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Policy Innovation in Human Space Flight

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An overview of the status of U.S. human space flight is provided, followed by a discussion of alternative approaches and common pitfalls in planning and implementing innovations in human space flight. In many cases, NASA has been given goals that proved out of reach, politically, technically, and economically. The challenge for a human spaceflight strategy lies not in creating ambitious goals but in determining just where the frontier for policy innovation truly lies. This knowledge is important to picking a strategy that is "ripe" for success, for knowing when the time is right to press forward with a political initiative, technology development, or a business plan. The true frontier for innovation in human spaceflight, whether in technical, organizational, or policy terms, is a shifting one and problems that were not ripe for solution yesterday may be ready tomorrow. Recommendations from a U.S. perspective are made on pragmatic next steps for human space transportation.

1.0 Introduction

Human space activities are among the most interdisciplinary of activities, requiring skills from every field of technical endeavor. Their successful accomplishment requires a degree of systems engineering skill found only in the most complex and demanding programs. The ability and willingness of a nation to lead such endeavors conveys much about the nature and intentions of that society. Thus, human spaceflight continues to possess great symbolic value, both domestically and internationally, and is a matter of considerable interest to policymakers. To be relevant and valuable, however, human spaceflight goals must be challenging but achievable, not only for nations also for those with whom they would hope to partner. In this regard, U.S. plans for human spaceflight have often overreached technically, economically, and politically while missing more achievable frontiers of innovation.

The process of successful innovation – in many areas, not just spaceflight – is a complex one, with technical, organizational, and economic aspects. Innovations in human spaceflight are more than just technical inventions, they also involve the creation of public and private sector organizations that are trained and equipped to conduct human spaceflight under conditions created by governments and markets. Over time, the technologies, organizations, and economics of human spaceflight have evolved and are continuing to evolve, but successful innovation is very difficult, and rare in retrospect. Wanting, needing, and intending innovation should not be confused with achieving and sustaining it.

1.1 U.S. Human Spaceflight Today

The loss of a second Space Shuttle, the *Columbia*, in 2003 resulted in the decision to retire the fleet after completion of the International Space Station (ISS). The *Columbia* Accident Investigation Board (CAIB) recommended that "because the Shuttle is now an aging system but still developmental in character, it is in the nation's interest to replace the Shuttle as soon as possible as the primary means for transporting humans to and from Earth orbit." The Board noted successive failures of the National Aerospace Plane, the X-33, X-38, or indeed any replacement for the aging Space Shuttle, represented a "failure of national leadership."[1]

One of the most important observations from the CAIB for steps the United States should take after the Space Shuttle retirement was the following:

"With the amount of risk inherent in the Space Shuttle, the first step should be to reach an agreement that the overriding mission of the replacement system is to move humans safely and reliably into and out of Earth orbit. "

Furthermore, the CAIB offered the admonition that:

"The design of the system should give overriding priority to crew safety, rather than trade safety against other performance criteria, such as low cost and reusability, or against advanced space operation capabilities other than crew transfer."

Plans to replace the Shuttle with a NASA-led system were disrupted by the 2010 decision to cancel the Constellation program (including the Ares 1 launcher and Orion spacecraft) and shift to reliance on new private providers for both cargo and crew launch services to the International Space Station. After a protracted political debate with Congress, NASA was authorized to proceed with programs that would develop privately owned and operated means of taking humans to low Earth orbit (LEO) as well as cargo to the International Space Station. In addition, NASA was authorized to proceed with development of a spacecraft that could carry humans beyond low Earth orbit, which after some additional study was retained as the Orion program.

The last Shuttle flight occurred in 2011, and the United States is now reliant on Russia for human access to space. In addition to the cost of paying Russia for crew transportation, ISS partners are concerned with relying on a single country for access to the ISS. Multiple Russian launch failures have raised concerns that Russia's traditional strength in reliable launch vehicles may be fading. By way of comparison, the Constellation Ares 1 program had set a goal for probability of loss of crew in excess of 1:1000 with design estimates for reaching over 1:2800. In comparison, the Space Shuttle's probability of loss has been estimated at less than 1:150.[2] No other vehicles, including existing Evolved Expendable Launch Vehicles (EELV), are expected to meet the 1:1000 standard. This is not to say they cannot do so in the future, but only after accumulating flight heritage comparable to the Shuttle solid rocket motors or the Russian Soyuz. In addition, liquid propulsion systems have more moving parts than solid propulsion systems and that complexity is an additional source of risk to be overcome.

NASA cannot return to the Constellation solution of a government-designed, prime-contractor-built, Ares-1/Orion combination. That solution addressed low Earth orbit and lunar transportation in a tightly integrated way, intentionally making maximum possible use of the Apollo- and Shuttle-era assets available at the end of the Shuttle program. The conditions NASA faces today are different than those of 2008. Decisions made over the past four years have separated LEO and beyond-LEO transportation system designs. Instead, NASA is separately leading the development of government owned systems for human missions beyond LEO and financing the development of privately owned systems for human mission to LEO.

Space Launch System/Orion

Multiple space architecture studies of how humans might travel to Mars or return to the Moon have identified the cost and operational benefits of using a heavy lift vehicle. The Space Launch System (SLS) is designed to be a heavy-lift vehicle, initially capable of lifting 70-100 metric tons before evolving to a capacity of 130 metric tons. (The Apollo era Saturn V payload capacity was 127 metric tons.[3])

In July 2013, the SLS completed its Preliminary Design Review. The SLS will use a liquid hydrogen/liquid oxygen propulsion system, with a Core Stage utilizing existing Space Shuttle Main Engines for its initial capability to save near term development costs. While the first two SLS launches will use five-segment solid rocket boosters (SRBs) based on the Space Shuttle SRBs, NASA hopes to move to more advanced designs that could be either solid or liquid rockets. For its upper stage, SLS will use an Interim Cryogenic Propulsion Stage (ICPS) for the first two missions, again to save near term development costs. NASA is evaluating the phasing of advanced boosters and upper stages to stay within available budgets as well as respond to whatever missions are assigned to it.[4] A different upper stage will be needed beyond 2021 to achieve the 130 metric ton capability.

The Orion will carry four astronauts to, and support operations at, destinations beyond LEO for periods of up to 21 days. Exploration Flight Test-1 (EFT-1) is an unmanned, atmospheric entry test mission of the Orion scheduled for FY 2014. In EFT-1, Orion will conduct two orbits of Earth and reenter the atmosphere at a high speed that is characteristic of a returning deep space mission. In 2012, NASA signed an agreement with the European Space Agency (ESA) for ESA to provide a service module for the Orion spacecraft's unmanned Exploration Mission-1 in 2017. This agreement was done in the context of existing International Space Station (ISS) agreements in which ISS partners trade capabilities and services of mutual interest on a "no exchange of funds" basis. The first crewed flight of SLS/Orion, known as Exploration Mission-2, is planned for 2021. These two missions will test and demonstrate these systems, which NASA currently intends to use to send a crew to visit an asteroid that has been redirected into a stable lunar orbit.

Commercial Cargo and Crew Programs

The successful berthing of the unmanned SpaceX Dragon cargo vehicle on the Station in May 2012 (COTS Demo Flight-1), and again in October (Commercial Resupply-1), were welcome steps in restoring a limited U.S. capability to send supplies to and bring back materials from the Station. For the second Commercial Resupply mission (CRS-2) mission, a Dragon spacecraft launched from Cape Canaveral Air Force Station on March 1, 2013, carrying about 1,268 pounds (575 kilograms) of payload. On March 26, it returned about 2,668 pounds (1,210 kilograms) of samples and equipment.

There are two U.S. companies currently supporting the ISS under Commercial Resupply Services (CRS) contracts. Space Exploration Technologies (SpaceX) was awarded 12 cargo flights to the ISS, and Orbital Sciences Corporation (Orbital) was awarded 8. Orbital's first contracted cargo resupply mission under CRS is slated for September 2013 and it expected to carry up to 1,550 pounds (700 kilograms) of payload. The cargo resupply missions are crucial to maintaining the ISS, but they are not meant to carry humans to space. SpaceX's Dragon capsule has been designed with the potential to carry humans, however, and experience with cargo missions is intended to "feed forward" to crew transportation.

Since the Commercial Crew Program (CCP) was initiated in 2009, NASA has conducted two Commercial Crew Development (CCDev) competitions for industry to advance commercial crew space transportation system concepts and mature system elements. In August of 2012, NASA announced new agreements with Boeing, Sierra Nevada and SpaceX to develop and demonstrate U.S. human spaceflight capabilities under the Commercial Crew Integrated Capability (CCiCap) program. NASA plans to bring two companies to the "critical design review" stage before developing operational vehicles. If successful, the first flights by a single company could occur by 2017.

Changing Roles of Government

The Bush Administration's budget contemplated a four-to-five year gap in U.S. human access to space. The budgetary and programmatic changes made by the Obama Administration caused the current gap to grow to more than six years. NASA is no longer managing the development of human space transportation systems for access to low orbit, but still provides the vast majority of funding for these systems. This policy of providing public funds without in-depth accountability for the manner in which they are used is a major change in strategic direction from that taken after the *Columbia* accident.

There is not yet a market for human space flight if the ISS were to be lost. Given U.S. reliance on private companies for sustaining the ISS and the lack of near-term market alternative to the ISS for those companies, a major accident has the potential to end of U.S. human space flight. The changing role of government in human spaceflight may be considered both an innovation and a risk. The primary risk components are those of cost, accountability, and safety.

Cost and Accountability
The cost per kilogram performance of "commercial cargo" has been disappointing to date. Initial cost targets in 2007 were for $30-40,000 per kilogram of payload. Current contract prices are almost $60,000 per kilogram.[5] This is more expensive than the Shuttle, which could deliver payload at about $40,000 per kilogram along with seven astronauts to the ISS. In addition, that Shuttle cost is "fully loaded" while the $59,000 per kilogram under the CRS contract is a marginal cost that does not include prior NASA investment. Given that projected the price per kilogram for cargo was significantly lower than that actual price by approximately 50%, caution is warranted on projected costs for "commercial crew" seats.

Compared to traditional government acquisitions, the commercial resupply flights have been achieved at greater efficiency.[6] It is somewhat misleading, however, to call the development effort a commercial one. The term "commercial" implies the existence of private markets where private capital is at risk to support privately developed capabilities. In this case, there were no services available in the market absent the government-funded development of such a market. In the commercial cargo and crew programs, it is more accurate to say the government is engaged in an innovative form of government contracting.

NASA is providing considerable financial support on terms more favorable to the companies than would be the case under a traditional Federal Acquisition Regulations-based contract. As an example of the relative size of NASA's investment, consider the case of SpaceX. As of December 31, 2012, SpaceX had received $966.2M in the form of Space Act Agreements, COTS funding, and CRS payments for "commercial cargo" efforts. In addition, NASA had provided $524.6M for "commercial crew" to SpaceX (CCDev2, CCiCap, and CPC).[7] In addition to the almost $1.5B the U.S. government had committed to date, SpaceX invested about $200M in private capital.[8] This is not unique to SpaceX. None of the CCiCap participants are contributing more than 10 percent private capital towards their development programs but they will retain 100 percent of the hardware, intellectual property and revenue. If a firm decides to get exit the business and sell their systems and hardware, NASA will have to purchase it back from them.

Some CCiCap companies are new to the development of human space capabilities and have limited access to capital outside of NASA's payments, should they need additional resources to meet the periodic milestones agreed upon with NASA. In the event they are unable to meet these milestones due to cost overruns or technical challenges, the firm(s) may require significant additional support payments to proceed – putting the United States in the difficult position of letting a potential provider go under, or needing to secure additional budget.

Certification of these privately developed systems for carrying humans is being done under a separate contract known as the Certification Products Contract (CPC). Once certified by NASA, the agency would then buy transportation services for NASA-sponsored personnel to travel to and from the ISS from private providers on a commercial-like basis. It is possible that the firm(s) will not have systems that can be certified as human-rated after their development under Space Act Agreements (SAAs). The United States could be put in another difficult position by having to change its certification requirements or incurring additional costs to redesign the planned systems to meet NASA standards. In effect, given the high percentage of public funds involved, the CCiCap Space Act Agreements are much like conventional NASA prime contracts. However, the agency lacks the oversight and enforcement mechanisms of normal prime contracts. In a more conventional "arms length" commercial arrangement, NASA would not be so dependent on the success of any given provider. In the current environment in which there are no U.S. alternatives for human access to orbit, however, this dependence is a major risk.

Safety
The issue of specifications is particularly important to questions of flight safety. Before NASA crew or personnel on NASA-sponsored missions can fly on commercially provided spacecraft, the systems will need to be certified. In August 2012, the Commercial Crew Transportation (CCT)-1100 Series documents were updated to identify and communicate the processes, requirements, interfaces, and design standards that NASA wants commercial providers to use in developing and operating human spaceflight systems for NASA missions. NASA faces a major challenge in compiling the lessons learned from decades of human spaceflight, while at the same time not being overly prescriptive and limiting industry's ability to develop innovative approaches.

As part of the Commercial Crew Integrated Capability Space Act Agreements, the partners were asked to provide NASA with recommendations for what they believe it would take to complete a certification milestone, including an "option" to conduct an orbital flight-test demonstration —under the SAA (i.e., outside of a NASA contract)—with a non-NASA crew. Although there is precedent for contractor test flights in government aviation developments, such flights are always under the certification authority of the government (either the contracting agency, Federal Aviation Administration, or both). NASA's Aerospace Safety Advisory Panel (ASAP) raised several questions about this option, as a demo flight would be outside of NASA's acquisition authority.[9] These included the following:

(1) Would the SAA partner's demo flight be conducted outside of NASA's launch and entry certification authority?
(2) To the extent that the required FAA license would not cover crew safety systems and procedures (FAA authority is limited by statute), would any other government agency step in to certify flight crew safety?
(3) If not, would NASA be legally obligated to certify for crew safety?
(4) If the answers to (1) through (3) leave a gap in government crew safety certification, would Agency stakeholders perceive NASA as irresponsible in its sponsorship/facilitation or tacit acceptance of a high-risk activity?

The ASAP went on to comment that even if the demonstration flight were successful, the statistical relevance of one flight (or even a few successful flights) is almost negligible without a thorough understanding of every aspect of the flight data.

In sum, there are detailed and on-going discussions of how safety will be assured for new commercially provide human launch services. NASA missions pose a particular challenge in that NASA astronauts cannot waive liability as a private space tourist might. On the other hand, NASA cannot impose its traditional practices and procedures, as this would likely suppress the very innovations that NASA seeks to encourage through this new form of contracting. The use of Space Act Agreements creates additional complexities in that the cost efficiencies from reduced oversight can also limit NASA's ability to confirm the safety of the systems it needs to use.

1.2 NASA Budget Instability

Large capital investments, large fixed costs, and highly specialized technical talent characterize human space flight. The timing, phasing, and stability of funding can be just as important as the total level of funding. Unfortunately, recent years have been characterized by both lower funding AND greater volatility for human space flight. The NASA budget has been in a long-term decline in real terms since the end of the Cold War but the volatility of recent years has been especially severe. Figure 1 shows NASA budget requests since the beginning of the current Administration. By way of comparison, in constant dollars, the NASA budget in 1992 would be equivalent to about $23 billion dollars today.

The FY 2010 budget was flat and characterized as a "placeholder" pending the Augustine Committee's review of plans for human space flight in 2009.[10] The FY 2011 request released in February 2010 restored the NASA top-line to the level it had been during the previous Bush Administration –

but with a significantly different portfolio, i.e., with more funds for commercial crew development, technology, and Earth science missions. The Obama Administration's budget proposal also cancelled the Constellation program to develop the Orion capsule, the Ares I launch vehicle, and the subsequent Ares V heavy lift vehicle. These capabilities were intended to support a human return to the Moon in the early 2020s and create the foundations for eventual human missions to Mars. The Congress opposed the cancellations and protracted political struggle ensued, which eventually resulted in the NASA Authorization Act of 2010. This Act did not provide significantly different total funding for NASA, but it did restore funds to develop the Orion and the Space Launch System. The lunar focus was replaced by what NASA termed a "capabilities-driven" evolution in which various missions would be defined as new capabilities were demonstrated.

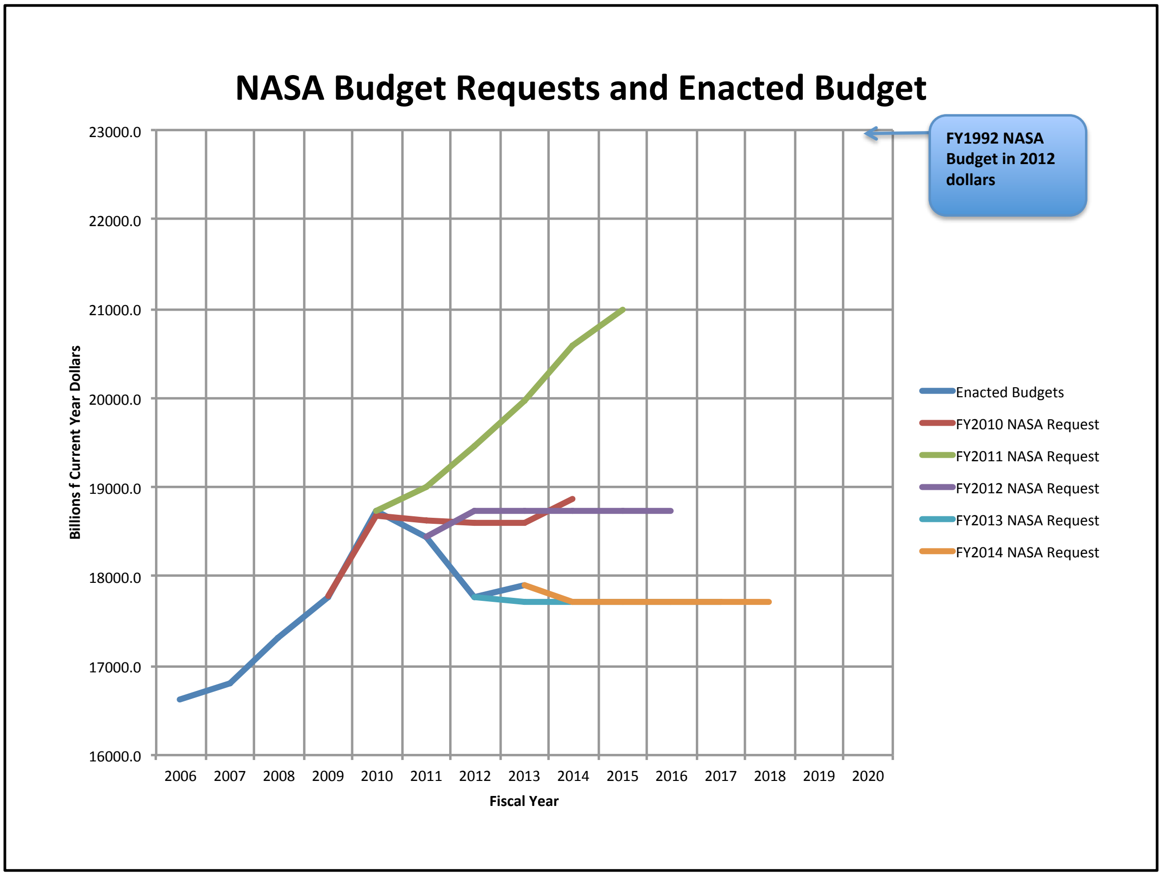

Figure 1 – NASA Budget Requests since FY 2010

The NASA budget profile again declined in the FY 2012 request. The budget was flat and at the level of the earlier FY 2010 "placeholder" proposal. The FY 2013 request declined again, with NASA now projected to be flat at even lower levels. Adding to the uncertainty, NASA and OMB did not even share the same projected spending levels in future years. In both the FY 2012 and FY 2013 budget requests, the phasing of reductions was different with near term declines and farther term increases contrasted with flat projections. The FY 2014 President's Budget Request continued to project flat NASA budgets at levels of about $17.7 billion dollars. This is virtually the same as it was for 2009. Within the NASA budget, the steady trend in human space exploration spending has also been down. The Aerospace Safety Advisory Board has highlighted funding as a "red" safety risk in its 2012 report to the Congress:

"For several years, there has been a significant gap between what NASA is attempting to do and what it is funded to do. This funding-planning mismatch, and in particular the uncertainty about future funding stability, has the potential to introduce new risks above and beyond those previously inherent in space travel."[11]

Some funding problems seem to be self-imposed. For example, NASA sets aside appropriated funds to cover potential contract termination liability on the Space Launch System and Orion. These funds cannot be used for actual work, as intended by Congress, and are in effect a budget reduction. This practice seems to be unique to SLS and Orion.

At an architectural level, funding constraints on the SLS are limiting its heavy-lift capability and thus its utility for human space exploration. The current SLS 70 metric ton "interim capability" is a test vehicle for the 2017 time frame, using an existing EELV (Delta 4) upper stage. Human exploration missions to the Moon and beyond require an upper stage capable of lifting 120-130 metric tons. This capability is required for lunar landers and other exploration elements. If the correct upper stage is not developed, then more launches of smaller vehicles and complicated in-space assembly will be required -- significantly increasing mission risk. For example, a human Mars mission would take about six 130 metric ton SLS vehicles in comparison to dozens of EELV class vehicles.

Funding constraints are also impacting the "commercial crew" program. NASA is currently supporting three contractor teams. Two of those teams, Boeing and SpaceX, were awarded $460 million and $440 million, respectively, last August to develop rival capsules. A third team, Sierra Nevada Corp., was awarded $212.5 million, an amount that puts the firm's winged spaceplane design on a trailing development schedule.[12] To date, Congress has been unwilling to fund the program at the level NASA argues is necessary to support multiple teams on a schedule that would enable crew transportation services by 2017. If NASA wants to keep to the 2017 date, as seems likely, then a selection of just one contractor in the near future will be necessary.

Finally, as the most recent example of a planning/funding mismatch, the FY 2014 NASA Budget Request proposed spending $105 million for an Asteroid Redirect Mission (ARM). This mission would redirect a 7-10 meter sized asteroid into cis-lunar space where astronauts using an SLS/Orion combination could visit it. This would meet the 2010 National Space Policy goal of sending astronauts to an asteroid in the 2025 time frame in a potentially feasible and affordable way.

The $105 million ARM request would be the initial payment for a mission that could cost $3 billion or more. The initial funding burden is to be distributed across the agency with $20 million in the planetary science line for efforts to locate asteroids (in addition to $20 million already planned); $45 million in the space technology line for development of high power solar electric propulsion and other technologies; and $40 million in the exploration account for studies. It is not clear what future offsets in planetary science, space technology, and exploration would be required.

A comprehensive workshop on the scientific, engineering, and programmatic aspects of ARM was held at the National Academy of Sciences on July 9, 2013. Participants noted that the mission does not meet scientific priorities specified by the National Academies. Save for the survey work, it is only weakly relevant to planetary defense against large asteroids. Most importantly, it does not have a clear connection to a longer-term human space exploration strategy. There is little apparent opportunity for international partnership or commercial participation. From a budget perspective, the ARM mission schedule was seen as too aggressive when coupled with technology development, mission complexity, multi-center implementation and funding uncertainties.[13] On the last point, Gentry Lee, the chief engineer for solar system exploration at the Jet Propulsion Laboratory, said "The schedule is not obtainable unless the mission goals are made laughable."[14] Not surprisingly, the Congress appears reticent to provide funding for ARM as currently understood.[15]

The NASA budget is ultimately a political choice – it is a reflection of what the United States values. In constant dollars, the Administration's stimulus program was greater than NASA's budget from 1958 to 2008. The United States sent humans to the Moon, built and operated a Space Shuttle fleet for 30 years, explored the solar system, and contributed its share of the International Space Station for less than the cost of the 2009 American Recovery and Reinvestment Act. The point of such a comparison is that sustaining discretionary expenditure for human space exploration requires a clear rationale linking such efforts to national interests that can be supported in a bipartisan manner. This has not occurred in recent years.

2.0 Real Reasons, Acceptable Reasons, and Magical Thinking

The central elements of the current U.S. approach toward human spaceflight are found in the 2010 National Space Policy, which says that the NASA Administrator shall "set far-reaching exploration milestones. By 2025, begin crewed missions beyond the moon, including sending humans to an asteroid." Unlike the carefully crafted text on national security and foreign policy, this section appears to have been directly taken from an April 15, 2010, speech by President Obama at the Kennedy Space Center in Florida. Certainly it was not shaped by any prior technical assessment, as subsequent work has shown that there are few, if any, scientifically attractive asteroids that could be reached on this schedule.

The international space community, which had been shifting attention to the Moon in anticipation of that being the next U.S. focus of exploration beyond low Earth orbit, felt blindsided. Countries in Asia, such as Japan, India, China, and South Korea saw the Moon as a challenging but feasible destination for robotic exploration and a practical focus for human space exploration, a goal offering missions in which they could reasonably expect to play a part. The proposed asteroid mission is not, and was therefore taken as a (perhaps unintentional) sign that the United States was not interested in broad international cooperation, but would focus on only the most capable countries, such as Russia. The perception that the next steps in human space exploration would be too difficult to allow meaningful participation by most spacefaring countries undercut international support for human space exploration more generally. The lack of U.S. support for a program to return to the Moon made it difficult for advocates of human space exploration in Europe, Japan, India, and elsewhere to gain funding for any efforts beyond the International Space Station. The ISS is itself under budget pressure to justify its construction and on-going operations costs, a task that has been made more difficult by the lack of a clear direction for human space exploration beyond low Earth orbit.

In contrast to the destination decision, the Administration was quite deliberate in its decisions to cancel the Constellation program and increase funding for the development of privately owned and operated cargo and crew transportation systems to low Earth orbit. The "commercial cargo" program is a continuation of an effort begun by the Bush Administration. The "commercial crew" program was envisioned as well, but was to be funded only after successful demonstrations of cargo delivery to the International Space Station. The Obama Administration has accelerated the funding of "commercial crew" efforts in parallel with "commercial cargo," while continuing efforts on the NASA-led Orion and Space Launch System projects at the insistence of Congress.

Understanding what the United States is seeking to do can be more clearly understood through funding decisions rather than policy statements. There is no organized effort for human space exploration beyond the International Space Station, as there is no real funding or sensible plan for such an endeavor. There is, however, a clear industrial policy to create new U.S. providers of cargo and crew services to low Earth orbit to replace government capabilities. Using the ISS as a captive early market, the hope is that new providers would provide lower cost services to meet government needs, and also be able to stimulate new demand with lower prices, compete for non-government payloads, and thus contribute to U.S. economic growth. If this approach fails, the loss will not be seen as too great, as U.S. human access to space today is not truly considered a truly strategic asset in the same way that having a Navy or Merchant Marine would be.

Arguments can be made in support of the current "capability-driven" and industrial policy approach to human spaceflight – with advocates believing this to be realistic in a tight fiscal environment. There are also beliefs that reliable access to space can be achieved at dramatically lower cost with known technologies, and that this will stimulate major new commercial space activities. The growth of private space activities, such as space tourism, would in turn make government-funded missions of exploration and technology development more affordable and thus more likely.

There are risks in the industrial policy approach, e.g., the United States is reliant on the economic success of private service providers. Through the intergovernmental agreements pertaining to the International Space Station, U.S. partners share this reliance. Should there be further delays in providing adequate cargo transportation to the ISS, a reduction in crew size may become necessary. This would reduce ISS utilization effectively to zero, as most crew time would be dedicated solely to maintaining the facility. More seriously, should there be a "bad day" on the Station, this would not only be a disaster for NASA, but also an end to the near-term market for the "commercial crew and cargo" companies. It would be very difficult to restart a U.S. human spaceflight effort without the pull of the ISS partnership, and it is unlikely that private firms could recreate a human spaceflight capacity without U.S. government demand.

The removal of NASA-led programs, the lack of self-sustaining private markets, and the need to ensure the success of private providers for missions of national importance have made the U.S. "portfolio" for human spaceflight much riskier than had earlier been the case. Despite these risks, supporters of current policy implementation have an optimistic view of the future for human space activities. Unfortunately, this optimism is built on a chain of assumptions and in a pattern that has historically failed when applied to human space activities.

At multiple times after the end of Apollo, the U.S. space community has tried different approaches to human spaceflight, each time falling prey to mistaken assessments of political, technical, and market risks. For years, the space community has sought a repeat of the Kennedy experience – a Presidential speech, robust funding, and ambitious achievements – without understanding the unique historical and political context of Apollo. President Reagan called for a space station 1984, but the program survived congressional cancellation by one vote less than a decade later. When President George H.W. Bush gave his Space Exploration Initiative speech in 1989, on the 20th anniversary of the Apollo 11 landing – the initiative quickly ran into opposition from Congress and even some parts of NASA. The Vision for Space Exploration called for by President George W. Bush in 2004 did not survive in the Obama Administration, despite the support of Congress, NASA, and most of U.S. industry.

NASA has a history of technical optimism – an attribute of its "can-do" culture. Under OMB pressure in the 1970s to prove its proposed Space Shuttle would be cost-effective, the agency committed to high flight rates that would amortize the large development costs. These flight rates, once a month for each of five Shuttle Orbiters, were wildly optimistic. Even after the first flight in 1981, projections of a flight every other month for a four Orbiter fleet were considered "nominal" – until the loss of *Challenger* forced a reexamination of the government policy to rely on a single launch system. Placing all U.S. payloads on a single launch system at artificially low prices resulted in a dangerous dependency for national security payloads and effectively stunted the ability of private providers of expendable launch vehicles to compete.

Technology optimism occurred again in the 1990s during plans to create a successor for the Shuttle. Of three competing designs for an experimental vehicle that could lead to a reusable replacement for the Shuttle, NASA picked the most technically ambitious one: the vertical takeoff, horizontal landing, single stage design termed the X-33. Compounding the risk, NASA and Lockheed entered into a "public-private partnership" that was intended to lead to a commercially competitive variant, termed "Venture Star." Realizing that a high flight rate was (again) necessary to justify the high development cost associated with unproven technology, advocates cited the expected demand for launches of large constellations for mobile satellite services. Unfortunately, launch technology again proved more challenging than expected, the rapid spread of terrestrial cellular phone service undercut demand for satellite-based phones, and the dot-com crash dried up capital for high-risk ventures. The program ended in 2001.

The situation today has echoes of the past. The White House and Congress are in conflict over the direction of human spaceflight, NASA is officially optimistic about the technical risks in creating a new vehicle capable of carrying humans, and industry is officially optimistic on the future private sector demand. Unlike the past, however, there is now a $100 billion plus international facility in orbit without an operational Space Shuttle. The private capabilities in development do not require technological breakthroughs, but they do require government funding, and the government has no alternatives if they fail.

In case after case, NASA has chosen (or, more accurately, been given) goals that proved out of reach, politically, technically, and economically. The challenge for a human spaceflight strategy lies not in creating ambitious goals – that has been done repeatedly at the highest levels – but in determining just where the frontier for innovation lies at a particular time. This knowledge is important to picking a strategy that is "ripe" for success, for knowing when the time is right to press forward with a political initiative, technology development, or a business plan. Having goals is not equivalent to having a strategy for achieving them.

The powerful symbolism of human spaceflight has historically led the space community to confuse what it wants to be true with what turns out to be true. High flight rates are needed to gain program approval, so high flight rates are built in as a requirement. Reusability is believed to lower launch costs so multiple complex engineering challenges to reusability are accepted. Fiscal constraints increase so it is assumed that private investors can be induced to provide capital. Public funds are given to industry to induce the provision of public goods in innovative ways.

In one of his speeches as NASA Administrator, Mike Griffin discussed what he called "real reasons and acceptable reasons" for human spaceflight.[16] Real reasons are personal motivations that attract people to the field – for example, the desire to make a difference in a project of historical significance, the desire for self-challenge and competiveness. Acceptable reasons are those motivations found in policy documents, such as national security, foreign policy, economic growth, and scientific knowledge. The two kinds of reasons are often conflated in the minds of the space community, but personal or "real" reasons, however powerful, cannot make a justifiable claim on public funds. Until human spaceflight can be fully financed and executed privately, it will have to be in the service of a larger public good, and "acceptable reasons" will be needed.

Not surprisingly, the search for a justifiable public good has been a torturous one since the space community realized that the reason it supported the Apollo program was not the same reason President Kennedy wanted it. The 1970s saw advocates for space solar power as an answer to the energy crisis of the day. The 1980s saw advocates of massive space industrialization to support space-based strategic defenses against the Soviet Union. The IT boom of the 1990s saw enthusiasm for launching clouds of small satellites. Today, we see enthusiasm for a new generation of space entrepreneurs who seem on the verge of historic shift to privately driven space activities – free of past political frustrations and limits.

While space-based commerce is growing in the provision of services such as direct-to-home television, the economics of space transportation are unlike other forms of transportation. Demand is thin with relatively few transactions, large fixed costs and high capital exposures, requirements for ultra-high reliability, and non-market competitors such as foreign governments. Applying market solutions while under non-market conditions is asking for disappointment. Parts and components developed for terrestrial commercial uses should not be expected to automatically meet the demands of space operations, technically or economically.

The tension between real reasons and acceptable reasons has routinely created what might be called magical thinking. Calling space a "frontier" carries with it symbolic imagery of other frontiers, such as the American West, but not necessarily Antarctica. Creating government incentives for commercial space transportation can be rationalized in analogy to past forms of transportation in the American experience, such as railroads and air transportation. Experience with rapid improvements in consumer IT leads to expectations that other forms of technology, such as space transportation can experience rapid, revolutionary change.

While individuals may believe they are behaving rationally or making the best of a difficult situation, logical fallacies in past decisions are not hard to find. There are mistakes in judgments of technological and political readiness and misplaced historical and economic analogies. Space technology is not IT and it is not aviation – it is harder, more complex, and more interdisciplinary. Space is not a physical frontier that is open to individual effort, but a truly alien environment that requires organizational as well as individual genius to master. Thinking otherwise is to experience "nostalgia for the future" – a future that reflects our expectations rather than real possibilities.

3.0 An International Approach to Human Space Exploration

While many supporters see human spaceflight as "inevitable" or "part of human destiny," those views are not widely enough held to ensure stable political support. At the same time, there is a level of support for the symbolism of human spaceflight and a sense that it may have longer-term practical value that make U.S. political leaders reluctant to cancel such efforts or to be seen as supporting such an action. Human spaceflight (if not pure exploration) may one day become a self-sustaining commercial activity, but that day has not yet come. The choice of a strategic approach to human spaceflight is thus a public policy question since, at the very least, public resources are involved.

Historically, the most common motivation for human spaceflight has been geopolitical. Today, new space actors are present who have the potential to affect the sustainability, safety, and security of the space environment and thus impact U.S. interests in space. These actors also lack experience in major space projects with the United States. A "geopolitically-driven" approach would seek to create incentives for them to align their space interests with those of the United States. For example, Asian space agencies have shown a common interest in lunar missions as the logical next step beyond low Earth orbit. Such missions are seen as ambitious but achievable and thus more practical than missions to Mars and more distant locations. They offer an opportunity for emerging and established spacefaring countries to advance their capabilities without taking on the political risks of a competitive race with each other.

A multinational program to explore the Moon, as a first step, would be a symbolic and practical means of creating a broader international framework for space cooperation. At the same time, the geopolitical benefits of improving intra-Asian relations and U.S. engagement could support more ambitious space exploration efforts than science alone might justify. Europeans were also interested in being part of a return to the Moon -- and as recently as June of last year, Russia proposed an international lunar program with the United States and publicly supported this position at international conferences.[17]

There are major policy and budgetary pressures against human spaceflight in the each of the major spacefaring nations, with the possible exception of China. In Japan, changes in space policy priorities are resulting in greater emphasis on national security and commercial uses of space relative to science and human space exploration. European interest in human spaceflight has never been strong aside from the International Space Station, compared to scientific missions such as a Mars sample return. The budget of the Canadian space agency has been dramatically reduced in the past year. Russia is also facing budget pressures and is facing increasing concerns about the reliability of its launch systems. India has moderated its ambitious plans for human missions, including flights to the Moon, while not forswearing them.

Proceeding at moderate pace, China has steadily gained human space flight experience since the launch of their first astronaut in 2003. China has conducted multiple flights to a manned space lab and appears on track to have a 60 metric ton space station, similar to the former Russian *Mir*, by the early 2020s. Work on robotic lunar landings and sample returns are proceeding, as are studies of a possible human mission to the Moon. Ironically, the Chinese space station may be deployed at about the same time that the International Space Station is reaching the end of its operational life.

The International Space Station has been a clear technical and diplomatic success, but it is not year clear if it will be a scientific success or how it will contribute to future human space exploration. All the partners are concerned with the challenges of utilizing this unique facility that has been built at great effort and expense. ISS utilization is important to being able to make a data-driven decision by about 2018, only five years from now, on whether to beginning budgeting in fiscal year 2020 for retirement and disposal. It is doubtful the Station can be operated beyond 2028 due to limitation on the lifetime of core modules built in the late 1990s.

For the United States, we might hypothetically assume that if ISS operating costs are moderate, say, $2 billion per year, and the scientific and technical results are excellent then the ISS will be continued beyond 2020. On the other hand, if operating costs are high, say, $4-5 billion per year, and the results of utilization are modest or disappointing, then a decision will be made to wind down ISS operations. It is possible, but unlikely, that significant private sector revenues would be generated by ISS utilization, sufficient to offset a significant portion of the operating costs. Commercial utilization would be welcomed and encouraged, but it is more likely that public benefits from science and technology application will determine the ISS operating lifetime.

After the ISS, the United States could potentially withdraw from human spaceflight, save for oversight of private sector activities and modest on-going scientific research. Private sector human spaceflight might develop on its own, but this seems unlikely without the market demand created by government funded exploration and scientific activities serving larger national interests. Alternatively, the United States might take a more integrated approach in which the seemingly separate threads of human, robotic, civil, commercial, and national security space activities are integrated into a geopolitical approach to human spaceflight.

Despite global volatility and uncertainty in plans and programs for human space exploration, an international consensus seems to be forming on important points:

- Mars is an ultimate destination for human exploration. Missions around Mars or to the Martian moons are less difficult than landing on the surface.
- Utilization of the International Space Station is the highest near term priority for the ISS partners.
- Human missions to an asteroid need greater and scientific technical definition.
- Human missions to the Moon offer a wide range of opportunities for international and private sector participation.
- Demonstration of human operations in cis-lunar space would be of value to a wide variety of future missions.

These views are reflected in the work of the International Space Exploration Coordination Group (ISECG) that was sent up in 2007.[18] The latest version of the group's document, the Global Exploration Roadmap, states:

The roadmap includes a single mission scenario reflecting the common strategy that begins with the International Space Station and expands human presence into the solar system leading to human missions to explore the surface of Mars. .... It demonstrates how early capabilities can achieve a variety of missions in the lunar vicinity, responding to individual and common goals and objectives, while working together to enable sustainable human space exploration.[19]

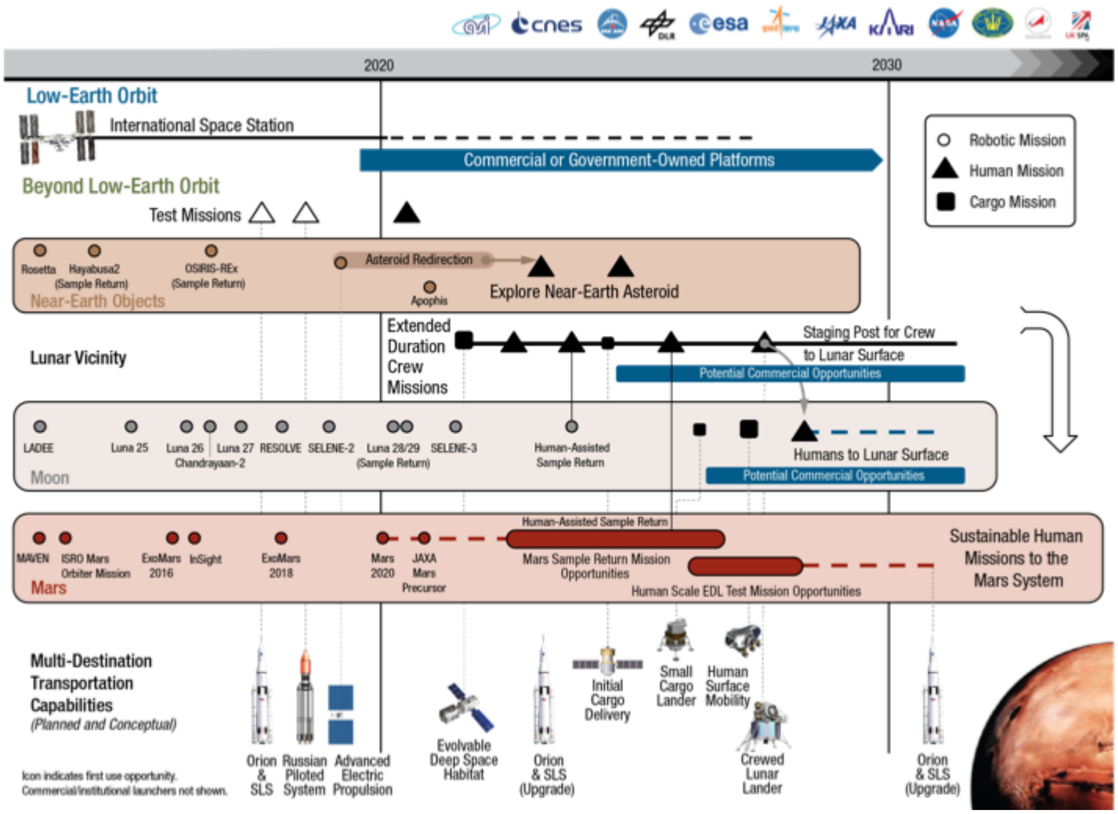

Figure 2 – Single Mission Scenario

The single mission scenario is shown in Figure 2. Note that this scenario still includes missions involving near Earth asteroids as well as activities near and eventually on the Moon. Previous version of the roadmap contained two major scenarios, both ending with human missions to Mars. One scenario showed human missions to an asteroid first, followed by Mars, while the second had human missions to the Moon occurring first. The "asteroid first" scenario reflected the U.S. Administration's position after the release of its 2010 National Space Policy, but it was not a path that attracted much international support. The "Moon first" scenario was more popular but it was not an approach that NASA could embrace. Without NASA support, other space agencies were also ambivalent. They would be willing to cooperate with NASA in an effort to return to the Moon but would not go there without NASA. Again, the exception to this pattern is China. The Chinese position was that they were open to international cooperation in human space exploration, but would continue their independent efforts regardless.

The United States will host a ministerial-level International Space Exploration Forum (ISEF) in Washington, D.C. on January 9, 2014. This meeting follows on the European Union-hosted International Space Exploration Dialogue held in Lucca, Italy, in November 2011. The purpose of the meeting is to build support at the political level for international cooperation in space exploration. In contrast to the competition of the Cold War, many countries have space capabilities that can potentially contribute to space exploration. This includes recognition that there are a growing number of with ambitious plans for space operations, including human spaceflight. As with the more technical ISECG, the ISEF is a forum for informal policy discussions among major spacefaring states.

A useful outcome for the ISEF would be greater international consensus on a strategy for the next steps in human space exploration. Given the fiscal constraints experienced by all spacefaring states, a repeat of the Apollo model looks unlikely. Rather, human spaceflight beyond low Earth orbit will take place in an international context, with potentially greater roles for private sector enterprises. Thus dialogues like the ISEF are important to determining what states are capable of doing, and what they are interested in doing, and what they are willing to do. Greater clarity on exploration priorities and sequences by space agencies would in turn make for better research, development, and programmatic decisions by participating states.

4.0 Conclusions and Recommendations

Human space exploration is at a crucial transition point with the end of the Space Shuttle program and the lack of clear objectives beyond the International Space Station. Technical and policy innovations are possible – and needed them in human spaceflight. Finding the actual frontier for innovation in human spaceflight can be difficult, however as technical, economic, and political conditions change. Some problems may not be ripe for solution, but will require other innovations to occur first. "Magical thinking" can make visionary possibilities more attractive than less ambitious but achievable realities.

An ISS "senior review" process in preparation for fiscal year 2020 NASA budget formulation is likely to be the next major decision point for human spaceflight. As with the *Columbia* accident, leading to the retirement of the Space Shuttle, the retirement of the ISS or even its continuation for a few more years, will raise fundamental questions as to the next steps and strategic rationale for human spaceflight. These questions will include the role of international cooperation, the relative roles of the public and private sectors, and how and why humans will venture beyond low Earth orbit.

Human missions to asteroids or Mars are beyond the practical capabilities of almost all potential partners (save perhaps Russia). If there is to be serious effort at engaging international partners, a lunar-based architecture is most likely to emerge as the next focus of human exploration. In addition, a lunar focus would provide practical opportunities for using private sector initiative, e.g., cargo delivery to the lunar surface. This could be done in a manner similar to International Space Station cargo delivery, but it would represent at least an order of magnitude greater addressable market even for an initial lunar base with the same number of crewmen as the Station.[20]

Public and private budgets will be a continuing, driving constraint for the foreseeable future. As a result, technical, managerial, and even regulatory measures will be needed to control costs while delivering results. For existing U.S. vehicles, such as the EELV and future vehicles such as SLS, the most expensive elements are the engines. Promising efforts to reduce engine costs and thus long-term operating costs include industry partnerships to develop new engine designs and updated production lines to create drop-in replacements for existing engines.[21] In addition, attention is needed as to what roles and responsibilities potential partners will want. As an example, growing out of the ISS partnership, ESA will be providing two service modules for the Orion program. Other examples of possible cooperation include the "Liberty" vehicle using U.S. solid rocket boosters and European liquid propulsion upper stages, or Japanese development of engines for a lunar lander.

A fundamental truth for government space programs is that budgets are policy. So the first consideration for any policy choice and implementing architecture is that it be funded – with clear priorities on which schedules and performance goals will be relaxed if resources are not forthcoming. To do otherwise is to imperil mission success and it would be more realistic to do and say nothing. Near-term actions should include the following:

- Develop a measurable strategic plan for effective use of the International Space Station in research and testing that prepares for future exploration.

- Develop a coherent roadmap for human exploration of space, based on stakeholder objectives and participation, including international collaboration.
- Reestablish lunar exploration as the highest near-term priority of the human space exploration strategy, with international partners and increasing roles for commercial providers.
- For the United States, accelerate development of the Space Launch System, including the Upper Stage and Advanced Booster needed for human exploration missions, i.e., 130 metric ton capability. The United States should eliminate the burden of reserving funds for termination liability on the SLS and Orion programs.
- Actively work on reducing operating costs for all space transportation systems, with particular attention to rocket engine production.
- The United States should select a single credible crew transportation provider to make most efficient use of constrained budgets. Further, it needs to ensure that the crew transportation solicitation includes provisions for technical and fiscal accountability and oversight.

There are remarkable opportunities for achieving innovating new capabilities and partnerships in human spaceflight. At the same time, it is possible that the capabilities built at great cost in both money and lives lost, could slip away. The choice is ours to make.

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