Microgravity Game Changers: Recent Accomplishments of Microgravity Assisted Experiments on the ISS

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This paper discusses important new materials, devices and technology produced in low-Earth orbit (LEO) that have been developed with funding from NASA's In Space Production Applications (InSPA) Portfolio. In coordination with the International Space Station (ISS) National Laboratory, InSPA supports innovative small businesses and other research & development organizations to develop microgravity-assisted applications that make significant impacts in a wide variety of industries on Earth. These technology development efforts are using the microgravity of orbital space to overcome gravity-induced defects on Earth to create high-value products for terrestrial markets in the areas of semiconductors, pharmaceuticals, and communications. Through 24/7/365 operation on ISS for 25 years, coupled with commercial space transportation and services to, in, and from orbit, the microgravity environment has enabled pioneering science and significant commercial applications, including novel medical advances. World-leading researchers, innovators, and space payload developers provide compelling evidence through demonstrations on the ISS that materials processing in microgravity improves outcomes for a wide range of materials and products at all levels of the organization of matter, from quantum entities such as Bose-Einstein condensates, to crystals, alloys, composites, thin films, and photonics, to stem cells, medical diagnoses, medical treatments, and medical devices for humans. As of 2026, numerous examples proved by demonstration on ISS show the potential of these technologies in various fields. In this paper, a summary of four important experiments is discussed.

I. Nomenclature

ISS = International Space Station
ISSNL = International Space Station National Laboratory
LEO = low-Earth orbit
InSPA = In-Space Production Applications
ZBLAN = Heavy metal fluoride glass composed of: **Z**irconium Fluoride, **B**arium Fluoride, **L**anthanum Fluoride, **A**luminum Fluoride and **N**atrium (Sodium) Fluoride.
MSG = Microgravity Sciences Glovebox
TRL = Technology Readiness Level

II. Introduction

The ISS National Lab is the first national laboratory beyond Earth [1]. It was chartered by Congress in 2005 to manage 50% of the United States R&D resources of the International Space Station (ISS). Complementing the basic research enabled by the ISS National Lab, NASA, through the ISS and Small Business Innovation Research (SBIR) programs, funds the In Space Production Applications (InSPA) Portfolio as the bridge from the laboratory in space to Earth markets [2]. The goals of NASA's InSPA are threefold: (i) to serve U.S. national interests by developing materials and technologies that strengthen industry leadership and national security, and create high-quality jobs, (ii) to provide benefits to humanity by developing products that significantly improve the quality of life for people on Earth, and (iii) to accelerate development of the orbital space economy by stimulating demand for scalable and sustainable non-NASA utilization of future commercial orbital destinations,. Since the beginning of 2024, InSPA awardees have been reporting exceptional results at an unprecedented rate. These results are critical for the Earth applications that serve

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as the primary objective of InSPA. Other U.S. government agencies that have shared interests are helping NASA to interpret these new findings and confirm the extraordinary results.

III. In Space Production Applications (InSPA) and microgravity assisted experiments

As illustrated in Figure 1, the InSPA Portfolio serves as a critical bridge across the "valley of death" for new technologies entering the middle zone of the Technological Readiness level (TRL) life cycle. It is important to acknowledge that the highly successful InSPA applications are built on the discoveries and knowledge of many predecessor efforts by NASA, including basic space research in materials science and biosciences, conducted since the Apollo-Skylab era in the 1970s, continuing through 30 years of the Space Shuttle era, and extending more than 25 years on the ISS. The United States, Russia, and Japan have provided much of the foundational knowledge, with China, India and other nations joining as new players in recent years. To an unprecedented degree, 21st century space development for Earth applications and markets is being pioneered by small businesses. Nearly half of all InSPA projects were started as SBIR projects, with successful awardees receiving SBIR Phase III funding in the form of InSPA Phase 1 awards. Other InSPA funds have been provided to US innovators through a NASA Research Announcement (NRA) NNJ13ZBG001N: Research Opportunities for International Space Station Utilization), with awards made on the basis of technical merit, feasibility, impact to the United States, and business cases. InSPA's objective is to enable microgravity demonstration of materials and devices that significantly impact future high-tech industries, as well as medical advances for some of humanity's most devastating medical conditions. Microgravity materials advances are expected for semiconductors, alloys, photonics, quantum applications, and medical devices and treatmeents. In many cases, these microgravity advances have the strong potential to fundamentally alter or replace existing terrestrial manufacturing approaches with space-assisted product development.

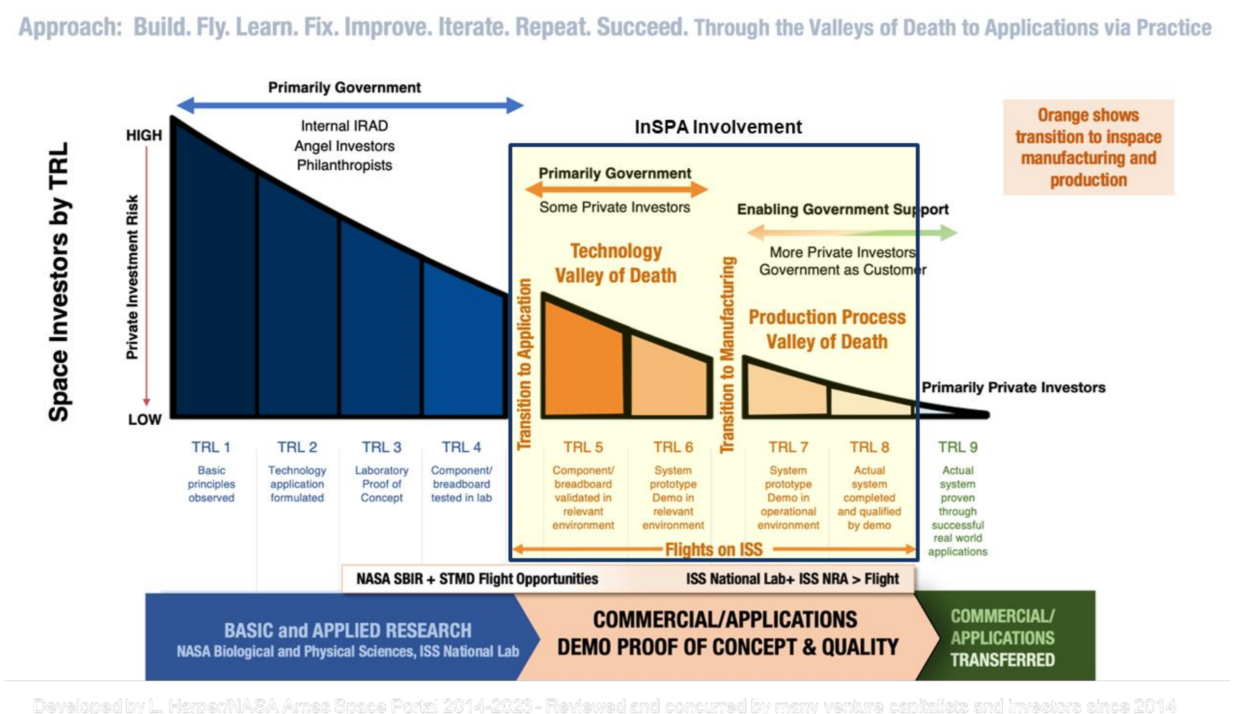

Figure 1. The InSPA funding model. This chart shows which investors fund research and development based on NASA's Technology Readiness Level (TRL), which traces advances from discovery to market/application. The X-axis shows TRL level. The Y-axis shows risk of failure to the investor. InSPA is one of the few government programs that invests in US innovators who use microgravity to develop important products from space for Earth, through technology's "Valley of Death" (TRL 4-9).

When defects at the atomic and molecular level matter, microgravity can often produce superior yields of superior products better, cheaper, and faster than can be accomplished on Earth. Microgravity has delivered significantly better yields of significantly superior products important for life saving advances, life enhancing medical devices, and high tech industries. Some of these advances are game changing – not just in space, but also on Earth. Since 2024, microgravity-assisted experiments have seen exceptional results with significant impacts [14]. These technologies are being produced in space for Earth markets and medicine by important new players, mostly from small businesses. Microgravity is improving the production of high-value materials and products at all levels of the organization of matter. By 2026, numerous examples have shown the potential of these technologies in various fields. Some of these results are illustrated in Figure 2. While most of the focus in LEO is on supply-side space transportation and commercial LEO destinations, this paper emphasizes the value of the demand-side payloads essential for successful commercial space development. In a mature LEO economy, payloads pay for commercial space transportation and in-space services.

Important characteristics of microgravity enabling new opportunities in manufacturing include absence of buoyancy, sedimentation, convection, hydrostatic pressure, and "containerless" processing [3]. The microgravity environment can enable superior quality, performance, and yields of a wide range of materials and devices, including biomaterials and medical devices. Microgravity processing enables unique structures, novel medical information, superior microstructure, significant reduction in defects, and superior uniformity. Microgravity improves homogeneity, orientation and stability of materials. According to a study by Butler University, growing crystals in microgravity has yielded superior results in more than 80% of more than 500 crystals grown in space since 1973 in ways that are important for high-tech and biotech industries. Microgravity's positive effects on surface tension and thin films, together with the high quality of crystal formation, enables precision and qualities that are not possible to achieve on Earth. Other advances include the formation of unique and longer lasting Bose-Einstein condensates in space near absolute zero [4] the development of new amorphous materials [5] as well as pioneering cell and tissue projects with extraordinary medical applications.

Improvements are being observed at all levels of the organization of matter, from subatomic particles to intact biological systems. The improvements are important to our national health, national wealth, and national competitiveness. NASA has seen evidence of exceptional performance consistently in these areas for decades, but it was the 24/7/365 operation of the ISS that allowed many of these advances to take place, especially in recent years. Research has now moved decisively toward applications that are important today and will become more so in the future as market demands push materials and products to achieve higher performance.

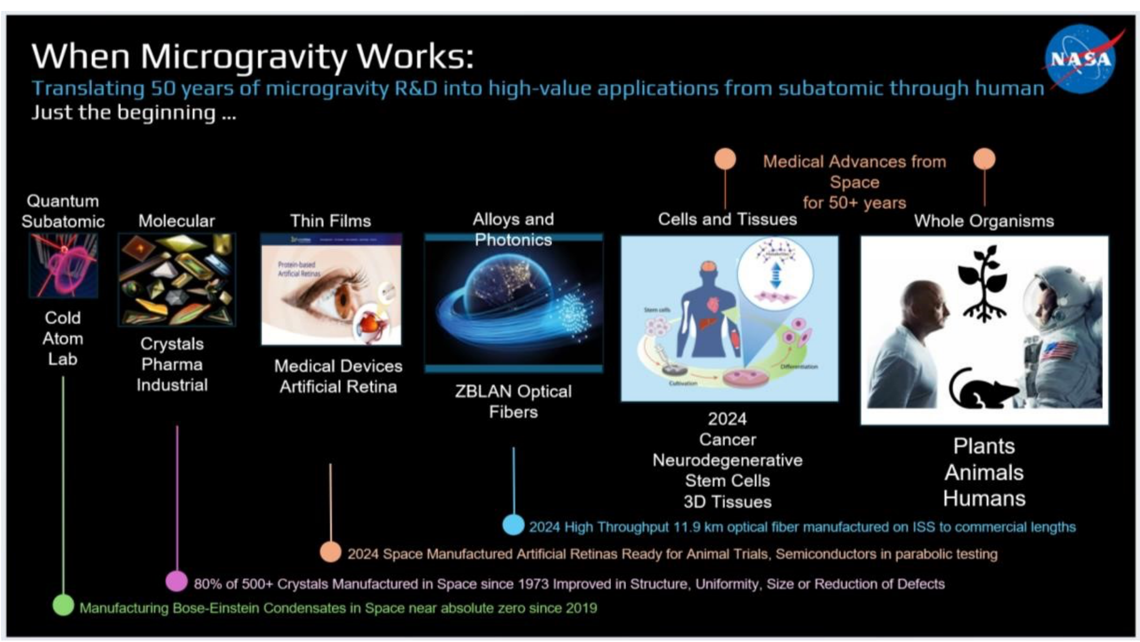

Figure 2. Results from microgravity experiments supported by InSPA have led to a wide range of "space assisted" products for high-value terrestrial applications. It is expected that these results will both increase and improve with experience and practice in microgravity.

IV. Selected Accomplishments

Examples of extraordinary results in materials processing are highlighted in the following sections. These results are historic firsts.

A. Crystal Growth and Material Growth

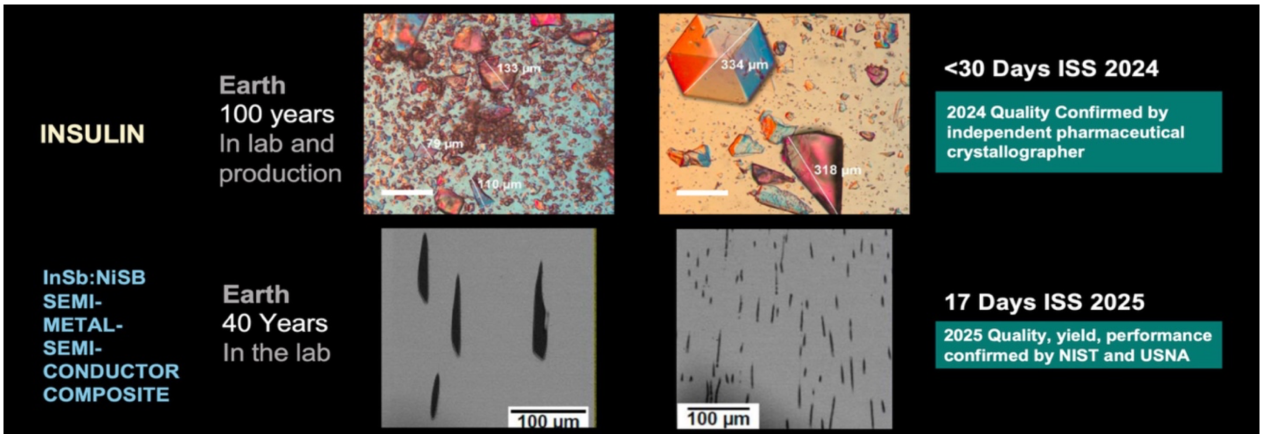

Figure 3. **The impact of microgravity on crystal growth.** The top row shows insulin and typical crystal quality after 100 years of effort on Earth (left). After just 30 days of effort on the ISS (right), exceptional crystal structural quality and size were achieved. The bottom set shows a semimetal-semiconductor composite material (InSb:NiSb). Even after 40 years of iterative effort to form this material on Earth, results were poor (left). After just 30 days on ISS, semiconductor composites with superior yield and microstructure were achieved (right). Results confirmed by NIST and USNA.

More than 500 crystals have been grown in space and reported in the scientific literature [5]. A single ISS hardware test flight in 2024 produced best-in-class insulin crystals, surpassing in size and quality more than 100 years of Earth-based effort. Similarly, United Semiconductor LLC proved by demonstration on ISS that InSb:NiSb semimetal – semiconductor composites showed exceptional microstructure and unique properties when processed in microgravity, as well as superior yields and superior performance in devices, opening important new opportunities for advanced electronics. Independent third parties have validated the quality and properties of this space manufactured composite compared with best on Earth (NIST and USNA). Eli Lilly confirmed the insulin quality.

B. Artificial Retina from Lambda Vision

LambdaVision from Connecticut [7] along with the implementation partner Space Tango from Kentucky demonstrated extraordinary control of the in-space manufacturing processes necessary to deliver 200 alternating layers of exceptional quality conductive polymer and bacterial rhodopsin assemblies to be used as artificial retinas [8]. LambdaVision and Space Tango have accomplished this several times on orbit, confirming their level of control. Confirmation of superior quality has been performed by independent experts. Currently, LambdaVision is working to scale up production in preparation for clinical trials in 2027-2028.

C. High Performance Optical Fiber

Microgravity can significantly impact the growth of amorphous materials such as ZBLAN. ZBLAN is a type of heavy metal fluoride glass (HMFG) used in many mid-infrared laser applications. It is composed of five elements with different densities that makes terrestrial manufacturing challenging: **Z**irconium Fluoride (ZrF_4), **B**arium Fluoride (BaF_2), **L**anthanum Fluoride (LaF_3), **A**luminum Fluoride (AlF_3) and **N**atrium (Sodium) Fluoride (NaF). ZBLAN glass is pulled into optical fibers used in optical communications, defense, and medicine, with potential high-tech applications supporting quantum technologies. In 2024, sponsored by the ISS National Lab, Flawless Photonics, the University of Adelaide, and implementation partner Visioneering Space (CA/Luxembourg/Australia/Utah) demonstrated and benchmarked the first commercial scale manufacturing in space. Apsidal LLC (CA) and implementation partner Axiom Space (TX) also demonstrated superior qualities of space manufactured ZBLAN in a separate project on ISS. Using the ISS Microgravity Science Glovebox (MSG), Flawless Photonics' microgravity optical fiber manufacturing system *"Excalibur"* was the first to produce commercial lengths of ZBLAN fiber in space.

In 9 out of 16 manufacturing runs on the ISS, the lengths of space manufactured ZBLAN fiber exceeded the best known commercial terrestrial runs recorded on Earth. Flawless Photonics produced 11.8 kilometers of optical fiber in space over 16 days [9,10]. To achieve this record in space, Flawless Photonics had to shrink the operations of a 30-foot ZBLAN fiber draw system on Earth down to ~30 inches to fit inside the MSG. Operating remotely through time delays and signal loss, the team had to heat, pull, and wind fragile hair-thin ZBLAN fibers with exceptional precision.

Flawless Photonics drew more than a kilometer of fiber in a single in-space manufacturing run 3 times, with the longest single length measured at 1,141 meters. Postflight analysis of the fibers by two separate labs showed an average of 5 to 10X improvement in attenuation over Earth manufactured fiber under the same conditions with the same hardware. Flawless Photonics' initial results revealed that their space grown fiber was about 2x stronger than terrestrial fibers, a finding also confirmed by Apsidal. This opens the door to wealth generation and manufacturing operations in LEO not only with ZBLAN as the trailblazer glass, but also many other lucrative formulations of specialty glasses for high tech applications whose production and quality are also constrained by gravity. This was the first proof by demonstration in space that microgravity processing can deliver superior yields of unique products at commercial scales. This was the first flight by the Flawless Photonics team. The fiber quality and length are expected to improve with more experience and practice in space processing.

D. "Small Molecule" Polymorphs of Pharmaceutical Crystals from Redwire and Butler University.

Many important pharmaceuticals are "small molecules" (under 1000 g/mol). In many cases, different crystalline forms of the same drug—termed polymorphs—must be considered to optimize drug stability, solubility, absorption and pharmacodynamics.

In a benchmark study on the ISS, Redwire and Butler University investigated the effect of microgravity on 5 polymorphic 'small molecule' crystals used in pharmaceutical applications [13]: Two amino acids (Glutamic Acid and DL-Methionine); an anticonvulsant (Carbamazepine); topical skin cream (Hydrocortisone 21 Acetate); and a cholesterol reducing medication (Atorvastatin Calcium). Postflight, the Redwire-Butler team took crystals from the space grown crystals and used them as seed crystals on Earth. The goal was to determine whether space crystals could be propagated on Earth for 10 generations without losing the desired space form. A summary of results from their paper is presented in Figure 4.

In general, the space crystals all grew larger than Earth crystals, with some hydrocortisone space crystals growing 80X larger than earth crystals with "striking clarity" and some DL-methionine space crystals growing 4X larger. Four (4) out of 5 of the crystals showed different polymorphs were present in space than on Earth (DL-methionine, Carbamazepine, Hydrocortisone, Atorvastatin). Two space crystals used as seed crystals on Earth retained their flight form for 10 generations from a single space crystal (Carbamazepine, Atorvastatin). DL-methionine showed that half of the crystals were space form and half were Earth form after 9 generations propagated from a single space manufactured seed crystal. Hydrocortisone was the most difficult to replicate from space seed crystals, with the unusual space form replicated in about half the attempts for a single generation only. Space grown hydrocortisone crystals were 80X larger than earth grown crystals.

This study shows the wide range of novel applications and unique manufacturing opportunities enabled by microgravity processing. It also proves by demonstration on Earth that space crystals can be used postflight to amplify the yields from in-space manufacturing, an important consideration for commercial scale-up.

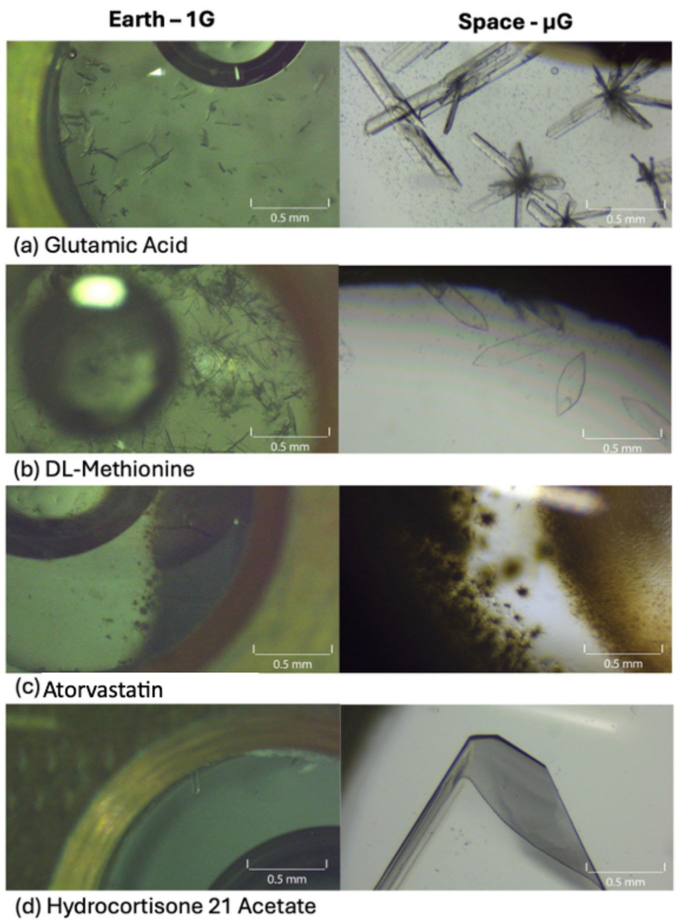

Figure 4. Polymorphs of 4 different pharmaceuticals grown in space by Redwire/Butler University and used as Seed Crystals Postflight on Earth To Amplify Yield. [13] Picture credits Redwire and Butler University. (a) Glutamic Acid. (MW 147 g/mol) is an amino acid with 2 polymorphic forms. Flight crystals grew much longer and especially wider, but Raman spectra showed that the space form was the same as the Earth form (beta glutamic acid) only much larger. (b) DL-methionine. (MW = 149 g/mol) is an amino acid with 3 polymorphic forms. Microgravity crystals were much larger than earth crystals grown under same conditions and had a different form. Ground samples were beta-DL-methionine. Flight samples were gamma-DL-methionine. Some space crystals grew up to 4X the size of earth crystals. Nine (9) generations of the space gamma form were grown postflight. In Generation 4, a small amount of the typical Earth beta form began to emerge. At the end of 9 generations postflight, half the crystals were the space gamma form and half were the typical Earth beta form. (c) Atorvastatin (MW 1155 g/mol) is a cholesterol reducing medication that has at least 15 polymorphic forms and is the most complex and amorphous of all the crystals studied by the Redwire/Butler University team. Flight clusters appeared slightly larger than Earth based crystals. However, ground crystals matched the Phase VIII polymorph, while flight crystals best matched MD-1 polymorph. Ten (10) generations were grown postflight from a single space manufactured seed crystal with no degradation of crystal form. (d) Hydrocortisone Acetate (MW 405 g/mol) is a corticosteroid for oral and topical use with 5 reported polymorphic forms that (on Earth) all convert to Form 1 in aqueous solution. In microgravity, the crystals grew significantly larger, with largest 80X the size of the Earth grown crystals. The authors noted that the space crystals had “striking clarity”. Earth crystals were mostly Form II. Space crystals were an unusual form with features of both Phase I and Phase 2 polymorphs that the researchers are calling Form III. This one was the hardest to replicate on Earth. The researchers were able to use space seed crystals to amplify results for only the first generation for space Form III about half the time, with the other half reverting to normal earth Form II. However, the yield on this crystal is expected to improve with practice.

V. Conclusions

As a result of the extraordinary advances in microgravity research, we now appreciate that billions of dollars on Earth each year are invested in trying to *see things that gravity does not let us see* and in trying to *do things that gravity does not let us do.* In the last few years, it has become clear that leaving Earth and working in a microgravity environment expands our ability to observe many chemical and biological phenomena that are not observable in 1g. Microgravity processing unlocks new and potentially revolutionary industrial processes. As commercial space flight becomes more available and more affordable, microgravity results show that it may be *better, cheaper, and faster* to leave Earth in order to accomplish highest-quality technology goals. Currently, there are more than 24 active projects in NASA’s InSPA Portfolio. Superior products with superior yields are consistently being demonstrated in orbit in these InSPA projects that are relevant to important high-tech areas that range from the atomic to macroscopic scales, with direct implications for national security, manufacturing and medical care. While these results are relevant to future space development goals, their real potential lies in the wide range of Earth applications and the potential for these applications to dramatically accelerate high value industries of great value to the nation.

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