnecessary for that purpose, but they are chewing up all the budget that could be going to things that *are* necessary, but are not being funded at all. NASA propaganda is that SLS/Orion are "stepping stones on the #JourneyToMars" but, in reality, they are exactly the opposite; they are a roadblock. (It's worth noting that, as of this writing, NASA has no current plans to send Orion beyond cislunar space, and it has never had any design requirements imposed on it that would allow it to effectively do so.)

In fact, the current general policy approach is to attempt to replicate Apollo in the sixties, except with the more distant target of Mars, and taking much longer than “before the decade is out.” But for reasons that will be explained, it is neither desirable or politically feasible to do what I have described as “Apollo to Mars,” and if it were, it would be as much a dead end as Apollo to the moon was, with more decades of space stagnation to follow. If we are serious about opening the high frontier, and maintaining public support, we need to provide much more value for the money than a few NASA boots and a flag on another planet decades from now. The purpose of this monograph is to point out an alternative vision to what I've come to call the Apolloistic religion, one that not only actually has realistic economic and technical prospects of getting humans to Mars in the foreseeable future, but offers a much more vibrant future for humanity in space in general.

1.0 Background

Over the decades, but particularly in the past couple years, in the wake of repeated failed attempts to initiate programs to get Americans once again beyond low earth orbit for the first time since that last man walked on the moon, a number of studies have been performed laying out policy or technical recommendations for doing so. This section presents a brief summary of the most recent ones, on which this monograph will build.

Apolloism: The Apollo Cargo Cult

On the 45th anniversary of the first human moon landing in July 2014, I wrote an op-ed for *USA Today*, in which I most recently described what I have come to call the Apollo Cargo Cult:

> The Apollo moon program was never really about space, or opening it to America or humanity. It was a peaceful battle in an existential war. In the post-Sputnik panic, the priority was not to do it affordably or sustainably but, to do it quickly — before the end of the decade, and win the race.
>
> Wernher von Braun [architect of Apollo] originally envisioned fleets of low-cost reusable launch vehicles to deliver parts to assemble into larger systems in low earth orbit that could head out to the moon and planets. But at the time there were too many technical uncertainties to do that quickly, with confidence. [For instance, we had no experience with orbital rendezvous.] Building a giant throw-away rocket to get the astronauts all the way to the moon and back from Florida was deemed the fastest, surest way to do it, albeit a very inefficient and costly one. Each lunar mission cost a few billion dollars in today's currency.
>
> But Apollo succeeded at its narrowly proscribed goal of "...landing a man on the moon and returning him safely to the earth," in 1969. And in so doing it provided a[n existence] proof of how to send humans beyond earth orbit that haunts and hobbles us to this day.
>
> In the Melanesian islands [during WW II], an interesting cultural phenomenon developed in the wake of contact with western civilization. The Europeans or Americans would come in, and build wharves, runways and control towers. Ships and planes would then appear bearing goods never seen before. After westerners left, "cargo cults" arose among them. For years afterward, they would build thatch docks or control towers or frond airplanes in expectation of the return of the manna from the seas and heavens. But because they didn't understand the underlying mechanisms, they waited in vain.
>
> Similarly, many in the space community, remembering [only] the glory of Apollo, repeatedly attempt to recreate it, not understanding the historical contingencies that improbably allowed it. They recall the goal, the date, and the ridiculously expensive large rocket, and hope that if only they can somehow repeat those things, we will once again send men (and this time women) out beyond low earth orbit. They lack the vision to conceive any other way of opening the solar system, though what has actually trapped us circling the earth for over forty years is not the lack of a giant rocket [and associated

> capsule], but the false belief that such a rocket is either necessary or sufficient to go beyond.

Beyond that, they believe that what we need to get to Mars is a “national commitment,” not understanding the difficulty, if not impossibility, of getting such a thing in a truly democratic republic, in which policy directions can change with the political winds. They view Apollo as the model for how large space programs should be done, when in fact it was an extreme historical anomaly that came very close to not happening at all.

In a sense, the reason we can't do what they seem to want — Apollo to Mars — or Apollo again at all, is because we never really did it the first time, in the sense that many imagine. Yes, we landed men on the moon, but the national commitment to it was actually brief; Kennedy was contemplating cancellation himself, or doing it in cooperation with the Soviets before his death. And there was never wide-spread public support for the program; it only briefly ever had majority support, during the first moon landing. The Appendix of this document is a draft chapter of a book I've been working on for years, that lays out what really happened in Apollo, to lay to rest the mythology about it that continues to encourage people to fantasize that it can (let alone should) be repeated.

But the space-policy establishment continues to cling to this failed model with an almost-religious belief that we could call “Apolloism.”

For instance, in that same Apollo anniversary summer of 2014, the National Research Council coincidentally issued a report on human spaceflight that laid out a "stepping stone and pathways" approach to Mars as a “horizon goal” that would culminate in sending a few NASA astronauts to that planet some time around mid century, after spending many tens of billions of taxpayer dollars. To me, the most profound flaw in it (of many) was this, from page 67:

> Carl Sagan wrote that “every surviving civilization is obliged to become spacefaring—not because of exploratory or romantic zeal, but for the most practical reason imaginable: staying alive. . . . The more of us beyond the Earth, the greater the diversity of worlds we inhabit . . . the safer the human species will be.” Stephen Hawking spoke in 2013 about the need for humanity to populate itself beyond Earth to survive: “We must continue to go into space for humanity. If you understand how the universe operates, you control it in a way. We won’t survive another 1,000 years without escaping our fragile planet.” Although a viable off-Earth settlement would by its very existence increase the odds of long-term human survival, it is *not currently known whether an independently surviving space settlement could be developed*. There are many technical challenges along the path from current capabilities to such a development, so this rationale speaks to a far-future aspirational goal. However, any progress in addressing the challenges requires a continuing human spaceflight program.

> *It is not possible to say whether human off-Earth settlements could eventually be developed that would outlive human presence on Earth and lengthen the survival of our species*. That question can be answered only by pushing the human frontier in space. [Emphasis added]

It could have been said in 1959 that “It is not possible to say whether it is possible to send a man to the moon and return him safely to the earth. That question can be answered only by pushing the human frontier in space.” Yet we made it a national goal two years later, even though we continued to lack the data.

In 2009, the Augustine Committee had issued a report which noted that the only valid justification for government-funded human spaceflight was space settlement. In the spring of 2016, Congressman Dana Rohrabacher (R-California) introduced a bill to Congress that would amend the Space Act (NASA's charter) to make space development and settlement the goal of our civil space activities. So why should we use different criteria for settlement than we did for Apollo?

Now it's fair to note that, while whether we could land a man on the moon in the 1960s was a technical problem (money was not an issue, at least in the beginning), the ability for a civilization to endure off planet is an *economic* one. That is, while we know in theory how to utilize extraterrestrial resources needed for human life, the question is whether or not we can do so affordably and sustainably, particularly without access to the industrial capacity of the home planet. I assume that is what the NRC meant when they said it was questionable whether human off-earth settlements could be feasible. I would say that if it is *not* currently known, then we should be trying to determine *as soon as possible* whether or not it is. This is because if we determine that it is absolutely *not* (unlikely to me) then (on the logic of the Augustine panel, with which I agree) we should at that point simply *stop wasting government money sending humans into space at high cost per mission*. And even if it could be accomplished politically, Apollo to Mars is *not the way* to learn that.

I don't want to imply that the report is without value. There are some things in it with which I agree. For example, these are good decision rules:

> A. If the appropriated funding level and 5-year budget projection do not permit execution of a pathway within the established schedule, do not start down that pathway.
>
> B. If a budget profile does not permit the chosen pathway, even if NASA is well along on it, take an “off-ramp.”
>
> C. If the U.S. human spaceflight program receives an unexpected increase in budget for human spaceflight, NASA, the administration, and Congress should not redefine the pathway in such a way that continued budget increases are required for the pathway’s sustainable execution; rather, the increase in funds should be applied to rapid retirement of

> important technology risks or to an increase in operational tempo in pursuit of the pathway's previously defined technical and exploration goals.
>
> D. Given that limitations on funding will require difficult choices in the development of major new technologies and capabilities, give high priority to choices that solve important technological shortcomings, that reduce overall program cost, that allow an acceleration of the schedule, or that reduce developmental or operational risk.
>
> E. If there are human spaceflight program elements, infrastructure, or organizations *that are no longer contributing to progress along the pathway, the human spaceflight program should divest itself of them as soon as possible*. [Emphasis added]

While what they may have had in mind was the International Space Station, that last one is amusing, given that SLS/Orion fall in that category today, an issue on which, reading between the lines, the NRC was apparently unable to reach a consensus. In fact, NASA's current approach, as compelled by Congress, pretty much violates all of those rules. In my opinion, if the implicit message of the NRC report can be boiled down to a single point, it would be this: *If the national goal is to get government employees to other planets, given the political and funding constraints dictated by politics and public opinion, the nation cannot afford SLS/Orion.* That is, it was the same message as the Augustine report about Constellation. But the report could not say that explicitly.

On page 114, it is clear that the committee also struggled for consensus on how to measure progress, as a result of the lack of consensus on the purpose of human spaceflight.

> It has been argued that public programs should be evaluated in terms of their ability to achieve a broad set of objectives (or "values") and of the efficiency with which the objectives are accomplished. The effectiveness of public programs in achieving a broad set of objectives forms the core of value-proposition analysis as applied to public-sector activities. The committee's review of the value-proposition analyses of public agencies in general—and of NASA's human space exploration efforts in particular—reveals that such a value approach lacks clear definition of objectives and lacks the formulation and tracking of appropriate metrics to measure the performance of any public agency along the path to meeting these objectives. Such analyses remain largely theoretical, and the notion that one can aggregate a variety of measures of outcomes, efficiency, and progress into any single equivalent of a business value proposition remains very difficult to realize.

I would argue that if we were to decide that the purpose of government-supported human spaceflight is the economic development and settlement of space, there are some obvious metrics we could track over time, e.g.: cost of access to orbit for people and other high-value payloads; cost of access to orbit for bulk cargo; number of people living in LEO; number of people living in cislunar space; number of people living beyond; annual gross solar-system product (GSSP); etc. Presumably, all of those would be rising, while the cost to the taxpayer (or at least the ratio of that value to the growth in GSSP as an ongoing national objective) was declining.

The next sentence, also from page 114, is true, but very misleading.

> The development challenges associated with any solar system destinations beyond the Earth-Moon system, Earth-Sun Lagrange points, near-Earth asteroids, and Mars are profoundly daunting, involve huge masses of propellant, and have budgets measured in trillions of dollars.

One could have as easily written in 1860, "The development challenges associated with any American destinations beyond the Mississippi are profoundly daunting, involve huge masses of fuel, and have budgets measured in billions of dollars." (A billion dollars in that era would have been viewed as perceptually equivalent to a trillion dollars today.) Yet that development happened, because the wealth generated thereby paid the ongoing bills.

I infer from the reference to the "huge masses of propellant" that the committee assumed all would be launched from the home planet but, as I'll discuss in the body of this monograph, such an approach, even at dramatically lower launch costs, would be economically insane. The fuel for the horses and trains (fodder, wood and coal) that opened up the western frontier was indigenous. So too will be the propellant that opens up the solar system.

Finally, this (correct) statement is worthy of comment.

> A sustained human exploration program beyond LEO, despite all reasonable attention paid to safety, will almost inevitably lead to multiple losses of vehicles and crews over the long term."

I've in fact written a book on this subject, and I agree. However, I don't view it as a problem. Moreover, in the context of their report, this actually seems unlikely to me, given how little activity they actually propose to do. We won't be sending enough people to have likely losses (particularly given NASA's ridiculously low probability-of-loss-of-crew goals). The goal for this monograph is in fact to show how to increase the activity level far beyond the paltry vision of the NRC, to the point at which the deaths of pioneers may become a realistic possibility, and the accepted norm, as it has been on any previous frontier.

Science, Exploration, or Development?

More recently, in the spring of 2015, the Planetary Society held a workshop about a report they had commissioned from the Aerospace Corporation and Jet Propulsion Laboratory that proposes a "low cost" mission to get NASA astronauts to Mars by the mid 2030s. On September 29th of that year, that report on the spring workshop was released.

The way they achieve the “low” cost is by not landing on Mars initially, instead first establishing a beachhead in Mars orbit, perhaps on one of its moons, Phobos or Deimos.

Setting aside the economic issue of whether to initially orbit or to go all the way to the surface, in my opinion, they got off on the wrong foot right from the beginning. On page 6, the report states that “The workshop did not attempt to address the overarching question of why we should send humans to Mars, as this topic has been widely discussed in other venues and identified as the 'Horizon Goal' by the National Academies [in the NRC report].”

As I wrote in 2009 in *The New Atlantis*, “To get past the misperceived lessons of the past four decades and to develop a 'safe, innovative, affordable, and sustainable' plan for manned [sic] spaceflight, we must begin by stating plainly why we should go into space, for the why gives shape to the how.”

On page 9 of the report appears this statement (and several suggestions how to implement it): “In order for the United States to send humans to Mars, the space science community and the human spaceflight community must work together.”

There is an implicit, and harmful, even *disastrous* assumption in here, which gets back to my point about how we must first determine purpose before we can determine the means of achieving it.

Almost everyone in the space-policy community uses the phrase “space exploration” as the primary purpose of NASA, and as though it is an end in itself, rather than a means. There are actually advocacy groups with names like “Coalition for Deep Space Exploration” and “Space Exploration Alliance.” Similarly, such “exploration” is generally equated with science, particularly by the planetary-science community, including the Planetary Society, who see the acquisition of pure knowledge, not necessarily sullied by any mundane purpose, as the noble goal for the taxpayers to fund. The phrase goes all the way back to the early days of the agency, and was nourished in the sixties, in the midst of Apollo (which, as I describe in the Appendix, actually had little to do with exploration) by the (now) popular television program *Star Trek*, in which the crew boldly went “where no [hu]man had gone before.”

But it's a dangerous phrase, when applied in this context, for human spaceflight. The reason is one that I described a couple days after the loss of the space shuttle *Columbia* in early February, 2003, in *National Review:*

> With the loss of another orbiter, policymakers are going to be looking for answers, about what to do — not only to minimize the chances of a recurrence with our smaller and now less-resilient fleet, but what should follow. Here are the kinds of questions that will be asked: — Does the shuttle need to be replaced? — How much capability should the vehicle that replaces it have? — Should it serve military as well as civil needs? — Should it be a

new reusable vehicle, or perhaps a small winged vehicle to go on top of an expendable? — Should we stop sending people into space and just "do it with robots"?

These are the wrong questions, however, at least for now. The last one in particular is egregiously pointless, because we don't even know what "it" is.

If history is any guide, policymakers won't ask the right questions, the useful questions, those fundamental metaquestions that haven't been asked since the dawn of the space age and NASA's founding. First and foremost among them are: Why do we have a "space program"? What are we trying to accomplish?

Every press interview, every congressional hearing, every blue-ribbon commission assumes answers to that question, and the assumption is assumed to be shared, and none of those assumptions are ever questioned. They must be, because they're not as obvious as many think, and they're definitely not shared, at least by me, and I suspect by many others as well.

Back in the bad old days of the Cold War, when NASA was formed, the answer was easy. It was to beat those godless commies to the moon, and thus demonstrate the inherent superiority of a democratic socialist state enterprise for space exploration over a totalitarian socialist state enterprise for space exploration. Oh, and while we're at it, Lyndon Johnson would like us to help industrialize the south.

Of course, it was couched in loftier terms. We were exploring space, for all mankind. Later, after we won the moon race, the real reason transmogrified to "maintain jobs in Houston, Huntsville, Florida, and California, and other key congressional districts," while maintaining the "exploration and science" fig leaf. At the end of the Cold War, the new real reason became "maintain jobs, and provide midnight basketball programs for Russian scientists, so they won't sell nukes to Kim Il Sung and Saddam." But if anyone asks, we're doing it for "science and exploration." And maybe a little "international cooperation."

Science has never been a good justification for a manned [sic] space program. It's simply too expensive, compared to all other federal science programs, particularly the way that NASA goes about it. [For example, NASA's budget is about $18B per year, o*ver twice the entire budget of the National Science Foundation*, at about $7B.] But more to the point, by focusing on this purpose of the space program, and excluding all others, it allows people to ask questions like "why don't we do it with robots?"

There are some space missions that will just never be jobs for robots. Building an orbital infrastructure that can both mine useful asteroids and comets, and deflect errant ones about to wipe out civilization, is unlikely to be done with robots [alone]. Building orbital laboratories in which biochemical and nanotechnological research can be carried out safely is unlikely to be practically done with robots. A new leisure industry, with resorts in orbit or on the moon, would be pointless, and find few customers, if we weren't sending up people. Establishing off-world settlements to get at least some of humanity's eggs out of the current single fragile physical and political basket is not exactly a job for a robot.

While I've been thinking about this problem for many years, I'm not the first to point it out. In 2009, as the Constellation program (and in some sense the 2004 Bush Vision for Space Exploration itself) was in its death throes, Dan Lester and Michael Robinson published a paper in *Space Policy* titled "Visions of Exploration," which described the history of exploration and elaborated on this theme. They note with a word cloud (shown in Figure 1) that it is the dominant word in a 2006 NASA strategic plan. They also note the policy convenience of the ambiguity of the meaning of the word.

Figure 1: "Exploration" Dominates NASA Strategic Thinking

Why does such an important term as "exploration" retain such ambiguity? One finds many answers, but perhaps comedian Gary Owen explains it best. Certain words, Owen states, are "freedom words," terms with meanings broad enough to label things that would be hard to categorize. Like Owen's made-up word "insegrevious," exploration has come to mean whatever its users want it to mean. In truth, the ambiguity of the term "exploration" has certain advantages, particularly from the perspective of funding and policy making. Because funding of NASA budgets requires broad agreement in Congress, the fuzziness of exploration often avoids triggering debates that would weaken political support. "In the political realm, it's not desirable to have too precise a definition," according to Scott Hubbard, Stanford Professor of Engineering and Former Director of NASA Ames Research Center, with respect to exploration.

Within this environment, explains Hubbard, defining exploration too narrowly "is not without some peril." Ian Pryke, Senior Fellow at George Mason University and Former Head

> of the European Space Agency's Washington Office, speaks in similar terms about the word. "A little bit of constructive ambiguity never hurts." [19].
>
> Yet this ambiguity comes with a price. If it makes it easier to craft policy and pass space budgets, it makes later decisions, such as policy implementation and mission metrics, more difficult. Five years after the announcement of VSE and four years after the Exploration Systems Architecture Study (ESAS), broad disagreement remains about core concepts in US space exploration. While VSE and the reports detailing and extending it deserve praise for being visionary and ambitious, they have also "kicked the can down the road," delaying, rather than resolving, debates about the ultimate goals of space exploration.

As an example of how it can confound policy, in mid-December of 2015, Pew Research released an opinion poll, in which they asked "what role the US government should play in advancing space exploration," in the context of a broader poll asking what the government role should be in a wide range of activities. For "space exploration," the public was basically split according to Pew, with almost half favoring a government role, and almost half favoring little or none. But there was a crucial assumption in the question: That everyone agreed on what "space exploration" meant.

I think polls like this are meaningless, because the public is so ill informed, and the notion of "space exploration" so (no pun intended) nebulous: Planetary probes? Space mining? Space settlement? Astronomy? ISS? The answer to the question of the degree of government involvement is going to depend very much on what the individual thinks that space exploration is.

It is probably not a coincidence that, in addition to reducing mission costs, JPL's plan of establishing a base in orbit first is also consonant with the Planetary Society's primary goal of space science, rather than settlement, by minimizing the risk of human contamination to the planet itself, at least initially. For example, when NASA announced that liquid water had been discovered on Mars in late September of 2015, Emily Lakdawalla, space-science blogger for the organization, posted her concern.

> ...all bets are off once you send humans to Mars. There is absolutely no way to make a human clean of microbes. We are filthy with microbes, thousands and thousands of different species. We continuously shed them through every pore, every orifice, with every exhalation, and from every surface. True, almost all of our microscopic friends would fail to thrive in the radiation-baked, intensely cold and arid Martian environment. But life is incredibly tenacious. Sooner or later, humans will get to Mars; even if they die in the attempt, some of their microbial passengers will survive even the worst crash. Once we've put humans on the surface, alive or dead, it becomes much, much harder to identify native Martian life.
>
> This is one of many reasons I'm glad that The Planetary Society is advocating an orbit-first approach to human exploration. If we keep our filthy meatbag bodies in space and tele-

> operate sterile robots on the surface, we'll avoid irreversible contamination of Mars -- and obfuscation of the answer to the question of whether we're alone in the solar system -- for a little while longer. Maybe just long enough for robots to taste Martian water or discover Martian life.

She clearly wants to do as much science (particularly science relating to the discovery of extraterrestrial life) as possible prior to a human landing, and the JPL plan helps with that goal. But a national goal and purpose for spaceflight of development and settlement, rather than science, would properly subordinate the science to *that* goal (just as Jefferson's primary purpose in sending Lewis and Clark into the American west was to survey the territory, newly acquired from France, for settlement).

I believe that in ignoring the Augustine committee's 2009 consensus that the only national purpose that justified government human spaceflight was ultimate settlement, the NRC got it wrong, and it led the JPL study similarly astray. Because if that is the purpose, Apollo to Mars will fail just as surely as the original Apollo failed to establish settlements on the moon. To do so requires a fundamentally different approach.

This is why we have to end not space exploration *per se*, but the phrase “space exploration,” at least as the reason we send humans into space. We must accept that exploration is merely a means to a broader end — space development and settlement — and that once we do so, it changes the fundamental nature of how we do it, as this monograph will describe.

The Need For New Approaches And Technology

The authors of the JPL report also state that their goal is to minimize costs by avoiding new developments. This is the general philosophy of SLS/Orion, which NASA simultaneously claims is a huge step on the road back to beyond earth orbit and that it is low risk because it uses sixties/seventies technology. In so doing, they provide very little value for the money, because if we are going to open up space, we need to *dramatically reduce the cost of orbital access and space operations*, and that is of necessity going to require new technological developments (such as the successful recovery and ultimately reflight of rocket stages, as SpaceX has been starting to demonstrate over the past few months).

The JPL team laid out a set of axioms on page 8. Let's take them one by one:

1. A “Kennedy Moment” (i.e., an enduring political commitment reflected in a high budget priority for NASA) will not come again.

I agree. Or at least, if it does, it won't be “enduring,” any more than it was in Apollo, and can't be counted on for planning purposes.

2. Any proposed program architecture must fit within projected NASA human spaceflight budgets (allowing only for inflation) before there can be a discussion of increases.

I agree with this as well.

3. We cannot afford to hit "reset" again. We should expect to use the Space Launch System heavy-lift rocket and Orion crew capsule capabilities currently being developed.

Here I profoundly disagree. I assume that by "hit 'reset'," they mean cancel those two systems and start different ones for the same functionality (as happened when Constellation with Ares was canceled and replaced with SLS/Orion). But the way that I'd "hit 'reset'" would be to cancel them completely as unneeded NASA functionality, as it is now, or will shortly become, available from the commercial sector. The only way to free up funds necessary to develop critical hardware and technologies under the constraints of (2) is to stop wasting them on things we don't need.

4. Past cost estimates of Mars missions developed from 1989 – 1998 (e.g., the $500 billion number from the Space Exploration Initiative's "90-day Study") have been demonstrated to be either incorrect or no longer relevant.

Yes, they have. I'd say the same is true of NASA's (recently deprecated) 2009 Design Reference Architecture 5.

5. Ongoing independent cost estimates are required in order to establish credibility and drive realistic budgeting.

Yes, they are.

6. A well-articulated strategy and baseline architecture (beyond the next five years) is needed to engage stakeholders. The interest horizon of stakeholders is the decade of the 2030s.

I think that interest horizon is much sooner than they think. I think those stakeholders would like to see serious things happening in the next decade. 2030s (let alone 2040s) are too far out to generate any enthusiasm. And 2020s can be achieved, if we stop wasting money on things we don't need and refocus on things we do.

7. Establishing a U.S.-led humans-to-Mars architecture will allow international and commercial partners to identify clear areas for contribution.

OK, maybe, but no single entity should be put on the critical path as (for instance) the Russians have been in many ways for the International Space Station (ISS). We need redundancy and multiple providers for every needed function (another reason that SLS/Orion are in themselves absurd on their face).

8. In order to fund any executable human exploration program, NASA must end its large financial commitment to operating the International Space Station by the late 2020s.

Probably, yes. This should be no problem. It will either be decommissioned or taken over by commercial interests by then, and there will likely be other commercial facilities to take up the slack.

On page 11, we find an interesting sidebar question related to Point 6 above: Are multi-decade space projects viable?

> The Space Launch System (SLS) and Orion crew capsule, while controversial in their conception and development, are programs whose success depends on their regular use. Cancelling either program at this point would have far-ranging negative consequences, not only forcing NASA to significantly restructure its workforce and redefine its goals at a number of major centers but also disrupting the existing political support system for the nation's space program. Alternatively, utilizing SLS and Orion in a way that maximizes stability could provide the deep political support and programmatic capability needed to pursue a program of human Mars exploration over multiple decades. This, of course, assumes that both SLS and Orion are affordable at a use rate adequate for programmatic safety and public engagement.

It is interesting that they recognize the need for regular use of the systems, something their proposal doesn't really provide, at least for some values of "regular." But the key sentence is the last one. The assumption is invalid. As will be discussed in the body of this monograph, SLS and Orion are in fact not affordable (or reliable, which is related to affordability) at that use rate (or any, really). It's worth noting also that in their Mars-mission scenarios, the JPL team take Orion all the way to Mars, even though it's not really designed for that, and NASA's own current (as of fall 2015) Evolvable Mars Architecture assumes the capsule will never leave cislunar space.

As for the concern about NASA having to significantly restructure its workforce, well, yes. That comes down to whether or not we think that it is more important for NASA to advance the nation into space, or for it to continue to build big rockets and preserve workforce. So far, Congress has insisted on the latter, to the detriment of the former.

As I write these words in the fall of 2015, it is the hundredth anniversary of the creation of NASA's predecessor, the National Advisory Committee on Aeronautics, in 1915. It had been created in recognition of the fact that due to ongoing patent battles between the Wrights and Glenn Curtiss, and others, the Europeans and particularly the French had taken the lead in aviation over America, where it had been invented. On October 1st of 1958 (literally the date I am writing these words fifty-seven years later), in recognition of the coming space age in the wake of Sputnik, that organization was transformed into NASA, by absorbing the Jet Propulsion Laboratory and parts of the Naval Research Laboratory and the Army's Redstone

Arsenal in Huntsville, Alabama that had been involved in spaceflight at that time. It was an organization similar in attitude and outlook to its predecessor, with the addition of space technology to its aviation portfolio. A little less than three years later (as discussed in the Appendix), Kennedy's decision to go to the moon fundamentally transformed it into the operational (and now bureaucratic) NASA we recognize today.

That was then, this is now. As we (sort of) did then, we have to have that national discussion of what we are trying to accomplish in space. If we can reach a consensus on that, then it would be appropriate to discuss how best to accomplish it, and it may mean another fundamental transformation of not just NASA, but of the entire federal space establishment (including the military). But with all respect to the people who performed the JPL analysis, it is futile to attempt to take the 1960s NASA beat-the-Soviets paradigm and expect it to continue into the 21^{st} century going forward.

On page 26 of their report, note these two long-term goals, in the 2040s, after the first landing on Mars. The first is that: "The Mars program would evolve to put in place a reusable transportation architecture between Earth and Mars with an increased flight rate."

I will argue that the first goal should not be done *after* the first Mars landing, decades from now, but that it should begin *today*. The commercial launch providers, with SpaceX (which has now successfully landed several Falcon first stages and plans to refly one in the fall of 2016) leading the way, now almost all recognize the need for at least some degree of reusability. So should NASA (another strike against SLS, which at least initially plans to throw away expensive Space Shuttle engines originally designed to be reused). Our Mars transportation architecture should not "evolve" to do so. If it's feasible, it should be *the baseline*, to make all space activities more affordable, and scalable. If it is not feasible, then we should *stop wasting government money on human spaceflight*, because if we continue to insist on throwing hardware away, it will never be affordable to achieve the purpose of human settlement and large-scale human activity in space in general.

But NASA gave up on reusability a decade ago, when Mike Griffin selected Constellation, with its expendable launch systems, capsule, insertion stages and landers. It could in fact be argued that Marshall Space Flight Center (MSFC) gave up on it after it was given responsibility for it in the 1990s, which it turned into the failed X-33 program, which failure the center then used as an excuse to illogically claim that reusability didn't work.

Here is the second long-term goal: "With the eventual acquisition of a water source on Mars, NASA could achieve a permanent presence with *an Antarctica-type population*." [Emphasis added]

It implies that the nation will remain stuck in the "science" model for space activities (as discussed in the previous section) *ad infinitum*. It's worth noting (as I have in the past) that the Outer Space Treaty of 1967 was modeled on the Antarctic Treaty of the late 1950s, on the assumption that there were no resources there, and it would never be "settled" on any basis other than scientific research stations, perhaps with an occasional tourist visit. If we are to open the solar system (and not just Mars) to development and humanity, the Antarctic model would be a disastrous one.

In the cases of both the aforementioned NRC report and the Planetary-Society/JPL one, those doing the studies were burdened by an almost-insurmountable constraint: A seeming implicit ground rule that the plans must include SLS/Orion. Given the high cost of operations of these systems, and their intrinsically low flight rate (once or twice a year at best, and likely much less), this is a millstone around the neck of any ambitious plans to even explore, let alone develop and settle space. The NRC report actually described very well the problem, on page 115:

> The business model and schedule for the SLS are almost totally driven by the projected costs and the flat budget profile established for the SLS program. A system that, like the SLS, is derived from mature systems could reach full operational capability in less time and at less total cost than currently planned if the funding profile resembled that for a normal development (that is, if funding ramped up as the program progressed from program initiation into advanced development and production). Much of the necessary design work was done under the Constellation program. Before that, vehicles derived from the space shuttle had been proposed several times, and considerable preliminary design work had been done. Nonetheless, the designs for the SLS were announced in September 2011 with a projected development cost (including ground-based infrastructure) of $12 billion through first flight in late 2017 and an additional $6 billion for development of the Orion Multi-Purpose Crew Vehicle. Orion is the crew capsule being developed in concert with the SLS to support human space exploration beyond LEO. Since then, NASA's budget uncertainty has increased, and this has put both the launch date and the cost at high risk.

What they don't say is that the reason the budget is flat is because it's not about developing hardware, or executing a typical aerospace program, but rather keeping a steady number of people employed in the correct zip codes. But they continue to assume that the NASA budget will be expended on a program to ultimately send a few civil servants to a planet, many years in the future, using a giant unaffordable rocket, and that political support will somehow be sustained for such a thing over that time (aka Apollo to Mars). This completely ignores the potential for improvements in technology that we know will be coming along (absent a collapse of the nation and western civilization itself). For example, at the time, in a piece titled "*Space Policy Through The Rear-View Mirror*," the National Space Society's Dale Skran characterized the NRC report this way at *The Space Review*:

> There is no discussion at all that the prospect for increased traffic to LEO for all purposes, including tourism, might lead to significantly lower costs; or that it may lead to reusable spacecraft with superior operational characteristics relative to existing vehicles or the SLS. This glaring absence seems remarkable given the stated goal of SpaceX to develop just such lower-cost, reusable craft, as well as their considerable progress in this direction [this was prior to the 2015 first-stage landing attempts of the Falcon 9 and successful landing in December of that year]. Of course, the efforts of SpaceX, Virgin Galactic, Blue Origin, XCOR Aerospace, and others to greatly reduce launch costs may all fail. However, the NRC report is based on the unstated assumption that over the entire period considered, all the way out to 2054, there will be essentially no progress in rocketry other than that funded by NASA exploration programs, and that for the entire period the SLS as currently envisioned will remain the preferred method for Americans to reach space. *It is difficult to imagine a more unlikely foundation for the planning of future space efforts than this*. [Emphasis added]

Indeed. I recommend reading the whole thing.

A Break From Apollo To Mars

In the summer of 2015, a NASA-funded study was released by NextGen Space LLC showing how the cost of getting humans to Mars could be dramatically reduced by utilizing lunar ice, beneficiated on the moon and delivered to cislunar space as rocket propellant. In what it called an “Evolvable Lunar Architecture” (ELA, not to be confused with NASA's current Evolvable Mars Architecture that has replaced DRA-5), it replaces earth-sourced propellants with lunar-derived ones, eliminating much of the potential planned payload for SLS.

It also promotes a continuation of the public/private partnership approach for this plan that has shown considerable success in the Commercial Orbital Transportation Services and Commercial Crew programs, in terms of dramatic reductions of cost compared to traditional NASA cost-plus contracting approaches. It was refreshing in that while it paid lip service to the existence of SLS, it made no explicit use of it in the stated plans. In fact, one of the remarkable things about the report is how punishing it is of that program by faint mention, without explicitly saying so. The section on mission risk, as I'll discuss in the body of this monograph, makes a damning technical case against it.

It is also worth reading for the much more extensive history of plans for beyond-LEO exploration over the decades than I am providing here. This point, from page 28, I think is key from a policy perspective:

> The most significant system-level technical risk of the entire ELA is the possibility we will not find abundant enough levels of accessible hydrogen, which is critical to enabling economical production of lunar propellant. While we have proven that there is hydrogen trapped in lunar polar craters, we do not know how deep the water/hydrogen is buried, or if it is locked up in some form that is uneconomical to release. To mitigate this risk, rovers and prospecting systems need to be developed, tested, demonstrated, and validated. The availability of readily and economically available water, or hydrogen, at the lunar poles

> needs to be proven before significant investments can be made in all the other ISRU systems and the reusable lunar module that depends on lunar propellant. To the extent national decision-makers value the economical production of propellant at the lunar poles, this objective *needs to be a top priority*. [Emphasis added]

It's one of many things that would be a “top,” or at least very high priority if we were serious about opening the solar system to humanity. In this monograph, I'll describe some of the others.

2.0 Study Assumptions

This monograph is not about “exploration” per se. The goal is not flags and footprints, or even science for science's sake. There is a planetary science program at NASA that is doing that (though if these recommendations are implemented, it will be able to do so much more effectively, at lower cost). To the degree we have “missions,” they must be focused upon, and lay the groundwork for development and settlement.

The 2010 NASA authorization says that “it is in the United States [sic] national interest to maintain a government operated space transportation system for crew and cargo delivery to space.” This language is the only real justification for the development of SLS and Orion. But it provides no reason or rationale for this. This monograph will assume extensive use of commercial suppliers. In fact, *all* transportation from earth to orbit and return, of both crew and cargo, would be done commercially.

NASA's plans, and the 2010 NASA authorization implicitly assume that resiliency of the architecture is unnecessary. It absurdly argues that a vehicle with the capability of SLS is absolutely required for expeditions beyond earth orbit (BEO), but apparently the ability to do so isn't very important, since it provides no redundancy. When in discussions with SLS proponents, I always make the following argument:

“You say that it is important that the nation have the capability to send humans BEO, right?”

“Right.”

“And you say that we cannot do so without a vehicle of the SLS class, right?”

“Right.”

“Well, Shuttle went down twice for almost three years each, and during that time period the nation had no capability to get astronauts into space at all. If it is so important to have the capability to get BEO, then why don't we need two of them?

The response is always an awkward silence, because they have no answer.

This is a lesson that the USAF learned in 1986 when, in addition to the failure of the Shuttle in January with the Challenger loss, a Titan 34D-9 and a Delta 3914 failed as well within months. From that point on, resiliency, or the ability to quickly recover from a failure, became a program requirement for military space launch. It is what drove the need for two EELV rockets in the 1990s (Atlas V and Delta IV), and what drives the current angst about the inability of the Atlas to fly Air Force payloads due to Congressional restrictions on the use of its

Russian RD-180 engines, making SpaceX the sole launch provider for some payloads. But obviously, NASA and (more importantly) Congress don't see this as important.

Unlike them, I really do think that it's important that we have a resilient transportation architecture, which means that we have to have at least two independent means of any critical function on any leg of a journey. And this is an achievable goal as long as we don't insist on dependence upon a giant NASA-owned rocket that rarely flies.

There is a general assumption (as with the JPL report) that going to Mars will be an international venture. While I don't intrinsically oppose international cooperation, I would say that the only desirable form of that is (potentially) purchase of redundant services from other countries (e.g., propellant delivery). I would put no other nation on the critical path (as Russia currently is with the ISS). As the NRC report itself said, "senior NASA officials reported to the present committee that international collaboration does not reduce costs." The goal of this project is in fact to show how to reduce costs while increasing activity levels, not to promote international cooperation.

Another key difference between my philosophy and that of those advocating Apollo to Mars is that I believe the architecture must be scalable – that is, it must be capable of dramatically increasing activity levels at low marginal cost. As I wrote at *The New Atlantis* in 2009:

> Low marginal costs mean that as demand for a service grows, the price can drop rapidly. For example, a large restaurant with a full staff (a high fixed cost) but only a couple of diners would have to charge thousands of dollars each for a meal. But the marginal cost of feeding the next diner is only the cost of the food, and as the restaurant fills, the average cost can drop to where the price of a meal becomes affordable. (In this analogy, our current spaceflight practices are akin to burning down all the restaurant's furniture after every meal and buying it all anew before the next one; marginal costs are quite high in that scenario.)
>
> High marginal costs will forever constrain the level of activity that's possible. That was true of Apollo, it is true of what NASA currently plans with Constellation, and it is true of any Constellation-like architecture (such as DIRECT [or SLS]): every flight will require throwing away tens if not hundreds of millions of dollars worth of hardware. If we were, say, to discover something on the Moon [or Mars] really worth going after, our ability to ramp up activity with Constellation [or SLS] would be severely limited by our budget. Low marginal costs provide scalability, which is essential for any technology that is going to open up large new markets. NASA's plans completely lack any understanding of this crucial principle.
>
> The principle of low marginal (and average) costs was why the [S]huttle was created, except that it ended up combining the worst of all cost worlds: the [S]huttle has high fixed costs (for the standing army needed to service it), high average costs (resulting from the low flight rates), and high marginal costs (due to the hardware thrown away with each flight). When you hear that a [S]pace [S]huttle flight cost hundreds of millions of dollars, that figure is an average cost — the annual cost of the overall shuttle program divided by

> the number of flights that year (dividing the total cost of the shuttle program since its inception by the total number of flights would result in a yet higher number). The actual marginal cost (the cost of flying one more mission, given that you are already flying) is much lower, at most $150 million — still ridiculously high, but comparable to other launch vehicles with much less capability.

Reusability, however, implies refuelability. I used an amusing but I think valid analogy in that same piece in *The New Atlantis*:

> Consider a thought experiment from an earlier frontier. Imagine that, on the settlers' hard trek to the western United States, there had been no vegetation along the way for the wagon-pulling horses or oxen to eat. To get across the country, each Conestoga would have to carry enough hay to feed the animals (not to mention supplies for the pioneers for months). The wagon would have been so large that the animals wouldn't have been able to pull it. The longest distance that could be traveled would be dictated by the largest size of wagon that they could pull when it was full, and the initial speed would be very slow, picking up as the wagon grew lighter. [One could consider the animals like rocket engines, that were slaughtered as they were no longer needed, like expending the stages of a rocket.] Once the final destination was attained, the [SSTO, or Single Stage to Oregon] wagon and the animals would be useless without more fuel, so presumably the wagon parts would be used to build a cabin or saloon. In reality, of course, such a system would never have been affordable; had the settlers not been able to avail themselves of food and water along the way, the West would never have been settled.
>
> Now apply that logic to space. The vast majority of the payload for heavy-lift launch vehicles is the propellant needed to send a relatively miniscule [sic] spacecraft to the Moon (or Mars or whatever destination) and back. Recall the Apollo missions' gargantuan Saturn V rocket; the tiny capsule atop it was all that came back. And much of the propellant used by Saturn V was needed just to deliver into space the propellant that will be used for the trip back, since there were no gas stations on the Moon. The Apollo missions' marginal costs were astonishingly high — but acceptable in the context of a race, since we did not have the time to set up the infrastructure, the needed service stations for fuel and food, along the way.

SLS is viewed by its proponents as a modern-day Saturn V, and it is exactly as absurd as having a Saturn today would be. Today we must eliminate the need to launch all needed propellant for a flight in a single launch from earth. Preferably, we'd get the propellant from sources already off planet, but even if we must initially launch it all from earth, there is no reason to put it up on a single launch of a hyperexpensive launcher.

Beyond that, refuelability implies ubiquitous fueling facilities. For example, it is possible to drive all the way across the country and back without stopping at a gas station (as Apollo did to the moon and back), but only with a diesel tanker truck, and the amount of fuel used would be huge, because it has to carry it all along with it, along with the much heavier hardware of the truck itself, dramatically reducing the per-mile fuel economy. Driving a small car, and periodically stopping for gas, is much more efficient and cheaper, which is why we have an infrastructure of fuel and service stations to allow this. The exponential nature of the rocket equation, in which doubling the velocity needed to get to a destination increases the propellant required by a factor of almost three, and tripling it by a factor of seven, makes this even more important in spaceflight. In order to make our trips affordable, we have to put in place the same kinds of facilities in space—in LEO, in cislunar space, on planetary surfaces and in planetary orbits, perhaps even in between planets, with affordable sources of propellant.

As the NextGen Space LLC study noted, it is critical technology to be able to fuel deep-space ships in cislunar space, from lunar resources if this can be done. However, it's not the only one.

The purpose of this monograph is to describe how we could in fact have many people venturing out into the solar system within two decades or less, utilizing soon-to-be existing commercial transportation and habitation systems, and new developments, in technology and hardware, that could and would occur if the money currently being wasted on SLS/Orion (~$3B per year) could be redirected to them. For example, they would include the required propellant storage facilities, and the beginning of the utilization of off-planet resources for both life support and propellant, technologies that have been starved for funding, but would be game changers in reducing cost and dramatically increasing activity levels. The "bang for the buck" that NASA is currently planning could easily be increased by a couple orders of magnitude. It would include techniques and facilities for in-space assembly, to allow large structures without a large launcher, and other enabling technologies that will be discussed.

As my generation was in the sixties, the American people, and particularly American's enthusiastic young people, are currently being fed a load of malarkey by the nation's space agency about how *they* will be going on a #JourneyToMars. They deserve to know the degree to which Congress is forcing NASA to waste money on these boondoggles, and the exciting things that could be happening if that money were actually being spent on the things needed to actually open up space. The purpose of this analysis is to provide an alternate vision as the basis for the needed and inevitable policy debate that will occur with the new administration in 2017 (as it did in 2009), as it once again becomes clear that the current path is unsustainable, and that, more than ever, commercial alternatives are increasingly viable.

3.0 The Case Against SLS

First, what is SLS?

Per the 2010 NASA Authorization, it is a vehicle developed from previous technology, mostly Shuttle, though at various points Apollo hardware, such as the F-1 or J-2 engines from the Saturn have been considered.

The initial version, called Block 1, has a stated performance of 70 tonnes to low earth orbit. This is the one planned for the first flight of Orion to go around the moon without crew, officially scheduled for late 2018, but likely to slip. It will use two five-segment Solid Rocket Boosters (a stretched version of those used on the Shuttle, which had four segments). They will be mounted to a fuel tank similar to the Shuttle External Tank, except with four "RS-25" engines below it (this is a new designation for the Space Shuttle Main Engines, of which they have a few left from the Shuttle program). Note that one of the craziest things about the SLS program is that they are taking engines originally designed to be reusable and throwing them away. Furthermore, if they plan to use them into the future, they will have to restart the production line for this expensive high-performance engine, because they only have enough inventory for the first two or three flights. The vehicle will initially use a modified Delta IV upper stage, and all liquid propulsion, in both the first and second stage, will use cryogenic liquid hydrogen fuel (LH2) and liquid oxygen (LOX) oxidizer.

The next version, Block 1B, will use the same boosters and first stage, but will have a new upper stage, called the Exploration Upper Stage (EUS). Expected to be available in the early 2020s (officially, as early as 2021, though this seems unlikely), with a payload capability of 97.5 tonnes (according the latest paper from Boeing in the spring of 2016), it is the version currently planned to be used to deliver a mission to the Jovian moon Europa (more on that in the next section).

The ultimate version, designated Block 2, will supposedly have a capability of 130 tonnes (as specified by the legislation). It will be available at some unknown date, and no actual design currently exists, other than that it will replace the five-segment SRBs with liquid boosters (probably hydrocarbon fuel and LOX). It is a notional rocket at this point, largely to simply satisfy the law. The figure is probably aspirational, as was the 65,000 lbm to orbit for the Space Shuttle, which it never achieved.

The Case For, And Against SLS

In order to make the case against the SLS, it is necessary to understand the case *for* it (to the limited degree that it exists). So I will start by laying it out, as best I can, based on what proponents say about it; I don't want to be accused of attacking a straw man.

Of course, the first argument for it is that (to paraphrase the billboards for the old double nickel speed limit), it's not only a bad idea, but it's the law, per the 2010 NASA authorization. But that doesn't address the technical merits.

I haven't done an exhaustive search, but I'd think that this softball interview from spring of 2013 by Jason Rhian of *America Space* with Dan Dumbacher of NASA (now retired and teaching at Purdue) would be fairly definitive and representative. This isn't the whole thing, but I've only deleted questions and responses that aren't relevant to SLS. I have the complete relevant responses here so as not to be accused of removing context.

> **Dumbacher:** "NASA needs Orion and the Space Launch System to conduct exploration beyond low-Earth orbit. All of our studies over the years have demonstrated the need for a launch vehicle that can get significant mass to orbit and can help us cut down on trip times, and we need that launch vehicle's capabilities to get us beyond Earth orbit, which we have been operating in for a little over 30 years. It has been over 40 years since we have been outside of Earth's orbit. If we are going to go beyond Earth orbit, then we need Orion and we need the Space Launch System, and that is why you heard NASA Administrator Bolden list Orion and SLS as some of his top priorities."

Note that this initial response is all non-quantitative motherhood. What is "significant," in terms of lift capability? Yes, we haven't been beyond LEO in over forty years, but that in itself does not demand a (in Senator Nelson's words) "big monster rocket." I would in fact argue that what has kept us trapped in LEO is not the lack of such a thing, but a false perception that it is needed. Next, the discussion turns to quantities.

> **...AmericaSpace:** *There have been several metric-ton [tonne] amounts that SLS is required to deliver to orbit. What caused those amounts to be selected? Why 70 and 110? Why does SLS have to have that capability to accomplish its objectives?*
>
> **Dumbacher:** "Seventy metric tons is the version of the launch vehicle that we are currently working on to send Orion to orbit for the 2017 mission. Ultimately, however, we are working toward the 130-metric-ton version that is planned to be used for the Mars missions. We need the 130-metric-ton version for the Mars missions. The 70-metric-ton variant is the vehicle that we could develop and have useful payload abilities within a reasonable timeframe and within the budget constraints. So, the 70-metric-ton version will provide us with the capability of sending Orion with crew to the area around the Moon and allow us to be able to work within that vicinity. We are also working on a plan to upgrade SLS after the first few missions to about 105-metric-ton capability on our way to 130. So, from an SLS perspective you should be hearing numbers of 70, 105, and 130." [Note: As of

2016, the current plan for the 105 MT version, or "Block 1B," has since been downgraded from that performance to 97.5 MT]

AmericaSpace: *The one that I think folks are most familiar with is 70.*

Dumbacher: "The reason that they have heard that one the most is because that will be our flight-capable version and the one used for our first crewed mission. It's the vehicle that we are designing now. We are designing it in such a way so that we don't have to redesign anything to go to the 105-metric-ton [now 97.5 metric-ton] capability, because everything is designed to build toward the 130-metric-ton class. We in the rocket business like to talk about things in terms of mass and volume and those types of considerations—one of the things that we are trying to figure out how to communicate better. When you think about it, a Curiosity lander was about 900 or 1,000 kilograms. So, with all her components, 70 metric tons would deliver to low-Earth orbit about 70 Curiosity landers."

AmericaSpace: *That's a lot of rovers.*

Dumbacher: (Laughs) "That's the message. A launch vehicle at 70 metric tons provides a lot of lift capability to get hardware to the orbits that we need to get to."

Had I been doing the interview, there are questions I would have asked Dumbacher that Mr. Rhian did not. For example, with regard to the discussion of payload tonnage requirements, I would have asked: "Can you provide us with the Design Reference Missions that drive those numbers?"

A design reference mission (DRM) is a description of how the mission will be accomplished, and what hardware functionality will be required to carry it out. The Apollo DRM was (very basically): deliver the capsule, the service module, the lander and the lunar injection stage to low earth orbit; reconfigure to connect lander and capsule/service-module to make into a single vehicle; inject into a new orbit to the moon; circularize in lunar orbit; separate lander, perform surface mission; return ascent stage to lunar orbit and reconnect to command/service-module; inject to return orbit; separate service module; enter and recover capsule. With this concept, they could calculate the individual element requirements, working backwards from the final piece that came home. Adding up all the weights of the components gave them payload tonnage requirement for the Saturn V (von Braun actually oversized the vehicle, knowing from experience that the payloads would grow in mass from their initial estimates).

It's also worth noting that, as I write this, it's almost exactly half a century since the first American orbital rendezvous and docking, in December 1965, between a Gemini capsule and Agena upper stage. Had NASA had more experience with this sort of thing and orbital assembly at the time, it's possible that they would have chosen to use smaller vehicles for Apollo (as they considered for lunar Gemini). In light of our experience in assembling the International Space Station, we have no such excuse today.

At the Global Exploration conference in DC a few years ago, former NASA administrator Mike Griffin (and father of Constellation, part of which was the Ares V, SLS's predecessor) was chairing a panel on exploration architectures. I asked from the floor the panel that he was on (it also included Ian Pryke of ESA): "What is the driving payload that requires a 130-tonne launcher?" He exploded at me, saying something like "Rand, we've been over this, and now is not the time to debate that," and came up with a straw man argument about how we can't build things by taking up every fastener individually, which neither I or (as far as I know) anyone else has ever proposed.

The honest answer to my question from Dumbacher would be "No. There are no DRMs." NASA is still tinkering with architectures. I have no way of knowing what he would have actually said. But the requirement is simply whatever NASA arbitrarily says it is, based on what Congress wrote into law in 2010. I'm quite confident that no one in the Senate was working to a DRM when they came up with the 130-tonne requirement.

> **AmericaSpace:** *I'm not sure if you'll recall, but during your presentation at the Cape regarding the future of Human Space Flight, we asked about what type of spacecraft would be required to go to Mars—that it'd probably need to be about twice the size of the ISS. The ISS is about the size of a football field, so if you think about it, you need to have large up-mass capabilities to send such a spacecraft into orbit. Is that what we are hearing?*
>
> **Dumbacher:** "That's exactly what you are hearing. All of our architecture mission analysis that we've done over the years always has shown us that we need lots of hardware to get to Mars, to get to the surface of Mars, and then back home safely. Depending on the hardware used and how you configure the mission, it takes multiple launches. Even using a 130-metric-ton class SLS, it still requires five or six SLS launches to do a Mars mission. In terms of Mars? Bigger launch vehicles are better."

With regard to payload size, saying that something is "twice the size of ISS" is meaningless. Does he mean by mass? He talks about football fields, but that's an area. A Mars-departure vehicle is not going to look anything like ISS, which is a space research station, with high power requirements and corresponding solar panels. I think that comparison obfuscates and confuses more than it illuminates.

Note again the lack of quantitative discussion: "...lots of hardware to get to Mars." Is that number in metric buttloads? Dumbacher simply says that "bigger launch vehicles are better." Well, yes, all else being equal. But all else is almost never equal, and it certainly isn't in this case. Cost has to be considered. So does flight rate, which can affect reliability if it is either too high, or too low (more on that to come).

So let's start by considering cost.

All of the recent studies discussed in the background section have assumed that SLS/Orion will consume about $3B per year indefinitely, with some growth for inflation (this would be in accordance with the Congressional requirement that it maintain the workforce in the right zip codes *ad infinitum*). It's unclear how that is allocated between the programs, but I would assume that once Orion is through development, it shouldn't require that much. If we allocate $2.5B annually to SLS, and take NASA at its word that it will only fly once every couple years, at least initially, that means that each flight will cost about five billion dollars. If we're generous, and have them fly it annually, then it's still $2.5B per flight. Even if they can somehow ramp up production to semi-annual flights, it is still *over a billion dollars per flight*. For 130 tonnes (if they ever get there), that would be about ten million dollars a tonne, or ten thousand dollars a kilogram, or about five thousand dollars a pound (there is no need for more precision than that in this analysis). And for 97.5 tonnes for the Block 1B, it's even more.

In contrast, SpaceX's Falcon 9 (current version as of this writing) is already delivering 13 tonnes for a *price* (not a cost) of ~$60M, or about $4M/tonne, less than half that (conservative – it's likely to be much higher) cost. The company's Falcon Heavy, currently scheduled for its first flight this coming fall of 2016, will purportedly deliver about fifty-five tonnes for ~$160M, or a little over *one quarter* of the cost per tonne of SLS. The United Launch Alliance's planned new Vulcan vehicle will presumably have to be competitive with SpaceX in price (and will get there with partial reusability, initially recovering the expensive engines and avionics from the first stage, with perhaps expanded reusability later).

Most of the payload delivered by the Saturn V to get the Apollo capsule to the moon and back was propellant. To an even greater extent, since it's farther away in terms of velocity, most of the mass initially in low earth orbit (or even cislunar space) for a Mars mission will be propellant. Since NASA has no stated plans to purchase or store propellants on orbit, presumably, they expect most of SLS's payload mass to be propellant. Unless it's something exotic, propellant costs about as much per pound as milk. So in declaring the need for SLS to do Apollo to Mars, they are proposing that we spend at least five thousand dollars to deliver to orbit something that costs on the order of one dollar on earth.

Let's go back to the schedule issue. If it takes six SLS flights to do a Mars mission, and it's only flying every couple years, that's *a dozen years* per Mars mission. Annual flights would still mean *over half a decade* per mission. If, somehow, they could ramp up to three times per year (in the 2030s), that still mean only one Mars mission per 26-month opportunity. With that kind of rate of a few NASA civil servants, there are going to be a lot of disappointed young people currently planning to go to Mars.

Next comes the standard “it's too complicated to do with smaller rockets.”

> **AmericaSpace:** *When this discussion broke out on AmericaSpace it became a very heated debate. Before we really got too involved we wanted to get our facts straight, which is why we*

contacted NASA Headquarters. One of the questions that was asked of us was, 'If NASA saw that they could conduct these missions less expensively using smaller commercial launch vehicles—perhaps with more launches—would NASA be willing to do this?' Would you say, 'Look, SLS is great, but we can do it less expensively using either the Delta IV Heavy or the Falcon Heavy'? If NASA crunched the numbers and discovered it could put the mass it needed up on say six Delta IV Heavy or Falcon Heavy launches instead of one SLS, would you do that?

Dumbacher: "If we could do it for less—that is the key. Our analysis using the best data that we can lay our hands on says that there is a trade off with the amount of payload delivered per launch, launch cost, and also the complexity of on-orbit operations, and this begins to impact crew safety as well. If I start to put it up in smaller pieces, then that means there has to be more on-orbit operations that are necessary to get everything attached. And, by the way, that means that the crew will have to contend with longer exposure time in the space environment, radiation exposure, micro-meteorites [sic], and so forth. All of that starts to play into the equation, so I think that gets lost sometimes in the debates that you've experienced. All of the considerations need to be factored into the analysis. It's not just a cost equation, and, in fact, it takes a dramatic reduction in launch costs for smaller launch vehicles to be competitive from a cost perspective. You have to recognize that it is not just a per-unit cost; you also have to include the infrastructure on the ground to manufacture and assemble all of those extra launch vehicles."

Ignoring the fact that three (not six) Falcon Heavy launches would deliver more than one Block 2 SLS (~160 tonnes versus 130) to LEO, note the implicit assumptions in the first half of his response. For instance, that it will require crew to do all these things, when we're getting better and better at automatic docking and mating, and orbital operations, and there is no reason to believe that this won't continue into the future. It also assumes that crew aren't already going to be up there for other reasons, in which case additional risk of exposure is a non-issue. Finally, he seems to assume that safety is the highest priority, and that we shouldn't consider increasing potential hazard to astronauts to reduce cost or increase activity levels (I wrote a book about that).

But I love the last half, in which he discusses cost. We've *already shown* here that the cost (that is, price) of the commercial vehicles will be dramatically lower. And that assumes no further price drops from future reusability, whereas SLS has zero chance of becoming cheaper in the future, given the choice of using seventies technology for it and remaining fully expendable. The last line is literally laughable. The launch prices of the commercial vehicle *already include the cost of all of that infrastructure*. The prices are the prices.

But what I find the most fascinating is what he didn't say. He talks about analyses, and implies that they were performed, and that they showed SLS is the way to go. But note he *doesn't actually say that*. He simply describes all the factors, and lets the reader assume that this is the result of the study(s).

Comparing SLS To Alternatives

In fact, there has only been one study (as far as I know) in which the two approaches were compared, considering all the factors that Dumbacher describes. It was done over five years ago at the Johnson Space Center, and the results were leaked by the NASA Watch web site in a briefing from the summer of 2011, and no doubt with great angst among SLS supporters. And what was the result?

It showed that the use of propellant storage on orbit with commercial launch systems *significantly reduced the cost of the missions*, compared to using SLS. That is, *exactly the opposite* of what Dumbacher implied (or at least hoped that we would infer). There is a chart in the briefing that explains why they considered their architecture.

- Large in-space mission elements (inert) can be lifted to LEO in increments on several medium-lift commercial launch vehicles (CLVs) rather than on one Heavy Lift Launch Vehicle (HLLV)
- Over 70 percent of the exploration mission mass is propellant that can be delivered in increments to a Propellant Depot and transferred to the in-space stages
- Saves DDT&E costs of HLLV
- Low-flight-rate HLLV dominated by high unique fixed costs. Use of CLVs eliminates these costs and spreads lower fixed costs over more flights and other customers.
- Use of large refueled cryo stages saves DDT&E/ops costs for advanced propulsion stages (e.g., SEP)
- Provides opportunity for more easily integrated commercial and international partner mission participation

I couldn't have put it better myself, at least on a chart (SEP is Solar Electric Propulsion, more on that in the next section, DDT&E is Design, Development, Test and Evaluation – all the things one needs to do prior to operations).

The assumptions the study team used were extremely conservative. For example, they assumed a loss of one in ten commercial launches (reliability is much higher than that). They used stated Falcon Heavy prices at the time, which will likely go down as the vehicle is improved, the stages are reused, and it faces competition from other players, such as the aforementioned new Vulcan rocket being developed by the United Space Alliance. They also looked at architectures using Delta IV Heavy, which is a very expensive rocket. They considered mixed architectures, and they traded hydrogen fuel versus kerosene.

Without getting into the details of a study that is probably already obsolete, whether for Near-Earth Asteroid missions, lunar missions, or Mars, the results always came out the same: As *reducing* the cost by *tens of billions* over a couple decades, compared to SLS, for the same mission. Nothing has occurred in the past half decade to increase the cost of their approaches, or to decrease the cost of an SLS-based approach. And for the latter (as previously noted), nothing is likely to, whereas the commercial approaches are going to continue to plummet in cost, due to competition in the industry, and improvements in the kinds of technologies that I'll describe in the next section. Of course, some of the savings from not spending money on DDT&E for the SLS are sunk, four years over the dam, but there is still plenty of savings to be had ahead. I would note that SEP would be a good idea, even with lower-cost cryogenic stages, but that is a trade for another day, that I'll discuss.

One argument that SLS proponents often make, but Dumbacher does not, at least in that interview, is that more launches translates to more mission risk, that is, an increased probability that a mission will be totally lost due to a launch failure. Prominent SLS proponents who have made this argument include current or former managers at the Marshall Space Flight Center (MSFC), where the vehicle is primarily developed. For example, in an editorial in the *Orlando Sentinel* in June of 2015 (later reprinted by *The Hill*), Doug Cooke, Steve Cook, and David King had an op-ed titled: "U.S. will keep lead in space with NASA's launch system." Cooke is a former head of exploration at NASA HQ, Cook is a former program manager on Constellation (part of which was SLS's predecessor), and King is a former MSFC center director.

They start off with a similar argument to Dumbacher's (not surprising, because editorials by such people use the same talking points, often almost to the word):

> There are significant reasons why heavy lift is crucial for deep-space human exploration. Future Mars landings, for instance, would require at least the equivalent mass of the International Space Station — which took 10 years and 30 missions to complete — to be launched from Earth. SLS, with its 130 metric-ton lift capability, could accomplish this in just six or seven flights, making the missions far less complex and more cost-effective.
>
> In contrast, it would take about 30 flights of our current Delta, Atlas or Falcon 9 heavy-launch vehicles to do the same job. More launches necessarily mean more cost and risk.

Note that they (as Dumbacher does) overstate the required number of non-SLS launches. For instance, six or seven 130-tonne SLS flights is 780 or 910 tonnes. That would be fewer than twenty Falcon Heavies, not thirty. They continue this disingenuousness in a discussion on volume:

> Only SLS has enough room to accommodate large, critical payloads like planetary landers and bulky in-space habitats and other structures. Packaging such systems into a space six times smaller would be extraordinarily challenging and would dramatically increase cost and risk while limiting overall mission capabilities.

First, they are again assuming a six-to-one ratio, when there is no reason to do so. If they need a wider fairing, I have little doubt that the Falcon Heavy could be “hammerheaded” (that is, put a payload fairing on top with a greater diameter than the stage), or they could come up with a way of repackaging to eliminate the need, for much less than SLS development costs.

Then they say “dramatically increase cost and risk,” without quantifying that, and no valid analysis to show how. Because they cannot. They haven't done the analysis. Those who have in fact done the analysis say (as I'll show shortly) that it *reduces* the risk.

They also don't quantify “extraordinarily challenging,” but $2.5B a year offers a lot of opportunities for creativity in packaging of landers, habitats and other structures. But they would seem to lack imagination (to be charitable). I'll discuss some of the concepts of which they are apparently unaware (or pretend to be) in the technology section.

In the next paragraph, they assume we are technical rubes:

> SLS's higher thrust also means faster transit times to deep-space locations, reducing the cost of mission operations, allowing simpler spacecraft design, and giving mission planners critical flexibility. For example, using the SLS reduces the transit time for the Europa mission by half compared to other launch vehicles. And ultimately, these benefits will accrue not just to space exploration and human spaceflight missions, but to all potential rocket users — including the Department of Defense, and civil and commercial operators.

It is not SLS's higher thrust that provides faster transit times; it is its greater throw weight, which in theory translates to larger planetary-insertion stages. This is the same technical fallacy that has the rocket's supporters mindlessly repeat “the world's most powerful rocket,” as though power was a figure of merit for launch systems (pro tip: it is not). I've noted often on Twitter that it's like NASA as Tim the Tool Man Taylor, from the popular 1990s television show *Tool Time*, with his patented “MORE POWER [grunt, grunt, grunt].”

In any event, two Falcon Heavies could easily deliver the insertion stage , and even more propellant than the SLS, allowing an *even larger* fast Europa mission (this will be discussed in more detail in the next section). If one insists on delivering a planetary mission (or any mission, for that matter) with a single launch, then the launch vehicle will always constrain the ultimate size of the mission. No matter how large a rocket you design, I can always come up with a mission that needs a larger one. With this kind of mentality, we'd design trucks to deliver a house, and a bigger house would need a bigger truck. We do this in the case of some mobile homes, but at some point we go to a “double wide,” making two deliveries, rather than building a bigger truck. Generally, houses are built from pieces delivered by standard trucks.

The obvious solution to this, with rockets as well as with trucks, is multiple launches, not to keep growing the rocket *ad infinitum*. But once one accepts that, then it's time to do a trade of what the right size for the launcher is. NASA has presented zero data, with any analytical basis, to tell us why 130 tonnes is that size. Because, as with the DRMs, it does not exist. As previously noted, 130 tonnes came from legislation in 2010, not analysis. And NASA doesn't even know how it's going to get to that capability; the new boosters to replace the SRBs, and the so-called Exploration Upper Stage (EUS) are still on the drawing board.

The next two grafs are laughable. I won't call them lies, but I'll let others draw their own conclusions, based on the previous discussion and analysis.

> The SLS vehicle design materialized from an extensive, unbiased set of NASA technical studies, which compared all possible scenarios, with a focus on efficiency and budget constraints. Experts inside and outside of NASA were fully integrated into the decision-making process. Among the factors driving the selection of the 130 metric-ton SLS design were human exploration requirements, the state of propulsion technology, the *health and capability of the industrial base*, and the overall budget outlook.
>
> The resulting choice built on propulsion technologies developed and "battle tested" in the Space Shuttle program, which has an unparalleled flight heritage and demonstrated record of reliability. That will drive down design and development risk and keep long-term costs low. Contrary to some suggestions, the SLS will be very competitive with the advertised price of commercial U.S. systems — on the order of $4.5 million per ton of payload. [Emphasis added]

I will consider the "health and capability of the industrial base" to be code for "We need a giant rocket to keep Senator Shelby (of Alabama, where Huntsville is, and who is chairman of the committee in the Senate that funds NASA) *et al* happy." I'll ask again, if the 130-tonne number is a result of "unbiased NASA technical studies," why haven't we seen them? The only one we have seen (as discussed previously) says nothing of the kind, and in fact says quite the opposite. As for the "demonstrated record of reliability," the Shuttle system destroyed two orbiters and killed fourteen crew. In one case it was due to the failure of a solid rocket motor, which SLS will also have (though an even larger, as-yet unflown version). The second was a result of the external tank design, which SLS will also have, though at least this time it won't have a fragile orbiter hanging off the side to get hit by stray frozen tank insulation. In both cases, it was a management failure, and the arguments made here on the behalf of SLS provide little confidence that that particular problem has been fixed.

They don't show their work for their $4.5M/tonne, and I've already shown that it will be at least twice that, and even if they could get it that low, it won't possibly be competitive with the prices of the new commercial vehicles inevitably coming down the pike. I can only guess that this is based on the marginal cost (as previously discussed). That is, it is the cost of flying the next flight, ignoring the fixed costs of the system, which in the case of an expendable rocket is basically the production costs of the vehicle, plus consumables (mainly propellant). But for a dedicated system like this, the use of marginal costs is deceitful: because Congress insists that it be NASA-owned-and-operated, the taxpayer is paying *all the costs for the launch system*, not just the cost of building a new rocket. As Keith Cowing at NASA Watch pointed out last summer, it was very clear that this number was a completely unsubstantiated talking point being parroted by SLS supporters in various venues. Basically, the proponents are insulting our intelligence. They think we were told there would be no math.

Mission Risk And Reliability

I'll conclude this section with a discussion on mission risk and reliability. SLS supporters make an argument like this:

> The greater the number of flights it takes, the more the probability of successfully delivering the elements needed for a Mars mission is reduced, because that probability is a multiplication of the individual probabilities of success of each rocket flight. For instance, if it takes thirty flights of a vehicle with 98% reliability, the probability of mission success (let's call it P_m) will be 0.98 to the thirtieth power, or only 55% or so. A rocket with the same reliability for which only six flights are required will have a much better P_m: 0.98 to the sixth power, or 89%.
>
> Moreover, because of NASA's superior experience and processes developed over decades, SLS will probably be greater than 98% reliability, compared to those amateur commercial rockets. SpaceX just blew one up in the summer of 2015, so their demonstrated reliability is only 24/25 (as of early June, 2016), or 96 percent. That means that a mission that required thirty successful Falcon flights would only have 0.96 to the thirtieth P_m, or about 30%, less than *a one in three chance*. Why are you trying to sabotage our Mars plans by insisting on using so many flights of these dinky, unreliable rockets?

I know that because I don't have a specific quote, this sounds sort of strawmanly, but there have been arguments like this made by SLS proponents for years. And the logic and math seems indisputable, right?

Well, it's a lot more complicated than that. In fact, a greater number of flights to accomplish a given job actually *increases* the chance of mission success. And also in fact, this would only be counterintuitive to someone in the warped space industry, stuck in the Apollo and general "mission" mindset. Let's unpack the above "analysis," to see why.

First, it assumes without basis that the loss of a single flight causes the loss of an entire Mars mission, ignoring the fact that the lost payload (e.g., propellant) could be delivered on another flight. The only flight failure that could by itself cause mission failure would be one carrying an irreplaceable mission element. But if we have irreplaceable mission elements, we're clearly doing it wrong.

We could do a *reductio ad absurdum*, and assume that we are going to deliver everything for a human mission beyond earth orbit and back in a single launch.

Oh, wait! That's what we did in Apollo!

For Apollo, the Saturn V carried all of the hardware elements described in the DRM, plus propellant. If the launch system failed, the mission failed. The reliability of the launcher put a ceiling on the P_m; if the Saturn was 95% reliable, the P_m could be no greater than that, and of course it would be less, because of the potential for failure of any of the other mission elements in the other mission phases (as happened with Apollo 13, when the liquid-oxygen tank in the Service Module exploded). For the launch system, it was all or nothing.

Let's go back to the truck analogy. Suppose we build the house in the factory, ready to live in, and then deliver it to its final destination on a giant truck. It's a very expensive payload, because of all the value added in the factory where it was built.

Now the success of getting your house to your building site is totally dependent on the truck not crashing somewhere along the way. Would you really want to make that bet? Because trucks do crash with some regularity. And if it happens, you've lost a hundred-thousand-dollar (or more) house.

That's why we build houses on site from much smaller, less expensive parts, and we add value by assembling them there. That way, if you lose a shipment, it's not that big a deal. You just send out another load of cheap cement or plywood or studs or drywall, or whatever.

This is the way we do things on earth. There is nothing magical about space that means we should do it any differently there, except that the one time we successfully did, half a century ago, what some would like to do again — send a handful of humans beyond earth orbit — we did it the crazy way, because we were in a hurry and didn't know how to do it any other way, and we didn't care what it cost, and we got away with it half a dozen times.

So what is the non-crazy way to manage risk? This is discussed extensively in the previously-mentioned NextGen Space LLC report, starting on page 48. Specifically with regard to launch systems, the author, David Cheuvront (now retired from JSC, but based on work he did there half a decade ago) says:

> The fundamental strategy to address the risk of launch vehicle failures is that *no single launch failure should ever be catastrophic to Program success*. This strategy is enabled by commercial acquisition and operation costs being nearly an order of magnitude lower than traditional approaches and is flowed through the entire architecture. The ELA features a large number of relatively low cost launches for each mission, potentially on some relatively immature new launch vehicles. This has raised concerns about what happens if one or more of these launches (or subsequent on-orbit operations) fail. This has been the subject of

> much investigation, both as part of this study and in prior studies by the author. A very effective strategy to manage this risk is to provide for contingency launches.
>
> Using what is called "M of N" reliability techniques, any desired level of reliability (sometimes referred to as the number of 9's) for any given number of required launches (M) can be provided by planning for some greater number of launch vehicles (N), assuming any reasonable level of inherent reliability of the base vehicle being used. The difference between N and M is the number of contingencies provided. Selection of the number of contingency launches should be based on the expected Probability of Success per launch, the required overall success probability for the mission set, and consideration for tolerance to payload loss and schedule risk. These parameters should be traded to identify the most cost-effective solution. This strategy...is effective when the consequence of losses, up to at least the planned number of contingency flights, is acceptable. [Emphasis added]

In other words, by planning for contingency flights, one can arbitrarily increase the probability of mission success, as long as (as I previously noted) there is no "irreplaceable" payload. But more importantly, reducing number of flights to "reduce risk," as SLS proponents recommend, *reduces vehicle reliability* by reducing flight rate. Cheuvront has a chart to illustrate this (Figure 2). (Note, though the chart says that the ejection seats were removed from the Shuttle after the first flight, this actually didn't occur until after the fourth flight.)

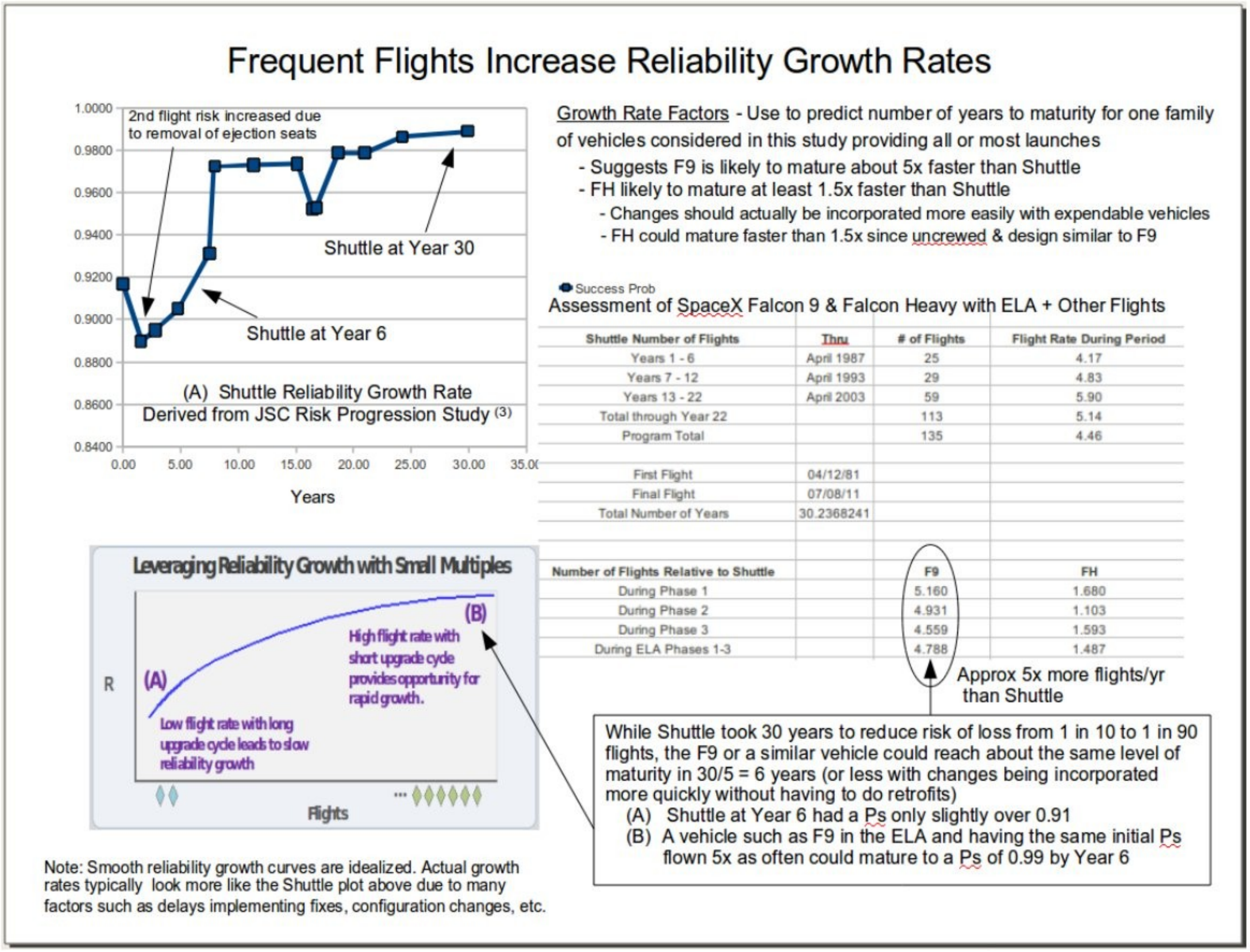


Figure 2. Reliability Increases With Flight Rate

He points out that:

> Another positive effect of the high flight rates needed for the ELA is that "demonstrated reliability" also increases rapidly. Although the curves follow a similar shape, *demonstrated reliability* is fundamentally different from *reliability growth*. While reliability growth involves correction of problems discovered from flight experience, demonstrated reliability is concerned strictly with increasing the number of trials to increase the level of certainty of the actual reliability of an unchanging design. High demonstrated reliability is often required for unique or exceptionally high value payloads. In such instances, launch on vehicles having the highest demonstrated reliability but significantly higher cost may be justified as a degree of "insurance" against loss. One risk strategy is to launch high value payloads on well-proven LV's until high reliability is demonstrated to reach similar confidence for new, lower cost options.

What he doesn't say, no doubt to avoid taking political heat, is that SLS *has precisely the* *opposite characteristics* (as I noted previously, SLS is barely mentioned in the report, other than as a line item in the life-cycle cost). As I pointed out in my book (page 65) with regard to its low flight rate:

> From a safety standpoint, it means that its operating tempo will be far too slow, and its flights far too infrequent, to safely operate the system. The launch crews will be sitting around for months with little to do, and by the time the next launch occurs, they'll have forgotten how to do it, if they haven't left from sheer boredom to seek another job.

Planetary scientist (and recently retired NASA Advisory Council member) Steve Squyres has expressed similar concerns:

> "I'm deeply worried," he told [Congresswoman] Edwards, because no other human spaceflight system has had such a low anticipated launch rate. The first SLS launch is expected in 2017, the second in 2021, and then once every two years thereafter. SLS and the Orion spacecraft need to be adequately funded "to be proven out on a pace that really supports … a safe pathway" to cis-lunar [sic] space, Squyres insisted.

Even at three per year, out in the 2030s, it would be a long time before SLS has high demonstrated reliability, and yet the plan is to put everything — from propellant to crew to landers — on it. And *demonstrated* reliability will be required, because in fact NASA does not possess the "superior experience and processes developed over decades." On page 118 of my book, I point out that:

> Organizations don't have knowledge—individuals do. And to the degree that NASA has any knowledge, it is because it has retained employees who have it. But many of those knowledgeable people have instead gone to work for the commercial companies, so there really is nothing "unique" about NASA [in that regard]. But to the degree that there is, it is primarily that, at least with respect to safety [and reliability] its policies have resulted in the loss of fourteen astronauts in flight.

When Mike Griffin announced Constellation (aka "Apollo on steroids") in 2005, he explicitly said that part of the purpose of NASA developing new rockets was so that it could learn how again, since it hadn't successfully done so since the seventies. Ares I was supposed to be a "training rocket" for Marshall to allow it to go on and develop Ares V (which has since morphed into SLS, even in the absence of Ares I). Given that Ares I was canceled because it was slipping in schedule at the time more than a year per year, there is no particular reason to think that NASA has in fact reacquired this knowledge, and thus no reason to imagine that SLS will be reliable.

As Cheuvront notes, the general philosophy should be to allocate different types of payloads to different types of launch systems, depending on the value of the payload and the system reliability. For instance, cheap bulk cargo, like propellant, water or other consumables should go up on cheap launchers, even if they're not reliable, because there is nothing of value at risk.

In fact this is an excellent payload for new, untested rockets, as a way to wring the bugs out of them. It's also a good way to incorporate international cooperation, by allowing other countries to deliver propellant as a contribution to a mission. High-value payloads, such as costly hardware, or humans, should go up on proven launchers.

If the anthropologist's proverbial objective Martian were to come to earth, it would probably look at the situation, and scratch its head (if it had one) with one of its tentacles (if it had any), and say: "¢–≈ß∂≥≥˚ ≠¡¡…•æ∆¶Ω ®$≠≠†µø¿¶ »æ£∞∂∏¢¡µδ –øç»£≈¢¢¶ œπ•αßœ«¶¶ ‰ ∫γ–'√çα".[1]

Contra claims by its proponents, SLS is neither cheap, or reliable, and won't be for decades, if ever. It is the most expensive and least robust means of getting a handful of NASA astronauts to Mars. The money being wasted on it would be much better spent on both reducing the cost of such expeditions, and increasing their scope and frequency. The next section will provide some examples of how to do so.

1 Translation from the original Martian: "You people have numerous ways of getting things into space, relatively affordable and reliable, with prices dropping and reliability increasing almost yearly. Why are you spending so much money on a rocket that you don't need, whose costs are much higher, will fly rarely, and whose demonstrated reliability won't even be known for decades or centuries at any affordable flight rate, while not developing anything you actually need to get to my home planet from yours? It's almost as though you don't really want to visit me."

4.0 Mission Alternatives And Technology Building Blocks

As we've seen, Congress insists that NASA develop and operate the largest rocket ever built and a super-sized Apollo capsule as part of its plans to go to Mars (even though the agency has no plans to send the latter beyond cislunar space, nor was it ever designed to do that). Absent a change in heart on the Hill, the agency will continue to be forced to spend about $3B/year on them indefinitely. The purpose of this section is to show specifically how that money could be better spent to address the issues that SLS/Orion are ostensibly supposed to (even thought they won't), while dramatically increasing the level of human-spaceflight activity and reliability in doing so.

Let's start by looking at what NASA proposes to do with the vehicle. In early March of 2016, at the IEEE Aerospace conference, Boeing (one of its primary contractors) presented a paper[2] with a number of mission scenarios for SLS, including lunar landings, delivery of large Bigelow habitats, Mars sample return, humans to Mars, and planetary missions, including previously mentioned probes to Europa.

I would argue that none of these missions require an SLS (though the Bigelow 2100 module as currently designed does require a 10-meter payload fairing). Many of the missions are multiple-SLS missions (the most recent plans for Mars are reported to require eight launches), so the argument that it eliminates orbital operations is spurious, and even reducing them then requires an actual cost/benefit analysis. And even if they could fly twice a year, that means that they could only do one Mars mission per every two 26-month opportunities. But let's take a different example often cited as a project that could benefit from SLS: the Europa mission.

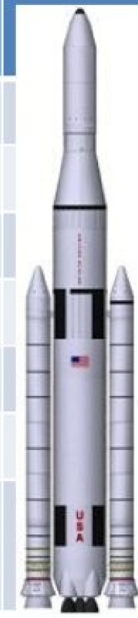
Europa

Europa is one of Jupiter's Galilean moons (the large four discovered by Galileo with his primitive telescope centuries ago, which was one of several things that got him into trouble with the Church). Recent scientific results indicate that it has a large subsurface ocean (in fact, like some other bodies in the solar system, it may have much more liquid water than earth), and many think it a prime location to search for non-terrestrial life in the solar system (though recently some, like Carolyn Porco, think that the Saturnian moon Enceladus may be a better target in that regard). The idea is to send a probe into orbit around it, and “sniff” geysers of water that appear to occasionally erupt from the surface. There are also potential plans for a lander, maybe with a submarine, to explore the ocean itself. Phil Culberson (R-Texas), chairman of the House Space Subcommittee, has a strong personal interest in the mission, and has been aggressive in pushing it.

2 Donahue, B., Burks, D., Cooper, D., Boeing Co., Exploration Opportunities Enabled by the Space Launch System, IEEE Aerospace Meeting, Big Sky, MT, March 7, 2016.

Table 1 Parameters for Europa Mission

Mission Overview	Original Design	With the SLS Direct Injection	With the SLS Direct Injection
Launch Vehicle	Atlas V 551	SLS Block 1	SLS Block I b
Upper Stage	Centaur	iCPS (1xRL10)	EUS (4xRL10)
C3 (energy)	15.0 km^2/sec^2	85.4 km^2/sec^2	85.4 km^2/sec^2
Injected Mass	3.6 mt	4.4 mt	6.9-8.3 mt
Launch Date	Nov 2021	June 2022	June 2022
Cruise Duration	6.5 years	2.0 years	2.0 years
Trajectory	Venus–Earth–Earth Gravity Assist (VEEGA)	Ballistic, Direct	Ballistic, Direct



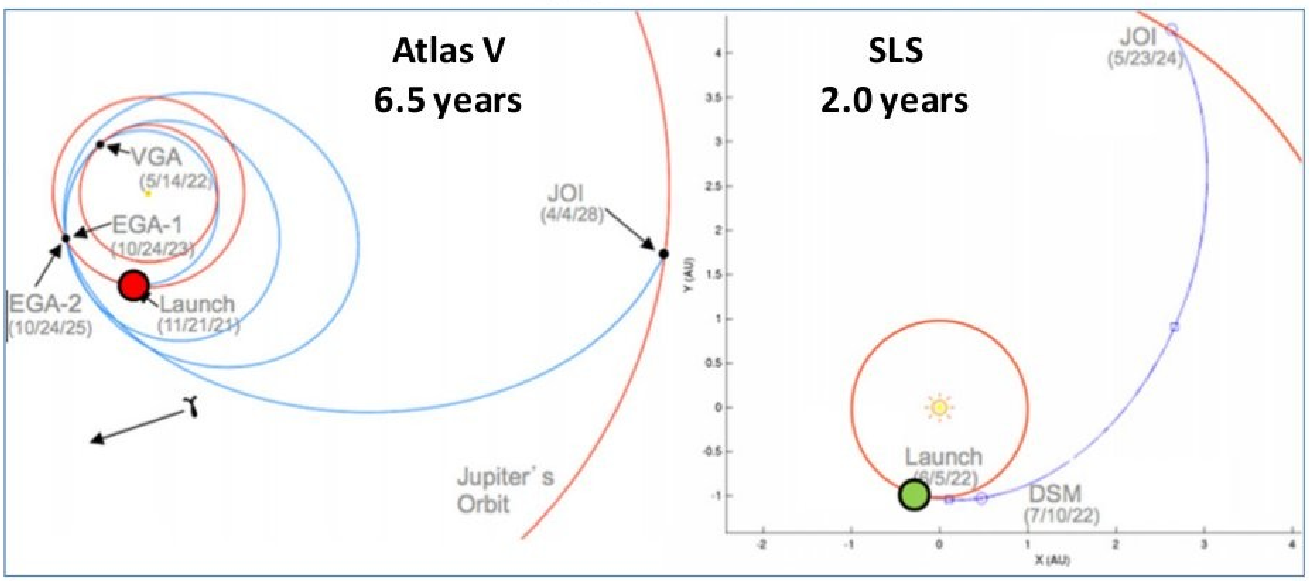


Figure 13 Europa Trajectories (image courtesy JPL/APL[1])

Traditionally, getting to Jupiter requires several years, and multiple flybys of other planets (such as Venus, or earth itself) to steal some momentum from them to get the necessary energy to go all the way out to the Jovian system. SLS proponents claim (correctly) that the vehicle has sufficient performance to do a direct injection on a fast trajectory that will get the payload there in a little over two years. In another paper presented at the annual AIAA space conference in Pasadena in September of 2015, Boeing presented a mission profile, shown as

Figure 13 from that paper. The most energy-efficient way to get from one circular orbit to another is to perform a half ellipse, with perigee at the lower orbit, and apogee at the higher one, with the ellipse tangent to both orbits (this is known as a “Hohmann” transfer). However, while efficient and relatively fast (a little less than three years), it can still be expensive for Jupiter in terms of velocity, beyond the capability of an Atlas V. It's possible to trade time versus injection velocity, as shown in the case shown on the left with gravity assists, one at Venus and two at earth, but it takes about six years. In the case shown for SLS, a much faster trajectory is taken, where the orbit must not only increase its speed, but “turn” when it reaches the distance of Jupiter, at a very high cost in velocity change (though this maneuver is helped by the gravitational presence of the giant planet itself).

C3 is the orbital energy needed to get to the shortened trajectory shown. In order to get that energy, the probe must depart from earth orbit with a velocity of over 14 km/second (escape velocity, the amount needed to simply leave the earth's gravitational influence, is a little over 11 km/second). Boeing estimates that the Block 1B SLS, with its currently planned 97.5-tonne capability to LEO, can throw something massing between seven and a little over eight tonnes to that fast-transfer orbit. The probe itself would use on-board propellant to orbit first Jupiter and then Europa upon arrival.

But is SLS the only way to do it?

I did my own calculation. According to the SpaceX web site, as of early May, 2016, the Falcon Heavy, with the improved performance of the new stretched and densified-propellant Falcon cores, can put 54.4 tonnes into LEO, and according to SpaceX sources, at a price of $150M-$180M (Note: Their current web site as of May 2016 lists a price of $90M, but that seems to be for a ride share to geosynchronous transfer orbit).

A cryogenic insertion stage capable of carrying tens of tonnes of propellant would have a dry mass of just a few tonnes (for example, the ACES upper stage from ULA, described in the next section, weighs a little over five tonnes dry, and has a propellant capacity of over 70,000 lbm). If we were to launch a cryogenic stage weighing five tonnes on the FH with a payload of 8.3 tonnes, it would only be able to carry ~41.5 tonnes of propellant. To get the 14+ km/s departure velocity from LEO (orbital velocity ~7.7 km/s) we need about 6.5 km/s of delta v. It turns out that at a conservative vacuum specific impulse of 460 seconds, such a stage could still provide it with propellant to spare.

That is, a single FH launch can do the same Europa mission as the SLS Block 1B. Even if the notional stage cost $50M (a number that seems quite high to me), the total launch price would still be less than $250M, a small fraction of even the marginal cost for an SLS flight.

But, as they say in the television ads, wait, there's more!

That mission is only an orbital probe. Current plans are for a *second* SLS flight to deliver a lander. But is it possible to do both in a single mission? It is. Behold the power of staging.

Launch an FH with a cryogenic stage carrying 50 tonnes of propellant in it. Launch a second one with 35 tonnes and a payload. In both cases, the delivery to LEO is 55 tonnes. Mate the two stages on orbit. It turns out that the first burn provides ~2.7 km/s of the needed 6.5, and the second provides the rest, with a payload to Jupiter of approximately 20 tonnes, over *twice* the payload of the SLS mission for the fast trip to Jupiter, again for much less launch cost. Of course, it probably doesn't make sense to send a lander until an initial reconnoiter with the orbiter, but the orbiter could also be much larger, which would (counter-intuitively) reduce its potential costs by not having to work so hard to keep mass down, and also allow it to carry much more maneuvering propellant.

There is one other option. A two-stage mission could be flown, while recovering the first stage back to cislunar space, by sacrificing some payload in order to have enough propellant remaining at the end of the burn to return (the same basic idea as the current first-stage recovery of the Falcon rocket, except it doesn't have to land). This would reduce mission costs further, by the cost of replacing the stage. But instead, NASA proposes to throw away an SLS at a marginal cost (at a minimum) of several hundred million dollars.

Orbital Assembly

Clearly, in order to be seriously space faring, we will need large-volume items in space. In particular, while volunteers could no doubt be found, and ancient explorers put up with much worse conditions, there will be a huge psychological benefit to large comfortable orbital habitats, both for living in general, and for journeys to distant destinations lasting several months or more (e.g., Mars). In addition, fluid storage, both gaseous and liquid, can benefit from larger tanks, rather than multiple smaller ones, in terms of mass/storage ratio. This is particularly important for propellant tanks for transportation systems, because heavier tanks means the need for more propellant to change their velocity. The question is whether or not the high launch cost of the SLS can justify the slight structural efficiency improvement (unlikely).

Large optics for space telescopes or lasers are also often cited as hardware that can't be easily reduced in size. For example, the James Webb Space Telescope (JWST) is being built in segments that will have to be unfolded deep in space, where no one is around to fix them as the Hubble Space Telescope was by the Shuttle, raising a very real risk that the mission will completely fail if the instrument doesn't deploy properly.

In any event, in the context of such requirements, on which few disagree, there are two arguments used by its proponents to justify the Space Launch System. The first is the supposed difficulty of orbital assembly (in which the International Space Station is sometimes used as a cautionary example, despite our clear success in building it), and the supposed risk of multiple launches. The latter was discussed in the previous major section, but this subsection will describe the state of the art in making big things in space from smaller ones, or improvements in technology that obviate the need for things to be big.

For optics, there have actually been recent breakthroughs in miniaturizing them beyond the origami approach of the JWST. For instance, Lockheed Martin recently announced a new concept called “Segmented Planar Imaging Detector for Electro-optical Reconnaissance” (SPIDER), in which the light is collected in hundreds of thousands of tiny lenses rather than a few large traditional reflectors or refractors. A large diameter is still required, but such a system would be much easier to fold, deploy and calibrate, and it could reduce the mass of the system by an order or two of magnitude, which would also eliminate any justification for a heavy-lift vehicle.

In terms of space assembly of structure, there have long been concepts for this going back decades. For instance, back in the 1970s, NASA developed a concept for a “beam builder” that was to go up in the Space Shuttle, a machine designed to extrude triangular trusses from thin aluminum sheets. It was tested on the ground, though never in space, as far as I know, but there is no reason to think that free fall would negatively affect its performance.

More recently, at least two private companies are exploring similar concepts, except with composite materials rather than metal.

Made In Space, a relatively new firm, started out as a business to do additive manufacturing (also known as 3-D printing) in orbit. It has already delivered a printer designed to operate in weightlessness to the International Space Station, and demonstrated it, using plastic filament as feedstock. While such technology doesn't in itself produce large structures, another project they've initiated will. Dubbed “Archinaut™, NASA has funded a demonstration to, in the company's words, build a machine that will “enable the first additive manufacturing, aggregation, and assembly of large and complex systems in space without astronaut extravehicular activity.” They are partnered with Oceaneering and Northrop Grumman.

Tethers Unlimited, a company that has been around much longer, has similarly established a division called Firmamentum to do something similar. I was at their facility in Bothell, WA in November of 2015, and held an amazingly stiff and light large composite truss that their own machine had created.

In either case, these kinds of systems could be the basis for much larger dishes and antennas, or other structure, than could fit on any launch system, including SLS. In response to a question I asked at a presentation in Pasadena in late May of 2016, Firmamentum also has plans for constructing large pressure vessels in orbit, which could be used for habitat or propellant tankage.

While these activities are being supported by NASA via Small Business Innovative Research (SBIR) and other grants, the amount of money that is going into them is infinitesimal compared to that being poured into the Rocket To Nowhere.

In-Space Propellant Storage

If we aren't going to deliver all the propellant for a Mars mission in a single launch (and we aren't), we are going to have to have some place in space to deliver, transfer (assuming that we don't just drop off tanks) and store it. In fact, SLS proponents often disingenuously say that this is a drawback with multiple launches and that, particularly for LOX/LH2, boil off will make such in-space storage impractical. It is a disingenuous claim because (as noted earlier) even they admit that multiple SLS launches will be required to do a Mars mission, which means that even an SLS-based architecture will require propellant transfer/storage technology. So it is a crucial technology for Mars missions. But NASA is not funding it in any significant way.

Fortunately, the United Launch Alliance is, with their Advanced Cryogenic Evolved Stage (ACES), which will contain the necessary technologies for LOX/LH2 transfer and storage. The current stage design will have a propellant capacity of up to 73 tonnes (or about the initial planned orbital payload for SLS). In order to get rid of the toxic hypergolic propellants normally used for attitude control of upper stages, they have developed a concept called Integrated Vehicle Fluids (IVF), in which the same propellants used for main propulsion can also be used to provide reaction control and vehicle electrical power, converting the oxygen and hydrogen from liquid to gas to liquid again, depending on the application. Based on discussions with ULA personnel, the company believes that there is no need for a space-based test of the concept; ground testing has provided confidence that it will work, and thus they are baselining it as the upper stage for the new Vulcan rocket. As they note in a recent paper, this is a revolutionary capability:

> Fundamentally IVF is a Hydrogen/Oxygen auxiliary power unit, that uses free boiloff hydrogen and oxygen to generate electricity (eliminating main vehicle batteries), provide autogenous tank pressurization (eliminating most or all Helium bottles), and feed GH2/GO2 reaction control system thrusters (eliminating all stored hydrazine). Power, He supply, and hydrazine supply are all current constraints on mission duration. With this change, coupled with straightforward low-boiloff enhancements on the upper stage, mission durations on the order of days vs. hours become practical. For example, ACES with IVF could perform a lunar orbit insertion burn for a commercial lunar mission without requiring another dedicated stage. Similarly, IVF can perform targeted disposal burns using waste boiloff, from essentially any orbit, due to its ability to operate longer, and perform

> propulsive RCS burns with durations limited only by having propellant remaining in the main tanks.

But perhaps what is most important about the design is that, while there are no plans to return it to earth for reuse, the stage is envisioned by the company to evolve to being capable of multiple missions, and *reusable in space (perhaps indefinitely, but certainly for many missions), requiring nothing but the constituents of water*. So it could have the capability to be refueled in weightlessness, and from extraterrestrial resources, such as asteroids or lunar ice. In other words, while it has powerful engines for injecting satellites or probes into high earth orbits, or heliocentric destinations, with that capability, it would also be a fully functional *cryogenic propellant depot*, expected to be available *in the next decade*. Its operating costs would essentially be the costs of delivering the LOX and LH2 to it, costs which will continue to come down as launch costs come down, or (as discussed in the next subsection) extraterrestrial sources are exploited. A version of it called Xeus (developed in partnership with Masten Space Systems) will actually be capable of landing on the moon vertically, but in a horizontal orientation, to reduce the height needed to get in and out of it. If it could be refueled on the lunar surface (perhaps, as will be discussed, from lunar water deposits), it could deliver substantial payload both up and down.

The company recently released a video describing its own vision for space over the next few decades. It includes not only the ACES stage, but the Xeus as well. The title of the video is “Cislunar 1000,” and the vision is a thousand people living and working in space in the same time period that NASA is proposing (without an actual plan) to send a handful of astronauts to Mars.

I would like to see others in addition to ULA get into this game, because of my ground rule that we should have at least two ways to perform a given function. NASA could encourage this by offering to purchase propellant on orbit from multiple providers, using the COTS model, but of course that would both take money from SLS, and indicate that SLS isn't needed.

Once depots exist, they would be proliferated in various locations, to reduce vehicle size to get from one location to another (like my previous analogy of cars versus tanker trucks). They'd be in low earth orbit, at earth-moon Lagrange points (EML1 and/or EML2) perhaps lunar orbit, or on the lunar surface. They'd be delivered to Mars orbit, and on the Martian surface as well. Eventually, there might even be fueling stations halfway to Mars, reducing needed vehicle size even further. For example, just as a thought experiment, a couple of years ago, I calculated the benefit of being able to refuel halfway to Mars.

> In my talk on the commercial space panel at the Mars Society Convention on Saturday afternoon, one of the things I said that we needed was “gas stations on the road to Mars.”

I'd never really thought about it much, because I don't think about Mars much, but I wondered just how advantageous it was, so I decided to take a break from the space-safety stuff and play with the idea in a spreadsheet.

[I assumed circular heliocentic orbits for both earth and Mars, and] I ignored the moon's gravity, just doing a departure from EML1 starting at EML1 velocity with patched conics (same thing going into Mars orbit to co-orbit with Phobos). I used a stage fraction (ratio of propellant to total stage weight) of 0.85 and an ISP [specific impulse, a measure of fuel efficiency] of 460 seconds (lower ISPs would just make the numbers even worse for the non-refueling scenarios). I also didn't do any aerobraking at Mars, so the numbers would work the same in either direction.

For a hundred metric tons of payload delivered to Mars orbit in the vicinity of Phobos, I looked at three mission scenarios: departure from LEO direct to Mars, departure from EML1 [Earth-Moon Lagrange point 1, the point between earth and Moon where gravity and centripetal acceleration are balanced] direct to Mars, and departure from EML1 with a fuel stop half way. For the latter scenario, you can deliver a ton of payload to Phobos's orbit for less than a ton of propellant. For the EML1 scenario without refueling, it takes [**almost three times as much total propellant, and over five times as much initially at EML1**]. For the LEO scenario, it takes [**almost five times as much total, and over nine times as much IMLEO**]. That is, for the refueling scenario, you start with an IMEML1 (Initial Mass in EML1) of about a hundred and fifty tons, **two thirds of which is payload bound to Mars** (the total mission propellant needed is twice as much as you start with, because you pick up the other half, about 43 ton[ne]s, on the way). For the non-refueling case in EML1, the IMEML1 [**for the same payload**] is [**about three-hundred fifty tonnes**], and for the LEO case, IMLEO is almost [**five hundred tonnes**].

Such is the power of the rocket equation, and refueling.

What's the catch? There are two. First, of course, it assumes the delivery of the propellants to EML1 and the gas-station orbit. If it were done chemically, the savings would go away, but it could be done electrically [as will be discussed in the next sections]. The other catch is that it obviously both complicates and increases the time of the mission. I'd recommend it for cargo only. The gas-station orbit I chose was at a distance of 1.256 AU (that is, about 25% further from the sun than the earth is), which turns out to exactly split the delta V between earth departure and Mars arrival, which means that you just refill the tanks at the gas station. That orbit turns out to have a synodic period with earth of about three and a half years [that is, the time between opportunities to efficiently get to something in it from earth], and with Mars of about five and a half years. But with the savings, you could afford to put a dozen stations in that orbit, which would give you an opportunity every month, and then you could take more of the savings and do faster trajectories, so you don't have to wait for more-efficient Hohmann line ups. So if Planetary Resources [one of the companies formed to mine asteroids] wants to sell water, that's the location for the gas station[s] — 1.256 AU.

> Just looking at the difference between LEO and EML1, it seems insane to not use propellant depots with electric propulsion. [Note: I edited this somewhat from the original blog posts, to correct some errors, and I show my work in a spreadsheet linked to the second one]

This is just one example of the huge benefits available via refueling early and often. The issue, of course, is where does the propellant come from, and how do we get it to where it needs to be? The next subsection will discuss this.

In-Situ Resource Utilization

Obviously, one source of propellant needed for deep spaceflight would be the source that we've been using since the beginning of the space age: the earth. Low-cost launch (that is, not SLS) will enable affordable propellant delivery to low earth orbit. From there, it could be dispersed out into cislunar space, though if it is done with the same propellant type that is being delivered using chemical rockets, much of the advantage of having dispersed depots would be negated. For instance, delivering propellant to the lunar surface all the way from earth would probably cost more than the value of the lunar ascent vehicle that would use it, making reusability for such a vehicle economically pointless. This is why everything in Apollo was expendable, other than the capsule itself, which had to come back to fulfill Kennedy's pledge to "return" them "safely to the earth." It is also why the planned (and expensive, and canceled) Altair lunar lander from Constellation would have been expendable.

One way around this, as suggested in the previous subsection and as will be discussed in more detail in the final subsection, is to use high specific-impulse (I_{sp}) systems, such as ion thrusters, to move the propellant from one orbit to another. The trip will take much longer, due to low thrust (unless they are nuclear thermal, as will be discussed in the final subsection), but that doesn't matter as long as there is a steady pipeline to the needed locations (just as there is always a slow oil tanker every few miles between the Persian Gulf and countries that need it, like Japan). This has in fact been proposed as an architecture for Mars missions, in which propellant needed to return would be pre-delivered to the planet using electric propulsion before sending crews there.

But ultimately, as previously discussed, if we are to open the solar system, we will have to learn to live off the land, just as we did when we settled the American west. In this case, as in that one, we need fuel for both transportation and and our (and our animals') metabolism, as well as oxidizer with which to burn it to provide the needed energy. In the case of the westward expansion, the fuel was first forage for the oxen and horses, and later coal for the trains. The food was provided initially by hunting animals, and later from farming and animal husbandry. In all cases, the oxidizer was oxygen from the air that both animals and machines could breathe.

In space, fuel for the machines will come in the form of various combinations of carbon and hydrogen (just as they do on earth), but we will have to manufacture it from those raw materials. Hydrogen is a good fuel by itself for chemical rocket engines, but it can be made more storable by combining it with carbon as methane (CH_4) or other hydrocarbons. Fuel for the animals, including humans, will either be grown with hydroponics, or (as is starting to occur on earth) manufactured in a lab from the raw materials. In both cases, oxygen will be the certain oxidizer for metabolism, and a likely one for chemical rockets. To have a standard atmosphere, we will also need nitrogen (which composes most of the atmosphere on earth). Nitrogen will also be needed for plant growth.

Where will we get these constituents?

We now know that there are billions of tonnes of water (H_2O) on the moon, much of it concentrated at the poles, in the form of ice. With sufficient energy (more on that in the final section), it can be cracked into its constituent components of hydrogen and oxygen through electrolysis. Oxygen can also be obtained from the lunar regolith, which consists of silicates (among other things), but this is a much more chemistry-intensive process. On the other hand, as by products, it also provides silicon, aluminum, titanium, iron, and other materials for the construction of structure and electronics (including solar panels).

So at a minimum we should be able to utilize the moon itself for propellant manufacture, which makes reusable landers and ascent vehicles practical. Such a vehicle, if its tanks were oversized for its mission, could also serve as a propellant tanker to deliver propellant to lunar orbit, Lagrange points (that could be useful departure points for excursions out into the solar system) and other cislunar locations. At some point, the market would decide the cheapest source in cislunar space for propellant: delivered from earth via commercial launchers, or from the moon. In either case, it would be much less costly than lifting it with an SLS.

For carbon and other elements (such as nitrogen), we would probably have to get it from a nearby (in an energetic sense) carbonaceous asteroid, but if propellant can be manufactured in situ after arrival, transportation costs to bring it back to cislunar space could also be quite low (particularly with electric propulsion, though it's not clear how the propellant for that would be attained; probably from earth initially). Made in Space recently won an SBIR for a proposal to convert an asteroid to a spaceship, utilizing its own mass as reaction mass. We haven't characterized Phobos and Deimos, the two Martian moons that are believed to be captured asteroids, but it's possible that they could be a source for propellant needed to descend to the red planet. (Nitrogen, and many other elements, such as helium, is also available in abundance as ammonia in the outer planets, but that is much further out in time, not an initial source.)

On Mars, we now know that there is not only water ice, but perhaps liquid water. The atmosphere is mostly carbon dioxide (CO_2) so it provides an easy source of both carbon and oxygen. Using hydrogen from the water allows the production of methane through the Sabatier process, so that will probably be the fuel of choice for Martian vehicles, for ascent and descent rockets, as well as ground-transportation vehicles, probably powered by methane/oxygen fuel cells.

The point is that if we were serious about developing and settling space, we would be spending money on the technology development needed to take advantage of these resources, that could dramatically reduce the cost and increase the activity level of moving around, working and living off the planet. But instead, each year, the NASA technology budget is slashed to fund a giant unneeded rocket.

Artificial Gravity

We know that there are numerous deleterious effects on the human body from free fall for long duration. NASA astronaut Scott Kelly recently completed almost a year in orbit on the ISS, returning with bone loss, kidney stones, skin soreness, and vision problems. His duration was comparable to that of a trip to Mars.

Overall, we have about a million hours of experience in living in weightlessness, a few tens of hours at 1/6th of a gravity on the moon, trillions of hours of experience in one gravity. But we have absolutely none at the 0.38 gravity of Mars.

Moreover, we have no experience whatsoever of creating human offspring in any gravity environment other than our own. We have absolutely no data on whether or not a mammal, let alone a primate, let alone a human, can conceive and gestate in gravity fields other than earth’s. And even if it is possible to do so, we don’t know what the implications would be for the children issued, in terms of birth deformities and resulting health problems.

Now, if the goal is Apollo to Mars, in which we send a few astronauts to walk around on the planet, and then return, or even to have a small permanent station where people serve for a short time, and return, perhaps this doesn't matter that much, any more than any of the Apollo astronauts suffered obvious long-term health effects from spending a few tens of hours in one-sixth gravity.

But if the goal is to *settle* Mars (as, for many, it is), then it matters *a lot*. And the consequences of a pregnancy could be far worse than a failed pregnancy; they could be a failed but born and living human being (in the sense of a creature with human DNA). I've argued that in fact, at our current state of knowledge, it would be unethical to attempt to procreate human beings on the planet Mars.

There were plans for a centrifuge on the International Space Station to investigate these issues, at least for mammals. They went so far as to actually build the device, by the Japanese space agency JAXA, but as a result of budget cuts, it was never flown, and sits rusting in a parking lot in Japan. The Space Studies Institute has had a proposal for years now to develop a Gravity Laboratory in LEO for a small fraction of the annual funding for SLS and Orion, but it has found no funding, either government or private, despite (for example) Elon Musk's extreme interest in Mars colonization.

Beyond that issue, the health problems caused by months of free fall on the way to or from other planets could be not just mitigated, but eliminated with artificial gravity via centripetal acceleration from spinning habitats. This wouldn't necessarily require large structures; it's possible that it could be done with a module, and counterweight, and a tether to connect them, but no experiments have been done to investigate the dynamic feasibility of such a system.

Because we are not serious about either exploring or developing space, only spending billions on a giant rocket and capsule.

Magnetoshell Aerobraking

There was an old saying on the American frontier about the Mississippi (or Missouri) River: “It's too thick to drink, but too thin to plow.” Similarly, the Martian atmosphere has been tantalizing aerodynamicists for decades. It's too thick to ignore, but too thin to practically use, at least for large payloads. While robotic landers have been parachuted to the planet's surface, there is a practical upper limit on the amount of payload that can be safely landed in that manner (which is why Mars Curiosity had its “minutes of terror” of being dropped down from a rocket-propelled sky crane), because parachutes don't scale well. This limit is far below what would be necessary for landing humans and their habitats and supplies. Hence SpaceX's plan to use retrorockets, which they announced in late April of 2016 that they'd be testing as soon as two-and-a-half years later on Mars.

However, ignoring landing issues, planetary atmospheres can be used to utilize drag as a vehicle approaches the planet from orbit to slow it down to orbital velocities, instead of expending rocket propellant. But the amount of braking is a function of the atmospheric density and the diameter of the hard aeroshell drag shield (“aerobraking” implies multiple lower-energy passes, while “aerocapture” means getting into orbit in a single high-energy one). One of the problems with this concept is that the atmosphere must be well characterized prior to designing the aeroshell, and conditions at the top of an atmosphere can vary depending on factors such as solar distance, current solar activity and time of day, all of which can vary. Also, from a dynamic standpoint, aeroshells are unstable, and can require active control.

Moreover, while a larger drag surface provides more braking, it also adds more weight, increasing the mass that must be decelerated (and that must have been accelerated in the first place to get it to Mars, with a concomitant increase in propellant requirements). If there were some way to increase the effective diameter of the drag surface without significantly increasing the mass, and to deal with the other associated issues, it would be a potentially huge breakthrough.

Well, it turns out that there may be.

A Seattle-area company, MSNW LLC, has developed a concept they call magnetoshell aerobraking in which, rather than compressing the atmosphere with a traditional aeroshell (converting the kinetic energy of the velocity into heat to slow the vehicle), it reacts electromagnetically against an induced plasma. It apparently not only provides much higher drag/mass ratios, but the effect can be electronically modulated in real time to account for unknown or dynamic atmospheric conditions. In addition, unlike a conventional aeroshell, the system doesn't accumulate heat (the heat of the energy conversion is apparently carried away in the wake). And despite these clear advantages, there does seem to be a free lunch – a dramatic (three orders of magnitude) increase in drag has demonstrated on the ground in vacuum chamber on a small scale.

The weight and mission-risk reduction is reportedly also dramatic. For example, for a human mission to Mars landing 30 tonnes on the Martian surface, it allows the mission to be broken into two lower-risk phases: first Mars orbit, and then deorbit and landing, rather than a single fast entry from heliocentric orbit, and a reduction of over 200 tonnes needed initially in earth orbit for the mission. From a paper on the concept:

> In addition to cargo missions, Plasma Magnetoshells would allow drastic design changes to crewed aspects of interplanetary missions architectures. DRA 5.0 [since deprecated by NASA for their Evolved Mars Architecture] does not us [sic] aerocapture for crew missions, largely because of the risk involved with conventional aeroshells. Plasma Magnetoshells allow for dynamic control at any altitude, therefore, they would be safe and reliable for human missions. Plasma Magnetoshells would add additional safety and health benefits as the plasma Magnetoshell could also be deployed during Mars transit to eliminate the effects of solar flares should they arise. It would have little effect on GCR as shown by numerous previous analyses, however [20]. Stopping GCR is a formidable challenge and the most effective solution is simply to reduce exposure. Plasma Magnetoshells would allow for faster transit times between planets thereby reducing exposure.
>
> Further, by simply simulating seasonal atmospheric increase or decrease the resulting trajectories can be simulated. Figure 76 is the optimal insertion trajectory at 70 km and the mean atmospheric model. By decreasing the density by 1/3rd the standard 1400 m^2 shell can no longer capture the 60 MT payload. If the density increases 2X as in a dust storm or local atmospheric anomaly, the capture trajectory because a full descent trajectory within on orbit, potentially leading to catastrophic burn up (Figure 77). Therefore, the ability to

> dynamically adjust the drag surface based simply on the drag (and deceleration) of the spacecraft allows the dynamic response of the trajectory (Figure 78) without additional ACS control, propellant, and computing.
>
> For Mars insertion, the primary benefit is mass savings. Any 20 MT aero shell could be replaced with a Magnetoshell system of less than one metric ton. This saves over 20 MT of launched propellant per launch. The Martian insertion was capable of supporting a 60 metric ton payload and fitting into a standard faring [sic] size. This mission is not possible without an aerocapture system and the authors believe that a Magnetoshell system both decreases cost as well as risk. It is thereby likely that once thoroughly demonstrated, a Magnetoshell system can be used for aerocapture on manned, on crewed missions, further decreasing propellant requirement.

A reduction of 200 tonnes is two SLS Block 1B flights (at a cost of several billion per flight at planned flight rates).

What is the status of the technology?

It's been tested in a ground vacuum chamber at small scale, and results appear to match up with the mathematical models. They need to mature it with first suborbital tests, and then one in orbit. If it pans out, it would significantly reduce the cost not only of entering and landing on Mars, but of operations in earth orbit, saving many tons of propellant for cryogenic tugs (such as ACES) coming back from GEO or cislunar space in general. It might even make it possible for them to enter and recover, making possible fully-reusable two-stage launch systems.

Happily (sort of, but better than the alternative), in May of 2016, NASA did announce a Phase II SBIR award to advance it, at a generous cost of about 0.05% of what it spends annually on SLS.

Why isn't it moving faster? Because Congress thinks it's more important to build a big rocket than to fund technology that could enable much more activity at lower cost.

Nuclear and Electric Propulsion And Power

As noted in the previous subsection, if propellants for chemical-rocket missions have to be delivered with those same rockets, there is little advantage to having propellant depots, because we still end up needing propellant to deliver propellant. The only benefit is that we can use smaller vehicles (which in fact is not insignificant, because they're more propellant efficient). But the real game changer comes if we can get the propellant to the fueling locations more efficiently, even if at the cost of time. It turns out that there is at least one way to do this (I'm ignoring things like light sails, which are another possibility).

I mentioned specific impulse (I_{sp}) in the previous subsection. This is a measure of fuel efficiency, and when expressed in the units of seconds (as it is in the English system – it is expressed as velocity in metric), it can be thought as the length of time you'll get a pound (force) of thrust out of a pound (mass) of propellant. So higher I_{sp} means that for a given propellant load, you can burn (and accelerate) longer at a given thrust level, and thus get more velocity change. While the I_{sp} of chemical rockets is low compared to other types of space propulsion, they have relatively high thrust and their engines have high thrust/mass ratios, which allows them to rapidly perform the velocity change needed to get to a different location in space (the closer one can get to an impulsive, or instantaneous burn, the more efficient the rocket will be). But they are limited by the amount of propellant that can be stored in them, which corresponds to the amount of total energy available. Thus, they are said to be high power, but energy limited.

There is another type of space propulsion that has high I_{sp} (on the order of thousands of seconds), so it can deliver much more velocity change for a given amount of propellant. One example of such a system is ion propulsion, in which a gas, such as xenon, is ionized to give it an electrical charge, and then accelerated out the rear of the rocket with electromagnetic force, such as via the Hall Effect, though there are other designs. Unfortunately, it has very low thrust, so it takes a long time to accelerate to the needed speed (which results in much more total required velocity change due to gravity losses during the maneuver). This kind of system is said to be power limited.

Such electric systems are currently being used on commercial communications satellites for station keeping and final delivery to geosynchronous orbit, but there have also been planetary missions performed with them. All uses of ion propulsion to date have been powered by solar panels so, to the degree that they are power limited in the inner solar system, they would become much more so at Mars and beyond, where the insolation (intensity of the solar radiation) is far lower.

If, however, we had nuclear reactors in space, it would present a major breakthrough in propulsion. The heat from a reactor could be used to increase the temperature of a working fluid (such as hydrogen, which is by far the best) to accelerate it out a nozzle at much higher exhaust velocities than those provided by the energy from the chemical reaction with oxygen. This would enable high-thrust systems with much higher I_{sp}, and much faster trip times for crew and passengers. Electricity generated by a space nuclear reactor could also power ion engines, ameliorating the power limitation of solar panels in the outer solar system, and allowing relatively high thrust continuously at high efficiency for delivering propellant to gas stations throughout the solar system.

Beyond propulsion, we will require nuclear power in space for survival itself. For instance, on the lunar surface, other than in some areas at the poles, the night lasts two earth weeks, so unless we have some sort of energy-storage systems, solar power will be impractical, except some locations at the poles which are in almost-permanent sunlight. Beyond that, the power necessary for propellant production will be very high, and nuclear will make much more sense. In a ship with nuclear propulsion, the power plant will power the rest of the ship as well, for life support and other needs. On the surface of Mars, it would make no sense to rely on solar power, given the distance from the sun and need for energy storage at night.

But there are no serious plans for space reactors, at either the Department of Energy or NASA, and haven't been since the Jupiter Icy Moons Orbiter (JIMO), which would have used one for electric propulsion, was canceled a decade ago. There were a lot of problems with JIMO; it was sort of an "X vehicle" for space nuclear power, but it unfortunately contained a lot of other high-risk technologies, such as power conversion from thermal to electric. For instance, they never decided whether to go with a pure inefficient but reliable thermocouple system or a more-efficient thermodynamic generator, such as a Combined Brayton Cycle, which would have rotating turbomachinery and need a working fluid subject to leaks. There were also issues with keeping the reactor cool, which would also require some sort of means of heat transfer. In addition, because it was going to be in the intense radiation environment of Jupiter, it was uncertain whether or not electronics could survive the mission, and there was no way to test and determine that prior to departure.

But space nuclear reactors are a key technology if we are to open the solar system. The fact that there is no significant funding, or political push to overcome public fears and resistance to it, instead fantasizing that all we need for Mars is a giant rocket, is a testament to how unseriously the political establishment considers this goal.

Conclusion

Half a century ago, America sent men to the earth's moon and back. Ever since then, it has been impossible for many to imagine any way to get humans beyond low earth orbit than the improbably contingent way by which they perceive that we did it then: With a huge unimaginably expensive rocket and capsule, owned and operated by NASA, an inspiring presidential speech with a destination and a date, and a multi-year commitment from the government. Moreover, those same people believe that it is politically possible for this to come to pass again in a constitutional republic with a new government in either the legislative or executive branch, or both, every two years. They also believe that it is about exploration and science, which in fact cannot themselves justify the billions of dollars that it would cost; a much more serious purpose than that is required to do so.

Many of the elder generation who lived through it the first time want to repeat it, and a younger generation to whom it is ancient history want to experience it themselves. Unfortunately, too many in the government are willing to allow them to sustain these multiple delusions, that I have come to call the religion of Apolloism. The political establishment at NASA and in the Congress take advantage of this false belief system to promote their own interests in keeping funding flowing to favored states and congressional districts to build the large unnecessary rocket and capsule, in the name of a mythical #JourneyToMars, while failing to properly fund (and in many cases, provide no funding at all) the critical technologies needed to actually get there: utilization of off-planet resources, propellant storage and transfer, aerobraking and aerocapture, nuclear power and propulsion, in-space assembly, artificial “gravity,” and others.

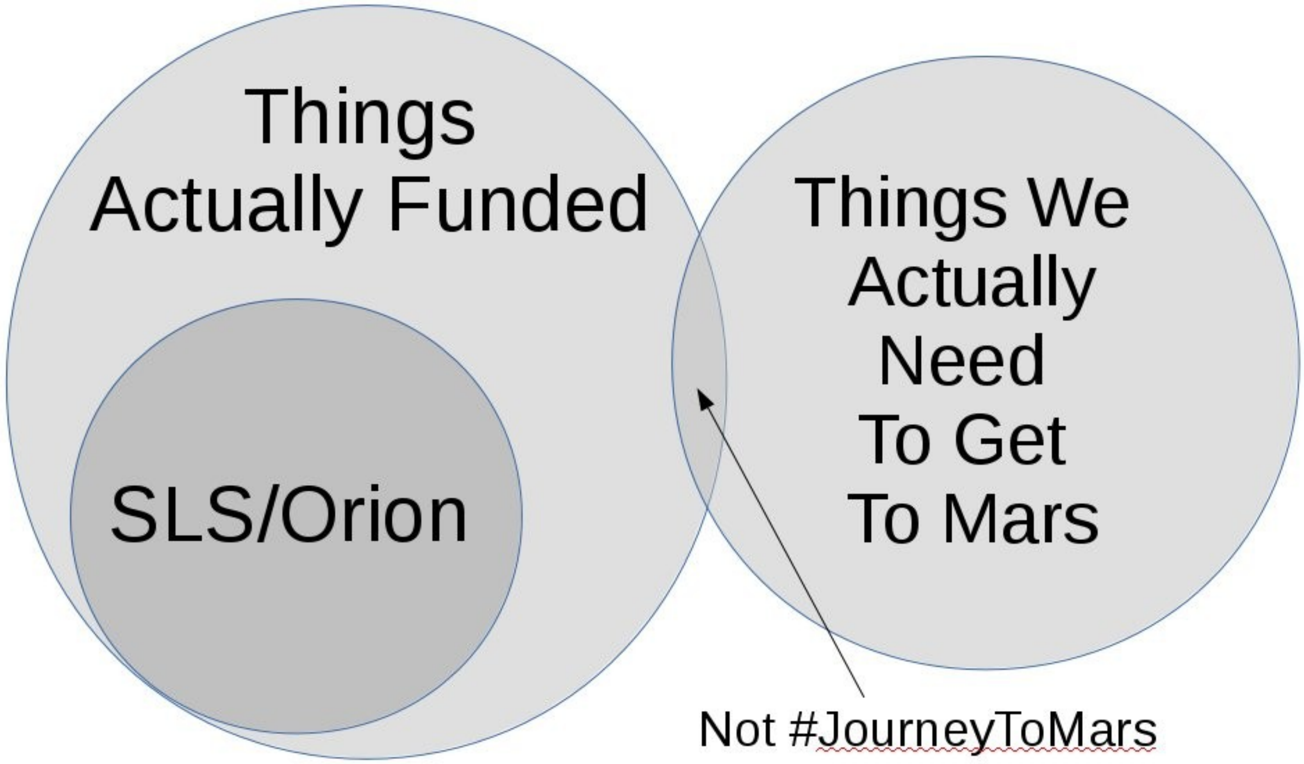


Figure 3. NASA's Problem With #JourneyToMars

Figure 3 displays a Venn diagram I created to show why there is no #JourneyToMars. The intersection of the two large circles represents NASA's Mars plans, such as they are or, rather, are not.

So it is a fraud on a young generation now, just as it was on another (mine) half a century ago. Until we can abandon these futile beliefs, we will not make progress in government human spaceflight, if such a thing should indeed even exist in an era of private tycoons with their own plans for humans in space, and in the continuing absence of any compelling reason for the taxpayer to fund it other than to pay off politicians in key states and congressional districts.

I hope that this document will play some role in starting to raise public consciousness about this issue. Most people don't have any deep interest in spaceflight, but for those who do, they should come to understand that their blind support of Congress's and NASA's plans will not achieve their goals, but continue to hinder them.

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Appendix: False Dawn

The 1950s were an age of what seemed to be technological marvels, and the United States of America (USA) had great technological self confidence, with its recent victory in the world war, the harnessing of the atom, jet aircraft, X-rays, radar, television, computers, the defeat of polio, and other feats. Beyond that, while WW II had left much of the industrialized world in ruins, the USA had been spared the carnage to its manufacturing infrastructure (not to mention its civilian population), so as it generously paid to rebuild its former enemies in Europe and Asia, the nation had become a superpower, standing astride the free world.

It was also an age in which many of its young people had grown up reading the hard science fiction of Robert Heinlein, Isaac Asimov, Arthur C. Clarke among others, and were expecting more technological breakthroughs to come, particularly in the area of space travel. This was reinforced in the early part of the decade by German rocket engineer Wernher von Braun who, in collaboration with *Colliers* Magazine and Walt Disney, familiarized the public with the topic of spaceflight. But in fact, had you asked even the boldest of them in say, 1954, whether men would walk on the moon within a decade and a half, they would have scoffed–and justifiably so.

It should be understood that, in a very real sense, much of the early space age occurred too soon. As Gene Cernan, the last man to walk on the moon (so far) later wrote, it was as though you'd reached into the twenty-first century, grabbed a decade, and plopped it down into the sixties and seventies. Even though writers of fiction and nonfiction alike had theorized for decades about putting objects into orbit, and even though work was already underway in 1954 to launch small, unmanned satellites, the notion that we could develop so rapidly the capability to put men on the moon on a politically feasible budget would have seemed ludicrous.

Unforeseeable in 1954 were the historical contingencies that led to the Apollo program’s conception: the panicked public reaction in 1957 in the United States to Sputnik; the young and charismatic Cold War president who ran and won on the issue of a “missile gap” with the Soviet Union in 1960; the Soviets’ success in putting the first man in orbit in the third month of the young presidency; and that president’s humiliation at the failed invasion of Cuba, at the Bay of Pigs. And who could have known that, just thirty months after announcing the goal “before this decade is out, of landing a man on the Moon and returning him safely to the Earth,” the young president would be cut down, leaving the nation—and and the next president—to achieve the goal now consecrated to his memory?

So what were those historical contingencies that led to Apollo? How did it happen? And why hasn't it happened again since, and is unlikely to happen again?

Werner von Braun was a German engineer, and early founder of a German spaceflight society in the 1930s. In collaboration with Willy Ley and Herman Oberth, other early German rocket pioneers, he started to develop rockets, based on the work of Robert Goddard in the USA.

As Hitler took over and started to build up the Nazi war machine, von Braun was essentially drafted to build weapons of war. He developed the world's first ballistic missile, called the V-2, which was used in desperation toward the end of the war to bombard Allied civilian targets. But his dreams had always been of missions to space, and on to the moon and Mars. In fact, he was once arrested by the German SS as a potential traitor to the Reich when he was overheard talking about plans for Mars missions at a party. Only the influence of General Walter Dornberger, the head of the V-2 project, spared him from prison or worse.

In the spring of 1945, as the Soviet army was advancing toward his location in eastern Germany, he made a plan, along with many of his colleagues from the program, to escape to the West and be captured by the Americans. This was to not only avoid capture by the brutal Soviets, but in the hope that the team would have a better chance of being able to continue the development of his rocket technology for more peaceful purposes.

Initially, it wasn't to be. He was put to work developing ballistic missiles for the U.S. Army at Fort Bliss in Texas, and later at the Redstone Arsenal in Huntsville, Alabama. His “Jupiter” missile, which would ultimately launch the first American satellite, was in many ways a direct descendant of the V-2 that had bombed London and Antwerp a little over a decade earlier.

But he had never lost his long-nurtured dreams of peaceful space exploration, and in the early fifties he leaped at the opportunity offered by *Colliers* magazine, a popular family venue of the time, to share his ideas with the American people. In his collaborations, he depicted fleets of reusable vehicles, with earth-orbiting space stations and assembly facilities, sending armadas of spaceships out to the moon and Mars. They used nuclear rockets for propulsion, this being the nuclear age, and it making the most sense for the job, then (and still today). It was a vision of the conquest of space.

These later became a series of animated shorts by Disney at the time it was still being run by its visionary founder, Walt Disney. They were shown on the Wonderful World of Disney, the classic Sunday-night family program, and later as educational films in the schools. They weren't just about dreams, but about basic physics as well, describing and animating the basics of spaceflight–Newton's laws, how orbits work, what weightlessness and vacuum are about. The idea was to create not science fiction, but what Disney called “science factual” movies that would introduce the public to the idea of space travel as a real possibility. Von Braun also consulted with Disney on the space rides in the Tomorrowland section of the new Disneyland theme park, which opened in California in 1955. In addition to Adventure Land, Fantasy Land, and Frontier Land, Tomorrow Land was the last “land” to be finished, because “tomorrow” was a very fluid concept. For example, it included a “flight to the moon,” which still hasn't happened for most of us. But all of this inculcated in many baby-boomer students, at an early age, the notion that exciting space adventures lay in their future.

Meanwhile, the National Advisory Committee on Aeronautics (NACA), the predecessor to NASA, and the Air Force were collaborating to build rocket planes at Edwards Air Force Base, located in the western portion of the Mojave Desert about 100 miles northeast of Los Angeles. They were planning to fly a new rocket plane, the North American X-15, into space. It would be carried to high altitude and dropped from a Boeing B-52 bomber. It would then ignite its LOX/alcohol-burning engines and rocket its way out of the sensible atmosphere. This would provide needed data on flying several times the speed of sound, and how well one could maneuver in the vacuum of space without aero surfaces, using only small rocket thrusters to orient the rocket plane so that it would properly enter the atmosphere. A decade later, these lessons would support the development of the Space Shuttle. Neil Armstrong, a former Korean War fighter pilot and the first man to walk on the moon, was a civilian X-15 test pilot for the NACA. While these test flights lacked the capability to achieve orbital velocity, it was hoped and even expected that the X-15 was just the first of a series of rocket-plane designs that would eventually get all the way to orbit, if not on their own, then as part of a two-stage system.

With all of this activity, in 1955, the same year that Disneyland opened its Mission To The Moon ride in Disneyland's Tomorrowland, President Dwight Eisenhower announced that the United States planned to launch a peaceful, civilian scientific research satellite as part of the upcoming International Geophysical Year (IGY) planned for 1958. The Naval Research Laboratory had been developing an orbital rocket named Vanguard. Though it was a Navy program, it was based on the Viking and Aerobee civilian sounding rockets rather than a ballistic missile, which reduced the appearance of a military program to more peaceful purposes. So it was made responsible for the launch of the first scientific satellite. The great venture beyond earth had begun. We were going to space!

But unfortunately, the nation's erstwhile ally in the world war, the Soviet Union, had become its totalitarian superpower nemesis in the new cold one. Not all of the German rocket engineers escaped to the West with von Braun. Many of them had been captured by the Soviets in the waning days of the war, and they became the foundation for the USSR's own missile and space program.

The Soviet Union didn't have the technological capability to miniaturize their nuclear weapons in the ways the US had, so they needed large rockets, termed Intercontinental Ballistic Missiles (ICBM), to deliver them to their targets in the West, and when it came to budgets, they had no consumers with the ability to vote to worry about. Accordingly, and of necessity, their early ICBMs were much larger and more capable than most American ones, giving them the potential to steal a march on the Eisenhower administration.

So in early October of 1957, months before the planned launch of the first US satellite, the nation's confidence in both its military strength and technical prowess was shattered when the Soviets used one of these oversized intercontinental missiles to launch Sputnik 1, the first artificial satellite ever placed in orbit around the earth. Sputnik was a 23-inch-diameter sphere with antenna rods that sent out beeping radio signals that amateur radio operators all over the world could pick up as it passed overhead.

The Eisenhower administration wasn't shocked that the Soviets had beaten us into space– they were aware of their progress from secret air surveillance from U-2 spy planes[3]. What they were surprised by was the reaction of the American public. For most, the implication was clear – if the Soviets could launch a satellite this large into orbit, sending a nuclear warhead to hit a city within the continental United States was clearly also within their capability.

In December of 1957, with an anxious nation watching live on television, the public's fears were compounded by an embarrassing failure of an attempt to place a satellite into orbit on the Vanguard rocket. The three-pound Vanguard I satellite was a 6.4-inch diameter sphere that, like Sputnik, featured extending antenna rods. But the satellite never made it to orbit as its Vanguard booster rocket exploded and burned on the launch pad just seconds after ignition.

In response, the administration authorized a go-ahead and acceleration of the Explorer program on an Army rocket, a proposal that von Braun had been making for years, but had not been previously authorized due to concern about the perception of the US militarizing space. Accordingly, on January 31, 1958, the Explorer I satellite was successfully launched atop a Juno booster, which was a modified Jupiter-C rocket that had been developed earlier by von Braun. This was followed by a successful Vanguard launch in March.

The administration decided to establish a new independent federal agency for space, deliberately civilian, to both focus the nation's efforts and to demonstrate that our intent was peaceful. The National Aeronautics and Space Administration (NASA) was chartered on

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They weren't concerned about not being first, and in fact were not necessarily unhappy to allow the Soviets to set the legal precedent of overflight of air space by satellites, which would allow them to do their own surveillance from orbit, avoiding the need to continue to do illegal aerial surveillance (which in fact later resulted in the embarrassment of the shoot-down of Francis Gary Powell's U-2 aircraft over Russia in 1960). Once the Soviets had broken the ice, so to speak, the US could pursue reconnaissance satellites with no fear of international legal challenge.

October 1st, 1958, a little less than a year after the first satellite was launched. It was initially formed from the old NACA: its research labs and wind tunnels at Langley Aeronautical Laboratory in Hampton, Virginia; Lewis Flight Propulsion Laboratory outside of Cleveland, Ohio; and Ames Aeronautical Laboratory in Mountain View, California. Other organizations were also absorbed, including the Jet Propulsion Laboratory (JPL) managed by the California Institute of Technology in Pasadena, the Vanguard team at the Naval Research Laboratory in Maryland, and the Army Ballistic Missile Agency at the Redstone Arsenal in Huntsville, Alabama. Huntsville was where von Braun's team was then based and they would develop the large rockets viewed necessary at the time to provide us with serious space capability. The new agency's first administrator was T. Keith Glennan, who oversaw the formation of the organization with its disparate facilities and cultures.

This all occurred in the context of a “space race” in which both sides vied for “firsts,” and in which the Soviets remained in the lead for the first few years, with bigger rockets, bigger satellites, dogs, and eventually the first man in space, Yuri Gagarin, in 1961. The 1960 presidential election campaign was waged in this environment, with the “missile gap” being a major issue between Democrat Senator John Kennedy and Republican Vice-President Richard Nixon. Kennedy won (closely and controversially), and was severely tested in his first few months of office.

The Gagarin flight on April 12, 1961, not even three months into the young president's first term, was yet another humiliating-to-the-US space “first” by the Soviets. This was followed a few days later by the failed attempt by the CIA at the Bay of Pigs to liberate Cuba from Fidel Castro's communist regime by fomenting a counterrevolution against Castro. The latter wasn't really Kennedy's project – the Eisenhower administration had been planning it for a year – but the buck stopped with the new president. A few week later, on May 5, 1961, America put its first astronaut, Alan Shepard, in outer space (internationally defined to start at an altitude of 100 kilometers, or about 62 miles). Shepard’s flight was a suborbital test of the Mercury capsule, launched on a Redstone booster. It traveled on a ballistic trajectory, reached an altitude of 116 miles, and then splashed down in the Atlantic about three-hundred miles down range from Cape Canaveral. In contrast, Gagarin had reached orbital velocity, and made one complete orbit of the earth (though he landed to the west of his launch site, due to earth rotation). After his capsule entered the atmosphere, he abandoned it and parachuted to the ground.

Kennedy realized that in the eyes of the world, the Soviets appeared to be more advanced than the US and he looked for a way to show the world that we were more technologically advanced than they were. Two space options were under consideration for such a demonstration: the construction of a space station in low earth orbit, or a landing on the moon. He consulted with von Braun, and asked him at which goal the nation had the best chance of beating the Soviets. Note that the question was not about how best to conquer space, but which would provide a near-term battlefield in the Cold War that we could win. Von Braun believed that the Russians were capable of building a space station in the near term, but that getting to and from the moon would be beyond them for some time to come. So the answer was the moon.

Accordingly, on May 21st, 1961, about a month after the foreign-policy fiasco at the Cuban Bay of Pigs, Kennedy announced that, “before the decade was out, the United States would send a man to the moon and return him safely to the earth.” Interestingly, it occurred in what was actually an off-calendar State of the Union address before Congress on a range of topics both foreign and domestic. The space announcement occurred almost as an aside – toward the end, and consuming less than ten percent of the words of a speech containing almost six thousand, but today it's what the speech is remembered for. In that era, the greatest war in history was still a recent memory. Kennedy and his generation had fought in it, and such a declaration, with the full might of the federal government behind it, was reminiscent to many of the Manhattan Project to develop the nuclear bomb, and the missile race of the past decade, against a threat to the nation as existential, if not more so, than the Nazis.

The effort to realize Kennedy’s goal became the biggest peaceful technology project in history, absorbing at one point four percent of the federal budget, and the motto was “waste anything but time.” To put it into perspective, this was a time when much of the federal budget was still discretionary. Social Security was still in a strong surplus, Medicare and the autopilot welfare programs of The Great Society still lay ahead, so four percent of the federal budget really meant something then. Total spending at that time was about a hundred billion dollars per year, compared to trillions today, when the dollar was worth a lot more. It would be as if, today, we were spending over a hundred billion dollars annually on NASA[4]. But such propaganda victories were viewed as a crucial part of the Cold War, and so the space race was truly on.

Three crucial decisions were made at this decisive branch point that would affect the course of human spaceflight for almost the next half century.

The first one was technical. The notion of space planes derived from the X-15 was abandoned because they were viewed as high risk in terms of our ability to get them operational – it would take too long to develop them. Instead, unreliable and expendable, but existing ICBMs were pressed into service as space launchers. At the same time, NASA, under the direction of von Braun in Huntsville, started to design from scratch the largest operational

4 The proposed NASA budget for FY 2017 is a little less than twenty billion, about half a percent of the total federal budget, including entitlements and interest on the debt.

rockets ever built to the present day, the Saturn series. ICBMs of the day (and even today) weren't designed to be as reliable as possible, because this would have cost too much, given how many were built, and it wasn't really a requirement. In order to ensure that at least one would get through any defenses, multiple missiles targeted many of the same strategic locations, so the military planners got redundancy in numbers of missiles, allowing the reliability of any individual one missile to be lower, and thus more affordable. But this theoretical level of reliability that was probably somewhere between 90% and 99% (no one really knows for sure, or ever will) was not acceptable for a vehicle that would launch humans into space, even test and fighter pilots who had probably done riskier things in their careers.

This decision had two long-term effects on space operations. The first is that it led to one of the most confusing and meaningless (at least in a modern context) concepts ever developed, which haunts us to this day: "man rating." The idea was to take ICBMs, munitions that had been designed to deliver nuclear warheads to another continent with an adequate reliability, and turn them into transportation devices to orbit with humans as payloads, with high reliability. This entailed an increase in redundancy and parts traceability (in some cases all the way back to the mine from which the ore for the metal was mined) for increased mission assurance. It also required monitoring of systems that would warn if the crew had to abort, and trajectories that would allow safe aborts at every stage of the ascent from the launch pad to orbit.

In the early 1960s, such "man rating" (now called "human rated") was applied to several rockets that included the Redstone, the Atlas, and the Titan II. No rocket built since (including the Saturn V and the Space Shuttle) has been "human rated" in this way, and none likely ever will be, because unlike those early missiles, every rocket since has been intrinsically designed for high reliability, with no need for design changes to improve it. Beyond that, the Shuttle failed to be human rated due to of its lack of abort capability for the first two minutes of flight. That is because its solid-rocket first-stage motors could not be shut down, which would be necessary in order for it to separate and fly to a designated landing site, and it had no crew-ejection capability (at least since the first four flights, after which it was declared "operational"). It was instead designed (in theory, though not in practice, as history shows) to be highly reliable, with no need for an escape system, just as airline passengers aren't provided with parachutes, because they add more weight and cost than they are worth, while not really reducing risk.

The second long-term effect of this technical approach was to lock us into a paradigm of very high launch costs, due to the fact that all of the expensive transportation systems were used only once, and then expended on each mission, and the systems were flown rarely.

The second of the three crucial decisions was one of policy and program structure. NASA's predecessor, the NACA, was not an operational agency. It did basic research in airfoils, propulsion, and other aeronautical technologies, in response to the suggested needs of the aviation industry. The only airplanes it developed and flew (in conjunction with contractors such as Bell and North American Aviation) were experimental aircraft such as the X-15, to prove out new technologies. When it was first formed in 1958, nothing in the NASA charter required that the new agency do more, except to extend the process to space technology development.

And in fact, in light of that, it's interesting to do something that few (including space enthusiasts) have ever done – to read that document. Note that it actually bears little resemblance to the agency that, in the wake of the decision to race the Soviets to the moon, suddenly morphed into the human-spaceflight behemoth that it became as a result of that decision:

> (a) The Congress hereby declares that it is the policy of the United States that activities in space should be devoted to peaceful purposes for the benefit of all mankind.
>
> (b) The Congress declares that the general welfare and security of the United States require that adequate provision be made for aeronautical and space activities. The Congress further declares that such activities shall be the responsibility of, and shall be directed by, a civilian agency exercising control over aeronautical and space activities sponsored by the United States, except that activities peculiar to or primarily associated with the development of weapons systems, military operations, or the defense of the United States (including the research and development necessary to make effective provision for the defense of the United States) shall be the responsibility of, and shall be directed by, the Department of Defense; and that determination as to which such agency has responsibility for and direction of any such activity shall be made by the President in conformity with section 201 (e).
>
> (c) The aeronautical and space activities of the United States shall be conducted so as to contribute materially to one or more of the following objectives:
>
> (1) The expansion of human knowledge of the Earth and of phenomena in the atmosphere and space;
> (2) The improvement of the usefulness, performance, speed, safety, and efficiency of aeronautical and space vehicles;
> (3) **The development and operation of vehicles capable of carrying instruments, equipment, supplies, and living organisms through space;**
> (4) The establishment of long-range studies of the potential benefits to be gained from, the opportunities for, and the problems involved in the utilization of aeronautical and space activities for peaceful and scientific purposes;
> (5) The preservation of the role of the United States as a leader in aeronautical and space science and technology and in the application thereof to the conduct of peaceful activities within and outside the atmosphere;
> (6) The making available to agencies directly concerned with national defense of

discoveries that have military value or significance, and the furnishing by such agencies, to the civilian agency established to direct and control nonmilitary aeronautical and space activities, of information as to discoveries which have value or significance to that agency;
(7) Cooperation by the United States with other nations and groups of nations in work done pursuant to this Act and in the peaceful application of the results thereof;
(8) The most effective utilization of the scientific and engineering resources of the United States, with close cooperation among all interested agencies of the United States in order to avoid unnecessary duplication of effort, facilities, and equipment.

The emphasis is mine. Note that while (c)(3) authorized the agency to "develop and operate" vehicles carrying "living organisms" (potentially including humans) *through* space, it says nothing about how they get there, and it doesn't require that NASA operate human-carrying spacecraft.

The development of the giant Saturn V was not driven by the NASA charter – it was driven by the need to kick up lunar dust before the Russians did. Take away that clause, and there is little difference between NASA's charter and what its predecessor, the NACA, did, other than adding "space" to aeronautics. The 1961 Apollo decision, in a very profound way, perverted the original intent of the founding of the agency almost three years earlier under Dwight Eisenhower. And it's interesting to point out that the controversial policy change of the Obama administration in early 2010 – to have astronauts delivered to low earth orbit (LEO) on commercial launchers while NASA focused its resources on the "development and operation of vehicles capable of carrying instruments, equipment, supplies, and living organisms *through* space" is nothing more than returning the agency to its original charter of half a century before (and prior to the wrong turn taken with Apollo).

The new agency could have continued on in the NACA model, with private industry developing space vehicles to provide services, for government or commercial markets, and NASA providing it with the key basic technologies to make it successful. But that approach, while more in keeping with our nation's successful history of affordable technology development, most likely wouldn't have achieved the president's stated objective, and couldn't be relied upon for it.

So with the new rush to get humans to the moon and back, decision makers, as already alluded to, relied on their own recent experience from the war, in which there had been a massive crash government effort funded by the taxpayer to achieve a critical national goal: the Manhattan Project to develop the atomic bomb. Given the perceived urgency of the space race in an existential Cold War, it seemed appropriate to set up a similar centralized command structure to achieve this new stretch technological objective. As a result, in essence, we established our own state socialist enerprise to compete with that of the Soviets (though, of course, rather than design bureaus, we had contractors operating under a mostly capitalistic system).

In fact, the space race was never framed as one of free enterprise versus socialism. Had it been, we might have, in fact would have *had to* have approached it much differently. It was instead framed as a competition of democracy versus totalitarianism to demonstrate which would prove more successful in a major technological achievement. And given the democratic socialist nature of much of Europe at the time (and to this day), not to mention powerful labor unions and key Democrat constituents at home, this had the additional advantage of being more politically palatable to the allies of both the nation and the White House. But it had the unfortunate effect of giving us a space program with distinctly non-traditional values for our nation, in terms of its founding principles of individualism and free enterprise and, as a result, it remains difficult for many to think of the possibility of any other way, even to this day.

Controversially, one could in fact go even further, and characterize the early U.S. space program as having characteristics of classical fascism–not the cartoon, jackboot, racist "right wing" type that is the myth of the Left, but as a continuation of the "progressive" policies that had dominated the nation's politics for over three decades since the Franklin (and earlier, even to Teddy) Roosevelt era.

In Jonah Goldberg's seminal 2008 book, *Liberal Fascism*, he points out that "...even Kennedy's nondefense policies were sold as the moral analogue of war...His intimidation of the steel industry was a rip-off of Truman's similar effort during the Korean War, itself a maneuver from the playbooks of FDR and Wilson. Likewise, the Peace Corps and its various domestic equivalents were throwbacks to FDR's martial CCC. **Even Kennedy's most ambitious idea, putting a man on the moon, was sold to the public as a response to the fact that the Soviet Union was overtaking America in science**..."

Emphasis mine. He goes on – the bracketed italicized comments are mine, to illustrate his points:

> "What made [Kennedy's administration] so popular? What made it so effective? What has given it its lasting appeal? On almost every front, the answers are those elements that fit the fascist playbook: the creation of crises [*We're losing the race to the Soviets! We can't go to sleep under a Russian moon!*], national appeals to unity [*They are our astronauts, our gladiators in the heavens! Our nation shall beat the Soviets!*], the celebration of martial values [*The astronauts were all military, the best of the best*], the blurring of lines between public and private sectors [*Systems Engineering and Technical Assistance (SETA) contracts, anyone? Cost plus? Our version of Soviet design bureaus? The cozy crony-capitalism relationships of the "iron triangle" of Congress, NASA and industry?*], the utilization of the mass media to glamorize the state and its programs [*There was a Life Magazine deal to chronicle a bowdlerized version of the Mercury astronauts' lives*], invocation of a "post-partisan" spirit that places the important decisions in the hands of experts and intellectual

> supermen, and a cult of personality for the national leader [*von Braun, and "rocket scientists." And not just Kennedy Space Center, but (briefly) Cape Kennedy, and later the Johnson Space Center*]."

Clearly, a program formed in such a sociopolitical environment, with a nation panicked, was not going to be likely to conform to more traditional and classically liberal American free enterprise and individualistic approaches.

Of course, there was that third key decision that also echoes down to the current day. Kennedy's vice president, former Senate Majority Leader (and Texan) Lyndon Johnson, was determined to use the program to help industrialize the south, much of which was still mired in poverty going all the way back to the Civil War and Reconstruction. The establishment of a manned space center in Houston, Texas (consisting of many of the NACA Langley people), the new Marshall Space Flight Center collocated with the Redstone Arsenal in Huntsville, Alabama, an engine testing facility in southern Mississippi, and the selection of Cape Canaveral on the central east coast of Florida as the launch site, all went a long way toward achieving this goal.

But as we'll see, it also had the effect, once the urgency of Apollo was gone, of turning what should have been a vibrant space program into a white-collar jobs program, with many political decisions hinging on continuing employment rather than progress into the cosmos. But few were concerned with these policy issues at the time; we were in a race to the moon. And it wasn't really about space, it was about a technological competition. It is important to understand that the opening of space as a goal in itself wasn't nationally important, and isn't to this day.

Regardless, in 1959, astronauts had been selected from a cadre of test pilots and became overnight national heroes. Now they had a goal. A vast infrastructure of test, assembly and launch facilities in Texas, Alabama, Florida and other places was constructed, and giant rocket parts rolled off assembly lines and were shipped to Florida from California and other places. Each flight would cost billions in today's dollars, but it was viewed as worth it, because we were going to space! And not just space, but to the moon!

Project Mercury was the beginning of the US manned space program. It started with two suborbital flights on Redstone boosters, followed by John Glenn's flight on an Atlas. Glenn was the first American in orbit. But recognizing that there would be a long gap between the end of the Mercury program and Saturn/Apollo, which was just starting development, NASA decided to have an interim program to demonstrate many of the capabilities needed to go to the moon. It was called Gemini.

Originally known as “Mercury Mark II” but later renamed after the twins of Greek mythology, Project Gemini started in 1965. It used a converted Titan II booster and, as its name implied, could send two men at a time into space. It was during these dozen flights that we learned and demonstrated many of the key technologies that would be necessary to carry out a lunar mission. The astronauts learned to rendezvous and dock with other vehicles, and to do “extravehicular activity” (EVA, aka space walks). On Gemini IV, Ed White opened the hatch and exited the capsule to float above the earth. As it rotated slowly below him, he traveled at seventeen-thousand miles per hour in nothing but a space suit. In Gemini VII, Frank F. Borman and James Lovell orbited in the tiny capsule for two weeks to determine if astronauts could function, both physically and psychologically, while being cramped and in weightlessness for a period of time that was a little longer than necessary to travel to the moon and back. It also established that lifting entry (that is, the ability to use the shape of the capsule itself to steer it in the upper atmosphere) was feasible, to provide cross range, with more flexibility in terms of de-orbit timing and more precise landings.

In retrospect, Project Gemini presented another crucial fork in the road to opening space.

While it had large overruns, and didn't achieve all its goals, Gemini was a cost-effective program that demonstrated many of the capabilities to not only get to the moon, but perhaps to do it even without the need for the expensive heavy-lift booster. By assembling pieces of the system necessary to go to the moon in orbit instead of lifting everything at once, we could have used relatively cheap and already developed launchers. There were many proposals from within NASA as well as from the contractors Martin and McDonnell, to continue to use Gemini as the basis for space stations, lunar orbit rendezvous, rescue vehicles and other applications, even with the development of the Saturn V. In addition, there was some interest from the Pentagon to use Gemini as the basis for its Manned Orbiting Laboratory (MOL) program (canceled in the late sixties). But once again, because the imperative was to get to the moon by the end of the decade—rather than building a sustainable foundation for human spaceflight—Gemini, with all its potential and modularity, came to an end to focus on the expensive, three-man Apollo and the mission to the moon.

As I have pointed out, and sadly for the enthusiasts, it wasn't really about space. Even the supposedly visionary Kennedy told his NASA administrator, James Webb, a few months before his assassination in 1963, “I don't care *that much* about space” (my emphasis, in the context of how much the program was costing). It was about national prestige, not space *per se*—space was just the venue in which the competition was to be fought. Had Kennedy not been assassinated, it's not clear that the Apollo program would have continued, or at least no more than it did under Lyndon Johnson who, under pressure from the Congress with the rising costs in blood and treasure from Vietnam, and the Great Society (and riots in Newark, Watts and

Detroit, and other inner cities), actually ordered the end of production of new space hardware in 1967, two years before the first landing. In fact, it was likely only the perceived martyrdom of the president who started the program that allowed it to go on as long as it did.

Beyond that, the space race was viewed as so expensive that many in the government, particularly those of a socialistic bent in the State Department, wanted to end it permanently, and in a sense they did, by signing and ratifying the Outer Space Treaty in 1967, which banned claims of national sovereignty off planet. Absent claims of national sovereignty, private off-planet property claims became, if not impossible, problematic. This had the intended effect of significantly reducing the incentive for nations to race to other worlds, including the moon. It also dramatically reduced the incentive for private enterprise to invest its own resources in doing so, even if there were some way of getting a return on the investment, by creating uncertainty in the legality of extraterrestrial property and real estate.

But as all this was happening with little attention paid by the public, Apollo remained the big story. Space enthusiasts thrilled to each milestone. There was the first Saturn V launch. Then came the flight of Apollo 8 around the moon at Christmas in 1968, which gave us the iconic earth-rise photo that quickly adorned posters in countless dorm rooms and launched the environmental movement. Then there were the lunar landings themselves. And children in schools continued to be taught that this was just the first step of many that would lead humanity out into the solar system, and beyond, with lunar bases in the 1970s, and Mars landings in the 1980s. And they'd get to go. Juan Trippe's Pan American Airlines and hotelier Barron Hilton thought that they would be flying and providing hotels for people in space in the future.

A little over a year before the first landing, in April of 1968, the Stanley Kubrick/Arthur Clarke movie *2001: A Space Odyssey* was released in theaters. Now considered a film classic, it was the most realistic science-fiction movie ever produced to that point in time, both in terms of visual presentation and technical accuracy, with Arthur C. Clarke himself on hand to make sure that no liberties were taken with physics. To the accompaniment of Johann Strauss' famous *Blue Danube* waltz, it depicted the terpsichorean approach of a Pan Am space clipper to a large rotating space station in orbit, from which the protagonist departed on a transfer vehicle to the moon. The vehicle heading out to Jupiter rotated to provide artificial gravity for its crew. It was nuclear powered, with no wings or fins or other aerodynamic surfaces, because it was a vehicle designed to live in space, never to enter a planetary atmosphere. And there were no whooshes as asteroids passed by in the vacuum of space—space is silent. For many who watched it, ignoring the mystical (and psychedelic) aspects, it seemed a realistic view of the world and solar system that awaited us a little over three decades hence.

Despite the fact that the decision to end it had essentially been made in 1967, Apollo continued on the inertia of the huge momentum built up in the early sixties. The new president in 1969, Richard Nixon, never really contemplated abandoning the initial landings, because the entire effort would have then been seen as a waste, even though we had essentially won the space race at Christmas time, 1968. That was when Apollo 8 circled the moon, and the Soviets essentially gave up, to the point of pretending that they had never been racing us to the moon at all.[5]

The first actual landing on July 20th of 1969 by Apollo 11 was an unqualified success. But in the following November, the next flight attempt, Apollo 12, was almost a disaster. The vehicle was struck by lightning shortly after liftoff, and at that point much of the telemetry was lost. Only the quick thinking of John Aaron, a flight controller who understood the problem and knew which switch to throw to reset the Apollo capsule, and Alan Bean, an astronaut on board who knew where that switch was located, saved the mission from an abort and allowed it to continue on to land on the moon and return.

There had initially been lunar missions planned through Apollo 20, and, prior to the order to end production in 1967, enough Saturn V rockets built to do that (that is, ten lunar landing missions in all). But by 1970, with the success of the two flights behind them, and Kennedy's original goal achieved, they started to be canceled, beginning with the cancellation of Apollo 20 in January, because the Saturn V assigned to it was needed to deliver the planned Skylab, a Saturn V-derived space station, to orbit.

With Apollo 13, in April of 1970, NASA came the closest it ever had to losing astronauts in flight. As a result a great and unfortunate mythology was built up about the agency, popularized in 1995 by the movie of the same name. As the film noted, the public had lost interest in the Apollo program after the first two successful flights, and few people, including the media, paid attention to it. Until, that is, on the way to the moon, the liquid oxygen tank exploded in Apollo 13’s Service Module, damaging the spacecraft and venting out into space the oxygen needed for life support. As portrayed in the movie, it was “NASA's finest hour,” in which flight controllers performed simulations on the ground, and improvised solutions to keep vital systems operational, and the astronauts alive long enough for them to complete a “free return” trajectory around the moon and return to earth. While Flight Director Gene Kranz

5 The Apollo team was in a dual race against time: the end-of-the-decade pledge made by Kennedy in 1961, and a more unknown deadline – the ongoing Soviet program. The Soviets had been performing unmanned lunar flybys with their “Zond” vehicle, and there was concern that they might beat the US to a manned flyby, if not a lunar landing itself, which would have been seen as a major propaganda defeat, reminding the public of how they had beaten the U.S. both in terms of the first satellite and the first astronaut years earlier. So NASA put a crew on a mission in October, despite the problematic second flight of the unmanned Saturn V, and then planned a new type of mission, to do everything that a lunar mission would except land (because the lunar module would not be ready for flight prior to early 1969). This was probably the gutsiest decision that the space agency ever made, before or since, because it was all about winning the race.

never actually said “failure is not an option,” it was the attitude, and it succeeded in getting the crew home. (In my book *Safe Is Not An Option*, I describe why that, while this is a good attitude to have in an emergency, it's a terrible one to have in general.)

It had the effect of creating unrealistic expectations for the agency in the years since–that there was nothing it couldn't do if it set its mind to it. This was an illusion that has been shattered since, not only by later losses of two Space Shuttle orbiters with seven astronauts on board each time, but by the bureaucratic ponderousness and cost of its subsequent programs. And it was a false myth from the beginning, because the belief didn't take into account the fact that, while Houston personnel and the astronauts did everything they had to do, and did it well, it wasn't sufficient – there was luck involved as well. The explosion occurred on the way to the moon, when they still had the lunar lander that they could use as a backup life-support system. If it had happened on the way back (and it easily could have), after the lander had been used and abandoned, they would have died, no matter how much of an option Kranz said failure wasn't.

For many, the close call reinforced the wisdom of ending the lunar flights–it was only a matter of time until a crew would be lost. In September, the Nixon administration did effectively cancel two more flights, Apollo 15 and 19, renumbering the rest to end at Apollo 17, which was the only one that had a trained scientist – Ph.D geologist Harrison “Jack” Schmitt – among the crew. But it also authorized follow-on missions to low earth orbit (LEO) from the remaining hardware, most notably Skylab, which was our first space station, that flew in 1973, and later, the Apollo/Soyuz Test Program (ASTP) in 1975, in which the Soviets and American met in space as a means of trying to tamp continuing Cold War tensions.

With damage caused during launch, *Skylab* became a harbinger of future NASA capabilities to repair space hardware in orbit, which would later be demonstrated many more times with the Space Shuttle. During ascent, one of the solar panels was torn off, along with a sun shield needed to keep the station cool. The first crew of astronauts to go up to it on a Saturn IB had to put on their space suits, erect a hastily improvised “parasol,” and deploy the remaining solar panel, which was jammed in a stowed position by debris lodged in the hinge. Their successful repair allowed Skylab to be used for two more crewed missions lasting months each before it was abandoned in 1974. It also demonstrated the value of having humans in space – even today, it's unlikely that a robot would have succeeded in doing what they did.

In the wake of the cancellation of the last two Apollo lunar missions, the nation saw the first appearance of an attempt at private spaceflight, though few were aware of it at the time.

During the sixties, Earl and Barbara Marx Hubbard (heiress to the Marx toy company fortune) had become interested in space as a spiritual venue, and the space age as the beginning of a new era on earth. In the summer of 1970, inspired by the Apollo flights, they founded an organization called the Committee for the Future, to promote their belief that it was the destiny of humankind to settle new worlds off planet. In the fall, they learned of the sudden availability of two Saturn Vs with the cancellation of the moon flights. They decided to start a citizen-based organization to raise money to fly the canceled Apollo 15H mission privately, and derive revenue by selling lunar rocks. Named “Project Harvest Moon,” the proposal was pitched to both NASA and Congress, and they even got the legendary Representative Olin “Tiger” Teague of Texas to introduce a House resolution to investigate the feasibility.

Unfortunately, due to resistance from NASA, the project never went anywhere. Marx Hubbard noted herself that “The corporate decision of NASA as a government agency was less responsive than the decision of any of its individual members.” And historically, the agency (and bureaucracies in general) often tends to take actions with which many individual employees of it disagree. It may not have worked out financially in any event, but it was the first of many attempts to democratize what many saw as a monolithic government bureaucratic smothering of private yearnings for space travel.

The Apollo era actually ended in 1979, when the *Skylab* space station ignominiously burned up in the atmosphere and tossed a few surviving pieces on western Australia and into the Pacific, because the new space program, the Space Shuttle, wasn't ready in time to save it as it had been scheduled to do. Many decried the waste of losing our first and only space station, but realistically, it was probably no longer usable anyway – it hadn't been designed for long duration in space, and it might have required a tremendous amount of work to refurbish it, costing more than just launching a new one.

Despite the sad end of Apollo, the space enthusiasts still assumed that the reusable Shuttle, which would be flying in the next couple years (it first flew in 1981, behind its original schedule of first flight in 1978), would bring in a new affordable era of space exploration and development in the eighties and beyond, including space stations and returns to the moon, and even space colonies. They little realized that in its cost-was-no-object mentality, its establishment of the false paradigm of the need for giant rockets operated by a government space agency for human space operations, and the foundation of Congressional pork for their states and districts, for all of Apollo’s technological achievements, it had laid the groundwork for continued failure into the future.