2

A Fast Track to Deep Space

Plans to put boots on the surface of Mars have been on the drawing board for decades. In the 1960s during the Apollo Era, the public anticipated that astronauts would be visiting Mars in the early 1980s, but in the United States, the euphoria of the first Moon landing faded quickly. The Americans had won the space race and their attention moved to more pressing earthly issues. The Vietnam war was a festering wound that needed urgent attention and the Watergate scandal plunged the nation into a deep reassessment of its core values. In 1973, the nation, along with most of the Western economies, was engulfed in an energy crisis driven by the Arab oil embargo, a crisis that touched all citizens in their most sensitive spot; their pocketbooks. Gasoline and heating oil shortages became commonplace, with long lines of thirsty motor vehicles patiently waiting for fuel at filling stations and prices skyrocketing overnight. Faced with all this, fanciful missions to the Red Planet were as far away as the planet itself.

In the intervening decades leading up to the present, global attention has shifted away from space to more pressing issues at home: terrorism, economics, energy and climate change. In the United States, the initial driving force for space exploration – military supremacy in the sky – was greatly diminished by the political collapse of America's only credible space competitor, the Soviet Union. Today, with more than half a million objects orbiting the Earth, space activity has morphed into a more complex ecosystem with a much larger and diverse set of stakeholders, including a growing number of space-faring nations and commercial satellite operators; a business opportunity in a growing $300 billion market. The machinery of global communications, spawned in large measure by the space age and later lubricated by the Internet, has, perhaps unexpectedly, democratized space. As a result, countries like India and China have built domestic space programs and rocket launch capabilities that rival those of the more established players, the US, Russia, Europe and Japan.

The United States has been slow to recognize and adapt to this organic transformation. Cargo and human transport to low Earth orbit (LEO) became technologically mature in the 1990s and needed to be privatized. Yet it was not until the turn of the 21st Century that the nation initiated a Commercial Orbital Transportation System (COTS) program to spur the private sector into providing these services more cost-effectively and efficiently, via Public Private Partnerships (PPPs) which could better leverage public funds. The sustaining cost

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of the old paradigm on an $18 billion dollar US civil space budget has been high, leaving very little wiggle room for deep space exploration. It is therefore no surprise that, half a century after humans visited the Moon, the date for a potential landing on the Red Planet has been pushed back to sometime in the 2030s.

Fifty years after Apollo, the problems associated with deep space travel remain as clear and present as they were in the 1960s. Amazingly enough, in the United States, the approach to their resolution also appears to be frozen in time. The technology of deep space transportation has advanced little, due to very low investment in new, "game-changing" systems, such as solar- and nuclear-electric propulsion (SEP and NEP, respectively). In the United States, the main transportation elements for deep human space exploration remain strikingly similar to those of Apollo: a very large chemical rocket and a capsule capable of returning a small human crew back to Earth from a point not much farther away than the Moon. The lion's share of the Mars mission architecture remains in the planning stage – where it has been for decades – and, while its transportation strategy does leave the door open for a nuclear-thermal option, the nuclear-electric approach has not been seriously explored. This is an omission of considerable significance, an arguably naïve and unsustainable strategy which needs to be re-examined, given what humans have learned from half a century of space flight.

The operational challenge of safely transporting humans to Mars and back is fundamentally different from a journey to Earth's Moon. Our Moon orbits the Earth, so missions to the Moon technically never completely leave Earth orbit. The Earth is always at the same distance and, in the event of a major malfunction, conveniently no more than 3-4 days away. The same is not true for a journey to Mars, as both Mars and the Earth orbit the Sun and their relative distance changes constantly – and by a much larger measure – over the course of two years. With current chemical rocket technology, typical one-way transits to Mars can take between 7-9 months, depending on fuel and rocket performance. Upon arrival, because of the long transit, the crew must await more than a year for the opening of the return window. This constraint imposes severe requirements on the reliability and survivability of the crew support infrastructure. There is no argument that such reliability could eventually be achieved with organic refinements of current technology. However, it would be foolish not to examine adjacent space transportation technologies, such as high power SEP and NEP, that could substantially change the operational landscape and enable a more rapid and sustainable Mars exploration program.

To be sure, getting to Mars is not the problem; getting to Mars *fast* is. Thus, the Mars debate centers around two important questions: Should we go to Mars now, or should we focus on developing the transportation technologies that will ensure a robust and sustainable program? On the one hand, one could argue that despite the long journey times inherent with conventional propulsion, Mars can be explored, maybe even colonized, with present technology. To many who wish to go now, the radiation threat associated with the long journey is acceptable; moreover, through the experience of ISS, the human space program has now developed the means to tackle many of the other human health and crew habitability issues associated with the mission. On the other hand, with current transportation technology, orbital mechanics and the sheer length of the flight produces a mission architecture that is operationally fragile. In addition, the ISS research continues to uncover as yet unexplained issues of concern in human physiology associated with long duration space flight.

In the post-Apollo era, the US debate on the journey to Mars has been fueled by these deliberations for many years. It has produced multiple embodiments of Apollo-like programs that have all stalled when confronted with budget realities. To avoid this pitfall, it is important to recognize the new chemistry of space. The US-Soviet dipole of the 1960s no longer exists. The forces driving space exploration are now truly global, commercial, economic and political, and with an increasing number of space-faring nations deeply involved, genuinely multinational. A sustainable human Mars exploration program must reflect all these elements and take advantage of this new paradigm. The exploration and colonization of Mars and other deep space destinations is no longer the business of one or two superpowers, but of all the people of Earth; a fact that could be turned into a major resource multiplier. In addition, rather than being a nationalistic Apollo-like stunt, the journey to Mars should take a more practical route by constructing a multinational scaffolding of technology-based transportation; one whose robustness is based on multiple players with overlapping – and even competing – capabilities and not solely on the nationalistic pride and political will of one nation. Such a construct could generate tangible commercial, scientific and economic dividends along the way, well before a landing on the Red Planet. For example, one could envision more cost-effective space logistics delivery, in-space resource utilization and commercial mining of space natural resources as potential benefits.

A TIME FOR CHANGE

In the last few years, the US space program has begun to address these elements with a renewed emphasis on high power electric propulsion, which could naturally evolve from solar to nuclear power sources. High power electric rockets, such as the VASIMR® engine and variants of the Hall thruster, have reached an advanced technology readiness level (TRL) and are poised to be demonstrated in space soon. These, and others still in early development, could provide the aforementioned scaffolding to Mars, while enabling revenue-generating business opportunities in efficient, low cost space transportation closer to home.

Advanced space transportation development must be a technology continuum, running from the near-term more mature systems to the more speculative ones, but always subject to rigorous, well-qualified scientific vetting and experimental verification. While it would be foolish to dismiss futuristic propulsion concepts, relying on matter-anti matter reactions, thermonuclear fusion and space-time warps, these systems, just like all the others, must respond to rigorous scientific scrutiny. Too distant a visionary outlook can be a detriment to progress, as it distracts attention from the middle ground, where new technologies do accrete into practical systems that could be early precursors to the more futuristic ones but can now be experimentally demonstrated and characterized. In fact, focusing too much on the far future is often a way to keep it from becoming the present. Disruptive technologies not only disrupt technologically but also financially, affecting funding streams to established programs and ultimately people. Therefore, to the established paradigm, it is non-threatening to support advanced technologies as long as they continue to remain in the realm of the future, where funding needs are minimal. This reality is often the reason why the middle ground is generally sparsely populated. The established paradigm resists change by clinging to the purse strings. It is thus important to recognize and address this pitfall.

It is also important to recognize that new technologies, such as high temperature superconductors, plasma engineering, nuclear power, advanced materials and manufacturing – all of which could be relevant to NASA's mission – often originate outside of NASA. Therefore, appropriate mechanisms for integrating these advances must be preserved through strong inter-agency programs and public-private partnerships that foster innovation and creativity while preserving scientific rigor.

High power electric propulsion is a case in point. Its genealogy has roots in the field of gaseous electronics as well as thermonuclear fusion, both of which were peripheral to the early NASA, who mainly focused on chemical propulsion. The space agency did undertake some preliminary incursions in these fields, with the work of Harold Kaufman on a variant of the "duoplasmatron" plasma source that led to the modern ion engine. In the late 1960s and 1970s, the space agency also delved briefly into radio frequency (RF)-heated plasmas and controlled fusion, with its research on the NASA-Lewis Bumpy Torus Experiment at the Lewis Research Center (now the Glenn Research Center at Lewis Field) in Cleveland, Ohio.

Early work on the VASIMR® engine was initiated at the MIT Plasma Science and Fusion Center (PSFC), as a non-fusion variant of the Tandem Magnetic Mirror fusion concept, with design features borrowed from magnetic divertors present in Tokamak fusion experiments. As we discuss extensively in the chapters that follow, this early work continued for more than a decade before the system was moved to NASA's Johnson Space Center. Another high power electric rocket, the Magneto Plasma Dynamic (MPD) Thruster, was originally developed in the late 1950s and early 1960s as a plasma injector by John Marshall at the Los Alamos National Laboratory and Hannes Alfvén at the Royal Institute of Technology in Stockholm. The device was known as a Marshall Gun and had applications in experimental plasma physics and the early work in controlled fusion. Later development on the thruster variant of this system was carried out primarily at Princeton University's Department of Mechanical Engineering and later at the Jet Propulsion Laboratory (JPL), a university laboratory closely associated with NASA. The pioneering work on the Pulsed Inductive Thruster (PIT) originated at Northrup Grumman, before the research was pursued by the NASA Marshall Space Flight Center (MSFC) in Huntsville, Alabama. Preserving this strong synergy of the space program with academia, national laboratories and private industry is essential to prevent scientific stagnation and technological inbreeding within NASA and to ensure a healthy accretion of new ideas and discoveries that are also scientifically well vetted and will enable advanced propulsion systems to eventually reach the mainstream.

CHARTING THE GLOBAL PATH TO SPACE EXPLORATION

The foregoing discussion should not project the impression that chemical propulsion is obsolete. Much to the contrary; for the foreseeable future, chemical rockets will remain the best and only practical means of leaving and landing on a planet. The technology of these systems has evolved over many decades to an exquisite level of refinement. The next generation of chemical rockets will enhance reusability and reliability and also reduce cost, all of which are necessary to deliver the optimal scaffolding for deep space exploration.

Although chemical rocket propulsion is a mature technology, and thus is well poised for cost reduction by the stimulation of strong commercial competition on a global scale, its widespread use has been hindered by international restrictions stemming from its military applications. That the rocket was introduced to the world as an instrument of mass destruction is sad and unfortunate. Perhaps humanity has matured sufficiently in the 21st Century, to recognize its value as an instrument of our survival. One would hope that unnecessary international restrictions will gradually disappear as more nations acquire rocket know-how or develop it indigenously. While orbital-capable rockets in the 1960s were the sole purview of the United States and the Soviet Union, nearly a dozen nations have this capability today, a number that is sure to grow quickly if a competitive, revenue-generating global market promotes it. The science and technology of rocket propulsion is today sufficiently well understood, to the point that nations with technologically well-educated populations should be able to master low Earth orbit space flight with moderate capital investment. As interesting examples, private companies such as SpaceX, Blue Origin and XCOR, in rather short timespans, have developed their own indigenous rocket technologies.

Just as space becomes truly multinational, the traditional role of the private sector in space is also beginning to change, from that of a mere government contractor to that of a government partner. This is a healthy evolution that fosters competition and will tend to increase efficiency and reduce both costs and technology maturation time. Humanity is increasingly dependent on a space infrastructure that supports global communications, provides situational awareness to people all over the planet and monitors the state of its life support system. The maintenance of these assets represents a $300 billion business with a lot of room to grow. Such growth can help finance a healthy and sustainable expansion of humanity into space.

In charting humanity's route to deep space, a great deal of debate has ensued regarding the role of the Moon and whether or not our natural satellite should be the next logical destination. It clearly is. We are, in fact, fortunate to have such an excellent proving ground so close to hand for the technologies that will enable astronauts to venture far into the solar system and learn to work efficiently on another world. As a convenient site for testing multi-megawatt plasma engines, the Moon is second to none, and Ad Astra Rocket Company intends to build a rocket test facility on its surface for long-duration tests of multi-megawatt VASIMR® engines under solar- or nuclear-electric power. These tests would become prohibitively expensive and complex in Earth-bound vacuum chambers or free flying spacecraft. Yet they will be required to certify these high power electric engines for long duration operation at full power.

We have spent a great deal of time talking about going to Mars, but looking through the optics of Apollo and conventional propulsion. In the meantime, other technologies have matured that could fundamentally change the architecture of the mission. In high power electric propulsion, these include high temperature superconductors, compact and high power solid-state RF technology, advanced materials and manufacturing, solar-electric power generation, nearly zero boil-off cryogenic propellant storage, advanced controls, and many others. These technologies should have been folded into the space transportation equation years ago. Unfortunately, this process was inhibited partly by the overly "operational" mind-set permeating much of the Space Shuttle Program in the 1980s and 1990s. During this period, the US space agency's long-term strategy for the nation's deep space transportation became fragmented and dispersed; nuclear-electric space propulsion and power has been explored with a great deal of institutional fear. This unfortunate condition may finally be abating with the new Space Technology Mission Directorate (STMD), recently established at NASA. With a sufficiently visionary and enlightened leadership, this centralized technology coordination entity could have the wherewithal to bring about the space equivalent of the "Nautilus Paradigm."

Finally, the focus on Mars has obscured the fact that several other solar system destinations also beckon humanity: the moons of Jupiter and Saturn, where water is now known to be abundant, may provide even more tantalizing opportunities for the existence of life and, with fast and robust space transportation, human explorers may be quickly drawn to these destinations. Journeys to these more distant worlds will indeed be long. They will be well beyond the capabilities of chemical or nuclear-thermal rockets and will require fully autonomous nuclear-electric ships with advanced life support systems and a nearly unlimited range, resulting from the long-lived nuclear fuel and the use of local resources. A power-rich nuclear-electric architecture will bring about these capabilities. The development of nuclear-electric propulsion and power is an urgent need that should not be postponed in the haste of reaching Mars, as without it, humanity will not be able to truly free itself from the bonds of Earth.

In the chapters that follow, we shall describe the history of the VASIMR® engine, from its genesis in the early 1980s to its present highly advanced technology maturation stage. There are many important lessons in this historical journey, but one that stands out is that the implementation of new ideas requires not only a sound technical base, but also a strong dose of persistence.

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