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PERSPECTIVE ARTICLE

Back to the roots: Process intensification in space exploration

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Abstract
In this cross-disciplinary perspective paper we focus on the relevance of process intensification (PI) for space exploration. We review past and current space-related research involving technologies from all four elementary domains of process intensification. We point out other PI technologies which have not yet been the subject of space-related research but may offer interesting new opportunities and help overcome certain challenges in space missions. Given the commonality of concepts and approaches, as well as the fact that both process intensification and space engineering address basically the same issues – equipment miniaturization and increased process efficiency, we advocate for more intensive interactions between both scientific communities to benefit from cross-fertilization and the exchange of new ideas and experiences.

Keywords
process intensification, space exploration, miniaturization, life support, environmental control, resource utilization

1. INTRODUCTION

In the context of Chemical Engineering, Process Intensification (PI) encompasses innovative apparatuses and techniques that offer drastic improvements in chemical manufacturing and processing, substantially decreasing equipment volume (miniaturization), boosting material and energy efficiency, reducing waste formation, and ultimately leading to cheaper, safer, sustainable technologies (Stankiewicz and Moulijn, 2000). Space technologies are also characterized by equipment miniaturization and efficiency boost, and while smaller plant size and higher process efficiency in terrestrial manufacturing are mostly driven by economic or environmental benefits, the very same features in space exploration become a necessity.

The story goes that the first research activities in the field of process intensification were triggered by experiments with artificially enhanced gravity in rotating centrifugal devices, that NASA carried out as part of one of its space projects (Stankiewicz and Moulijn, 2000). Those experiments inspired the Imperial Chemical Industries (ICI) New Science Group, led by Colin Ramshaw, to develop a concept of the Rotating Packed Bed (RPB) as a potential replacement for conventional distillation columns (Ramshaw, 1983). Today, more than four decades later, we go back to the roots and examine how process intensification, until now almost exclusively focused on chemical industries, could contribute (or is already contributing) to the progress of space exploration. This article takes a look at PI in space from two different perspectives: that of a chemical engineer and expert in process intensification, and that of an astronaut and expert in aerospace engineering.

2. SETTING THE SCENE: SPACE EXPLORATION

Generally speaking, systems seen in space exploration can be divided into two basic categories: closed, in-flight systems, where humans are isolated from external supplies and are entirely dependent on the resources available onboard at the start of the mission, and semi-closed systems, either orbital (e.g. International Space Station) or on-surface (lunar or planetary), where periodic supplies from Earth and/or extraction of some components from the local environment (In-Situ Resource Utilization – ISRU) are possible. An excellent example of the latter is MOXIE (Mars Oxygen ISRU Experiment) a project developed by NASA's Jet Propulsion Lab and MIT and tested on Mars, in which oxygen was produced by the solid-oxide electrolysis of CO_2 taken from the Martian atmosphere (Hecht et al., 2021; Hoffman et al., 2022). Human Mars exploration is an example of how a system can have aspects of both categories. During transit to Mars, there will be no resupply. However, once on the surface of Mars, resupply will probably occur only every 26 months. Between resupply visits, a crew on Mars plus whatever ISRU systems they rely on can be treated as a closed system.

Regardless of the type of space mission, a basic technological issue for human survival is the Environment Control and Life Support System (ECLSS), that provides or controls atmospheric pressure, fire detection and suppression, oxygen levels, proper ventilation, waste management and water supply (NASA, 2025). Core components of an ECLSS include: the Water Recovery System (WRS), the Air Revitalization System (ARS) and the Oxygen Generation System (OGS), although the short missions can operate without water recovery or oxygen generation. The WRS and the OGS on the ISS are schematically presented in Figure 1. Looking at the Water Recovery System from the chemical engineering perspective, one recognizes several unit operations which include distillation (in the microgravity environment carried out in a rotary Vapor Compression Distillation device), gas-liquid separation (also in a rotary device), several filtration steps and a catalytic oxidation reactor. The Oxygen Generation Unit usually comprises a Solid Polymer Electrolyzer (SPE) for oxygen and hydrogen generation, and a Sabatier Reactor for CO_2 methanation with hydrogen. The Air Revitalization System (not shown in Fig. 1) includes several filtration and adsorption steps (on active carbon, molecular sieves) and, similarly to the WRS, a catalytic oxidation reactor.

Next to the above, for long-term Space missions other ECLS-oriented systems need to be developed, among others including:

- material recycle systems, e.g. trash-to-gas, (Anthony and Hintze, 2014; Caraccio et al., 2013; Meier et al., 2021; Nur, 2013);
- manufacturing systems, e.g. for additive manufacturing of advanced materials, biomanufacturing or manufacturing of pharmaceuticals (Seoane-Viaño et al., 2022; Subin et al., 2025);
- plant-growth systems (Reed and Vanden Bosch, 2023; Zabel et al., 2016).

An obvious additional challenge in case of long-term missions beyond low Earth orbit (LEO) is the lack or limited availability of supplies from Earth. This imposes extra requirements on, for instance, the lifetime and regenerability of catalysts and adsorbents used, or the robustness and reliability of materials and devices. The envisaged possibilities of the In-Situ Resource Utilization (ISRU) in already established facilities on the lunar or Martian surface, using local atmosphere or soil to generate oxygen, water or propellants (Bennett et al., 2020; Pino et al., 2022; Rapp, 2018; Starr and Muscatello, 2020), offer only a partial solution to the problem.

3. SPACE EXPLORATION AND ELEMENTARY DOMAINS OF PROCESS INTENSIFICATION

Process intensification comprises four elementary domains: spatial, thermodynamic, functional and temporal (Van Gerven and Stankiewicz, 2009). Below, we present and discuss the selected, relevant technologies in each of those elementary domains of PI, focusing on their applicability and the role they play or may play in space exploration.

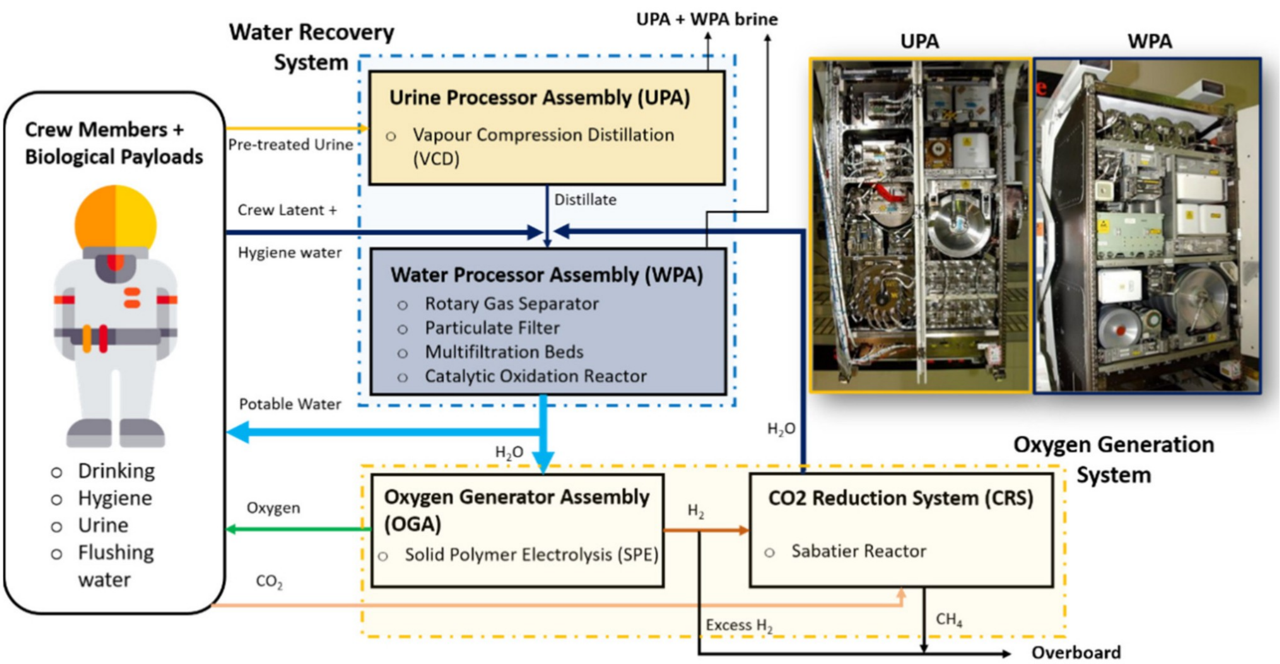


Figure 1. Simplified scheme of Water Recovery System and Oxygen Generation System onboard the International Space Station. Reproduced from (Volpin et al., 2020). Copyright ©2020 Volpin F., Badeti U., Wang C., Jiang J., Vogel J., Freguia S., Fam D., Cho J., Phuntsho S., Shon H.K. Licensed under CC BY 4.0.

3.1. Spatial domain

The spatial domain of process intensification is characterized by the multi-scale structuring of system geometries, in order to eliminate or minimize randomness. Randomness at any scale in a chemical processing system leads to reduced predictability and control of the system behaviour, while a purposeful introduction of a reproducible structure should result in the improvement of both. A structure is much easier to understand than a randomly arranged space. Also, mathematical descriptions (models) of structured systems are simpler and can be done with less human/computer time and effort. A typical example of a random system in industrial equipment is a fixed bed of catalyst particles in a catalytic reactor, while a monolithic catalyst consisting of straight, regular channels presents an example of a structured alternative. Structures in the spatial domain of process intensification cover a wide range of scales, from the molecular, nanometer scale, up to the scale of an industrial apparatus. They target four elements of chemical processes: reactions, heat transfer, mass transfer and fluid flow/mixing (Stankiewicz et al., 2019).

3.1.1. Structures at molecular scale

Shape-selective catalysts and adsorbents present the largest group of artificially created structures at molecular scale, that significantly increase the selectivity of catalytic reactions or molecular separation processes. *Zeolites* are widely used in the chemical industry, for instance as catalysts in Fluid Catalytic Cracking (FCC). In space exploration their most important role is that of selective adsorbents for CO_2 removal (Miteva and Stoyanova, 2020; Son, 2018). Importantly, several types of zeolites (A, X and modernite) were successfully grown in space, showing larger crystals with less defects than the ones grown in terrestrial conditions (Sacco et al., 1994; Warzywoda et al., 2000).

Another, more recent group of molecular-scale structures that can be used for shape-selective operations, are *Metal-Organic Frameworks (MOFs)*. Hydrogen storage is the most important terrestrial application of Metal-Organic Frameworks. Other applications resulting from MOFs' unique structural properties include CO_2 or isomer separation. Similarly, in space exploration Metal-Organic Frameworks are investigated as potential solutions for CO_2 adsorption (Glover et al., 2014; Thornton et al., 2020 – Fig. 2), hydrogen storage (Zhang et al., 2021) and volatile organic compounds (VOCs) removal (Sun et al., 2024).

3.1.2. Structures at supramolecular scale

Monolithic catalysts are commonly applied in the cleanup of the automotive exhaust gases and a small number of industrial gas-liquid catalytic reactions (Heck et al., 2001; Nijhuis et al., 2001). Thanks to their structure comprising multiple straight, parallel channels, they offer large specific surface areas at a very low-pressure drop. The most important space-related application of monolithic catalysts investigated in the literature is in the propulsion systems (Amariei et al., 2010; Amrousse et al., 2010). An interesting, structured alternative to monoliths are the so-called Microliths®, developed at Precision Combustion, Inc. (Junaedi et al., 2016). The Microlith substrate consists of a series of metal meshes with very small channel diameters (Fig. 3). The metal meshes can be coated with either active metals, such as base metals, transition metals, and noble metals, or active sorbent materials, such as zeolites, metal organic frameworks, and activated carbon. They can therefore be applied in CO_2 adsorbers, in Sabatier reactors, or in methane reformers for Solid Oxide Stack systems. According to Junaedi and co-authors (Junaedi et al., 2016), the Microliths provide high heat and mass transfer coefficients, low thermal masses, and extremely high reaction rates.

Another type of supramolecular-scale structures with a considerable potential for applications in space exploration are *ceramic or metallic foams*. They are in fact "random structures", because the spatial distribution of pore sizes in a foam is random. In contrast to monoliths, the open structure of foams allows efficient heat transfer via convection in all directions. In classical chemical engineering research foam catalysts have been studied in a variety of processes, particularly gas-phase reactions, such as CO_2 reduction, methane reforming, CO oxidation or methane combustion. Recently, an interesting concept of foams packed with a particulate catalyst have been

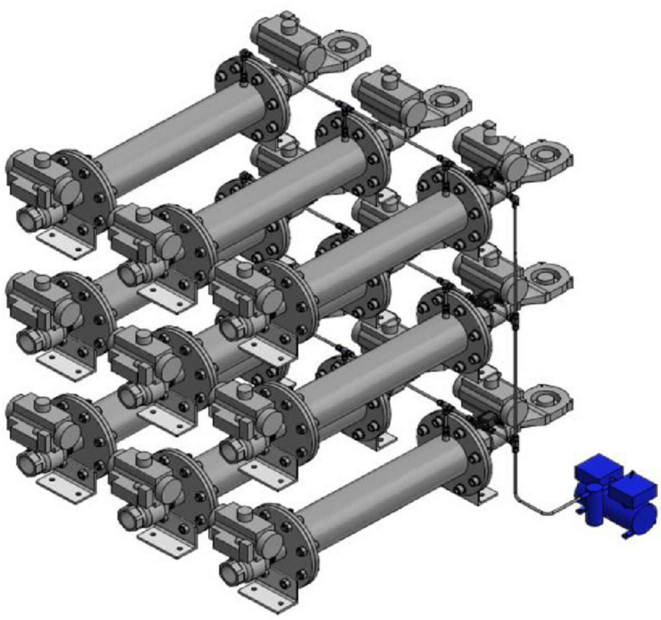
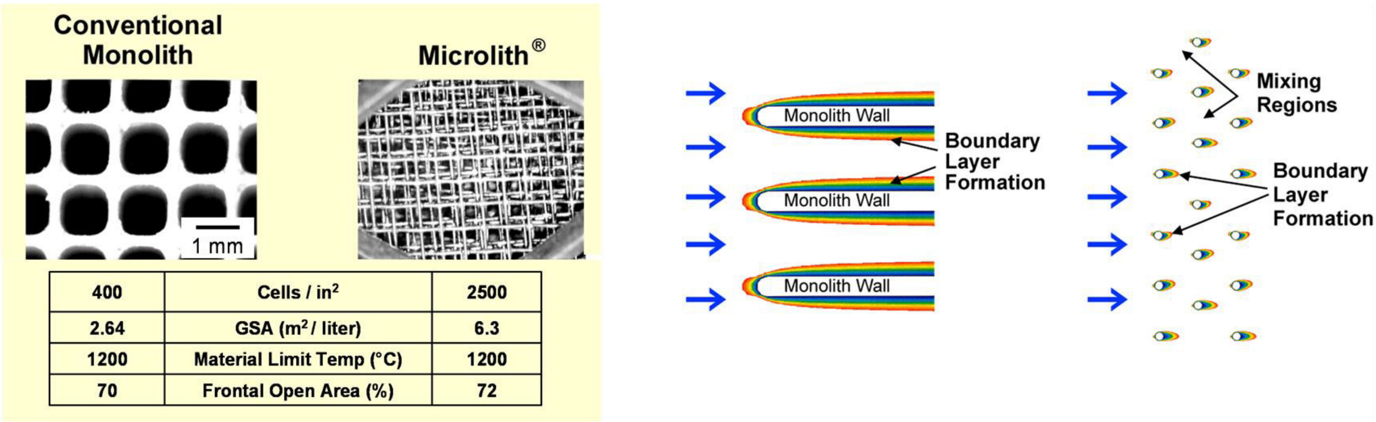


Figure 2. A MOFs-based adsorption-desorption system for CO_2 removal from the space station atmosphere. The removal capacity of the nine-module system amounts to 18 kg_{CO_2}/day. Reproduced with permission from (Thornton et al., 2020). Copyright ©2020 CSIRO.

proposed for methane steam reforming by researchers at the Politecnico di Milano (Zaio et al., 2025). In space-related research, foam structures have been investigated less intensively. Among a few works related to this topic one should mention an interesting process concept for *in-situ* propellant production (ISPP) on Mars, presented by Hu et al. (2007), where Sabatier reaction and water-gas shift reaction are carried out in microchannel reactors fitted with catalysts on FeCrAlY foam substrates (Fig. 4). Recently, a novel dehumidification device for the space station environment, based on copper foam, has been presented by Zhu et al. (2025a).

3.1.3. Structured equipment

Micro- and milli-structured equipment, mostly reactors and heat exchangers, offer extremely high mass and heat transfer rates and have already found numerous applications in terrestrial chemical processes. An excellent example here is the *microchannel reactor* applied at a fine chemical process at DSM in Linz (currently ESIM Chemicals), where a continuous structured device of ∼ 3 L volume replaced a batch-operated, 10 m^3 large conventional reactor, retaining the same production capacity. The spectacular equipment miniaturization



400	Cells / in^2	2500
2.64	GSA (m^2/ liter)	6.3
1200	Material Limit Temp (°C)	1200
70	Frontal Open Area (%)	72

Figure 3. Physical characteristics of conventional, long honeycomb monolith and Microlith® substrates, and CFD analysis of boundary layer formation for a conventional monolith and three Microlith screens. Reproduced with permission from (Junaedi et al., 2016).

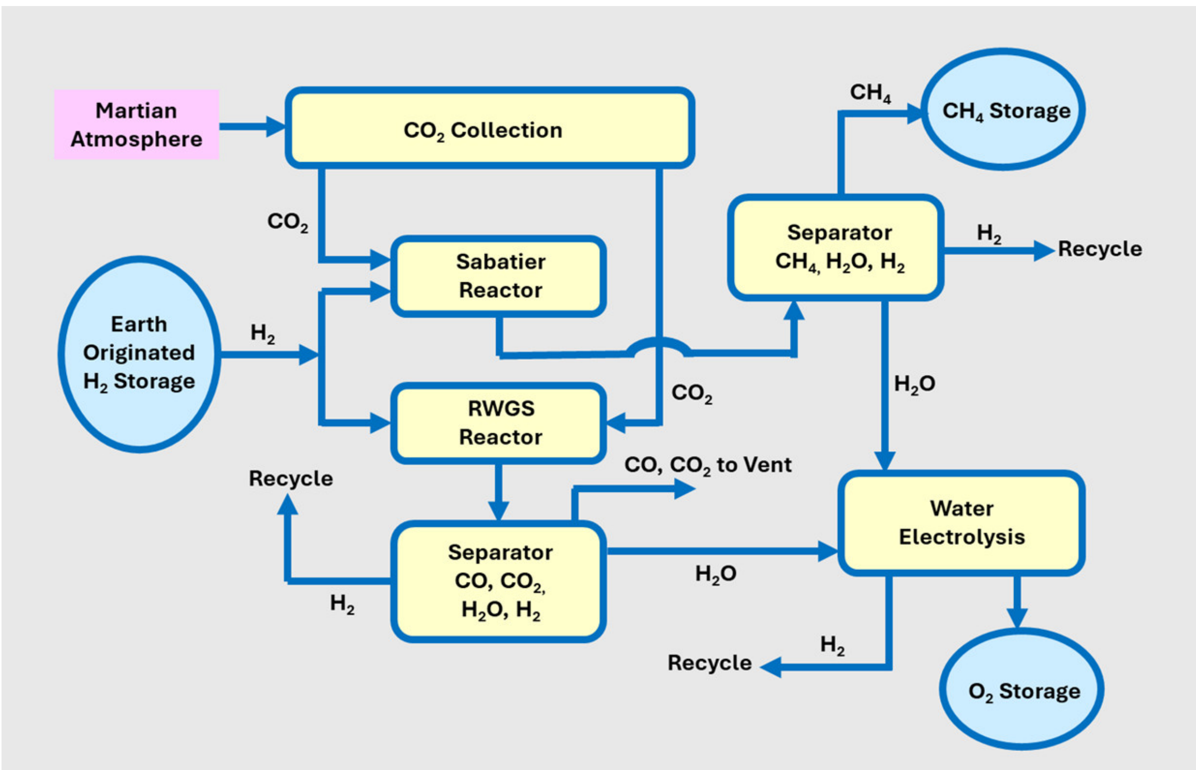


Figure 4. Concept of the integrated foam catalyst-based reactor and separator system for CO_2 conversion to CH_4 and O_2 on Mars, as proposed by Hu et al. (2007).

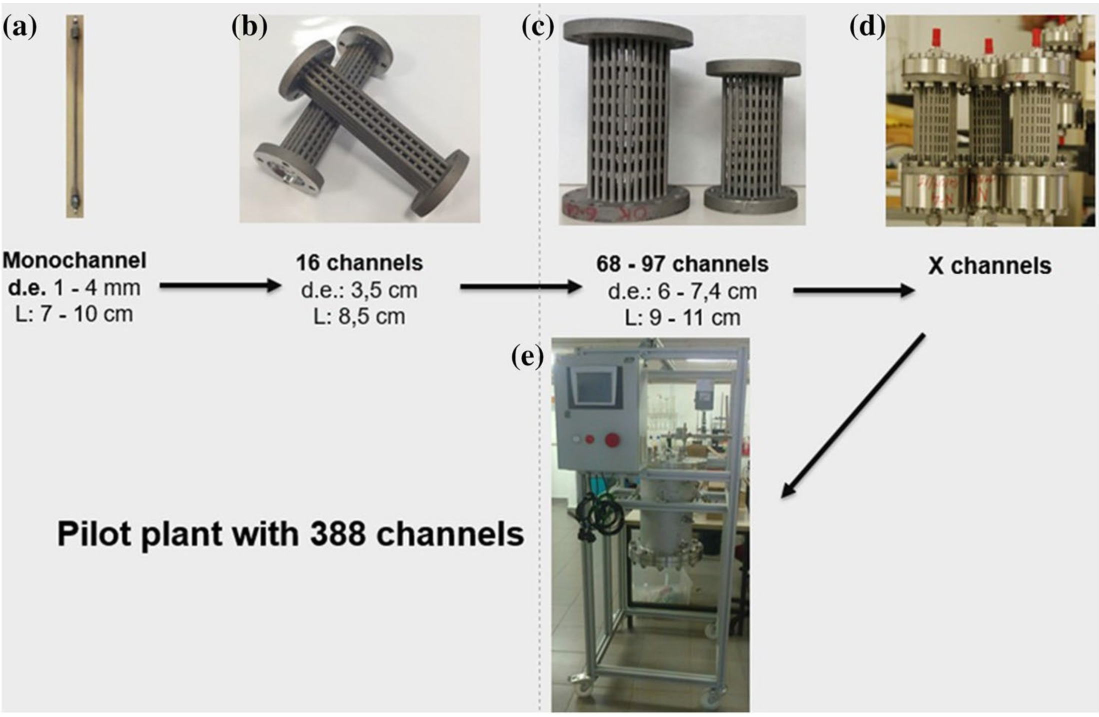


Figure 5. Scale-up of a millichannel Sabatier reactor by numbering up from monochannel to pilot scale. Reproduced from (Pérez et al., 2019). Copyright ©2019 Pérez S., Aragón J.J., Peciña, I., Garcia-Suarez E.J. Licensed under CC BY 4.0.

by a factor of more than 3,000 was accompanied by a 20% increase in the material yield and product selectivity (Poechlauer et al., 2009). The Sabatier reaction presents undoubtedly the most important target process relevant for space exploration that can be improved by application of microchannel reactors. One of the proposed designs is the earlier mentioned microchannel reactor with foam catalyst, developed by researchers at the Pacific Northwest National Laboratory and the Colorado School of Mines (Brooks et al., 2007). In the subsequent step, the microchannel Sabatier reactor can be integrated with a similar water-gas shift reactor and an electrolyzer, resulting in a complete system for the in-situ propellant production from CO_2 on Mars (Holladay et al., 2007; Hu et al., 2007). An alternative Sabatier reactor design, based on diffusion-bonded microchannel plates, has been proposed by Thompson (2015). An important advantage of micro- or milli-channel reactors is the easiness of their capacity increase, by simple numbering up the reaction channels, as shown in the work of Pérez et al. (2019) – see Figure 5. Next to the Sabatier reaction, other processes relevant for Space exploration may benefit from microstructured reactors. Recently, Chinese researchers developed a concept of a gas-liquid microchannel reactor for the in-situ electrochemical production of methanol from CO_2 in the Martian atmosphere (Rizhi et al., 2024). In the future, long-duration space missions, microfluidic reactors may find application in the on-board production of some basic pharmaceuticals (Averesch et al., 2023; Kuang et al., 2022; Seoane-Viaño et al., 2022), although in many cases product purification steps will present a considerable techno-economic challenge (McNulty, et al., 2021).

Besides chemical reactors, structures are commonly applied in high-performance, compact heat exchange equipment. *Plate and microchannel heat exchangers* are often seen in the space sector, e.g. Hasan et al. (2006); Lee and Mudawar (2016); Shin et al. (2011). Additive manufacturing offers here further possibilities with regard to types of structures, their optimization and materials used, as presented in the excellent review by Careri et al. (2023). In the earlier described MOXIE project six heat exchangers were made using additive manufacturing and became the first 3D-printed devices to operate on Mars (Hecht et al., 2021, Fig. 6).

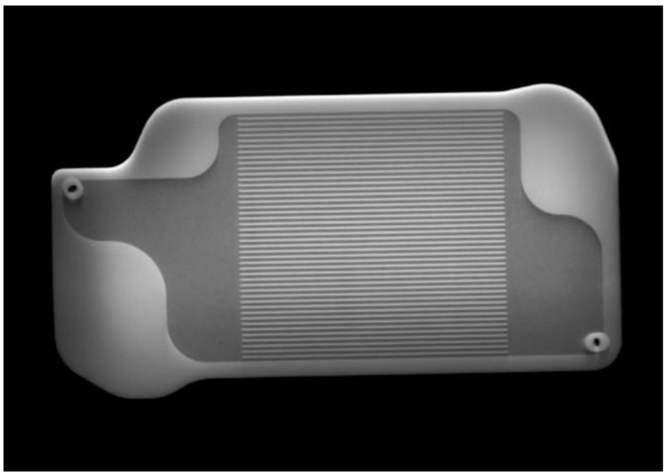


Figure 6. X-ray of the interior of a 3D-printed heat exchanger inside Perseverance's MOXIE instrument (Courtesy: NASA).

3.2. Thermodynamic domain

The thermodynamic domain of process intensification focuses on energy. The basic question here is how energy can be transferred from its source to the recipient in the optimal way, which includes the right form, amount, time and position. All energy that does not fit the above (i.e. "wrong" form, more than needed, too early or too late, wrong place) is not used optimally and (partially) dissipates. Although heat is an important form of energy, the term "energy" is by no means restricted to it. On the contrary, the thermodynamic domain of PI is characterized by the use of alternative energy forms and transfer mechanisms. Among them, the development of novel, intensified processes based on electricity (preferably from renewable sources) as a primary source of energy presents a key path to decarbonization of terrestrial chemical manufacturing and should also play a significant role in the development of extra-terrestrial technologies.

3.2.1. Electric and magnetic field energy

The most common process applications of the *electric fields* today, both on Earth and in space, are in electrochemical and electrocatalytic processes. Typically, electrolytic units, whether alkaline, PEM or SOXE cells, present stationary assemblies or stacks of flat, parallel electrode plates – see, for example the SOXE stack of the earlier described MOXIE system in Fig. 7 (Hinterman and Hoffman, 2020). Other, intensified designs, e.g. rotating electrode, "Swiss-roll cell", capillary-gap cell or rotor-stator spinning disc membrane units, have also been reported (Stankiewicz and Nigar, 2020). An interesting electrochemical reactor with microchannels for carbon dioxide reduction in space has been proposed by Feng et al. (2022).

Electric fields are also used in chemical industries for intensification of liquid-liquid extraction (controlling droplet break-up and coalescence) and in electrostatic precipitators for gas cleaning. In the space sector, they have been proposed and investigated as the so-called dry triboelectrostatic separation technology for retrieving oxygen from lunar regolith. Here, the electrostatic field helps separate the lunar ilmenite ($FeTiO_3$), which can be used as an oxygen source, from other, unwanted minerals (Li et al., 1999; Trigwell et al., 2009).

Magnetic fields can, in normal gravity, change properties and behaviour of fluidized beds containing magnetizable particles (Rosensweig, 1979). The presence of a uniform magnetic field oriented parallel to the gas flow prevents the formation of the gas bubbles in the fluidized bed and enables operation in a stable emulsion up to high gas velocities. This phenomenon, although never implemented on the industrial scale on Earth, can have interesting applications in space exploration and can enable operating fluidized-bed systems in microgravity conditions. This was shown by, among others, researchers from Oregon State University, who conducted experiments with Gradient-Magnetically Assisted Fluidized Bed (G-MAFB) under non-uniform magnetic field conditions and showed that magnetic forces may indeed be employed for producing stable fluidization in microgravity environment (Jovanovic et al., 2004; Sornchamni et al., 2004). The researchers also showed that the G-MAFB can be used as a renewable filter, in which granular ferromagnetic filtration media are magnetically consolidated into a packed bed (Sornchamni et al., 2005).

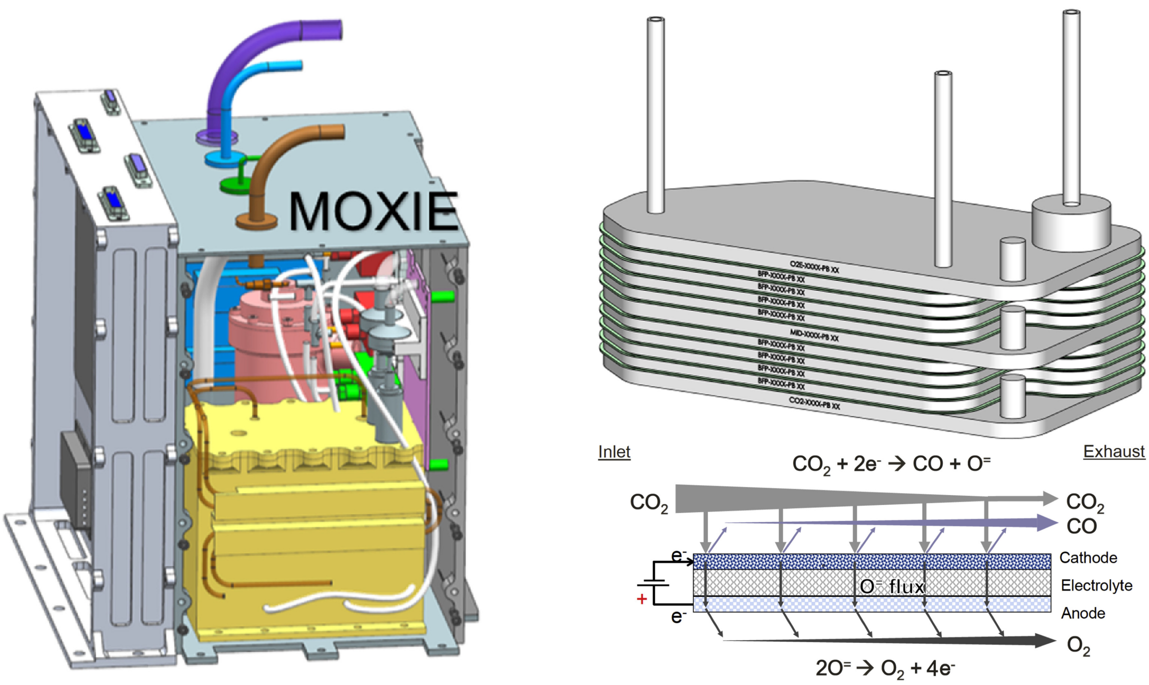


Figure 7. Flat-plate electrodes SOXE stack of the MOXIE experiment. Reproduced from (Hinterman and Hoffman, 2020), with permission of Elsevier Ltd. Copyright ©2020 IAA.

An important application area of magnetic fields on Earth is mineral processing. Commercial-scale separations of paramagnetic or ferromagnetic minerals exist, and Figure 8 presents an example of a high-gradient magnetic mineral separator developed by METSO Corporation. Similarly, magnetic fields could be used for the beneficiation of lunar regolith, as shown in publications from the University of Warmia and Mazury, Poland (Kobaka et al., 2023) and the Missouri US&T (Bachle et al. 2024a; 2024b; 2025).

Finally, in a microgravity environment magnetic fields can also be applied in gas-liquid systems (e.g. microalgae reactors), facilitating the separation of the gas phase via magnetically induced buoyancy (Kura, 2024; Romero-Calvo et al. 2022).

3.2.2. Electromagnetic-to-thermal energy conversion

Electricity-based heating methods utilizing electromagnetic-to-thermal energy conversion are gaining increasing interest in the context of industry decarbonization. *Microwaves*, that generate heat via internal molecular friction and magnetic hysteresis in the processed material, have long been used on the industrial scale for, among other things, food pasteurization and sterilization, drying of pharmaceuticals, or sintering of ceramic products. Microwave technology is also being intensively investigated in the context of intensification of homogeneous and heterogeneous (catalytic) reactions (Stankiewicz et al., 2019). Also, deep adsorbent regeneration can be advantageously performed using microwave heating as reported by various groups (e.g., Cherbański et al., 2011; Chronopoulos et al. 2014; Ellison et al., 2021; Meloni et al., 2021). On the other hand, investigators working in space research focus on the application of microwaves as a method of heating lunar regolith, which appears to possess good dielectric properties and responds well to microwave irradiation. Using microwave heating may facilitate fracturing and fragmentation of lunar regolith, to extract water and other volatiles (Cole et al., 2023; 2025; Etheridge and Kaukler, 2011; Wang et al., 2025) or to mine and process it for construction materials (Nejati and Radziszewski, 2014; Satish et al., 2006; Srivastava et al., 2016). Fig. 9 shows a concept of the Microwave Heating Demonstrator (MHD) payload prepared in a project coordinated by the Open University, UK, and supported by the UK Space Agency (Lim et al. 2022; 2024a).

Induction heating generates eddy currents to heat a material placed in an alternating magnetic field. In the case of ferromagnetic materials, part of the heat released is the result of hysteresis losses. This type of heating is extremely intensive and opens interesting opportunities for endothermic catalytic processes, e.g. steam or dry methane reforming (e.g. Almind et al., 2020; Nguyen et al. 2022; Varsano et al., 2019). In space exploration induction heating can be used as a fast heating method for CO_2 desorption. This was proposed by Thornton et al. (2020), who investigated the application of induction heating to a CO_2 adsorption-desorption system, where a MOF-based adsorbent was washcoated onto an induction-responsive Fecralloy^{TM} monolithic substrate (Fig. 10).

Similarly to induction heating, research on resistive *Joule heating* focuses on different applications on Earth and in space. The chemical process industry-oriented research sees Joule heating primarily as a convenient method of thermal energy transfer to endothermic catalytic processes, such as methane reforming. For example, Tronconi and co-workers in Politecnico di Milano investigated innovative structured catalysts for Steam and Dry Methane Reforming based on SiSiC open-cell foam, that can be directly heated using Joule heating (Zheng et al., 2023a; 2023b). In the space domain, researchers from the Kennedy Space Center and MIT proposed and studied a concept of Joule-heated Molten Regolith Electrolysis Reactor, in which a simultaneous production of oxygen and metals from regolith on the Moon or Mars could be realized (Sibille and Dominguez, 2012; Schreiner et al., 2016 – Fig. 11).

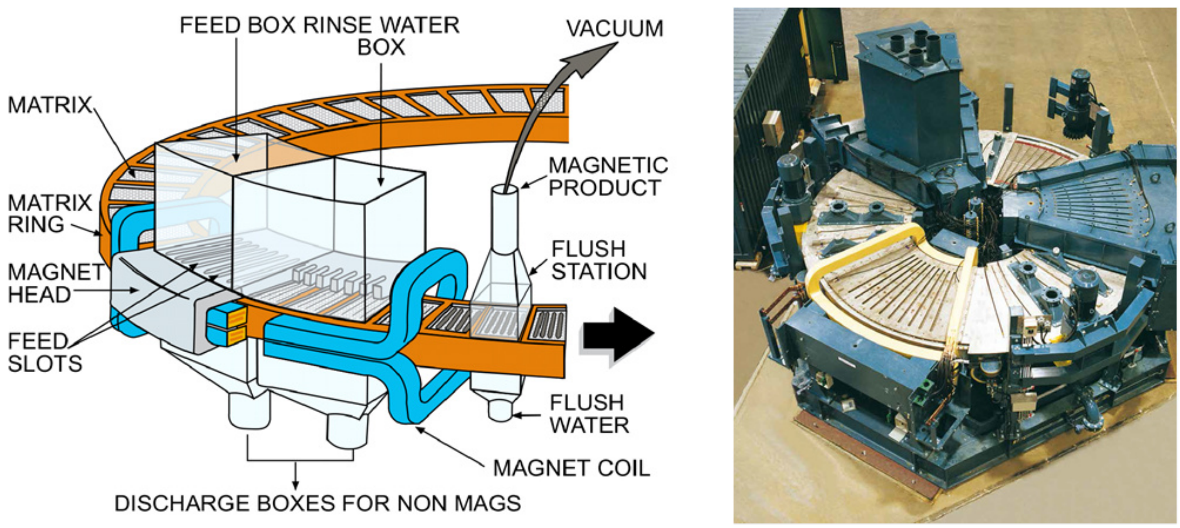


Figure 8. High-field magnetic separator for mineral processing. Courtesy: METSO Corporation, Finland, www.metso.com.

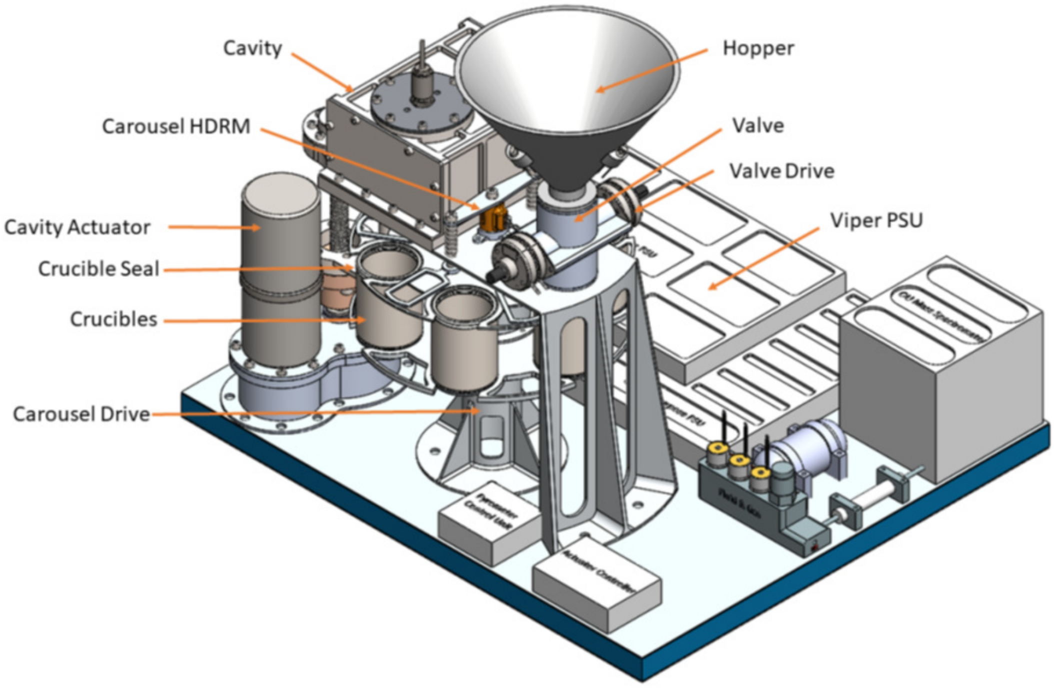


Figure 9. A model of the conceptual design of Microwave Heating Demonstrator payload for lunar application. Reproduced with permission from (Lim et al., 2024a).

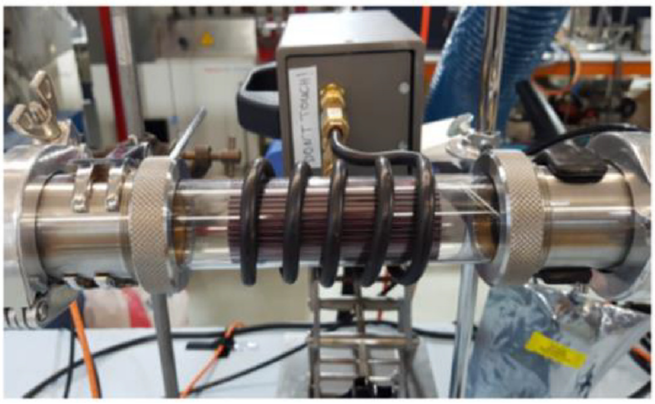


Figure 10. Induction heating of the Fecralloy^{TM} substrate inside the glass adsorption column. Reproduced with permission from (Thornton et al., 2020). Copyright ©2020 CSIRO.

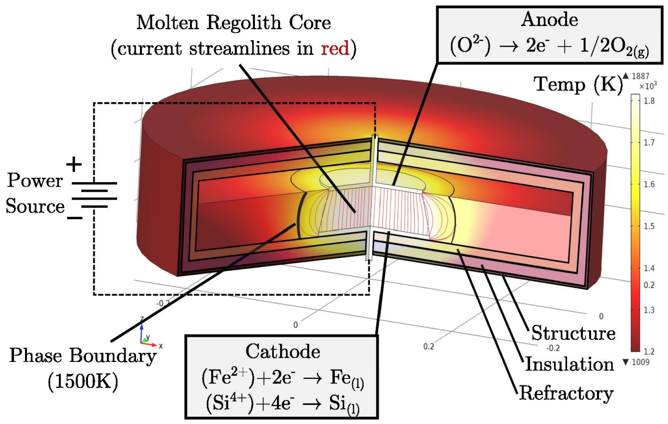
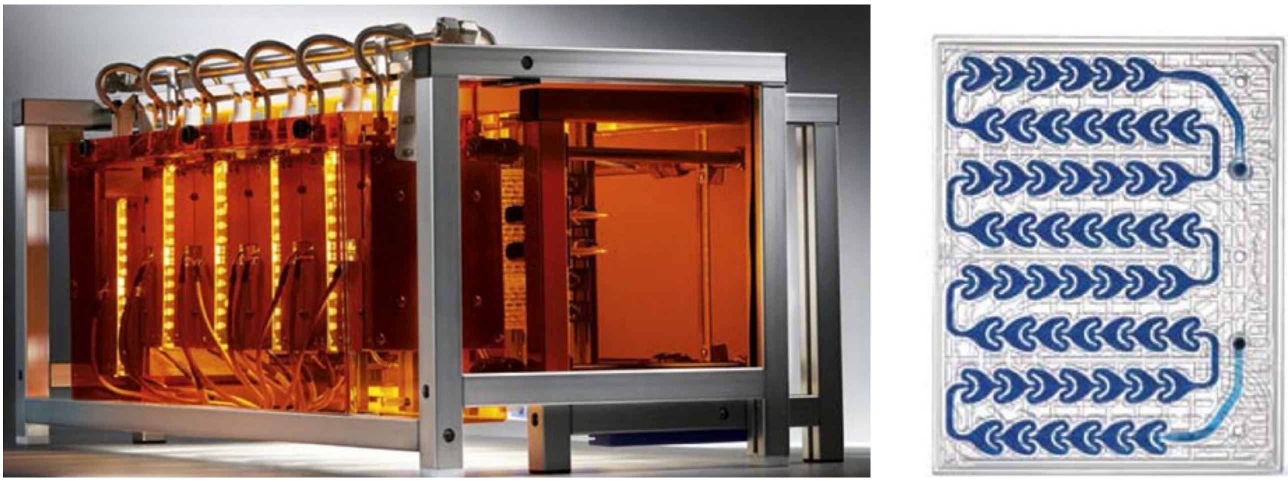


Figure 11. Joule-heated Molten Regolith Electrolysis reactor that produces oxygen gas at the anode and molten metals at the cathode. Reproduced from (Schreiner et al., 2016), with permission of Elsevier Ltd. Copyright ©2016 COSPAR.

3.2.3. Light energy

Similarly to electrochemistry, *photochemical and photocatalytic processes* have a long history and cover a wide range of industrial applications. Process intensification research in this area aims at development of innovative photochemical reactors utilizing more energy-efficient light sources and addressing the most important limitation, the photon transfer from the light source to the reaction location. Examples of such intensified designs are the LED-based Corning®Advanced-Flow™G1 Photoreactor (Elgue et al., 2015; Fig. 12), annular reactors (De Hert et al., 2025; Khodadadian et al., 2018) or the Rotor-Stator Spinning Disk Photoreactor (Chaudhuri et al., 2022). Photocatalytic processes are also highly relevant for space exploration, and various groups are working in this area. Applications investigated are numerous and include photopolymerization of composite materials (Kondyurin et al., 2006), photodegradation of wastewater contaminants (Antoniou and Dionysiou, 2007; Mezzina et al., 2022; Udom et al., 2013; Xia, 2022), photocatalytic CO_2 conversion to fuels (Low et al., 2023; Yang et al., 2021) or carbon nanotubes (Wang et al., 2024), or Volatile Organic Compounds removal from the spacecraft cabin atmosphere (Perry et al., 2011).



(a) (b)

Figure 12. Corning® Advanced-Flow™G1 Photoreactor: (a) 5-plate assembly; (b) reactor plate. Copyright ©2016 Corning Incorporated.

Lasers are a special category of monochromatic light sources that can be used for efficient, precise control of photocatalytic processes (De Hert et al., 2025). The vast majority of research papers on the use of laser technology in space exploration is dedicated to laser-based propulsion systems (e.g. Duan et al., 2022; Duplay et al., 2022; Michaelis and Forbes, 2006; Zhang et al., 2024; Zhu et al., 2024). Another envisaged potential application area of lasers in Space exploration is the oxygen extraction from lunar regolith via vacuum laser pyrolysis (Robinot et al., 2025).

3.2.4. Ultrasound energy

The most important application area of the *ultrasonic energy* in Earthbound processes is cavitation-based intensification of liquid-phase reactions. The implosion of ultrasound-generated cavitation microbubbles releases an energy impulse powerful enough to form free radicals and change the reaction mechanism or to destroy interfacial films, boosting the rate of mass transfer in the system (Stankiewicz and Nigar, 2020). In space exploration the primary applications of ultrasound energy are in planetary drilling and sample (pre)processing (Bar-Cohen et al., 2001; Firstbrook et al., 2017; Sherrit et al., 2022; Wang et al., 2018).

Micro- and nanobubbles, a technology closely related to the ultrasound-induced micro cavitation, presents a fast-growing research and application area (Marui, 2013; Zhao et al., 2025). The technology was shown to be effective in, among other things, water pollution control and in crop yield enhancement. Both of these applications can be relevant for long-term space missions. On the one hand, nanobubbles that exhibit clear anti-microbial working and were shown to reside in water more than 6 months, could be effectively used for astronauts drinking water sanitation (Shimada, 2017). Furthermore, they could be used to increase harvest efficiency in spaceflight food production systems (Morón-López et al., 2023).

3.2.5. Special states of matter

The thermodynamic domain of process intensification also includes the utilization of two "special" states of matter: plasmas and supercritical fluids. On Earth, applications of non-thermal plasmas are mostly seen in materials engineering (synthesis, spraying, etching, CVD or treatment of surfaces) and in medicine (sterilization of surfaces, tissue engineering, wound healing or treatment of skin diseases). Despite intensive research efforts in the field of plasma reactors, only few commercial-scale plasma processes have emerged so far, including the classical Hüls technology for hydrocarbon cracking to acetylene, ozone generation and incineration (Stankiewicz and Nigar, 2020).

Both in Earthbound and in space-related research numerous studies are being carried out on plasma CO_2 conversion – on Earth as an environmental measure to slow down global warming, while in space as an ISRU method for oxygen generation from Martian atmosphere. Several interesting papers have been published on plasma-assisted CO_2 dissociation on Mars (Guerra et al., 2022; Ogloblina et al., 2021; Wang et al., 2022; Zhu et al., 2025b). In one experimental study sponsored by the European Space Agency, the researchers report generation of oxygen from the simulated Martian atmosphere using a microwave-induced plasma (Kelly et al., 2024). Other authors postulate integration of heterogeneous catalysts in the plasma reactor (Alhemeiri et al., 2024). Next to the CO_2 dissociation, another process that could potentially benefit from plasma technology is the hydrogen recovery from methane generated in the Sabatier unit (Abney et al., 2010; Atwater et al., 2009). Also, plasma reduction of lunar regolith to extract oxygen has been investigated (Currier and Blacic, 2000; Gott et al., 2021; Osborne et al., 2024).

Two *supercritical fluids*, CO_2 and H_2O, are of special interest for the chemical industry and find applications, among other things, in extraction (food, cosmetics and pharmaceuticals), and oxidation (waste management) processes. Similarly, concepts investigated in the context of space missions include the supercritical CO_2-based extraction from Martian regolith (Menlyadiev et al., 2019; Wang, 2005) and Supercritical Water Oxidation for water reclamation (Hicks et al., 2012; Riggins, 2023; Scott, 2025).

3.3. Functional domain

The functional domain of process intensification is characterized by synergisticly combining process steps and operations. Integration of reaction and separation (reactive separation) or integration of different separation techniques in a single step (hybrid separation) are two of the most important groups of intensification methods belonging to this domain. Among them, membrane-based integrated systems attract particular attention in the field of space exploration.

Membrane reactors can be applied in a broad range of single-phase or multiphase chemical processes, and a membrane can play diverse functions in the reactor, as reviewed by Sirkar et al. (1999). In applications for space, research efforts are predominantly focused on membrane-aerated bioreactors (MABR) for wastewater treatment (Bullard et al., 2023; Chen et al., 2008; Christenson et al., 2015; 2018; Hooshyari et al., 2024; Rector et al., 2006). Figure 13 presents one of the proposed designs – the Counter-diffusion Membrane Aerated Nitrifying Denitrifying Reactor (CoMANDR), based on a submersible membrane module (SMM – Christenson et al., 2015).

An interesting concept of a gas-phase membrane reactor for CO_2 removal in the life support system has been proposed by Hwang et al. (2008). Here, carbon dioxide is separated from the air by the membrane in a concentric system and is immediately catalytically hydrogenated in the Sabatier reaction on the sweep-side.

Membrane distillation, a technology well known in the terrestrial water desalination sector, has attracted research interest in the context of wastewater treatment and reclamation for use on space stations (Cath et al., 2005; Sagar et al., 2024; Tabasian et al., 2024; Volpin et al., 2020). It can be further combined with titania-based photocatalysis, which could help in the removal of nitrogen-containing compounds, thus improving the overall recovery efficiency (Rangan, 2019). An important advantage of membrane distillation is that is utilizes low-temperature heat sources, which makes is an attractive option for lunar conditions. To this end, Wong et al. (2025) investigated the direct-contact membrane distillation as a potential method for reconcentrating Ionic Liquids used to separate metals and oxygen in lunar regolith – see Figure 14.

Carbon capture is the primary target application of the *membrane absorption* systems, both on Earth and in space. An important difference is that the usually large-scale terrestrial processes utilize amines as CO_2 absorbents, while the small-scale spacecraft systems are based on Ionic Liquids. Figure 15 presents a scheme of Honeywell's Carbon Dioxide Removal by Ionic Liquid Sorbent (CDRILS) system with hollow-fibre membrane absorption. The system is designed for the International Space Station and offers rapid CO_2 transfer and efficient capture within a small equipment volume (Yates et al., 2018; Knox, 2017). Another option for the Ionic Liquid-based membrane absorption are liquid membranes, in which an ionic liquid absorbent fills a porous membrane, while the gas phase flows on both sides of the membrane. Such systems have been investigated in the context of ISRU (Tata et al., 2023) and long-term CO_2 management in space suits (Wickham et al., 2015).

The last group of technologies representing the functional domain of process intensification that are of interest for Space applications are heat-integrated separations, in particular *heat pump-assisted distillation systems*. Heat pumps are designed to move thermal energy opposite to the direction of spontaneous heat flow by absorbing heat from a cold space and releasing it to a warmer one. In distillation systems, they are used to upgrade the discharged lower-temperature heat from the condenser, improving the overall energetic efficiency of the

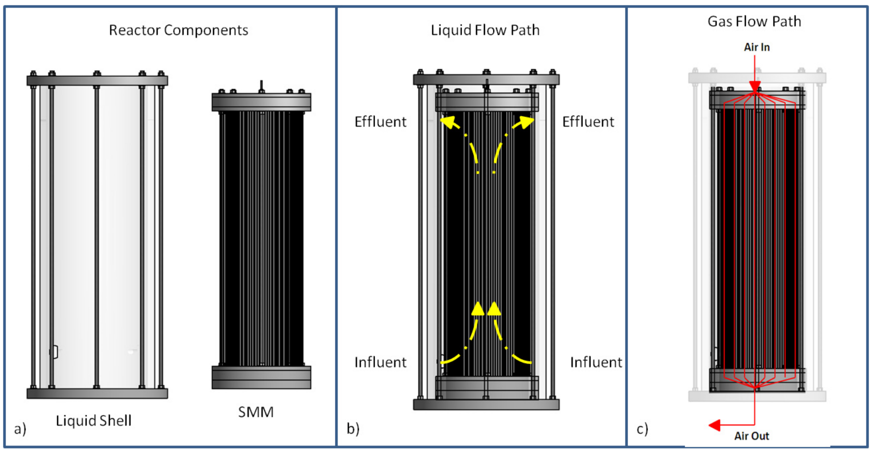


Figure 13. CoMANDR membrane bioreactor for treating Space-based waste stream. Reproduced from (Christenson et al., 2015), courtesy: NASA.

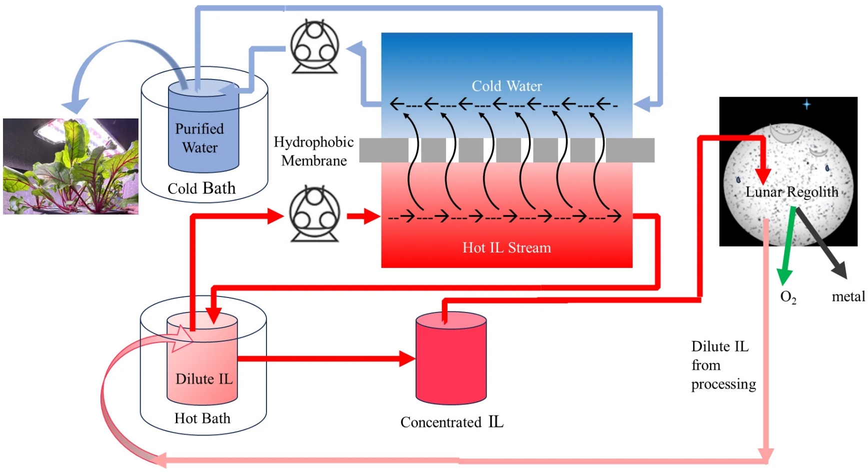


Figure 14. Membrane distillation system for reconcentration of Ionic Liquids in processing lunar regolith. Reproduced from (Wong et al., 2025). Copyright ©2025 Wong M.J., Sagar V., Lynam J.G. Licensed under CC BY 4.0.

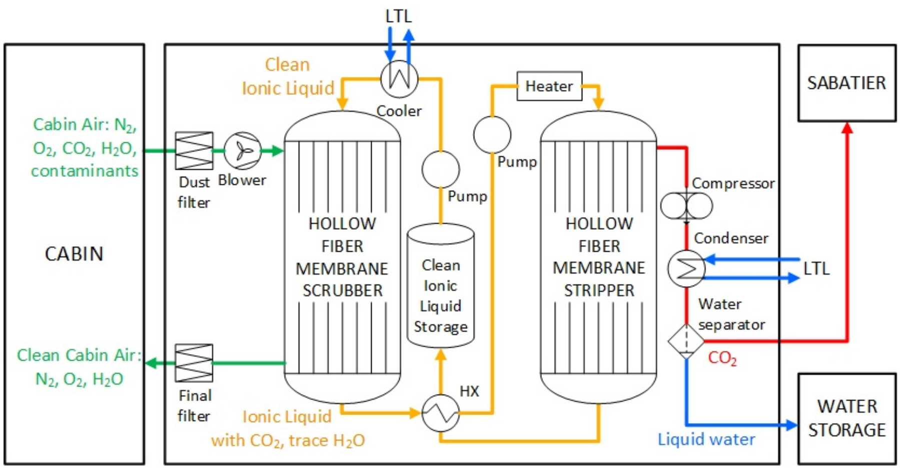


Figure 15. Scheme of Honeywell's Carbon Dioxide Removal by Ionic Liquid Sorbent (CDRILS) system. Reproduced from (Knox, 2017), courtesy: NASA.

system. Heat pumps are extensively investigated in terrestrial technologies and early industrial-scale applications have been reported (Kiss and Olujić, 2014). In space domain, integration of thermoelectric heat pumps in wastewater distillation systems has attracted considerable attention (Anatychuk et al, 2023; Erickson and Ungar, 2013; Rifert et al., 2019a; 2019b; 2021). Another interesting concept is for a thermoelectric heat pump-assisted membrane distillation system, where the TE heat pumps are positioned between water vapor selective membranes (Lee et al., 2018 – Figure 16).

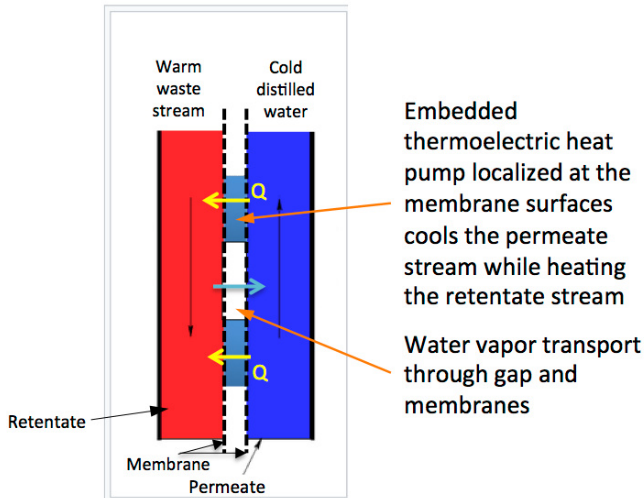


Figure 16. Thermoelectric heat pump-assisted membrane distillation system proposed by Lee et al. (2018). Courtesy: NASA.

3.4. Temporal domain

The underlying manipulative parameter in the temporal domain of process intensification is time. The most important approach in this domain concerns purposeful introduction of unsteadiness or periodicity (e.g. cyclic operation) in process units. Two technologies belonging to this domain have attracted research interest related to space exploration and are discussed below.

Pressure Swing Adsorption (PSA) is a technology widely applied on the commercial scale in the chemical sector, for example in oxygen or hydrogen purification processes and. particularly, in CO_2 removal from process off-gases and flue gases. PSA is currently the most important adsorption-based industrial technology for CO_2 capture. Not surprisingly, PSA has also been investigated in the context of CO_2 removal in Life Support Systems (Erden, 2016; Papale et al., 2006; Smalls et al., 2020). Among others, Papale and co-workers presented an interesting concept of a PSA system based on solid amines, combining both the CO_2 and humidity control requirements into a single, lightweight device (Figure 17). According to the authors, the regeneration of the proposed system into space vacuum or by an inert purge stream can significantly extend the maximum duration of an extravehicular activity mission and can reduce the overall subsystem weight compared to conventional technologies (Papale et al., 2006). Other, space-related applications of the PSA technology discussed in the literature include trace impurities removal (Wójtowicz et al., 2021) and oxygen concentration (Gilkey and Olson, 2015).

Pulsating heat pipes (PHPs), also known as Oscillatory Heat Pipes, are simple tubular devices for intensified heat transport in small-scale systems that utilize oscillatory gas-liquid slug flow between the evaporator and the condenser. PHP technology has been virtually non-existent in the chemical process industry so far and related research is still in its infancy. In contrast, the research literature on applications of Pulsating Heat Pipes in space is very rich and includes experimental investigations carried out both under normal gravity (ground) and micro-/hyper-gravity (parabolic flight) conditions (Cattani et al., 2023; Gu et al., 2005; Mameli et al., 2018; Mangini et al., 2015; Marengo et al., 2023; Slobodeniuk, 2022; Yoon et al., 2025; Zhao, et al. 2023). The parabolic flight experiments showed that PHPs operational and heat transfer performance was better under microgravity than under normal or hypergravity, which makes them particularly suitable for the deployment in space applications (Gu et al. 2005).

3.5. PI and system reliability

System robustness and reliability expressed by the Mean Time Between Failures (MTBF) are of fundamental importance for any chemical manufacturing process run in terrestrial conditions and are absolutely critical for systems used in space exploration, where any repair or replacement of system component presents a major issue. Studies on reliability aspects of process intensification are scarce, and the conclusions presented in those studies cannot be generalized, as they concern particular cases and technologies. For example, Baldissone et al. (2016) investigated the reliability issues in the catalytic after-treatment of lean volatile organic compounds–air streams and concluded that the intensified process using reverse-flow reactor (PI temporal domain) was more reliable than the conventional one. Pistikopoulos et al. (2021) state that having intensified systems consisting of smaller, modular and parallel units instead of one larger unit can enhance the plant disturbance rejection performance. Definitely, process intensification may improve reliability, for example via better reactor cooling to prevent thermal instabilities, catalyst degradation or even sintering. It may enable replacement of the equipment having moving parts – a frequent source of leakages or failures. A classical example is the replacement of a stirred mixing vessel (possible problems with sealing the stirrer shaft) by a motionless (static) mixer (Green, 2004). Integrated intensified systems in the functional domain may reduce the number of equipment or process stages, thereby decreasing the probability of failures. On the other hand, one has to realize that PI technologies possess also important limitations, which have to be accounted for in order to prevent a decrease rather than increase in operational reliability. For example, microchannel reactors can be very reliable when it comes to heat removal and reaction temperature control but can be quite unreliable in reactions where solids are formed (channel clogging). Functional integration, e.g. reaction with separation, may require more complex control systems with increased probability of failures. A membrane-based technol-

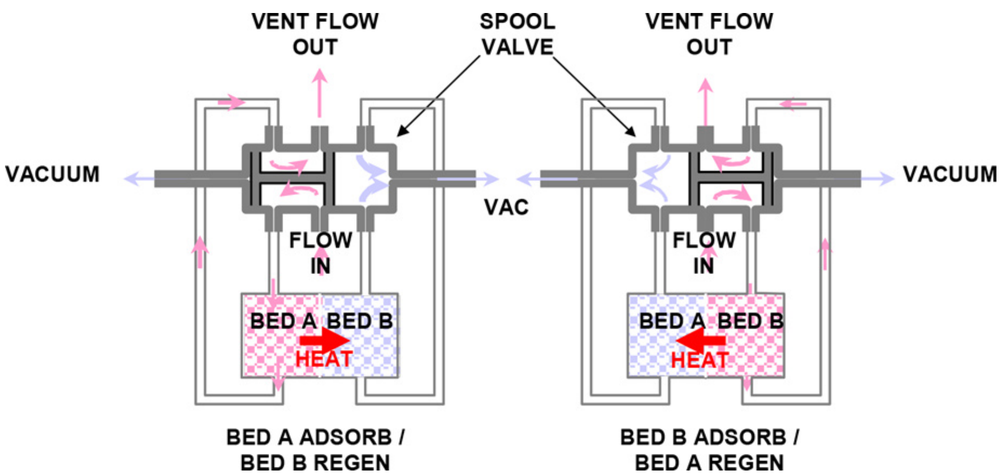


Figure 17. Scheme of a solid amine-based pressure swing adsorption system for CO_2 and humidity removal from spacesuits. Reproduced from (Papale et al., 2006), courtesy: NASA. Copyright ©2006 SAE International.

ogy may decrease the equipment volume, but fragility of the membranes themselves may become an issue. Summarizing, process intensification, both on Earth and in space, can deliver significant reliability benefits but should be used with care. To make right choices, Hazard and Operability (HAZOP)-like methodologies for process intensification have been developed (Klais et al., 2009a; 2009b; 2010a; 2010b).

4. CONCLUSIONS – THE WAY AHEAD

The review presented in this paper clearly proves high relevancy for the exploration of space of many technologies constituting the four elementary domains of process intensification. This is not surprising bearing in mind that both process intensification and space engineering address basically the same issues – equipment miniaturization and increased process efficiency, and that "much more from much less" could be the guiding principle of both. Obviously, the targeted applications are frequently different in both cases, as shown in Tab. 1, with Earthbound PI so far exclusively focused on the chemical manufacturing and space-based PI focused on ELCSS and ISRU problems, but the commonality of concepts and approaches is striking.

The question arises whether, in addition to the already mentioned technologies, there are other developments in the field of process intensification that could become relevant for further progress in space exploration. We believe that there are.

Table 1. PI technologies investigated in the context of Space exploration.

PI Domain	Technology	Applications on Earth	Applications in Space
Spatial	Zeolites	Numerous, e.g. Fluid Catalytic Cracking, hydroisomerizations	CO_2 removal
	Metall Organic Frameworks	H_2 storage, CO_2 adsorption, isomers separation	H_2 storage, CO_2 adsorption, separation of Volatile Organic Compounds
	Monolithic catalysts	Numerous catalytic processes, gas-phase (e.g. automotive exhaust gases) or gas-liquid	Propulsion, Sabatier reaction, methane reforming, CO_2 adsorption
	Solid foams	Various, mostly CO_2 reduction, methane reforming, CO oxidation or methane combustion.	In-situ propellant production on Mars, dehumidification
	Microchannel reactors	Various, primarily pharmaceuticals and specialty chemicals, mobile Fischer-Tropsch	Sabatier reaction, methanol from CO_2, pharmaceuticals
	Plate and microchannel heat exchangers	Cooling/heating	Cooling/heating
Thermodynamic	Electric fields	Electro(cata)lysis, liquid-liquid extraction, gas cleaning	Electro(cata)lysis, oxygen extraction from regolith
	Magnetic fields	Fluidized-bed stabilization, minerals separation, biopharmaceuticals (separation of cells or macromolecules)	Fluidized-bed stabilization, regolith separation, microalgae separation
	Microwave heating	Pasteurization, sterilization, thawing, drying, adsorbent regeneration, various reactions in liquid and gas	Fracturing and defragmentation of regolith
	Induction heating	Endothermic catalytic processes, e.g. reforming	CO_2 desorption
	Joule heating	Endothermic catalytic processes, e.g. reforming	Oxygen and metals from molten regolith electrolysis
	Photochemistry and catalysis	Various liquid- and gas-phase reactions for manufacturing and waste management	Polymerization, CO_2 conversion, degradation of water or air contaminants
	Lasers	None	Propulsion, oxygen extraction from regolith
	Ultrasound	Liquid-phase reactions	Planetary drilling and sample preprocessing
	Micro- and nano-bubbles	Water pollution control, food production	Drinking water sanitation, food production
	Plasmas	Reactions, material synthesis and processing, medicine	Oxygen from CO_2 on Mars, hydrogen recovery from Sabatier unit, oxygen extraction from regolith
	Supercritical fluids	Food, cosmetics, pharmaceuticals (extraction), waste treatment (oxidation), dyeing	Extraction from regolith, water reclamation

Table 1 continued on the next page

Table 1 continued from the previous page

PI Domain	Technology	Applications on Earth	Applications in Space
Functional	Membrane reactors	Various	Wastewater treatment, CO_2 removal from air
	Membrane distillation	Water desalination	Water treatment and reclamation
	Membrane absorption	CO_2 removal	CO_2 removal
	Heat-pump assisted distillation	Various	Wastewater treatment
Temporal	Pressure-Swing Adsorption	Oxygen and hydrogen purification, CO_2 removal	CO_2 and trace impurities removal, oxygen concentration,
	Pulsating Heat Pipe	None	Heating/Cooling

For example, as an alternative to the Pressure Swing Adsorption one could explore the possibility of CO_2 removal using *Temperature Swing Adsorption* (PI temporal domain), which has already been successfully applied on an industrial scale. Svante Inc. has commercialized the intensified Rapid-Cycle Temperature Swing Adsorption (RC-TSA) VeloxoTherm^{TM} process for CO_2 capture with a MOFs-based structured adsorbent (PI spatial domain). The process uses a rotary adsorber to capture the CO_2 and then desorb it using steam or vacuum (Guo et al., 2024).

Additionally, one could consider improving the above process further by the use of *microwaves* (thermodynamic domain) to desorb CO_2 and regenerate the adsorbent. Fundamental studies by Cherbański et al. (2011) revealed the unique thermal non-equilibrium effect of microwaves, where the adsorbent regeneration accelerates despite the lower temperature of the adsorption bed compared to that of conventional TSA. Microwave-enhanced TSA (MWe-TSA) was extensively investigated with regard to CO_2 capture systems: Chronopoulos et al. (2014) achieved fourfold acceleration in AC desorption through MWe-TSA, while Ellison et al. (2021) reported 50% faster regeneration rates in zeolite 13X. Also, the recent studies by Erguvan et al. (2024) and by Lim et al. (2024b) confirm the reduced regeneration time that should allow for a more compact system and a drastically reduced energy demand that could bring the process close to the sorbent's thermodynamic energy limits.

The Sabatier process also offers room for potential improvement. Among other things, two methods from the thermodynamic domain of PI, *plasma-assisted catalysis* and *plasmonic/photothermal catalysis*, have been extensively studied (Molinet-Chinaglia et al., 2024). One could also consider integrating the Sabatier reaction in the desorption step of the earlier described TSA system for CO_2 capture. This would lead to a novel type of *separative reactor* (PI functional domain). The idea of *bifunctional catalyst-adsorbent materials that* could be employed in such a reactor is not entirely new and goes back to a concept studied in the group of Agar about 20 years ago (Dietrich et al., 2005). The same group also developed an interesting concept of *desorptive cooling* (Grünewald and Agar, 2004), that could potentially be used in the previously described hypothetical separative reactor to better utilize the heat released in the Sabatier reaction.

In yet another application of PI to the Sabatier process, researchers form NTNU, Trondheim, Norway proposed to carry out the Sabatier process in aqueous solutions at ambient conditions using *ultrasonic cavitation* (Islam et al., 2021). Also, Liu et al. (2025) hydrogenated CO_2 to formic acid and oxalic acid in a *nanobubbles*-water system. Both these technologies belong to the thermodynamic domain of process intensification, and their important feature is that they could potentially allow performing the Sabatier reaction *in-situ*, in the spacecraft's wastewater treatment system. Another feature of both is that they are catalyst-free, which can make them relevant for long-duration missions, cut off from fresh catalyst supplies.

In case of the post-Sabatier, methane-based reactions, the same problem of limited access to catalysts could potentially be addressed by the *pulsed compression reactor (PCR)* – a technology from the temporal domain of process intensification. The PCR has been investigated in methane-to-syngas and methane-to-ethylene processes. It does not require a catalyst and, therefore, does not deactivate over time, and it operates at a low reactor temperature (Slotboom and Kersten, 2023; Slotboom et al., 2021).

The above-mentioned PI technologies are only examples, and we do not claim that they all will find space-related applications. We only want to underline that there are still many innovative, potentially attractive concepts in process intensification and that more knowledge/information transfer is needed between the worlds of process intensification and of spaceflight. For more than four decades process intensification and space engineering have been functioning next to each other, with only occasional interactions between the researchers involved. Intensifying those interactions and contacts will enable both scientific communities to benefit from cross-fertilization and the exchange of new ideas and experiences.

In 1878 Jacobus van't Hoff, a chemical technologist by education and later the first Nobel Prize winner for chemistry, delivered his inaugural address at the University of Amsterdam.

The speech was entitled "Verbeeldingskracht in de Wetenschap" (The Power of Imagination in Science). Van't Hoff praised the crucial role of human imagination in scientific discovery, exemplified by great scientists like Newton and Galileo. This remains true today, where the benefits to be gained from interaction between process intensification and space technology are limited only by human imagination.

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