R&D and Manufacturing in Space BLUprint

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Acknowledgement

Manufacturing in space is not an upcoming technological dream or possibility, but a present day reality, the need of which arose to achieve conditions that could either be not achieved simultaneously or sustainably while keeping the processes economical.

These conditions serve not a niche range of products but a wide range of materials including pharmaceutical drugs, semiconducting crystals, superconducting alloys, quantum materials, optical fibres, protein crystals, aerogels, etc.

I want to acknowledge the invaluable contribution of **Jainam Singhvi** on this thesis in analysing the in-space manufacturing industry to cover all important aspects like investment opportunities and risks, technological and scientific developments, applications, and use-cases.

If you are a founder, researcher or stakeholder in space manufacturing and would be interested to chat more about our work or discuss yours, feel free to reach out at **akhilesh@blume.vc**

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Terrestrial production is not favorable in many cases…

Manufacturing advanced materials on ground while ensuring high purity and quality lacks a conducive environment due to several factors including the force of gravity and the presence of gases.

These are the primary factors that hinder the production of high-purity, high-quality advanced materials on Earth

- **Sedimentation**
- **Contamination**
- **Convection**

- **Oxidation**
- **Buoyancy**
- **Hydrostatic Pressure**

Source: NASA, Journal of Manufacturing and Materials Processing (MDPI), National Centre of Biotechnology Information

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…because the hidden physics quietly sabotages material quality

Of the six mentioned, Sedimentation, Convection and Buoyancy and Density Driven Segregation are the major factors that hurdle high quality terrestrial manufacturing of pharmaceutical drugs and advanced materials used in the production of superalloys and semiconductors.

Sedimentation: The downward migration of solid particles through a fluid under gravity.

Sedimentation in pharmaceutical mfg occurs when solid particles - active pharmaceutical ingredients (APIs), excipients, or stabilizers settle out of suspension under gravity.

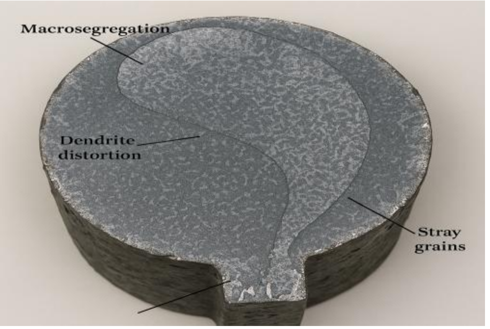
This causes non-uniform concentrations in mixing tanks, vessels, or dosage forms, so early portions may have higher API levels than later ones, risking efficacy and patient safety.

Convection: The bulk movement of fluid driven by density differences, usually due to temperature gradients.

In Czochralski (CZ) growth (for producing silicon crystals), hotter, less-dense fluid rises at the center while cooler fluid sinks near the crucible walls.

This uneven convective flow distributes dopant atoms irregularly, so wafers cut from different boule regions show variable resistivity, lowering device yield.

Buoyancy: The upward force on an object immersed in a fluid, equal to the weight of the displaced fluid.



In the production of superalloys, lighter alloying elements rise and heavier species sink and macrosegregation bands form.

This causes uneven γ′-phase strengthening and crack-initiation sites that erode creep and fatigue life.

Source: NASA, ESA, NASA PSI, ISS National Lab Research, NIST Advanced Manufacturing Series

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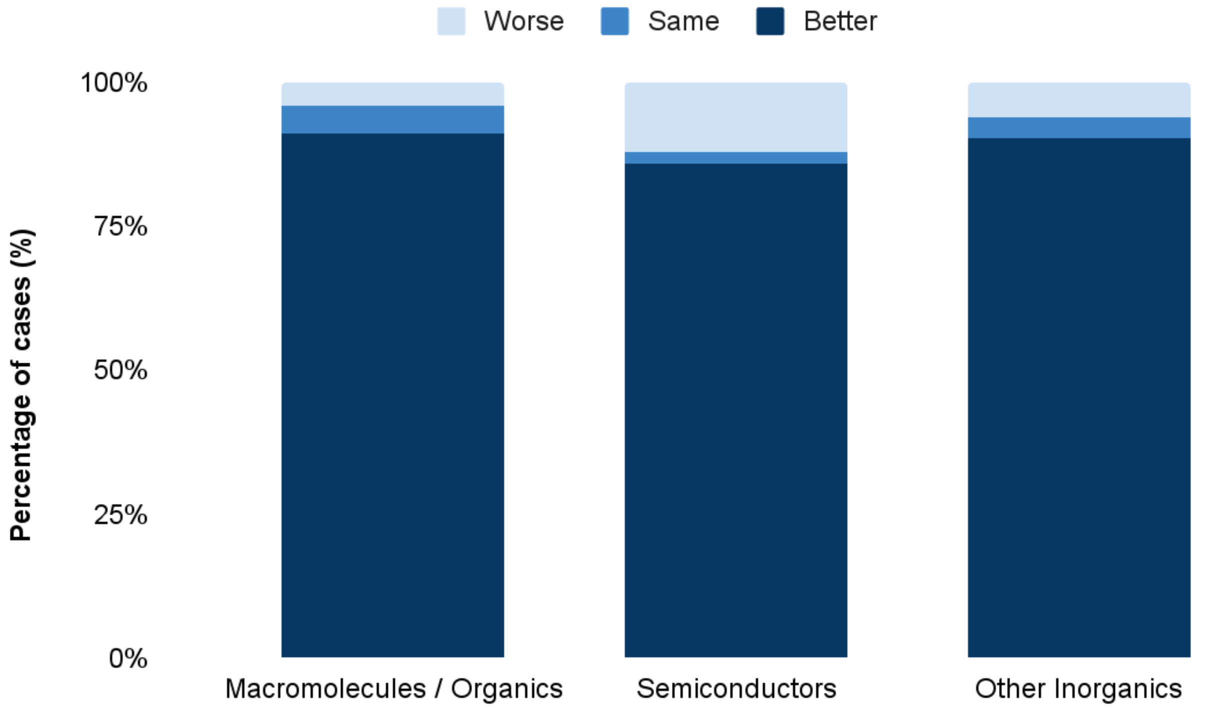
Space provides a set of conditions…

Microgravity tremendously enhances the output quality, as compared to terrestrial versions, of various categories of advanced materials including macromolecules, semiconductors and other inorganics as observed by Butler University with the ISS's inSPA initiative.

Microgravity consistently improves crystal quality across material classes



Over **90%** of macromolecules, semiconductors, and inorganic crystals grown in space show measurable improvements in size, uniformity, or performance

Benefits of microgravity

In microgravity, owing to the absence of hydrostatic pressure and elimination of buoyancy driven convection and sedimentation, melts, solutions and suspensions can solidify or crystallize purely ensuring better precision, material structure and uniformity.

This leads to:

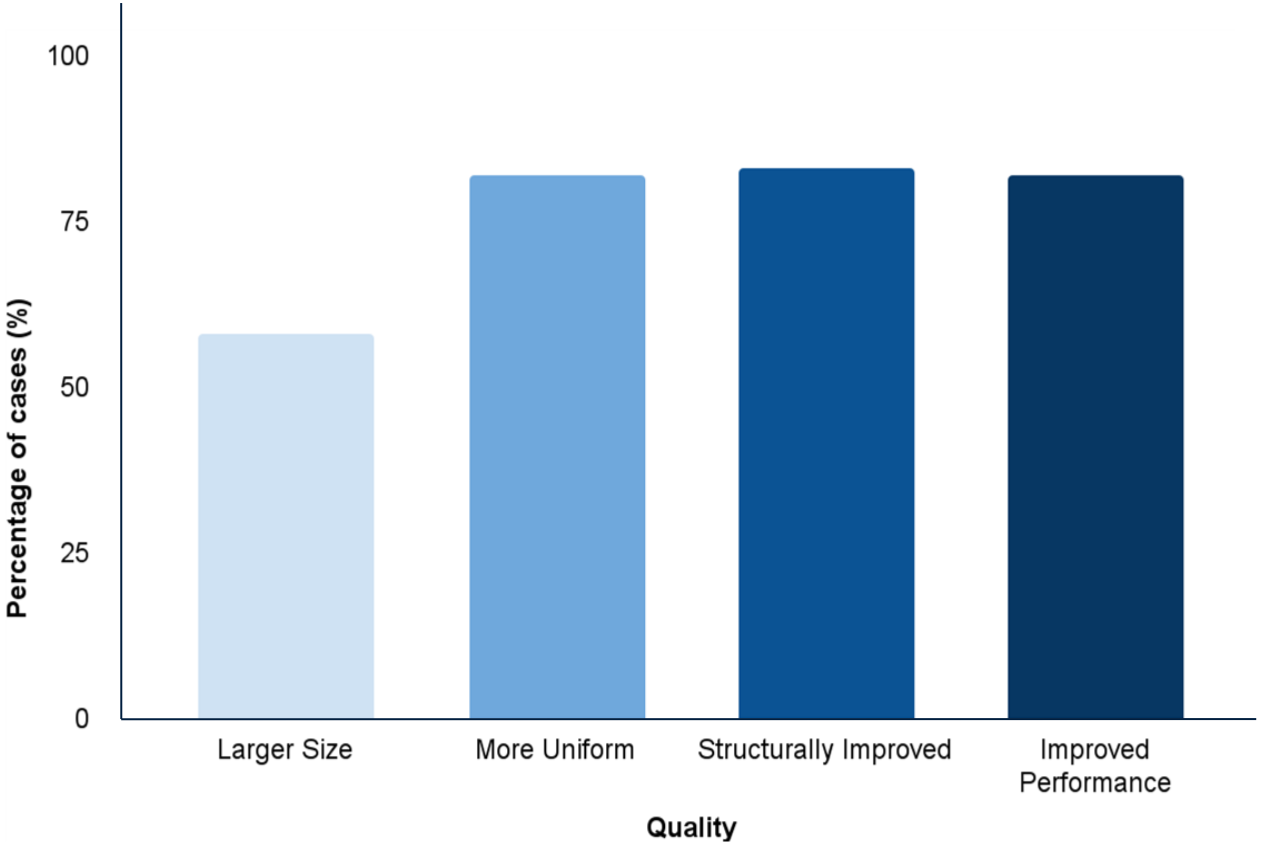
- Uniform crystal growth, with far fewer dislocations or grain boundary defects (critical for semiconductors, optical crystals, protein lattices)
- Homogeneous composite structures, since particles or reinforcing phases don't settle or float

Source: NASA & ISS National Lab inSPA, FactoriesinSpace, MDPI

…conducive to high quality production of advanced materials…

Vacuum eliminates oxidation, porosity, and contamination, hence unlocking pristine surfaces and structurally superior crystals essential for next-gen electronics, optics, and coatings

Increase in quality of semiconductor crystals in vacuum



Why better quality in vacuum?

Hard vacuum eliminates atmospheric contaminants, preventing oxidation and porosity to yield ultra pure, defect free materials - alloys, semiconductor crystals, etc. It ensures uniform, convection free heat transfer producing consistent microstructures and high performance coatings. Examples:

- Metals, semiconductors and optical glasses grow with pristine, uncontaminated surfaces crucial for high-efficiency electronics and low-loss photonics
- Precise vapor transport growth, where reactants travel unimpeded over long distances, enabling high-quality single crystals and aerogels

Source: Blume Research

…and nearly unattainable simultaneously on ground

Earth can only mimic microgravity or vacuum for moments, but space offers both continuously and naturally

1 Microgravity

- On Earth infrastructure includes drop towers, parabolic flights, sounding rockets, suborbital vehicles, etc
- However, the zero-gravity environment in these survives only for seconds to a maximum of a few minutes.
- Most protein and semiconductor crystals, owing to the slow kinetics, grow at rates that require continuous microgravity environment for tens of thousands of seconds to fully suppress convection and sedimentation, which these non orbital infrastructure fail to provide

2 Vacuum

- Ultra high vacuum (UHV) chambers and industrial vacuum systems are the source for vacuum on earth
- These sources not only cost extremely high to build but have severe operational costs as well
- Besides, even the most advanced terrestrial chambers suffer from contamination from residual gases, outgassing from walls and tiny leaks and permeations
- In LEO, this build of ambient atoms (mostly oxygen) is much slower, conducive to the production of advanced materials

Achieving both, microgravity and hard vacuum, on earth individually is already challenging but bringing them together is a complexity which has not been built for enough yet.

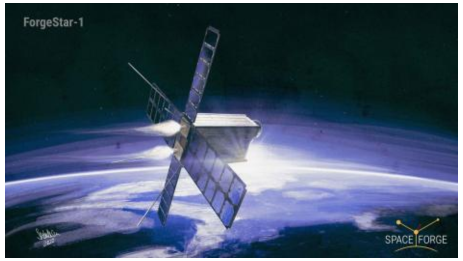
For a near zero gravity vacuum environment, there exist only a few devices - vacuum drop towers (eg. ZARM drop tower), suborbital vehicles etc. which, too, have similar limitations to those of the infrastructure providing microgravity and vacuum individually.

Source: ESA, Airbus, NASA, Universität Bremen, MDPI

Infrastructure for space manufacturing

The major infrastructure being actively worked on include - Free Flying Capsules (independent satellites), Space Station Based Modules (attached to a space station, currently the ISS), Upcoming Commercial Space Stations.

Free Flying Capsules



These satellites (capsules) orbit around the Earth freely while materials are manufactured inside it.

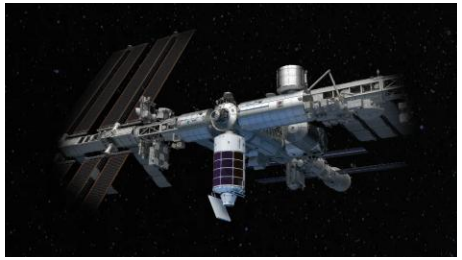
After the production, these capsules prepare themselves for reentry into the atmosphere without the need of another launch vehicle, softly landing on the surface.

Space Station Modules

Procurement & encapsulation of raw materials; integration with launch vehicle; docking with the space station for the core manufacturing process.

After the production, return to Earth via a reentry capable vehicle. Majorly meant for R&D.

Commercial Space Stations



It is an upcoming infrastructure for R&D and commercial production of advanced materials.

The processes are expected to be similar to the modules currently aboard the ISS, the difference being the scale of production.

Source: Blume Research, FactoriesinSpace

Breaking down the value chain of space manufacturing

Each step in the chain adds cost and risk, players who streamline logistics and own critical nodes (launch, in-orbit processing, or re-entry) will shape the economics of space manufacturing.

On Ground Operations	Launch & Orbital Placement	Manufacturing Execution	Product Readiness & Reentry
Design and engineering of manufacturing infrastructure (capsule or station modules), Procurement and encapsulation of raw materials, integration with launch vehicle	Launched into space via launch vehicles either as primary or secondary payload. Deployment of capsule/station module into the orbit (for station module, berthing with the station is needed too)	Execution of the core manufacturing process - Process monitoring, control, and in-situ quality checks; Internal handling & storage of finished products	For capsule - initiate de-orbit, reentry, and soft landing. For station modules - package finished goods into a return vehicle which would bring them back to Earth

Source: Blume Research

Realising the scale of the opportunity

Falling launch costs + scalable space infrastructure = space made materials poised to become a multi-billion-dollar market.

Pharmaceutical

- Advanced crystalline drugs cost millions per kilogram and their high quality production, due to terrestrial hurles, is hindered
- Varda recently manufactured extremely pure Ritonavir in space which can cost thousands of $ per kilogram
- Pembrolizumab, a cancer drug, is being considered for in space manufacturing and it can cost anywhere between $50m and $100m per kilogram
- In, 2024, sales of Keytruda (Pembrolizumab) were more than $20bn

Optical Fibres

- Owing to gravity driven convection, optical fibre production was tested in space. In 2024, 11.8 km of ZBLAN optical fibre cable was manufactured in space by Flawless Photonics
- These cost of these cables can range from hundreds of thousands to millions of $ per km of length
- NASA’s In Space Production Applications program is now supporting a new preform manufacturing experiment by Flawless Photonics, Australia’s University of Adelaide, Axiom Space and Visioneering Space

Semiconductor

- Semiconductors are not being mass produced currently but extensive R&D has been conducted over the past few years with the results being highly conducive to shift to space for large scale production
- Major companies like Intel showing interest in the possibility of space production
- Several materials for semiconductors have been produced in space like Silicon, Gallium Arsenide, Indium Phosphide, etc

Other Advanced Materials

- Several startups are developing infrastructure for the in space manufacturing of advanced materials and processes like 3D bioprinting, metal additive manufacturing, ceramics manufacturing, etc
- Notable efforts are being put in for the scalable production of certain aerogels (some of which cost millions) and quantum materials

Source: NASA, ISS National Lab, InSPA, FactoriesinSpace

Part 1: Free Flying Capsules

Free Flyers: Deeper into the manufacturing process

In depth picture of the pre, core & post manufacturing processes of a free flying capsule. The flowchart follows the manufacturing of majorly crystalline materials (semiconductor crystals, pharmaceutical drugs, etc.) which most free flyer startups are aiming to manufacture in space.

Preparation of Buffer Solution

Integrating the solution into the flyer

Other on ground operations

Pre-Launch Operations

Launch & Orbital Placement

In Microgravity, Solutions mix without Convection & Sedimentation

Slow solvent evaporation through a membrane - Supersaturation achieved

Maintaining right temperatures, usually cooling to let crystals grow slowly and evenly

Core Manufacturing Process

On growth completion - washing solvent replaces mother liquor and removes surface impurities

Washed and dried crystals packaged into protective vials

Prepare for reentry

Atmospheric reentry and soft landing on ground

Terminology

Nucleation: first step in the formation of a new phase (the first tiny bits of a crystal in a solution)

Buffer Solution: The solution that contains the active pharmaceutical ingredient (API) and other solutes to be crystallized

Mother Liquor: Liquid that remains after the crystals are harvested from the buffer solution (Buffer solution which could not be crystallized)

Source: Blume Research

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VARDA
SPACE INDUSTRIES

Foundation and Investments

Founding year: 2021
Funding: >$300m
Stage: Series C ($187m latest round)
Location: United States
Investors: Khosla Ventures, Lux Capital, Founders Fund, Caffeinated Capital, etc

About

Varda Space Industries designs and builds autonomous orbital laboratories that primarily manufacture pharmaceuticals in microgravity

Major Features

- Full mission operations and experimental controls from ground based facilities
- On Earth, sample recovery, handling and analysis via a full suite of analytical testing capabilities
- Re-enters the Earth's atmosphere at speeds above Mach 25 offering a real flight environment for hypersonic reentry vehicle subsystems testing
- Planning monthly reentry cadence by 2026

The W - Series

Varda's W - Series capsule is an autonomous free-flying microgravity formulation platform intended for terrestrial landing.

It has a payload capacity of tens of kilograms and plenty of area for TPS (for testing purposes)

Source: VardaSpaceIndustries

SPACE FORGE
MAKING SPACE WORK FOR HUMANITY

Foundation and Investments

Founding year: 2018
Funding: A total of $42m
Stage: Series A ($30m latest round)
Location: United Kingdom
Investors: Innovate UK, World Fund, SpaceFund, Type One Ventures, etc

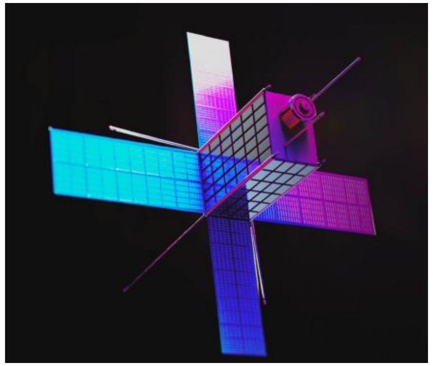
About

Space Forge focuses on developing reusable on orbit fabrication capabilities to enable the novel production of semiconductors, alloys, and pharmaceutical drugs in microgravity

Major Features

- Placed in an SSO between 500 & 800 km
- 10x launches annually - reusable and returnable
- Return / Soft landing anywhere on Earth directly from space
- Offer both - Pressurised as well as Unpressurised manufacturing
- 60% reduction in energy consumption (operating in W, not kW)
- 15 tonnes of CO_2 prevented per KG manufactured by Space Forge

ForgeStar



ForgeStar is the manufacturing satellite (Free Flyer) by Space Forge.

Each vehicle consists of an orbital module and a microgravity capsule, operating at an altitude of 480 km for a period of one to six months

Source: SpaceForge

Part 2: Station based modules

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Into the process: Station Based Modules

Station based modules are the testbeds of space manufacturing – where automation and standardized racks de-risk early experiments before scaling to commercial flyers.

1. **Formulation prep on Earth** Protein solution, bioinks, or stem cell suspensions are prepared

2. Payloads are then packaged in **standardized form factors.** (Eg. CubeLab (Space Tango): 4U, 8U, or 16U size, like a shoebox)

3. Container loaded into a **cargo spacecraft** (SpaceX Dragon, Northrop Grumman Cygnus, Sierra Space Dream Chaser in future) and launched into the orbit

4. Astronauts transfer payloads into the **ISS lab module** where commercial racks are installed. The **crew's involvement is minimal** they just insert the payload. Everything else is automated

5. Once integrated, **ground control remotely operates the module**

6. The **core manufacturing processes** of Pharmaceutical APIs, semiconductor and protein crystals, etc. are almost similar to that in free flying capsules

7. Once the manufacturing is complete, astronauts **remove the completed payload** (crystals, fibres, tissues etc.) and **pack into return stowage**

8. **Return to Earth:** payloads are loaded into a return capable spacecraft (Eg. SpaceX Dragon) and returned to Earth

Source: NASA, ISS National Lab, Blume Research

REDWIRE

Foundation and Investments

Founding year: 2020
Funding: >$100m via PIPE
Location: United States
Investors: No traditional VC funding, It's a public company now

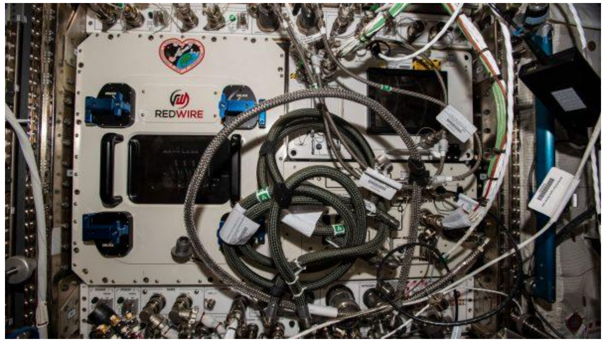
About

Redwire Corporation is a leader in space manufacturing with a strong focus on tissue bioprinting, semiconductors, pharmaceuticals, superalloys, ceramics and also, space farming

Major Features

- First 3D bioprinter in space
- 9 facilities aboard the ISS for the manufacturing of advanced materials.
- Building Microgravity Semiconductor Technology Innovation Centre (MSTIC) for autonomous high performance semiconductor manufacturing in space.

Redwire's Modules



Redwire Space has multiple R&D facilities aboard the ISS - 3D Biofabrication Facility (BFF), Additive Manufacturing Facility (AMF), Ceramics Manufacturing Module (CMM), Fibre Optics Facility, etc

SPACE TANGO

Foundation and Investments

Founding year: 2014
Funding: >$5m
Stage: Not known
Location: United States
Investors: NASA Award (most investors not publicly disclosed)

About

Builds and operates automated micro gravity R&D/manufacturing hardware (TangoLab, CubeLab, TangoBox). Focus on Stem Cell, Tissue Chip and Organoid Platforms.

It also offers Volumetric Additive Manufacturing & 3D Bioprinting Platforms

Major Features

- Permanent ISS facilities (TangoLab)
- All platforms are highly automated, needing minimal astronaut handling support
- Custom Design Aspects: Pressurization, Spectrometry, Spectrophotometry, Electrical Stimulation etc.
- Thermal Control: Individual, discrete component control from 4C to 37C

The CubeLabs

CubeLab is a standardized, modular research unit (in 1U, 2U, 4U and 9U). It is a plug and play mini laboratory that fits within the TangoLabs rack on the ISS for R&D of advanced materials

Source: SpaceTango, Blume Research

Comparing Capsules & Station Based Modules

Space manufacturing will likely follow a two-step path where modules propel R&D, and flyers fuel the commercial scale.

	Flyers	Modules
Payload capacity	10s of kilograms	Grams to a few kilograms
Major purpose	Mass production of advanced materials	R&D to identify possibilities of mass production
Logistics cost	1 way *(but heat shield for re-entry costs extremely high)*	2 way *(launch and return vehicle cost)*
Delivery	Lot of startups provide a soft landing / delivery option as per the client needs	Return vehicles usually have a fixed return site *(SpaceX dragon splashes down in water bodies in US)*
Dedicated environment	Flyer environments are customised per mission needs or specific material requirements	As most missions are rideshare, spacecraft environments are generalised for all payloads
Mission flexibility	High *(on demand)*	Low *(rideshare missions)*
Automation	Almost completely automated (excluding manual ground stations for controls)	Most modules are plug-and-play, but crew must transfer them from the launch vehicle to the rack
Scaling path	Increased fleet size and more number of launches / missions	Integrating more racks on the ISS or other upcoming commercial space stations

Source: NASA, InSPA, Blume Analysis

Global Startup Activity

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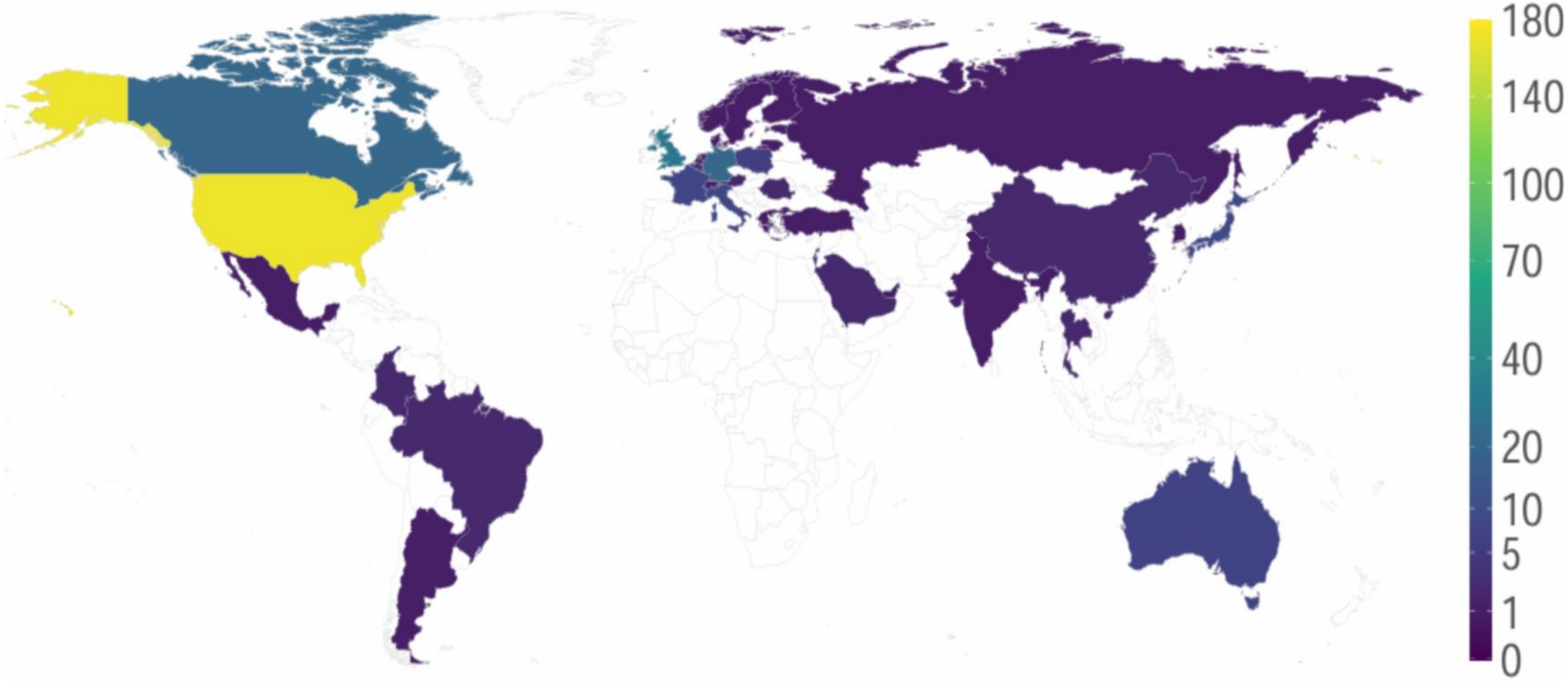
Global startup activity

Over the last decade, there have been over a billion $ invested, across the globe, in companies building infrastructure for manufacturing in space.

Number of In-Space Manufacturing Startups *(as of mid 2024)*

Investments

- Axiom Space: >$400m
- Varda Space Industries: >$300m
- Redwire Space: >$100m
- Space Forge: >$40m
- Space Pharma: >$25m
- Elevation Space: >$16m
- Space Tango: >$5m



The volume of advanced materials and companies that manufacture them which could meaningfully benefit from in-space manufacturing is significant. Startups operational currently, can serve only a small fraction of the total need. This gap is likely to attract many new entrants and significant capital inflow in the near future.

Source: FactoriesinSpace, Blume Research

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Indian Startups

founded in **2024**, Serendipity Space has raised a pre-seed round.

founded in **2024**, Inbound Aerospace has raised approximately $1m in pre-seed funding.

Serendipity Space aims to produce materials and products of superior quality compared to the ones on Earth, using the microgravity assist, kickstarting the industrialization of LEO.

They are building reusable satellites with re-entry capability, that can bring payloads back from space to earth.

Inbound Aerospace is focused on providing a spacecraft platform that utilizes the microgravity environment of space to manufacture products that impact and improve the lives on Earth.

Their recoverable spacecraft platform enables customers to conduct in-orbit technology demonstrations and microgravity experiments, accelerating their product development timelines.

founded in **2024**,Catalyx Space has raised over $7m with the latest Series A round

Catalyx Space mentions building the AWS for Space, the fastest and cheapest way anyone can deploy new solutions into orbit and bring them back.

They are working in the direction of full vertical integration - from the tip of the rockets (deployers) to spacecraft to data (ground stations).

Learnings for upcoming startups

We spoke to these founders and here are some of their words of wisdom

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India is witnessing unprecedented ambition in the space sector. In-space manufacturing as an industry has taken off. The convergence of falling launch costs and commercial breakthroughs that have happened on the ISS due to microgravity over the past three decades, makes it the perfect time for kickstarting the production of high value materials in orbit.

The strategic importance of this industry for India is two-fold: **kickstarting a materials revolution**, and **providing the economic incentive** to sustainably explore outer space. Microgravity provides a unique environment with a "gravity off-switch" to either produce novel materials that are not possible on Earth or enhance the quality of existing materials. These materials already have gigantic terrestrial markets, be it pharmaceuticals, fiber-optics, semiconductors or metal alloys. At Serendipity Space, we are building reusable satellites that can produce novel pharmaceuticals in space and bring them back to Earth, opening up an entirely new portfolio of drugs to treat diseases such as cancer, Alzheimer's and others.

The technologies to keep the space industry alive and thriving already exist, as we have reusable rockets, satellites that can mine asteroids, and also spacecraft that can take humans to the moon and back. What's in its infancy is an economic flywheel that justifies and accelerates the exploration of outer space. In-space manufacturing can produce materials that can be continuously consumed terrestrially, creating a market that produces the demand of regular cadence to LEO and back to Earth.

For the in-space manufacturing industry to mature and produce venture scale returns, there are some necessities: **regular and low-cost cadence to space**, sufficient **risk capital** and **regulatory nimbleness**. We shall need multiple launch vehicle companies providing weekly trips to space and fearless individuals who back young teams with the necessary capital to go out and capture that value. It goes without saying that regulatory bodies also need to approach this industry with optimism, agility and support for the ambitious startups trying to make this vision a reality. From the founders' side I believe that early customer engagement is an absolute necessity to go after the right use case and the right technology to solve it, as that will determine the scale of innovation that can produce unbridled differentiation and value.

All the founders and backers thinking about this industry should remember the words of Edwin Land, the founder of Polaroid, **"Don't undertake a project unless it is manifestly important and nearly impossible."**

Antariksh Parichha
Co-Founder & CEO – Serendipity Space

Our team at Inbound aerospace is in the business of building reusable spacecraft platforms to enable long duration microgravity research and in-space manufacturing, and we're bullish on the potential of in-space manufacturing, especially from India. We understand that, at least initially, a majority of our in-space manufacturing customers would be from the west, specifically the US and European markets. Although, we were surprised to learn that big pharma from the US seems to have been more keen on using the potential of microgravity to develop the next blockbuster drug than their counterparts in Europe. This is surprising, given that Europe had equal uninterrupted access to the long duration microgravity environment on the International Space Station (ISS).

When we look at the same problem from an Indian lens, we anticipate that there will be some hesitance on the part of the big pharma players or researchers on the potential of this strange new environment. But, we're playing the long game here. While Indian researchers and Industry did not have the same access to the ISS as their western counterparts, the fact that the recent Axiom-4 mission which took our own astronaut, Group Captain Shubhanshu Shukla to space and allowed him to perform seven experiments in microgravity, combined with plans to build our own space station by 2035, has really accelerated public knowledge and perception of this unique environment.

We should know, when we tried to explain the term microgravity before the Axiom-4 mission, we would usually be met with a confused "What?". But now, there is an immediate recognition of the term. It's not all rosy though; space is an expensive destination, and has been ever since it has been accessible to us. This is in-spite of pioneers like SpaceX bringing down the cost of access significantly. What has successfully worked in the US are federal government organisations like the ISS National Laboratory (ISSNL) heavily subsidizing the cost of building experiment hardware, sending it to the ISS and bringing it back. We have no doubt that there needs to be an equivalent organization in India to subsidize the cost of access, at least to get the ball rolling, before the industry can maintain momentum on its own. Whether this access is through our platform or our competitors', the ecosystem benefits as a whole regardless. That being said, we like to think of ourselves as the shovel sellers in the microgravity gold rush. Keep digging.

Vishal Reddy
Co-Founder – Inbound Aerospace

Insights and Learnings from Global Founders

People under-appreciate that it's not just the launch cost, there're flight computers, batteries, mission operations etc. Maturity of the low cost supply chain for all these components is actually a bigger lever than launch cost alone.

Just because drugs are so expensive and because microgravity has such a significant impact on that chemistry, the first 300 things are drugs.

~ Will Bruey, Varda Space Industries

To truly realize the full potential for space exploration, innovation must change the economics.

~ P. Cannito, Redwire Space

Business in orbit requires a longer time to mature than software, data, or AI startups do, and can take between eight and ten years to go public; it requires a lot of patience and patients.

~Yossi Yamin, SpacePharma

Meet our author

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Blume Ventures is among India's leading early-stage venture funds, investing in tech led ventures across sectors. We are presently investing out of our US $290m fund IV. We are sector agnostic investors and typically invest through Seed to Series A stages with a preference to come in early.

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Thank you!

While we are thesis driven, we are also open to questioning and changing our views as we learn from founders and the market. If you have any feedback on this thesis, or would like to push back on any view, please reach out!

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