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Engineering the Final Frontier: The Role of Chemical and Process Systems Engineering in Space Exploration

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ABSTRACT

Space exploration demands the integration of multiple scientific and engineering disciplines, with chemical engineering and process systems engineering playing pivotal roles. This paper examines their critical contributions to propulsion systems, life support mechanisms, and advanced materials essential for space missions. Recent advancements in chemical propellants and rocket fuels, illustrated by SpaceX and NASA missions, have significantly improved propulsion efficiency and safety. Chemical engineering is vital in developing air purification, water recycling, and bioregenerative life support systems, ensuring astronaut survival and mission sustainability. Additionally, creating heat-resistant, lightweight materials enhances spacecraft durability under extreme space conditions. Process systems engineering (PSE) complements these efforts by integrating, simulating, and controlling complex systems. PSE ensures reliable subsystem integration and uses predictive analytics and advanced modeling for mission planning and risk mitigation. Automation and control systems are essential for maintaining operations with minimal human intervention. The synergy between these fields is evident in in-situ resource utilization (ISRU) technologies, which extract and process local resources on extraterrestrial bodies, reducing reliance on Earth supplies and enhancing mission viability. Despite significant progress, challenges remain. Addressing harsh space environments, ensuring long-duration mission sustainability, and advancing energy sources and materials are ongoing research areas. This presentation underscores the indispensable roles of chemical and process systems engineering in overcoming space exploration challenges.

Keywords: Space exploration, chemical engineering, process systems engineering

1. INTRODUCTION

A few years ago, I read somewhere in a popular magazine about the *Mars Oxygen In-Situ Resource Utilization Experiment* (MOXIE). A project by NASA where a mobile reactor was landed on Mars. The equipment could capture carbon dioxide and convert it into oxygen. The start of a science fiction story! Such equipment could be used in terraforming (making Mars suitable for humans to live). The chemical engineer in me was also thinking about how such equipment had to be completely autonomous and that communication with Earth would lead to large delays (the average distance between Mars and Earth is 140 million miles). This probably required a big deal of *control systems engineering*. At that time, I was still working at Bremen University (Germany), and one of my colleagues, Lucio Colombi Ciacchi, was also thinking about how *chemical engineering* could be of importance in space exploration. He was reasoning that if men wanted to live on the moon or Mars, for that matter, shooting rockets with construction materials into space would be hard to impossible. In other words, materials should be locally produced. As a materials scientist, Colombi Ciacchi was especially interested in developing electrochemical processes to make metal alloys; see, for example, [1].

I also got back in touch with Volker Hessel, one of my former colleagues at Eindhoven University (the Netherlands), who moved to Australia and took up a new research direction. Hessel was very much interested in exploring how space conditions (e.g., vacuum, no gravity, extreme pressures/temperatures) affected and/or could be used to benefit the design of new pharmaceuticals [2,3].

Figure 1: Manufacturing equipment could be much lighter than on earth because of the moon's gravity. The first things you would want to make would be mining devices to speed up production. After that you would make the things you need for a power grid, including solar panels. You might also make robots that are remotely operated by humans on earth for general maintenance tasks. The last thing to produce would be rockets since they don't offer much for base expansion and self sufficiency. Heat shields are heavy so a rocket could launch off earth without one and then one made on the moon could be attached. Taken from [4]

You can imagine that my attention to this topic was caught, and I was looking around for possibilities to hook up or launch some projects that linked chemical engineering to space exploration. Figure 1 shows an artist's impression of how a lunar industrial site could look.

It turned out that there are not so many direct references to chemical engineering in space [5,6]. I found inspiration in a short chapter that Isaac Asimov wrote in 1989 in "*The Tyrannosaurus Prescription and 100 Other Essays*" [7]. Chapter 6 deals with the future of chemical engineering, where he concludes that "orbital chemical engineering" is a new and spacious branch of the field in which engineers deal with new situations and new problems. For sure, we can hope that finding new solutions will make the 21st century as different from the 20th as the twentieth is from Roger Bacon's 13th!

When sharing my enthusiasm about this with my colleagues, I often was answered with frowning eyebrows and replies like, "Let us first try to find solutions for the problems we have on earth". When reaching out to students to probe if they would be interested in researching the topic, they'd politely thank me and preferred to stay with a more conventional topic.

Maybe a focus on solving Earth's problems is indeed more appropriate. But there already exists something like a space economy. In 2022, OECD countries spent 75 billion US dollars on space-based systems [8]. That means especially satellites. More than 100 countries have already managed to launch satellites into space. These satellites provide information on climate variables (e.g., methane emissions in landfills), and this data is used, of course, to monitor and control greenhouse gas emissions globally. Satellites also support our critical infrastructures on Earth (transport, energy, food supply, and law enforcement). Especially via communication and positioning instruments. Although most of the spending still comes from governments, more and more commercial space activities commence. In other words, space exploration also contributes to solving problems on Earth.

I got stuck with the question: What kind of problems might we encounter when doing space exploration, and what type of solutions could chemical engineering offer to such problems? It stayed with being a question until I submitted an abstract to the ESCAPE, which was accepted. Not hindered by any knowledge, the accepted abstract forced me to look into the matter, so here we go!

Space exploration is a paramount scientific and engineering pursuit that involves overcoming numerous challenges. Chemical and process systems engineering are critical in developing the technologies necessary for successful and sustainable space missions.

This paper explores the significant contributions of these fields to space exploration, focusing on propulsion systems, life support mechanisms, materials engineering, systems integration, simulation, automation, and in-situ resource utilization (ISRU).

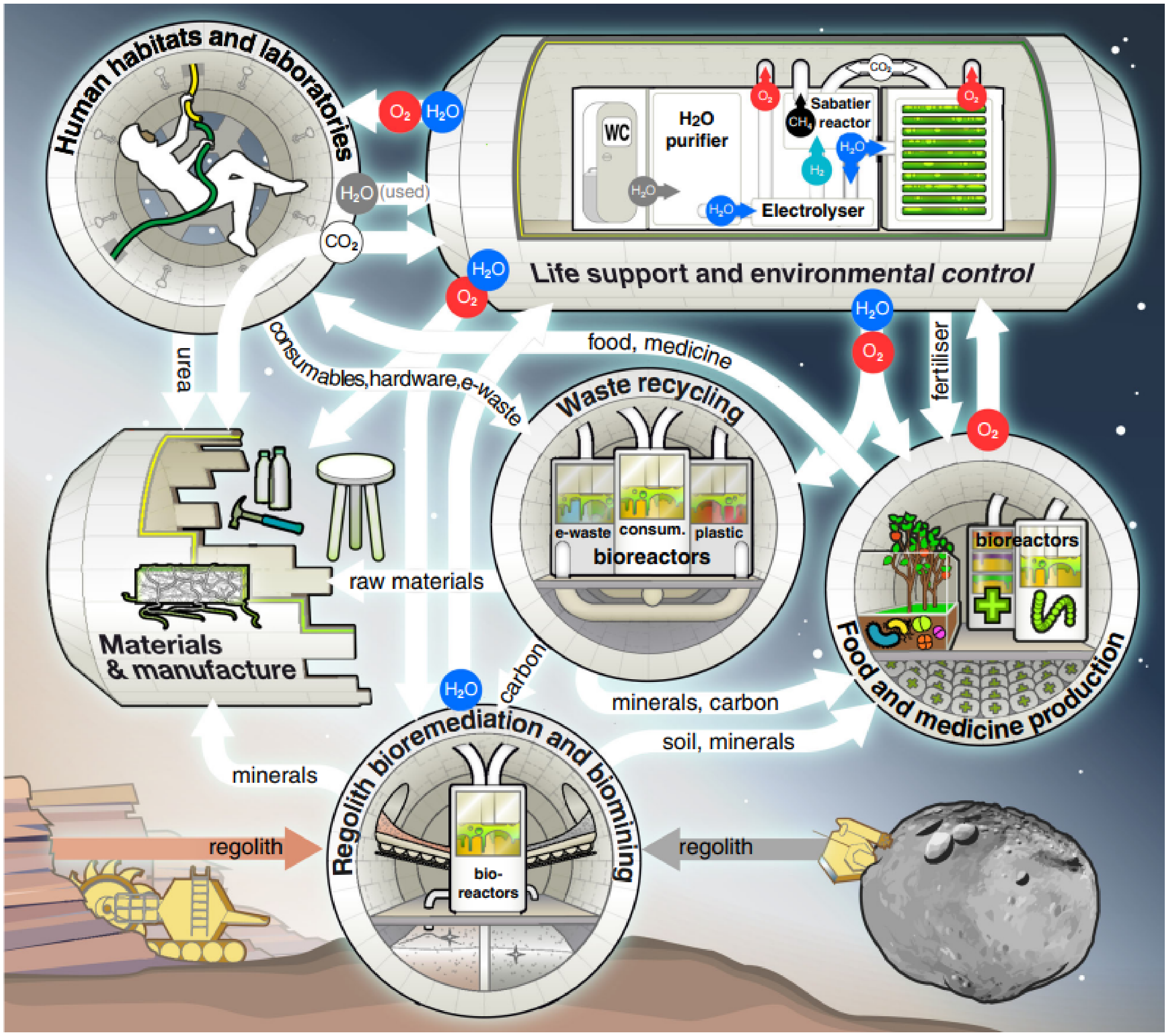

Figure 2: Impression of a biotechnology based life support system in an agnostic space environment. This figure was taken from [9]

2. CHEMICAL ENGINEERING IN SPACE EXPLORATION

Role of Chemical Engineering

Chemical engineering involves the application of chemical processes and principles to create and optimize products and systems. In space exploration, chemical engineering is vital for developing propulsion systems, life support technologies, and advanced materials.

Propulsion Systems

Propulsion systems are fundamental to space travel. Chemical engineers develop and optimize rocket fuels and propulsion technologies to enhance efficiency and safety. Innovations in chemical propellants, such as liquid hydrogen and oxygen, hypergolic fuels, and ion propulsion systems, have revolutionized space travel. Case studies from SpaceX and NASA missions illustrate these advancements' practical applications and benefits. For instance, SpaceX's Falcon 9 and NASA's Space Launch System (SLS) utilize advanced chemical propellants for higher performance and safety (You might think of hypergolic fuels or ion propulsion systems).

Life Support Systems

Life support systems are essential for maintaining astronaut health and safety. Chemical engineers design air purification systems that remove carbon dioxide and other contaminants from the spacecraft environment.

Water recycling systems convert wastewater into potable water, ensuring a sustainable water supply. Bioregenerative life support systems, which include the cultivation of plants for food and oxygen production, have also been developed by chemical engineers. These technologies are critical for long-duration missions, such as those planned for Mars exploration. Figure 2 renders an impression of a life support system, see also [9], basically (re)cycling water, oxygen, and carbon dioxide, mining regolith (space rock), and then producing materials, food, medicine, and fertilizer.

Materials Engineering

Materials engineering, a subset of chemical engineering, focuses on developing materials that can withstand the extreme conditions of space. Engineers create heat-resistant and lightweight composites and alloys for spacecraft construction. These materials must endure high radiation levels, temperature fluctuations, and mechanical stresses. Innovations in materials engineering enhance the structural integrity and durability of spacecraft, ensuring mission safety and longevity.

3. PROCESS SYSTEMS ENGINEERING IN SPACE EXPLORATION

Role of Process Systems Engineering

Process systems engineering (PSE) focuses on designing, integrating, optimizing, and controlling complex systems. In space exploration, PSE is crucial for ensuring the reliability and efficiency of spacecraft systems.

Systems Integration

Systems integration involves the seamless combination of various subsystems, such as power, life support, and thermal management. PSE ensures that these subsystems work together reliably and efficiently. Redundancy and reliability are critical as any subsystem failure can jeopardize the mission. PSE methodologies, including systems engineering principles and integration frameworks, are employed to achieve this goal.

Simulation and Modeling

Simulation and modeling are essential tools in PSE. They provide a means to plan missions, assess risks, and

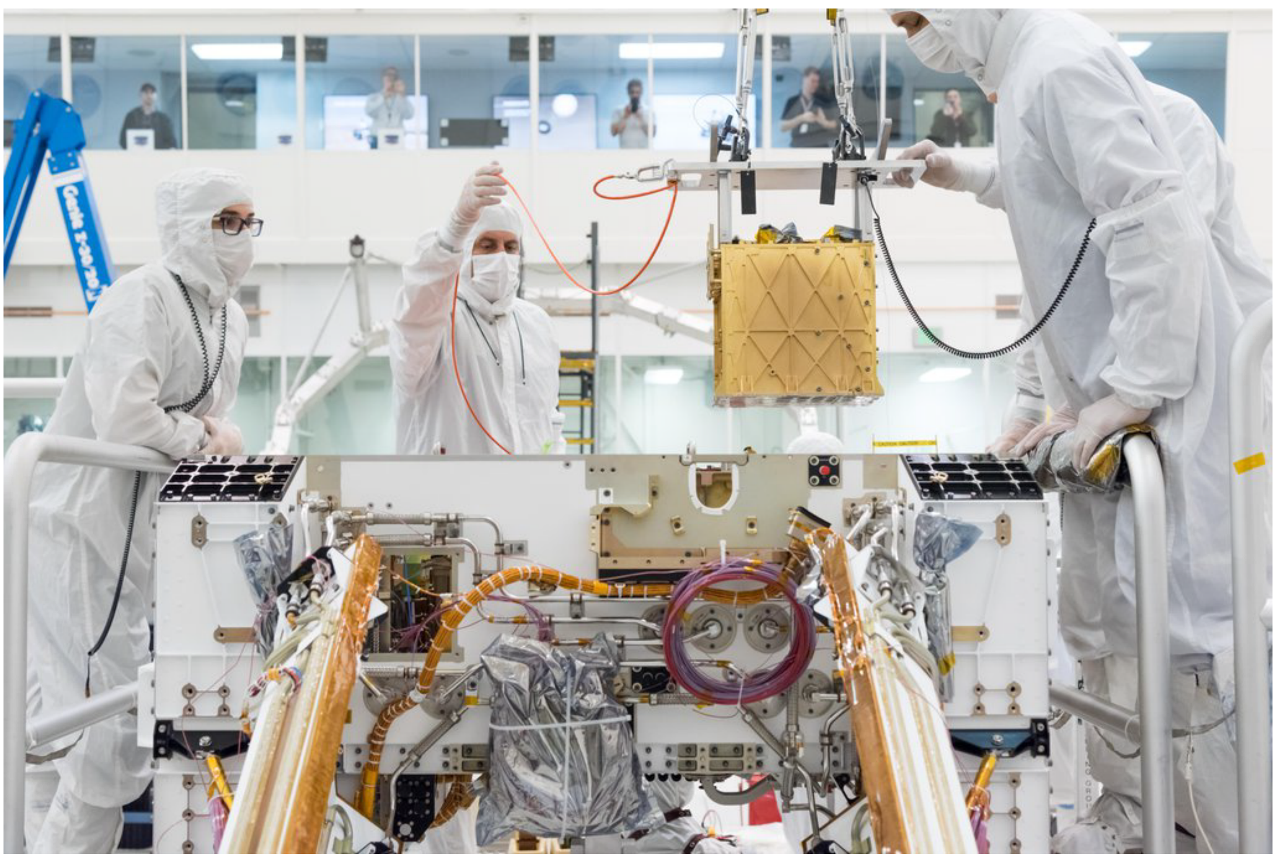

Figure 3: MOXIE (Mars Oxygen In-situ Resource Utilization Experiment) is lowered into the chassis of NASA's Perseverance in 2019. During the mission, MOXIE extracted oxygen from the Martian atmosphere 16 times, testing a way that future astronauts could make rocket propellant that would launch them back to Earth.
Credit: NASA/JPL-Caltec

optimize systems. Predictive analytics and advanced modeling techniques allow engineers to anticipate potential issues and develop effective mitigation strategies. For example, thermal modeling ensures that a spacecraft can maintain optimal temperatures in the harsh environment of space, while life support models simulate the long-term sustainability of air, water, and food systems.

Automation and Control

Automation and control systems are critical for maintaining spacecraft operations and habitat environments with minimal human intervention. PSE develops automated control systems that manage various functions, such as navigation, thermal regulation, and life support. These systems enhance mission efficiency and reduce the risk of human error. Examples include automated docking systems used by the International Space Station (ISS) and autonomous rovers deployed on Mars.

4. SYNERGISTIC APPLICATIONS

Combined Use in Life Support Systems

The integration of chemical and process systems engineering is particularly evident in life support systems. Chemical processes are used to purify air and recycle water, while PSE integrates these processes into a reliable and efficient system. Case studies, such as the ISS life support systems, demonstrate how these disciplines work together to ensure sustainability.

In-Situ Resource Utilization (ISRU)

ISRU involves extracting and processing local resources on extraterrestrial bodies, such as the Moon and Mars, to produce water, oxygen, and building materials. Chemical engineering develops the extraction and processing techniques, while PSE integrates these processes into a coherent system. For instance, lunar regolith can be processed to extract oxygen, which can then be used for life support and propulsion. Efficient ISRU systems reduce reliance on Earth-supplied resources and enhance mission viability. With Figure 3, I am returning to my opening statement. Figure 3 shows MOXIE, the reactor that can convert captured carbon dioxide from Mars's atmosphere into oxygen. A lighting example of reactor engineering (chemical engineering) and automation and control (process systems engineering).

Advanced Manufacturing and Repair

Advanced manufacturing technologies, such as 3D printing, are crucial for space exploration. These technologies enable the in-situ production of tools, spare parts, and even habitats using local materials. Chemical engineering develops the materials and processes for 3D printing, while PSE ensures the integration and reliability of these manufacturing systems. This capability is vital for long-duration missions where resupply from Earth is not feasible.

Illustrative example: distillation on the Moon

NASA and other space agencies are making plans to develop ISRU technologies on the moon, including distillation. Distillation could be used to purify water (that is available in lunar ice) or extract oxygen, water or other byproduct after regolith is treated chemically (e.g. via hydrogen reduction, carbon thermal reduction or molten salt electrolysis). It might also be useful as part of a process to locally produce rocket fuels.

But distillation on the moon poses several (chemical engineering) challenges. For example:

- The Moon's gravity is about 1/6th of Earth's, which could affect the separation of liquids and vapors during distillation. However, this is a manageable issue with the proper equipment design;
- The Moon has no atmosphere, meaning distillation would need to occur in a pressurized, controlled environment to prevent liquids from boiling away instantly in the vacuum.
- Lunar temperatures range from extremely cold (-173°C at night) to very hot (127°C during the day). Distillation systems would need robust thermal insulation and temperature control to function effectively.
- Distillation requires energy to heat liquids. On the Moon, energy would likely come from solar panels or nuclear power sources, both of which are feasible but require careful planning.
- Equipment would need to be lightweight, durable, and capable of operating in harsh conditions. Transporting materials to the Moon is expensive, so efficiency is critical.

PSE can tackle lunar distillation challenges through a structured, holistic approach. It uses system modeling and simulation to predict performance and address low-gravity issues like phase separation.

PSE integrates distillation with power, water extraction, and life support systems for optimal resource and energy use. It optimizes designs to balance mass, efficiency, and reliability for lunar operations. Risk analysis identifies failure points and incorporates safeguards for harsh environments. Automated control systems enable real-time monitoring and adjustment, reducing human intervention.

And, PSE designs gravity-independent solutions using centrifugal force, capillary action, or pressure gradients. It also ensures sustainability and validates designs through microgravity and lunar simulations for reliable performance.

5. CHALLENGES AND FUTURE DIRECTIONS

Technical Challenges

Space exploration faces numerous technical challenges, including harsh environmental conditions, long-duration mission sustainability, and system reliability.

Engineers must develop technologies that can withstand high radiation, extreme temperatures, and mechanical stresses. Ensuring the durability and efficiency of life support systems, propulsion systems, and materials is paramount.

Future Research Areas

Future research must address the development of new energy sources, advanced materials, and sustainable life support systems. Innovations in biotechnology, such as bioengineered organisms for life support, and the application of artificial intelligence (AI) in process systems engineering, hold promise for future space missions. AI can optimize system performance, predict failures, and enhance automation.

Potential Breakthroughs

Potential breakthroughs include the integration of biotechnology and AI in space exploration. Bioengineered organisms could be used to produce food, oxygen, and other essential resources. AI-driven process systems could enhance the reliability and efficiency of spacecraft systems. These innovations could revolutionize space exploration, making long-duration missions more feasible and sustainable.

6. CONCLUSION

Chemical engineering and process systems engineering are indispensable for the success and sustainability of space missions. These fields contribute to the development of propulsion systems, life support technologies, materials, systems integration, simulation, automation, and ISRU. As humanity continues to push the boundaries of space exploration, innovations in these disciplines will be crucial in overcoming the challenges of the final frontier. The collaboration between chemical engineering and PSE will play a pivotal role in ensuring the success of future space missions, making it possible to explore and inhabit new worlds.

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