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SPACE MOBILITY AND LOGISTICS:

ENABLING SUSTAINED SPACE MANEUVER THROUGH IN-SPACE REFUELING

by

John B. Stryker, Maj, USSF
Shaun C. Perry, Maj, USSF

A Research Report Submitted to the Air Force Fellows
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Advisors:
Dr. Holly Franz, Military Strategic Advisor, Strategic Deterrence, Lawrence Livermore National Laboratory
Lt Col Andrew Small, Special Assistant to the Director and Space Force Liaison, Defense Advanced Research Projects Agency (DARPA)

Department of the Air Force Fellows (AFF), Air War College (AWC)
Maxwell Air Force Base, Alabama

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Abstract

The United States Space Force currently operates spacecraft as expendable, fuel-limited assets within a psychology of scarcity that constrains operational flexibility and limits space superiority. The prevailing resilience strategy of proliferation offers advantages in complicating adversary targeting, but rests on assumptions about reconstitution capacity and mission effectiveness without maneuver that have received insufficient validation. This paper examines whether proliferation alone is sufficient for Dynamic Space Operations, Sustained Space Maneuver, and space superiority, or requires an enabling logistics architecture.

This research argues that proliferation is critical but insufficient. Joint doctrine favors maneuver and initiative over attrition. Proliferation without logistics accepts attrition while forfeiting maneuver. Space Mobility and Logistics provides reusability and reconstitution that transform static mass into sustainable combat power.

SML extends asset life through refueling, reduces reconstitution demand, and provides operational flexibility that static constellations cannot deliver. Most fundamentally, SML transforms $350 million expendable spacecraft into reusable capital platforms. The United States Space Force must develop comprehensive Space Mobility and Logistics capabilities to strengthen proliferated architectures while enabling Dynamic Space Operations.

The paper provides an analytical framework for the operational, technical, economic, and organizational dimensions of Space Mobility and Logistics. It evaluates proliferation versus sustained maneuver strategies, proposes organizational constructs, and concludes with recommendations and critical decision points for senior leaders.

Preface

This research is motivated by the recognition that the United States Space Force is at a pivotal stage in its evolution as a military service. Achieving and maintaining space superiority in an increasingly contested domain requires rigorous analysis of alternative operational concepts and organizational frameworks. The shift from treating spacecraft as expendable assets to viewing them as sustainable platforms capable of dynamic maneuver marks a fundamental change in the national approach to space operations.

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Special recognition is due to the operators, planners, and acquisition professionals across the space enterprise who shared their expertise and operational perspectives. Their insights into the practical challenges and opportunities of space logistics proved invaluable in grounding this academic analysis in operational reality.

Chapter 1

Introduction

Space operations today are conducted in a manner remarkably similar to how air operations were accomplished before the conception of aerial refueling. Operations remain confined to simple, predictable positional orbital physics with very limited ability to dynamically affect outcomes in and from the domain. Space operations are severely constrained by the satellite's lifespan, a limitation realized immediately upon launch. Currently, there is no way to extend the spacecraft's life except through careful planning and extremely frugal use of consumable resources. Space operations are positional and depend entirely on Kepler's Laws, with any desire to significantly change orbital parameters being cost-prohibitive from a resource perspective.

Lieutenant General John Shaw, former Deputy Commander of the United States Space Command, offered a compelling analogy: *modern national security space operations are like conducting air operations with a dirigible (i.e., airships)*. It is possible to accomplish the mission, but operators are significantly influenced by the domain's nature. The lack of speed and dynamism significantly reduces resilience and agility in responding to a changing threat environment. More critically, it constrains the ability to generate operational surprise and drive battlespace conditions in accordance with national interests and advantages. In-space refueling and reusability have the potential to drastically increase operational effectiveness, transform how resilience is conceptualized, enable operators to employ space capabilities with the ability to sustain space maneuver, and generate operational surprise to achieve space dominance.

Meanwhile, an asymmetry is emerging between American and adversary approaches to space operations. The People's Republic of China has demonstrated operational on-orbit refueling, conducted multi-satellite maneuvering exercises, and is training satellite operators for refueling operations in both peacetime and wartime. Russia has gained over 25 years of experience of on orbit propellant logistics by being the only country to refuel the International Space Station. Currently, the American space architectures remain optimized for Positional Space Operations in a benign environment while potential adversaries develop the capabilities for Dynamic Space Operations in a contested domain. This divergence creates strategic risk that compounds the infrastructure, organizational, and analytical gaps identified above.

Problem Statement

In-space logistics infrastructure does not currently exist. Space missions are fundamentally limited by the amount of fuel loaded onto spacecraft before launching. Once in orbit, satellites and other space assets operate as isolated systems with predetermined lifespans based on their initial resource allocation. This creates a use and discard (attrition) paradigm where spacecraft become inoperable once they exhaust their onboard resources, regardless of their mechanical integrity or mission value.

The United States Space Force currently operates within a psychology of scarcity with respect to limited consumables. This term describes the cognitive and organizational phenomenon whereby perceived resource constraints drive conservative decision-making, risk aversion, and the centralization of authority to higher echelons. When operators and commanders believe resources cannot be replenished, they instinctively hoard capability for anticipated future contingencies, even when employment would deliver immediate operational value because they may need it later. This mindset has negative implications across training, readiness, tactics development, campaigning, strategic messaging in the domain, and even undermines the service's efforts to implement true mission command. With consumables being so precious, decisions are retained at higher levels (O-6 and above) because of the current inability to replenish at acceptable cost. This dynamic decreases operators' ability to accomplish the mission and execute commanders' intent in the domain.

Today's prevailing strategy for achieving resilience in space architectures centers on proliferation (i.e., attrition): deploying large numbers of relatively inexpensive satellites such that the loss of individual spacecraft does not critically degrade overall capability. This approach has been implemented across multiple programs, including the Space Development Agency's proliferated constellation of missile warning and tracking satellites in Low Earth Orbit and Medium Earth Orbit (Proliferated Warfighter Space Architecture). Yet no comparative analysis has evaluated this strategy against alternative frameworks for achieving Dynamic Space Operations and Sustained Space Maneuver.

Research Question

This research addresses the following question: Is the prevailing resilience strategy of “proliferation” (i.e., attrition) sufficient for Dynamic Space Operations, Sustained Space Maneuver, and Space Superiority, or does it require an enabling logistics architecture?

Thesis

This research argues that proliferation is critical and necessary but insufficient. Joint doctrine establishes that maneuver warfare is superior to attrition. Proliferation without logistics accepts attrition while forfeiting maneuver. Space Mobility and Logistics provides reusability and reconstitution, transforming static mass into sustainable combat power.

This analysis employs the ends-ways-means strategic framework. The end is space superiority achieved through Dynamic Space Operations and Sustained Space Maneuver. The ways include depot-based logistics architecture, organizational transformation, and career field development. The means encompass propellant depots, servicer spacecraft, trained personnel, and sustainable funding mechanisms. Strategy achieves balance when ways and means are sufficient to achieve ends at acceptable risk. The current imbalance, where ends require maneuver but ways and means provide only attrition, represents a strategic gap that this paper addresses.

Scope and Methodology

This paper provides a lifecycle economic comparison of three architectural approaches for achieving Dynamic Space Operations capability under propellant consumption driven by delta-v requirements. The analysis examines proliferation with mid-life replacement, commercial refueling services, and organic depot infrastructure. The paper proposes organizational frameworks, resourcing mechanisms, and policy recommendations for implementing space logistics as a core Space Force competency.

This paper does not provide detailed engineering design specifications for depots, servicers, or client spacecraft. It does not develop wartime concepts of operations, targeting analysis, or force-on-force engagement modeling. It does not provide analysis for every mission type, only assumptions based on current available unclassified data. These are essential follow-on efforts that require classified program data and operational testing not available to this research. This analysis provides the strategic and economic foundation upon which such detailed follow-on work can be developed in partnership with multiple agencies and organizations.

The research employs a qualitative methodology combining doctrinal analysis, literature review, comparative case study, and policy analysis. Primary sources include official doctrine, Congressional testimony, Government Accountability Office assessments, and technical literature from NASA and DARPA. Secondary sources include peer-reviewed academic literature, industry publications, think tank analyses, and multiple 1:1 interviews/conversations. The comparative analysis applies criteria derived from military effectiveness literature, examining each approach against metrics of operational flexibility, resilience, cost-effectiveness, and scalability.

Assumptions and Limitations

This research operates under several assumptions that bound the analysis. First, the analysis assumes that space will remain a contested domain for the foreseeable future and that peer competitors will continue developing counterspace capabilities. Second, the analysis assumes that the laws of orbital mechanics and propulsion physics will constrain operational concepts regardless of technological advancement. Third, the analysis assumes that the United States will continue to rely on space-based capabilities for national security and economic prosperity.

Several limitations constrain this research. Classification restrictions prevent detailed analysis of specific threat capabilities and some United States Space Force operational concepts. Economic analysis relies on publicly available cost data, which may not reflect actual program costs or classified acquisition strategies. The analysis does not examine all possible space logistics architectures, focusing instead on representative courses of action to illustrate key tradeoffs. Finally, the rapid pace of commercial space development means that some technical assessments may be overtaken by events between research and publication.

Literature Foundations

This research builds upon several streams of scholarly and professional literature. The theoretical foundation draws from spacepower theory as articulated in the Space Capstone

Publication, which identifies Space Mobility and Logistics as one of five core competencies of military spacepower alongside Space Security, Combat Power Projection, Information Mobility, and Space Domain Awareness. Dr. Everett Carl Dolman's work on space strategy provides the broader theoretical context for understanding spacepower as a distinct form of military power with unique characteristics deriving from the physics of the orbital environment.

Military logistics scholarship informs the organizational and operational analysis. Classical works establish that logistics is constitutive of military power; forces that cannot be sustained cannot achieve objectives regardless of tactical excellence. The challenge of projecting logistics into the space domain represents an extension of enduring principles to a new operating environment, requiring adaptation of concepts developed for terrestrial warfare.

The Government Accountability Office's Technology Assessment on In-Space Servicing, Assembly, and Manufacturing provides the most comprehensive unclassified analysis of the current state of ISAM technologies and the challenges facing their development and deployment. The GAO identified four key challenges: differing priorities between government and industry for ISAM technology; reluctance of satellite operators to require serviceability in satellite design; limited in-space test opportunities; and unclear or emerging regulations and standards. This research addresses each of these challenges in the context of military space logistics requirements.

The Mitchell Institute for Aerospace Studies has produced a series of analyses on Dynamic Space Operations and space logistics that inform this research. Their work on Competitive Endurance, the theory of success articulated by the Chief of Space Operations, provides the doctrinal context for understanding how Space Mobility and Logistics contributes to avoiding operational surprise, denying first-mover advantage, and conducting responsible counterspace campaigning.

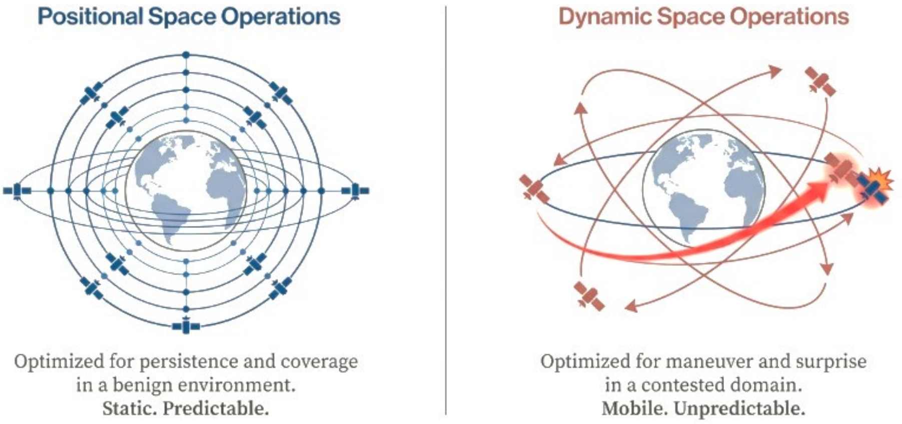
Chapter 2

Context: Dynamic Space Operations and In-Space Refueling

Introduction to Dynamic Space Operations

The nature of space is inherently dynamic. Space vehicles are perpetually moving as they orbit the Earth. Additionally, those orbits precess, meaning a single space vehicle will pass over a different part of the Earth on each orbit. These physical properties distinct to the space domain simultaneously present challenges and opportunities to be considered in capability architecture, force design, and operational employment. Movement and maneuver in space is entirely critical to all other Principles of War, and to the ability to respond to threats and take positions of advantage. The predictability of orbital mechanics alone is not sufficient to guarantee the United States Space Force's ability to gain positions of strategic, operational, and tactical advantage.

Dynamic Space Operations incorporates the concepts of military operations of movement and maneuver sustained in space to enhance resilience and lethality through the physical and network domains.[1] Dynamic Space Operations encompass and are accomplished through a combination of various methods: Sustained Space Maneuver, rapidity of data transport, and effects delivered whether in space, cyber, or electromagnetic spectrum to achieve a frequency and magnitude of maneuver as a principle of war. A precise definition of Sustained Space Maneuver is warranted here. Specifically, Sustained Space Maneuver is accepted to be the sustainment of operations until objectives are achieved. It is a methodology to gain positions of advantage, though this advantage need not always manifest through physical orbital maneuver. Dynamic Space Operations is a broader concept that includes, but is not synonymous with, Sustained Space Maneuver. Rather, Sustained Space Maneuver is one component within Dynamic Space Operations as a larger operational framework.



Dynamic Space Operations Concepts of Operations

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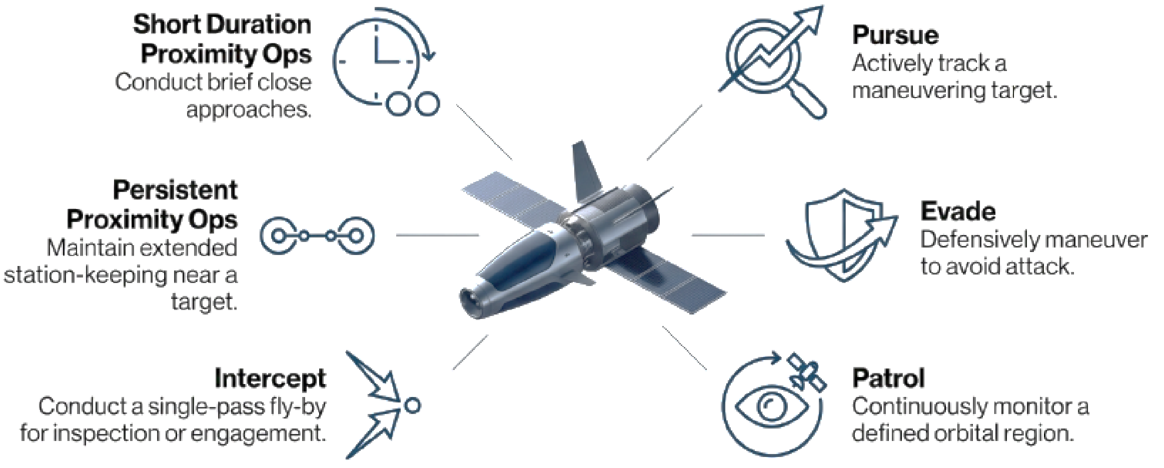
[1] Chris Williams, "Dynamic Space Operations: An Overview and Assessment," National Security Space Association (April 2, 2024): 1.

Dynamic Space Operations enables at least six primary concepts of operations that consume propellant and require sustained maneuver capability. The operational concepts below represent the different tactical and operational employment options of maneuvering spacecraft, each imposing distinct delta-v requirements that drive space logistics planning and cost. Understanding these concepts of operations clarifies why in-space refueling is essential for sustained combat effectiveness.

Table 2.1. Dynamic Space Operations Concepts of Operations

Concept of Operations	Description	Propellant Implications
Flyby or Intercept	Single-pass trajectory bringing spacecraft into close proximity with target for inspection, characterization, or engagement	Moderate delta-v for trajectory shaping; minimal station-keeping; one-time maneuver cost
Pursue	Active tracking and following of a maneuvering target spacecraft to maintain proximity or close distance	High delta-v to match target maneuvers; unpredictable consumption based on target behavior
Short Duration Proximity Ops	Brief close approach to target for inspection, servicing, or effects delivery followed by departure	Moderate delta-v for approach, station-keeping, and departure phases
Patrol	Continuous monitoring of a defined orbital region or specific assets through repeated coverage passes	Sustained delta-v for orbit maintenance and repositioning; cumulative consumption over time
Evade	Defensive maneuvering to avoid pursuit, inspection, or attack by adversary spacecraft	High delta-v for responsive maneuvers; unpredictable consumption driven by threat behavior
Persistent Proximity Ops	Extended station-keeping in close proximity to target for long-duration inspection, escort, or presence missions	Very high cumulative delta-v for continuous station-keeping against orbital perturbations

Each of these concepts of operations, to include training, readiness, and campaigning to execute, requires propellant expenditure that conventional spacecraft must budget from launch to the entire mission lifetime. Spacecraft designed for a single flyby mission carry minimal excess propellant, while those intended for patrol or persistent proximity operations must carry substantially larger propellant loads. The unpredictable nature of pursuit and evasion operations creates particular challenges for propellant budgeting, as defensive maneuvers cannot be precisely anticipated. In-space refueling transforms this calculus by enabling spacecraft to conduct any combination of these operations, replenish propellant reserves, and continue operating indefinitely rather than being constrained by fixed fuel loads.



Each maneuver consumes propellant we cannot currently replenish.

The Need for Dynamic Space Operations

Relative positions of advantage in space enable space forces to protect and defend capabilities that the service and the Joint Force rely on as essential to operational success. Sustained Space Maneuver is key for both Space Force and Joint Force operations across all domains. Moreover, peer competitors have come to the same conclusion. Dr. Kelly Hammet, director of the Space Rapid Capabilities Office, articulated this challenge:

> *"If somebody is sending a co-orbital anti-satellite missile at you, you can actually run away. You can move. You can respond and do things. The other piece is maneuver for space warfighting. Our commercial systems are watching what the Chinese in particular are doing on orbit right now. They're practicing tactics and techniques. They're maneuvering, they're showing how they would ingress on potential targets. They're completing robotic maneuvers and rendezvous and proximity operations. How will we have capabilities to address those threats and potentially fight the space war fight?*[2]*"*

Additionally, the United States Space Command and the United States Space Force have recently committed to furthering an understanding and development of Dynamic Space Operations capability and in-space refueling. As the current Chief of Space Operations stated, *"We know speed to orbit, and we know resiliency on orbit are fundamental principles that we want to adhere to. Now how do we take advantage of it, if we were to have it? That's the work left to be done."*[3]

Robust space logistics are essential for Dynamic Space Operations, and a critical enabler to Sustained Space Maneuver is in-space refueling.

The Case for In-Space Refueling

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[2] Greg Hadley, "Dynamic and Responsive: Space Force Leaders Plan for a New Kind of Operations," Air and Space Forces Magazine (December 20, 2023).

[3] Ibid.

In-space refueling refers to operations to replenish consumable resources on board a spacecraft while in orbit. Resources such as propellant (or batteries) that have been depleted or reached the end of their life cycle can be replenished and replaced, enabling Sustained Space Maneuver until the end of the mission. This mission area has significant implications across all sectors of a space-faring nation: military, civil, and commercial. Key arguments justifying in-space refueling center on **endurance, mobility, new mission capabilities, space exploration, debris mitigation,** and **economic development**.

Senior Space Force leadership has explicitly recognized this imperative. As General B. Chance Saltzman, Chief of Space Operations, noted, aerial refueling revolutionized air power by extending range and endurance; similarly, developing logistics capabilities in space is crucial for future operations.[4] This parallel to aerial refueling is instructive. Just as the KC-135 and KC-46 transformed airpower from range-limited sorties to global power projection, in-space refueling can transform spacepower from static, fuel-constrained assets to dynamic, sustained combat platforms capable of maneuver warfare.

Historical precedent powerfully supports this transformation. In the autumn of 1943, Admiral Chester Nimitz ordered the creation of Service Squadron Ten to provide mobile service to the Pacific Fleet. Commodore Worrall Reed Carter devised a system that brought the port to the Navy, creating repair and resupply facilities thousands of miles from any fixed base.[5] The operational impact was decisive. After Operation Flintlock in early 1944, the Pacific Fleet remained at sea for the duration of the war. During the Battle of Okinawa, carrier task forces remained in fighting condition for eighty-nine consecutive days. Nimitz called these service squadrons his secret weapons. The critical insight for space logistics is this: Carter's innovation reframed logistics from a support function to an operational center of gravity that allowed the fleet to remain in the fight. Without mobile logistics, the Pacific campaign would have required repeated withdrawals to distant ports, surrendering initiative and tempo to the adversary. The Space Force faces the identical choice: accept the limitations of shore-based logistics or develop the in-domain capability that enables sustained offensive operations.

Endurance

The first benefit is the ability to extend a spacecraft's mission life.[6] All space missions are constrained by their limited fuel capacity. Once a satellite's service life has been reached or exceeded, the asset becomes space junk, cluttering the orbit in which it is parked. In-space refueling extends service life beyond end-of-life, enabling enduring mission operations and enhancing resourcing for space capability through a combination of continuous operation and next-generation capability delivery on orbit.

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[4] General B. Chance Saltzman, Remarks on contested space and space mobility, United States Space Force Headquarters (2024).

[5] Carter, Worrall R. Beans, Bullets, and Black Oil: The Story of Fleet Logistics Afloat in the Pacific During World War II. (November 6, 2015)

[6] Manny Shar, "How Orbital Refueling will unlock humanity's potential in space," The Space Review (October 2, 2023).

General Stephen Whiting, Commander of United States Space Command, notes that current satellites delivered to orbit have no more ability to conduct Dynamic Space Operations than systems fielded more than half a century ago.[7] In fact, the average expected lifespan of current satellites is five to 15 years, depending on orbital regime and how well operators can bias operations to save propellant.[8] This reality represents a far cry from conducting Dynamic Space Operations. Complementarily, there appears to be a market for this capability. Twenty geosynchronous orbit satellites are retired each year due to reaching the end of their lives, typically due to propellant exhaustion.[9]

In-space refueling has application across all sectors: military, civil, and commercial space operations. The longer a spacecraft can perform in space, the better able each sector is to deliver effects, achieve desired outcomes, and reduce resources needed to reconstitute spacecraft at end-of-life.

Mobility

From a military perspective, movement and maneuver are traditionally considered terrestrial warfighting operations. In space, movement and maneuver are physically limited by the trade-off between achieving the desired effect and the mission life of the space asset. All other domains are far less limited by this trade constraint. Further, in-space refueling in a military context is not primarily about extending the service life of an asset, but rather about introducing the ability to conduct operations free of the constraint of non-replenishment. The best defense is a robust maneuvering offense, supported by strong logistics frameworks. This lesson from military history is directly applicable to the space domain and potential conflict in space.[10] In-space refueling enables spacecraft to conduct Sustained Space Maneuver and with far less need to make trade-offs to perform missions, while simultaneously increasing the ability to protect and defend space capability.

New Missions and Increased Payload Capability

With an infrastructure for in-space refueling, new missions and new designs become possible where perhaps physical or economic limitations previously rendered them unsustainable. Missions can be launched with lower size, weight, and power specifications to be fueled (additionally or entirely) through in-space refueling infrastructure. Conversely, higher size, weight, and power spacecraft designs and missions can be developed and fielded since it is no longer necessary to account for propellant as part of mass transport to orbit. This opens the possibility of alternate launch capabilities separate and other than traditional launch vehicles if mass-to-orbit can be significantly reduced, which opens further possibilities in space reconstitution strategy across military, civil, commercial sectors. The military could increase

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[7] Shawn Hendricks, "Sustained Maneuver: Why the time is now for in-space refueling," Govexec Space Project (December 18, 2024).

[8] Physics Frontier, "What Is the Lifespan of a Satellite?" (August 12, 2025).

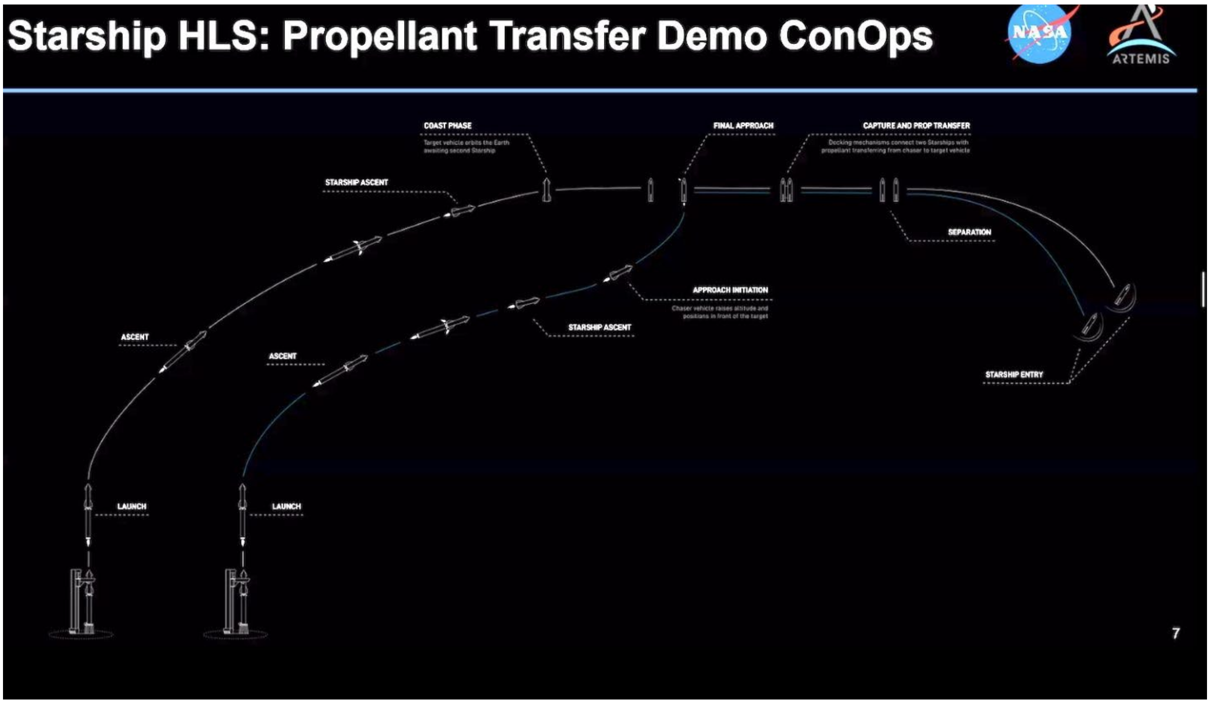
[9] NASA, "On-Orbit Satellite Servicing Study," National Aeronautics and Space Administration Goddard Space Flight Center (October 2010): 41.

[10] Aidan Poling, "Refueling and Maneuvering Satellites in Orbit is Key to National Security," Air and Space Forces Magazine (December 23, 2024).

resilience of reconstitution through proliferation of launch sites. Civil and commercial sectors could see a drop in launch cost due to increased options for delivering mass to orbit or increasing value-generating potential with larger or more capable designs and payloads.

Exploration

An extension of reducing launch vehicle requirements is the ability to refuel exploratory spacecraft as they depart Earth's orbit and venture into deep space. SpaceX is designing Starship to be refueled in space (by other Starships), enabling Lunar missions and the exploration of Mars. In-space refueling is crucial to enabling regular missions to Mars to transport 100 metric tons or 100 passengers to Mars and enabling our civilization to become multiplanetary.[11] Without the successful implementation of multiple refueling maneuvers during transit, SpaceX's Starship will not be able to make it to Mars without multiple refuels along the way.



Starship HLS: Propellant Transfer Demo ConOps

[12]

Sustainability and Debris Mitigation

All spacecraft have limited life due to limited propellant and other consumables. Once end-of-life is reached, that spacecraft becomes debris. Space sustainability goes hand-in-hand with endurance. Service life extension represents a method of sustaining operations for longer periods, meaning fewer space vehicles become debris.

Economic Viability

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[11] Matthew Williams, "Starship's next launch is imminent. Its real risk is still in orbit," Interesting Engineering (May 27, 2025).

[12] NASA/SpaceX/Amit Kshatriya, "illustration of SpaceX's ship-to-ship refueling demonstration"

The economy driven by the fielding of an in-space refueling infrastructure is another important benefit. In-space refueling and servicing yield an entirely new and additional industry. Depending on the design and implementation of the infrastructure, the industry will need to grow to meet the increased demand for fuel production, transportation, storage, and the maintenance of the on-orbit infrastructure potentially spread across many different orbital regimes. A NASA study indicates through historical data there is significant opportunity for in-space refueling industry. Forty-four satellites per year, looking particularly at the geosynchronous regime, are serviceable through some form of in-space refueling.[13] Between the years of 1994 and 2003, $750 million in insurance losses were covered each year resulting from serviceable failures.[14] More recently, from 2006 to 2010, $700 million was covered through insurance losses for satellite failures caused by propellant issues alone.[15] This data indicates a strong case and need for a commercial market centered on in-space refueling.

There are clearly many good arguments to be made in support of in-space refueling. Many of these benefits are cross-cutting for the military, civil, and commercial sectors, with each playing a crucial role in development, operationalization, and sustainment of an in-space refueling and servicing architecture.

Considerations and Opportunities for Innovation

There are numerous technical challenges to in-space refueling, from fluid dynamics modeling in microgravity to material compatibility. There are several enterprise-level challenges that must be understood and overcome, or accepted as risk or cost, to allow in-space refueling infrastructure to succeed. From the operational design perspective, automation in space represents a key opportunity. Automation in the form of automated rendezvous and capture is an obvious first step in refueling on orbit. This capability has been demonstrated in a DARPA program called Orbital Express launched in 2007.[16] The program set out to buy down risk in this area of automated rendezvous and capture along with other challenge areas facing the concept of in-space refueling.

Another opportunity for innovation addresses the economic viability of an in-space refueling architecture. The case has been made for pursuing the architecture, but there is a barrier to commitment centered on initial cost. The prevailing perception is that it is cheaper to build and launch new satellites, rendering the need for in-space refueling moot in many cases. Additionally, there is a perception that building satellites with common interfaces to enable their refueling would increase costs. As stated earlier in this paper, the desire must be to make this infrastructure viable for all three sectors of military, civil, and commercial use. Generally, if there is a commercial market or use case, the combination of government and private resourcing and engineering support to the idea contributes to success. At the core of this

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[13] NASA, "On-Orbit Satellite Servicing Study," 27.

[14] Ibid.

[15] Ibid., 28.

[16] Robert Friend, "Orbital Express Program Summary and Mission Overview," The Boeing Company, Advanced Network & Space Systems (2008): 1.

challenge is analysis suggesting that a servicing space vehicle must refuel three to five client satellites on average to be economically viable.[17]

Currently, there is also a prohibitive dilemma stunting progress in the area of in-space refueling despite the expressed desire from United States Space Command. There is no widespread standard for satellites to be built with the ability to be refueled or serviced, so companies specializing in refueling and servicing struggle. Conversely, satellite manufacturers are hesitant to build satellites with the ability to be refueled or serviced because the refueling and servicing technology and infrastructure does not yet exist. Finally, in fielding an in-space refueling system, the question arises whether we are creating more military targets in time of conflict, levying an additional burden on the protect and defend mission sets. Do the benefits outweigh this risk?

Strategic Threat Environment: The Imperative for Dynamic Operations

The strategic context for Space Mobility and Logistics extends beyond operational efficiency and economic optimization. A fundamental asymmetry is emerging between United States and adversary approaches to space operations that demands examination. American space architectures, including the mega-constellations currently under development, are designed primarily for Positional Space Operations: activities where mission effects are achieved by keeping spacecraft in fixed, predetermined positions with minimal movement. These architectures optimize for coverage, persistence, and cost efficiency in a benign environment. They are not optimized for maneuver in a contested domain.

The People's Republic of China has pursued a markedly different approach. Intelligence suggests the People's Liberation Army likely sees counterspace operations as a means to deter and counter United States military intervention in a regional conflict, and is actively developing and fielding a wide range of counterspace capabilities.[18] China's space growth has been explosive: since 2015, China's on-orbit presence has grown by approximately 520 percent, adding more than 818 satellites. As of May 2025, China operates more than 1,007 satellites, including over 510 intelligence, surveillance, and reconnaissance capable platforms with optical, multispectral, radar, and radio frequency sensors. In 2024 alone, China conducted 68 space launches placing 260 payloads into orbit.

The PLA's counterspace arsenal spans the full spectrum of effects. China tested a direct-ascent antisatellite missile in 2007, destroying a defunct weather satellite and creating more than 2,700 pieces of trackable debris that remain in orbit today. That missile evolved into an operational ground-based system intended to target low Earth orbit satellites on which the PLA actively trains. The Defense Intelligence Agency assesses the PLA probably intends to field antisatellite weapons able to reach geosynchronous orbit at 36,000 kilometers; a 2013 ballistic test that peaked at 30,000 kilometers suggests China may already possess basic capability against higher orbits. The PLA has also deployed multiple ground-based laser weapons able to

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[17] Brook Rowland Sullivan, "Technical and Economic Feasibility of Telerobotic On-Orbit Satellite Servicing," University of Maryland Space Systems Laboratory (2005): 56.

[18] Headquarters Space Force Intelligence, "Space Threat Fact Sheet," Updated 20250516 (v8).

disrupt, degrade, or damage satellite sensors, with higher-power systems capable of damaging satellite structures expected by the mid-to-late 2020s.[19]

Most directly relevant to this analysis, China is developing satellite inspection and repair systems which could function as weapons, and has demonstrated operational on-orbit refueling. The Shijian-21 satellite moved a derelict BeiDou navigation satellite to a graveyard orbit above geosynchronous orbit in January 2022, demonstrating the ability to grapple other satellites. Multiple SJ-series and TJS-series experimental satellites have conducted unusual, large, and rapid maneuvers in geosynchronous orbit with military applications. In 2025, China performed on-orbit refueling that extended the mission performance of SJ-21.[20] China also launched Shijian-25 in November 2023 specifically to test on-orbit refueling and mission extension technologies, demonstrating sustained investment in space logistics capability.[21] Chinese spacecraft have also demonstrated multi-satellite dogfighting tactics. These are not the station-keeping adjustments of Positional Space Operations. These maneuver profiles are consistent with missions that could support surveillance, positioning advantage, or counterspace options, depending on payload and doctrine.

Beyond hardware demonstrations, China is institutionalizing space logistics as an operational capability. The People's Liberation Army is preparing satellite operators for on-orbit refueling in both peacetime and wartime, developing training simulators for satellite servicing missions.[22] Chinese engineers have tested technologies for refueling and debris removal in orbit and are integrating these capabilities into military doctrine and exercises. While the United States debates organizational frameworks for space logistics, China is building the human capital and operational experience to employ these capabilities in conflict.

China has also launched three reusable spaceplanes, with the first in orbit for two days, the second for over nine months, and the third for nearly nine months. All three released unidentified objects while on orbit. The G60 constellation has placed 90 communications satellites in low Earth orbit as part of a planned 14,000-satellite proliferated architecture by 2030, while the China Satellite Network Group is pursuing a separate 13,000-satellite constellation. China continues testing next-generation quantum capabilities including free-space quantum key distribution, a major milestone toward a global ultra-secure communications network independent of American systems.

Against this backdrop, American space posture appears increasingly misaligned with the emerging threat environment. The United States maintains limited capacity for Dynamic Space Operations. The X-37B Orbital Test Vehicle represents the most visible American

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[19] U.S.-China Economic and Security Review Commission, (December 8, 2025).

[20] Logistics Officer Association, "Logistics: Powering the Space Fight" (May 29, 2025), citing Chinese demonstration of on-orbit refueling that extended SJ-21 mission performance. See also Space Force Intelligence, "Space Threat Fact Sheet" (Updated 20250516).

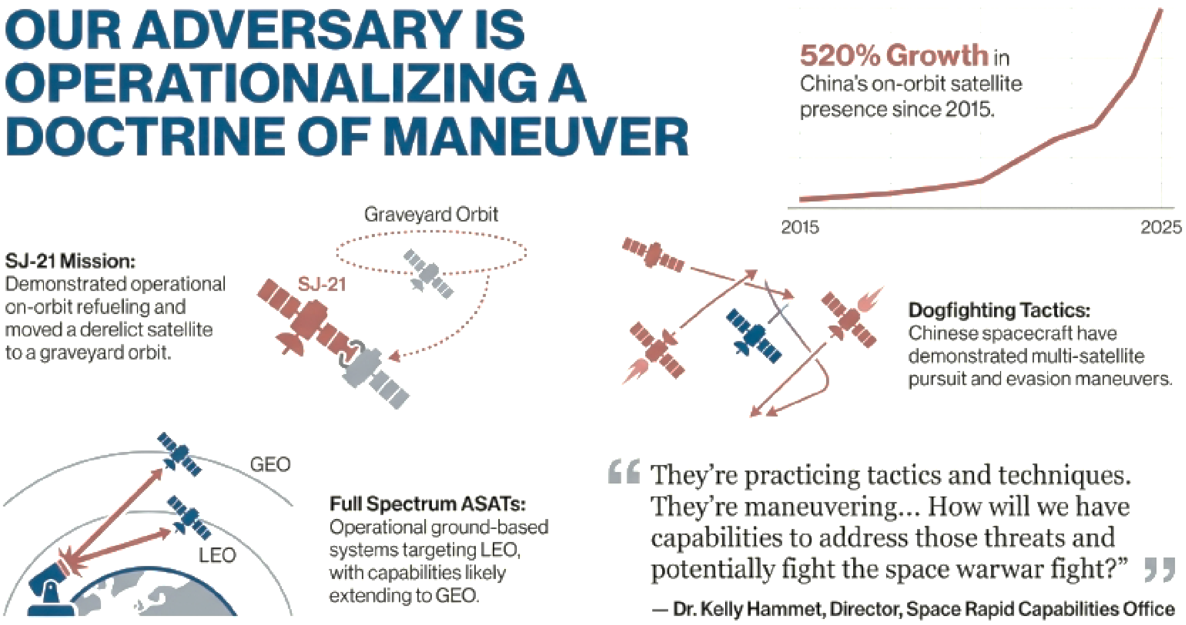
[21] Sandra Erwin, "China launches Shijian-25 satellite to test on-orbit refueling and mission extension technologies," SpaceNews (November 13, 2023).

[22] Logistics Officer Association, "Logistics: Powering the Space Fight" (May 29, 2025). The article notes Chinese engineers have tested technologies for refueling and debris removal in orbit and are integrating these into military doctrine and exercises.

capability for maneuvering space operations, yet its capacity is limited to a single vehicle with extended turnaround times between missions. American operational satellites, including those in proliferated architectures, are designed with fuel loads calculated for station-keeping and end-of-life disposal rather than sustained maneuver. When propellant is exhausted, the spacecraft becomes a static target incapable of evasive action.

This asymmetry creates strategic risk. An adversary capable of Dynamic Space Operations facing a defender limited to Positional Space Operations holds fundamental advantages in initiative and tempo. The defender cannot reposition to avoid threats, cannot pursue fleeing adversary spacecraft, and cannot concentrate capability at decisive points in the domain. Proliferation provides resilience through numbers but does not address the operational deficit. The United States requires the ability to conduct Sustained Space Maneuver, which in turn requires the space logistics infrastructure to replenish propellant and extend spacecraft operational life. The threat environment makes this capability strategically essential.

Delay in developing this capability carries a warfighting cost. While the United States debates organizational frameworks, conducts additional studies, and awaits commercial market maturation, China is operationalizing space logistics. The People's Liberation Army is training satellite operators on refueling simulators. Chinese engineers are integrating servicing technologies into military doctrine and exercises. Shijian-series satellites are demonstrating the maneuvers that will characterize future space conflict. Each year of American delay is a year in which the adversary builds operational experience, refines tactics, and extends its lead in a domain where the United States has historically maintained superiority. The technology is proven. The threat is clear. The cost of continued delay is measured in lost advantage that may prove difficult to recover.



SJ-21 Mission: Demonstrated operational on-orbit refueling and moved a derelict satellite to a graveyard orbit.

Dogfighting Tactics: Chinese spacecraft have demonstrated multi-satellite pursuit and evasion maneuvers.

Full Spectrum ASATs: Operational ground-based systems targeting LEO, with capabilities likely extending to GEO.

> “They’re practicing tactics and techniques. They’re maneuvering… How will we have capabilities to address those threats and potentially fight the space warwar fight?”
>
> — Dr. Kelly Hammet, Director, Space Rapid Capabilities Office

Historical Demonstrations

There have been many demonstrations of various elements of in-space refueling over the decades. Russia has proven particular success in this mission area beginning with Progress 1, launching in 1978 to refuel their Salyut 6 space station.[23] To date, subsequent iterations of Progress 1 are responsible for successfully transferring more than 4,000 kilograms of propellant to the International Space Station.[24] China has developed the Tianzhou space vehicle to resupply and refuel the Tiangong China Space Station, completing 9 successful missions with the latest occurring as recently as July 2025.[25]

The institutional arrangement underlying Russia's ISS refueling experience warrants examination. Russia conducts all propellant transfer operations aboard the International Space Station because the station's propulsion modules are Russian-manufactured, a division of responsibility established in the original ISS partnership agreements.[26] This arrangement has proven cost-effective for American taxpayers, avoiding the expense of developing and maintaining redundant refueling infrastructure. However, the arrangement carries a significant operational consequence: American operators have accumulated no hands-on experience conducting orbital refueling operations during the entire operational life of the International Space Station. While American astronauts and ground controllers have developed extensive expertise in rendezvous and proximity operations through cargo vehicle berthing and docking, the actual propellant transfer operations, including valve sequencing, flow rate management, leak detection, and contingency procedures, remain exclusively within Russian operational experience. This experience gap compounds the asymmetry identified in Chapter 1: potential adversaries are training operators for refueling operations while American operators lack equivalent operational currency. Addressing this gap requires deliberate investment in training infrastructure and operational opportunities, a requirement that reinforces the organizational recommendations in Chapter 7 regarding Space Training and Readiness Command responsibilities.

There have been several American demonstrations from Orbital Express to Robotic Refueling Mission. Orbital Express was a program conceived by the Defense Advanced Research Projects Agency and performed in partnership with Boeing. The flight demonstration was executed in a Low Earth Orbit at 492 kilometers, circular, and inclined 46 degrees from the equator.[27] Two satellites were launched together: one servicing spacecraft and one demonstration client spacecraft. Autonomous Space Transfer and Robotic Orbiter was the servicing spacecraft designed to rendezvous and capture the client satellite, Next Generation Satellite. Next Generation Satellite was simultaneously a client satellite demonstrator and a commodity

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[23] John Uri, "45 Years Ago: Progress 1 Begins the Era of Space Station Resupply," Johnson Space Center (January 20, 2023).

[24] Charles W. Pierce et al., "A Review of In-Space Propellant Transfer Capabilities and Challenges for Missions Involving Propellant Resupply," NASA Engineering and Safety Center (September 2020): 22.

[25] Uri, "45 Years Ago."

[26] Interview with Jeffrey A. Sheehy, NASA International Space Station Logistics Lead, January 9, 2026.

[27] Friend, "Orbital Express Program Summary," 2.

depot.[28] The system demonstrations were 100 percent successful in proving technology readiness for non-proprietary servicing interfaces, autonomous operations and servicing software, autonomous proximity operations, autonomous guidance, navigation, and control, autonomous capture and mating, orbital replacement unit transfer, zero gravity fluid transfer, avoidance of contamination, and advanced robotics.[29]

Orbital Express proved across 4 months and 9 test scenarios that the technology needed to perform end-to-end in-space refueling and servicing exists and is not a limiting factor for Dynamic Space Operations.[30] The demonstration followed a deliberate autonomy progression that validated operational scalability. The first propellant transfer required 23 separate ground approvals before the spacecraft could execute each step. By Scenario 8, the design reference mission, ASTRO executed all servicing activities, including separation to seven kilometers, rendezvous, free-flyer capture, propellant transfer, and battery and computer replacement, with a single command and no required ground confirmations.[31] Equally significant was the demonstration of operational robustness under failure conditions. During Scenario 3, a sensor computer failure caused ASTRO to autonomously abort to a 120-meter safe standoff, eventually drifting to six kilometers separation. The operations team successfully recovered, re-rendezvoused, and completed the mission objectives, demonstrating that the system could handle real-world anomalies. DARPA concluded that the mission achieved its overarching goal of proving that the technology hurdles required to enable on-orbit servicing were achievable, effectively taking the technology excuses off the table.[32]

The Orbital Express demonstration proved the technology for servicing a client space vehicle that was indeed designed for in-space refueling. The Robotic Refueling Mission launched in 2011 on the final Space Shuttle mission to demonstrate the technology and ability to service satellites not designed for refueling.[33] The exposed, open facility platform on the International Space Station was used along with the Canadarm to successfully demonstrate fuel transfer between various commercial and government legacy satellites using four prototype tools.[34]

These are two prominent and successful demonstrations by the United States in the recent past. There are several exciting and potentially pivotal initiatives for in-space refueling and servicing looking to the present and into the future. Robotic Servicing of Geosynchronous Satellites is a DARPA program in partnership with the Naval Research Labs and SpaceLogistics designed to deliver Mission Extension Pods to three clients in geosynchronous

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[28] Ibid.

[29] Ibid., 3.

[30] Friend, "Orbital Express Program Summary," 10-11.

[31] Friend, “Orbital Express Program Summary,” 5, 9. The first propellant transfer required 23 ground approvals; Scenario 8 executed all servicing activities with a single command.

[32] Friend, “Orbital Express Program Summary,” 11. The mission “accomplished the overarching goal of proving that the technology hurdles required in order to enable on orbit servicing were achievable. It achieved the DARPA goal of taking the technology excuses off the table.”

[33] Jacopo Prisco, "Ambitious Plans for Gas Stations in Space Could Extend the Lives of Satellites," National Air and Space Museum (December 21, 2022).

[34] Stephen Clark, "Satellite Refueling Testbed Completes Demo In Orbit," Spaceflight Now (January 25, 2013).

orbit. The Mission Robotic Vehicle was developed by the Naval Research Labs, based on SpaceLogistics' already operational Mission Extension Vehicle, while DARPA provided a robotic system payload for integration to create the Mission Robotic Vehicle. SpaceLogistics, a subsidiary of Northrop Grumman, has developed Mission Extension Pods designed to attach to client space vehicles and extend service life of a 2,000 kilogram satellite by 6 years. DARPA brokered the partnership between the Naval Research Labs and SpaceLogistics to combine both technologies in a launch where a Mission Robotic Vehicle and three Mission Extension Pods will be delivered to geosynchronous orbit. Once positioned in geosynchronous orbit, the Mission Robotic Vehicle captures each Mission Extension Pod, maneuvers to a client space vehicle where the Mission Extension Pod is attached and acts as a propulsion pack.[35]

Other companies already exist with on-orbit servicing and in-space refueling as their mission. Astroscale and Orbit Fab have created a partnership with the goal of conducting the first mission to refuel a military satellite, the Space Force's Tetra-5.[36]

The pursuit of in-space refueling should be driven by the United States Space Force to ensure maximum ability to conduct Sustained Space Maneuver and Dynamic Space Operations. The current landscape for in-space refueling is ripe for the development of a strategic vision of Dynamic Space Operations from the military perspective to be coupled with resources to develop the future of space operations.

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[35] Sandra Erwin, "Northrop Grumman to Launch New Satellite-Servicing Mission in 2024," SpaceNews (February 21, 2022).

[36] Douglas Gorman, "Astroscale, Orbit Fab Pair to Gas Up DoD," Payload Space (April 9, 2025).

Chapter 3

Operational Considerations

The space community stands at a nexus specifically regarding the pursuit of in-space refueling and servicing to enable Dynamic Space Operations. The commercial sector has taken the initiative in this mission area and is starting to see growth with the emergence of several companies invested in a handful of methodologies. These efforts are indeed impressive and extremely valuable for pathfinding in how a larger architecture might be designed. Options are being cultivated from which the military and civil sectors can choose towards building an architecture of in-space refueling and servicing. This chapter baselines the technical foundations followed by the broader considerations for the operation of an in-space refueling architecture.

Technical Foundations

There are many types of propellant used by spacecraft on orbit to conduct various maneuver types. Propellants typically fall into several categories: cryogenic, earth-storable, noble gas, green propellant, and nuclear. All propulsion systems use some form of fuel to generate thrust through the physical law of equal and opposite forces. Ejecting a mass in a direction imparts an equal and opposite force. Cryogenics function at extreme low temperatures and must be stored in this way since, at room temperatures, they would exist in a gaseous state. These propellants are used in rockets primarily and include Liquid Oxygen, Liquid Hydrogen, Liquid Methane, and Kerosene. Hypergolics are a type of storable liquid propellant highly common in spacecraft today. Hypergolics ignite spontaneously on contact when a fuel and oxidizer mix, making them ideal for reliable propulsion methods.[37] Storable liquid propellants are more easily stored than cryogenic propellants and are quite suitable for long-duration missions. Hydrazine is an example of a storable liquid monopropellant where the fuel and oxidizer are contained in the same molecule. Electric propulsion uses noble gases like Xenon, Krypton, or Argon, which can be refueled in space.[38] Green propellants are being developed to provide alternative sources for space propulsion to mitigate the need to deal with highly toxic materials and mitigate supply issues. Ionic liquids are being examined as a possible replacement for Hydrazine through their use in electrospray thrusters for small satellites.[39] Nuclear Thermal Propulsion uses a nuclear reactor to superheat a liquid propellant to a high-pressure gas to generate thrust.[40]

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[37] NASA, "Propellant Transfer Technologies," National Aeronautics and Space Administration (January 11, 2024).

[38] Dawn Aerospace, "A Comparison of Electric and Chemical Propulsion in the Era of Low Launch Costs" (July 18, 2024).

[39] Isaac Sam et al., "Exploring the Possibilities of Energetic Ionic Liquids as Non-Toxic Hypergolic Bipropellants in Liquid Rocket Engines," Journal of Molecular Liquids 350 (March 15, 2022).

[40] Office of Nuclear Energy, "6 Things You Should Know About Nuclear Thermal Propulsion," U.S. Department of Energy (July 23, 2023).

All of these fuel types can be replenished on orbit through in-space refueling and servicing to enable Dynamic Space Operations and increase service life and efficacy for civil and commercial purposes. Hydrazine is an extremely common propellant used in space and is one of a number of propellants capable of being refueled on orbit. For example, a private company, Orbit Fab, has developed the ability to refuel Hydrazine, Xenon, High-Test Peroxide, Propene, Ethane, N2O, water, and Krypton with their Rapidly Attachable Fluid Transfer Interface.[41] It is clear that in-space refueling technologies are already developed to the point where the vast majority of standard propellant types can be replenished. This maintains and generates operational flexibility to continue using existing methods of propulsion knowing that they can be replenished on orbit.

The distinction between propellant types carries significant implications for understanding the commercial market landscape. Xenon and krypton are primarily used in electric Hall-effect thrusters that provide extremely efficient but low-thrust propulsion suitable for station-keeping and gradual orbit-raising over weeks or months. Commercial geosynchronous satellite operators favor these electric propulsion systems because time-to-station is not operationally critical and the fuel efficiency reduces launch mass. In contrast, hydrazine provides the high-thrust chemical propulsion necessary for rapid orbital maneuvers measured in hours rather than weeks. Dynamic Space Operations, which require spacecraft to reposition quickly in response to threats or operational demands, depend on high-thrust chemical propulsion that electric systems cannot provide. This propellant market segmentation means commercial refueling services, if they emerge, will likely focus on xenon delivery for Low Earth Orbit constellations where the commercial business case appears strongest. The high-thrust hydrazine refueling capability required for military Dynamic Space Operations in geosynchronous orbit represents a distinct market with the government as the primary customer.

General Process

In-space refueling at a macro level can be simplified to rendezvous, capture and docking, fluid transfer, and undocking followed by a continuation of operations. The starting status for refueling a spacecraft presents significant complexity. Space vehicles with propellant are extensively sealed once fueled prior to launch. The fill valve is closed, wired shut, followed by installation and securing of two safety caps. Finally, thermal blanketing is wrapped on top of those safety caps to ensure thermal protection. A refueling vehicle must be able to essentially perform space surgery to cut through the blanket, hold it back while removing the safety caps to access the fill valve. Then a robotic arm needs to select a refueling hose, create the connection, and fluid transfer can begin. Finally, the client spacecraft fill valve is resealed and made thermally safe once more.[42] Key technologies are needed to perform this kind of space surgery and refueling operations on orbit: Automated Rendezvous and Capture, advanced robotics, and zero gravity fluid transfer.

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[41] Orbit Fab, "Fuel Delivered When and Where You Need It," Orbit Fab (n.d.).

[42] Prisco, "Ambitious Plans for Gas Stations in Space."

The Orbital Express program out of a DARPA and Boeing partnership demonstrated all of these technologies completely successfully in 2007.[43] The demonstration in Low Earth Orbit ran through nine test scenarios. The first several were performed prior to the spacecraft stack separation between Next Generation Satellite and Autonomous Space Transfer and Robotic Orbiter, while the remaining tests were conducted after stack separation and validated Automated Rendezvous and Capture capability. Automated Rendezvous and Capture operations were successfully performed multiple times with approaches from various distances, some from separation distances exceeding 300 kilometers.[44] Prior to refueling, Autonomous Space Transfer and Robotic Orbiter performed an extremely complex set of movements with its robotic arm to checkout both Next Generation Satellite and Autonomous Space Transfer and Robotic Orbiter structures, modules, and interfaces, demonstrating significant levels of advanced robotic capability in space.[45] Additionally, the program successfully performed 20 propellant transfers of hydrazine between the two spacecraft in both directions. Simultaneously, the technology to perform pressure fed fuel transfers was successfully demonstrated.[46] This highly successful demonstration showcases how the United States is starting from a significantly advantaged position in these key technological areas.

Challenges and Opportunities

The approach to the space domain and technology in general have advanced significantly in the time since the Orbital Express demonstration. This technology delta creates additional challenges and opportunities for further development. Different vendors may use a wide variety of different propellants, increasing the diversity of refueling methods, hardware, and interfaces needed to deliver.[47] Docking and refueling interfaces therefore become more varied. There is also the aforementioned dilemma where industry is hesitant to delve deeper into this capability until space vehicles are more commonly equipped with refueling capability, yet space vehicle vendors are hesitant to build in the ability to be refueled until there is a robust service to do so. The Government Accountability Office highlights additional contributing factors to this dilemma. Government and industry have differing objectives and requirements for how this technology could be used. Government and private satellite operators do not currently require any refueling capability included in designs. There are few opportunities to test the necessary technologies, which deters risk-averse entities from developing the capability.[48]

In addition to technological opportunities, there are industrial base challenges when it comes to implementation that need to be carefully planned and thought out. An intersectional strategy should be developed to understand how each of the sectors contributes to the overall development, delivery, and sustainment of an in-space refueling architecture. There are

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[43] Friend, "Orbital Express Program Summary," 2.

[44] Lt Col Fred Kennedy, "Orbital Express," Defense Advanced Research Projects Agency (March 17, 2008): 3.

[45] Friend, "Orbital Express Program Summary," 5.

[46] Kennedy, "Orbital Express," 3.

[47] Theresa Hitchens, "In a first, Space Force to require refueling capability for next-gen neighborhood watch sats," Breaking Defense (September 24, 2025).

[48] Government Accountability Office, "In-Space Servicing, Assembly, and Manufacturing: Benefits, Challenges, and Policy Options," GAO-25-107555 (July 2025): 4.

currently several budding commercial companies who are building the industry for in-space refueling and servicing today. These companies are trending towards the utilization of universal interfaces designed to be used across a host of propellant types. For example, Astroscale and Orbit Fab are working together to build an industry of in-space refueling and servicing using common interfaces and refueling architecture designed to maximize the number of client satellites which can be refueled.[49]

From the military perspective, the United States Space Force has been driving a faster solution to United States Space Command's demand for Sustained Space Maneuver by building in requirements language for a spacecraft supplier to provide their own refueler as an additional unit upon delivery.[50] Both approaches expect to yield results, but one lends itself much better to a sustained architecture of in-space refueling capability. If the United States Space Force approach wins out, dozens of spacecraft vendors will find their own methods for refueling, which may decrease interoperability and reduce overall operational effectiveness of an in-space refueling architecture and concept of operations. Additionally, from the economic perspective, companies like the Astroscale and Orbit Fab collaboration may see fewer opportunities and end up out of business. The partnership between military and commercial is critical for enabling and building a sustained industrial base and architecture for in-space refueling, optimized and maximized across all space-faring sectors: military, civil, commercial. Getting this right at this nascent stage is imperative.

Finally, an important question operationally is one of how we might protect and defend an in-space refueling architecture. Whichever force structure and design the nation pursues, are we just creating more vulnerable points in space? How do we mitigate or negate this potential risk? Is proliferation in combination with the gained ability of Sustained Space Maneuver enough to outweigh this risk?

Next-Generation Propellant Requirements for Sustained Operations

The preceding discussion of propellant types addresses the current state of spacecraft propulsion. However, a critical examination of total cost of ownership reveals fundamental limitations in existing propellants that will constrain truly sustained space operations. Hydrazine, the most common spacecraft propellant, illustrates this challenge. While the raw material cost of hydrazine is approximately one hundred dollars per kilogram, this figure dramatically understates the true expense of operating a hydrazine-based logistics architecture.

The total cost of ownership for hydrazine extends far beyond procurement. Hydrazine is a highly toxic, carcinogenic substance that requires extensive safety infrastructure throughout its lifecycle. Shipping hydrazine demands specialized hazardous materials transportation with associated regulatory compliance, insurance, and security requirements. Ground handling requires dedicated facilities with vapor containment systems, emergency response equipment, and decontamination capabilities. Personnel must complete rigorous

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[49] Gorman, "Astroscale, Orbit Fab Pair to Gas Up DoD."

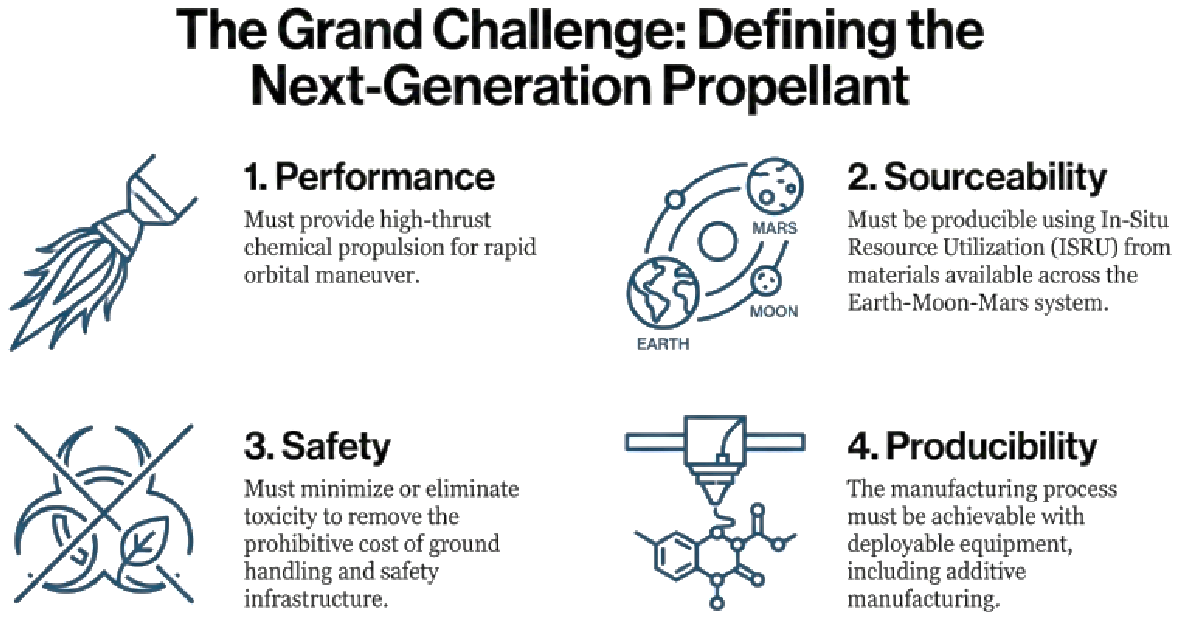
[50] Hitchens, "In a first, Space Force to require refueling capability."

certification programs and maintain ongoing medical monitoring due to hydrazine's carcinogenic properties. Fueling operations impose significant schedule constraints as non-essential personnel must evacuate surrounding areas during propellant loading. When these factors are aggregated across the enterprise, the effective cost per kilogram of hydrazine delivered to a spacecraft reaches into the millions of dollars. This cost structure fundamentally limits the scalability of any space logistics architecture dependent on Earth-manufactured toxic propellants.

Requirements Considerations for Next-Generation Propellants

The United States Space Force and broader national security space enterprise require propellant solutions that satisfy multiple criteria simultaneously. First, the propellant must provide sufficient thrust for operational maneuvers including orbital transfer, station-keeping, and evasive action. Second, the propellant must be producible using resources available across the Earth-Moon-Mars system to enable true In-Situ Resource Utilization. Third, the propellant should minimize or eliminate the toxicity concerns that drive hydrazine's prohibitive handling costs. Fourth, the manufacturing process should be achievable with deployable equipment, potentially including additive manufacturing or 3D-printing technologies that could be transported to and operated at remote locations.

The selection of propellant chemistry will fundamentally shape the design of depots, tankers, and refueling interfaces. A propellant that can be manufactured in space rather than transported from Earth transforms the economics of sustained operations. The research and development investment required to mature ISRU-compatible propellants should be weighed against the perpetual costs of maintaining Earth-dependent toxic propellant supply chains.



The Grand Challenge: Defining the Next-Generation Propellant

1. Performance
Must provide high-thrust chemical propulsion for rapid orbital maneuver.

2. Sourceability
Must be producible using In-Situ Resource Utilization (ISRU) from materials available across the Earth-Moon-Mars system.

3. Safety
Must minimize or eliminate toxicity to remove the prohibitive cost of ground handling and safety infrastructure.

4. Producibility
The manufacturing process must be achievable with deployable equipment, including additive manufacturing.

Hydrazine depot infrastructure therefore represents a necessary bridge capability that enables near-term Dynamic Space Operations. However, acquisition strategy must not lock the architecture into permanent Earth dependence. The long-term requirement is a propellant ecosystem that severs the Earth logistics umbilical cord through In-Situ Resource Utilization. Lunar water ice can theoretically be processed into hydrogen and oxygen[51] through electrolysis. Martian atmospheric carbon dioxide combined with subsurface water could produce methane and oxygen[52] via the Sabatier reaction. If resource assessments prove accurate, these materials may exist in quantities sufficient to sustain operations across the Earth-Moon-Mars system for extended durations. The strategic imperative is to build now with hydrazine, but design for transition. Depot architecture must incorporate propellant modularity from inception, enabling evolution from Earth-supplied hydrazine to ISRU-derived propellants as production capabilities mature.

Shifting the Center of Gravity: Depot Architecture as Strategic Deterrent

The selection of space logistics architecture deliberately shifts the strategic center of gravity in ways that can favor the defender. Joint doctrine defines center of gravity as the source of power that provides strength, freedom of action, or will to act.[53]

Depot-based logistics architecture deliberately presents adversaries with a targeting dilemma that transforms apparent vulnerability into strategic advantage. Understanding this dynamic reframes depot infrastructure from potential weakness to vital component of deterrent strategy.

Table 3.1. Shifting the Center of Gravity: Proliferation versus Depot Architecture

Factor	Proliferation/Attrition Architecture	Depot/Reuse Architecture
Center of Gravity	Distributed across constellation nodes; no single point of failure	Deliberately shifted to defended depot infrastructure
Adversary Targeting	Must attrit multiple spacecraft; costly if nodes are hardened	Must choose: attack depots first or face fully-fueled constellation
Adversary Dilemma	Gradual attrition may not achieve decisive effect before reconstitution	Attack depots = lose surprise; ignore depots = face sustained maneuver capability
Strategic Warning	Attack patterns difficult to distinguish from debris or anomalies	Depot attack = unambiguous hostile intent; defender gains escalation control
Defensive Options	Hardening, maneuver (if fuel available), signature reduction	xGEO positioning, active defense escorts, deception/decoys, depot proliferation
Asset Value at Risk	$350M per spacecraft with mission payload	$100M per depot; $7B fleet capability preserved through attack
Cost-Exchange Ratio	Adversary destroys $350M asset per successful attack	Adversary expends weapons on $100M target; $350M spacecraft survives
Escalation Control	Ambiguous attacks complicate attribution and response options	Clear threshold crossing provides defender with response clarity and tempo

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[51] Anthony Colaprete et al., "Detection of Water in the LCROSS Ejecta Plume," Science 330, no. 6003 (October 22, 2010): 463–468. The LCROSS mission confirmed water ice concentration of approximately 5.6% by mass

[52] Michael H. Hecht et al., "Mars Oxygen ISRU Experiment (MOXIE): Preparing for human Mars exploration," Science Advances 8, no. 35 (August 31, 2022). MOXIE demonstrated oxygen production from Martian atmospheric CO2 via solid oxide electrolysis. The Sabatier reaction ($CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$)

[53] Joint Publication 5-0, Joint Planning (December 2020), IV-22 to IV-24

The strategic logic of depot-based architecture rests on a fundamental insight from deterrence theory: clear, identifiable thresholds provide stronger deterrent value than ambiguous red lines because they reduce miscalculation risk for both parties.[54] Any adversary attack on propellant depots is the clearest possible signal of hostile intent. Unlike attacks on dual-use communications satellites where attribution may be contested or escalation thresholds debated, an attack on military propellant infrastructure is unambiguously an act of war. This clarity provides the United States with escalation control and tempo advantage: the defender gains strategic warning before primary mission systems are targeted, enabling response options ranging from diplomatic protest to proportionate counterspace action.

Depot architecture forces the adversary into a dilemma with no favorable resolution. If the adversary attacks depots first to deny American maneuver capability, they sacrifice the element of surprise and cross an unambiguous escalation threshold while American operational spacecraft remain intact with residual propellant. The United States gains warning, retains operational capability, and holds escalation advantage. If the adversary bypasses depots to preserve surprise for attacks on primary mission systems, they must face a fully-fueled, fully-maneuverable American constellation capable of evasion, pursuit, and sustained operations. Either choice disadvantages the attacker. This dilemma is the essence of deterrence: presenting an adversary with options that all lead to unfavorable outcomes.[55]

The cost-exchange calculus reinforces this strategic logic. Depots cost approximately $100 million versus $350 million for operational spacecraft. An adversary expending counterspace resources against depots achieves lower returns per weapon than attacks against mission platforms. Furthermore, the twenty operational spacecraft, representing $7 billion in mission capability, survive depot attacks intact and resume full operations once logistics capability is restored. The adversary trades surprise and escalation control to destroy the lowest-value nodes in the American space architecture. An adversary would need to spend time and resources optimizing for targeting against logistics infrastructure when higher-value mission systems exist, while also ignoring the logistics infrastructure would mean facing a sustained American space maneuver capability.

Active defense multiplies this strategic advantage. Decoy depots presenting similar radar and thermal signatures force adversaries to expend intelligence, surveillance, and reconnaissance capacity distinguishing real from false targets. If five operational depots are accompanied by ten to fifteen decoys, adversary weapons expenditure per successful depot kill increases three to four fold. Each decoy absorbing a $50 million ASAT weapon at $15 million decoy cost delivers favorable exchange ratios while preserving operational infrastructure. Extended geosynchronous orbit (xGEO) positioning places depots beyond where most ASAT systems are optimized to engage, further complicating adversary targeting. The investment

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[54] Thomas C. Schelling, Arms and Influence (New Haven: Yale University Press, 1966), 99-125

[55] Herman Kahn, On Escalation: Metaphors and Scenarios (New York: Praeger, 1965), 37-95

thesis is clear: $200 to $300 million in depot defense infrastructure protects access to $7 billion in operational capability while providing strategic warning that the current architecture lacks.

This reframing transforms the depot from potential vulnerability to vital component of deterrent strategy. Senior leaders seeking strategic certainty should recognize that depot-based logistics architecture provides something proliferation cannot: an unambiguous tripwire that clarifies adversary intent, provides warning before primary systems are attacked, and offers escalation control that ambiguous constellation attrition denies. The depot serves as more than a fuel tank; it is a strategic warning indicator, a targeting dilemma for adversaries, and a defended asset that shifts the center of gravity in favor of the defender. Chapter 6 quantifies the economic dimensions of this strategic framework, and Chapter 8 addresses depot defense concepts in greater detail.

Chapter 4

Attrition & Reusability

The question of how best to achieve resilience in space architectures stands at the center of current debates within the United States Space Force. Two competing paradigms have emerged: resilience through Proliferation (i.e., attrition), which assumes the ability to absorb losses and rapidly reconstitute degraded constellations, and resilience through Sustained Space Maneuver (i.e., reusability), which assumes the ability to dynamically reposition assets to avoid threats and maintain operational effectiveness. This chapter examines both conceptual frameworks and assesses the practical viability of proliferation as a singular strategy.

Conceptual Frameworks

Operationally, the idea of resilience through proliferation requires examination. The United States Space Force has pursued this resilience design for space architectures already. The Space Development Agency and Space Systems Command have partnered to develop a lower cost, proliferated constellation of missile warning and tracking satellites spread across Low Earth Orbit and Medium Earth Orbit.[56] Another example is Starlink. Starlink resilience is ensured through the proliferation of thousands of satellites. This architecture is capable of enduring the loss of some satellites.[57] The concept of resilience by design through proliferated constellations has been under-evaluated in terms of end-to-end implementation rather than just examining an ability to absorb a punch in space.

A piece of the ongoing deliberations as to whether in-space refueling and Sustained Space Maneuver is the preferred path forward for space operations includes the narrative that resilience through proliferation and rapid reconstitution is the current chosen path and is more cost beneficial than fielding a space architecture supporting Sustained Space Maneuver. Several inconsistencies emerge upon examination of this narrative.

First, the idea of proliferation as a resilience measure means that losing a few within a proliferated constellation is acceptable. From a cost perspective, this means losing a spacecraft that costs multiple millions of dollars. Currently, the other service components do not normally treat their deployable capability in this manner. The United States Air Force does not procure fighter jets in such a manner as to throw wave after wave into a fight expecting to win through attrition, being willing to either fight in that manner or lose that amount of capability that cost as much as it did to generate in the first place. The United States Air Force has learned to procure assets in certain quantities, which has garnered lessons learned and tactics development to know how to optimize and maximize the numbers they possess. Proliferation of a capability in space also means the United States Space Force has subscribed to a notion that to deliver

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[56] Space Systems Command, "USSF Strengthens Resilience in Missile Warning, Tracking with New Epoch 2 Constellation in MEO" (June 2, 2025).

[57] Sandra Erwin, "Starlink's survivability in war a good sign for DoD's future constellation," SpaceNews (October 25, 2022).

more capability to more of the domain, we need higher numbers of assets on orbit. With in-space refueling enabled reuse of space assets, we can employ capability in a manner similar to the United States Air Force. If the joint fight needs more fighter or bomber capability in the fight, they have learned to increase the operational tempo using the numbers of aircraft they have rather than go through the decades-long process of getting Congressional funding to procure more aircraft.

Next, we can examine the psychology of scarcity and how that applies to the space domain with respect to limited consumables. This concept underlines the notion often held by operators and decision-makers that due to limited resources, it's prudent to conserve capabilities for future needs. Such a mindset has negative implications across training, tactics development, strategic messaging in the domain, and undermines the service's efforts to implement true mission command. Decisions are retained at higher levels (O-6) due to the current inability to replenish consumables at an acceptable cost, decreasing operators' ability to fulfill space superiority missions effectively.[58]

Practical Viability of Proliferation and Rapid Reconstitution

Beyond the conceptual and doctrinal questions surrounding proliferation as a resilience strategy, a rigorous assessment must examine whether the United States possesses the practical infrastructure to execute rapid reconstitution during conflict. The strategy of proliferation implicitly assumes an ability to replace degraded constellations at operationally relevant timescales. Four critical questions emerge: Does the United States maintain ready reserves of spacecraft? Can the industrial base surge production? Does sufficient launch infrastructure exist? And can unhardened commercial satellites survive the threat environment?

Spare Satellite Inventory and Ready Reserves

The United States does not maintain warehouses of spare satellites awaiting rapid deployment. Current satellite production lines are optimized for just-in-time commercial delivery schedules rather than the surge capacity required to replace entire constellations. This manufacturing philosophy, borrowed from commercial industry to reduce costs, creates a fundamental tension with reconstitution requirements.

Companies like Capella Space now maintain three to five satellites worth of component inventory on a continuous basis to mitigate supply chain risks, yet this practice requires substantial capital investment and introduces its own complications.[59]

Satellites degrade in storage. Electronic components, propellants, batteries, and thermal systems all experience degradation when maintained in ground storage for extended periods. Maintaining a ready reserve of flight-qualified spacecraft would require significant infrastructure investment in climate-controlled storage facilities, periodic testing and

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[58] Marcus Shaw, Technical Director to the Commander, USSPACECOM, Interview (November 4, 2025).

[59] Frank Backes, CEO of Capella Space, remarks at Satellite 2025 Conference (March 2025).

refurbishment, and eventual acceptance that stored assets may require substantial rework before launch. The economics of maintaining such reserves have historically been deemed prohibitive compared to building replacement satellites as needed.

Industrial Base Capacity for Surge Production

The satellite manufacturing industrial base faces significant constraints on rapid scaling. According to industry executives, the United States space industry remains several years away from achieving continuous satellite production capacity.

As Robert Lightfoot, president of space at Lockheed Martin, noted in 2025, the company plans to build 650 percent more satellites over the next five years than were in its pipeline five years prior. Yet component suppliers have not scaled proportionally to meet this demand. Ed Zoiss, president of space and airborne systems at L3Harris, acknowledged that some component suppliers that manufacturers rely on have not yet scaled up enough to meet demand, though they are in the process of scaling.[60]

Supply chain bottlenecks for specialized components represent a critical constraint on rapid scaling. Space-hardened electronics such as focal plane arrays, artificial intelligence processors, and inertial navigation systems remain in high demand with limited supplier options. Matt Jenkins, chief space systems officer at Maxar Intelligence, observed in 2025 that these technologies are big drivers in what his company can produce and when it can produce it. The competition for these components extends across military, civil, and commercial programs, creating scheduling conflicts that would intensify dramatically during a reconstitution surge.[61]

The space sector faces persistent challenges with long lead times and supply chain gaps for critical components, particularly radiation-hardened electronics and advanced propulsion systems. Industry analysis indicates that a delay from a single sole-source supplier of a critical microchip or valve can cascade upward, threatening the schedule and budget of multi-billion-dollar space programs.[62] The near bankruptcy of Astra Space in 2023, which had acquired Apollo Fusion, a major producer of Hall Effect Thrusters, delayed the Space Development Agency's first operational data relay and missile tracking satellites, demonstrating how fragile these supply chains remain.[63]

Scheduling and mating satellites to launch vehicles remains a time-intensive process that cannot be arbitrarily compressed. The integration of payloads with launch vehicles requires extensive testing, validation, and coordination among multiple organizations. While commercial launch providers have dramatically reduced costs and increased cadence, the

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[60] Jason Rainbow, "Industry eyes continuous satellite production to keep pace with demand," SpaceNews (April 8, 2025).

[61] Debbie Werner, "Working around ongoing supply-chain bottlenecks," SpaceNews (March 11, 2025).

[62] New Space Economy, "The U.S. Satellite Manufacturing and Supply Chain Ecosystem" (July 25, 2025).

[63] Theresa Hitchens, "Space supply chain gaps: Propulsion, hardened electronics and laser links," Breaking Defense (March 17, 2025).

logistics of integrating dozens or hundreds of satellites for rapid deployment would stress existing processes beyond demonstrated capabilities.

Launch Infrastructure Constraints

Partners like SpaceX have provided unprecedented access to orbit, achieving over 160 orbital launches in 2025 alone and demonstrating pad turnaround times as short as two days.[64] The Florida ranges at Cape Canaveral and Kennedy Space Center projected 92 orbital launches in 2023, compared to 57 in 2022, while Vandenberg launches were expected to double from 19 to nearly 40 in the same period.[65] This represents remarkable progress in launch capacity.

Yet range availability and pad turnaround times remain bottlenecks that would constrain reconstitution timelines. SpaceX's record pad turnaround of approximately two days represents optimal conditions with a single vehicle type on a dedicated pad. Reconstituting multiple constellations simultaneously would require coordinating across multiple launch providers, vehicle types, and pad configurations. The infrastructure supporting high launch cadence, including propellant storage, payload processing facilities, and range safety systems, was designed for peacetime commercial operations rather than wartime surge.

The logistics of launching entire constellations to reconstitute degraded architectures during active conflict presents a coordination challenge that currently exceeds proven capabilities. While the rockets exist, the end-to-end process of manufacturing replacement satellites, integrating them with available launch vehicles, scheduling range time, and coordinating orbital insertion for hundreds of assets simultaneously has never been tested. Moreover, launch facilities themselves may become targets during conflict, further complicating reconstitution planning.

Radiation Hardening and Survivability Concerns

The shift to commercial off-the-shelf components has lowered satellite costs but introduced survivability risks that merit careful examination. Many Low Earth Orbit satellites in proliferated constellations lack the robust radiation shielding characteristic of legacy Medium Earth Orbit and Geosynchronous Earth Orbit military assets. The Air Force Research Laboratory has explicitly sought to use relatively high-risk commercial off-the-shelf electronics technologies with relaxed space qualification requirements and radiation hardening in next-generation satellite buses and payloads with limited life cycles.[66]

This design philosophy accepts that satellite failures due to space radiation or other environmental conditions are tolerable for lower-tier satellites because the relatively low costs of these spacecraft enable periodic replacement.[67] Industry sources indicate that commercial

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[64] Spaceflight Now, "SpaceX breaks launch pad turnaround record" (December 11, 2025).

[65] Sandra Erwin, "SpaceX to take over West Coast launch pad previously used by ULA," SpaceNews (April 26, 2023).

[66] Military Aerospace Electronics, "Space electronics low-Earth orbit (LEO) satellites" (May 2019).

[67] International Defense Security & Technology, "New Radiation-hardened electronics enable military small satellites" (2024).

components with 5 kilorad total dose resistance may function in certain orbits for one to three years of mission life, but higher orbits and traditional space applications with longer mission lives would require substantially more robust components. The difference in cost is significant: radiation-hardened-by-design parts can cost 100 times the price of pure commercial components.[68]

In a high-intensity conflict involving nuclear detonations in space, directed energy weapons, or high-power microwave attacks, unhardened constellations could experience catastrophic losses. A nuclear detonation in low Earth orbit would generate an electromagnetic pulse and enhanced radiation environment that could instantly disable satellites lacking hardened electronics across a wide swath of orbital space. The question becomes whether proliferation in numbers compensates for individual fragility, or whether an adversary could achieve a cost-effective exchange ratio by targeting the architecture's inherent vulnerabilities.

The Proliferated Warfighter Space Architecture represents a deliberate acceptance of this risk calculus, betting that numbers and rapid replacement will offset individual satellite vulnerability. Yet this bet has not been tested against a peer adversary capable of generating the threat environments that would stress unhardened electronics. The assessment of whether the numbers game adequately compensates for individual fragility requires honest analysis of adversary capabilities and the realistic timelines for reconstitution discussed above.

Table 4.1. Proliferation Strategy Assumptions versus Current Reality

Factor	Strategy Assumption	Current Reality
Spare Inventory	Ready reserves available for rapid deployment	JIT manufacturing; no warehoused spares; satellites degrade in storage
Industrial Surge	Rapid scaling of production capacity	Years from continuous production; component suppliers not scaled
Launch Infrastructure	Sufficient capacity for reconstitution	Payload processing bottlenecks; peacetime optimization
Radiation Hardening	Adequate survivability in threat environment	COTS components 5 krad; rad-hard 100× cost premium

Implications for Resilience Strategy

This examination reveals that resilience through proliferation and rapid reconstitution rests upon assumptions that have received insufficient empirical validation. The strategy assumes spare inventory that does not exist, manufacturing surge capacity that remains years away, launch infrastructure operating at peacetime efficiency during conflict, and constellation nodes sufficiently hardened to survive the weapons effects they may encounter. Each assumption introduces risk that compounds across the system.

This analysis does not argue that proliferation lacks value as a component of resilience strategy. Distributed architectures offer genuine advantages in complicating adversary targeting calculations and providing graceful degradation rather than catastrophic single-point failures. However, proliferation's effectiveness depends on assumptions about reconstitution, launch infrastructure, and mission effectiveness that the preceding examination reveals to be

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[68] Military Embedded Systems, "Contested space, small sats, and the gamble on COTS in space" (2024).

incompletely validated. Space Mobility and Logistics addresses each of these limitations directly: by extending asset life through refueling, SML reduces the demand for rapid reconstitution; by enabling spacecraft to launch with reduced propellant loads, SML decreases the burden on launch infrastructure; by enabling maneuver, SML provides the operational flexibility that static constellations cannot deliver. Rather than an alternative to proliferation, Space Mobility and Logistics is the critical hedge that prevents the high-attrition scenarios proliferation is designed to absorb.

Addressing Common Counterarguments

The preceding analysis of the proliferation (attrition) strategy must be balanced against an honest assessment of the current state of on-orbit logistics. Several counterarguments and market realities warrant acknowledgment to ensure this analysis maintains intellectual rigor.

First, the commercial space logistics industry has yet to demonstrate operational high-thrust refueling at scale. Industry is trending from Geosynchronous Earth Orbit servicing toward Low Earth Orbit applications, where the business case currently appears stronger. High-thrust propellant transfer for military applications, enabling the rapid orbital maneuvers required for Dynamic Space Operations, is not inherently a commercial market. The demanding performance requirements for military refueling, including speed, reliability in contested environments, and compatibility with maneuvering spacecraft, exceed what commercial customers typically require. This reality suggests that if the United States Space Force requires high-thrust refueling capability, it must be prepared to fund the development and potentially operate organic assets rather than relying entirely on commercial services.

Second, critics argue that fuel depots would represent large, vulnerable targets in the space domain. This argument merits reframing rather than dismissal. If an adversary expends counterspace resources attacking fuel depots, those resources are not being used against exquisite spacecraft carrying costly sensors and mission-critical capabilities. A fuel depot, while valuable, is fundamentally a tank of propellant. It can be replaced more rapidly and at lower cost than the sophisticated satellites it supports. Moreover, a fuel depot destroyed is fuel lost; a spacecraft without fuel is a persistent liability, unable to maneuver to avoid subsequent attacks and contributing to debris if destroyed. From a cost-exchange perspective, an architecture where adversaries target depots rather than mission systems may represent a favorable trade for the defender. The defensive measures leveraged for today's GEO missions could be applied to the fuel depots, freeing up the size, weight, power limitations on limited space assets.

Third, the institutional prioritization of Sustained Space Maneuver remains insufficient to drive industry investment. United States Space Command has identified Sustained Space Maneuver as Priority Number Five in its strategic guidance. However, industry prime contractors have indicated that this prioritization level is not high enough to justify significant Independent Research and Development investments in space logistics technologies. Primes allocate IRAD funding toward capabilities they expect to result in funded programs within planning horizons. A fifth-tier priority does not generate the acquisition signals that drive private investment. This dynamic creates a gap: the Department of War identifies a requirement but does not prioritize it sufficiently to attract the industrial base investment needed to mature the capability. Closing this gap requires either elevating the priority of Sustained Space Maneuver in official guidance or providing direct government funding to bridge the development phase until a commercial market emerges.

Fourth, the frequently cited "chicken or egg" problem mischaracterizes the market structure for military space logistics. The Government Accountability Office and Mitchell Institute have both observed that industry hesitates to develop refueling services until serviceable spacecraft exist, while spacecraft manufacturers hesitate to incorporate refueling interfaces until services are available. This framing implies symmetric uncertainty where either party could rationally move first. However, the underlying market structure reveals a fundamental asymmetry that symmetric coordination cannot resolve. Commercial satellite operators in geosynchronous orbit require station-keeping capability at approximately 50 meters per second annually, a demand efficiently served by low-thrust electric propulsion using xenon or krypton propellants. Military spacecraft conducting Dynamic Space Operations require high-thrust chemical propulsion at 680 meters per second annually, using hydrazine. These are distinct propellant markets with distinct performance requirements. Commercial operators have no requirement for high-thrust hydrazine refueling; the government is effectively the sole customer for this capability. The GAO's own analysis supports this conclusion: agency officials and experts agreed that the federal government has the potential to "crack the chicken-and-egg problem" by being the first mover. The reason government must move first is that government is the only party with a requirement to move at all. Framing this as a coordination problem amenable to market signals obscures the reality that Dynamic Space Operations refueling is a government requirement that only government action can fulfill.[69]

These counterarguments do not invalidate the case for Space Mobility and Logistics; they illuminate the challenges that must be addressed for successful implementation. Commercial industry may not organically develop military-grade refueling capability without government investment. Indeed, current demonstration programs such as the Astroscale Prototype Servicer for Refueling and Starfish Otter are government contracts funding commercial development, not commercial services purchased on the open market.[70] This distinction matters: the existence of companies capable of executing government development contracts does not equate to a functioning commercial market that will sustain itself without continued government funding. Depot vulnerability, properly understood, may actually favor the defender in cost-exchange calculations. And institutional prioritization must align with stated requirements if the industrial base is to respond with independent investment. The path forward requires deliberate action rather than assumption that market forces will deliver the required capability.

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[69] GAO-25-107555, 17, 25. The GAO observes that agency officials and experts were in broad agreement that the federal government has the potential to "crack the chicken-and-egg problem" by being the first mover.

[70] Department of the Air Force, "Space Mobility and Logistics," FY25 Congressional Report to Committees (June 2025), 5.

This chapter establishes that proliferation's viability as a resilience strategy depends on conditions that are currently not completely met: reconstitution capacity, launch resilience, and mission effectiveness without maneuver. Space Mobility and Logistics addresses each limitation, transforming expendable assets into reusable platforms and reducing the demand on the very infrastructure proliferation requires. Chapter 5 presents deployment options for space logistics architectures. Chapter 6 then subjects these options to quantitative economic analysis, demonstrating that organic depot infrastructure delivers superior lifecycle economics at operational tempo. The progression from understanding how SML overcomes proliferation's limitations to quantifying the economic advantage forms the analytical foundation for the organizational and policy recommendations that follow.

Chapter 5

Dynamic Space Operations Deployment Options

Having established the case for Space Mobility and Logistics and examined the limitations of proliferation as a singular resilience strategy, this chapter presents five deployment options for enabling Dynamic Space Operations through in-space refueling architectures. These options represent a spectrum of approaches examined by United States Space Force and Combatant Command studies, ranging from responsive launch concepts to comprehensive depot-based logistics infrastructure. Multiple USSF and CCMD studies favor Option 4, Dedicated Servicers with Depots, at the expected fuel quantities needed for maneuver-intensive operations.

Option 1: Deploy Maneuver Responsively

The first deployment option relies on responsive launch to deploy maneuvering spacecraft on demand. Under this approach, spacecraft with full propellant loads are manufactured, stored, and launched in response to operational requirements. This concept leverages the responsive space launch initiatives currently under development across the Department of War and commercial sector.

The responsive maneuver approach offers simplicity in concept of operations: when maneuver capability is needed, launch a maneuvering asset. This approach avoids the complexity of on-orbit refueling operations, rendezvous and proximity operations, and depot infrastructure. However, the limitations identified in Chapter 4 regarding industrial base capacity, launch infrastructure bottlenecks, and just-in-time manufacturing constraints apply directly to this option. The approach essentially doubles down on the proliferation strategy, extending it to include maneuver assets launched responsively rather than pre-positioned.

Critical vulnerabilities include dependence on launch infrastructure availability during conflict, manufacturing timelines that may exceed operationally relevant windows, and the inability to sustain maneuver operations once initially launched assets exhaust their propellant. This option provides no mechanism for extending the operational life of assets already on orbit.

Option 2: Commoditize Maneuver on Orbit

The second deployment option treats maneuver capability as a commoditized service procured from commercial providers. Under this approach, the government would contract with commercial space logistics companies to provide propellant delivery or maneuver augmentation services on a transactional basis. Companies such as Orbit Fab, Astroscale, and others would develop and operate the infrastructure, with the government serving as an anchor customer.

Commoditization offers potential benefits in risk transfer, capital efficiency, and innovation incentives. Commercial providers bear the development risk and infrastructure investment, while the government pays only for services consumed. It is critical to affirm that this commercial model represents a transformative breakthrough for specific orbital regimes. Companies such as Orbit Fab and Astroscale are pioneering capabilities that solve the logistics challenge for Low Earth Orbit constellations and Geosynchronous station-keeping. For these mission sets, the commercial 'pay-per-sortie' model is efficient, scalable, and operationally superior. The United States Space Force views these commercial innovators as essential partners in the broader logistics ecosystem, particularly for sustaining the proliferated architectures discussed in Chapter 4. However, this option faces a fundamental structural challenge for Dynamic Space Operations: the asymmetric demand for high-thrust refueling. Commercial geosynchronous satellite operators require only station-keeping capability, efficiently served by low-thrust electric propulsion using xenon or krypton. Military spacecraft requiring rapid orbital maneuver represent an entirely different propellant market. The government is effectively the sole customer for high-thrust hydrazine refueling in geosynchronous orbit. This is not a coordination problem awaiting mutual first-mover initiative; it is a government requirement that only government action can fulfill.

Current programs often cited as evidence of commercial progress reinforce this reality. The Astroscale Prototype Servicer for Refueling and Starfish Otter programs are not commercial services that the government is purchasing; they are government contracts funding commercial companies to develop and demonstrate capabilities.[71] When the government is the sole funder and the sole customer, the label of commercial becomes a distinction without operational difference.

Option 3: Deploy Dedicated Servicers

The third deployment option employs dedicated servicer spacecraft that dock with client satellites to provide propellant transfer or propulsion augmentation. This approach is exemplified by the Robotic Servicing of Geosynchronous Satellites program and commercial offerings such as Mission Extension Vehicles. Servicers can either transfer propellant to client spacecraft or attach propulsion packs that assume maneuver control of the client satellite.

Dedicated servicers offer operational flexibility and multi-mission utility. A single servicer can support multiple client satellites sequentially, providing propellant delivery, inspection, maintenance, or relocation services.[72] The technology has been demonstrated operationally through the MEV-1 and MEV-2 missions, reducing technical risk compared to less mature alternatives. Servicers can be pre-positioned in operational orbits, reducing response timelines compared to Earth-based launch.

The limitation of dedicated servicers without depot support is finite propellant capacity. Each servicer carries a fixed propellant load that depletes with each client engagement. Once a servicer exhausts its propellant, it must be replaced through launch of a new asset. This creates a recurring replacement cycle that, while less constraining than expendable client spacecraft,

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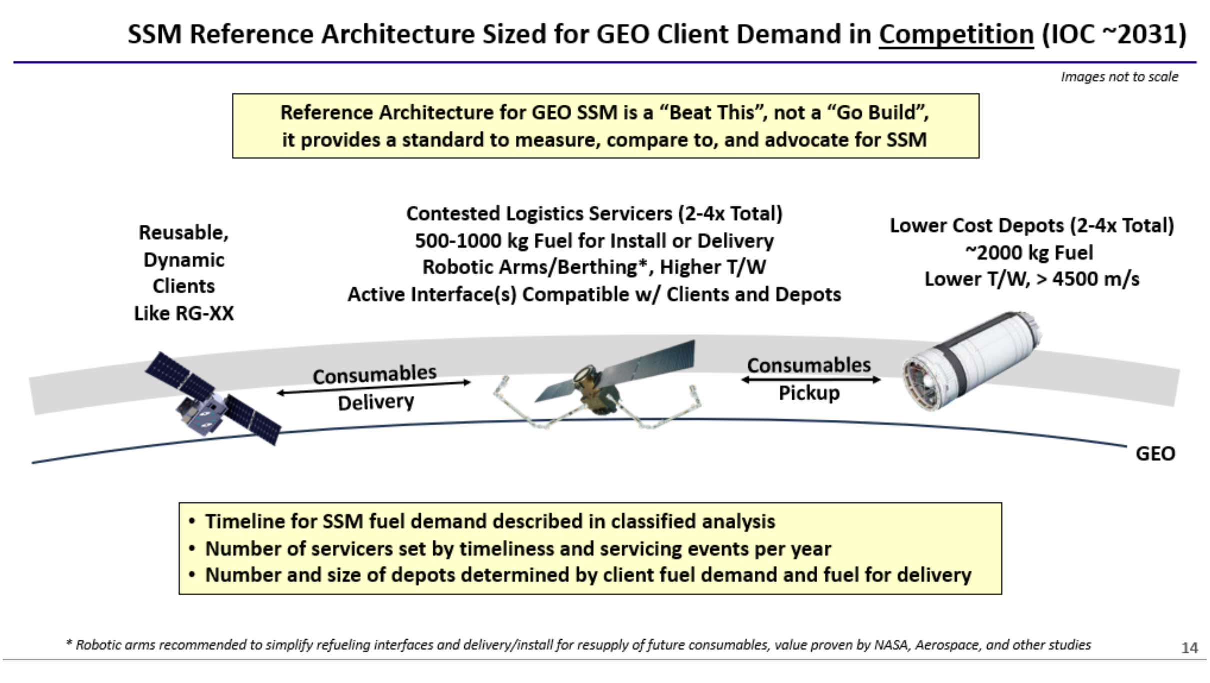
[72] Erwin, "Northrop Grumman to launch new satellite-servicing mission."

still imposes ongoing launch dependencies. The approach improves operational flexibility but does not fully break the Earth-based supply chain constraint.

Option 4: Deploy Dedicated Servicers with Depots

The fourth deployment option combines dedicated servicer spacecraft with bulk propellant depot infrastructure positioned in extended geosynchronous orbit. Servicers shuttle between depots and client satellites, drawing propellant from depot storage to refuel clients throughout the geosynchronous belt. This architecture requires approximately 10,000 kilograms of bulk hydrazine on orbit to maximize economy of scale for sustained operations.[73]

Multiple United States Space Force and Combatant Command studies favor this option at the expected fuel quantities needed for maneuver-intensive Dynamic Space Operations.[74] The Aerospace Corporation's October 2025 briefing to USSPACECOM on Sustained Space Maneuver presents a reference architecture for geosynchronous operations calling for two to four lower-cost depots with approximately 2,000 kilograms fuel capacity each, and two to four contested logistics servicers with 500 to 1,000 kilograms fuel capacity for delivery, with initial operational capability targeted for approximately 2031.[75] This reference architecture is presented below as a baseline to measure against and advocate for Sustained Space Maneuver, acknowledging that timeline and specific quantities derive from classified operational analysis.



SSM Reference Architecture Sized for GEO Client Demand in Competition (IOC ~2031)

Images not to scale

Reference Architecture for GEO SSM is a "Beat This", not a "Go Build", it provides a standard to measure, compare to, and advocate for SSM

Reusable, Dynamic Clients Like RG-XX

Contested Logistics Servicers (2-4x Total)
500-1000 kg Fuel for Install or Delivery
Robotic Arms/Berthing*, Higher T/W
Active Interface(s) Compatible w/ Clients and Depots

Lower Cost Depots (2-4x Total)
~2000 kg Fuel
Lower T/W, > 4500 m/s

- **Timeline for SSM fuel demand described in classified analysis**
- **Number of servicers set by timeliness and servicing events per year**
- **Number and size of depots determined by client fuel demand and fuel for delivery**

** Robotic arms recommended to simplify refueling interfaces and delivery/install for resupply of future consumables, value proven by NASA, Aerospace, and other studies*

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[73] Lt Col Alexander Jehle, Senior Program Manager for On-Orbit Servicing, Mobility, and Logistics, Interview (October 9, 2025).

[74] Shaw, "SSM Imperative," 18. The briefing notes: "Multiple USSF and CCMD Studies Favor Approach 4 at Expected Fuel Needed for Maneuver."

[75] Shaw, "SSM Imperative," 14. The reference architecture calls for 2-4 depots with approximately 2,000 kg fuel capacity each and 2-4 contested logistics servicers with 500-1,000 kg fuel capacity, with IOC approximately 2031.

The urgency of this architecture is underscored by current acquisition trajectories. Over 14,000 kilograms of fuel will be launched for many dozens of space combat capabilities between 2026 and 2033, yet more than 90 percent of these platforms by number will not be refuelable or reusable.[76] This represents a substantial missed opportunity: the military value of even a fraction of these platforms being refueled and resupplied would justify substantial in-space logistics infrastructure and generate the campaigning and combat advantages required by the Commander of United States Space Command. As the Aerospace Corporation briefing concludes, USSPACECOM requires sustained maneuver on combat platforms immediately, and reuse via resupply is an obvious opportunity to provide it.

The depot-servicer combination addresses the limitations of servicer-only approaches by providing a replenishment mechanism that extends servicer operational life indefinitely. Depots positioned in extra-geosynchronous orbit operate outside the primary operational zone, reducing vulnerability to counterspace threats while remaining accessible to servicer vehicles. Client spacecraft can be refueled repeatedly, extending operational life beyond conventional fifteen-year replacement cycles. The economic case for this architecture is developed in Chapter 6.

Implementation requires development of depot systems capable of long-duration cryogenic or storable propellant storage, servicer vehicles with rendezvous and proximity operations capability, and standardized refueling interfaces across the client spacecraft fleet. Each of these technology elements has been demonstrated individually; the integration challenge involves combining them into a cohesive operational architecture.

Option 5: Refuel Opportunistically to Reuse

The fifth deployment option employs opportunistic servicers that recover propellant from end-of-life spacecraft and redistribute it to operational assets requiring fuel. Under this approach, spacecraft approaching retirement due to factors other than propellant depletion, such as payload obsolescence or mission completion, would donate residual propellant to servicers. The servicers would then deliver recovered propellant to spacecraft with continued operational utility but depleted fuel reserves.

Opportunistic refueling offers potential to extract additional value from spacecraft that would otherwise be decommissioned. Many satellites are retired with substantial propellant remaining due to technology obsolescence, mission changes, or conservative fuel budgeting. Recovering this stranded propellant could reduce overall system costs and extend the operational life of other assets.

However, opportunistic approaches face significant operational constraints. Propellant availability depends on the timing and location of end-of-life spacecraft, which may not align with operational refueling requirements. The approach cannot guarantee propellant supply for time-critical operations. Different spacecraft may use incompatible propellant types, limiting

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[76] Marcus Shaw, "The Sustained Space Maneuver (SSM) Imperative," The Aerospace Corporation, Briefing to USSPACECOM (October 22, 2025), 13.

the donor pool. Residual propellant quantities vary unpredictably based on individual spacecraft operational histories. These uncertainties make opportunistic refueling unsuitable as a primary logistics architecture, though it may provide supplementary capability within a broader depot-based system.

Other Options Not Fully Considered

Several additional approaches warrant acknowledgment, though they have not received comprehensive analysis in USSF and CCMD studies to date. These alternatives may offer long-term potential or address niche requirements within a broader space logistics architecture.

Space launch vehicle upper stages could potentially serve as disposable servicers, leveraging residual propellant and maneuvering capability following primary payload delivery. Fission reactors could provide high-power electric propulsion enabling efficient orbit transfers, though regulatory and safety considerations complicate near-term implementation. Accepting maneuver disadvantage while proliferating smaller, cheaper systems with reduced power and aperture represents a strategic alternative that trades individual capability for aggregate numbers. Improvements in propulsion system thrust-to-weight efficiency could reduce propellant requirements, partially mitigating the logistics challenge through technology advancement rather than infrastructure development.

These options remain at varying levels of conceptual maturity and have not been evaluated against the operational requirements and expected fuel consumption rates that drive preference for Option 4 in current studies. Future analysis may identify circumstances where alternative approaches offer advantages for specific mission sets or technology evolution pathways.

Comparative Analysis of Deployment Options

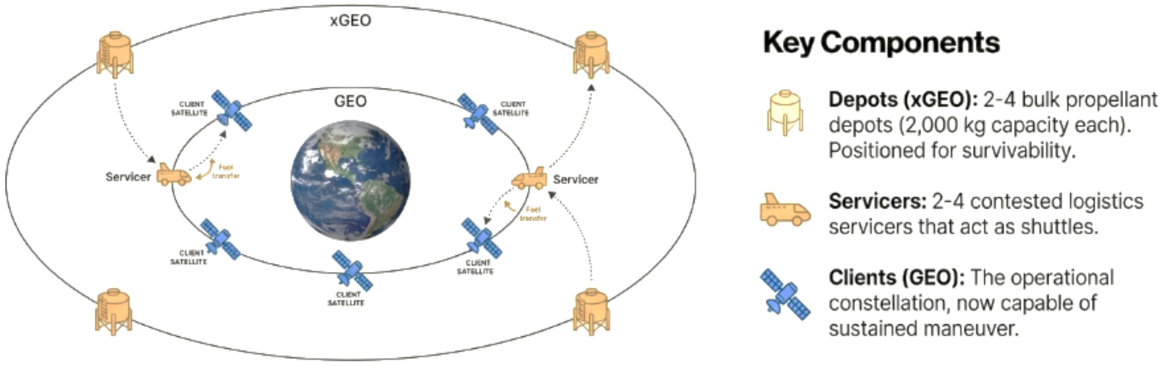
The five deployment options represent a progression from Earth-dependent responsive concepts toward increasingly autonomous on-orbit logistics capability. The following comparison highlights key differentiating factors that inform architectural selection.

Table 5.1. DSO Deployment Options Comparison Matrix

Dimension	Option 1: Responsive	Option 2: Commercial	Option 3: Servicers	Option 4: Servicers + Depots	Option 5: Opportunistic
Concept	Launch maneuver assets on demand	Procure maneuver as commercial service	Pre-position servicers to support clients	Servicers shuttle from xGEO depots	Recover and redistribute EOL propellant
Earth Dependence	High (launch required)	Moderate (provider infrastructure)	Moderate (servicer replacement)	Low (depot replenishment only)	Low (opportunistic recovery)
Propellant Availability	Per-launch quantity	Per-contract delivery	Fixed servicer capacity	Bulk depot reserves	Variable (EOL dependent)
Scalability	Linear with launches	Contract-limited	Servicer production rate	Economies of scale	Donor availability

Dimension	Option 1: Responsive	Option 2: Commercial	Option 3: Servicers	Option 4: Servicers + Depots	Option 5: Opportunistic
DSO Suitability	Limited	Cost-prohibitive	Partial	Full support	Supplementary only
Technology Maturity	High	Emerging	Demonstrated	Integration needed	Conceptual
USSF/CCMD Preference	–	–	–	**FAVORED**	–

Option 4, deploying dedicated servicers with depot infrastructure, emerges as the preferred approach based on multiple USSF and Combatant Command studies examining expected fuel requirements for maneuver-intensive Dynamic Space Operations. This option alone provides the combination of bulk propellant availability, operational flexibility, and favorable economics necessary to sustain high-tempo maneuver operations over extended campaign timelines. The economic analysis in Chapter 6 provides quantitative comparison of lifecycle costs across architectural alternatives, demonstrating the cost efficiency advantages of the servicer-depot architecture at operational scale.



Key Components

Depots (xGEO): 2-4 bulk propellant depots (2,000 kg capacity each). Positioned for survivability.

Servicers: 2-4 contested logistics servicers that act as shuttles.

Clients (GEO): The operational constellation, now capable of sustained maneuver.

Chapter 6

Economic Analysis: Proliferation versus On-Orbit Refueling Architectures

The economic viability of space mobility and logistics infrastructure represents a critical consideration in determining optimal force architecture for sustained space operations. This analysis examines competing architectural approaches: proliferation of expendable spacecraft versus deployment of on-orbit refueling infrastructure, with examination of intermediate alternatives including commercial refueling services. Central to this comparison is the relationship between operational tempo (delta-v consumption), propellant demand, refueling cadence, and lifecycle cost. This relationship determines which architecture provides optimal value across different mission profiles.

Analytical Assumptions

The following assumptions govern this analysis. These parameters derive from program office planning factors, Government Accountability Office assessments, industry data, and physics-based calculations using the Tsiolkovsky rocket equation. All costs are expressed in constant FY2025 dollars without discounting or net present value adjustment. Readers should interpret findings as comparative economic relationships between architectural alternatives rather than precise budget projections. This analysis examines a single representative example mission profile within a single orbital regime to demonstrate the economic methodology and illuminate key architectural tradeoffs. A comprehensive analysis addressing every combination of mission type, orbital altitude, inclination, and operational concept would require classified program data and exceed the scope of any single research effort but would be a recommended follow-on effort. These assumptions are not representative of a past, present, or future program of record.

Assumptions Box • Orbit Regime: Geosynchronous Earth Orbit (GEO) and extended GEO (xGEO) • Spacecraft Dry Mass: 2,500 kg (payload, bus, and empty tanks) • Propellant: Hydrazine monopropellant (Isp = 220 seconds) • Commercial Refueling: 100 kg delivered per sortie at $20M per sortie (Orbit Fab advertised pricing)* • Organic Depot Servicer: 500 kg delivered per sortie (per USSF reference architecture) • Delta-V Profiles: Station-keeping (50 m/s/yr typical GEO), Moderate (200 m/s/yr), DSO (680 m/s/yr per AATS) • Spacecraft Unit Cost: $350M (representative GEO national security spacecraft) • Launch Cost: $48.5M per spacecraft (Falcon Heavy to GEO at ~$97M, 2 S/C per launch) • Constellation Size: 20 spacecraft; Analysis Period: 20 years • All costs in constant FY2025 dollars (no inflation escalation or NPV discounting)
**Provider-stated price; actual costs may vary by orbit, schedule, and mission constraints.*

Delta-V Budget and Propellant Requirements

The Tsiolkovsky rocket equation governs propellant consumption: $m_{propellant} = m_{dry} \times (e^{\Delta V/(I_{sp} \times g_0)} - 1)$, where I_{sp} denotes specific impulse (220 seconds for hydrazine) and g_0 equals standard gravitational acceleration (9.81 m/s^2). The effective exhaust velocity for hydrazine monopropellant is therefore 2,158 m/s. For a 2,500 kg dry mass spacecraft, this relationship yields the annual propellant requirements shown in Table 6.1.

Table 6.1. Physics-Based Annual Propellant Requirements by Mission Profile

Mission Profile	Annual ΔV	Propellant Required	Calculation	Refuel Cadence (100 kg)
Station-Keeping (Positional Ops)	50 m/s	59 kg/yr	2500×(e^0.023-1)	0.6/yr (20 mo.)
Moderate Maneuver	200 m/s	243 kg/yr	2500×(e^0.093-1)	2.4/yr (5 mo.)
High-Maneuver (DSO)	680 m/s	926 kg/yr	2500×(e^0.315-1)	9.3/yr (39 days)

The physics reveal a fundamental challenge for commercial refueling architectures at Dynamic Space Operations tempo. At 680 m/s annual delta-v, each spacecraft consumes 926 kg of propellant per year. With commercial services delivering 100 kg per sortie, each spacecraft requires 9.3 refueling missions annually, or roughly one refueling operation every 39 days. For a constellation of twenty spacecraft, this translates to 186 refueling sorties per year across the fleet.

The Commercial Refueling Packaging Problem

Commercial refueling services are designed for the station-keeping market, where satellites require infrequent propellant replenishment to maintain orbital position over fifteen-year design lives. Orbit Fab publicly advertises hydrazine delivery to GEO at $20 million per 100 kg sortie.[77] At station-keeping tempo (approximately 50 m/s per year for GEO north-south station-keeping[78], requiring 59 kg/yr propellant), a 100 kg delivery provides approximately twenty months of operational capacity. This cadence aligns with commercial business models: predictable scheduling, low operational complexity, and sufficient margin for service provider profitability.

This packaging strategy is rational and highly effective for the commercial sector's primary markets. The industry has rightly optimized for the vast majority of users who require life-extension and station-keeping services. However, a divergence emerges when applying this commercially optimized model to the high-thrust requirements of military maneuver. The physics of moving a 2,500-kilogram combat platform across the geosynchronous belt creates a demand signal that commercial station-keeping architectures were never designed to absorb.

At Dynamic Space Operations tempo, the commercial packaging model breaks down operationally and economically. Table 6.2 demonstrates the impact of the 100 kg sortie constraint across mission profiles.

Table 6.2. Commercial Refueling (100 kg/sortie) Cost Scaling by Mission Profile

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[77] Orbit Fab, "Refuel Your Spacecraft: Hydrazine Delivery in GEO for 100kg...$20M," https://www.orbitfab.com/refuel (accessed December 24, 2025). This is the provider's publicly advertised price; actual costs may vary by orbit, schedule, and mission constraints.

[78] D. Chu et al., "GOES-R Stationkeeping and Momentum Management," NASA Goddard Space Flight Center (2006). North-south station-keeping for GEO satellites typically requires approximately 50 m/s per year due to gravitational perturbations from the Sun and Moon.

Mission Profile	Sorties/S-C/Yr	Cost/S-C/Yr	Fleet Cost/Yr	20-Yr Total (20 S/C)
Station-Keeping	0.6	$12M	$240M	$4.8B
Moderate Maneuver	2.4	$48M	$960M	$19.2B
High-Maneuver (DSO)	9.3	$186M	$3.72B	**$74.4B**

The DSO row reveals the commercial model's fundamental unsuitability for high-tempo operations. At $186 million per spacecraft per year and $3.72 billion annually for a twenty-spacecraft fleet, commercial refueling at DSO tempo would cost $74.4 billion over twenty years in refueling operations alone. This figure excludes initial constellation acquisition, making commercial refueling at DSO tempo economically infeasible based on the current assumptions.

Beyond economics, the operational implications are equally problematic. Managing 186 refueling sorties per year across a constellation requires continuous rendezvous and proximity operations scheduling, continuous servicer repositioning, and acceptance of extended periods when individual spacecraft are unavailable for mission tasking during refueling operations. The commercial 100 kg packaging, optimized for station-keeping cadence, becomes operationally impractical when the mission demands ten times the sortie rate.

The Depot Architecture: Bulk Transfer as the Solution

The organic depot architecture with dedicated servicers addresses the packaging problem through bulk propellant transfer. The United States Space Command Sustained Space Maneuver reference architecture specifies servicers capable of 500 to 1,000 kg fuel delivery per sortie, with depots providing approximately 2,000 kg storage capacity.[79] At 500 kg per servicer sortie, the DSO refueling cadence transforms from 9.3 sorties per spacecraft per year to 1.9 sorties per spacecraft per year. Table 6.3 compares refueling architectures at DSO tempo.

Table 6.3. Architecture Comparison at DSO Tempo (680 m/s/yr, 926 kg/yr propellant)

Parameter	Commercial (100 kg/sortie)	Organic Depot (500 kg/sortie)
Sorties per S/C per Year	9.3	1.9
Fleet Sorties per Year (20 S/C)	186	38
Days Between Refueling	39 days	192 days
Operational Feasibility	Impractical	Manageable

The five-fold reduction in sortie rate, from 186 to 38 fleet sorties annually, transforms an operationally impractical scheduling burden into a manageable logistics operation. Each spacecraft requires refueling approximately twice per year rather than nearly ten times, with six months between operations rather than thirty-nine days. This cadence permits deliberate mission planning, allows spacecraft to complete extended operational taskings between refueling, and provides margin for contingency operations.

Organic Depot Infrastructure Cost Analysis

Comprehensive cost comparison between proliferation and organic depot refueling strategies for a twenty-spacecraft operational constellation over a twenty-year program lifecycle reveals the economic case for depot infrastructure at DSO tempo. The proliferation strategy reflects contemporary Space Force acquisition practices employing just-in-time manufacturing when propellant is exhausted. The depot architecture includes spare depot units given their relative simplicity and shelf-stability compared to exquisite operational spacecraft.

Table 6.4. Twenty-Year Program Cost Comparison: Proliferation versus Organic Depot (DSO Profile)

Cost Element	Proliferation	Organic Depot
Initial Constellation (20 S/C)	$7.97B	$7.88B
- Spacecraft Acquisition	$7.0B	$7.0B
- Launch Costs (10 FH @ $97M)	$970M	$880M
Depot Infrastructure (5 + 2 spare)	N/A	$1.6B
Mid-Life Replacement (Year 10)	$7.97B	$0
Annual Depot Operations (20 years)	N/A	$1.84B
TOTAL 20-YEAR COST	**$15.9B**	**$11.3B**
SAVINGS vs PROLIFERATION	Baseline	**$4.6B (29%)**

At DSO tempo, spacecraft exhaust their propellant capacity more rapidly than at station-keeping rates. For proliferation approaches with fixed onboard propellant, this accelerates the replacement timeline from the traditional fifteen-year design life to approximately ten years when operating at 680 m/s annual delta-v with 926 kg annual propellant consumption. A spacecraft with 1,000 kg propellant capacity (reasonable for a 2,500 kg dry mass vehicle) exhausts its reserves in approximately thirteen months at DSO tempo, necessitating either massive initial propellant loading, which drives launch costs, or acceptance of abbreviated operational lifetimes, which drives replacement costs.

The organic depot architecture eliminates the replacement cycle entirely within the analysis period. Refuelable spacecraft sustain operations indefinitely through periodic propellant resupply, avoiding the $7.97 billion mid-life replacement cost that proliferation requires. The depot infrastructure investment of $1.6 billion and annual operations of $1.84 billion over twenty years total $3.44 billion, substantially less than a single constellation replacement.

Mission Extension Vehicle Economics

Mission Extension Vehicles and Mission Extension Pods represent an alternative approach for satellites already on-orbit without refueling interfaces. Rather than refueling spacecraft, these systems dock with existing satellites and provide station-keeping thrust through attached propulsion modules. This approach proved commercially successful: Northrop Grumman's MEV-1 began servicing Intelsat-901 in 2020, and MEV-2 attached to Intelsat-10-02 in 2021. Reported pricing for MEV services is approximately $13 million per year.[80]

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[80] Stephen Clark, "Aging Intelsat satellite resumes operations after docking of robotic servicer," Spaceflight Now (April 21, 2020). Public reporting indicates MEV services cost approximately $13 million per year based on Intelsat contract disclosures.

Table 6.5. MEV/MEP Life Extension Services

Parameter	MEV/MEP Service	DSO Applicability
Service Type	Station-keeping life extension	Positional Ops only
Reported Annual Cost	~$13M/year	Attractive for legacy assets
Operational Capability	Station-keeping (~50 m/s/yr)	7.4% of DSO requirement
Maneuver Support	None (positional only)	Inadequate for DSO

MEV/MEP economics prove attractive for extending the operational life of legacy satellites that lack refueling interfaces. For commercial operators seeking to defer replacement costs and maintain revenue-generating assets in their assigned orbital slots, the MEV business case is compelling. However, MEV/MEP represents a fundamentally different service than propellant delivery. These systems outsource station-keeping propulsion rather than replenishing onboard capability. The operational implication is decisive: MEV-equipped satellites remain incapable of orbital maneuver, plane changes, or responsive repositioning. For the 680 m/s annual delta-v requirement of Dynamic Space Operations, MEV/MEP delivers only 7.4 percent of needed capability. MEV/MEP serves a legitimate market for Positional Space Operations life extension but cannot contribute to Sustained Space Maneuver requirements.

Comprehensive Architecture Comparison

Table 6.6 synthesizes the economic analysis across all architectural alternatives at DSO tempo, incorporating the physics-based propellant requirements and corrected refueling cadences. The comparison reveals stark differences in economic viability when operational requirements demand high-tempo maneuver.

Table 6.6. Twenty-Year Lifecycle Cost Comparison at DSO Tempo (680 m/s/yr, 20 S/C)

Architecture	Initial Cost	Recurring Cost	Total 20-Yr	Cost per m/s ΔV
Organic Depot	$9.5B	$1.84B	**$11.3B**	**$41,500**
Proliferation	$7.97B	$7.97B	$15.9B	$58,500
Commercial (100 kg)	$7.88B	$74.4B	**$82.3B**	**$302,600**

Note: MEV/MEP excluded from this comparison as it provides station-keeping only (50 m/s/yr) and cannot satisfy DSO maneuver requirements.

The analysis reveals three distinct tiers of economic viability at DSO tempo. Organic depot infrastructure achieves optimal economics at $11.3 billion total and $41,500 per meter per second, representing 29 percent savings versus proliferation. Proliferation occupies the middle tier at $15.9 billion, incurring replacement costs that depot refueling avoids. Commercial refueling at 100 kg per sortie is economically indefensible at $82.3 billion total, more than seven times the cost of organic depot architecture. The commercial model, designed for station-keeping cadence, fundamentally breaks down when physics demands 9.3 refueling sorties per spacecraft per year.

Break-Even Analysis

The economic case for organic depot infrastructure depends on amortizing fixed infrastructure costs across sufficient operational demand. At DSO tempo, depot infrastructure investment of $1.6 billion (five operational depots plus two spares) amortizes across the fleet through avoided replacement costs. The annual cost advantage per spacecraft comparing depot refueling versus proliferation replacement is approximately \$280,500 per spacecraft annually. The break-even fleet size is therefore approximately six spacecraft, beyond which depot infrastructure generates positive return. For a twenty-spacecraft constellation, the economics strongly favor depot architecture.

Critically, this break-even analysis applies specifically to DSO tempo operations. At station-keeping tempo, the calculus shifts: commercial refueling achieves economic viability because the physics demand only 0.6 sorties per spacecraft per year, and proliferation spacecraft operate for fifteen years before replacement. The strategic insight is that architectural selection must align with operational concept: depot infrastructure for maneuver-intensive operations, commercial services or MEV/MEP for positional operations.

These baseline findings warrant scrutiny through parametric sensitivity analysis. Appendix C presents a detailed examination of how the economic comparison responds to variation in four key input parameters: spacecraft unit cost (\$200 million to \$500 million), depot infrastructure investment (\$1.0 billion to \$2.5 billion), annual depot operations cost (\$50 million to \$150 million per year), and launch cost (\$60 million to \$180 million per pair). The parametric analysis demonstrates that depot architecture savings remain positive across all single-variable excursions, ranging from 16 percent to 35 percent at DSO tempo. At the baseline spacecraft cost of \$350 million, savings range from 17 percent to 36 percent even when varying all depot-specific assumptions simultaneously. Break-even fleet size remains below typical constellation sizes across all examined infrastructure cost assumptions. These findings establish that the 29 percent baseline savings estimate represents a central value within a robustly positive range, enabling leadership to evaluate the conclusion under their own assessment of each input parameter.

The RG-XX program lends immediate programmatic weight to this economic analysis. As the follow-on to GSSAP, RG-XX represents the first major USSF acquisition program to require that performers incorporate refueling capability into the spacecraft design.[81] This requirement reflects an institutional recognition that maneuver-intensive GEO operations consume propellant at rates incompatible with traditional single-load spacecraft design. By mandating refueling capability at the acquisition level, the Space Force is effectively acknowledging the central premise of this paper's analysis: that dynamic space operations require logistics infrastructure to sustain combat power. RG-XX transforms on-orbit refueling from a theoretical capability into a programmatic requirement with defined demand signal, and the economic framework presented in this chapter provides the analytical basis for evaluating the infrastructure options to meet that demand.

Several ongoing demonstration programs are maturing the technology base required to service platforms like RG-XX. The Tetra-5 mission, planned for launch in 2026, will demonstrate cooperative docking and refueling between an Orbit Fab fuel depot and an Astroscale servicer spacecraft, hosted on a ROOSTER-5 propulsive ring. The Astroscale

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[81] Shaw et al., *Dynamic Space Operations*, 16. Shaw notes that "the Space Force is seeking commercial options for the GSSAP follow-on system with refueling ports, RG-XX."

Prototype Servicer for Refueling (APS-R) is under contract to deliver a launch-ready prototype satellite capable of refueling compatible spacecraft in orbit. Separately, Starfish Space's OTTER vehicle is under contract to demonstrate docking and augmented maneuver services for national security space assets.[82] These efforts represent initial steps along the technology maturation pathway toward the organic depot architecture this paper advocates. Each addresses a discrete element of the servicing problem, from cooperative refueling interfaces to autonomous rendezvous and proximity operations. The transition from demonstration to operational capability will require the organizational and doctrinal integration examined in Chapters 7 and 8. This paper intentionally limits its discussion of these programs to publicly available information to avoid disclosure of procurement-sensitive details; the strategic conclusions of this analysis hold independently of any specific vendor implementation.

Contested Environment Reconstitution Analysis

The preceding economic analysis assumed peacetime operations. Contested environment analysis examines reconstitution requirements following loss of critical assets, revealing fundamental differences between architectural approaches. For proliferation architecture employing just-in-time manufacturing, loss of five spacecraft represents twenty-five percent capability degradation requiring complete asset replacement. For depot architecture, simultaneous destruction of all five operational depots creates infrastructure loss while twenty operational spacecraft remain intact.

Table 6.7. Contested Environment Reconstitution Comparison

Factor	Attrition (5 S/C Lost)	Depots (5 Depots Lost)
Assets Destroyed	5 operational spacecraft	5 operational depots
Immediate Capability	75% (15 of 20 S/C) (no spares)	40% (2 spares deploy)
Reconstitution Cost	$2.4B	$450M
- Manufacturing	$1.75B (5 × $350M)	$300M (3 × $100M)
- Launch	$243M (5 × FH share)	$145M (3 × FH share)
- Integration/Ops	$5M	$5M
Timeline to Full Capability	24-36 months	12-18 months
Reconstitution Cost Savings	Baseline	**81% ($1.95B saved)**

Proliferation strategy provides no immediate reconstitution capability beyond remaining constellation capacity. Loss of five spacecraft requires $2.4 billion in replacement costs including spacecraft manufacturing ($1.75 billion at $350 million each), launch ($243 million at $48.5 million per spacecraft share of Falcon Heavy), and integration operations. Timeline to full reconstitution extends twenty-four to thirty-six months for spacecraft manufacturing, integration, and orbital checkout. The remaining fifteen spacecraft sustain operations indefinitely at seventy-five percent capacity, providing distributed resilience through disaggregated architecture.

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[82] GAO-25-107555, 20. For APS-R and Starfish OTTER programmatic details, see Department of the Air Force, *FY25 Congressional Research Report: Space Mobility and Logistics* (2025), 5.

Depot architecture maintains shelf-stable spares enabling forty percent logistics capacity restoration within weeks through spare deployment. The remaining capability gap requires manufacturing only three replacement depots rather than five spacecraft, reducing reconstitution costs to $450 million (eighty-one percent reduction) and accelerating timelines by twelve to eighteen months. Depots are architecturally simpler than exquisite operational spacecraft integrating complex mission payloads, sophisticated communications systems, and radiation-hardened processors. Critically, all twenty operational spacecraft remain intact and resume full operations once depot capability is restored.

The contested environment analysis demonstrates how depot spares fundamentally alter resilience calculations compared to just-in-time spacecraft manufacturing. The cost-exchange ratio favors the defender: adversaries expend counterspace resources against depots costing approximately twenty-nine percent of equivalent spacecraft value ($100 million depot versus $350 million spacecraft), while the operational spacecraft themselves remain intact and capable. This economic reality reinforces the operational argument that depot-centric architectures may improve resilience by redirecting adversary targeting toward less consequential and more rapidly replaceable assets. However, as noted in the limitations discussion, depot survivability in contested orbits represents a point of strategic disagreement requiring detailed analysis beyond this paper's scope.

Strategic Synthesis

This economic analysis yields four principal findings that inform strategic force structure decisions.

First, operational tempo fundamentally determines architectural viability creating complementary roles for government and industry. Commercial services prove viable for station-keeping (0.6 sorties per spacecraft per year, $4.8 billion total) but prohibitive for DSO (9.3 sorties per spacecraft per year, $81.8 billion total). This seventeen-fold cost variation, driven solely by the physics of propellant consumption at chemical specific impulse, explains why commercial refueling models designed for Positional Space Operations cannot support Dynamic Space Operations doctrine.

Second, the commercial 100 kg packaging constraint becomes operationally impractical at DSO tempo. Managing 186 fleet refueling sorties annually, with each spacecraft unavailable for mission tasking during thirty-nine-day refueling cycles, imposes scheduling burdens that degrade operational effectiveness regardless of cost. Bulk transfer through organic depot servicers (500 kg per sortie) reduces fleet sorties to 38 annually and extends refueling intervals to six months, transforming an impractical scheduling burden into manageable logistics operations.

Third, organic depot infrastructure delivers superior cost efficiency for maneuver-intensive missions. At $41,500 per meter per second delta-v capability, depot architecture achieves 29 percent improvement over proliferation ($58,500 per meter per second) and 86 percent improvement over commercial services ($302,600 per meter per second). The infrastructure investment amortizes across decades of operations, with break-even occurring at approximately six spacecraft.

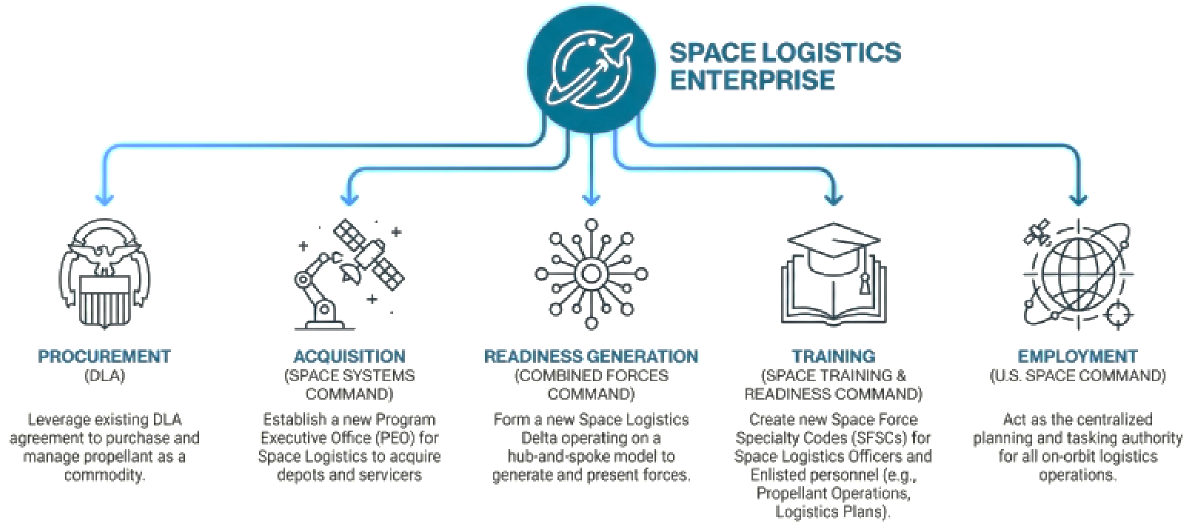
Fourth, architectural selection must align with operational requirements. Mission Extension Vehicles provide exceptional efficiency for station-keeping ($15,000 per meter per second) but deliver only 7.4 percent of delta-v required for Dynamic Space Operations. Commercial services enable market-based logistics for predictable, low-cadence operations but cannot sustain the tempo that contested space operations demand. For Dynamic Space Operations emphasizing Sustained Space Maneuver and sustained operational flexibility, organic depot infrastructure provides the only economically and operationally viable architecture.

While this specific economic case is compelling, these findings warrant validation through independent agency analysis, peer-review, and modeling and simulation across wartime scenarios including degraded logistics, mission types, training, readiness, contested launch infrastructure, allied campaigning, and adversarial counter-space campaigns. The parametric sensitivity analysis confirms that the directional finding is robust: savings range from 16 to 35 percent under single-variable excursions and from 17 to 36 percent under combined uncertainty at the baseline spacecraft cost. At the operational tempos required for Dynamic Space Operations, organic depot infrastructure delivers superior economics across the plausible range of cost assumptions, enabling leadership to hold high confidence in the architectural conclusion regardless of their specific assessment of any individual input parameter.

Chapter 7

Organizational Framework for Space Mobility and Logistics

The preceding chapters established that Option 4, deploying dedicated servicers with depot infrastructure, provides the optimal combination of operational capability, lifecycle economics, and strategic resilience for Dynamic Space Operations. Implementing this architecture requires more than acquiring hardware; it demands deliberate organizational transformation to generate, present, and employ space logistics forces. This chapter proposes the organizational framework necessary to institutionalize Space Mobility and Logistics as a core competency of the United States Space Force, establishing logistics echelons using the United States Transportation Command and United States Air Force logistics relationship as the model and leveraging the Defense Logistics Agency and the existing Field Command structure of the service.



Leverage existing DLA agreement to purchase and manage propellant as a commodity.

Establish a new Program Executive Office (PEO) for Space Logistics to acquire depots and servicers

Form a new Space Logistics Delta operating on a hub-and-spoke model to generate and present forces.

Create new Space Force Specialty Codes (SFSCs) for Space Logistics Officers and Enlisted personnel (e.g., Propellant Operations, Logistics Plans).

Act as the centralized planning and tasking authority for all on-orbit logistics operations.

Organize, Train, and Equip Functions

The Defense Logistics Agency is a joint organization ultimately responsible for the purchase and delivery of fuel for the joint force. Critically, DLA is the only organization that certifies Military Specification compliance for space propellants, making it an essential node in any space logistics architecture.[83] The Defense Logistics Agency is already the purchaser of hydrazine and rocket fuels needed by the United States Space Force, so this relationship would be leveraged and grown to meet the demand of an in-space refueling architecture. Importantly, this relationship has recently been formalized. In September 2024, the Defense Logistics Agency and the Space Force signed a framework agreement establishing standards for aligning Space Force supply requirements with DLA's worldwide logistics system.[84] This agreement, the result of twelve months of joint work, focuses on readiness-based support and ensures that

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[83] Interview with Robert Gloria, Defense Logistics Agency Aerospace Energy Customer Operations, January 23, 2026. Industry representatives confirmed the subcontracting practice and liability-driven cost structure in separate discussions.

[84] Defense Logistics Agency, "DLA, US Space Force formalize support agreement" (September 13, 2024).

Space Force now has equal priority within DLA alongside the other military services. The agreement establishes governance bodies including a Partnership Agreement Council and Executive Steering Group to synchronize efforts and develops metrics to track performance in areas such as order response times and parts availability for Space Force systems.

The current institutional arrangement reveals both strengths and gaps that space logistics planning must address. Hydrazine possesses essentially indefinite shelf life when properly stored, an advantageous characteristic for logistics planning that permits strategic stockpiling and reduces concerns about propellant expiration. However, DLA's current role terminates at delivery of propellant containers to the customer. Once handed off to the launch service provider or spacecraft integrator, typically a third-party propellant loading contractor, DLA no longer retains responsibility for use-control. This handoff creates a fragmented chain of custody that contributes to the cost structure discussed in Chapter 3.

Industry representatives confirm that prime contractors routinely subcontract propellant handling, along with rocket and spacecraft fueling operations, precisely because of hydrazine's toxicity. The handling, training, certification, and liability requirements associated with carcinogenic propellants represent risks that prime contractors prefer to transfer rather than retain. This deliberate risk allocation is economically rational for individual firms but creates enterprise-level inefficiency: each handoff in the liability chain adds cost, and no single entity optimizes the end-to-end propellant logistics process. Industry acknowledges that vertically integrated propellant handling could reduce costs, but firms are unwilling to accept the associated liability, training burden, and regulatory compliance responsibility.

This institutional reality has direct implications for space logistics architecture. As the United States Space Force scales propellant demand for Dynamic Space Operations, the current fragmented model will amplify costs proportionally. An alternative approach would extend DLA's role, or establish a dedicated military propellant handling capability, that consolidates the currently dispersed liability and training requirements under unified management. This institutional foundation can be expanded to encompass on-orbit propellant commodities as space logistics infrastructure matures, potentially including extended chain-of-custody responsibility that addresses the current handoff gap.

United States Transportation Command serves as the fusion center for all Combatant Command fuel requirements and service funding and has been designated the intermediary with the Defense Logistics Agency. As with other Combatant Commands, United States Space Command would provide fuel requirements to United States Transportation Command, while the service provides the funds to procure that fuel. The Defense Logistics Agency is then able to purchase the fuel required and retains ownership of that fuel until it is delivered to a weapons system, the same construct as the United States Air Force.

Space Systems Command would be responsible for acquiring and sustaining in-space refueling capability: hardware, software for the ground and space architecture. While a Space Mobility Command would standardize the United States Space Force structure with the United

States Air Force and United States Army, Space Systems Command is already structured such that a new Program Executive Office should be created to support space logistics.

Combined Forces Command would be the nexus for in-space refueling capability and Space Logistics personnel to generate readiness within this force and amongst the larger operational space forces for force presentation to United States Space Command. A new Space Logistics Delta should be formed to operate on the hub and spoke model. The Delta would retain Administrative Control and Organize, Train, and Equip functions to space logistics squadrons embedded in each operational Delta in Combined Forces Command. Space Logistics Squadrons and Operational Squadrons would be entrenched together to generate readiness as a more complete force package and presented to United States Space Command through the Space Force Generation construct. Readiness should include evaluation such as specific "wargaming" requirements to validate that logistics officers are trained in both supply chain management and contested logistics

Space Training and Readiness Command would train Space Logistics personnel, perhaps with a distinct Space Force Specialty Code for space support and logistics, similar to other services. This training could be supported within the current Officer Training Course structure that Space Training and Readiness Command runs. Beyond initial qualification, STARCOM would establish readiness standards for space logistics forces, develop certification requirements for wartime competencies, and integrate space logistics scenarios into exercises that stress contested sustainment planning. Curriculum development should extend beyond technical proficiency to include the operational art of space campaigning and readiness (i.e., how logistics decisions shape maneuver options, how adversary counter-logistics campaigns alter depot employment, and how propellant reserves translate to freedom of action for combatant commanders). STARCOM should establish training partnerships with NASA, leveraging decades of on-orbit servicing research and operational experience, with commercial space logistics providers such as Orbit Fab and Astroscale for emerging technologies, and with terrestrial logistics enterprises such as FedEx, UPS, and Amazon to gain insight from mature supply chain optimization, demand forecasting, and distributed network management practices. This educational foundation ensures space logisticians understand their role in enabling sustained operations and support future campaigns and commander intent.

Finally, Headquarters Space Force S4 needs to expand its scope to include battlespace and in-domain logistics, servicing, sustainment, and developing logistics policy guidance, whereas today the focus is on Base Operations and Sustainment.

Table 7.1. Space Logistics Organizational Responsibilities

Organization	Functional Role	Space Logistics Responsibility
DLA	Procurement	Purchase hydrazine, propellants, and orbital commodities
USTRANSCOM	Requirements Fusion	Integrate CCMD fuel requirements; interface with DLA
SSC	Acquisition	Acquire depots, tankers, servicing vehicles; establish PEO
STARCOM	Training	Develop career fields, SFSCs, and training pipelines
CFC	Readiness & Campaigning Generation	Generate space logistics force packages via SPAFORGEN

Organization	Functional Role	Space Logistics Responsibility
USSPACECOM	Employment	Centralized logistics planning and operational orders
HQ USSF S4	Policy	Expand scope to in-domain logistics (currently base ops focus)

Personnel Development and Career Field Structure

Organizational structures require trained personnel to function. The United States Space Force must develop dedicated career fields for space logistics to generate the human capital necessary for Space Mobility and Logistics operations. The United States Air Force logistics career field structure provides a useful model for adaptation to the space domain, with distinct officer and enlisted pathways that could be translated into Space Force Specialty Codes.

Space Logistics Officer Career Field

The United States Space Force should establish a Space Logistics Readiness Officer career field, analogous to the Air Force's Logistics Readiness Officer (21RX) designation. This officer specialty would lead and manage integrated space logistics operations, overseeing supply chain management for orbital commodities, transportation coordination for launch and on-orbit delivery, propellant and consumables management, and logistics planning for sustained space operations. These officers would be responsible for ensuring warfighting readiness across the space logistics enterprise.

Core responsibilities for Space Logistics Officers would include directing joint and combined space logistics operations across military, civil, and commercial partners; developing contingency plans for reconstitution, resupply, and sustained operations during conflict; managing the sustainment pipeline from ground-based production through launch integration to on-orbit delivery; and integrating logistics considerations into operational exercises and wargames. As the space logistics enterprise matures, these officers would serve as the primary interface between Space Systems Command acquisition programs, Space Training and Readiness Command training pipelines, and Combined Forces Command operational units.

The accession pathway for Space Logistics Officers would parallel existing commissioning sources. Candidates would require a college degree with preference for engineering, supply chain management, or operations research backgrounds. Commissioning would occur through the Reserve Officer Training Corps, Officer Training School, or the United States Space Force Academy once established, followed by specialized training at Space Training and Readiness Command facilities. Initial qualification training should include orbital mechanics fundamentals, propellant chemistry and handling, rendezvous and proximity operations planning, and joint logistics doctrine.

Enlisted Space Logistics Career Fields

The enlisted force forms the backbone of any logistics enterprise, executing the day-to-day functions that sustain operations. The United States Space Force should establish several enlisted Space Force Specialty Codes to support space logistics operations, drawing lessons from Air Force logistics career fields while adapting them for the unique requirements of the space domain.

A Space Logistics Plans specialty, analogous to the Air Force's Logistics Plans (2G0X1) career field, would be essential for planning on-orbit refueling missions, coordinating with commercial providers, handling contingency scenarios, and ensuring safe and successful operations. These enlisted personnel would work directly with Space Logistics Officers to translate operational requirements into executable logistics plans, manage scheduling for refueling windows, and coordinate deconfliction with other orbital activities.

A Space Propellant Operations specialty, analogous to the Air Force's Fuels (2F0X1) career field, would manage the ground-based and potentially future on-orbit propellant distribution and storage infrastructure. These personnel would require specialized training in handling hydrazine and other spacecraft propellants, understanding the unique challenges of cryogenic storage and transfer, and managing the supply chain from production facilities through launch integration. As on-orbit depot operations mature, this career field would expand to include remote monitoring and control of orbital propellant storage systems.

A Space Materiel Management specialty would oversee equipment, spare components, and supplies for the space logistics enterprise. This career field would manage inventory of refueling interfaces, robotic servicing components, and orbital replacement units. Personnel in this specialty would coordinate with Space Systems Command acquisition programs to ensure adequate stockpiles of critical components and manage the distribution of materiel to operational units.

A Space Transportation Coordination specialty would manage the interface between space logistics requirements and launch service providers. These personnel would coordinate payload integration timelines, track launch manifest schedules, and ensure logistics assets reach orbit when and where needed. This career field would be particularly critical for coordinating with commercial launch providers and managing the complex scheduling requirements of a multi-provider launch architecture.

Table 7.2. Proposed Space Logistics Career Fields

Career Field	USAF Analog	Core Functions
Space Logistics Readiness Officer	21RX	Lead integrated logistics ops; contingency planning; interagency coordination
Space Logistics Plans (Enlisted)	2G0X1	Mission planning; refueling window scheduling; deconfliction coordination
Space Propellant Operations	2F0X1	Propellant handling; distribution; ground and orbital storage management
Space Materiel Management	2S0X	Equipment inventory; spare components; ORU distribution
Space Transportation Coord	2T1X1	Launch provider interface; manifest coordination; payload integration

Training Pipeline Development

Space Training and Readiness Command would be responsible for developing and executing training pipelines for all space logistics career fields. Initial skills training should be established at existing Space Training and Readiness Command schoolhouses, with specialized modules developed for space logistics fundamentals. The training curriculum should include orbital mechanics sufficient to understand refueling window calculations, propellant chemistry and safety procedures, rendezvous and proximity operations awareness, joint logistics doctrine and planning processes, and commercial space industry familiarization.

Advanced training should include joint exercises with United States Transportation Command to build interoperability with the broader defense logistics enterprise. Space logistics personnel should participate in large-scale exercises that stress the end-to-end supply chain from propellant production through on-orbit delivery. Partnerships with commercial space logistics providers such as Orbit Fab and Astroscale should be leveraged to provide real-world exposure to emerging operational concepts and technologies.

The Space Force Generation process would integrate space logistics personnel into the broader readiness generation cycle. Space Logistics Squadrons embedded within operational Deltas would train alongside the forces they support, building the relationships and mutual understanding necessary for effective logistics support during operations. This integrated training model ensures logistics considerations are integral to operational planning from the outset.

Force Presentation

Current practice in the United States Air Force centers on United States Transportation Command as the generator of logistics plans and orders to logistics forces to provide sustainment and support to a geographic Combatant Command. Those requests come through the service component commands. United States Space Command would serve the role of United States Transportation Command in this aspect, as this Combatant Command is best placed with the right expertise to understand operations and logistics requirements in the space domain.

Therefore, Space Component Commands would generate requests for effects to United States Space Command. United States Space Command would be the centralized planning organization for operations and logistics forces and generate orders to space logistics forces alongside operational space forces as a supporting Combatant Command, and for its own missions in the domain.

Chapter 8

Discussion

The preceding chapters have established the strategic imperative for Space Mobility and Logistics, examined the limitations of proliferation as a singular resilience strategy, presented deployment options with economic analysis, and proposed organizational frameworks for implementation. This chapter examines the relationship between these findings and existing doctrine, considers implementation challenges, and acknowledges the limitations of this analysis.

Implementation Challenges

The Government Accountability Office conducted a comprehensive technology assessment of In-Space Servicing, Assembly, and Manufacturing in 2025, identifying four challenges that impede development and use of ISAM technologies.[85] These challenges illuminate a fundamental market structure problem: the conditions necessary for commercial space logistics to emerge organically do not exist and will not emerge without deliberate government action.

Government agencies and industry have differing priorities for ISAM technology. NASA prioritizes deep space exploration. The Department of War prioritizes national security applications. Commercial operators prioritize revenue-generating services for geosynchronous communications satellites. Each community pursues different technical solutions optimized for specific requirements, fragmenting demand and preventing the consolidation that would drive economies of scale.

Government and private satellite operators are generally not requiring that satellites be designed for future servicing. This creates the asymmetric demand problem analyzed in Chapter Five: without a fleet of refuelable spacecraft, there is no market for refueling services; without refueling services, there is no incentive to design refuelable spacecraft. The framing of this as a coordination problem amenable to market solutions understates the fundamental asymmetry. Commercial operators have no requirement for high-thrust hydrazine refueling. The government is effectively the sole customer for Dynamic Space Operations propellant delivery. If demand is highly concentrated in government missions, market incentives alone may be insufficient to align standards and service availability without policy or acquisition intervention.

Few in-space test opportunities are available for developers to demonstrate ISAM technology at operational scale. Orbital Express in 2007 and the Robotic Refueling Mission demonstrated technical feasibility, but operational service delivery remains unproven. Risk-averse satellite operators hesitate to commit to purchasing services that have not been demonstrated. This creates a demonstration gap that private investment alone cannot bridge.

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[85] Government Accountability Office, "In-Space Servicing, Assembly, and Manufacturing: Benefits, Challenges, and Policy Options," GAO-25-107555 (July 2025), 17-23.

Regulations and standards remain unclear or emerging. There are few widely accepted standards for interfaces such as refueling ports, which contributes to satellite manufacturers' hesitancy to design for servicing.[86] The Space Force designation of two preferred refueling port standards in 2024 represents progress, but preference is insufficient to drive industry adoption.

Beyond market structure, technical foundation challenges constrain long-term scalability. Hydrazine and its derivatives provide the high-thrust performance required for rapid orbital maneuver, but their specific impulse is moderate compared to more advanced propulsion concepts. Furthermore, hydrazine is toxic, expensive, difficult to handle, and entirely dependent on Earth-based production and launch. Any space logistics constellation built on hydrazine inherits these limitations permanently. The long-term requirement is clear: a high-thrust propellant with improved specific impulse that can be produced from resources available at multiple locations in the solar system. This is a generational challenge that exceeds the expertise of any single organization and requires partnership between the Department of War and the Department of Energy.

Institutional challenges may prove more significant than technical barriers. United States Space Command has identified Sustained Space Maneuver as Priority Number Five in strategic guidance. Industry prime contractors have indicated that this prioritization is insufficient to justify significant Independent Research and Development investment. Current space operations are funded primarily through Research, Development, Test and Evaluation and Procurement appropriations, but sustained space logistics operations more closely resemble the recurring costs addressed through Operations and Maintenance funding. Space Mobility and Logistics spans the entire Organize, Train, and Equip enterprise, but no single organization owns it. These institutional challenges are interconnected: low priority reduces funding, which limits organizational investment, which prevents concept validation, which reinforces the perception that the capability is not ready for higher priority.

This analysis should not be read as suggesting that transitioning to a depot-based architecture is straightforward or inexpensive. The pivot requires sustained senior leadership commitment across multiple budget cycles, organizational boundaries, and political administrations. It demands investment in infrastructure before requirements are fully validated, acceptance of near-term costs for long-term capability, and tolerance for the inevitable setbacks that accompany any transformational program. The Department of War[87] does not have a strong track record of managing such transitions smoothly. The history of military innovation is littered with promising concepts that failed to achieve operational capability due to insufficient institutional commitment, competing priorities, and leadership turnover. Successfully fielding Space Mobility and Logistics will require a coalition of senior leaders across the Department, the Services, the Combatant Commands, the Congress, and

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[86] GAO-25-107555, 22-23. As of August 2024, Space Force had designated two refueling port designs as preferred interface standards. CONFERS has developed standards adopted by ISO and AIAA for approaching another satellite, power and data interfaces, and fluid transfer.

[87] This paper uses "Department of War" to reflect the legislative renaming enacted in the fiscal year 2025 National Defense Authorization Act, which redesignated the Department of War as the Department of War effective January 2025.

industry who commit to shepherding this capability through the inevitable obstacles. The analysis presented here makes the case for why the effort is strategically necessary; actually executing the transformation will require a sustained campaign of institutional change management that is beyond the scope of any single paper to prescribe.

Finally, this analysis has focused exclusively on unilateral American solutions. The Combined Space Operations initiative, which includes Australia, Canada, France, Germany, New Zealand, and the United Kingdom, offers potential for burden-sharing, distributed resilience, and interoperability that could strengthen space logistics architectures beyond what any single nation can achieve. Allied nations bring unique geographic advantages for ground-based infrastructure, complementary industrial capabilities, and shared interest in deterring adversary counterspace operations. A comprehensive space logistics strategy should examine how allied contributions could reduce American investment requirements, provide redundancy through geographically distributed infrastructure, and complicate adversary targeting calculations. These international dimensions warrant dedicated analysis that exceeds the scope of this paper but should inform future implementation planning.

Underpinning all organizational and acquisition actions is the requirement for doctrinal foundation. Space Force Doctrine Document 1 currently nests sustainment under Space Access, conflating launch with on-orbit logistics. The doctrine provides no Mission Area designation for depot or refueling operations, leaving the proposed Mission Delta without institutional anchor. Appendix B provides specific recommended verbiage updates to SFDD-1 that would establish Space Logistics as a formal Mission Area with On-Orbit Refueling as a designated Mission Set, creating the doctrinal mandate to organize, train, and equip for this capability.

Limitations of This Analysis

This analysis has several limitations that should inform interpretation of its findings and recommendations. First, the economic analysis relies on cost estimates derived from public sources and commercial pricing data. Actual acquisition costs for military space logistics systems may differ significantly due to unique military requirements, security considerations, and acquisition process inefficiencies. The relative comparisons between deployment options should prove more robust than absolute cost figures.

Second, the operational analysis assumes contested space operations at tempo and intensity that have not been empirically validated. The maneuver requirements that drive the economic case for organic infrastructure are projections based on doctrine and threat assessment rather than operational experience. Actual conflict dynamics may differ from planning assumptions in ways that alter the optimal architecture.

Third, the organizational framework draws heavily on analogies to Air Force and Navy logistics structures. The space domain has unique characteristics, including the physics of orbital mechanics, the absence of terrain, and the transparency of space domain awareness, that may require organizational innovations beyond what terrestrial analogies suggest.

Fourth, this analysis focuses primarily on the tactical and operational levels of war. The strategic implications of space logistics, including escalation dynamics, arms control considerations, and alliance management, warrant additional examination that exceeds the scope of this paper.

Fifth, the analysis assumes continued American technological and industrial competitiveness in space. Adversary investment in counter-logistics capabilities, including attacks on depots, servicers, and ground infrastructure, could alter the cost-benefit calculus in ways not fully explored here. The survivability analysis addresses this concern but does not definitively resolve it.

Sixth, this analysis does not adequately resolve the question of depot survivability in contested orbits. Propellant depots represent large, relatively stationary targets containing volatile materials. Defending such infrastructure against kinetic or directed energy attack presents operational challenges that differ fundamentally from defending maneuvering combat spacecraft. The counter-argument is significant: concentrating propellant in depots may create attractive targets that an adversary could destroy more easily than distributed proliferated constellations.

Several mitigations merit consideration. Depots can be positioned in extended geosynchronous orbit (xGEO), or in Lagrange points (L1/L2), beyond the operational zone where most ASAT systems are optimized to operate, complicating adversary targeting geometry and increasing attack costs. Active defenses, whether co-orbital escort spacecraft or ground-directed counterspace systems, could provide protective capability for high-value logistics infrastructure. Depot proliferation, deploying multiple smaller depots rather than few large ones, distributes risk and complicates adversary targeting calculus. Hardening, mobility between refueling operations, and deception through decoys all offer additional protective measures. These concepts require detailed analysis of adversary capabilities, cost-exchange ratios, and operational employment that exceeds the scope of this paper. The survivability question represents a point of strategic disagreement where reasonable analysts may reach different conclusions based on threat assumptions and risk tolerance rather than a structural flaw that invalidates the depot-based architecture.

Despite these limitations, the central findings of this analysis are robust to reasonable variations in assumptions. The strategic requirement for space logistics capability is clear regardless of precise cost figures. The inadequacy of proliferation as a singular strategy is supported by multiple independent lines of evidence. The organizational transformation required is consistent across a range of implementation scenarios. Chapter Nine presents recommendations designed to address the challenges identified while acknowledging the uncertainties that remain.

Chapter 9

Conclusion and Recommendations

Answer to the Research Question

This research addressed a fundamental question facing the United States Space Force: Is the prevailing resilience strategy of "proliferation" (i.e., attrition) sufficient for Dynamic Space Operations, Sustained Space Maneuver, and space superiority, or does it require an enabling logistics architecture? The evidence demonstrates that Space Mobility and Logistics is the critical hedge that prevents the high-attrition scenarios proliferation is designed to absorb.

Proliferation and attrition mass offers real advantages that deserve acknowledgment. The combat utility of Starlink in Ukraine has demonstrated that sheer numbers provide a form of extreme resilience that adversaries find difficult to degrade. Distributed architectures complicate targeting, provide graceful degradation, and enable rapid reconstitution through replacement rather than repair. These advantages have been validated in active conflict. An alternative approach to the spare satellite problem would maintain warehouses of ready-to-launch replacements rather than build orbital refueling infrastructure. This approach might be technically simpler and potentially cheaper in the near term. However, the warehouse approach requires redesigning every component for extended shelf stability, which carries its own costs and technical risks. More fundamentally, spare satellites in warehouses still cannot maneuver once deployed; they remain in Positional Space Operations assets regardless of how quickly they can be launched.

The operational flexibility required for space superiority demands capabilities beyond what proliferation alone provides. Proliferation provides numbers but not maneuverability or reusability. It provides redundancy but not persistence beyond designed propellant limits. It provides a hedge against attrition but not the ability to sustain operations when that hedge is exhausted. The examination of proliferation strategy viability revealed critical assumptions that have received insufficient empirical validation. These concerns do not invalidate proliferation as a strategy but rather argue for a portfolio approach that combines proliferated architectures with maneuver-capable reusable assets sustained by in-space logistics.

The United States Space Force must develop comprehensive Space Mobility and Logistics capabilities centered on in-space refueling to enable Dynamic Space Operations and Sustained Space Maneuver. This conclusion is supported by strategic analysis, economic modeling, organizational assessment, and historical precedent. The transformation from static, expendable spacecraft to dynamic, reusable platforms sustained by in-domain logistics is not the only approach to space resilience, but it is a necessary complement to proliferation for achieving the full spectrum of space superiority requirements.

Returning to the ends-ways-means framework established in Chapter 1: the end of space superiority through Dynamic Space Operations requires ways and means that the current architecture does not provide. Proliferation provides means (mass on orbit) but not the ways (maneuver, reusability, sustained operations) to achieve the end. Space Mobility and Logistics closes this strategic gap by providing the ways (depot-based logistics, organizational transformation) and means (propellant infrastructure, trained personnel, sustainable funding) necessary to achieve space superiority at acceptable risk.

Summary of Key Findings

The analysis presented in this paper yielded several key findings that inform the recommendations that follow.

First, the strategic context establishes urgency. American space architectures are designed primarily for Positional Space Operations: achieving mission effects by keeping spacecraft in fixed positions with minimal movement. Meanwhile, the People's Republic of China has demonstrated selected capabilities relevant to Dynamic Space Operations, including proximity operations, on-orbit servicing experimentation, and notable GEO maneuver activity. This asymmetry creates strategic risk: an adversary capable of Dynamic Space Operations facing a defender limited to Positional Space Operations holds fundamental advantages in initiative and tempo.

Second, Space Mobility and Logistics is the critical hedge that prevents the high-attrition scenarios proliferation is designed to absorb. In-space refueling extends asset life, reducing reconstitution demand. Launching spacecraft with reduced propellant loads decreases mass-to-orbit requirements, easing launch infrastructure burden. Enabling maneuver provides operational flexibility that static constellations cannot deliver. Most fundamentally, refueling transforms $350 million expendable spacecraft into reusable capital platforms, shifting the strategic calculus from acceptable attrition to sustained capability.

Third, based on baseline assumptions, organic depots plus servicer architectures show the lowest cost per unit of maneuver delivered at higher operational tempos. The sorties-per-target optimization framework reveals that when maneuver requirements exceed approximately twelve operations annually per spacecraft, organic infrastructure achieves cost superiority over commercial alternatives.

Fourth, Space Mobility and Logistics cannot be treated as an auxiliary function appended to existing structures. The capability requires deliberate institutionalization across the entire Organize, Train, and Equip enterprise, including new organizational constructs, career fields, training pipelines, and funding mechanisms.

Fifth, historical precedent validates the transformation model and illuminates critical success factors. The development of mobile service squadrons by the United States Navy during World War II enabled sustained offensive operations far from fixed bases. Three lessons emerge from this precedent. First, logistics transformation must precede, not follow, the operational requirement, as the Pacific Fleet's pre-war organizational preparation enabled rapid wartime scaling; second, the capability must be designed for contested employment from inception, as Service Squadron Ten operated under threat of air and submarine attack; third, senior leadership must commit to the transformation despite initial costs and institutional resistance. The Space Force faces an analogous transformation from shore-based to mobile logistics, and these historical lessons should inform implementation planning.

Sixth, the theory of Competitive Endurance articulated by the Chief of Space Operations provides the doctrinal framework, and Space Mobility and Logistics directly enables each of its three tenets. Avoiding operational surprise requires the ability to reposition assets in response to emerging threats; static, fuel-limited spacecraft cannot reposition and therefore cannot avoid surprise. Denying first-mover advantage requires the ability to sustain operations through an adversary's initial attack and respond with counteraction; spacecraft that exhaust propellant reserves during defensive maneuvers surrender the initiative regardless of their survival. Conducting responsible counterspace campaigning requires the operational endurance to maintain persistent presence and pressure across extended timelines; this endurance is impossible without the logistics infrastructure to replenish consumed resources. Each of these doctrinal requirements points toward Sustained Space Maneuver enabled by Space Mobility and Logistics.

Seventh, propellant strategy must balance near-term capability against long-term scalability. Hydrazine provides proven high-thrust performance for immediate Dynamic Space Operations requirements, but as OECA reports, its toxic, Earth-dependent, and incompatible with In-Situ Resource Utilization constrain the architecture’s strategic reach. A space logistics infrastructure permanently tethered to Earth resupply cannot support sustained operations across the cislunar environment or beyond. The acquisition strategy must therefore pursue parallel paths; build depot infrastructure now using hydrazine to address urgent operational requirements, while also designing for propellant modularity that enables transition to ISRU-compatible alternatives as they mature.

Recommendations for Senior Leaders

Based on the analysis presented in this paper, the following recommendations are offered for consideration by senior leaders across the Department of War, the United States Space Force, and Congressional Committees. These recommendations are organized into four categories: strategic actions that establish priority and demand signals, acquisition actions that build capability, organizational actions that institutionalize the enterprise, and resourcing actions that enable sustainment. The sequencing is progressive: capability acquisition precedes organizational standup, and organizational standup precedes sustainment funding.

Strategic Actions

First, the Commander of United States Space Command should elevate Sustained Space Maneuver to Priority 2, integrated with active protection measures for space-based assets, and direct development of operational requirements. The current fifth-tier prioritization is insufficient to generate the acquisition signals that drive industrial base investment. Prime contractors have indicated that this priority level does not justify significant Independent Research and Development investment in space logistics technologies. Elevating Sustained Space Maneuver and issuing a Capabilities Development Document for Contested Space

Logistics by Q2 FY27 would signal institutional commitment and provide the requirements foundation for acquisition.

Second, the Under Secretary of Defense for Acquisition and Sustainment should direct all future national security space acquisitions to incorporate standardized refueling interfaces as a mandatory design requirement. The Government Accountability Office has identified the coordination problem where industry hesitates to develop refueling services because spacecraft lack refueling capability, while spacecraft manufacturers hesitate to add refueling interfaces because services do not exist.[88] However, as analyzed in Chapter Five, this framing understates the fundamental asymmetry: commercial operators have no requirement for high-thrust hydrazine refueling, making the government effectively the sole customer for Dynamic Space Operations propellant delivery. Government mandate of refueling interfaces would create the demand signal that only government action can provide. Rather than mandating specific commercial interfaces, Space Systems Command should publish a government interface control document by Q4 FY26, derived from industry input and international partner coordination, that enables multi-vendor competition while ensuring interoperability for refuel and servicing. All future national security space acquisitions programs of record should comply with this standard once adopted.

Acquisition Actions

Third, Space Systems Command should initiate acquisition of Contested Space Logistics infrastructure with mandatory propellant modularity. The economic analysis in Chapter 6 demonstrates that organic depot architecture delivers superior lifecycle economics at Dynamic Space Operations tempo, with 29% cost savings compared to proliferation. However, Chapter 6 explicitly acknowledges that these directional findings require validation against classified operational requirements and threat data. Space Systems Command should conduct an Analysis of Alternatives for Contested Space Logistics Architecture by Q4 FY27, with Milestone A decision by Q2 FY28 and on-orbit prototype demonstration targeted for FY30. Critically, the acquisition requirement must mandate propellant modularity from inception, enabling transition from hydrazine to ISRU-compatible propellants as they mature. This design requirement preserves near-term capability while ensuring the architecture does not foreclose long-term strategic options. This should be in coordination with allied partner nations.

Fourth, the Deputy Assistant Secretary of Defense for Space and Intelligence should establish a Combined Space Operations Space Logistics Working Group to examine allied partnership opportunities. As discussed in Chapter 8, the Combined Space Operations initiative offers potential for burden-sharing, distributed resilience, and interoperability that could strengthen space logistics architectures beyond what any single nation can achieve. Allied nations bring unique geographic advantages for ground-based infrastructure, complementary industrial capabilities, and shared interest in deterring adversary counterspace operations. Allied ownership of distributed depot infrastructure changes the adversary's targeting calculus

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[88] GAO-25-107555, 25. GAO notes that requirements could establish a user base and incentivize servicing providers, and could be relatively inexpensive compared to the overall cost of a satellite

(i.e., attacking Australian or United Kingdom space logistics assets represents a different escalation threshold than attacking solely American assets). The working group should deliver a partnership framework by Q4 FY27 to inform the Milestone A acquisition decision, examining burden-sharing models, interoperability requirements, and distributed infrastructure architectures.

Fifth, the Under Secretary of Defense for Research and Engineering should establish a joint ISRU Propellant Development Program in coordination with the Department of Energy and NASA. As Finding 7 establishes, hydrazine provides necessary near-term capability but cannot serve as the foundation for a scalable space logistics architecture. A space logistics infrastructure permanently tethered to Earth resupply cannot support sustained operations across the cislunar environment or beyond. The program should identify candidate high-thrust propellants producible from lunar water ice and Martian atmospheric constituents, demonstrate technology readiness level 6 by FY32, and deliver interface specifications to inform depot design evolution. This development timeline must synchronize with depot architecture decisions to ensure the propellant transition pathway remains viable. The Department of Energy possesses unique capabilities through its national laboratory system, including Lawrence Livermore, Los Alamos, Sandia, Oak Ridge, and Idaho National Laboratory, where decades of research on advanced propulsion concepts, energetic materials, and ISRU technologies provide the foundation for this effort. The nation that first develops high-thrust propellants with improved efficiency that can be produced from in-space resources will possess enduring advantages in sustained space operations. A hydrazine-based depot architecture is a necessary bridge capability, not the recommended end-state.

Organizational Actions

Sixth, the Chief of Space Operations should establish an integrated Mission Delta for Space Logistics that combines operational and acquisition authorities under unified command, with organizational design complete by FY28 and Initial Operating Capability concurrent with first system fielding (estimated FY31). The Space Force is moving toward integrated mission deltas that consolidate operations and program executive office functions, eliminating the traditional separation between operators and acquirers. A Space Logistics Mission Delta with both operational command authority and acquisition execution authority would accelerate capability development by placing requirements generation, system acquisition, and operational employment under single leadership accountable for end-to-end mission success. This organizational construct addresses the GAO finding that ISAM development requires a government champion.[89] The hub-and-spoke model proposed in Chapter Seven, with a central Space Logistics Delta and embedded squadrons in operational Deltas, provides the operational framework.

Seventh, Headquarters United States Space Force S1 and Space Training and Readiness Command should establish career fields and training pipelines for space logistics personnel, synchronized with system fielding. HQ USSF/S1 should publish Space Logistics Space Force

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[89] GAO-25-107555, 29.

Specialty Codes by Q4 FY28, including Space Logistics Officers analogous to Air Force 21R Logistics Readiness Officers and enlisted specialties for propellant operations, depot management, and servicer employment. STARCOM should achieve training pipeline Initial Operating Capability by Q2 FY30. The organizational structures proposed in this paper require trained personnel to function; without deliberate investment in human capital development synchronized with system delivery, organizational constructs remain hollow.

Resourcing Actions

Eighth, the United States Space Force Financial Management directorate should develop a legislative proposal enabling Operations and Maintenance appropriations for space logistics sustainment, submitted for the FY30 President's Budget to enable recurring funding concurrent with Initial Operating Capability. Current space operations are funded primarily through Research, Development, Test and Evaluation and Procurement appropriations. However, sustained space logistics operations, including propellant purchase, depot maintenance, and refueling services, more closely resemble the recurring costs addressed through Operations and Maintenance funding. The Aerospace Corporation's analysis of budget structures across military services reveals a critical insight: other domains use production funding (RDT&E and Procurement) to create capability and O&M funding to scale it, whereas the Space Force's limited use of O&M hinders its ability to scale combat capability when campaigning or warfare protracts.[90] Explicit Congressional authorization of the O&M funding pathway would enable the Space Force to scale space logistics operations the way the Air Force scales aerial refueling, the Navy scales underway replenishment, and the Army scales fuel distribution: through recurring sustainment funding rather than continuous acquisition of new systems.

Table 9.1. Summary of Recommendations for Senior Leaders

#	Recommendation	Decision-Maker	Timeline
1	Elevate SSM to/with Priority 2; issue CDD for Contested Space Logistics	CDRUSSPACECOM	FY27
2	Mandate open refueling interface standard on all future NSS PoR Acquisitions	USD(A&S)	FY27
3	Initiate Contested Logistics Infrastructure acquisition with propellant modularity	SSC	FY27-30
4	Establish Combined Space Ops Space Logistics Working Group	DASD(Space)	FY27
5	Establish joint ISRU Propellant Development Program	USD(R&E)/DOE/NASA	FY27-32
6	Establish integrated Mission Delta for Space Logistics	CSO	FY28-31
7	Establish career fields and training pipelines	S1/S4/STARCOM	FY28-30
8	Enable O&M funding for space logistics sustainment	USSF/S8	FY30

The implementation timeline reflects deliberate sequencing of interdependent actions. Strategic actions (Recommendations 1-2) must precede acquisition (Recommendations 3-5) to establish requirements and demand signals. Organizational actions (Recommendations 6-7) must synchronize with system fielding to ensure trained personnel and command structures are

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[90] Shaw, "SSM Imperative," 7.

ready when capabilities arrive. Resourcing actions (Recommendation 8) enable sustained operations once initial capability is fielded. The critical path runs through Recommendation 3: the Analysis of Alternatives in FY27 informs Milestone A in FY28, which drives prototype demonstration in FY30 and Initial Operating Capability in FY31. Delays in early strategic decisions cascade through the entire timeline. The compressed schedule reflects strategic urgency; adversary capabilities are advancing while American space forces remain constrained by finite propellant and limited maneuver options.

Areas for Future Research

This research has addressed the strategic question of whether Space Mobility and Logistics is necessary for space superiority. The analysis supports an affirmative answer but also identifies areas that warrant additional research to inform implementation decisions. Table 9.2 summarizes five priority research areas.

Table 9.2. Areas for Future Research

Research Area	Description	Methodology	Key Questions
Cost-Benefit Analysis	Detailed comparison of specific acquisition alternatives using validated cost models and system parameters; test & train	Operations research; parametric cost modeling; sensitivity analysis	Break-even fleet sizes? Optimal depot architecture? Tempo-cost relationships?
Wargaming and Simulation of CONOPs & Depot Defense	Contested space logistics operations modeling to inform CONOPS and force structure decisions; include ramp-up events (degraded systems)	DOE TS/SCI/SAP HPC M&S with SWAC; campaign-level wargames; tabletop exercises	Operations under counterspace pressure? Depot defense? Campaign integration?
Military Strategy Studies	Deep analysis of analogous logistics transformations including WWII Service Squadrons, aerial refueling adoption, and underway replenishment development	Comparative historical analysis; organizational change theory. History rhymes	Critical success factors? Institutional resistance patterns? Scaling timelines?
International Partnerships	Allied space logistics cooperation opportunities within Combined Space Operations framework	Policy analysis; technical interoperability assessment; treaty review	Burden-sharing models? Interoperability requirements? Allied access arrangements?
Cislunar Logistics	Extension of space logistics theory to cislunar environment including Lagrange points and lunar surface positions	Strategic studies methodology; orbital mechanics analysis; ISRU feasibility assessment	Critical cislunar positions? Logistics lines of communication? First-mover advantages?

The cost-benefit analysis would provide the quantitative foundation for acquisition decisions that this paper addresses only at the conceptual level. Using validated cost models and actual system parameters, such analysis could determine precise break-even fleet sizes, optimal depot positioning, and the sensitivity of conclusions to key variables such as launch costs, propellant prices, and operational tempo.

Wargaming and simulation would stress-test operational concepts against realistic adversary behavior. Traditional space wargames have focused on satellite-to-satellite engagements and ground-based counterspace threats. Future wargames must incorporate logistics as a warfighting function, examining how logistics infrastructure is defended, how logistics operations are prioritized under resource constraints, and how logistics enables or constrains operational options. Because the Center of Gravity shifts from the high-value assets to logistics, depot defense strategies must be developed. High-Performance Computing Modeling and Simulation conducted in partnership with the Space Warfighting Analysis Center should develop Dynamic Space Operations courses of action that examine operations under counterspace pressure.

Studies on Military Strategy would identify organizational change patterns that accelerate or impede capability adoption. The development of naval mobile service squadrons, aerial refueling adoption by the Air Force, and underway replenishment by the Navy all offer lessons for space logistics transformation. What were the critical success factors? How was institutional resistance overcome? What timelines proved realistic for scaling from demonstration to operational capability?

International partnership analysis would expand the aperture beyond unilateral American solutions. As noted in Chapter 8, the Combined Space Operations initiative offers potential for burden-sharing and distributed resilience that warrants dedicated analysis. The Combined Space Operations nations, including Australia, Canada, France, Germany, New Zealand, and the United Kingdom, each bring unique contributions to a distributed space logistics architecture. What burden-sharing models are feasible? What interoperability requirements must be addressed? How can allied capabilities and geographic advantages be leveraged?

The cislunar logistics research area warrants particular attention as American and Chinese activities extend beyond Earth orbit. Lagrange points, cislunar transfer orbits, and lunar surface positions may become the contested terrain of future competition. How do logistics lines of communication function in cislunar space? What positions offer first-mover advantages? How does In-Situ Resource Utilization from lunar ice transform the economics of sustained operations? This research would provide the theoretical foundation for space logistics doctrine applicable to the expanding operating environment.

Concluding Thoughts

Multiple states and commercial firms are actively developing on-orbit servicing and refueling capabilities, accelerating competitive pressure in this mission area. China is pursuing on-orbit servicing capabilities and training satellite operators for refueling operations in both peacetime and wartime. Russia has gained 25 years of experience by refueling the International Space Station. The United States possesses decades of technology demonstration as a foundation for implementation, from Orbital Express through the Robotic Refueling Mission to current commercial partnerships. Key enabling technologies have been demonstrated in relevant environments and demonstrations, but operational scaling and contested employment remain the primary gaps. The strategic requirement is clear. What remains is the institutional will to make the decisive choice to transform the space architecture from one paradigm to another.

Implementation will require sustained senior-level prioritization across budgeting, requirements, and force development. The temptation to wait for technologies to mature further or for concepts of operation to be validated before committing resources is understandable but strategically perilous. Open-source reporting indicates continued PRC investment and experimentation in on-orbit servicing and related mission sets. Every year of delay is a year in which adversary capabilities advance while American space forces finite propellant and limited replenishment options constrain maneuver planning, often pushing risk decisions upward and reducing tactical flexibility.

The historical parallel to naval and air domain mobile logistics illuminates both the stakes and the pathway. Those capabilities were built on decades of doctrinal development and pre-war organizational preparation. The Space Force must begin the same preparation now: developing concepts, building organizations, training personnel, and fielding infrastructure before the contingency that demands their employment.

The depot architecture proposed in this analysis extends beyond geosynchronous orbit operations. It is the first node in a space logistics network that must eventually span the Earth-Moon-Mars system. The strategic competition with China will not remain confined to the GEO belt. Cislunar space, including the gravitationally stable Lagrange points and the lunar surface, represents the next contested domain. A space logistics architecture permanently dependent on Earth-launched propellant cannot sustain operations at these distances. The nation that first develops the capability to produce propellant from in-space resources, whether lunar water ice or Martian atmospheric constituents, will possess enduring advantages in sustained space operations beyond Earth orbit. The recommendations in this paper address the urgent near-term requirement for Dynamic Space Operations capability. But they must be understood as the foundation for a larger strategic architecture. We build the GEO depot network now because we need it now. We design it for propellant modularity because we are not building for this decade alone. We are building the logistics infrastructure that will sustain American spacepower for the remainder of this century.

The United States Space Force has the opportunity to lead a transformation as consequential as the introduction of aerial refueling to airpower. Just as tanker aircraft transformed bombers and fighters from short-range platforms into instruments of global reach, space logistics can transform satellites from static assets into dynamic instruments of national power capable of maneuvering, persisting, and prevailing in a contested domain. The choice to pursue this transformation rests with senior leaders. The analysis presented in this paper demonstrates that the choice is not whether to develop Space Mobility and Logistics, but how quickly and with what level of commitment. The strategic environment demands urgency. The time for action and decision is now.

Appendix A: Glossary

AR&C Automated Rendezvous and Capture
ASTRO Autonomous Space Transfer and Robotic Orbiter
CFC Combined Forces Command
DARPA Defense Advanced Research Projects Agency
DLA Defense Logistics Agency
DOTmLPF-P Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, Facilities, and Policy
DSO Dynamic Space Operations
EP Electric Propulsion
GEO Geosynchronous Earth Orbit
GSSAP Geosynchronous Space Situational Awareness Program
HVA High Value Asset
ISAM In-Space Servicing, Assembly, and Manufacturing
ISS International Space Station
LEO Low Earth Orbit
MEO Medium Earth Orbit
MEP Mission Extension Pod
MEV Mission Extension Vehicle
MRV Mission Robotic Vehicle
NRL Naval Research Laboratory
OT&E Organize, Train, and Equip
RAFTI Rapidly Attachable Fluid Transfer Interface
RPOD Rendezvous and Proximity Operations and Docking
RRM Robotic Refueling Mission
RSGS Robotic Servicing of Geosynchronous Satellites
SDA Space Development Agency
SML Space Mobility and Logistics
SPAFORGEN Space Force Generation
SpOC Space Operations Command
SSC Space Systems Command
SSM Sustained Space Maneuver
STARCOM Space Training and Readiness Command
SWaP Size, Weight, and Power
USSF United States Space Force
USSPACECOM United States Space Command
USTRANSCOM United States Transportation Command
xGEO Extra-Geosynchronous Orbit

Appendix B: Recommended SFDD-1 Doctrine Updates

Space Force Doctrine Document 1 (SFDD-1), dated April 3, 2025, currently nests "sustainment" under "Space Access," which conflates launching a satellite with refueling one. To support the depot and servicer architecture proposed in this paper, doctrine must distinguish between getting to space and sustaining operations within it. The following four recommendations provide specific verbiage updates to establish the doctrinal foundation for Space Mobility and Logistics.

Recommendation 1: Rename and Expand the Space Access Core Function. The current name "Space Access" with definition "The movement and sustainment of equipment in, from, and to the space domain" implies entry (launch) rather than persistent on-orbit infrastructure. While the definition includes "in" and "sustainment," the title creates a doctrinal bias toward expendable launch vehicles. Recommend renaming to **Space Access, Mobility, and Logistics** with updated definition: "The movement, refueling, maintenance, and sustainment of equipment in, from, and to the space domain. These activities set and sustain the space theater for military operations." This aligns the core function with the Space Mobility and Logistics competency in the Space Capstone Publication, ensuring refueling is a primary function.

Recommendation 2: Add a Space Logistics Mission Area to Appendix B. Appendix B currently lists only three Mission Areas under Space Access: Satellite Control, Spacelift, and Launch Range Control. There is no designation for a depot or refueling tanker. A tanker is not a launch vehicle (Spacelift) and is not a ground antenna (Satellite Control). Currently, a depot has no doctrinal home. Recommend adding **Mission Area 3.4: Space Logistics** defined as "Activities to transport material, refuel spacecraft, and perform on-orbit servicing to extend the life and maneuverability of space assets." Additionally, add **Mission Set 3.4.1: On-Orbit Refueling** defined as "The transfer of propellant between spacecraft to enable sustained maneuver and competitive endurance." This provides the Mission Set terminology required for the Mission Delta proposed in this paper to exist within the force structure.

Recommendation 3: Redefine Recovery to Enable Reuse. The current definition of Recovery is "The recovery of payloads (spacecraft or other materials) returning from space." This implies a one-way trip back to Earth and does not cover in-space recovery where a servicer captures a client satellite to repair or tow it. Recommend updating to: "The retrieval or capture of payloads (spacecraft or other materials) within the space domain or returning from space." This enables active debris removal and tug operations under the Spacelift or Logistics mission area, supporting the reuse aspect of the proposed architecture.

Recommendation 4: Explicitly Link Orbital Warfare to Logistics. The current definition of Orbital Warfare is "Combat operations conducted through fires, movement, and maneuver to control the space domain." This mandates maneuver but fails to acknowledge the physical impossibility of sustained maneuver without refueling. Recommend adding: "Orbital Warfare relies on responsive logistics and refueling to maintain the energy advantage required to out-maneuver adversaries." This creates a requirement linkage establishing that Orbital Warfare cannot function without Space Logistics, mirroring how Air Force doctrine links fighter squadrons to tanker support.

These changes would move the proposed architecture from theoretical concept to doctrinal mandate. By adding On-Orbit Refueling as a formal Mission Set in Appendix B, the Space Force would be institutionally required to organize, train, and equip for that specific mission.

Appendix C: Parametric Sensitivity Analysis

Note: The parametric sensitivity computations and associated figures in this appendix were generated using computational modeling tools with artificial intelligence assistance. All assumptions, parameter ranges, model structure, and interpretive conclusions were determined by the author. The underlying economic model is calibrated to the baseline values presented in Chapter 6, Tables 6.1 through 6.6.

The preceding analysis established a baseline economic comparison yielding 29 percent savings for organic depot architecture over proliferation at DSO tempo. These findings rest on specific numerical assumptions about spacecraft cost, depot infrastructure investment, annual operations expenditure, and launch pricing. To strengthen the analytical foundation and enable leadership to evaluate conclusions under their own assessment of these variables, this appendix treats each key assumption parametrically. By varying inputs across plausible ranges and observing how outcomes shift, the analysis moves beyond defense of any single point estimate toward identification of robust directional trends.[91] Table C.1 presents the parameters, baseline values, and ranges examined.

Table C.1. Parametric Assumptions and Ranges

Four parameters govern the comparative economics. Spacecraft unit cost, baselined at $350 million, ranges from $200 million (representing a simplified or commoditized platform) to $500 million (representing an exquisite, multi-payload spacecraft with advanced sensors and radiation hardening). Depot infrastructure investment, baselined at $1.6 billion for five operational and two spare depots including servicers and launch, ranges from $1.0 billion (optimistic design maturation and commercial partnerships) to $2.5 billion (accounting for development risk, cost growth, and hardened survivability requirements). Annual depot operations cost, baselined at $92 million per year, ranges from $50 million (lean operations with autonomous servicing) to $150 million (labor-intensive operations with continuous ground support). Launch cost per Falcon Heavy equivalent, baselined at $97 million for two spacecraft, ranges from $60 million (reflecting continued launch cost reduction) to $180 million (reflecting constrained launch market or surge pricing). These ranges encompass the plausible uncertainty space for each variable based on historical cost data, Government Accountability Office assessments, and industry projections.[92]

Single-Variable Sensitivity

Figure C.1 presents a tornado diagram showing how depot architecture savings respond to variation in each parameter independently, with all other parameters held at baseline values.

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[91] This parametric approach follows established operations research practice for defense cost analysis. See Gene H. Fisher, *Cost Considerations in Systems Analysis* (Santa Monica, CA: RAND Corporation, R-490-ASD, 1971), a methodology widely adopted across Department of War cost analysis organizations.

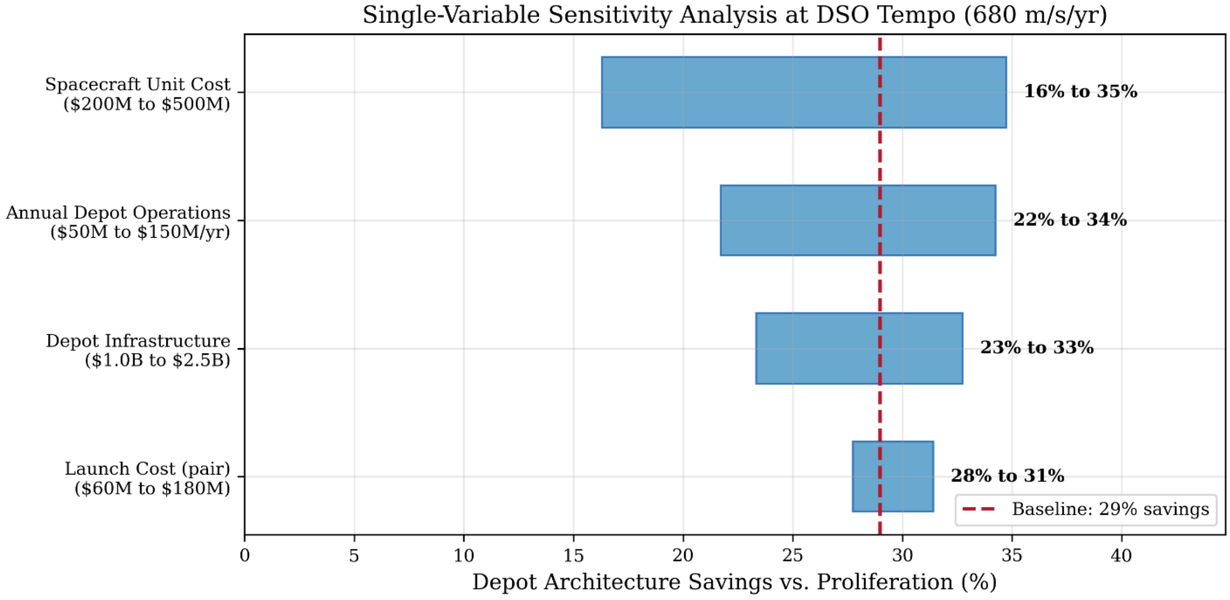
[92] Parameter ranges informed by GAO-25-107555 and The Aerospace Corporation, *Commercial On-Orbit Refueling Landscape* (El Segundo, CA: Aerospace Corporation, August 2024). Aerospace's ICAM-based cost modeling estimated initial refueling infrastructure at $635 million, providing a reference point for depot cost ranges.

The analysis reveals that spacecraft unit cost exerts the strongest influence on the savings calculation, with savings ranging from 16 percent when spacecraft cost only \$200 million to 35 percent when spacecraft cost \$500 million. This sensitivity is intuitive: depot architecture derives its primary advantage from avoiding mid-life constellation replacement, and the economic value of that avoided replacement scales directly with the cost of the spacecraft being replaced. More expensive spacecraft amplify the savings from extending their operational lives through refueling.

Annual depot operations cost represents the second most influential parameter, producing savings between 22 percent and 34 percent across the examined range. This finding highlights the importance of designing depot operations for efficiency from inception rather than accepting the labor-intensive ground operations models characteristic of current space programs. Depot infrastructure investment, the third most sensitive parameter, yields savings between 23 percent and 33 percent. The compressed range reflects that infrastructure is a one-time capital expenditure amortized across twenty years of operations, diluting its impact on total lifecycle cost. Launch cost demonstrates the least sensitivity, with savings between 28 percent and 31 percent, because launch costs affect both architectures roughly proportionally.

The critical observation from the tornado analysis is that savings remain positive across all single-variable excursions. Under every parameter variation examined, organic depot architecture retains an economic advantage over proliferation at DSO tempo. The floor of 16 percent savings, occurring only when spacecraft are assumed to cost \$200 million, still represents a meaningful economic difference over a twenty-year program lifecycle.

Figure C.1. Single-Variable Sensitivity of Depot Savings at DSO Tempo



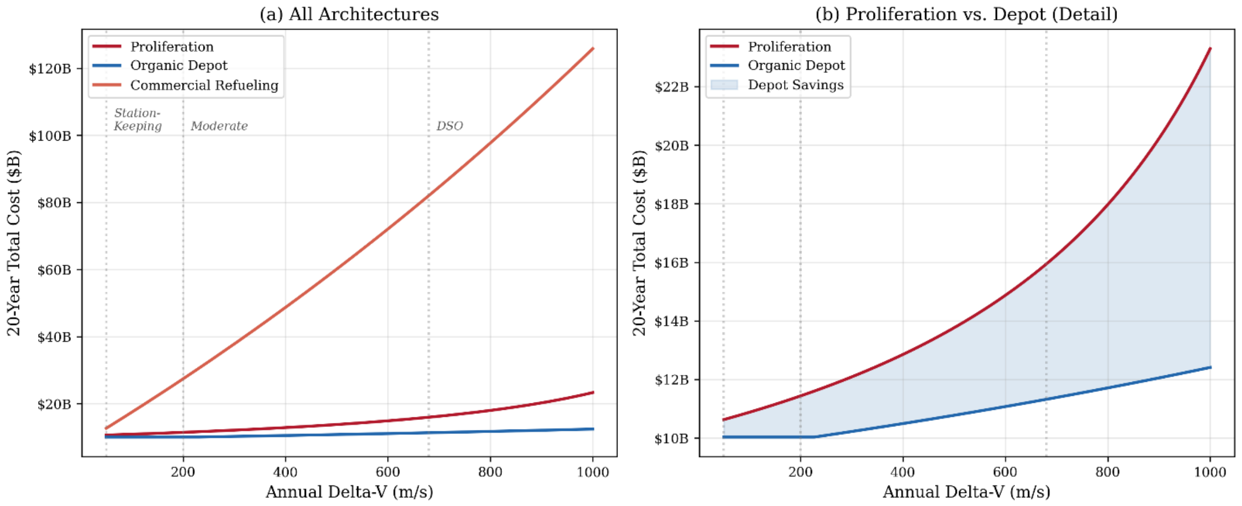
Operational Tempo as the Dominant Variable

While individual cost parameters shift savings by approximately 10 to 19 percentage points, operational tempo produces the most consequential variation in the architecture comparison.

Figure C.2 illustrates twenty-year total cost for all three architectures as annual delta-v increases from station-keeping through DSO requirements. Commercial refueling costs scale linearly with propellant demand, creating an exponentially widening gap against the other architectures. Proliferation costs increase as higher operational tempos accelerate propellant exhaustion and compress replacement timelines. Depot architecture costs increase more gradually because the infrastructure investment is fixed and only annual operations scale with propellant demand.

The divergence between proliferation and depot curves widens as delta-v increases, producing larger absolute and percentage savings at higher operational tempos. This relationship is strategically significant: the missions most demanding of delta-v capability are precisely those where depot architecture delivers the greatest economic advantage. At the moderate maneuver profile of 200 meters per second per year, depot architecture already achieves meaningful savings over proliferation. At DSO tempo and beyond, the savings compound further. The operational tempo finding reinforces a core theme of this analysis: the economic case for depot infrastructure strengthens as the Space Force moves toward more dynamic operational concepts.

Figure C.2. Architecture Cost Comparison Across Operational Tempos



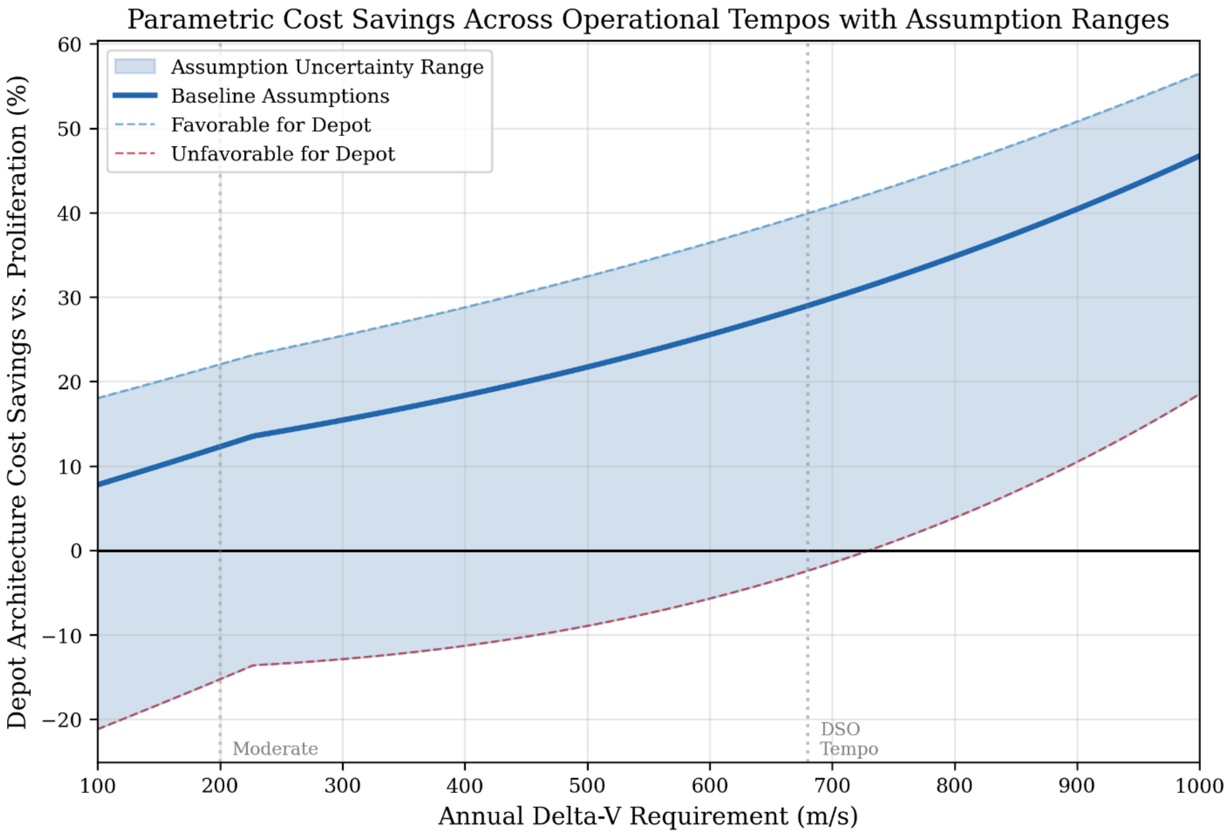
Combined Assumption Uncertainty

Real-world conditions involve simultaneous variation across multiple parameters. Figure C.3 presents savings as a function of operational tempo with an uncertainty band reflecting combined variation across all cost parameters. The baseline curve represents the central estimate using all baseline assumptions. The favorable bound assumes expensive spacecraft ($500 million), lower depot infrastructure ($1.0 billion), and efficient operations ($65 million per year). The unfavorable bound assumes inexpensive spacecraft ($200 million), higher depot infrastructure ($2.5 billion), and expensive operations ($140 million per year).

At DSO tempo under baseline assumptions, savings are 29 percent. The uncertainty band at DSO tempo spans from approximately negative 2 percent under the most unfavorable combined assumptions to approximately 40 percent under favorable assumptions. The unfavorable scenario deserves careful interpretation: it assumes simultaneously that spacecraft are inexpensive (reducing the value of avoiding replacement), depots are expensive to build (increasing capital requirements by 56 percent), and operations are costly (increasing annual expenditure by 52 percent). This combination, while plausible as a bounding case, represents a worst-case confluence that would also indicate broader programmatic challenges warranting reassessment of the entire acquisition strategy.

At the baseline spacecraft cost of $350 million, holding spacecraft cost constant while varying only depot-specific assumptions, savings range from 17 percent to 36 percent at DSO tempo. This narrower band provides a more operationally relevant uncertainty range because spacecraft unit cost is the most well-characterized parameter given existing program data. The finding that savings remain robustly positive (17 percent or greater) when varying depot-specific costs across wide ranges strengthens confidence in the directional conclusion.

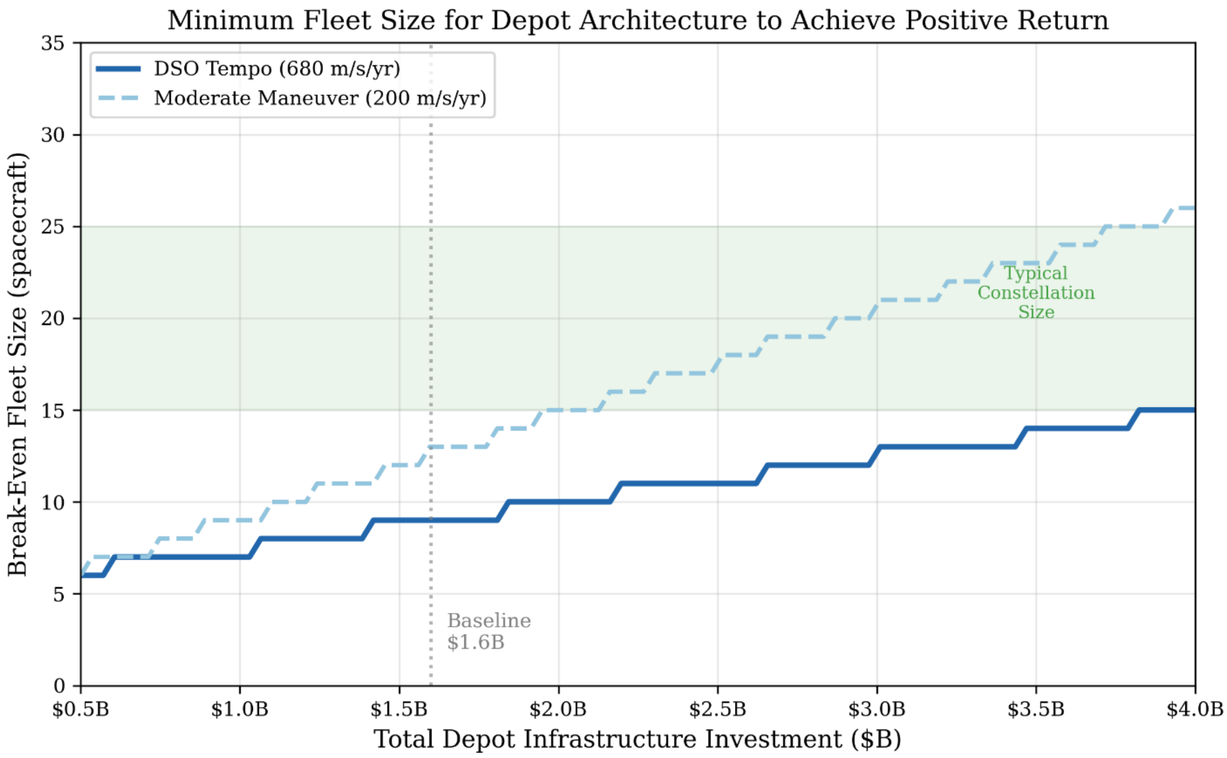
Figure C.3. Cost Savings with Combined Assumption Uncertainty



Break-Even Fleet Size Under Uncertainty

The preceding break-even analysis identified six spacecraft as the minimum fleet size for depot architecture to achieve positive return at baseline assumptions. Figure C.4 extends this analysis by examining how break-even fleet size varies with total depot infrastructure investment across operational tempos. At DSO tempo with baseline infrastructure investment of $1.6 billion, break-even occurs at approximately six spacecraft, well below typical constellation sizes of fifteen to twenty-five platforms. If depot infrastructure costs doubled to $3.2 billion, break-even would shift to approximately twelve spacecraft, still below operational constellation sizes. At moderate maneuver tempo of 200 meters per second per year, break-even fleet sizes are larger because the per-spacecraft annual savings are smaller, though they remain below twenty spacecraft for infrastructure investments up to approximately $2.5 billion.

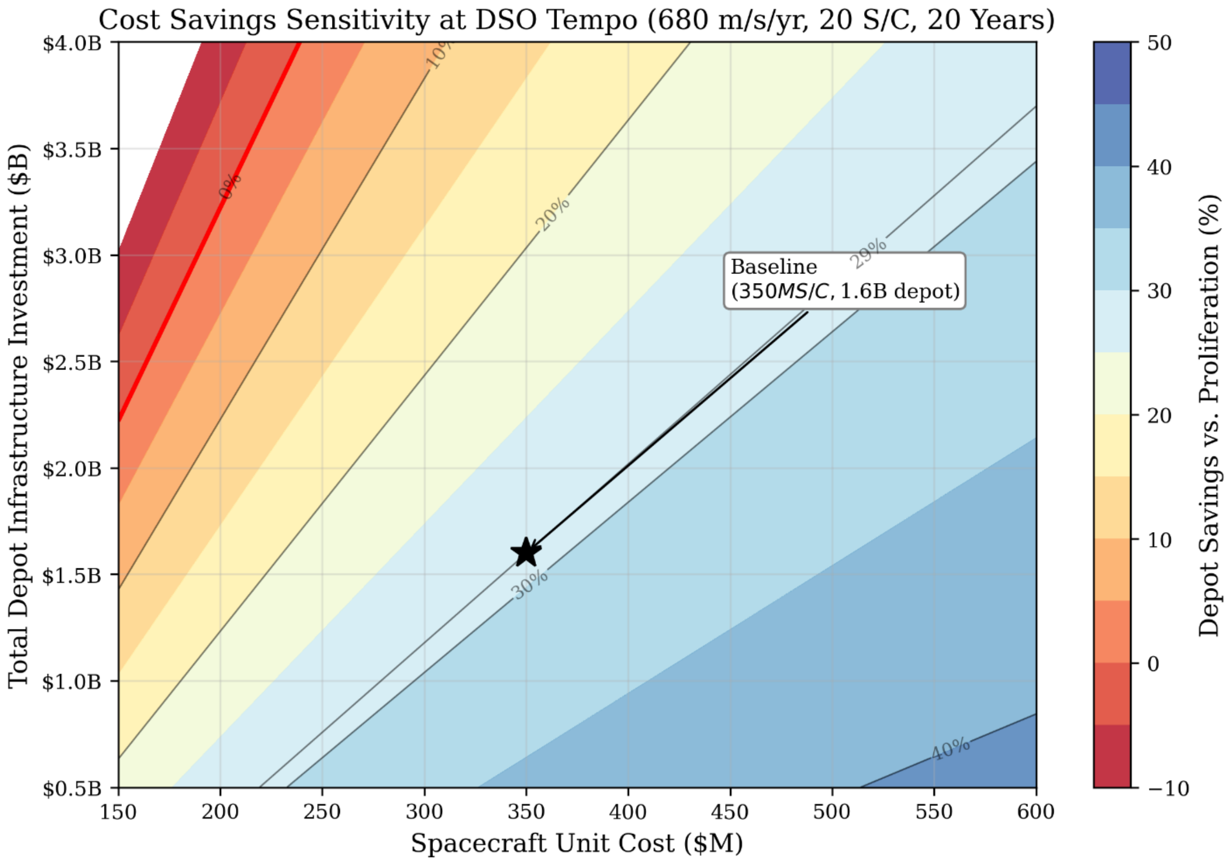
Figure C.4. Break-Even Fleet Size vs. Depot Infrastructure Investment



Two-Variable Sensitivity: Spacecraft Cost and Infrastructure Investment

Figure C.5 presents a contour plot examining the interaction between the two most consequential variables: spacecraft unit cost and depot infrastructure investment. The contour lines represent constant savings percentages. The red contour at zero percent marks the break-even boundary between the two architectures. The baseline assumption (marked by the star) sits well within the positive savings region. Savings increase toward the upper-left of the plot (expensive spacecraft, modest depot investment) and decrease toward the lower-right (inexpensive spacecraft, large depot investment). The zero-percent contour reveals that depot architecture achieves positive return for all combinations where spacecraft cost exceeds approximately $250 million at reasonable infrastructure levels, or for all infrastructure investments below approximately $3.5 billion at the baseline spacecraft cost.

Figure C.5. Two-Variable Sensitivity: Spacecraft Cost vs. Depot Infrastructure (DSO Tempo)



Parametric Analysis Implications

The parametric analysis yields three findings that strengthen the overall economic argument.

First, the depot architecture advantage is directionally robust. Under single-variable excursions across all four parameters, savings remain positive, ranging from 16 percent to 35 percent. The baseline 29 percent estimate represents a central value within this range, and no single parameter variation reverses the economic conclusion. Combined multi-variable uncertainty at the baseline spacecraft cost produces savings between 17 and 36 percent, confirming that the directional finding holds under simultaneous perturbation of depot-specific assumptions.

Second, spacecraft unit cost and operational tempo drive the economic comparison more than any depot-specific parameter. This finding is significant because spacecraft cost is the most well-characterized input, grounded in actual program data, and operational tempo is a doctrinal requirement rather than an assumption. The parameters most subject to uncertainty, specifically depot infrastructure cost and annual operations expense, exert comparatively modest influence on the savings calculation. Decisionmakers who accept the spacecraft cost baseline and the DSO operational tempo requirement can hold high confidence in the directional conclusion regardless of their assessment of depot-specific costs.

Third, break-even analysis confirms operational relevance. At DSO tempo, depot architecture achieves positive return for constellations larger than six spacecraft under baseline assumptions, and larger than twelve spacecraft if infrastructure costs doubled. Both thresholds fall below the operational constellation sizes envisioned for next-generation national security space architectures. The margin between break-even fleet size and planned constellation size provides meaningful resilience against cost growth. These parametric findings establish that the economic case for depot architecture is a robust trend warranting programmatic investment, rather than a fragile point estimate dependent on optimistic assumptions.

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