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Building an In-Space Circular Economy – Seminar Series Report

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Abstract

Traditional space activities have followed a linear, single mission model in which spacecraft are designed, launched, operated, and ultimately disposed of through atmospheric reentry or relocation to graveyard orbits. As the commercial space sector grows, this “take-make-use-dispose” paradigm is increasingly challenged by the economic and operational realities of long-duration space activity. This report captures key themes from the 2025 Building an In-Space Circular Economy seminar series, convened by the Department of Commerce Office of Space Commerce and the National Institute of Standards and Technology. The seminars examined the technical, regulatory, and economic requirements needed to support a transition toward circular space operations. Major themes include the need for streamlined regulations alongside government procurement strategies that establish dependable demand, clarification of salvage rights and ownership transfer pathways, and the development of standards to support servicing, refueling, reuse, recycling, and data exchange. Additionally, the report highlights the importance of orbital infrastructure, including servicing hubs, modular platforms, recycling architectures, logistics networks, and energy systems, as well as the critical role of materials science and manufacturing innovation. Key concepts such as design for circularity, materials passports, feedstock processing, and in-space manufacturing are identified as enabling tools for extending the value of space assets. The multidisciplinary nature of the participants, presentations, and discussions highlighted that building an in-space circular economy will require coordination among policy, finance, technology, and standards organizations.

Keywords

Circular space economy; design for circularity; in-situ resource utilization; in-space manufacturing; in-space recycling; in-space servicing, assembly, and manufacturing; interoperability; interoperability standards; modularity; orbital infrastructure; space policy; space resource utilization; space sustainability; standards.

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Author Contributions

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Executive Summary

Space is a resource-constrained environment because nearly all materials and equipment must currently be launched from Earth. Although commercial launch services have reduced transportation costs, delivering mass to orbit remains expensive and logistically challenging. As commercialization of the space industry continues to expand, the traditional single mission, linear operational model is increasingly challenged. Historically, spacecraft are designed, launched, operated, and then deorbited or moved to graveyard orbits. However, an in-space circular economy model could reduce dependence on terrestrial resupply by extending asset lifetimes and enabling the inspection, servicing, repair, reuse, repurposing, recycling, and remanufacturing of materials and systems already in space.

The 2025 Building an In-Space Circular Economy seminar series, convened by the U.S. Department of Commerce Office of Space Commerce and the National Institute of Standards and Technology, brought together representatives from government, industry, academia, and nonprofit organizations. Each seminar attracted more than 300 registered attendees, roughly half of whom represented industry. Participants examined the technical, regulatory, economic, infrastructure, and standards-related conditions needed to transition towards circular space operations. A central finding was that circularity requires many elements to work together. It depends on coordinated circular design practices, clear ownership pathways, and strong market demand. Additionally, it needs physical and digital infrastructure, financing mechanisms, and trusted operational standards.

Circularity must begin during the design of space systems. Future assets developed with defined pathways for servicing, repair, and upgrades are essential. Modular components, standardized interfaces, accessible attachment points, reduced material complexity, and digital records such as ‘materials passports’ are needed to make future servicing and recovery feasible. Without these provisions, assets remain difficult or uneconomical to repair, repurpose, or recycle. This perpetuates the traditional linear operating model.

Policy and regulatory uncertainty remain a significant barrier. Circular activities such as inspection, servicing, and debris capture do not fit cleanly within regulatory systems originally developed for launch, reentry, remote sensing, and spectrum use. Companies face overlapping jurisdictions, uncertain authorization pathways, and unpredictable timelines. Seminar participants identified the need to clarify salvage permission, ownership transfer, custody, operational control, and liability before defunct assets or debris can legally become inputs for reuse or recycle.

Seminar participants emphasized that government demand is essential for establishing early markets. Circular space infrastructure requires substantial upfront investment before a commercial customer base is established. Discussions highlighted that government agencies could reduce this market uncertainty by acting as anchor customers, purchasing services, supporting demonstration missions, and incorporating servicing and/or reuse requirements into procurements. It was noted that long-term service contracts will provide the dependable revenue and operational evidence needed to attract private investment, lower financing costs, and improve insurability.

A functioning circular space economy will also require persistent physical and digital infrastructure. Servicing hubs, modular platforms, transportation networks, manufacturing and recycling facilities, power generation, and communications must operate as parts of an interconnected system. For example, recycling will not be successful processing technology alone. Additional supporting infrastructure is required to identify, capture, transport, store debris/materials. Seminar participants emphasized that the transition from the International Space Station to commercial low-Earth-orbit infrastructure represents an important period for maintaining the power, logistics, robotics, and operational continuity needed to mature the ongoing development of key circular infrastructure capabilities.

Standards, cybersecurity, and trusted operations are equally important. Consensus frameworks are needed for docking interfaces, refueling ports, modular connectors. As orbital systems become more interconnected, secure communications, and resilient command-and-control networks will be necessary to protect both digital systems and physical assets. Trusted and interoperable operations will increase confidence among operators, regulators, insurers, investors, and customers.

The seminars also highlighted the economic role of in-space manufacturing. Manufacturing products in microgravity for terrestrial use can help establish commercial demand, operational experience, transportation capacity, and orbital infrastructure. Improvements in manufacturing yield and product performance will support high-value markets such as advanced materials, semiconductors, optical fibers, pharmaceuticals, and biomedical products. Over time, the capabilities developed for manufacturing in space for Earth will contribute to the transition toward manufacturing in space for use in space.

The seminar discussions highlighted several areas for further consideration. Participants focused on integrating circularity into spacecraft design and examining opportunities to improve policy and regulatory coordination. Additionally, they explored the role of government procurement in supporting early demand. Further efforts should include advancing standards and considering approaches for coordinating implementation across the broader ecosystem.

1. Introduction

Traditional space activities have chiefly functioned under a linear, single-use paradigm, as displayed in Figure 1a. This "take-make-use-dispose" model tends to be characterized by non-serviceable space assets that are frequently decommissioned, whether via atmospheric reentry or disposal into high-altitude graveyard orbits upon the depletion of onboard propellant or the onset of subsystem obsolescence.

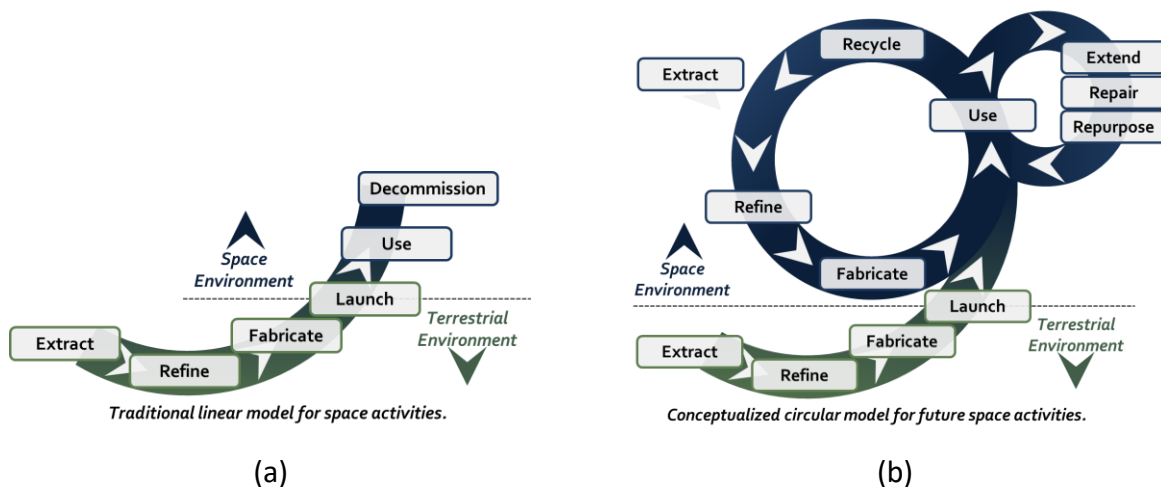


Figure 1: Comparison of the (a) traditional linear model and (b) conceptual circular model for in-space activities. Green denotes terrestrial activities, while blue denotes in-space activities.

Economic and practical factors are increasingly challenging the traditional linear model as the space industry moves rapidly toward commercialization. Consequently, there is a shift from the traditional linear model towards more circular operations, as illustrated in Figure 1. Within this model, circular loops exist within the space environment, which are enabled by in-orbit refueling, servicing, and refurbishment, debris-to-feedstock workstreams, orbital manufacturing, and even closed-loop life support. These loops are supported by terrestrial resupply, in addition to in-space resource extraction, processing, and reutilization. Transitioning to the in-space circular economy is a multidisciplinary endeavor that will require coordinated progress across technological development, finance, regulation, and policy.

To facilitate this transition, the Department of Commerce Office of Space Commerce (OSC) and the National Institute of Standards and Technology (NIST) convened a two-part seminar series titled "Building an In-Space Circular Economy." The first seminar, held on February 13th, 2025, established the concept for an in-space circular economy and identified the technical, policy, and strategic challenges to its implementation. The second seminar, held on August 27, 2025, advanced the discussion towards implementation, focusing on commercialization, financing, collaborative consortia, enabling infrastructure, interoperability, and practical pathways for developing an in-space circular economy.

1.1. The Circular Space Economy Framework

The circular space economy concept is still developing, with international organizations, government agencies, commercial consortia, and non-profit organizations helping shape its definition, as summarized in Table 1. For purposes of this report, the circular space economy is best understood as a broader economic and operational model in which space assets, materials, data, energy, and functions are designed to retain value across multiple missions, users, and life-cycle phases rather than being abandoned, discarded, or destroyed after a single mission.

This concept is related to, but distinct from, space sustainability (highlighted in the United Nations Committee on the Peaceful Uses of Outer Space definition within Table 1), debris mitigation, in-space servicing, assembly and manufacturing (ISAM), in-space manufacturing, and recycling. Space sustainability and debris mitigation are important objectives, but they do not by themselves create a circular economy. ISAM, in-space manufacturing, in-space recycling, resource utilization, servicing, repair, reuse, and repurposing are enabling capabilities within the larger model. The circular space economy depends on these capabilities being integrated with compatible policy, standards, logistics, financing, ownership-transfer mechanisms, and trusted operational practices. Its goal is not only to reduce waste, but to create a more resilient and productive space economy in which orbital and planetary-surface assets can be serviced, upgraded, reused, repurposed, transferred, or recycled over time.

Table 1: Several Definitions of the Circular Space Economy

Organization	Definition	Ref.
United Nations Committee on the Peaceful Uses of Outer Space ^(a)	<u>Sustainability of Outer Space Activities</u> : The ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations.	[1]
European Space Agency ^(b)	<u>Circular Space Economy</u> : A space economy in which novel methods of design and managing space systems allows systems, subsystems, components, and materials to remain in orbit and be refurbished or re-used using an ecosystem of advanced in-orbit servicing techniques. This approach will preserve the space environment for future generations while meeting current economic needs.	[2]
Consortium for Execution of Rendezvous and Servicing Operations ^(b)	<u>Circular Space Economy</u> : The circular space economy is a systems-level economic model in which the design and operation of space activities evolve around preserving, regenerating, and extending the functional	[3]

Organization	Definition	Ref.
	value of assets beyond traditional lifetimes. This approach aims to minimize waste, maximize value from resources, and support the long-term viability and economic growth of space activities.	
Secure World Foundation	<u>Circular Space Economy</u> : A circular space economy is one in which space systems are designed and operated in a manner that enables those systems and their subsystems, components, and materials to remain in use through an ecosystem of space-based servicing and manufacturing techniques. This approach seeks to minimize waste, optimize resource use, and preserve the space environment for future generations, while supporting the long-term sustainability of space activities in all its aspects.	[4]
<u>Notes:</u> (a) This definition captures ‘sustainability of outer space activities’, not necessarily the circular space economy. (b) At the time of publication, this represented a working definition rather than a settled consensus. It is included here to share multiple perspectives and to illustrate that the concept remains actively evolving.		

1.2. Seminar Objectives and Series Structure

The Building an In-Space Circular Economy seminar series convenes leaders from government, industry, and academia to define and advance the technical, policy, standards, and economic frameworks needed for a circular space economy. The first seminar, held on February 13, 2025, focused on the foundational strategies for in-space circularity. It highlighted advancements in on-orbit recycling technologies and innovative policies for managing shared space resources, emphasizing the need for environmental stewardship alongside economic growth. The second seminar, held on August 27, 2025, shifted toward implementation, exploring the nature of technology applications and the tactics for finance and investment. See Appendix A for seminar agendas.

Key objectives included:

- Connecting emerging space companies, government agencies, researchers, and other stakeholders to strengthen relationships between the public and private sectors;
- Exploring the role of government in fostering commercialization, public-private partnerships, and the future of space-based infrastructure;
- Building a shared understanding of the in-space circular economy, including opportunities and challenges related to commercialization, investment, standards, interoperability, and space situational awareness; and

- Examining the technical and operational capabilities needed to support circular space activities, including on-orbit servicing, in-space manufacturing, recycling, resource utilization, and strategies to reduce waste and extend mission lifetimes.

1.3. The Role of the U.S. Department of Commerce

Several existing Department of Commerce (DOC) missions and capabilities are relevant to the development of an in-space circular economy. It was discussed at the seminar that DOC's role should support the commercial, regulatory, data, and standards infrastructure needed for circular space activities to become viable and scalable. Through the Office of Space Commerce, National Oceanic and Atmospheric Administration (NOAA), NIST, and other Commerce bureaus, the Department could help advance space situational awareness and space traffic coordination, convene public and private stakeholders, support commercialization pathways, and develop the measurement and standards frameworks needed for interoperability, servicing, reuse, refurbishment, in-space manufacturing, and recycling.

It was highlighted at the seminar that this engagement leverages NIST's mission to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve quality of life. In the context of a circular economy, NIST provides the measurement science and collaborative technical frameworks necessary for innovation and fair competition. By developing best practices and supporting the technical basics for standards development, NIST helps U.S. companies maintain global competitiveness.

Complementing this technical foundation, the OSC carries out its mission to foster the conditions for the economic growth and technological advancement of the U.S. commercial space industry. The OSC advocates for the U.S. commercial sector by removing bureaucratic hurdles, streamlining regulation, and representing U.S. commercial interests both domestically and internationally. Furthermore, through the development of the Traffic Coordination System for Space (TraCSS), the OSC ensures the safety and sustainability of the orbital environment. Through TraCSS, OSC is developing civil space situational awareness and space traffic coordination services intended to support safer space operations.

2. The Policy and Regulatory Landscape

The transition from a linear model to a circular one is currently constrained by policy and regulatory ambiguity. As highlighted in the 2025 seminars, the existing regulatory framework, which was designed in a relatively static era of space activity for discrete launches and satellite operations, is challenged by the dynamics of in-space servicing, recycling, and manufacturing. This section outlines key policy and regulatory considerations discussed in the seminars.

2.1. Regulatory Challenges for Circular Space Operations

Seminar participants identified the absence of a clear Mission-Based Authorization system as a policy barrier to the ISAM sector. Speakers highlighted the current U.S. regulatory system for commercial space is fragmented across multiple agencies depending on the function, technology, and data involved, as shown in Figure 2, and summarized below.

Launch, launch-site operations, and re-entry are regulated by the Department of Transportation through the Federal Aviation Administration (FAA), while spectrum management is shared between the Federal Communications Commission (FCC) for commercial users and the National Telecommunications and Information Administration (NTIA) for federal users. Remote sensing data is overseen by the Department of Commerce through the Office of Space Commerce, and export control responsibilities are split between the Department of State's Directorate of Defense Trade Controls (DDTC) and the Department of Commerce's Bureau of Industry and Security (BIS). Space activities are regulated across multiple agencies depending on the function, technology, and data involved.

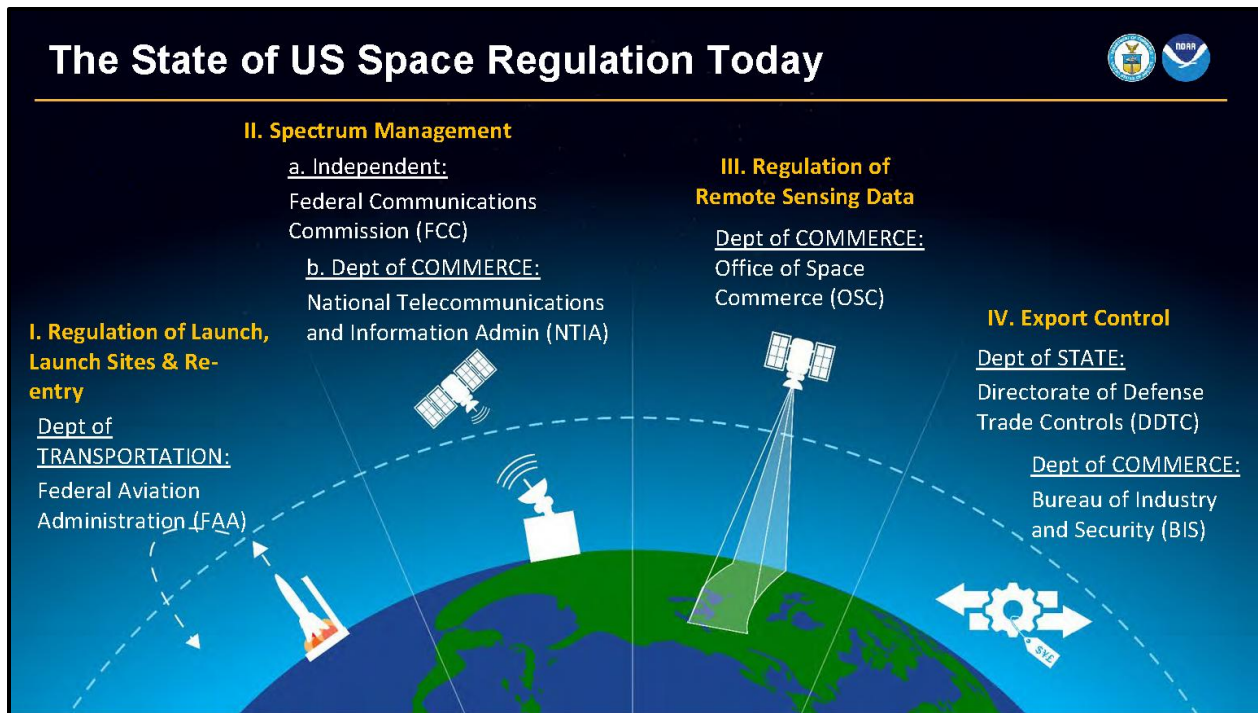


Figure 2: Infographic titled “The State of US Space Regulation Today,” showing Earth from space with satellites, a rocket launch, a ground antenna, a remote sensing satellite, and an export-control icon. The figure summarizes four major areas of U.S. space regulation and the responsible agencies. *Image Credit: U.S. Office of Space Commerce.*

Activities that enable circularity, including on-orbit recycling, manufacturing, and refueling, do not align with traditional commercial space regulatory categories. For example, a space asset may inspect, refuel, relocate, or capture debris. The existing regulatory system addresses individual functions such as launch, spectrum use, and remote sensing, but does not clearly cover the complete range of ISAM activities within one mission. Additionally, ISAM spacecraft will likely carry cameras and other sensors for navigation, inspection, and proximity operations. Depending on their capabilities and intended use, these systems may trigger commercial remote-sensing licensing requirements, even when Earth imaging is secondary to the primary servicing mission. Although the existing tiered remote-sensing framework provides streamlined requirements for many systems, novel ISAM missions require clarity regarding when and how those requirements apply. As a result, the industry faces three systemic risks:

- 1) **Investment challenges:** without a defined approval pathway, investors are hesitant to fund high-capital projects,
- 2) **Insurance deadlocks:** without a predictable legal lifecycle, high-CAPEX missions face prohibitive premiums or a total lack of coverage, and
- 3) **Jurisdictional overlap:** companies face duplicative regulatory submissions and inconsistent standards across multiple agencies.

Seminar participants expressed concern that existing function-based regulatory frameworks may not fully address certain multifunction ISAM missions.

2.2. Creating Demand Through Government Procurement

A recurring theme across both seminars was the demand problem. The industrial base needed to support a circular space economy cannot scale on policy statements, strategic endorsements, or general expressions of support alone. Companies require funded procurements, service purchases, anchor-tenant agreements, and other contractual commitments that provide predictable revenue and demonstrate a credible customer base. The ISAM sector currently faces a dynamic in which companies are hesitant to invest in high-CAPEX infrastructure without clear customers, while government and commercial customers are reluctant to rely on services that lack operational history. Seminar participants suggested that government agencies are necessary to break this cycle through long-term service contracts, procurements, and contractual requirements for capabilities such as servicing, refueling, debris removal, manufacturing, or logistics. Such commitments could provide the certainty and evidence needed to attract private investment financing while reducing insurance risk. As highlighted at the seminar, this challenge aligns with the 2022 In-Space Servicing, Assembly, and Manufacturing National Strategy [5], which emphasized consistent demand, scalable ISAM infrastructure, and standardized practices to advance the sector.

Seminar participants discussed several procurement mechanisms through which the government could serve as an early customer or anchor tenant for circular space capabilities:

- **Infrastructure-as-a-service and service-based contracts:** Shifting from the procurement of custom hardware to the purchase of specific outcomes (e.g., delivered propellant volumes or manufacturing capacity). This model helps convert capital-intensive infrastructure into service offerings, allowing customers to purchase capabilities without owning the underlying asset.
- **Servicing ready requirements for government-funded assets:** Encouraging or requiring government-supported spacecraft and infrastructure to incorporate standardized interfaces, refueling compatibility, modular components, and other features. By adopting this strategy, future capacity for inspection, repair, relocation, life extension, and reuse is effectively supported.
- **Active debris removal and salvage awards:** Implementing a fee-for-service model for the remediation, relocation, or recovery of nonoperational government-owned objects. Such mechanisms provide a revenue stream for capture, transport, and processing technologies while clarifying the laws around ownership, liability, and salvage rights.
- **In-space manufacturing for national missions:** Prioritizing government use cases where in-space manufacturing, assembly, or repair provides value. For example, government investment in leveraging microgravity for materials synthesis demonstrates success and advances technology by improving material properties or performance [6].

These procurement actions are examples of foundational validation tools for circular space markets. As noted in finance, infrastructure investors need dependability evidence to lower capital costs. In this context, securing a government contract acts as a validation, mitigating perceived risks for insurers and lower-cost capital providers.

2.3. Salvage Rights

A circular space economy requires resolving the legal status of "space junk" and establishing frameworks for the handling of defunct assets in orbit. Under the Outer Space Treaty [7] the state of registry retains jurisdiction and control over its space objects, and ownership is not extinguished merely because an object has reached end-of-life. A salvage framework must address object identification, salvage permission, transfer of control, allocating liability, safe rendezvous and proximity operations (RPO), and maintaining custody after recovery.

The permission, transfer, and liability aspects of this salvage framework were discussed at length. Specifically, participants highlighted that this creates a gap in which commercial entities cannot legally recycle or repurpose another nation's or company's defunct satellite, or even debris, without explicit, and often complex, permission. The following policy approaches were proposed during the seminars to enable a functional salvage regime to unlock an estimated 10,000 metric tons of potential orbital mass already in space:

- Permission-based salvage was discussed as creating agreements where trusted countries or operators give explicit permission to recover designated defunct space assets, while clarifying ownership, liability, and operational responsibilities in advance.
- Ownership transfer was also presented as another mechanism that would allow operators to legally transfer defunct satellites or components to another party for reuse, recycling, or materials recovery, turning end-of-life hardware from a liability into a potential resource.
- While not permission-based, one proposal drew on a provocative historical analogy, referencing 'letter of marque and reprisal'. In this analogy, governments create a formal licensing pathway for commercial companies to recover designated end-of-life space objects and deliver them to either on-orbit, planetary surface, or Earth-based recycling or reprocessing facilities.

Although these ideas differ in mechanism, they address similar challenges surrounding salvage rights. Each approach creates a pathway for authorized recovery and control of orbital debris, allowing debris to be reused, repurposed, and recycled as part of a circular resource model.

2.4. The Role of Standards

Harmonization and interoperability serve as the foundational structure of a circular space economy. Without the establishment and adoption of standards, ISAM missions remain highly customized, isolated events that reinforce linear operational dynamics. As emphasized by NIST leadership in the seminars, voluntary, consensus-based standards act as a systemic discipline grounded in shared definitions and repeatable pathways. These provide the collaborative technical framework necessary to promote innovation and fair competition. The seminars identified several priority areas for standards development, specifically physical and operational interface, data and materials traceability, cybersecurity and trust, and service definition and performance standards.

Physical and operational interfaces were repeatedly highlighted, including docking systems, refueling ports, modular connectors, and features that would allow spacecraft and infrastructure from different providers to interact safely and reliably. By adhering to standards, such as the American National Standards Institute (ANSI) / American Institute of Aeronautics and Astronautics (AIAA) durable fluid transfer guidelines [8], the industry can ensure that the assets can be serviced by various providers. Furthermore, establishing best practices for rendezvous and proximity operations is essential for operational safety. These ensure that the servicing of one asset does not pose a kinetic risk to others within a crowded orbital regime.

The discussion extended beyond mechanical interfaces. Participants identified the need for standards around data exchange, materials identification, and design-for-reuse. In addition, logistics standards for the handling, storage, certification, transfer, and resale of recovered materials will be needed if orbital debris and end-of-life hardware are to become inputs for in-space manufacturing.

Cybersecurity and trust standards were also identified as necessary to support secure communications, authentication, data sharing, access control, threat reporting, and trusted interactions among operators. In addition, service definition and performance standards are needed to establish common terminology, performance metrics, and verification methods for commercial services. These include refueling, inspection, life extension, debris removal, recycling, and delivered manufacturing capacity.

Ultimately, the development of standards depends on trust, coordination, and information sharing. Organizations such as Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) and Space Information Sharing and Analysis Center (ISAC) support different but complementary parts of this ecosystem. CONFERS helps advance norms, best practices, and industry-derived standards for on-orbit servicing and related activities, while Space ISAC supports risk management and threat information sharing across the space community. Together, these organizations can reduce operational, physical, and cyber risks while increasing confidence among operators, regulators, insurers, and investors. This seminar series has already helped advance that goal by catalyzing the formation of a CONFERS special interest group focused on the circular space economy, developed in response to the NIST-OSC seminar series. In this broader context, NIST's could help by convening technical experts, supporting standards coordination, and developing standard reference materials and data can help establish the stable operational framework needed for U.S. companies operating within an emerging circular space economy.

There are currently no International Organization for Standardization (ISO) standards developed exclusively for the circular space economy, but the aerospace sector uses a combination of two frameworks: the ISO 59000 series for general circular economy practices [9] and ISO 24113 [10] for space debris mitigation.

Established by ISO Technical Committee (TC) 323, these foundational global standards for a circular economy (ISO 59000 Series) offer a universal structure for organizations seeking to move away from traditional linear economic models:

- ISO 59004, Circular economy - Vocabulary, principles and guidance for implementation [9]
- ISO 59010, Circular economy - Guidance on the transition of business models and value networks [11]
- ISO 59020, Circular economy - Measuring and assessing circularity performance [12]
- ISO 59014, Environmental management and circular economy - Sustainability and traceability of the recovery of secondary materials - Principles, requirements and guidance [13]

Beyond general circular economy standards, several other documents/standards exist that are relevant to circular space economy principles:

- United Nations, Guidelines for the Long-Term Sustainability of Outer Space Activities [1]
- Inter-Agency Space Debris Coordination Committee, Space Debris Mitigation Guidelines [14]
- ISO 24113:2023, Space systems - Space debris mitigation requirements [10]
- ISO TC 20/SC 14, Space systems and operations [15]
- ISO 24330:2022, Space systems - Rendezvous and Proximity Operations On Orbit Servicing - Programmatic principles and practices [16]

Standardization for advanced circular concepts, such as satellite recycling, active removal of debris, and in-orbit servicing, remains in development. NIST and the Office of Space Commerce are coordinating efforts from the terrestrial circular principles for the unique challenges of space operations. Through their efforts with ISO these principles may become the basis for an international standard in this area in the future.

3. Economic and Financial Models

The transition to an in-space circular economy is also an economic challenge that requires shifting from short-term, single mission thinking, to longer-term life cycle thinking. While technological capabilities are maturing, financial aspects remain a challenge. This is due to high upfront capital expenditures and the risk associated with early-stage space infrastructure. The seminars identified several economic enablers and frameworks to support the transition of the space industry from an emerging market to a more mature and sustainable ecosystem.

3.1. Resource Scarcity as a Driver of In-Space Production

The economic logic for circularity in space is driven by the high cost and difficulty of resupplying materials from Earth. Because launch costs remain a primary bottleneck, estimated at approximately \$7,000/kg to low-Earth orbit, the traditional take-make-dispose model is structurally and financially inefficient. A seminar speaker illustrated this point with a “space hamburger” analogy. While a hamburger has little intrinsic value on Earth, its effective cost in orbit rises once the mass of each ingredient must be launched from Earth. The example highlights a general economic principle supporting the circular space economy, when transportation costs dominate material value, in-space reuse, recycling, and production become increasingly attractive.

As discussed by the seminar participant, the resource-constrained environment of space creates an immediate waste-to-value opportunity. Rather than treating decommissioned satellites and debris as liabilities, these are concentrated, valuable spare parts or feedstock for manufacturing in a circular model. By recycling or reusing the estimated 10,000 metric tons of orbital mass already in space, the industry can move beyond the high-cost terrestrially based supply chain and establish a more circular in-space supply chain.

The urgency of this waste-to-value opportunity will grow as orbital infrastructure scales. Recent orbital data center proposals suggest that the mass placed in orbit over the next decade could exceed today’s entire artificial orbital mass many times over. Even a single gigawatt-class orbital data center architecture could require tens of thousands of metric tons of satellites, solar arrays, radiators, computer hardware, power systems, and support structure. Larger proposed constellations could eventually place hundreds of thousands, or even millions, of metric tons of engineered material in orbit. If those assets are designed for single use and disposal, the industry risks converting a historic infrastructure buildout into debris, uncontrolled waste, or atmospheric reentry products. If they are instead designed from the start for servicing, modular replacement, component recovery, ownership transfer, and reuse as feedstock, orbital data centers could become a driver within the in-space circular economy.

3.2. Project Finance Transition

A critical aspect to scale the circular space economy is the evolution of funding models. Currently, the industry relies heavily on high-cost venture capital and private equity, which is not well-suited for the longer time horizons and heavy capital requirements associated with orbital

infrastructure development. For the circular space economy to scale, companies need access to lower-cost, longer-term financing. That requires moving beyond venture capital toward project-finance models supported by predictable service contracts, where customers pay for infrastructure services rather than owning the infrastructure themselves.

It was highlighted at the seminar, that this evolution requires shifting away from speculative equity rounds to debt-based financing supported by predictable cash flows. By utilizing long-term, fixed-price contracts, often anchored by government procurement, companies can de-risk their operations and attract lower-cost capital from institutional investors. This shift allows payload developers to focus on core technology while specialized service providers handle the deployment, logistics, and operational maintenance of the orbital assets.

Seminar participants discussed the potential role of tax incentives, grants, public loans, anchor customers, service-based infrastructure, and longer-term project-finance models in supporting capital-intensive orbital infrastructure. Building on these discussions and experience from other U.S. infrastructure sectors, policymakers should evaluate whether additional mechanisms, such as direct loans, loan guarantees, or tax incentives, are appropriate as orbital infrastructure matures.

3.3. Market Incentives

Deposit-refund systems were proposed for satellites to manage the risks of orbital congestion and ensure responsible end-of-life management. Drawing on terrestrial examples, such as can and bottle deposit-return programs that substantially increase recycling rates, a similar framework could be adapted to encourage end-of-life management of space assets. These systems could provide financial incentives for companies to verify that their assets have been properly deorbited or transferred to a designated recycling facility at the end of their functional life. The motivation of these incentive structures aims to mitigate the risk of Kessler Syndrome [17], a scenario where the density of orbital objects triggers a cascade of self-sustaining collisions that could render specific orbits unusable. This framework effectively transforms a potential orbital liability into a tradable asset, incentivizing the recovery of high-value mass for the circular economy.

3.4. Economic Advantages of Microgravity Manufacturing

Although manufacturing in space for Earth may fall outside the in-space circular economy framework introduced in Section 1, it is the primary focus of NASA's In-Space Production Applications (InSPA) portfolio [18]. InSPA is specifically intended to demonstrate and commercialize advanced materials and products manufactured in low-Earth orbit for terrestrial markets. The technical and commercial success of these projects is helping to establish the infrastructure, operational experience, and market confidence needed to support the transition toward manufacturing in space for space and a more circular space economy.

3.4.1. Improved Manufacturing Yield

One seminar participant reported that, for a specific specialized crystal growth process involving semimetal-semiconductor composites, the material yield is low under terrestrial processing conditions and could potentially approach 90 % under microgravity conditions. Although application-specific, this example illustrates how improved yield could help offset the cost of orbital manufacturing. This significant increase in efficiency demonstrates how in-space products are the economic foundation for the orbital industrial base. These products provide the high-margin revenue needed to support a self-sustaining ecosystem. In addition to improved yield, the profitability of enhanced material performance and device performance demonstrates further financial justification for the high initial capital expenditures required for space infrastructure.

3.4.2. Improved Product/Material Performance

As discussed by seminar participants, the absence of gravity-induced convection and sedimentation allows the production of materials difficult to achieve on Earth. By eliminating the turbulence and settling of materials that naturally occur in Earth's gravity, manufacturers can produce advanced materials such as compound semiconductors [19] and exotic fiber optics [20] with improved properties compared to terrestrial fabrication.

Beyond materials, microgravity was also highlighted as an opportunity for biopharmaceutical production and biomedical research. Reduced buoyancy-driven convection and sedimentation can support the growth of more uniform crystals with higher yields compared to terrestrial approaches. This is advancing drug development, formulation, and delivery [21]. Microgravity is being used to enable the production of biomedical products. A significant example is protein-based implants such as LambdaVision's artificial retina [22]. Microgravity conditions promote scaffold-free tissue formation representing a methodology for regenerative medicine [23]. Although the commercial production of organoids and engineered tissues in space remains an emerging field, these applications were identified as potentially high-value markets for future orbital research and manufacturing.

4. Physical and Digital Infrastructure

A circular space economy requires persistent physical and digital infrastructure that enables materials, energy, data, and services to circulate rather than lose their value at the end of a single mission. Seminar participants emphasized that orbital platforms should be components of an interconnected system analogous to terrestrial ports, transportation networks, utilities, and communications infrastructure. Within this system, servicing hubs, modular platforms, logistics networks, and power generation enable circular activities, such as reuse, repair, manufacturing, recycling, and life-cycle management.

Various key physical infrastructures were discussed, including on-orbit servicing hubs, modular platforms, manufacturing facilities, power generation, and storage systems. Digital infrastructure was also identified as a requirement for coordinated operations. A central insight from the seminars was that circularity requires persistence; ‘end of mission can no longer be end of life’. The shift from designing isolated spacecraft to enduring architecture was repeatedly identified as a key to building a circular space economy.

4.1. Reuse, Repair, and Servicing Infrastructure

The connection between infrastructure and circularity is direct, reuse and repair require infrastructure to enable them. This is highlighted through a historical lens, considering the Space Shuttle and the Hubble Space Telescope. From 1993 to 2009, the Space Shuttle was the key infrastructure that enabled repair/servicing of Hubble [24,25], shown in Figure 3. The missions enabled continued operation and improved performance beyond the telescope’s original baseline. While the Shuttle/Hubble interactions were crewed activities, fully autonomous servicing was demonstrated in 2007 with DARPA’s Orbital Express, performing refueling activities that extended the life of a satellite [24,25]. The Shuttle/Hubble and Orbital Express are examples of critical infrastructure that enables circularity within the space ecosystem.



Figure 3: Corrective Optics prior to its installation into the Hubble Space Telescope. Image Credit NASA (public domain) [26].

Autonomous service infrastructure was highlighted as a commercial technology to support orbital life extension. DARPA’s Robotic Servicing of Geosynchronous Satellites (RSGS) Program was discussed, which can assist, inspect, correct, and install payloads on geosynchronous satellites currently in orbit [25,27], as outlined in Table 2. This platform has missions planned for 2026 [28], enabling satellite repair rather than abandonment. Commercial companies are also pursuing the satellite life extension market [29]. This has been forecasted as a multibillion-dollar industry by the 2030’s [30], representing a significant opportunity of the in-space circular economy.

Table 2: Core Capabilities and Strategic Goals of the DARPA RSGS Program (Adapted from the U.S. Naval Research Laboratory and DARPA)

Operational Mission Capability	Primary Technical & Economic Enablers
Cooperatively <u>Assist</u> with Orbital Adjustments	Rescue, relocation, satellite retirement, fuel-use deferral, and dynamic space operations
Cooperatively <u>Inspect</u> Spacecraft Experiencing Anomalies	Attribution and diagnostics via orbital survey and ultra-close inspection
Cooperatively <u>Correct</u> Mechanical Problems	Recovery of lost or damaged spacecraft (characterized by a low occurrence rate, but a very high payoff)
Cooperatively <u>Install</u> Self-Contained Payloads On-Orbit	Component upgrades, technology refreshes, mission adaptation, and operational augmentation
Note: The overarching strategic goal of the RSGS program is to create a dexterous robotic operational capability in Geosynchronous Orbit that can both provide increased resilience for the current US space infrastructure and be the first concrete step toward a transformed space architecture	

Building upon servicing infrastructure, scalable modular platform concepts were discussed as supporting an in-space circular economy. The advantage of modular architecture is that it extends beyond life-extension activities and can also support other technologies/infrastructures, such as in-space manufacturing (e.g., crystal growth, biomanufacturing, and welding). It was emphasized that spacecraft should be designed with standardized interfaces to allow them to accept new payloads or subsystems after launch [31] transforming them from single mission infrastructure into multi-use adaptable platforms. This need is being addressed by CONFERS through its mission to support the in-space servicing community by promoting interoperability and advancing voluntary consensus standards. See Section 2.4 for more discussion on standards.

In the near term, modular autonomous platforms will be especially important because they can provide repeatable access to hosted payloads, manufacturing environments, technology demonstrations, and logistics services during the transition from International Space Station (ISS) operations to fully mature commercial Low Earth Orbit (LEO) destinations. By enabling payload refresh, subsystem replacement, servicing, repair, and reuse, these platforms can help move orbital infrastructure away from single mission designs and toward adaptable assets that retain value across multiple missions and customers. Furthermore, the addition of uncrewed

architecture will enable the in-space manufacturing economy to develop toward commercial scale.

4.2. Infrastructure to Support Recycling

Recycling requires infrastructure for capturing, storing, and processing. Space debris capture robots were highlighted as a promising technology to support the in-space circular economy. A recent successful technology demonstration was discussed that captured and released an object 170+ times in microgravity aboard the ISS [32]. The seminar also explored whether in-space recycling would follow a just-in-time manufacturing model or require dedicated storage infrastructure. This is analogous to terrestrial salvage yards or material depots to stage materials prior to processing. Related to depot infrastructure, further concept development and debate was recommended while minimizing collision probability and the risks associated with the Kessler Syndrome [17].

Beyond capture and storage, reprocessing architectures were identified as critical to advancing in-space recycling. A Modular Space Foundry [33] was presented as an example of technology scheduled to fly a demonstration on the ISS in 2026. Key challenges to enable these technologies include the lack of gravity, no crew maintenance, no historical precedent for orbital foundries, and material handling in a vacuum. Complementary processes, such as friction-stir additive manufacturing, were also discussed [34]. These can produce metallic materials through solid-state processes, rather than fully melting material. Collectively, these technologies point towards an industrial layer where capture, staging, and reprocessing function together to transform end-of-life components into resources within a circular space economy.

In addition to the technical challenges associated with orbital foundry operations, two foundational infrastructure constraints were identified: logistics and power. Space lacks the equivalent of terrestrial “roads and trucks” that enable routine transport. Seminar speakers discussed that while some payload delivery/return pathways exist, high-volume material transport, and current launch architectures, do not yet support continuous bidirectional flow of payloads and recovered materials between Earth and orbit [35]. While a mature circular system should function predominantly within orbit, current architectures require bidirectional logistics between Earth and space, underscoring the importance of scalable transportation infrastructure during transitional phases. Energy infrastructure presents an equally significant constraint. Material reprocessing/refining and manufacturing are inherently power-intensive. Industrial recycling in orbit cannot operate at scale without scalable systems for power generation, storage, and distribution. Together, logistics and energy systems form the backbone upon which capture, storage, and reprocessing architectures must rely for a viable circular space economy.

4.3. The ISS Transition and the Future of Orbital Infrastructure

ISS has functioned as the primary orbital infrastructure platform for maturing many of the technologies required for a circular space economy. While the ISS is not a fully circular industrial system, it incorporates subsystem circularity through closed-loop water recovery, oxygen regeneration, and solar power generation. As was quipped during the seminar, on the ISS

“yesterday’s coffee is today’s coffee,” alluding to the station’s closed-loop water recovery system. The seminars highlighted that the circularity principles implemented in space and on the ISS were not driven by environmental stewardship, as is often assumed from a terrestrial perspective. Rather, they come from the economic and logistic realities of operating in a resource-constrained environment. This logic highlights why circular principles will be critical as the commercial space economy develops. More critically, the ISS has provided persistent power, robotics, and logistics that have enabled numerous technologies to be demonstrated in a space environment. These demonstrations form the technological foundation upon which future servicing, repair, recycling, and manufacturing architecture will depend.

As discussed at the seminar, the planned 2030 retirement of the ISS could represent a significant juncture for orbital infrastructure. As outlined in a NASA whitepaper [36], options such as uncontrolled re-entry, disassembly, boosting to a higher orbit, and transitioning to a commercial operator were considered. Ultimately, a targeted deorbit into a remote ocean using a deorbiting vehicle, planned for launch in 2028, was identified as the most viable path due to the ISS’s structural complexity and international governance requirements.

While a 2018 assessment [37] found no feasible industry proposals for a commercial takeover of the station, seminar speakers indicate that the current landscape has evolved. The maturation of the space economy and increased entrepreneurial capacity suggest that previous barriers, such as engineering interfaces, intellectual property, and data, may now be more surmountable. During the seminar, it was emphasized that, given the escalating geopolitical competition and the need for a continuous U.S. presence in LEO, ensuring a transition to commercial LEO destinations is essential to avoid a significant capability gap.

It was discussed at the seminar that current market dynamics and the emergence of high-margin manufacturing (as discussed in Section 3.4) may require a re-evaluation of the 2030 deorbit timeline to better align with commercial return-on-investment horizons. Although a controlled deorbit remains the baseline, preliminary analysis indicates that the primary U.S. Orbital Segment could support operations beyond 2030 [36] if commercial alternatives are not yet mission ready. Seminar participants emphasized that maintaining infrastructure continuity is paramount to providing the stable environment necessary for the long-term growth of the circular industrial base.

4.4. Cybersecurity

Operations such as refueling, servicing, material transfer, and debris capture require close physical proximity between spacecraft. Consequently, any compromise of navigation, authentication, command, or data systems poses direct threats to the target asset as well as the broader orbital environment. Cybersecurity was identified as a foundational requirement for the physical and digital infrastructure supporting on-orbit operations. As space systems become increasingly interconnected, circular space economy activities will depend on secure communications and trusted command-and-control networks. Seminar participants emphasized

that, as the growing need for threat intelligence, vulnerability assessment, intrusion detection, secure software architectures, authentication, access control, and information sharing across both ground-to-space and space-to-space networks. The Space ISAC was highlighted as an important public-private mechanism for identifying, evaluating, and communicating threats to space systems through its vulnerability laboratory, watch center, and information-sharing activities (see Section 2.4 for more discussion about the Space ISAC). Seminar participants emphasized that commercial space operations increasingly adopt service-oriented business models, cybersecurity must be incorporated into infrastructure design. Secure and resilient digital infrastructure will be essential for establishing trust among operators, customers, regulators, and insurers within an in-space circular economy.

5. Materials Science and Manufacturing Innovations

Leveraging materials science and manufacturing innovations is critical for the transition from a linear to a circular space economy. Speakers in the seminar series emphasized that the current model for designing, launching, using, and disposing of space assets cannot meet the long-term needs of the commercial space sector. Transitioning to a circular system capitalizes on the inherent value of materials, components, and systems, beyond their first mission. This shift relies on both materials science and manufacturing innovations.

5.1. Designing for Circularity

A paradigm shift in design philosophy is required for space applications. Circularity must be considered at the beginning of the design process. Traditional materials and component design have prioritized performance, with reuse or recycling as an afterthought or even neglected entirely [38]. However, speakers argued that, given the high launch costs and limited resources in space, materials/components should be designed with clear plans for future use.

Several participants emphasized that early progress toward circularity comes from relatively simple design choices, such as standardizing components, interfaces, and materials, as discussed in Section 2.4. Standardized interfaces, ports, and connectors support modular component design, making it easier to reuse, replace, or repurpose space hardware. Materials standardization was also discussed as a potential strategy. Limiting the number of materials incorporated into a design simplifies future recycling or material recovery efforts by reducing the complexity of separation and/or processing. However, this approach is inherently limited by the material property and performance requirements that dictate material selection for space hardware.

Recognizing the limitations of material standardization, participants also identified the concept of a “materials passport” as a possible tool for future circularity. Analogous to a material traveler, which is used in traditional manufacturing to document material specifications, processing history, and inspections, a materials passport would extend this record across the full life cycle of space hardware. In this model, hardware would carry a digital record of its material composition and processing history. This information would inform future reuse, recycling, or extraction activities.

5.2. Feedstock to Support Circular In-Space Manufacturing

In-space manufacturing was framed as a key enabler of a circular space economy because it could reduce dependence on terrestrial supply chains and support repair, modification, and replacement activities. Given the early stage of this topic, industry designs for circularity can be incorporated early. Both man-made in-orbit materials and in-space resource utilization were identified as potential feedstocks for in-space manufacturing; however, these two resource

classifications have different timelines, legal issues and logistics. Speakers identified three core value propositions related to in-space manufacturing:

- producing materials or products that cannot be made on Earth,
- improving responsiveness by avoiding relaunch, and
- using resources already located in space rather than transporting everything from Earth.

Speakers emphasized that manufacturing capability must be paired with feedstock processing. The CisLunar Industries Modular Space Foundry [33] was presented as one step toward orbital materials processing, using contactless manipulation and autonomous operation to address microgravity conditions. Remaining challenges include material handling in vacuum, refractory degradation, limited maintenance access, logistics, and high-power requirements. Lunexus described approaches for capturing defunct satellites, extracting usable materials, and preparing them for orbital manufacturing. These pathways shift away from the traditional linear material usage model to one based upon more circular principles.

6. Activities to Facilitate an In-Space Circular Economy

The transition from a linear to a circular space economy requires deliberate, coordinated action across public and private sectors to convert strategic intent into a functioning orbital marketplace. Based on the discussions from the seminar series, several priority activities and operational pathways have been identified to guide stakeholders toward building a resilient, closed-loop industrial base in space.

6.1. Incorporate Circularity into Design Requirements

A fundamental requirement for the implementation of a space circular economy is a systemic shift in how space hardware is engineered before launch. Traditional space engineering prioritizes initial performance metrics, frequently treating end-of-life disposal or recovery as an afterthought. To facilitate circularity, design decisions must incorporate end-of-life reclamation, servicing, and material recovery from the conceptualization phase onward. Initial industry steps can leverage practical mechanisms, such as component and material standardization, to simplify servicing, repair, reuse, and recycling. Deploying digital tracking systems, such as ‘materials passports’, across an asset’s lifecycle will provide future servicing and recycling platforms with the structural and chemical composition data required to safely execute orbital recovery and manufacturing processes. These offer approaches to evaluate the entire lifespan of a product or project, from raw material extraction to manufacturing, distribution, use, and end-of-life disposal.

6.2. Harmonize Policy and Regulatory Frameworks

Commercial implementation remains constrained by the lack of clear authorization pathways for non-traditional on-orbit operations. Transitioning from fragmented, functional licensing models toward unified, mission-based authorizations was identified by participants as an important milestone for reducing investor and insurance risk. Furthermore, addressing the legal status of defunct assets, including their salvage for reuse, and space debris under current interpretations of the Outer Space Treaty was also identified as important. Developing authorized legal pathways, such as permission-based salvage registries, bilateral title-transfer agreements, or formal licensing regimes, could enable commercial operators to lawfully collect and process legacy or orphaned hardware, effectively transforming orbital debris into manufacturing feedstock.

6.3. Create Early Demand and Attract Investment

To scale the orbital industrial layer, the space sector must overcome the high upfront capital expenditures associated with persistent infrastructure. Government entities could help de-risk the market by acting as early anchor tenants or service buyers, transitioning from hardware ownership to service-based contracts such as purchasing delivered propellant volumes or active debris removal outcomes. Participants also noted that government support, such as tax credits and grants, could help incentivize commercial activities. In addition, participants also discussed

whether circularity requirements are appropriate for government procurements as a mechanism for influencing the market transition. These early mechanisms create the necessary demand and evidence required to shift commercial space funding from high-cost speculative venture capital to lower-cost, long-term project finance.

6.4. Develop an Integrated Implementation Strategy

The transition to an in-space circular economy will require a coordinated implementation strategy that aligns technical development, policy, standards, finance, insurance, infrastructure, market formation, and workforce development. No single organization or stakeholder group can create this ecosystem independently. Progress will depend on government agencies, commercial companies, investors, insurers, standards organizations, hubs and consortia, academic institutions, and international partners advancing complementary activities toward shared outcomes.

A strategy should identify the principal workstreams, clarify their dependencies, and establish an appropriate sequence for implementation. Early activities should include developing common terminology, identifying priority policy and standards gaps, defining credible use cases, and establishing measurable demonstration objectives. These efforts can enable interoperable demonstrations, generate evidence of technical and commercial dependability, support customer and insurer confidence, and create the conditions for larger-scale private and public investment. Over time, the strategy could support routine servicing, repair, reuse, ownership transfer, logistics, material recovery, and recycling as economically sustainable elements of space operations.

That implementation should be iterative rather than fixed. Stakeholders should establish shared milestones, regularly evaluate technical and market progress, identify emerging gaps, and adjust priorities as capabilities mature. Seminar participants argued that the goal should not be to impose a single centralized plan, but to coordinate otherwise fragmented efforts so that advances in policy, technology, standards, capital, infrastructure, and demand reinforce one another. The stakeholder roles described below in Section 6.5 provide a framework for executing this shared strategy.

6.5. Call for Stakeholder Actions

Building a persistent orbital ecosystem is inherently an urban-planning effort in space, requiring coordinated advances across technology, policy, law, finance, standards, and market development. No single stakeholder group can provide all these capabilities. Progress therefore requires a coordinated division of roles among government agencies, commercial industry, hubs and consortia, and academic and research institutions, with each group contributing distinct but interdependent capabilities to a shared implementation strategy. The seminar series' discussions identified several stakeholder actions necessary to advance an in-space circular economy. The following sections summarize these perspectives.

- **Government Agencies:** While governments can help create the conditions in which a circular space economy can develop, they cannot do it alone. Its role includes providing

regulatory clarity, acting as an early customer, supporting measurement science and voluntary consensus standards, enabling demonstrations, sharing appropriate data and infrastructure, reducing first-of-a-kind financial risk, and coordinating policy with international partners. These actions should be designed to enable private investment and commercial innovation while protecting safety, security, sustainability, and the public interest. Government roles include:

- using their respective authorities and missions to accelerate development of the circular space economy by acting as early service buyers and anchor customers through funded procurements, demonstration missions, and long-term service contracts;
- examining legal and regulatory barriers associated with debris management and other circular activities; and
- streamlining regulations to continue aiming for "light-touch" regulation to prevent bureaucratic hurdles from slowing innovation.

Entities such as NIST and the Office of Space Commerce are well-positioned to support the development of standards, advance measurement science, provide space situational awareness, and establish predictable regulatory pathways to foster global competitiveness, furthering capabilities for the technical, security and economic aspects of a circular space economy.

- **Commercial Industry:** Commercial industry will play a central role in translating circular space technologies from demonstrations into economically viable business models and markets. Commercial actors must identify paying use cases, translate demonstrations into repeatable services, design for interoperability and lifecycle value, generate the operational evidence needed by customers and insurers, and develop business models that can attract sustained private capital. For example, space operators and hardware developers should:
 - pivot toward modular spacecraft architectures and adopt voluntary consensus standards, and
 - establish specialized service models in which logistics, transportation, refueling, power, and other supporting functions are provided by dedicated operators.

Both of these activities will allow commercial entities to focus on their specialized activities, rather than expecting every company to own and operate every part of its orbital supply chain.

- **Hubs and Consortia:** Hubs and consortia can play a critical role in reducing coordination costs across a fragmented ecosystem and provide neutral forums for resolving issues that no single company or agency can solve independently. Seminar participants highlighted that coordination among consortia should be encouraged so that overlapping organizations complement and reinforce one another rather than duplicate efforts.
 - Hubs and consortia should convene stakeholders across sectors to:

- coordinate shared priorities,
- establish common terminology,
- align roadmaps,
- accelerate precompetitive collaboration, and
- support the development and adoption of interoperable standards, and best practices.

- **Academia and Research Institutions:**

Academic and research institutions can contribute to the development of an in-space circular economy by:

- Targeting translational research that helps bridge critical TRL gaps and overcome the “valley of death” between laboratory research and commercial deployment.
- Seeking technology transfer opportunities that enable successful laboratory innovations to transition toward commercial deployment.
- Providing independent measurement, testing, validation, economic and policy analysis, product-qualification methods, and neutral evidence that helps technologies cross the gap from research to commercial adoption.
- Prioritizing workforce development.
- Expanding access to test facilities and specialized research infrastructure to accelerate technology development and validation.
- Given the interdisciplinary nature of the circular space economy, success will depend on cross-disciplinary collaboration that breaks down traditional research silos and integrates expertise across fields.

7. Conclusion

Hosted jointly by the Office of Space Commerce and NIST, the Building an In-Space Circular Economy seminar series brought together stakeholders across industry, academia, and government through both in-person and virtual participation. This series explored critical opportunities and challenges facing sustainable space operations while providing actionable frameworks for an emerging orbital industrial base.

Core sessions highlighted breakthroughs in emerging technologies, including sustainable satellite design, in-orbit recycling, and robotic repair and manufacturing. Participants examined novel policy strategies for managing shared space resources and pinpointed vital areas requiring standardized material management guidelines. Furthermore, the event accelerated commercial collaboration by bringing together investors, researchers, and space sector professionals to evaluate business models and funding mechanisms for on-orbit servicing and manufacturing.

A key measurable outcome of this collaborative effort is the creation of the Circular Space Economy Special Interest Group (SIG) under the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) [39]. Developed directly out of the seminar discussions, the SIG is dedicated to developing foundational principles, core definitions, and official position papers to shape the circular space economy.

Ultimately, building a circular space economy is essential to ensuring long-term operational sustainability and securing U.S. industrial competitiveness in orbit. By aligning regulatory frameworks and establishing measurement science foundations, the Department of Commerce and its partners are laying the groundwork for a persistent, scalable, and resilient space industrial base.

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Appendix A. Seminar Agendas

February 13, 2025

<https://www.nist.gov/news-events/events/2025/02/seminar-building-space-circular-economy>

Opening Remarks by Event Chairs • <i>Dianne Poster, Senior Advisor, NIST, Office of Space Commerce</i> • <i>Carolyn Pace, Space Policy Analyst, Office of Space Commerce</i>
Keynote – Government LEGOS: Building a Supportive Policy Framework for In-space Servicing, Assembly, and Manufacturing • <i>Gabriel W. Swiney, Director, Policy, Advocacy, and International Division, NOAA Office of Space Commerce</i>
Roundtable – The Circular Economy in Space • <i>Moderator: Rob MacPherson, Rogue Space Systems Corporation</i> ○ <i>John Roth, University of New Hampshire</i> ○ <i>Joe Pawelski, Cislunar Industries</i> ○ <i>Matt Cunningham, Lunexus space</i> ○ <i>Olivia Gámez Holzhaus, Rhodium Scientific</i>
Moderated Panel - Emerging Technologies for the In-Space Circular Economy • <i>Andrew Iams, NIST, Discussion Leader</i> ○ <i>David Barnhart, Arkisys</i> ○ <i>Andrew Parlock, Space Phoenix</i> ○ <i>Bernie Kelm, Naval Center for Space Technology</i> ○ <i>Rick Rasansky, XCMR</i> ○ <i>Scott Zweibel, Stoke Space</i>
Moderated Panel – Recycling and Life Cycle Management • <i>Moderator: Jeff Burton, NOAA Office of Space Commerce</i> ○ <i>Kyle Cybul, Clean Orbit Foundation (now Institute for a Resilient Space Economy)</i> ○ <i>Edward Tate, Virtus Solis</i> ○ <i>Kelsea Schumacher, NIST</i>
Special Presentation – National LEO Science and Technology Strategy Updates • <i>Christie Cox, International Space Station Division Utilization Manager, NASA Headquarters</i>
Closing Keynote – Industry Perspectives & Looking Ahead • <i>Jon Beam, Rogue Space</i>
Wrap-Up and Closing Remarks • <i>Dianne Poster, Senior Advisor, NIST, Office of Space Commerce</i> • <i>Carolyn Pace, Space Policy Analyst, Office of Space Commerce</i>

August 27, 2025

<https://www.nist.gov/news-events/events/2025/08/second-seminar-building-space-circular-economy>

Opening Plenary Session

- **Event Welcome & Introductions - Chairs**
 - *Dianne Poster, Senior Advisor, NIST, Office of Space Commerce*
 - *Carolyn Pace, Space Policy Analyst, Office of Space Commerce*
- **Welcome Remarks**
 - *Stephanie Hooker, Associate Director, Material Measurement Laboratory, NIST*
 - *Gabriel Swiney, Director, Policy, Advocacy and International Division, Office of Space Commerce*
- **Keynote - Finance Models and Resource Utilization**
 - *Aaron Ratner, Investor, Kingston Infrastructure Partners; Senior Advisor, The Extraterrestrial Mining Company*
- **Keynote - Blueprint for an In-Space Circular Economy**
 - *Kyle Cybul, Co-Founder, Clean Orbit Foundation (now Institute for a Resilient Space Economy)*
- **Moderated Plenary Q&A**

Special Presentation: How NASA Will Deorbit the ISS

- *Jacob Keaton, Senior Policy Advisor in the International Space Station Division, NASA*

Roundtable - Hubs and Consortia for Developing the In-Space Circular Economy

- *Moderator: Jon Beam, Cofounder, President, and Chief Strategy Officer, Rogue Space*
 - *Greg Richardson, COSMIC Executive Director, Principal Engineer, Civil Systems Group, The Aerospace Corporation*
 - *Steve Putna, Director, Texas A&M Semiconductor Institute, Chips in Space Consortium / TAMUS*
 - *Brian Lagana, Executive Director, CONFERS*

Moderated Panel - Balancing Supply and Demand for a High Growth and Resilient In-Space Circular Economy

- *Moderator: Anna Brady-Estevez, Founding Partner, American DeepTech*
 - *Troy Morris, Co-Founder and CEO of KMI*
 - *Mari Anne Snow, CEO and Co-founder, Eascra Biotech*
 - *Kevin Engelbert, InSPA Portfolio Manager, International Space Station (ISS) Research Integration Office, NASA*
 - *Andrew Parlock, Founder and CEO, Space Phoenix Systems*

Moderated Panel - Advanced Materials and Manufacturing in a Circular Space Economy

- *Moderator: Andrew D. Iams, Materials Research Engineer, Materials Science and Engineering Division, Materials Measurement Laboratory, NIST*
 - *Gary B. Rodrigue, President, Allbright Consulting*
 - *Rose M. Hernandez, Chief R&D Strategist, JavaroTech*
 - *Partha S. Dutta, Chief Technologist, United Semiconductors, Professor Emeritus, Electrical, Computer and Systems Engineering Department, Rensselaer Polytechnic Institute*
 - *John T. Roth, Director, John Olson Advanced Manufacturing Center, Professor in the Mechanical Engineering Department, University of New Hampshire*

Technical Presentation - Circular Economy of Space Economics

- *George Pullen, Chief Economist, MilkyWayEconomy*

Closing Keynote - Perspectives on Challenges, Current Activity, and a Pathway to the Future

- *Greg Richardson, COSMIC Executive Director, Principal Engineer, Civil Systems Group, The Aerospace Corporation*

Closing Remarks

- *Dianne Poster, Senior Advisor, NIST, Office of Space Commerce*
- *Carolyn Pace, Space Policy Analyst, Office of Space Commerce*

Appendix B. List of Symbols, Abbreviations, and Acronyms

AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
ANSI/NISO	American National Standards Institute / National Information Standards Organization
BIS	Bureau of Industry and Security
CAPEX	Capital Expenditures
CEO	Chief Executive Officer
CONFERS	Consortium for Execution of Rendezvous and Servicing Operations
COSMIC	Consortium for Space Mobility and ISAM Capabilities
DARPA	Defense Advanced Research Projects Agency
DDTC	Directorate of Defense Trade Controls
DOC	Department of Commerce
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
ISAC	Information Sharing and Analysis Center
ISAM	In-Space Servicing, Assembly, and Manufacturing
ISS	International Space Station
ISO	International Organization for Standardization
InSPA	In-Space Production Applications
LEO	Low Earth Orbit
MML	Material Measurement Laboratory
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NTIA	National Telecommunications and Information Administration
OSC	Office of Space Commerce
R&D	Research and Development
RSGS	Robotic Servicing of Geosynchronous Satellites
SC	Subcommittee
TAMUS	Texas A&M University System
TC	Technical Committee
TraCSS	Traffic Coordination System for Space
TRL	Technology Readiness Level
U.S.	United States