Chemistry Beyond Gravity:

Unlocking the Potential of Space Chemistry for Exploration & Industry

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The Value of Space Chemistry

Fostering Exploration, Commercialization, and Research

The growing LEO and cis-lunar economy is set to revolutionize the space industry, making research and manufacturing in space increasingly vital. As humans venture further away from Earth, advancements in space-based research and manufacturing capabilities will be crucial to support long-term exploration missions, resource utilization, and the development of a sustainable space infrastructure.

1

Unique Environment

The microgravity environment in space offers unique conditions for experiments that cannot be replicated on Earth. This allows researchers to study chemical reactions and processes in ways that would otherwise be impossible, leading to new discoveries and insights

2

Space Exploration

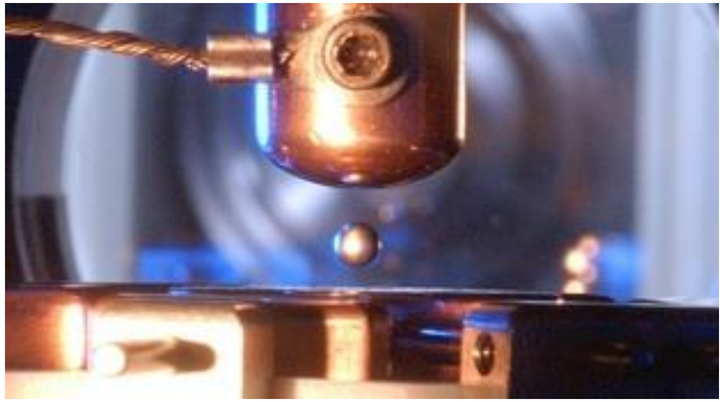
Advancements in space chemistry are critical for long-term space exploration missions, such as those to the Moon and Mars. Developing efficient and sustainable chemical processes in space can enable the production of essential resources, such as fuel, water, and oxygen, reducing the need for resupply missions from Earth.

3

In-Space Manufacturing

Space chemistry research can help develop new technologies for in-space manufacturing of advanced materials and biomedical products. These materials and products can have unique properties and applications due to the microgravity environment, potentially leading to breakthroughs in various industries.

Advantages of Space



Microgravity

Microgravity alleviates challenges posed by a material's weight and inhomogeneity.

- Weightlessness
- No sedimentation
- No buoyancy-driven convection
- Containerless processing
- Interfacial forces and diffusion become dominant

Extreme Environment

Extreme conditions in space are great for testing and qualification of materials.

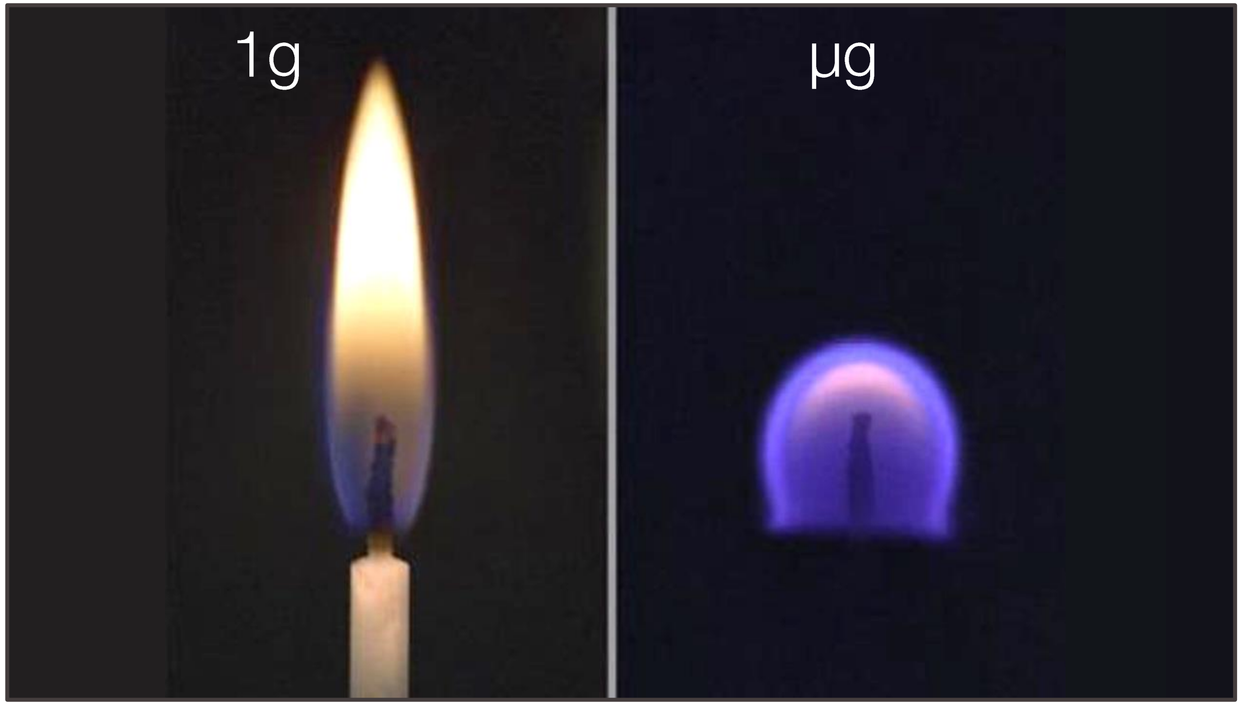
- Vacuum (10^{-9} - 10^{-6} torr)
- Atomic oxygen (4.5 eV)
- Ionizing space radiation (0.3 Sv/year)
- Extreme temperatures (-120 to +120 °C)
- High speed micrometeorites (8 to 60 km/s)
- UV radiation

Unique Location

The low-earth orbit location offers many positional advantages

- Unique vantage point at 400 km to view earth and space
- 90 min orbit cycles with an orbital path over 90% of earth's population.
- In-space assembly of space structures
- Orbital services

Convection-Free Environment



Credits: NASA

On Earth, hot air rises, making fames long and thin. In microgravity, fames are spherical in shape

Density differences in fluid (caused by thermal or concentration gradients) do not lead to convection in microgravity

- Achieves **purely diffusion driven** process for alloying, doping etc.
- Alters **grain growth** during solidification and crystallization
- Changes **heat and mass transfer** characteristics during manufacturing

Lack of Buoyancy Forces

Lakos.com

- **Density differences** between particles and fluid do not result in sedimentation or flotation in microgravity.
- **Absence of hydrostatic pressure** head affects mechanical and thermophysical properties in soft materials.

Improving Colloidal Products


Seeker/Xlab (Stanford University)

Consumer products

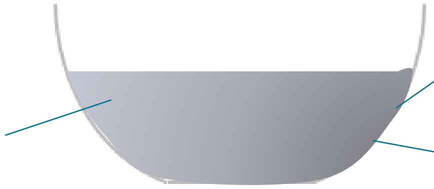
Isolating effects of phase separation from coarsening, for extending shelf life of food, cosmetics, cleaning solutions etc.

Graphene aerogels

Uniform dispersion of graphene flakes in the hydrogel during gelation, providing improved electrode material for supercapacitors, Li-S batteries, fuel cells etc.

Containerless Processing

1g

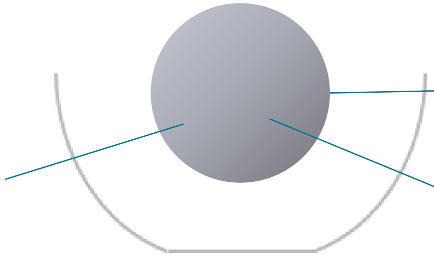


Heat transfer controlled by conduction, convection & radiation

Impurities transferred from crucible

Grain growth affected by crucible material structure

μg



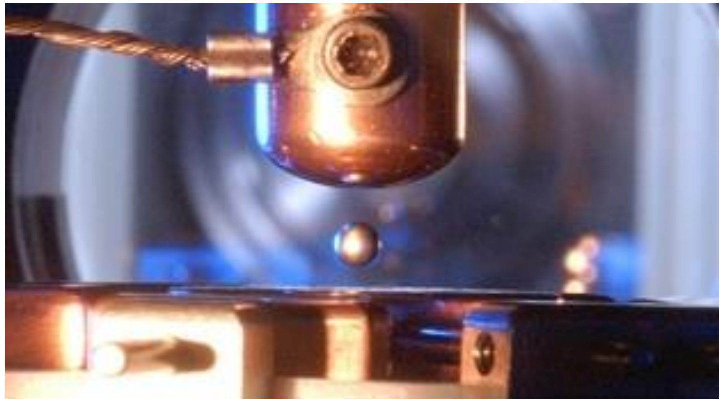
Lack of nucleation sites for defects

Enhanced visual and probing access to the material interface

Shape governed by surface tension

- **Grow, form and reshape materials** using fundamentally different forces and methods from that used on earth
- **Prevent defects** induced by surface/crucible contact
- Promote **reactions in the bulk** verses the surface
- **No shear stress** from surface contact
- **Observe material processes** without obstruction

Advantages of Space



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- In-space assembly of space structures
- Orbital services

Extreme Environment of Space

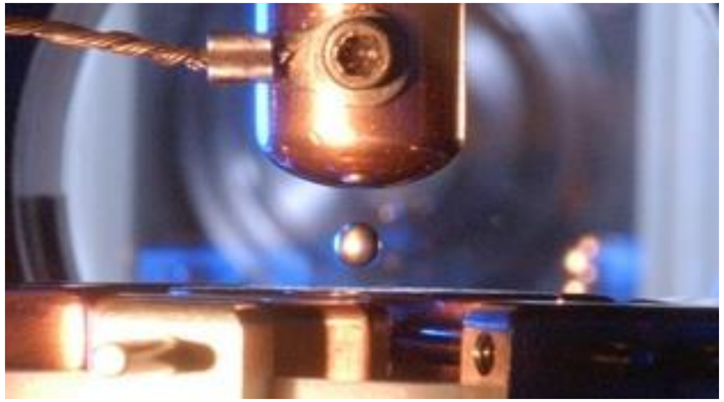
Vacuum | Atomic oxygen | Ionizing space radiation | Extreme temperatures | High speed micrometeorites | UV radiation

Testing
Extreme conditions in space are great for testing and qualification of materials for space applications.

Accelerated aging
The quick and extreme temperature cycling and UV radiation in space can be used for accelerated testing.

Manufacturing sensitive substances
Ultra-high vacuum of space can be used to process oxygen/humidity sensitive materials.

Advantages of Space



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Chemistry in Space – Enabling Exploration

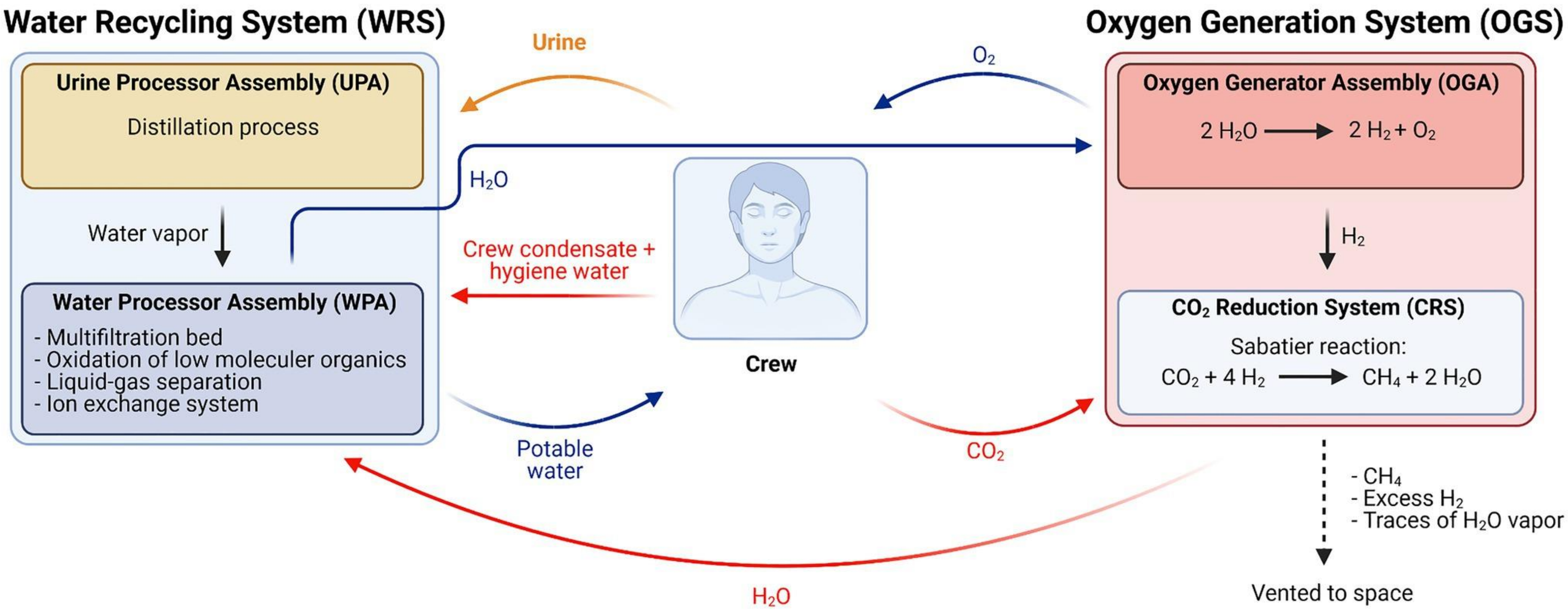
Credits: NASA/MSFC

Environmental Control and Life Support System (ECLSS) is a system of regenerative life support hardware that provides clean air and water to the International Space Station (ISS) crew and laboratory animals through artificial means.

The ECLSS consists of two key components, the Water Recovery System (WRS) and the Oxygen Generation System (OGS).

The system was delivered to ISS on STS-126 on November 14, 2008, with the UPA activated on November 20, 2008, and the WPA activated on November 22, 2008

Chemistry in Space – Enabling Exploration



Water Recycling System (WRS)

Urine Processor Assembly (UPA)

Distillation process

Water vapor

Water Processor Assembly (WPA)

- Multifiltration bed
- Oxidation of low moleculer organics
- Liquid-gas separation
- Ion exchange system

Urine

H_2O

Crew condensate + hygiene water

Crew

Potable water

O_2

CO_2

H_2O

Oxygen Generation System (OGS)

Oxygen Generator Assembly (OGA)

$2\ H_2O \longrightarrow 2\ H_2 + O_2$

H_2

CO_2 Reduction System (CRS)

Sabatier reaction:

$CO_2 + 4\ H_2 \longrightarrow CH_4 + 2\ H_2O$

- CH_4
- Excess H_2
- Traces of H_2O vapor

Vented to space

Credit: Front. Microbiol., 13 October 2021

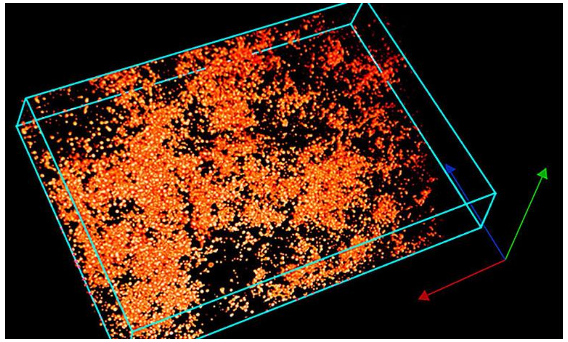
Oxygen is produced in two interconnected processes: (1) in the oxygen generation assembly (OGA), the water (H_2O_{liquid}) obtained from Earth supplies and (2) from the WRS, where H_2O is electrolyzed to H_2 and O_2.

Prior Commercial Engagements in Microgravity

MERCK

Keytruda

Keytruda monoclonal antibodies crystallization, which has led to 6 subsequent clinical trials.



Procter&Gamble

Consumer products

Sent to space to optimize colloidal products, resulting in 4 new patents.

adidas

Foam Formation

Study pellet motion and location in space to enhance product performance and comfort.

Bristol Myers Squibb

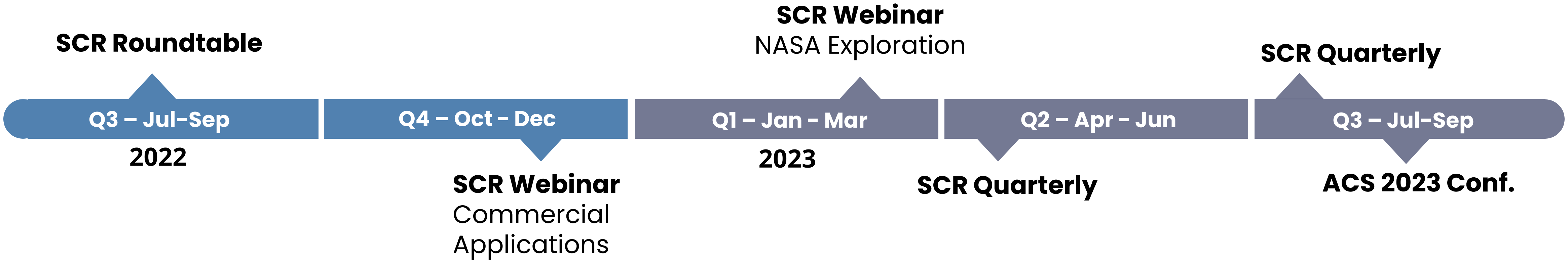
Protein and Biologics Purification

Sent to space to explore crystallization conditions and new manufacturing techniques.

Space Chemistry Roundtable Recap

CME
NASA STEM
SUSTAINABILITY
August 2022

Topics: NASA exploration, In-Space manufacturing, and Commercial Space Economy
Featured speakers: Jim Green, Ferenc Darvas, Jana Stoudemire, and Kenneth Savin
Output: Identified focus area considerations, capabilities considerations, roadmap development timeline, future speakers identified and workshop report.


SCR Roundtable

Q3 – Jul-Sep

2022

Q4 – Oct - Dec

SCR Webinar
Commercial
Applications

SCR Webinar
NASA Exploration

Q1 – Jan - Mar

2023

Q2 – Apr - Jun

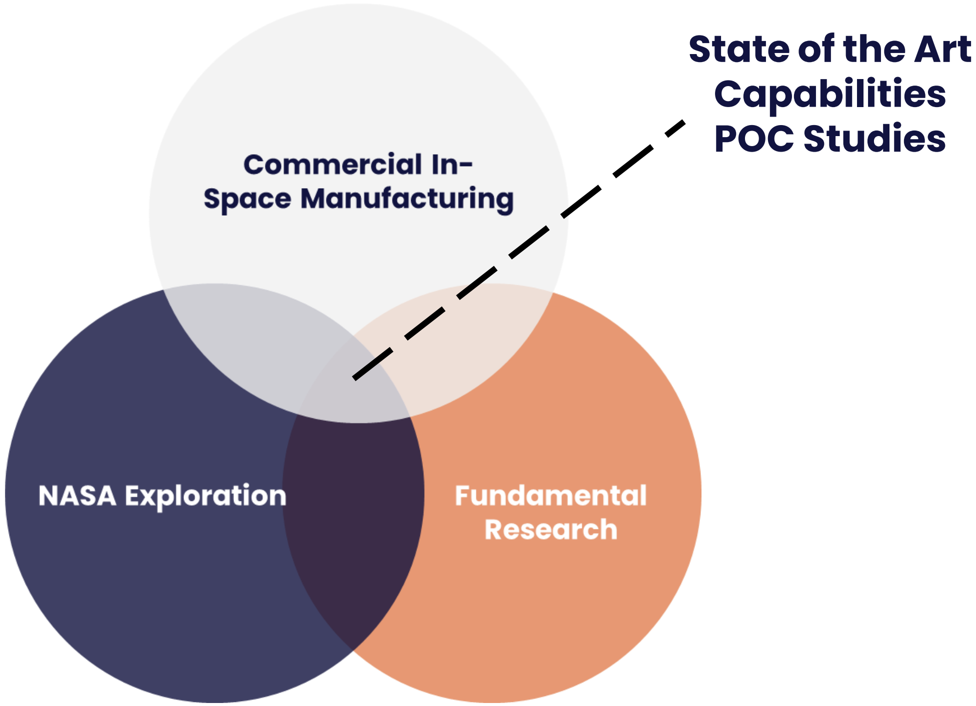
SCR Quarterly

SCR Quarterly

Q3 – Jul-Sep

ACS 2023 Conf.

Roadmap Objectives


State of the Art Capabilities POC Studies

Commercial In-Space Manufacturing

NASA Exploration

Fundamental Research


Focus Areas & Capabilities Defined
1Q23

Proof of Concepts Defined
2Q23

Space Chemistry Roadmap Draft
3Q23

To create a comprehensive, actionable space chemistry roadmap, that:

1. Identify 3-5 key focus areas where alignment between exploration, fundamental, and commercial goals exist.
2. Develop robust proof-of-concepts studies that leverage the unique opportunities and state-of-the-art capabilities offered by the International Space Station (ISS) and future commercial space stations.
3. Advance in-space manufacturing for advanced materials and biomedical products.
4. Present draft Space Chemistry Roadmap at CME NASA Symposium in August 2023 at the ACS Fall Meeting.

Key Opportunities Identified

Proposed Focus Areas

1 **Crystals**
Organic & Inorganic Crystals

2 **Quantum**
Materials, Sensors, Networks

3 **Flow Chemistry**
Pharmaceuticals

4 **Nanomaterials**
CNT's, Graphene, Nanoparticles

Polymers, MOFs, Ring opening/closing reactions, Thin Films, Optical Fibers, CO_2 conversion

Capability Considerations

1 **Remote Control & Data Management**
Remote control of on-orbit operations
Near-real time data downlink

2 **Reactors & Analytical Methods**
Modular systems and reactors
On-orbit characterization techniques

3 **Automation and Delivery Systems**
Universal delivery systems incorporating robotics and automation
Transition from analog to digitized chemistry

4 **Reagents and Feedstock**
Transport of reagents to ISS vs. on-board
Pluripotent materials as starting feedstocks for multiple products

Proof-of-Concept Template

Proof of Concept Overview

Please give an overview of the proof-of-concept developed by the team, what is the broader impact to space chemistry, and overall timing needed to execute this PoC.

Goal Alignment

Which space chemistry area or areas does this project align to: Commercial In-Space Manufacturing, NASA Exploration or Fundamental Research

Next Steps

What are the critical next steps to get this project fully realized? (i.e. partnerships, workshop, funding)

Experimental Plan Overview

1

Hypothesis

Hypothesis or expected outcomes of this PoC.

2

Capabilities Needed

What infrastructure and/or capabilities needed aboard the ISS (whether existing or needs to be developed) to execute the PoC?

3

Success Criteria/Risks

What does success look like for this PoC? What are some of the experimental or technical risks associated with this PoC?

Funding/Resource Needs

- What is the expected cost of executing this experiment?
- What resources are needed to execute (resources external to the space chemistry roadmap)
- Funding opportunities already identified?

Crystals

In-Space Polymer Crystallization /Vitrification for Fabrication of Molded Micro/Nano Devices with Precise Shape and Isotropy

Overview

Explore manufacturing benefits and the LEO market for micro/nano-molded polymeric devices such as medical devices, micro implants/implant components, drug delivery systems, microelectromechanical systems (MEMS), microfluidic, and Lab-on-a-Chip (LOC) applications. This series of studies would explore the melting and crystallization of micro/nano polymeric fibers and the injection of molten polymer and composites into molds and release from the molds before, during and after solidification on orbit. Comparison of microgravity-based work to ground-based studies (evaluating the distribution of materials in the molded products, shape tolerance, mechanical and other application-relevant properties and degree/type of crystallinity in the final products). The effort will include techno-economical assessment/analysis, including the identification of specific, critical applications and evaluation of commercialization efforts to support national needs.

Goal Alignment

The development of specialty micro and nano polymeric and hybrid devices for bio-medical and other applications. Developing a greater understanding of the factors influencing polymer crystal and glass formation and its industrial applications. A focus on microgravity for earth-based applications to demonstrate the economic viability and benefits in the form of unique outcomes impossible terrestrially.

Next Steps

We will, in this first phase, collaborate with academics at Clemson University, ISS National Lab, NASA, and space industry partners. The funding will support fundamental aspects of novel manufacturing technique(s) and new product R&D, and lead into infrastructure development.

Experimental Plan Overview

1

Hypothesis

Microgravity conditions enable the preparation of micro/nano polymer and polymer composite structures by facilitating semi-container less (withdrawing the samples from the mold prior to crystallization and/or vitrification) production and the benefits to homogeneity and high degree of crystalline makeup of products as a result of the microgravity environment (little to no effect of the mold walls on the crystallization/vitrification, convection, density-driven segregation and sedimentation). This will lead to unique products with improved performance, novel intellectual property, and expansion of technological applications.

2

Capabilities Needed

While initial proof-of-concept efforts will be limited and can be executed by the smaller team, the long-term program will require Industry informed development of orbital polymer molding platforms and the execution of the studies to demonstrate all benefits of the new technology. Pooling resources from both private and public sectors will be necessary to develop the required industrial scale hardware processing requirements, analytical hardware/expertise, automation, and to provide logistical support for increasing supply chain cadence and capacity.

3

Success Criteria/Risks

Demonstration of the melting and molding of polymers using small systems to produce superior molded products (properties-performance (depending on application), using industry evaluation standards and considering the manufacturing feasibility, cost and comparison them with terrestrial derived analogs.

Risk: dependency on supply chain ecosystem, consistency of process condition, safety guardrails and benefits relative to the a products manufactured terrestrially.

Funding/Resource Needs

- What is the expected cost of executing this experiment? ($0.75Mil-5Mil). What resources are needed to execute (resources external to the space chemistry roadmap)
- - Experiment Preparation and Setup(Academia lead), Hardware Development, Payload Development, Flight, Ground Evaluation/rheology and Application Evaluation.
- Funding opportunities already identified? [Yes] – CASIS (NLRA), NASA (NRA), NSF.

In-Space Production of Semiconductor Crystals

Overview

Fuel the development of a LEO market for semiconductor technologies by enabling R&D demonstrations of semiconductor crystal synthesis, growth, and performance. These include the development of processing and metrology capabilities capable of harnessing microgravity conditions for developing the next generation of semiconductor technologies only possible in microgravity; and the identification of profitable applications and commercialization efforts in support national needs.

Goal Alignment

Production semiconductor crystals and related technologies produced in microgravity for earth-based applications to demonstrate the economic viability and benefits in the form of unique outcomes not possible terrestrially.

Next Steps

We will collaborate with semiconductor industry and organizations (SRC, NIST), academics, ISS National Lab, NASA, and space industry partners. The funding will support novel materials R&D, manufacturing R&D, and infrastructure development.

Experimental Plan Overview

1

Hypothesis

Microgravity conditions enable the synthesis and growth of larger, defect free semiconductor single crystals by enabling containerless synthesis and growth, and removing influences such as natural convection, density driven segregation and sedimentation. This will lead to increased yield and performance, novel intellectual property, and expansion of technological applications.

2

Capabilities Needed

Industry informed development of orbital semiconductor crystal synthesis and growth platforms and the execution of the studies to demonstrate the benefits of doing this work in space demands collective effort. Pooling resources from both private and public sectors will be necessary to develop the required hardware processing requirements, analytical hardware/expertise, automation, software, and to provide logistical support for increasing supply chain cadence and capacity.

3

Success Criteria/Risks

Demonstration of the synthesis and growth of highly ordered-defect free- stable semiconductor crystals in space, increased yield, superior properties-performance (depending on application), manufacturing feasibility, automation, Earth cost reduction, and potential of breakthrough microelectronics materials.
Risk: high dependency on supply chain ecosystem to reach the pace of Earth’s 5–10-years technology development cycles, process temperatures, safety guardrails.

Funding/Resource Needs

- What is the expected cost of executing this experiment? ($5Mil-100mil).
- What resources are needed to execute (resources external to the space chemistry roadmap)
- - Experiment Preparation and Setup(Industry/Academia lead), Hardware Development, Payload Development, Flight, Analytical and Application Evaluation.
- Funding opportunities already identified? [Yes] – CASIS (NLRA), NASA (NRA), NIST-CHIPS.

In-Space Production of Molecular Therapeutic Crystals

Proof of Concept Overview

Enable therapeutic development by building orbital drug processing and manufacturing systems for small-molecule and biologic crystallization. Study will support the development of hardware and techniques for the execution of this program as well as target identification and commercialization efforts.

Goal Alignment

Production of pharmaceuticals and related materials produced in microgravity but for earth-based applications to demonstrated the economic viability and benefits in the form of unique outcomes not possible terrestrially.

Next Steps

We will collaborate with leading biopharma organizations, experts in parallel industries, academics and public health agencies. The funding will support the discovery, development, and manufacturing of novel forms, formulations and morphologies improving patient outcomes and with applications to other industries.

Experimental Plan Overview

1

Hypothesis

Microgravity processing enables the creation of unique small molecule and biologic forms ad formulations by removing influences such as natural convection and sedimentation. This will lead to enhanced bioavailability, extended shelf-life, novel intellectual property, and alternative routes of administration.

2

Capabilities Needed

The development of orbital drug R&D and manufacturing platforms and the execution of the studies to demonstrate the benefits of doing this work in space demands collective effort. Pooling resources from both private and public sectors will be necessary to develop the required automation, analytical hardware/expertise and software, and to provide logistical support for increasing flight cadence and capacity.

3

Success Criteria/Risks

Demonstration of small and large molecule therapeutics in space could revolutionize drug quality, cost, and patient compliance. However, the complexity of this multidisciplinary and costly initiative necessitates strong partnerships between aerospace, biopharma companies, and health regulatory agencies. New crystal morphologies can be evaluated for structure, but the value and applicability is something that is evaluated by customers (our partners) and access to markets.

Funding/Resource Needs

- What is the expected cost of executing this experiment? ($200K, $500K-2Mil, $250K, $100K-$7 mil, $200k-1Mil).
- What resources are needed to execute (resources external to the space chemistry roadmap)
- - Experiment Preparation and Setup, Hardware Development, Payload Development, Flight, Analytical and Application Evaluation.
- Funding opportunities already identified? [Yes] – CASIS (NLRA), NASA (InSPA),

Quantum

Quantum mechanics is a fundamental theory in physics that describes the behavior of matter and energy at the smallest scales, such as atoms and subatomic particles.

Secure Communcations and Quantum Key Distribution (QKD) in LEO

Overview

Q-communication utilizes principles of q-mechanics to transmit and exchange information securely to ensure the confidentiality, integrity of data.

A method to transmit entangled particles as information, such as photons, has the capability of detecting eavesdropping.

QKD in LEO satellites and devices is an application of secure communication to extend the range and global coverage including reduced transmission losses and vulnerability to attacks.

Goal Alignment

Maintaining the stability of q-systems in the harsh space environment, dealing with atmospheric disturbances, and overcoming the limitations of **satellite power** and **computational resources** remains a hurdle.

Secure satellite-to-satellite links, inter-satellite communication, and even the establishment of a global q-communication network would lead to the advancement of **NASA exploration**.

Next Steps

Knowledge partnerships with current QKD manufacturers to create workshops and a robust knowledge base of LEO QKD devices is critical for success of enhancing space exploration and terrestrial/extraterrestrial communications.

Experimental Plan Overview

1

Hypothesis

Improving QKD hardware for LEO applications and utility will advance space exploration and secure communications.

2

Capabilities Needed

High precision and stability in the harsh space environment.

Improved satellite power (see PoC 2: **Quantum Batteries (QB)**).

Increase of computational resources (see PoC 3: **Quantum Computing (QC)**).

3

Success Criteria/Risks

Advancement of sophisticated q-cryptographic techniques and protocols.

Improved integrated systems such as:

classical communication interfaces,

data processing units,

secure key management modules.

Funding/Resource Needs

- What is the expected cost of executing this experiment? **Under consideration with future innovation developments.**
- What resources are needed to execute (resources external to the space chemistry roadmap)? **Support and collaboration from NIST, DHS, NASA, and academic/industry members from QED-C.**
- Funding opportunities already identified? **H.R.2739 - Quantum Sandbox for Near-Term Applications Act of 2023**

Quantum Batteries (QB) for Power in LEO

Overview

A practical QB stores energy in q-states using principles like superposition, entanglement, and coherence, which requires these systems operate at extremely low temperatures to minimize thermal noise.

QBs remains a theoretical construct due to a variety of technological hurdles

Using quantum batteries for powering satellites could be a way to increase the resilience of secure communications within LEO, on earth, and beyond.

Goal Alignment

The equipment necessary to maintain and manage a quantum battery is currently bulky and power-hungry, which would be problematic in space where every kilogram of weight and watt of power is precious.

Next Steps

Knowledge partnerships with current battery, semiconductors, and QC manufactures to create workshops and a robust knowledge base of LEO QB devices is critical for success of enhancing space exploration and terrestrial/extraterrestrial communications power supply.

Experimental Plan Overview

1

Hypothesis

QB could possibly provide more efficient power to satellites in LEO provided qubit systems can scale to the millions with high coherence and low noise.

2

Capabilities Needed

Maintaining q-coherence.

Releasing energy very quickly, in a process called q-supercharging.

A 3-volt, 1-amp battery would deliver 3 joules of energy per second (since 1 ampere = 1 coulomb/second and energy = charge * voltage.

A large number of qubits would be needed to deliver this amount of power.

3

Success Criteria/Risks

Isolation from any sort of disturbance that could cause decoherence such as sources of radiation and particles that could interfere with the delicate quantum states.

Large number of qubits (in the millions).

Funding/Resource Needs

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Quantum Computing (QC) in LEO

Overview

Current QCs are noisy intermediate-scale quantum (NISQ) devices, limited in the number and complexity of the quantum operations which can perform due to noise and error.

However, researchers are actively working on developing and implementing error correction techniques to overcome these limitations and perhaps if quantum computing was moved to low earth orbit some of the engineering efforts can be overcome due to microgravity effects.

Current experiments are conducted with trapped-ions at NASA's cold atom lab (CAL) with preparation for launch to the ISS.

Goal Alignment

Low earth orbit quantum computing could lead to the achievement of having fault-tolerant quantum computers, where the engineering process could be optimized for Commercial In-Space Manufacturing.

Further, the Fundamental Research of quantum computing use case applications would accelerate.

Next Steps

Knowledge partnerships with current trapped-ion, and semiconductor manufacturers to create workshops and a robust knowledge base of LEO quantum computing is critical for success of obtaining universal quantum computers.

Experimental Plan Overview

1

Hypothesis

Atomic quantum sensors for quantum computing are much more precise under zero gravity conditions than on Earth, which also makes them interesting for basic research in physics.

2

Capabilities Needed

Large scale, low-error, universal QCs called fault-tolerant QC.

Large number of qubits.

3

Success Criteria/Risks

Large scale, low-error, universal QCs called fault-tolerant devices.

Funding/Resource Needs

- What is the expected cost of executing this experiment? **Under consideration with future innovation developments.**
- What resources are needed to execute (resources external to the space chemistry roadmap)? **Support and collaboration from NIST, DHS, NASA, and academic/industry members from QED-C.**
- Funding opportunities already identified? **H.R.2739 - Quantum Sandbox for Near-Term Applications Act of 2023**

Nanomaterials

Vapor–Phase Synthesis of Nanostructures

Proof of Concept Overview

Low-dimensional (1D & 2D) nanostructures to enable *quantum computing*, novel *bio-medical devices*, *high-efficiency portable electronics* and *green energy*. Low-dimensional nanostructures such as defect-free nanoparticles, multi-layered 2D nanosheets and 1D nanotubes, composed of, for example, transition metal chalcogenides or multi-component misfit layered compounds, belong to the nano-systems, whose structures, morphologies and properties may be strongly affected by gravitational forces during their conventional gas-phase generation.

Timing: 2 Years

Goal Alignment

Aligns with fundamental research and commercial in-space manufacturing of nanostructures and contribute to NASA exploration of chemical processes in microgravity environment.

Next Steps

Secure funding to support fundamental aspects of novel manufacturing technique(s), and new product R&D, and lead into infrastructure development.

Experimental Plan Overview

1

Hypothesis

1D-nanomaterials and heterostructures, specifically inorganic nanotubes synthesized at elevated temperatures possess high crystalline order that allows them to withstand high mechanical strain. However, if nanotubes consist of heavy elements or rare earth metals, their vapor-induced growth is critically influenced by the gravity of earth. Microgravity could enable generation of these heavy-element nanostructures with high precision and quality that are commensurate for their applications.

2

Capabilities Needed

- Process equipment with temperature up to 900 °C (specialized furnaces)
- In-space analytical systems
- Application-oriented testing of the new technology(ies).

Note: Pooling resources from both private and public sectors will be necessary to develop the required industrial scale hardware, analytical equipment, automation, and to provide logistical support for increasing supply chain cadence and capacity.

3

Success Criteria/Risks

Success:

- Demonstration of unique 1D-nanomaterials and heterostructures manufactured in space whose performance is superior to that of terrestrially manufactured materials and the cost acceptable for target applications.
- Development of a technology platform that can be extended onto broad range of nanomaterials

Funding/Resource Needs

- Expected cost of executing this experiment? ($750K – $5M)
- Resources needed: Experiment Preparation and Setup (Industry and Academia lead), hardware development, flight, ground evaluation and application evaluations
- Funding opportunities: DOE, ARPAe, DoD, DARPA may be interested

Solution-Based Synthesis of Nanostructures

Overview

Nanostructure synthesis using solution-based reactions to create materials like Carbon quantum dots, colloidal gold particles, ceramics/glass from sol-gel synthesis. The goal is to push the manifold potential of nanomaterials, which is unreleased to imperfections in synthesis.

Timing: 3-4 years

Goal Alignment

Fundamental knowledge for commercial in-space manufacturing

Support NASA space exploration by leveraging the capabilities developed for on-orbit drug synthesis.

Next Steps

Proposition of case studies

Secure funding

Earth-based experiments simulating space-analogue studies

Space experiments

Experimental Plan Overview

1

Hypothesis

Manifold mechanisms guide perfect nano-material synthesis and most of these are expected to be impacted by microgravity.

- Mixing of reactive solutions for seed formation in liquid phase
- High-temperature synthesis, deman-ding fast, accurate T-setting

Those rely on elementary physical transport mechanisms: Diffusion, Convection, Buoyancy, Heat conduction. Those are likely to be different in space.

2

Capabilities Needed

Reactor to perform controlled mixing of solutions in microgravity

Cutting-edge analytical technologies

3

Success Criteria/Risks

Success:
Demonstration of step-changed improved nanomaterials

Demonstration of unique, new nano-materials

Demonstration of business-directed sustainability. Use an investor-driven view take; stock exchange-rated ESG (Sustainalytics, Circularytics)

Development of a technology platform that can be extended onto broad range of nanomaterials

Funding/Resource Needs

- Expected cost of executing this experiment? ($750K – $5M)
- Resources needed: Experiment Preparation and Setup, hardware development, flight, ground evaluation and application evaluations
- Funding opportunities: Raise awareness of space agencies and government to influence their funding programs

Nanomaterials for Space Exploration

Overview

Nanomaterials are needed for crucial life-supporting functions in space explorations. For example: nano-pesticides/-fertilisers for growing plants in space; nano photocatalysts for wastewater and other recycling, astronaut health etc. This requires us to understand the engineering of their production and sensitivity of nanomaterials to the production process.

Timing: 3-4 years

Goal Alignment

Aligns with fundamental Research, NASA Exploration

Next Steps

Nanomaterials commercial supply is typically done by small companies. For a space breakthrough, the engagement of a global group would be needed.

Experimental Plan Overview

1

Hypothesis

There is a need to test if ground-based synthesis methods can be successfully adapted for space production and if they can produce at the same quality or above.

2

Capabilities Needed

Leverage Earth capabilities to simulate space manufacturing to predict the potential and to select the hardware.

Adapt earth hardware to space while re-designing for (i) compactness, (ii) energy efficiency, (iii) functioning under microgravity, and (iv) production capacity.

3

Success Criteria/Risks

Operate at industrial productivity

Quantify the cost and environ-mental benefits by sustaina-bility metrics . Use a 'performance chemical' view take (utility-driven circularity).

Potentially achieve superior properties by leveraging the space environment.

Funding/Resource Needs

- Costs: need to support essential proof-of-concept funding of a few studies, e.g. 2-4, founding studies; US$3M
- Resources: support from global group partner to allow 1-2 ISS studies; US$3M
- Funding opportunities: raise awareness of space agencies and government to influence their funding programs

Flow Chemistry

Advancement of Hybrid Material Manufacturing in Microgravity

Proof of Concept Overview

Explore synthesis and characterization of materials using a custom designed and flexible flow chemistry and material deposition platform.

Will explore synthesis of homopolymers & crystallization of polymer-grafted nanoparticles.

Goal Alignment

Which space chemistry area or areas does this project align to: Commercial In-Space Manufacturing & Fundamental Research

Next Steps

Officially kick-off Flow Chemistry working group and recruit external experts to build out additional proof-of-concepts.

Experimental Plan Overview

1

Hypothesis

In the synthesis of some homopolymers, viscosity of the reaction solution is dictated by the polymer architectures and that interconversion between linear and cyclic polymers. possible by removing density and convection (the metathesis reaction is exothermic) effects of the fluid dynamics, diffusion control will be absolute which we believe will enhance the viscosity effect observed.

2

Capabilities Needed

Flow Chemistry Reactor + Reagents

Flow Coating Deposition Sealed Chamber

3

Success Criteria/Risks

Successfully fabricate polymer-grafted nanoparticles that have significantly fewer defects and are larger, given the lack of sedimentation.

Control the purity of homopolymer reactions, and show that stable monomers can be used in microgravity to make a wide range of homopolymers and copolymers.

Funding/Resource Needs

- What is the expected cost of executing this experiment? $300 - $500K + Cost of Flight
- What resources are needed to execute -
- Funding opportunities already identified? NLRA, TechFlight Demo’s, DoD Funding

Next Steps

Space Chemistry Roadmap Workshop –
8/16/23 - Wednesday 8:00 – 11:30 AM PST | Marriott Marquis Room - Foothill F