NATIONAL SPACE COUNCIL

USERS' ADVISORY GROUP

Assessing the Utility of a U.S. Strategic In-Space Propellant Reserve: Economic Development in Low Earth Orbit and Cislunar[1] Space

National Space Council Users' Advisory Group
Economic Development and Industrial Base Subcommittee
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[1] Defined here as the region of space between the Earth and the orbit of the Moon.

Purpose

This paper discusses the potential for a new and significant commercial economy to be created in space, with particular focus on how the United States Government (USG) might both stimulate and secure it by way of an in-space propellant reserve, maintaining America's leadership in space and enhancing our global economic position.

Background

We will soon reach a moment in time where both America's industrial capabilities and our understanding of space, the Moon, and near-Earth objects (NEOs) will make it possible to establish significant commercial activities in this region. Space has several unique attributes: microgravity, hard vacuum, radiation, natural resources, novelty, and its location as a global high ground. There are several new economic activities that can be derived from these unique attributes. These include specialty manufacturing, industrial research, tourism, energy, and natural resource mining.[2] For example, there are a number of useful and high purity materials that can only be practically manufactured in space where the influence of gravity to separate materials by density or prevent complex microstructures is eliminated.[3]

One significant potential in-space economic activity is industrial development of the retrieval of natural resources from space, recently recognized as a key aspect of U.S. and international activities in space.[4] Over the last 50 years it has been discovered that many useful materials exist on the Moon and NEOs. Solar wind volatiles, particularly hydrogen, helium (including the fusion fuel ^{3}He), carbon, and nitrogen, exist in the lunar regolith in significant concentrations and are the most readily available resources.[5] Iron, silicon, aluminum, magnesium, chromium, calcium, nickel, titanium, and trace amounts of molybdenum, rhenium, and other metals are the building blocks for in-space construction, eliminating the need to bring everything from Earth at high cost and logistical difficulty.[6] Water can be produced from water-ice present at the lunar poles or by heating the hydrogen-rich regolith. For example, deployment of resilient habitats, environmental control systems, transportation systems, and power generation and transmission capabilities on the Moon and NEOs that are necessary for long-term, sustainable space exploration and development[7]

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[2] Weinzierl, M. (2018) "Space, the Final Economic Frontier," *Journal of Economic Perspectives* 32, no. 2 (Spring 2018): 173 – 192.
[3] Downey, J. P. (2016) "Microgravity Materials Research," in A Researcher's Guide to the International Space Station, NASA ISS Program Science Office, July 6, 2016. https://www.nasa.gov/sites/default/files/atoms/files/np-2015-09-030-jsc_microgravity_materials-iss-mini-book-508c2.pdf
[4] The White House (2020) "Executive Order on Encouraging International Support for Recovery and Use of Space Resources". April 6. https://www.whitehouse.gov/presidential-actions/executive-order-encouraging-international-support-recovery-use-space-resources/
[5] Schmitt, H. H., 2006, Return to the Moon, Springer, and references therein.
[6] Lewin, S. (2018), "Making Stuff in Space: Off-Earth Manufacturing is Just Getting Started," Space.com, May 11, 2018, https://www.space.com/40552-space-based-manufacturing-just-getting-started.html
[7] The White House/National Space Council (2020), "A New Era for Deep Space Exploration and Development". July 23. https://www.whitehouse.gov/wp-content/uploads/2020/07/A-New-Era-for-Space-Exploration-and-Development-07-23-2020.pdf

will require and spur industrial activity making use of such metals, together with volatiles and other materials. Because of the low gravity of these bodies, it is hoped that these deposits are accessible and, therefore, can be extracted, although the very low gravity of NEOs present significant production challenges. Production of life-support and propulsion consumables from solar wind volatiles on the Moon are possible within the next decade or so. While development of the industrial capability to access and make use metals and other materials "in situ" (on site) will take longer, designing and securing the infrastructure that supports it is a task that should not continue to be postponed: The nation that first profitably develops these resources will secure a position of global economic and geopolitical leadership for generations to come.

Transportation

Because of the vast distances of space, transportation is one of, if not the, key practical elements required to develop these resources and return them to Earth for use. Unfortunately, the cost of space transportation is currently very high and effectively inhibits the initiation of this space economy. Today's costs are approximately $10,000/kg to $50,000/kg to take material to and through space, depending on destination and the size of the rocket (larger rockets being somewhat more efficient relative to this measure, by virtue of their scale).

The cost of transportation in space is driven by factors that are somewhat different than here on Earth. The distance to be transited from one point on the globe to another is an important factor on our planet. Distance in space, however, is largely irrelevant with respect to cost. Space transport costs are driven by the mass and heavily influenced by the gravity of the bodies that are traveled between. While relatively easy to transit between asteroids with low gravity, the cost to transit in and out of Earth's gravity well – and that of other planetoids – can be a major cost factor.

Today, everything we use in space is carried there from Earth. This includes propellant. Rockets are the primary means of space transportation and a rocket, unlike a terrestrial vehicle, is mostly propellant. For ships, trains, planes, and trucks, the cargo is a significant portion of the total mass of the vehicle, with the fuel usually being the smallest portion. Rockets are exactly the opposite: 80% of the mass of a typical rocket is propellant and often only 1% or so of its initial mass is the cargo. If propellants were available in space, the cost of in-space transportation could be significantly reduced, depending on the burdened cost of production, thus potentially enabling meaningful economic development.

Space Resources for Propellant

Fortunately, it has also been discovered that the raw material for manufacturing propellant in space also exists there in abundance. The most readily available rocket propellants currently in use are oxygen and hydrogen, the building blocks of water, with oxygen and methane also potentially competitive. It is now known that water, in the form of ice particles, resides in large quantities at the poles of the Moon and on NEOs. It is estimated that over twenty billion metric tons of water exists at the lunar poles. Water also can be produced directly from the lunar regolith through the combination of solar wind hydrogen with the oxygen in glass and mineral particles. Water's availability, both on the Moon and other bodies throughout the Solar System, such as asteroids, moons, and other planets, makes it the "crude oil of space."

Once extracted, there are several methods for converting this water into propellant. Perhaps the simplest one is electrolysis. When electrical current is passed through water, it readily breaks down into oxygen and hydrogen. This is a common high school chemistry experiment that many children perform every year. While the power requirements for extraction and processing of lunar volatiles (for example) is significant, electricity could be generated for this process in space via solar, nuclear, fuel cells, or other means.

In-Space Propellant Reserve

The factors described above provide an opportunity for the USG to take a single, high leverage action to help enable the eventual development of a new commercial economy – specifically, the creation of a U.S. Space Propellant Reserve, modeled after the U.S. Strategic Petroleum Reserve (SPR). Propellant is a necessary commodity upon which all manner of in-space operations depends – among them, on-orbit operations and operations in deep space, emplacement of in-space communications infrastructure, safety of crew members and passengers, and rescue. Such a reserve would facilitate these functions as well as enable three key outcomes.

First, it would stimulate economic development by reducing uncertainty regarding availability of propellant, enhancing confidence for governments and private interests alike. Secondly, it would buffer U.S. future in-space economic interests from temporary interruptions in supply. Finally, a reserve would also provide a significant means to help stabilize a future space commodities exchange, in which forward purchases (futures) of commodities such as water, oxygen, hydrogen, metals, and propellant, could be traded.[8] All of these commodities are driven by transportation; therefore, investing up front in a strategic reserve can enable greater predictability in access, delivering, and utilizing them, creating some assurance and greater security in commercial activity.

These three outcomes would also help to address the growing aspirations and intentions of other nations to establish leading positions in the economic and strategic use of Cislunar space. China, for example, shares with the U.S. a determination to achieve a leading position in Cislunar space, viewing it as of immense strategic value and also as a means to develop economic value by participating in – or dominating – a space-based economy via the development of solar power and resource utilization/exploitation.[9]

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[8] Cahan, B.S., Pittman, R. B., Cooper, S., and Cumbers, J (2018) Space Commodities Futures Trading Exchange: Adapting Terrestrial Market Mechanisms to Grow a Sustainable Space Economy. New Space, September 1. Retrieved at https://www.liebertpub.com/doi/abs/10.1089/space.2017.0047?journalCode=space

[9] U.S. – China Economic and Security Review Commission, "China's Ambitions in Space: Contesting the Final Frontier," in *2019 Annual Report to Congress*, November 2019. https://www.uscc.gov/sites/default/files/2019-11/Chapter%204%20Section%203%20-%20China%E2%80%99s%20Ambitions%20in%20Space%20-%20Contesting%20the%20Final%20Frontier.pdf

As on Earth, the presence of a strategic reserve would protect U.S. interests – whether public or private – from potential disruptions in the production or transport of this crucial commodity. More broadly, the creation of space commodities exchange, which has been recommended as a means by which "…the United States drives the creation of international standards for interoperable space commercial space capabilities,"[10] will require foundational elements that could include government-backed financing models as well as space-based infrastructure that would support the exchange.

Alternatively, USG stimulus of private sector investment in a Strategic Propellant Reserve, through initial tax policy, loan guarantees, and/or being a confirmed anchor customer, might have advantages over a government-owned Strategic Propellant Reserve. It could be less costly to the taxpayer than a government owned and managed reserve as well as providing additional symbiotic commercial opportunities.

On Earth, the SPR holds over 700 million barrels of crude oil. It protects the U.S. from interruptions in supply of not less than 90 days. The Department of Energy administers the reserve under the control of the President. It was established via a USG investment of $5B in infrastructure and through the initial acquisition of $21B of crude oil. Today, it both provides a backstop to manage disruptions in supply and generates revenue through sales and exchanges both to USG customers and to other, commercial entities with whom it contracts.[11]

This government or private infrastructure, and its resulting commercial propellant availability, could be a critical enabler in the creation of the full spectrum of economic activities in space. This single action of the USG could stimulate the creation and growth of an enormous new economic activity, and ensure America's leadership across the globe and beyond, while also improving the economic stability of the world economy and improving the general state of human dignity that would naturally result.

Recommendations

This paper is a first step exploring the concept of a strategic in-space propellant reserve; however, to develop it the concept should undergo further detailed study including the trade-offs between a government or private approach. The following recommendations are offered:

1) The National Academy of Sciences, Engineering, and Medicine may be a logical body to undertake the task of conducting a detailed study. The Academies bring a breadth of disciplines and natural synergy with the topic of space by virtue of their role with NASA in performing the Decadal Surveys as overseen by the Space Studies Board[12] - particularly those focused on planetary science. Additional expertise resides in the Aeronautics and

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[10] Ibid, pg. 360.
[11] Office of Fossil Energy, "About the SPR," Energy.gov, https://www.energy.gov/fe/services/petroleum-reserves/strategic-petroleum-reserve
[12] Space Studies Board of the National Academies of Sciences, Engineering and Medicine: The Decadal Surveys. https://sites.nationalacademies.org/SSB/SSB_052297

Space Engineering Board and in their history of extensive study of human spaceflight topics.[13]

2) A comparable study by another entity such as the American Institute of Aeronautics and Astronautics, in cooperation with representatives from the commercial space, energy and investment industries, might be commissioned to fully examine a private sector approach to a strategic in-space propellent reserve. The two studies would then provide decision-makers with a broader context in which legislation could be proposed to Congress.

3) Topics to be considered in these studies could include the following:

- The advantages and disadvantages to a government reserve versus a non-government commercial reserve;
- The location and size of reserves required to stimulate and sustain economic growth;
- Required technical means to develop, build, and provision the reserves – to include assessment of the viability and timeline for in-situ propellant manufacture;
- Connection logistics standards, e.g. development of international standards for equipment needed access to and transfer of fuel;
- Transport and storage of propellant from Earth;
- Identification and characterization of potential markets, with an understanding that nascent markets may be difficult to model;
- National security implications and requirements, including impacts of a reserve upon both 'hard' and 'soft' security concerns;
- The investment required, modeled in light of the aforementioned variables; and
- Potential funding models.

Reviewer Comment

The following comment was provided by a member of the UAG upon review of this paper.

(1) I would suggest that we might want to reach back to the historical analogy of "water stops" along the transcontinental railroad system when steam trains were mostly used. These tanks were positioned so that the steam locomotives could fill up with their "fuel," which was then converted into steam through the burning of coal, thus converting that marvelous plant-based fossil fuel into energy in yet another amazing way. https://en.wikipedia.org/wiki/Water_stop

Maybe rather than the last sentence of the first paragraph under "In Space Propellant Reserve," we could include this historical analogy by saying:

"An historical analogy might be made in terms of the age of steam locomotives. Water tanks were stationed along railroad tracks to provide water for steam so that trains, otherwise limited in range, could travel across vast distances. Similarly, space-based water or other propellant

[13] See for example, "Pathways to Exploration", 2014. https://www.nap.edu/resource/18801/deps_088247.pdf

storage tanks strategically placed would put the solar system within reach. Such platforms would also facilitate the aforementioned functions and enable three key outcomes."