

Implementing an ISAM National Strategy

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I. Introduction and General Considerations

The Office of Science and Technology Policy's Request for Comments¹ regarding an In-space Servicing, Assembly, and Manufacturing National Strategy² implementation plan contains five questions that correspond to the sections below.

Many of the recommendations are issues at the heart of how to maintain the progress of the US space sector (both commercial and governmental), the most fundamental of which is that applications beyond Geosynchronous Earth Orbit (GEO) often involve sequencing actions where each action depends on others being done first with no single action being capable of enabling progress. The classic example is missions will not be designed to be refuelable unless there are fuel depots but fuel depots can't be financed if there are no missions willing to use them.

In previous decades the assumption was that only Governments could afford to develop space because of the amount of capital necessary. If costs had stayed as high as they were prior to the enablement of the commercial launch industry that assumption would remain to be true. Lower launch and spacecraft build costs have now enabled commercial markets that have attracted significant private capital:

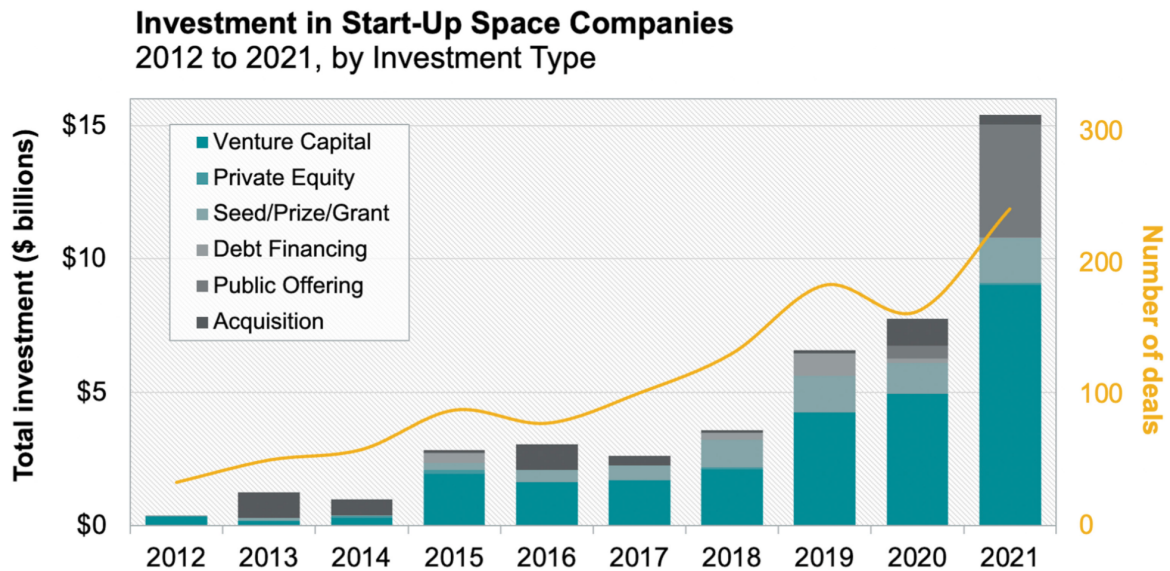


Figure 1. Investment in Start-Up Space Companies. Start-up space ventures attracted over \$15 billion in total financing during 2021, breaking the \$7.7 billion record set in 2020 (see Figure 1). In addition, 2021 was a record-setting year for the number of start-up space deals (241, up 48% from 2020), recipients (212, up 46%), and average deal size (\$64 million, up 35%).³

The chart above demonstrates that *access to capital is not an issue if there is some evidence that commercial markets actually exist*. When demand in those markets is unclear and products and services are inhibited by the circular sequencing actions discussed above, that capital will decide to wait for someone to solve that problem. That someone can be the Federal Government if it creates incentives that are limited in scope, exempt from FAR as much as possible, and are 'mechanical' in nature. A 'mechanical' incentive is one where no Agency or committee exercises

judgment over which company receives an incentive or not, e.g. if the product or service is delivered then payment is sent regardless of any other consideration. Mechanical incentives are one way to prevent rent-seeking behavior.

II. R&D Focus

What specific technologies and capabilities require priority R&D focus to enable and advance the development of a suite of commercial ISAM capabilities over the next 10-15 years?

A. Less ‘R’. More ‘D’

Over the past decade, NASA and DoD have awarded several cycles of SBIR/STTR solicitations related to many ISAM technologies and capabilities. Unfortunately, there has been little coordination between awards and programs to advance those capabilities beyond TRL 7. Nascent ISAM technology and service providers require less Research and more Development in the form of missions, interoperability programs, and “bake-offs”.

As the very early Internet began to grow in the late 1980s the number of TCP/IP-based hardware and software products became numerous enough that interoperability testing became impossible for any single user to manage. In 1988 the Interop conference was established as a companion to the IETF and other standards organizations to provide real-world, hardware-in-the-loop interoperability testing. These brutal bake-offs significantly accelerated not just time to market for vendors but adoption by customers as integration costs dropped.⁴

The establishment of an industry lead Interop-equivalent would significantly accelerate the commercial availability of ISAM technologies and services

B. Technology Development

While the following general technology areas could benefit from some additional R&D funds, dedicating significant budgets to speculative R&D for an imagined ISAM market could slow down the development of that market as businesses chase Government R&D dollars rather than customer revenue. ISAM R&D should follow the industry-focused model of the aeronautical side of NASA and its predecessor, NACA.

1. Cryogenic and non-cryogenic storage and transfer of liquids and solids

While there have been significant developments with the storage and transfer of both cryogenic and non-cryogenic liquids in zero gravity over the past few years, there is little operational testing. NASA and DoD should begin technology demonstration flights that mimic full operational profiles as soon as possible. The goal should be to mature as many ISAM technologies and services to TRL 9 as possible.

2. Attachment and coupling of electrical and mechanical interfaces

Multi-vendor electro-mechanical interface interoperability tests should begin as soon as possible. NASA/DoD should investigate a joint ISAM testbed co-orbital with the ISS where ISAM tests can take place using ISS launched and recovered systems.

3. Dense in-space nuclear power

Many in-space manufacturing processes require dense power that solar panels may not be able to provide. NASA and DoD should cooperatively accelerate the use of small modular nuclear systems specifically for ISAM applications.

4. Non-debris creating additive and subtractive manufacturing in-vacuum/zero-g

There is very little development-oriented research in manufacturing complex, high-strength structures and components in either zero-g or vacuum. Basic research in tooling, cooling, vacuum welding prevention, “chip” prevention and collection, etc should be encouraged across all space-related technology R&D.

III. Enabling Infrastructure and Resources

What infrastructure, ground, space-based, or digital, or other non-monetary resources will be critical to enabling the advancement of ISAM capabilities and the commercial ISAM industry?

A. Picosecond position, navigation, and timing service (PNT)

Position, navigation, and timing (PNT) services are key enablers for spacecraft navigation and communications. High-resolution PNT services allow spacecraft to cooperate over very long distances in cislunar space and beyond which is critically necessary for a transition from RF to laser communications. System-wide PNT coupled with sub-picosecond clock synchronization between spacecraft enables very close automated proximity operations between multiple spacecraft.

B. Commodities depots and delivery infrastructure

Discussed in detail in Section IV and in the Appendix, a commodity storage and transportation network in cislunar space both incentivizes a transportation infrastructure and provides reliable access to the commodities that any major facilities may require without incurring the direct costs of launch from Earth.

IV. Economic and Policy Factors

What factors (*e.g.*, demand for services, lack of regulation, government funding, USG space priorities and space architecture decisions, significant debris event) may accelerate or decelerate progress in the development and advancement of the ISAM industry?

Much of the growth in the space sector over the past decade has been in LEO since all of the closeable business cases exist on Earth. As many have pointed out, there are few business models that justify the development of space resources and infrastructure for use in space.⁵ One widespread hope has been that reducing the cost components of space transportation infrastructure would make some resource extraction markets economically viable but so far, no math suggests that is feasible.

A. Strategic Space Commodities Reserve (SSCR)

The lack of any commercial demand-pull for anything beyond GEO will decelerate ISAM adoption since the most cost-effective solution for improving the capacity of a LEO satellite is to replace it, not service it. This lack of beyond GEO demand-pull is the largest sequencing action coordination problem in the commercial space sector. One well-known solution to solving such sequencing action problems is for one player in the market to temporarily act as both sides of the market (e.g. the chicken also pretends to be an egg).

One possible program that would satisfy these various requirements is a Strategic Space Commodities Reserve (SSCR). The Reserve is a proposed program where the US Government acts as an in-space commodities market maker by purchasing a set number of commodities at specific transportation points within cislunar space. The proposal outlined in the Appendix below provides 1) the Space Force with a civilian force projection capability, 2) infrastructure for extending the useful lifetime of Government and commercial in-space assets, and 3) market demand signals for commercial space commodity developers and transportation services. The program is designed to grow alongside commercial capabilities in order to limit the amount of appropriated Federal funds and to prevent contractor capture that can come from large Government facilities.

B. Space-Based Solar Power (SBSP)

Taking a page from the market enabling national infrastructure development in the 1940s such as the Tennessee Valley Authority, a program to develop and deploy space-based solar power systems to provide a sustainable alternative energy source by collecting sunlight in space and beaming it back to Earth in ways that are not hampered by weather or day/night cycles. Such a program would provide a sustained demand signal for the emerging ISAM industry, increase the energy security of the country, and decrease the environmental impact of energy production.

It is difficult to imagine the cost-effective assembly and maintenance of SBSP systems without an extensive commercial ISAM capability. Specifically, SBSP systems can provide a set of performance requirements that ISAM companies can aim to achieve. Unlike proposed ISAM-enabled large telescopes, SBSP testing and development requires much lower tolerances and will serve as an ideal learning and development application for ISAM companies.

As energy is a marginal commodity, a government-sponsored SBSP system would allow companies to take risks necessary to hone their products. As such, the commercial ISAM industry will be instrumental in determining if SBSP is feasible in the next decade, and the US Government can create significant demand through explicit support and initiation of a large pilot SBSP system.

As mentioned above, ISAM systems are a tool looking for an application, whereas SBSP is a solution looking for tools to make it feasible. By signaling demand in SBSP, the US Government is indicting enough desired use for the tools to allow them to improve and develop other markets.

Government demand signaling for SBSP could also bring energy companies into the fold who would be employing ISAM in more and different ways. This evolution catalyzes the need for ISAM and generates customers for ISAM industries for the foreseeable future. While there will be a requirement for initial government investment there is a transition path from government-led to industry-led applications.

C. Settlement as a goal

Most Government economic policies fall into either the carrot or the stick categories. Sometimes, though, simple goal setting and leadership can have an even larger and more sustained effect. As mentioned above, it is difficult to justify the use of space resources in space without a large, resource-intensive market that is also in space. There is some speculation that Space-Based Solar Power could be such a market but it may not be very broad-based or commercial in nature.

The only market that justifies significant in-space development and infrastructure is people. Large numbers of people living temporarily and permanently in space would require significant and reliable access to water, propellant, air, construction materials, and energy from all sorts of ISAM-enabled businesses. Settlement of space is an organic market that would not respond well to a Government program. But it would respond to leadership. Simple statements such as a new long-term national space goal that thousands of US citizens would be living permanently in space by a specific date would energize and motivate an entire industry that is currently in the shadows. SpaceX, Blue Origin, and the United Arab Emirates are the only large, well-funded organizations dedicated to the permanent human expansion into space. Making the peaceful settlement of space a national goal would help attract private investment dollars and incentivize the long-term investments such a goal would require.

D. Standards

ISAM standards should be developed in an open forum that does not require payment or membership to participate. ISAM standards should also be voluntary and the status of being adopted as an industry should only come through widespread and voluntary industry adoption. The standards process should follow the Internet model⁶ rather than the ITU model in order to prevent market share capture through standards.

V. Partnerships

What are the most effective kinds of partnerships, between the U.S. Government, industry, and academia, that would advance ISAM industry maturity and ISAM capabilities? What partnership opportunities exist, both nationally and internationally, outside of the Federal Government?

Public-Private Partnerships should have crystal clear and 'mechanistic' participation criteria rather than proposals evaluated by a selection committee. In all cases, partnerships should work to avoid the involvement of political and parochial interests.

The US Government should also begin to apply standard PPP models from the industrial infrastructure finance industry. The nascent ISAM industry should understand that the goal is to finance the ISAM industry the same way any other national infrastructure development is financed.

VI. Priorities

What are the highest priority actions that the USG can take over the next five years to implement the goals outlined in the ISAM strategy?

A. Concrete demand signals

Create concrete demand signals as outlined above that cannot be gamed by politics.

B. Office of Space Commerce

Elevate the Office of Space Commerce to a Bureau and make it Federal policy that OSC is responsible for space industrial policy and that the bulk of ISAM policy is administered there and not NASA.

Acknowledgments

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Appendix

Strategic Space Commodities Reserve

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Abstract

The Strategic Space Commodities Reserve is a proposed program where the US Government acts as an in-space commodities market maker by purchasing a set number of commodities at specific transportation nodes within cislunar space. The proposal outlined here provides the Space Force with a civilian force projection capability, infrastructure for extending the useful lifetime of in-space assets, and market demand signals for commercial space commodity developers and transportation services. The program is designed to grow alongside commercial capabilities in order to limit the amount of appropriated Federal funds and to prevent the capturable build-out of large Government facilities.

1. Space Infrastructure and Applications Market Problems

The space industry faces several significant problems as it attempts to move beyond the communications and Earth observation applications of the 1960s. Applications beyond Geosynchronous Earth Orbit (GEO) often involve sequencing actions where each action seems to depend on others being done first (colloquially known as a “chicken and egg” problem).

For example, the space industry generally agrees that fuel depots at strategic points in the Earth-Moon system and beyond can enable far lower exploration and development costs. But fuel depots require four actors: spacecraft manufacturers willing to make their systems refuelable, spacecraft operators that structure missions assuming fuel depots exist, fuel depot developers willing to build and maintain the facilities, and fuel providers capable of refueling the depots. Typically, no single actor is capable of filling all four roles and any single actor requires the others to exist in order to fulfill its role.

1.1. A Government Policy Role

In 2021 the Biden Administration published the “United States Space Priorities Framework” [1] which outlined a small, but important, list of priorities for the Executive Branch. Under the overarching goal of “Maintaining a Robust and Responsible U.S. Space Enterprise”, the framework listed six policy priorities:

1. The United States will maintain its leadership in space exploration and space science.
2. The United States will advance the development and use of space-based Earth observation capabilities that support action on climate change.
3. The United States will foster a policy and regulatory environment that enables a competitive and burgeoning U.S. commercial space sector.
4. The United States will protect space-related critical infrastructure and strengthen the security of the U.S. space industrial base.

5. The United States will defend its national security interests from the growing scope and scale of space and counterspace threats
6. The United States will invest in the next generation.

The inability of any commercial companies or Government programs to garner the financial support necessary to make any development moves beyond GEO suggests that there is a significant and near-term barrier to goals 1, 3, 4, and 5. Because of their priority, there is a natural question as to whether there is a Government role to play in breaking through some of those early “chicken and egg” problems.

That role must be carefully crafted since it comes with budgetary and market-distorting risks, especially if it enables rent-seeking behavior by non-Government actors. Therefore, such a program should be *targeted* and *limited*.

Targeted

One of the often observed mistakes with early industrial and economic development policy is the exuberant attempt to design an entire industry in its final and complete state. Just as “no plan survives first contact with the enemy” so does no product survive first contact with its market. The interaction between industry participants, both upstream and downstream, will find an active equilibrium that often bears no resemblance to what the original policy advocates envisioned. Indeed, a perfect example is comparing the national telecommunications policy in 1992 to that developed in response to the explosive growth of the Internet in the late 1990s.

Limited

Another industrial policy mistake is attempting to fix problems that may or may not exist. Simplicity provides clarity which is what the market is looking for. If mistakes are made then their impacts are limited. The policy with the simplest solution possible preserves the ability of the market to discover the other solutions on its own.

1.2. A Proposed Solution

The National Science and Technology Council recently published the findings of the In-space Servicing, Assembly, and Manufacturing Interagency Working Group as a National Strategy [2]. In its summary, the report says, “This ISAM National Strategy directly supports the United States Space Priorities Framework, with a focus on scientific and technological innovation, economic growth, commercial development, the rule of law, open markets, freedom of navigation, and fair trade.” The report further summarized the benefits of the strategy as “Fostering an ecosystem that leverages ISAM capabilities can expand the performance, availability, resilience, and lifetime of space systems compared to the status quo.”

One of the four primary goals of the Strategy is to accelerate the emerging ISMA commercial industry:

Provide a sustained demand signal for ISAM capabilities. The USG will define and describe its requirements for ISAM-relevant missions, and prepare for the procurement of ISAM capabilities that meet these requirements. The USG supports the ownership and operation of space launch, in-space logistics, spacecraft servicing, assembly, and manufacturing systems and services provided by the U.S. commercial space industry. The USG will assess emergent commercial ISAM capabilities for their applicability in supporting USG space missions. The USG will prioritize procurement and operation of ISAM servicing and lifetime extension capabilities from commercial providers over the development of USG capabilities, consistent with U.S. law and national policy.

A key goal of this Strategy is that the Government supports the *ownership and operation of in-space infrastructure* by the commercial sector rather than Government-owned and operated facilities.

This policy requirement plus the rough consensus in the industry that a transportation network of fuel depots is a necessary infrastructure for nearly every possible mission architecture is what forms the basis of a strategic space commodities reserve.

Governments create commodities reserves for various reasons. Some exist as price supports while others are used for disaster preparedness. The US has run several such reserves over the years such as Petroleum Reserve [3], the recently dismantled Federal Helium Program [4], various grain reserves in the late 20th century, the US Remount Service for military horses in 1908 [5], and the National Defense Stockpile [6]. The closest antecedent to this proposal is the development of coaling stations in the Pacific in the late 1800s. The differences are that the stations are run commercially and the commodities stored are expanded somewhat.

2. Features and Mechanisms

2.1. Basic Model

Using the methods outlined below, the US Government will purchase a set of commodities at various Nodes within the Earth/Moon system (and potentially other locations around the Solar System). Nodes are locations where the orbital mechanics of the system dictate useful low energy transfers to other orbits (see Figure 1 below). Commercial companies will apply to run commodity storage and transfer facilities at each node and will be paid storage and transfer fees by the US Government for operating the facility. The companies are free to offer other services at each Node beyond commodity storage and transfer.

Unlike previous proposals, the commodities purchased are not limited to rocket fuel but include other consumables (air, water, coolant, etc) plus precursor chemicals (ammonia, methane, etc) sufficient to produce a variety of derivative chemicals and products.

The funding and payment system is intended to start as close to zero as possible and grow as the industry grows to service Nodes and provide commodities. If Congress sets the budget for the purchase of commodities at zero then a provision outlined below provides for privileged appropriations legislation only on an as-needed basis. Once these become frequent Congress can appropriate a standing budget for the program.

2.2. Node Physics

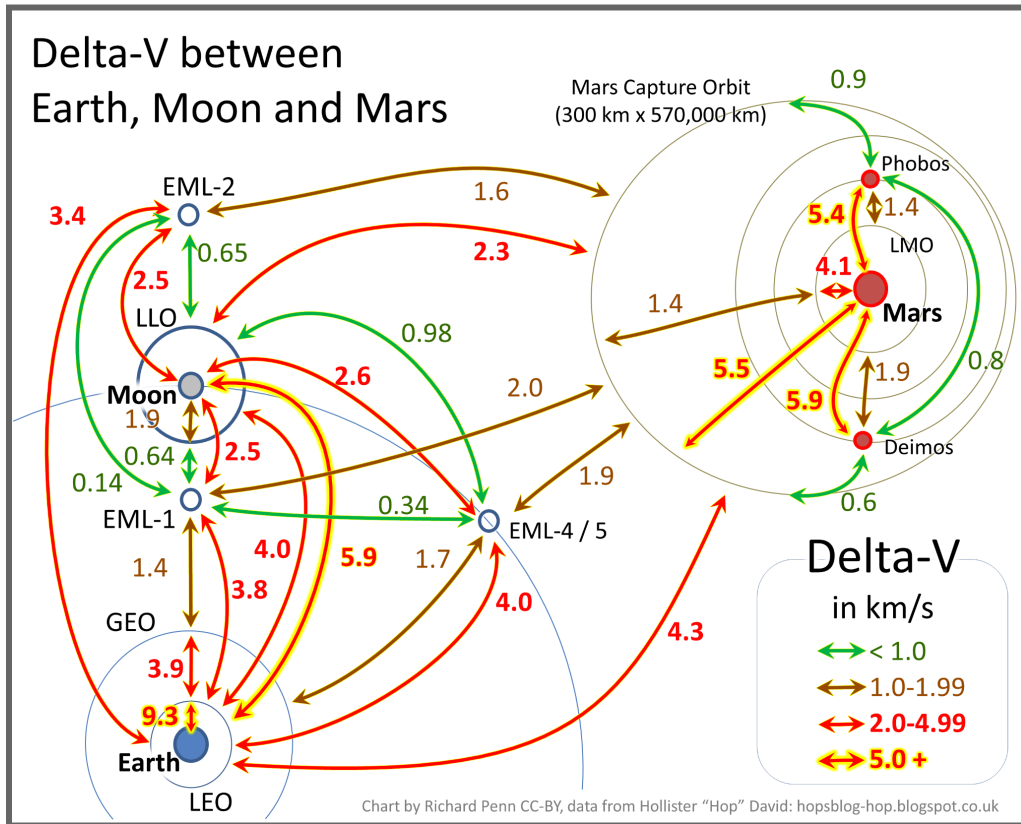


Figure 1 [7]

The basic framework for the reserve is driven by the orbital mechanics of the inner Solar System (planets inside the orbit of Jupiter) and the unique pattern of transfer orbits between them. These transfer orbits dictate the basic costs of moving anything around in space and are measured in the change in velocity needed to move from one point to another. This change in velocity is referred to as Δv or "delta-v" where the Greek letter Δ represents the rate of change. Figure 1 illustrates the basic Δv values for most of the interesting locations in the inner Solar System.

As an example, one of the highest, and thus most expensive, Δv requirements is from the surface of the Earth to Low Earth Orbit at 9.3 km/s. That is roughly the same Δv required to go from Earth to the surface of Mars.

An important feature is that there are natural ‘balance’ points where the gravity of the Earth and the Moon cancel out and thus provide low Δv routes to other locations. EML-1 and EML-2 are two such locations and are extremely valuable and strategic waypoints.

2.3. Pricing

The fundamental problem of any commodities reserve is understanding how to price the commodity when purchased or sold. In space, the cost of moving a commodity from one Node to another is many orders of magnitude higher than the value of the commodity itself. But each commodity has a different mass (water is heavy, hydrogen is very light) and mass greatly affects the Δv calculations.

A proposal for how to calculate a price that takes Δv and commodity mass into account is included in the Appendix at the end of this proposal. Using that method, transporting 10kg of water from EML-1 to GEO would cost \$22,661 whereas that same 10kg of water from the Earth to the Lunar surface would cost \$257,057. This proposal is included to demonstrate one possible method for calculating a price standard but further analysis of other possible methods is a necessary next step.

2.4. Commodities

Organic Consumables and Propellants

The original version of this proposal focused exclusively on propellants as the primary goal. After discussions with stakeholders, it became clear that there was sufficient demand for other commodities, especially for the International Space Station and Gateway programs, that other basic commodities should be included. There was also some consensus that the Reserve should focus on “precursor” materials that can easily be turned into other materials using well-known processes. Examples include water providing O_2 and H_2 for fuel and breathable oxygen. Methane (CH_4) as propellant is growing in popularity but can also be processed into fertilizer, simple carbohydrates, and even plastics. Ammonia (NH_3) is a precursor for both fertilizer and hydrazine, a common in-space propellant. The commodities are all basic combinations of carbon, hydrogen, oxygen, and nitrogen and are commonly referred to by the acronym CHON. By adding phosphorus and sulfur compounds (e.g. CHONPS) a system has the ability to create most organic molecules which often include high thrust rocket fuels.

Electric Propulsion Propellants

Electric propulsion systems such as Hall Effect thrusters or Field Emission Electric Propulsion (FEEP) thrusters use propellants with high atomic mass and low energy ionization such as iodine, xenon, or krypton. Many spacecraft currently in production or already on orbit use various eclectic propulsion systems.

Construction Materials

While in-space manufacturing of complex components using additive manufacturing (e.g. “3d printing”) is a very recent development, there have already been several space-compatible feedstocks identified that could become valuable commodities in the short term. Companies have already demonstrated the manufacturing and assembly of components made from

vacuum-compatible polymers in microgravity. Stockpiles of feedstocks within the Reserve can provide the rudimentary supply chains necessary for in-space manufacturing of large and complex structures.

2.5. *Funding Mechanisms*

Prior to the delivery of any commodity to any Node, no appropriation would be required other than that required for a Federal loan guarantee to enable commercial providers to build, launch and operate commodity storage and transfer facilities at Reserve recognized Nodes. Following the process below, if no commodity delivery appropriations have been passed then the process in Section (e) is followed. This provides a feature where Federal spending for the Reserve grows in lockstep with the growth of the commodities delivered to the Reserve and initially requires no appropriations at all.

Within the Reserve program, as with other Reserve programs, if the Commodity at a Node that was previously purchased by the Reserve is then sold to a non-US Government entity at a price higher than it previously paid, the profit is returned to the US Treasury.

The compensation plan language found in the launch indemnification section of [8] and the payments of claims sections of [9] provide an existing and compatible template for payments for a delivered commodity. The language below is lifted directly from those statutes and has been slightly modified for this application. Essentially, if payment for delivery of a commodity to a Node exceeds the Agency's existing appropriated budget (including any reprogramming authority) and the commodity/Node is not already covered by an existing contract (e.g. water/air/propellant to the ISS), then the Agency will indicate to the President of an unappropriated liability at which point the following process would be triggered:

(d) Compensation Plans

(2) Not later than 90 days after the Agency indicates that the delivery of a commodity to a Node represents a liability larger than the Agency's existing appropriated budget, the President, on the recommendation of the Agency, shall submit to Congress a compensation plan that—

(A) outlines the total dollar value of the delivery;

(B) recommends sources of amounts to pay for the delivery;

(C) includes legislative language required to carry out the plan if additional legislative authority is required; and

(D) for a single delivery, may not be for more than \$100,000,000.

(3) A compensation plan submitted to Congress under paragraph (2) of this subsection shall—

(A) have an identification number; and

(B) be submitted to the Senate and the House of Representatives on the same day and when the Senate and House are in session.

(e) Congressional Resolutions.—

(1) In this subsection, "resolution"—

(A) means a joint resolution of Congress the matter after the resolving clause of which is as follows: "That the Congress approves the compensation plan numbered _____ submitted to the Congress on _____, 20__.", with the blank spaces being filled appropriately; but

(B) does not include a resolution that includes more than one compensation plan.

(2) The Senate shall consider under this subsection a compensation plan requiring additional appropriations or legislative authority not later than 60 calendar days of continuous session of Congress after the date on which the plan is submitted to Congress.

(3) A resolution introduced in the Senate shall be referred immediately to a committee by the President of the Senate. All resolutions related to the same plan shall be referred to the same committee.

(4)

(A) If the committee of the Senate to which a resolution has been referred does not report the resolution within 20 calendar days after it is referred, a motion is in order to discharge the committee from further consideration of the resolution or to discharge the committee from further consideration of the plan.

(B) A motion to discharge may be made only by an individual favoring the resolution and is highly privileged (except that the motion may not be made after the committee has reported a resolution on the plan). Debate on the motion is limited to one hour, to be divided equally between those favoring and those opposing the resolution. An amendment to the motion is not in order. A motion to reconsider the vote by which the motion is agreed to or disagreed to is not in order.

(C) If the motion to discharge is agreed to or disagreed to, the motion may not be renewed and another motion to discharge the committee from another resolution on the same plan may not be made.

(5)

(A) After a committee of the Senate reports, or is discharged from further consideration of, a resolution, a motion to proceed to the consideration of the resolution is in order at any time, even though a similar previous motion has been disagreed to. The motion is highly privileged and is not debatable. An amendment to the motion is not in order. A motion to reconsider the vote by which the motion is agreed to or disagreed to is not in order.

(B) Debate on the resolution referred to in subparagraph (A) of this paragraph is limited to not more than 10 hours, to be divided equally between those favoring and those opposing the resolution. A motion

further to limit debate is not debatable. An amendment to, or motion to recommit, the resolution is not in order. A motion to reconsider the vote by which the resolution is agreed to or disagreed to is not in order.

(6) The following shall be decided in the Senate without debate:

(A) a motion to postpone related to the discharge from committee.

(B) a motion to postpone consideration of a resolution.

(C) a motion to proceed to the consideration of other business.

(D) an appeal from a decision of the chair related to the application of the rules of the Senate to the procedures related to a resolution.

2.6. Storage and Transfer Facility Financing

Reserve facilities are located at the International Space Station (51.6° orbital inclination), equatorial LEO, EML-1, EML-2, Low Lunar Orbit, the Lunar Surface, EML-4, and EML-5. The Artemis Gateway facility in a near-rectilinear halo orbit about the Moon and a potential facility in Mars orbit are also options. The facility or facilities at each Node may be financed using limited Federal Loan Guarantees and will charge all users, including the Federal Government, standard storage and transfer fees. The Agency will determine and publish storage and transfer fee schedules for Reserve commodity transactions on a yearly basis.

2.7. Existing Contracts

The facility at an orbital inclination of 51.6 degrees is assumed to be the International Space Station. The existing ISS contracts for consumables such as air and water should be subsumed under the Reserve system of contracts.

2.8. Home Agency Considerations

The current assumption is that the program will be administered by the Commerce Department's Office of Space Commerce in order to ensure that the program does not impact NASA's existing R&D programs and to prevent conflicts arising from NASA acting as both the Reserve's administrator and one of the customers of the commodities being purchased or sold.

3. Additional Work Needed

Additional work is needed to fill in details on the following:

- Further analysis of the pricing model in order to balance incentivization against protecting the taxpayer. A higher price for transport creates more of an incentive but at some risk of socializing excess profits to taxpayers.
- A strategy for pricing of storage and transfer fees that encourages Node facilities to provide other services
- An appropriate mechanism for folding in existing commodities contracts within the ISS partnership

4. Conclusion

The Strategic Space Commodities Reserve is a program where the US Government acts as an in-space commodities market maker by purchasing a set number of commodities at specific transportation nodes within cislunar space. The proposal outlined here provides the Space Force with a civilian force projection capability, an infrastructure for extending the useful lifetime of in-space assets, and a market pull signal to commercial space commodity developers and transportation services. The program uses limited Federal funds appropriated only upon physical delivery of a commodity to purchase assets that may be sold at a profit.

5. Appendix - Pricing Strategy

The fundamental problem with creating such a reserve is creating a clear, predictable method of calculating a transportation cost cap that respects the costs associated with the underlying orbital mechanics.

As mentioned above, the overwhelming cost driver for in-space commodities is the cost of transporting them within the system. That system is dominated by a complex interaction between the Earth, the Moon, and the spacecraft referred to as a “three-body problem”. The basic unit of measure within that system is Δv , or the rate of change in velocity, necessary to move between an origin and destination orbit. The chart below indicates the Δv for most cislunar orbits and Mars orbits. The reader is cautioned not to simply add up the numbers to get a final Δv for a route not indicated since there are interactions that prevent such simple addition from being accurate.

Even then Δv is not sufficient since the relationship between mass to be transported and the Δv necessary is not a linear one. The classical rocket equation

$$\Delta v = v_e \ln \frac{m_0}{m_f} = I_{sp} g_0 \ln \frac{m_0}{m_f},$$

shows the relationship between Δv and mass is exponential and driven by the I_{sp} , or “specific impulse” of the vehicle. Specific impulse is how efficiently the rocket uses its fuel. Calculating the effort necessary to transport something within the network would be relatively easy if specific impulse could be ignored since all other terms are known.

While the problem of knowing the specific impulse may be difficult, the resulting pricing mechanism should reward technology that increases vehicle efficiency. In this particular case, the actual specific impulse of a vehicle transporting a commodity to a Node is irrelevant. Instead, a reasonable but arbitrary specific impulse can be used to calculate a default price cap for the route. Whether or not the vehicle can achieve a more efficient way of moving the commodity from the source to the destination is an economic decision left up to the company doing the transportation. This proposal will use a method developed by Peter Hague to calculate a mass value [10] metric for comparing the relative value of various missions to the same location. Hague postulates a hypothetical transport vehicle with 300 seconds of I_{sp} and a general mass fraction based on the payload mass. The mass value is “the mass that would be required to be delivered to 300 km circular Earth orbit to accomplish the same mission, using the most basic methods”. The mass value formula requires two basic inputs: the dry mass of the vehicle and payload and the total Δv necessary to reach the final orbit:

$$M_v = M_0 + k e^{\frac{\Delta v}{v_e}} M_0^{2/3}$$

Where M_0 is the dry mass of the vehicle, k is the mass fraction, v_e is the fuel efficiency in seconds, and Δv is the total change in velocity necessary to achieve the final orbit. For this proposal, the formula is modified slightly such that the Δv input is not from an Earth equatorial orbit but from the source to the destination. This modified mass value is then divided by the modified mass value of the Earth’s surface to an equatorial orbit. This final number represents the percentage difference between the modified mass value of the mission with the modified

mass value of simply launching the payload into that same equatorial orbit from the surface. From the chart above the Δv from the Earth's surface to LEO is 9.3 km/s. For example, the difference in the modified mass value of 10 kgs from EML-1 to GEO is 7 kg whereas the modified mass value of that same 10kg from the Earth's surface to LEO is 218 kg. Thus the EML-1 to GEO route is 3.16% of the effort of Earth to LEO.

The next challenge is having an easily understood base price that can be used as the other input to a function that produces a viable price cap. As with other economic metrics, it is often sufficient to use a well-known and publicly published price from a competitively bid and awarded contract as a proxy price. A realistic assumption can be made that the current price per kilogram of cargo from the Earth's surface to the International Space Station is a reasonable proxy. That price is currently \$71,800/kg according to the most recent Commercial Resupply Services 2 contracts as reported by the NASA Inspector General [11].

Using these two methods, it is now possible to calculate a potential transportation price cap for each route. This table illustrates the percentage and price for delivering 10 kg of water to various cislunar destinations and routes:

Source	Destination	Route	Δv	% M_v of Earth to LEO	Price of delivery
EML-2	GEO	EML-2 - EML-1 - GEO	1.54	3.16%	\$22,661.43
EML-1	Moon	EML-1 - LLO - Moon	2.54	6.29%	\$45,168.67
EML-1	Moon	EML-1 - Moon	2.5	6.14%	\$44,113.96
Moon	GEO	Moon - EML-1 - GEO	3.9	12.68%	\$91,063.36
Earth	Moon	Earth - Moon	6.4	35.80%	\$257,057.88
Earth	EML-1	Earth - LEO - EML-1	13.1	388.97%	\$2,792,794.36
Earth	LEO	Earth-LEO	9.2	100.00%	\$718,000.00

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