Continuous-Flow Extraction of Adjacent Metals – a Disruptive Economic Window for In-Situ Resource Utilization of Asteroids?

Volker Hessel[a,*], Nam Nghiep Tran[a], Sanaz Orandi[a], Mahdieh Razi Asrami[a,d], Michael Goodsite[b], Hung Nguyen[c]

[a] School of Chemical Engineering and Advanced Materials, University of Adelaide, Australia

[b] School of Civil, Environmental & Mining Engineering, University of Adelaide, Australia

[c] Teletraffic Research Centre, University of Adelaide, Australia

[d] Department of Applied Chemistry, Bu-Ali Sine University, Hamadan, Iran

[*] *Corresponding author*

Abstract

For in-situ resource utilization (ISRU), the cost-mass conundrum needs to be solved, before any other formidable challenges may be tackled. Technologies may need to be conceptualised from first principals, rather than taking the most advanced technology of today. Using this approach, this paper seeks to provide a think tank about how chemical process intensification can help with technology and business case disruption of ISRU matters, how this might influence Space-industry start-ups, and first of all even Earth-industry transformations. The disruptive technology considered is continuous micro-flow solvent extraction and, as another disruptive element therein, the use of ionic liquids (instead of conventional organic solvents). The Space business considered is Asteroid mining, as it is probably the most challenging resource site, and the focus is on its last step: the purification of adjacent metals (cobalt versus nickel). The key economic barrier is defined as the reduction of the amount of process water used in the Asteroid mining process. This paper suggests a pathway toward water savings by orders of magnitude, up to the technological limit of best Earth-process intensification and their physical limits (e.g. of solubility). This is believed to provide a solution to a major economic bottleneck, whilst leaving many technology developments to be achieved before a holistic system and business picture can be given.

1. Introduction and Motivation

1.1. Resource depletion on Earth

The increase in human population and growing demand for natural resources in both developing and developed countries will lead to depletion of the Earth's resources within the next 60 years. Key elements such as phosphorus, silver, copper, gold, etc. will be soon become critical or run out. To deal with this problem, space mining appears to be a potential solution, following technology developments that have led to the discovery of the tremendous precious metal reserves in Asteroids.

1.2. Resource in Space - ISRU

In-situ resource utilization (ISRU), as termed by NASA [1], or more simply Space mining, is a near-commercial business opportunity [2] and figures significantly in NASA's Strategic Knowledge Gaps (SKGS) [3]. There is technological scouting of state of the art equipment for ISRU Space applications, especially for water mining and fuel processing thereof, and a number of test projects have been run [4]. Advanced state-of-the-art machinery is being considered as part of a sound total system design approach, yet, the literature lacks detailed descriptions of most other relevant kinds of mining, such as that of minerals and metals. While water and fuels are needed to start up colonisation of Space,

metal/mineral mining could be the starting point for an economic business. Knowledge of metal/material mining in space can be directly translated to terrestrial 'zero-entry mining' [5]. For this, it will not be enough to have an isolated description of possible modules, but rather a whole process system design is needed to enable economic validation and demonstration of a conceptual business case; as has been given for the 'business case of Space medicine' [6]. Moreover, a supply-chain model for the ISRU business is needed, given the enormous distances for transport and the need to make partial use of local resources (which are still unknown to an extent). Only such a top-down approach with an early-bird economic evaluation can pre-select the right processing equipment, before starting the experimental test runs. An ISRU value chain will be an important demonstration of a circular economy [7], and necessary for sustainable colonization of any space body by man or machine.

Yet, we are far from this. Thus, a bottom-up approach is advised at this stage. That would mean validating concrete 'Earth-proven' chemical engineering equipment under the new economic process conditions assumed to be essential for Space. It then may turn out that the current processing options being investigated may not be economic. Likely, new equipment needs to be developed under the new economic boundary guidelines and environmental engineering requirements, as applied to Off-Earth environments reinvented as a new paradigm. Given the current ambitious foci of Space Agencies and the opportunity to translate innovation to improve terrestrial applications, such investigations are urgently needed.

This feature paper seeks to make the first step to close this knowledge gap. It will focus only on that kind of equipment which is based on chemical engineering design and function. Generally, such modules play a central role, e.g., in water mining, water harvesting and splitting it electrolytically into hydrogen or oxygen. Given the topic of this feature paper, metal mining, leaching (with acids) and solvent extraction (with scavengers) are the two focal processes. Based on our sound background in the latter field, we will focus on solvent extraction to purify metal mixtures.

1.3. Chemical process intensification

It is most evident that, for the very few chemical engineering-type ISRU modules, process intensification approaches have hardly been considered to date [8]. Yet, that means missing big opportunities, as those concepts have recently transformed major industries on Earth, such as the pharmaceutical industry, which decided on a game change from batch to continuous-flow [9]. Those disruptive technologies have proven to be enablers for business cases, which cannot be sustained by conventional technologies [10].

While there is a plethora of process intensification technologies and ISRU approaches, this paper focuses on the use of solvent micro-flow extraction for the purification of mixed metal salt solutions to obtain the purified metal as a semi-finished product. Solvent extraction is an essential part of a typical mining process, typically consisting of excavation, crushing of rocks, flotation, and leaching [11]. After leaching, metal salts are obtained, and there is a mixture of diverse, so-called adjacent (occurring in coexistence) metals [12]. Continuous-flow processing has been acclaimed as prime Space manufacturing technology [13], and thus is the spearhead of Earth-based process intensification [13].

1.4. Asteroids as a Space mining site for metals

The Space mining site and resources to be considered will be Asteroids. Pros and cons of Asteroid versus planet mining have been discussed [14]. Sonter [14] has even described Asteroid mining as the key to the future economy of Space. Asteroids are, according to Sonter, the most cost-effective way to commercialize Space, and about 10% of NEAs are energetically more accessible than the Moon, meaning that less cost is needed to visit them. While this discussion is certainly open and undecided, this paper focuses on Asteroid resource exploitation. This is mainly done because the respective processing conditions will demand even more innovative processes and equipment solutions

(compatible with vacuum, zero-gravity, automation) than are expected for planet mining. A second argument for Asteroids is their wealth of resources. Asteroid-based ISRU sources are, by definition, particularly rich in metals, and give unique processing challenges (vacuum, zero-gravity, automation); in addition, Asteroids are high on the public agenda.

1.5. Motivation

This paper presents a techno-economic scouting of water provision, as the essential process medium for the solvent extraction of metals. In simple words, it aims to answer how much the water content can be reduced, to lower water-transport or water-ISRU costs. The borderline of water reduction is determined by the capability of the current chemical process intensification. We will consider what that means for ISRU-required developments of the process intensification equipment. Hopefully, the 'micro-analysis' given here can shed some light on the big picture of ISRU commercialisation and be a guide for future experimental and technological studies in the field.

2. The site of opportunity – Asteroids mine atlas and elemental map of resources

Asteroid-mined resources may once have multiple uses in Space: examples are water as life support and propulsion fuel precursors, metals for large scale construction and catalysis, and silicon for solar panels.

2.1. Asteroids, types and wealth

It has been more than 200 years since the first Asteroid, Ceres, was discovered in 1801 [15]. By September 2019, NASA reports that the number of discovered Asteroids are 796,990 and this number is increasing continuously with the development of modern discovery techniques. Asteroids are different in shape and size. The shape is typically changed from spherical to ellipsoid or even irregular. The size of the Asteroids varies from the biggest, Ceres (974 km in diameter and containing about 25% of the mass of all the asteroids combined), to the tiny 25143 Itokawa (0.5 x 0.3 x 0.2 km) and even smaller objects could have the same size of a car. It is estimated that more than 75% Asteroids are C-type (C stands for carbon and their surfaces are almost coal-black). Carbon, nitrogen, and water are the main compositions of most C-type asteroids. The stony or S-type Asteroids account for approximately 17% of the total number. Metallic nickel-iron mixed with iron- and magnesium-silicates is popularly found in this type of Asteroids [16]. The most important and valuable Asteroids would be the M-type (M stands for metallic) which make up 6%-8% of the total. The massive amount of precious metal groups such as iron, nickel, aluminum, platinum/palladium, and rare Earth elements make metallic Asteroids the treasure chest of the Solar System[16-17]. For example, a 10-km-diameter M-type Asteroid could contain approximately 4,000 times higher the value of mineral mined on Earth. Interestingly, there are more than 1,200 near-Earth Asteroids, which are at least 1-km diameter, have been detected in which one Asteroid might contain nearly 4 times the amount of metal mined in all of human history [18]. It is estimated that a single spherical Asteroid 25 m in diameter will provide a potential revenue of 2,8 tons of water and 143 tons of platinum/palladium group [18a].

The Near-Earth Asteroids (NEAs), whose minimum orbit intersection distance (MOID) is approximately within 0.3 Astronomical Units (AU) of Earth, are likely to be mined first since they are easier to reach than the Moon [19].

2.2. Asteroid mine atlas – elemental map

The concept of Asteroid mining has been proposed for decades, and even assigned as an incentive to colonise Space [20]. However, it is not until recently that the technology and theories for such a mission were developed advanced enough to be considered. In particular, orbiting Near-Earth Asteroids (NEA) have a perihelion (closest distance to Sun) less than or equal to 1.3 astronomical units (AU: distance

Earth-Sun), and so maybe the first port of call for future enterprise [21]. Other near-Earth objects (NEO), such as comets, are also possible targets for prospecting [22]. They supposedly contain both the volatile materials (ice and dust) and high-value minerals which are basic assets to form a business case.

Table 1 gives an elemental map of the resources of the various Asteroids, classified according to common practice and nomenclature. It is evident that most of these were only discovered in the last 20-40 years, i.e. all after the first Moon landing in 1969. Their value is immense. Together with their much higher metal load than on Earth, this justifies higher exploration costs. Refinery-grade iron, nickel, and cobalt are the prevalent valuable resources; with molybdenum, aluminium, silicon, titanium, and platinum group metals (PGMs) being present in smaller amounts [18a, 23]. The subsequent considerations of this paper are based on the extraction of nickel and cobalt, since we have worked on this in the past, could show advantages of using continuous-flow, and it also of industrial relevance [12, 24]. Asteroids YU55 and Ryugu are closest to Earth (lowest MOID), contain both nickel and cobalt, and, especially Ryugu, have resources of the highest commercial value. Some Asteroid types comprise the metal in alloy state, e.g iron-nickel.

Table 1. Metal contents and distributions in the diverse types of most valuable Asteroids

Name	Type	Discovered year	Composition	MOID (AU)	Value ($)	Δv (km/s)
Ryugu	Cg	1999	Ni, Fe, Co, H_2O, N_2, H_2, NH_3	0.000638	82.7 billion	4.67
1989 ML	X	1989	Ni, Fe, Co	0.082029	13.9 billion	4.89
Nereus	Xe	1982	Ni, Fe, Co	0.003153	4.7 billion	4.99
Bennu	B	1999	Fe, H_2, NH_3, N_2	0.003223	669.9 million	5.10
Didymos	Xk	1996	Ni, Fe, Co	0.039777	62.2 billion	5.16
2011 UW158	Xc	2011	Ni, Fe, Co, Pt	0.002914	6.6 billion	5.19
Anteros	L	1943	$MgSiO_3$, Al, Fe, Fe_2O_4Si	0.062212	5.5 trillion	5.44
2001 CC21	L	2001	$MgSiO_3$, Al, Fe_2O_4Si	0.083067	147.0 billion	5.64
1992 TC	X	1992	Ni, Fe, Co	0.167212	84.0 billion	5.65
2001 SG10	X	2001	Ni, Fe, Co	0.017183	3.0 billion	5.88
2002 DO3	X	2002	Ni, Fe, Co	0.029415	334.4 million	5.90
2000 CE59	L	2000	$MgSiO_3$, Al, Fe_2O_4Si	0.008298	10.6 billion	6.01
1995 BC2	X	1995	Ni, Fe, Co	0.135685	78.8 billion	6.01
1991 DB	C	1991	Ni, Fe, Co, H_2O, N_2, H_2, NH_3	0.102803	168.2 billion	6.14
2000 RW37	C	2000	Ni, Fe, Co, H_2O, N_2, H_2, NH_3	0.008221	29.2 billion	6.22
1998 UT18	C	1998	Ni, Fe, Co, H_2O, N_2, H_2, NH_3	0.037188	644.7 billion	6.22
Seleucus	K	1982	Ni, Fe, Co, H_2O, N_2, H_2, NH_3	0.102357	33.5 trillion	6.29
1998 KU2	Cb	1998	Ni, Fe, Co, H_2O, N_2, H_2, NH_3	0.060029	80.3 trillion	6.30
1989 UQ	B	1989	Fe, H_2, NH_3, N_2	0.01398	600.7 billion	6.40
1999 KV4	B	1999	Fe, H_2, NH_3, N_2	0.172981	25.6 trillion	6.38
1988 XB	B	1988	Fe, H_2, NH_3, N_2	0.006611	217.0 billion	6.41
1997 RT	O	1997	Pt, Ni-Fe	0.059847	174.3 billion	6.50
1997 XF11	Xk	1997	Ni, Fe, Co	0.000531	383.9 billion	6.55
1996 FG3	C	1996	Ni, Fe, Co, H_2O, N_2, H_2, NH_3	0.028342	1.3 trillion	6.61
1992 QN	X	1992	Ni, Fe, Co	0.132115	253.7 billion	6.60
2001 TY44	X	2001	Ni, Fe, Co	0.148551	3.5 billion	6.58
1999 JV6	Xk	1999	Ni, Fe, Co	0.031786	12.0 billion	6.70
2002 EA	L	2002	$MgSiO_3$, Al, Fe_2O_4Si	0.03561	672.1 million	6.75
2001 HK31	X	2001	Ni, Fe, Co	0.117916	1.3 billion	6.72
2005 YU55	C	2005	Ni, Fe, Co, H_2O, N_2, H_2, NH_3	0.000467	49.8 billion	6.91
1992 BF	Xc	1992	Ni, Fe, Co, Pt	0.062737	2.9 billion	6.98
2001 PD1	K	2001	Ni, Fe, Co, H_2O, N_2, H_2, NH_3	0.239755	646.0 billion	6.86
Lucianotesi	Xc	1994	Ni, Fe, Co, Pt	0.248206	53.1 billion	6.99
2002 CS11	X	2002	Ni, Fe, Co	0.220314	766.1 million	6.92
1992 NA	C	1992	Ni, Fe, Co, H_2O, N_2, H_2, NH_3	0.063013	4.5 trillion	7.00

2002 AV	K	2002	Ni, Fe, Co, H_2O, N_2, H_2, NH_3	0.019524	17.7 billion	7.02
2002 BM26	X	2002	Ni, Fe, Co	0.032462	77.7 billion	7.07
1999 NC43	Q	1999	Ni-Fe	0.024621	2.6 billion	7.13
2000 CO101	Xk	2000	Ni, Fe, Co	0.021957	29.2 billion	7.23
Dionysus	Cb	1984	Ni, Fe, Co, H_2O, N_2, H_2, NH_3	0.02062	2.6 trillion	7.18
1999 CF9	Q	1999	Ni-Fe	0.018825	152.7 million	7.24
2002 AH29	K	2002	Ni, Fe, Co, H_2O, N_2, H_2, NH_3	0.1103	7.7 billion	7.21
1986 DA	M	1986	Ni, Fe, Co	0.190995	4.2 trillion	7.23
1996 BZ3	X	1996	Ni, Fe, Co	0.275839	73.1 billion	7.23
Davidharvey	C	1999	Ni, Fe, Co, H_2O, N_2, H_2, NH_3	0.2037	53.9 trillion	7.23
2001 HA8	C	2001	Ni, Fe, Co, H_2O, N_2, H_2, NH_3	0.121856	1.5 trillion	7.31
Apollo	Q	1932	Ni-Fe	0.025757	805.0 million	7.48
2000 LC16	Xk	2000	Ni, Fe, Co	0.212293	4.2 trillion	7.33
2001 WH2	X	2001	Ni, Fe, Co	0.195226	4.6 billion	7.54
2000 WC67	X	2000	Ni, Fe, Co	0.232789	296.2 billion	7.49

3. The Cost-Mass Conundrum

3.1. Launch costs to Asteroids

However, many barriers and technical challenges must be overcome before we dare venture into Space for profit. The foremost problem of Space mining is cost, and within that, the very first thing is to overcome launch and transport costs. For example, lifting 1 kg out of the Earth's gravity well to a Lagrange point (a place where the Earth and the Moon's gravities cancel each other out) costs about $100,000 [25]. Planetary Resources urges the need to bring down the cost of Space flight [26].

3.2. Water launch to Asteroids

Yet, the true challenge might not be the lifting up of the technology equipment itself, but of the processing media (and fueling liquids) to operate it; as their weight is far heavier. So operational costs (OPEX) need to be approached first, and not capital (CAPEX); in the same way that OPEX has a much higher share than CAPEX on Earth. Contemporary mining processes are mostly fluidically based; e.g. flotation, and leaching and solvent extraction, the latter being considered here. Water is the prime solvent in all of these. Accordingly, reducing water payload is the focus of this feature paper.

4. Water Supply Chain in Space

There are several potential sources for using water as a process fluid in Space manufacturing. Three known sources are discussed here: Moon, Asteroids, and Earth.

5.1. Moon water

Even though the source of Moon water is still an active topic of investigation [27], it is clear from multiple studies [28] that the Moon has significant ice-water. The strongest direct confirmation of Moon water was made in 2009 when the Lunar Crater Observation and Sensing Satellite (LCROSS) [29] crashed its spent rocket booster into the Cabeus crater, near the south pole. LCROSS found water in the debris from the impact. More recent data from a NASA instrument aboard the Indian Space Research Organization's Moon-orbiting Chandrayaan-1 Spacecraft has also revealed the presence of exposed water ice on the Moon's surface [30]. NASA presents a discussion of the extraction of resources from regolith [31], where scientific reviews of lunar regolith have also been discussed [32].

It is important to note that water-ice is not distributed equally on the Moon's south pole. By inspecting the volatiles at the south pole, researchers [33] found that the Shackleton, Sverdrup, Haworth, Shoemaker, and Faustini craters might have the most abundant ice deposits. The lunar south pole offers

another unique advantage: the lowland basin at the south pole receives sunlight for as many as 200 lunar days. This has a variety of positive impacts on exploration architectures, including a benign thermal environment, and the ability to leverage solar power systems to facilitate surface presence.

The actual quantities of ice at a given site, its physical state, depth of burial and other properties still need to be determined. Missions to get instruments down on the surface of the Moon at the poles for in situ measurement of the ice layer thickness will provide accurate estimations of the amount of water-ice on the Moon and are important for formulating good engineering decisions about lunar outpost(s) and harvesting the Moon's water [28], including for mining.

Several estimates using indirect measurements for Moon water exist. Li et al. [28a] report that water ice is most likely mixed in with surface soils and that there could be between 10 thousand and a hundred million tons of it at the south pole alone. A more recent study by Spudis et al. [34] estimates that there are between 100 million to one billion tons of water present at each pole. The principal advantage of using Moon water at another site in Space is the lower launching costs from the Moon relative to Earth, due as there is lower gravity to be overcome.

A detailed cost breakeven analysis for extracting Moon water to be used as fuel in Cis Lunar for future Mars missions is given in [14]. The authors show that even though the launch cost from the Moon to the Cis Lunar orbit is much cheaper than from Earth (currently about $40,000/kg), the initial cost of deploying water mining and logistics infrastructure on the Moon is significant. Using various models, the authors conclude that it will require a total demand of at least 2,065 tons of propellant (or 7 Mars missions) in Cis Lunar for the cost to produce propellant on the Moon to break even with the cost of delivering it from Earth. A "propellant efficiency" metric is introduced, which is "the ratio of usable propellant for Mars delivered to Cis-Lunar to the total propellant produced on the Moon". Using current technologies, the efficiency is between 10%-20%. With that figure, it is concluded that an extraction cost of $4000 - $8000 per kg of propellant on the Moon is needed for a better cost trade-off than using current Earth-based launch solutions. The most relevant conclusion of the study is that, while there may be benefits to using lunar in-situ resource utilization to support lunar missions, it will not suffice to support human missions to Mars. This economic conclusion likely applies to use of Moon water for Asteroid mining too.

5.2. Asteroid Water

In the last twenty years, a vast amount of data and results from Space missions have been collected. Observations from spacecraft are mainly used to complement theories and findings deduced from ground-based Asteroid data. There is evidence that Asteroid impacts could have brought a significant amount of water to the young terrestrial planets [35]. The meteorites collected on Earth combined with the samples returned from the Hayabusa2 and OSIRIS-REx missions will deepen understanding in the near future [36]. Some Asteroids are formed with water ice as a constituting material, as a "hydrated mineral" [37]. It is believed that early in solar system history ice melted and reacted with rock to create that type of hybrid material.

Near-Earth Asteroids (NEOs) may be a rich source for water harvesting. It should be noted that these Asteroids are more accessible than the surface of the Moon [38]. By collating data from previous studies, Rivkin et al. found the best estimate for Near Earth Asteroids (NEOs) was that they would contain 17% ± 3% water [39]. These Asteroids are typical of small size, yet there is a multitude of them. Hundreds of known 1-km NEO Asteroids are hydrated with approximately 8×10^{11} kg (or 800 million tons) of water. Recent studies, such as [38] and [40], found hydrated Asteroids of various smallest sizes (5-10 m) [40] and more than 100 m [38]. The study revealed many more such objects than projected from the known frequency of meteorite events hitting the Earth.

5.2. Earth water

About 71 percent of the Earth's surface is water-covered, and the oceans hold about 96.5 percent of all of the Earth's water. Water also exists in the air as water vapor, in rivers and lakes, in icecaps and glaciers, in the ground as soil moisture and in aquifers. The volume of all water on Earth (oceans, icecaps and glaciers, lakes, rivers, groundwater, and water in the atmosphere) would be about 1.386 million cubic kilometers (km^3) or $1{,}386 \times 10^{18}$ litres of water [41]. Water extraction and recycling are well-established technologies on Earth.

It is safe to assume that the Earth could supply the water for in-Space Asteroid mining. However, the cost of bringing water to Space is prohibitively expensive, even to low Earth orbit (LEO). Part of that high price is because it takes so much energy to escape Earth's gravity. Fortunately, the development of commercial launch systems has substantially reduced the cost of Space launches [42]. NASA's Space shuttle had a cost of about $54,500/kg to Low Earth Orbit (LEO) whereas SpaceX's Falcon 9 now advertises a cost of $2,720/kg to LEO - a cost reduction by a factor of 20 [42]. Note that this cost does not include the Space shuttle that delivers the cargo and crew to a specific destination. For example, the Falcon 9 must also use the Dragon capsule to deliver to the ISS, which adds costs and reduces payload [42]. The cost of a Falcon 9 and Dragon capsule mission to ISS is about $23,300/kg - a cost reduction by a factor of 4 [42]. The recently reduced Space launch cost can be expected to impact substantially on human Space flight [42] but it will be a long time before launch costs fall low enough to deliver water from the Earth at an economically viable price for Asteroid mining, as shown in Sonter's original analysis [14].

5. Water Needed for Mining on Earth and Projection to Space – Setting the Economic Boundary

5.1. Water as a challenge for Asteroid mining

Current mining technologies are very water-intensive. A life-cycle study summed up that 190 tons of water are needed per ton of cobalt (190: 1) [43]. For example, the largest mine on Earth, Glencore's Mutanda, in the Republic of Congo, produced 23,900 tons of cobalt in 2017 [44]. With water versus copper processing ratio of 190:1, Mutanda might need 4,500,000 tons of water per year. Assuming that 1% of Moon water is used for resource processing, and taking water:metal ratio of 200:1, the best estimate is that lunar water would only suffice to produce 50,000 tons of cobalt. Applying the same analysis for Asteroid water, and assuming 1% of it is used for processing, that would only leave enough to process 40,000 tons of copper in total.

Admittedly, the real processing situation in Space will not be as harsh as given here, since water can be recycled, and that will be mandatory in Space, which will reduce the water amount needed. Yet, that alone will not solve the problem but only will smooth it out somewhat. So, it is crystal clear that with the current technologies, no operation is feasible according to Earth standards of cobalt production, whether using lunar/Asteroid water or launched Earth-water. This would only suffice for the world top-1&2 cobalt mines (Mutanda, Tenke Fungurume), and could not mine iron, platinum, and other resources. Accordingly, new disruptive technologies are needed with much-reduced water usage and recycling.

5.2. Recommendations for the water supply chain

In the near term, the following course of action regarding water management is the most feasible:

- Fast and efficient at-site water recycling is mandatory [45]
- Reduction of the water content per ton of cobalt is mandatory. Rough, yet realistic guesses advise that the ration needs to decrease to 10:1; ideally to 2:1 [46]
- In the mid-term, bringing water to orbit is the most practical option and on the horizon, Moon water may be used as a start-up [47]
- It may be possible to bring very rich, high-value resources, such as alloys, to Earth, if the

product manufactured from the ore is to be used on Earth [47]

6. Geologic processes of Asteroids making their metal composition different from Earth

6.1. Origin of difference between Asteroid and Earth resources

Asteroids and Earth formed from the same materials at the starting stage; however, the Earth pulled all the heavy siderophilic (iron-loving) elements into its core due to relatively stronger gravity during its molten youth, which occurred more than four billion years ago [48].

Therefore, the Earth's crust was depleted of valuable elements until it was impacted by the rain of Asteroids and re-infused with metals like nickel, cobalt, iron, gold, manganese, molybdenum, osmium, rhodium, palladium, platinum, rhenium, ruthenium and tungsten. As a result, a flow from the core to the surface occurred that formed a rich source of platinum-group metals, such as the Bushveld Igneous Complex [49]. These metals are now essential for economic and technological progress and are mined from the Earth's crust. Therefore, the geological history of Earth could well set the stage for the future of Asteroid mining.

6.2. Geological processes of Asteroids making their distinctive resource footprint

At the center of the solar nebula, in a collapsing cloud of gas, the Sun formed. As the Sun condensed to its ultimate size, a hot disk with the Sun at the center formed from the surrounding cloud [50]. The composition of the Sun and the disk was similar, mainly helium and hydrogen with some percentage of all other elements that originated from the giant interstellar cloud in which they formed. Different compounds condensed as the disk and the gas turned into solid grains. Iron and rocky minerals were the only compounds of the granite forming near the Sun, whereas the ones which formed beyond the orbit of Mars contained carbon and water. An unknown process caused some of the grains to melt and form drop-like chondrules [51]. The same elemental abundance as the Sun is in the grains loaded with carbon and water, hence they can be considered "sun stuff", without the hydrogen and helium that mainly sustained as gases in the nebula.

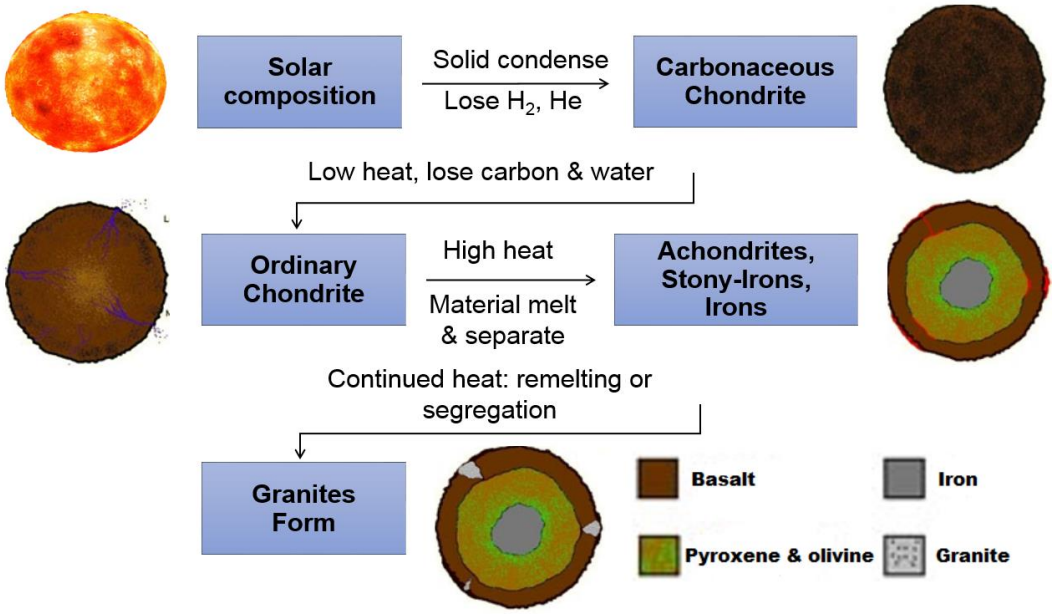


Figure 1 *Geological processes in Asteroids during the formation (redrawn following [52])*

The primitive Asteroids formed when the grains and chondrules clustered together due to gravity over time [53]. These original Asteroids, derived from the "sun stuff" materials, are now called carbonaceous chondrites (see Figure 1, Asteroid at upper right, classes C1, C2, etc.,). These Asteroids were shaped in a range of sizes, from tiny rocks to mini-planets, with hundreds of kilometers in diameter.

The different amount of heat affects Asteroids compounds [52]. The "parents" of the C1-type meteorites formed from the Asteroids that received hardly any heat and stayed cold, far below freezing. Due to this condition, their compounds, including carbon and water, were maintained almost unchanged. The other Asteroids, that were heated slightly, lost some of their water and carbon, driven out of the grains into Space because of the low gravity on these small bodies. These Asteroids are the parents of the C2 meteorites.

Increased heat in some of Asteroids caused the release of most of the carbon and water so serpentines formed, a mineral containing chemically-bound water, metamorphosed to the mineral olivine [54]. These Asteroids are the sources of C3 and C4 meteorites. Tiny fissures in some carbonaceous meteorites can now be seen, which show where the ancient water flowed. The soluble minerals that were left behind as the Asteroid dried filled the fissures.

Some of the carbonaceous Asteroids received heat at temperatures of several hundred degrees centigrade, which was enough to boil off all the water and carbon [39].

Depending on the amount of heating, the remaining rocky materials were heated sufficiently (not to the melting point) to cause the original minerals to metamorphose into different minerals [55]. In the spheroidal bodies of Asteroids, the center reached a higher temperature than the surface layer, so different minerals were created at different depths. These Asteroids became the origins of the various types of ordinary chondrites (Asteroid at the middle-left in Figure 1).

Some of the Asteroids were heated and molten, therefore all the original structures like chondrules disappeared and the melted materials separated by density (a process called "differentiation"). A three-layered body formed (Asteroid at lower right in Figure 1) [56]. The center contains dense iron and nickel surrounded by a "mantle" of less-dense olivine and pyroxene. At the core-mantle interface, some mixing of the iron and olivine occurred. A basaltic crust forms when the least-dense minerals rise to the surface and flow out in massive volcanic eruptions. The iron core is insulated by many kilometers of rock. It cools slowly and solidifies over periods of tens of millions of years. These Asteroids become the sources of several different types of meteorites: stony-irons come from the core-mantle boundary, iron meteorites come from the iron cores, mantle-like achondrites come from the mantle, and the basalt-like achondrites come from the crust.

The granite-like rocks would have formed as on Earth if an Asteroid were heated long enough and hot enough (Asteroid at lower left in Figure 1) [57]. No granite-like mineral has yet been found in any meteorite, so no Asteroid reached this last stage of modification.

After the formation of Asteroids, impacts released pieces of them into Space [58]. Some of the pieces became located in orbits that intersected with Earth, and those became the meteorites in our collections. The different compositions and structures of meteorites present in the familiar geologic processes on Earth operated on the Asteroids as well. Carbonaceous chondrites representing sedimentary rocks by showing the effects of minerals being dissolved, transported and redeposited through flowing groundwater. Ordinary chondrites are metamorphic rocks transformed by heat and pressure. Irons, stony-irons, and achondrites are volcanic rocks shaped out of large-scale differentiation.

7. Orbital economics of Asteroids

7.1. Orbital velocity

Orbital velocity (Δv) and the travel time to and back from the asteroids are crucial factors in considering the economic potential of any future mission. It has been found that direct Hohmann trajectories are faster than Hohmann trajectories assisted by planetary and/or lunar flybys, which in turn are faster than those of the Interplanetary Transport Network [59].

The Near-Earth Asteroids should be the first option to be considered for early Asteroid mining activities since they are likely recoverable. Importantly, their low velocity allows the extraction of usable materials to be used for the construction of a hub/interchange for near-Earth facilities, which might reduce the cost of the supply chain from the Earth [59].

Table 2 shows the velocity required for various space missions. It can be seen that a mission to a near-Earth Asteroid could be favourable when compared with later native mining missions in terms of propulsion energy demands [59].

7.2. Easily recoverable Asteroids

4660 Nereus can be taken as an example of an easily recoverable Asteroid. It has very low velocity in comparison with lifting up material from the Moon. Yet the round-trip would take a much longer time to bring the material back [22]. A class of easily recoverable objects (EROs) was identified by a group of researchers in 2013. Twelve Asteroids made up the initially identified group, all of which could potentially be mined with present-day rocket technology. Of the 9,000 Asteroids searched in the NEO database, these twelve could all be brought into an Earth-accessible orbit by changing their velocity by less than 500 meters per second (1,800 km/h; 1,100 mph). A dozen of these Asteroids range in size from 2 to 20 meters (10 to 70 ft) [60].

Table 2 *Comparison of velocity requirements for standard Hohmann transfers*

Mission	**Velocity, Δv**
Earth to LEO	8.0 km/s
LEO to near-Earth Asteroids	5.5 km/s
Leo to the lunar surface	6.3 km/s
Leo to moons of Mars	8.0 km/s

8. Mining of Asteroids

8.1. Hubs and logistics for Asteroid resources

The following three options could be applied for Asteroid mining [59]:

1. Catching and bringing back the raw material from Asteroids to use on Earth
2. Mining the precious materials on the Asteroids themselves and bringing the processed resources back to Earth
3. Constructing a space hub, i.e. the Moon or Mars, to process the raw materials obtained from the surrounding asteroids.

An effective solution to reduce the energy consumption and fuel costs for transporting raw materials to

space might be in-situ processing, providing that mining facilities have been transported and constructed on the mining sites. Basically, this in-situ mining process would include drilling boreholes, injecting hot fluid or gas, and extracting the solute from the liquid mixture created by either reaction or melting processes. Nonetheless, this activity might cause severe disturbances and create dust clouds due to the Asteroids' lack of gravitational fields. A transportation hub on the Moon, near the Earth, or on the ISS might provide access to technology hubs, while significantly reducing transportation costs [61]. Planetary Resources underline that the construction of hubs ("Space infrastructure") will help to reduce long-term running costs [61].

8.2. Asteroid mining operations

Special equipment, which can work in harsh space conditions, will be required for the extraction and processing of space mining ore [52]. The processing facilities will need to be attached to the object, taking advantage of zero- or micro-gravity conditions to remove the ores from the mining site and transport them to the next processing step. However, there are currently no techniques for ore processing in harsh space conditions. The harpoon-like process suggested by James [62] might be a potential solution, providing that the Asteroid is steady and structural enough for such a harpoon to penetrate the surface.

The technologies involved may be:

(i) Surface mining - material may be scraped off the surface using a scoop or auger, or for larger pieces, an "active grab" [52].
(ii) Shaft mining – a mine could be dug into the Asteroid and material extracted through the shaft.
(iii) Magnetic rakes - Asteroids with a high metal content may be covered in loose grains that can be gathered by means of a magnet.
(iv) Heating - Asteroids such as carbonaceous chondrites that contain hydrated minerals, water, and other volatiles can be extracted simply by heating. [63]
(v) Mond process – for nickel- and iron-rich Asteroids. [64]
(vi) Self-replicating machines - a complex automated factory on the Moon for building 80% of a copy of itself, the other 20% being imported from Earth [43], or a "bootstrapping" approach to establishing an in-space supply chain with 100% closure [65].

Technology propositions for staged-wise Asteroid mining have been given by companies specialised in the exploration of this field. Planetary Resources proposes three different types of satellites:

(i) The Arkyd Series 100 (the Leo Space telescope) will analyse the resources of nearby Asteroids [66]
(ii) The Arkyd Series 200 (the Interceptor) would actually land on the Asteroid to get a more in-depth analysis [66]
(iii) The Arkyd Series 300 (Rendezvous Prospector) Satellite would be used for finding resources deeper in Space [66].

Deep Space Industries also propose a three-stage approach: (i) FireFlies are CubeSat-form Spacecraft to examine Asteroids [67]; (ii) DragonFlies would gather small samples (5–10 kg) and return them to Earth for analysis [68]; (iii) Harvestors would gather hundred tons of material for return to a high Earth orbit for processing [69]. Deep Space Industries plans to begin mining asteroids by 2023 [70].

9. Continuous-flow processing and microfluidics as Space enablers

9.1. Continuous-flow

Continuous-flow processing is considered by many experts as an ideal processing and manufacturing technology in Space [71]. This is partly validated by the fact that continuous-flow and microfluidic

experiments are widely run on the International Space Station, and a conference, specifically related to biological subjects using that technology, is dedicated to that [72].

Continuous manufacturing technologies produce products without ceasing. Conversely, batch manufacturing technologies produce products in a charge-wise manner, with start-up and shutdown procedures. Henry Ford's automated production lines for cars are a pivotal example of continuous production [73]. One car is made after the other – stepwise in time and space; without any stop. Continuous-flow uses continuous techniques, which are made in flow. A flowing solution of chemicals that react to a product is an example of this. Continuous-flow is particularly efficient when made at a small scale, i.e., so-called microfluidics [74]. Then, mixing and heat transfer are maximised, which means that it is possible to boost chemical production to the best performance possible [75]. Similar arguments hold for bioprocesses being conducted in micro Space [76].

9.2. Continuous-flow in Space

Having realised this potential, all the major pharmaceutical companies undertake experiments in Space. Eli Lilly, a top-15 global pharmaceutical company, have undertaken experiments at the International Space Station (ISS) [77]. Recently, MIT's spin-off Zaiput Flow Technologies send their flow extractor via the CRS-13 cargo resupply service to the ISS [78]. The possible use of nanoparticles to treat osteoporosis has been tested during the recent Italian mission by Futura on the ISS [79].

9.3. Continuous-flow suitability for Space

Besides practical evidence of use, there are several fundamental arguments that microfluidics and continuous-flow manufacturing can meet the major challenges of Space processing.

- Zero gravity processing feasible
- Vacuum processing feasible
- Compactness / Light-weight
- Automation is advanced
- Modularisation = LEGO of process modules
- Process intensification = processing at first principles

Capillary forces dominate in microcapillaries [80]. Thus, the gravity force does not play a role. Microprocessing happens in enclosed process chambers, and there is no headSpace. The compactness of micro-processing systems reduces the payload and launch costs significantly. Microprocessing provides ideal processing conditions, which offers the opportunity to include artificial intelligence technologies.

10. Continuous-flow solvent extraction in a coiled micro-flow inverter

10.1. Metal extraction in coiled micro-flow inverter

We previously investigated the extraction performance of a coiled micro-flow inverter using a segmented-flow in terms of the purification of cobalt in the presence of nickel, following recipes typical for Earth mining [12, 24]. The micro-flow is generated in a micro-capillary fed by two pumps. The two feeds are water containing the metals and kerosene as an extraction medium, facilitated by a scavenger that catches the metal. Both feed solution, which is immiscible, into a contactor, typically a T- or Y-shaped piece of equal or similar internal dimensions to the micro-capillary. That leads to the formation of liquid slugs, which give an alternately patterned, highly regular water-kerosene flow array under

proper conditions. Due to the very high specific interfaces and intense recirculation within the slugs, interfacial and mass transfer are best, respectively. The micro-capillary is coiled to utilise Dean forces for further intensification of the extraction. After a few such turnings, the direction of the coiling is changed, e.g. from clockwise to counterclockwise [81]. Computational fluid dynamic simulations and experiments have shown that this leads to better recirculation patterns, and thus mass transfer, than when leaving the coiling direction the same [82]. Separation of the two dispersed fluids into pure fluids can be achieved by settling (although the waiting time needed might falsify results) or be further advanced through the use of a micro-flow separator. The latter devices may operate by virtue of surface forces or by using a membrane for the selective solution of one solvent.

10.2. Selective cobalt extraction in continuous-flow

In such a process set up, cobalt has been extracted efficiently out of a Co/Ni sulphate solution with Cyanex 272 as the scavenger [12]. Compared with batch extraction, the segmented micro-flow extraction process shows order-of-magnitude faster extraction times, higher extraction ability for Co, lower extraction for Ni, and therefore a better selectivity between Co and Ni at industrial-matching concentration. The continuous-flow extraction can be 7 times more selective, and 10 times faster than for batches. The results indicate that the extraction efficiency in a micro-flow is dependent on mass transfer by molecular diffusion, this being enhanced by the internal circulation flow generated within the slugs. Key parameters to describe the mass transfer efficiency are the volumetric mass transfer coefficient k_La and overall mass transfer coefficient k_L. Compared with batches, the k_La value of Co (0.26–0.017 s^{-1}) is 4.5 times higher than for Ni (0.053–0.013 s^{-1}) when measured in micro-flow, demonstrating asynchronous extraction between Co and Ni. Figure 2 shows the experimental setup for the extraction of mimicked Asteroid ore using a coiled flow inverter.

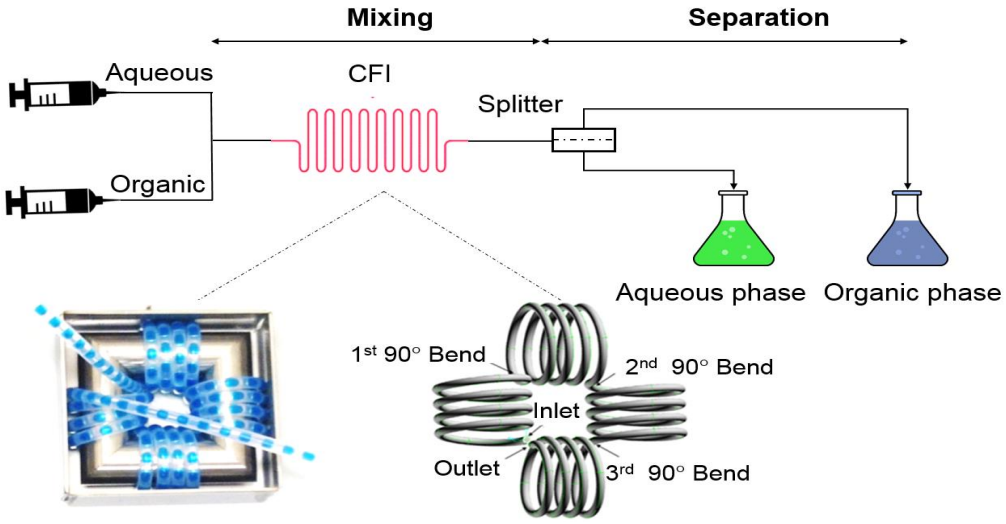


Figure 2 *Selective Ni-Co extraction using a coiled micro-flow inverter*

11. Derivation: Space-given boundaries for continuous-flow solvent extraction

11.1. Boundary conditions for economic Asteroid solvent extraction of metals

With the system analysis (Asteroid, transport, resources, and process technology) being completed, a ‘realistic’ scenario will be derived for a chemical process technology to exploit Asteroid metal

resources. This scenario is, however, as yet unproven economically, yet it has been selected as the best-known technological approach for one economic key driver: water saving. This scenario is proven technologically on Earth and it is likely to meet Space requirements, either fully or to an extent.

Thus, Space requirements need to be defined. Table 1 gives the elemental compositions of the Asteroids. The mass-corundum analysis, as given above, predicts water-metal use ratios of between 10:1 and, at best, 1:1. That issue is very challenging, which means any solvent extraction processing in Space has to approach physical and chemical engineering limits. The physical limits are defined by the solubility limits. In terms of cobalt and nickel, their nitrates are the salts of highest solubility, reaching about 10 mol/l. Under such conditions, a water-metal ratio of nearly 1:2 is reached. It is assumed that continuous-flow extraction can cope with such conditions. Tests are running, although reporting on these is beyond the scope of this paper.

11.2. Key differences between Space and Earth processes for Asteroid mining

When translating those system boundary conditions in process mass flows for solvent extraction, there are key differences between Space and Earth processes; as follow:

- Metal concentration: 10 mol/l (Space) vs. 0.1 mol/l (Earth);
- Relative metal load: Ni:Co = 10:1 in Space vs. Ni:Co = 3:1 on Earth;
- Metal mixture complexity: might be higher in Space, e.g. encompassing Fe, Ni, Co, Pt, …
- The microenvironment is different in Space, as not only minerals are found (as on Earth) but also alloys such as Kamacite, α-(Fe, Ni); Fe0+0.9Ni0.1

Our unpublished experiments with a much higher concentration of the metal (up to 10 mol/l, matching the demand as given above) confirm that the favorable hydrodynamics of the segmented flow can be maintained. Thus, Space solvent-flow extraction will also profit from the intensified mass transfer. We will report this in a technical paper in due course.

When massively reducing the use of water as a solvent and thus operating with highly concentrated aqueous metal salt solutions, the process media will have an unusually high density and viscosity and possibly operation at a temperature higher than ambient might be needed. For 10 mol/L of nickel (II) nitrate solution, the density is approximately 2.9 g/cm^3 while the solution is nearly solid at room temperature. Processing of such solutions is practically unknown on Earth, both academically and also in industrial practice; so these are really "space fluids". Both the density and the viscosity impact the fluid dynamics, which are the pivotal performance key of microfluidics.

To give evidence for that, using the example of solvent extraction in a coiled micro-flow inverter, some relevant dimensionless numbers have been calculated (see Table 3 and Table 4). This includes the Reynolds number (Re) defining the ratio of inertial to viscous forces that are used to help to predict flow patterns in different fluid flow situations. The Weber number (We) defines the ratio of inertial forces per liquid-liquid surface tension and stands for the relationship between the deforming inertial forces and the stabilizing cohesive forces for liquids flowing through a fluid medium. If the deforming force increases, the drops will be dispersed easily and inversely as high interfacial tension counteracts this process. The Capillary number (Ca) defines the ratio of viscous forces and surface tension and determines, for example, if a droplet flowing in a liquid-liquid stream is deformed (until rapture) or not. Finally, the Dean number (De), defined as a function of the Reynolds number and the curvature ratio, stands for the effect of torsion on the slugs in the segmented; in the context of multiphase flow processing considered here. The higher the Dean Number, the stronger the vortices in the slugs of the segmented flow. Therefore, by increasing the De and torsion, mass and heat transfer can be increased.

Some assumptions had to be made for the calculations, due to lack of data. Chloroform has been taken as a substitute for kerosene, as its properties with regard to water, such as interfacial tension, are known (and not for kerosene). When calculating the dimensionless numbers, the total flow rate is considered; which is the main way used in literature for biphasic flows (note: those numbers hold strictly only for monophasic flows). To consider the interfacial tension of a 10 mol/l $NiNO_3$ solution versus the ionic liquid phases, data were taken known for a water phase; in view that this parameter hardly varies with salt concentration.

Table 3 *Dimensionless numbers for water, when being the disperse phase in a water/chloroform segmented flow. Shown is the variation of the total flow rate, curvature , and inner capillary diameter.*

Total flow rate (ml/h)	**U (m/s)**	***Re***	***Ca***	***We***	**d_i (mm)**	**d_c/d_i**	***De***
960	0.34	372	0.01	3.6	1	5	166
1,080	0.38	418	0.01	4.6	1	5	187
1,200	0.42	465	0.01	5.7	1	5	208
960	0.34	372	0.01	3.6	1	10	118
1,080	0.38	418	0.01	4.6	1	10	132
1,200	0.42	464	0.01	5.7	1	10	147
960	0.03	116	0.001	0.1	3.2	10	37
1,080	0.04	131	0.001	0.2	3.2	10	41
1,200	0.04	145	0.001	0.2	3.2	10	46

Table 4. *Dimensionless numbers for a 10 mol/l $Ni(NO_3)_2$ solution, when being the disperse phase in a 10 M $Ni(NO_3)_2$ solution/BMIM NTf_2 segmented flow. Shown is the variation of the total flow rate, curvature, and inner capillary diameter.*

Total flow rate (ml/h)	**U(m/s)**	***Re***	***Ca***	***We***	**d_i (mm)**	**d_c/d_i**	***De***
10 mol/l $Ni(NO_3)_2$							
960	0.33	27.6	0.68	18.7	1	10	8.7
1,080	0.38	31.1	0.76	23.7	1	10	9.8
1,200	0.42	34.5	0.85	29.3	1	10	10.9
BMIM PF_6							
960	0.34	2.3	6.93	15.6	1	10	0.7
1,080	0.38	2.5	7.80	19.8	1	10	0.8
1,200	0.42	2.8	8.66	24.4	1	10	0.9
BMIM Ntf_2							
960	0.34	9.4	1.33	12.5	1	10	3.0
1,080	0.38	10.5	1.50	15.8	1	10	3.3
1,200	0.42	11.7	1.67	19.5	1	10	3.7

The analysis shows that both the Re and De numbers are mostly in the range of 50 or higher for the flowing water/chloroform system in a microcapillary, which is considered to be fully beneficial for mass and heat transfer (see Table 3). An increase in the flow rate is beneficial (yet might need longer capillary equipment and thus necessitate larger pressure drop), an increase in the curvature (d_c/d_i), and miniaturization (of the capillary diameter, d_i).

However, when a highly concentrated aqueous metal salt solution flows through a microcapillary, both the Re and De numbers decrease largely. This is because the viscosity effect is more pronounced than the density effect (albeit being large as well). Only future experiments can show how much that might reduce performance in terms of mass and heat transfer, yet it is likely the effect will be drastic. Virtually the same happens when introducing ionic liquids in place of the extraction medium kerosene. They have much higher viscosity and so the Re and De number go down (see Table 4).

According to Tables 3 and 4, the use of highly concentrated metal solutions and ionic liquids, instead of water and an ordinary organic phase, do increase the Weber number. That might favour the formation of smaller slugs which likely is good for mass and heat transfer. Because of the high viscosity of the ionic liquid, the Ca numbers increase for the concentrated metal solutions and the ionic liquids as well. This, e.g., could lead to a decrease in the thickness of the liquid film surrounding the disperse slugs.

Thus, this all shows that new frontiers in chemical engineering are tackled and that the proposition of measures to overcome this new limit in flow processing is demanded. While the space conditions are not beneficial concerning the Re and De numbers, and thus the recirculations within the process volume, there may be opportunities stemming from the We and Ca numbers, concerning the interfaces provided between the volumes.

Miniaturisation would decrease productivity. Thus, the view might be on alternative intensification solutions. As viscosity is the major issue, the reduction in viscosity with temperature is a suitable means to overcome that effect. To understand how strong such an effect would be, the viscosity reduction of highly concentrated sodium chloride (brine) solutions is plotted in Figure 3; assuming similar effect might be given for a 10 mol/l $NiNO_3$ solution (for which such data do not exist).

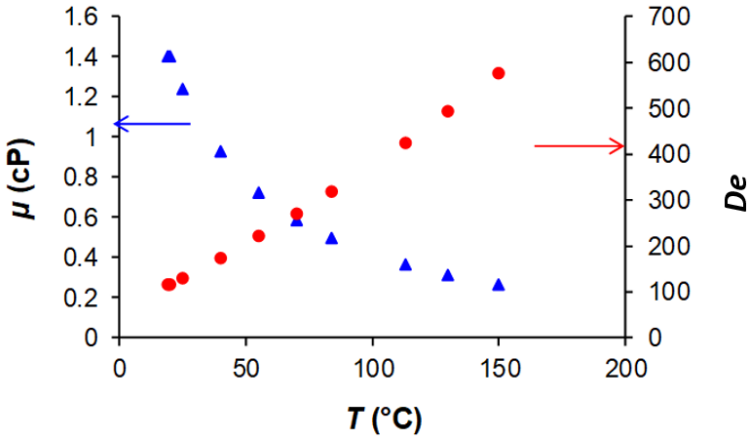


Figure 3 *Viscosity and Dean number trends of highly concentrated sodium chloride (3.2 mol/l). Data are taken from Scranton and Lindberg* [83]

The data points larger than 100°C were measured at high pressures of several ten bars. These were taken because a continuous-flow operation would be needed under superheated processing, in order to avoid boiling of the flowing solution. This concept has been termed high-p,T in flow chemistry and is a novel process window, which denotes operation setting in micro-flow far from any conventional practice [84].

The plot shows that viscosity can be reduced to a level, changing the micro-flow to the desired Re- and De-range. Thus, hot processing is demanded in the ice-cold space environment.

12. Disruptive Potential of Ionic Liquids for Space Resources

12.1. Ionic liquids as master solvents

While kerosene is a cheap, standard solvent in metallurgical extraction, it might be asked if there is not a better solvent, especially seeing the need to bring kerosene as well to the Asteroid. As any other solvent will likely have a higher price, so the selection should be for the believed-best solvent available; in the hope of an even lower solvent inventory, even higher efficiency, and even better recyclability.

There is a common belief that ionic liquids (ILs) have such potential, and this is why they are termed designer and master solvents [85]. ILs comprise organic cations in combination with various anions, as any ion, yet they are in a liquid state at room temperature (or slightly elevated temperature); much unlike normal ions. The term 'Designer Solvents' refers to the fact that their physicochemical properties, such as solubility, melting point, density, or viscosity, can be controlled and fine-tuned by the selection of the cation and/or anion [23, 86]. Depending on the cationic or anionic structure of ILs, they can be miscible with organic solvents and/or water. In one step further, task-specific ionic liquids (TSILs) have functional groups appending to the cation or anion (or both), which can modify their extraction performance to the new conditions to be expected in Space [87]. One of the important strengths of ionic liquids is their thermal and chemical stability, which allows them to be used at high temperatures in the presence of acids and even super-acids [88].

12.2. Master solvents for metal solvent extraction

ILs have been considered in the process of metal-solvent extraction in recent years [89]. The main motivation is the assumed greenness of IL, as they may provide a more environmentally friendly solution [89b, 90]. Traditional solvent extraction processes are based on organic solvents, which are generally hazardous and toxic. ILs are believed to have zero vapour pressure [91]. This enables minimization of solvent losses in low pressure or vacuum conditions, such as those experienced on the Moon, Mars, and Asteroids [92]. ILs may be able to be handled openly under vacuum conditions, i.e. eliminating the need for a closed processing system. If true, that would mark a unique asset that no other class of solvents shares. Yet this remains to be demonstrated definitively in Space, to show if the vapour pressure really is zero or only negligibly low but existing nonetheless.

Up to now, numerous ILs have been investigated for their use in the extraction of metal ions. Imidazolium-, phosphonium-, ammonium- and pyridinium-based cations with halide-, $[PF_6]$-, and $[Tf_2N]$-anions are the most frequent choices. A comprehensive list of such studies is given in Table 5.

12.3. Comparison of the performance of ILs and conventional solvents

ILs can add superior performance to the use of conventional solvents for metal extraction, as follows:

Extraction efficiency

Some ionic liquids can extract metal ions, even at 100% efficiency, and where the given conditions are more selective than for conventional solvents [93]. It is likely that this high performance can be explained by using the ion exchange as the predominating mechanism for the extraction of the used metal ion by the ionic liquids [93].

Table 5 *Performance of ILs evaluated as extracting agents of selected metals of Co, Ni, Fe, and PGMs*

Ionic liquid	Metal ion	Mechanism	Ligand/solvent	Performance (E %)	Stripping agent	Reference
[HMIM][BF_4]	Co(II)	IE[a]	NaCl	Co(II), D= 5.8	$NaPF_6$ (0.03 M): Co(II),100%	[94]
[HJMT][Cy272]/Kerosene, Exxon D100 and Solvesso 200	Co(II), Ni(II)	IE	HCl (1 M)	Co(II),>99%; Ni(II),11%	EDTA (0.02 M): Co(II) ,95%; Ni(II), 83%	[95]
[BuGBOEt][Dca]	Cu(II), Ni(II), Pb(II), Cd(II)			Pb(II), 858%;Cd(II), 95%;Ni(II), 82%;Cu(II), 83%	EDTA (0.1 M): Ni(II), 100%; Cu(II), 100%	[93]
[BuGBOEt][Tf_2N]	Cu(II), Ni(II), Pb(II), Cd(II)			Pb(II), 38%; Cd(II), 41%; Ni(II), 20%; Cu(II), 22%	EDTA (0.1 M): Ni, 100%; Cu, 100%	[93]
[Dibutyl IM][Br]	Co(II), Ni(II)	AE[b]	Acidic thiocyanate HNCS	Co(II), >99%	NH_3 (1.0 M): Co(II), >93%	[96]
[N_{8888}][oleate]	Zn(II), Co(II) ,Ni(II)	IL metal complex	HCl	Co(II), D=20.4; Ni(II), D=13.5; Zn(II) D>200		[97]
$BuNC_2OC_4$ -Sac,	Cu(II), Ni(II), Co.(II), Pb(II), Cd(II)	cation exchange and IP[c]		Cu(II), 30%; Ni(II), 5%; Co.(II), 10%; Pb(II), 20%; Cd(II), 95%	EDTA (0.1 M)	[98]
$BuNC_2OC_4$-Clsal	Cu(II), Ni(II), Co.(II), Pb(II), Cd(II)	cation exchange and IP		Cu(II), 100%; Ni(II), 96%; Co.(II), 94%; Pb(II), 100%; Cd(II), 100%	EDTA (0.1 M): Ni(II), 100%; Co(II), 100%, Pb(II), 100%; Cd(II), 100%	[98]
$BuNC_2OC_4$-Dca	Cu(II), Ni(II), Co.(II), Pb(II), Cd(II)	cation exchange and IP		Cu(II), 98%; Ni(II) 98%; Co(II), 95%; Cd(II), 95%	EDTA (0.1 M): Ni(II), 100%; Co(II), 100%; Pb(II), 100%; Cd(II), 100%	[98]
Cyphos IL 101	Co(II), Ni(II)	AE and split-anion	H_2SO_4 , $(NH_4)_2SO_4$	Co(II),>90%	Water: Co(II)>99%	[99]
[P_{44414}][Cl]	Co(II), Ni(II)	-	NaCl	Co(II), D=100; Ni(II), D=0.2	-	[100]
[A336][CA-12] $[A336]_2SO_4$	Co(II), Ni(II)	ion association	Toluene, Na_2SO_4	Co(II), D>95% ; Ni(II), D>65%	H_2SO_4: Co(II), 100%; Ni(II)>99%	[100]
[P_{66614}][Cl]	Cu(II), Co.(II), Fe(III), Cu(II)	-	HCl (9 M)	Co(II), > 98%; Fe(III), >99%	(EDTA + Water): Fe(II)>80%	[101]
[P_{66614}][Cl]	Co(II), Ni(II)	AE	HCl (8 M)	Co(II), D= 460; Ni(II), D= 0.0088	(Water, after 4 steps): Co(II)>99%	[102]

Aliquat-336/ benzene	Au(III), Pt(IV), Pd(II)	AE		Au(III), >99%; Pt(IV) , <5%; Pd(II), <7%	(Thiourea (0.05 M) + HCl (0.1 M)): Au(III), 100%; Pt(IV), 100%; Pd(II), 100%	[103]
[HMIM][PF_6]/ diisopentyl sulfide (S201)– nonane	Pt (IV), Pd (II), Rh (III)	AE	HCl	Pt (IV), 70%; Pd (II), 7.7% ; Rh (III), 6.8%	Ammonia water: Pd (II), 93.4%, HNO_3 (3 M): Pt (IV) 68.5%,	[104]
[THN][Tf_2N]	Au(III), Pt(II), Pt(IV)	IPand AE	-	Au(III), >95%; Pt(IV), < 5%; Pt(II)<15%	((NH_2)$_2$CS (0.2M) and HCl (0.5M)): Au(III) >85%	[105]
[TON][Tf_2N]	Au(III), Pt(II), Pt(IV)	IP and AE	-	Au(III), >95%; Pt(IV), <5%,; Pt(II),<5%	((NH_2)$_2$CS (0.2M) and HCl (0.5M)): Au(III) >98%	[105]
[THN][Dca]	Au(III), Pt(II), Pt(IV)	IP and AE	-	Au(III), >95%; Pt(IV), >100%; Pt(II), >95%	((NH_2)$_2$CS (0.2M) and HCl (0.5M)): Au(III) >68%; Pt(IV), 76%	[105]
[TON][Dca]	Au(III), Pt(II), Pt(IV)	IP and AE	-	Au(III), >95%; Pt(IV), >100% ; Pt(II) >95%	((NH_2)$_2$CS (0.2M) and HCl (0.5M)): Au(III) >54%; Pt(IV) 69%	[105]
[THN][SCN]	Au(III), Pt(II), Pt(IV)	IP and AE	-	Au(III), >95%; Pt(IV), >100%; Pt(II) >95%	((NH_2)$_2$CS (0.2M) and HCl (0.5M)): Au(III) 26%	[105]
[THN][Br]	Au(III), Pt(II), Pt(IV)	IP and AE	-	Au(III), >95%; Pt(IV), >100%; Pt(II), >95%	((NH_2)$_2$CS (0.2M) and HCl (0.5M)): Pt(IV)<2%; Au(III)<2%	[105]
[TON][Br]	Au(III), Pt(II), Pt(IV)	IP and AE	-	Au(III), >95% Pt(IV), >100%; Pt(II),>90%	((NH_2)$_2$CS (0.2M) and HCl (0.5M)): Au(III) <75%	[105]
(CP-AMIN)/(CP)	Pt(IV), Pt(II), Pd(II)	AE	HCl (0.1 M) at 60 °C	Pt(IV), >94%; Pt(II) > 95%; Pd(II), > 98%	Thiourea solution (1 M): Pt(IV)> 97%; Pt(II) > 95% ; Pd(II)> 99	[106]
[OMIM][NTf_2]	Pt(IV), Pd(II)	IE	HCl (1 M)	Pt(IV), 89%; Pd(II), 4%	-	[107]
Cyphos 102	Pt(IV), Pd(II)	IE	HCl (1 M)	Pt(IV), >99%; Pd(II), >99%	-	[107]
Cyphos IL 101	Pt(IV), Pd(II), Rh (III)	AE	HCl	Pt(IV), >98%; Pd(II), > 99%; Rh (III), <5%	(NH_4)$_2$CS in 5% v/v HCl: Pd(II), 100%, NH_4OH: Pd(II)>94%; Pt(IV)> 81%	[108]
[HBBIM][Br]/Chloroform	Pd(II), Pt(IV)	AE	HCl	Pd(II), >99%; Pt(IV), > 99%	(Thiourea (0.5 M) + HCl (1 M)): Pd(II)>99%	[109]

$[C_6bet][Br]/ [C_6mim][NTf_2]$	Pt(IV), Ir(IV)	AE		Pt(IV), 99%; Ir(IV), 88%	HCl (8 M) , $N_2H_2.H_2O$: Pt(IV) >90%, Ir(IV)>90%	[110]
$[TOAH][NO_3]/[TOAH][NTf_2]$	Pt(IV), Pd(II)	IE	HCl (0.1 M)	Pt(IV), 92%; Pd(II), 99.8%	HNO_3 (0.10 to 8.0 M): Pt(IV), 91%; Pd(II), 57%	[111]
$[C_{16}mim][Cl]/[C_8mim][PF_6]$	Pt(IV)	AE	HCl (0.8 M)	Pt(IV), 97.8%	Hydrazine: Pt(IV)>90%	[112]
$[C_8mim][PF_6]$	Pt(IV)	AE	HCl (0.8 M)	Pt(IV), >60%	Hydrazine: Pt(IV) >90%	[112]
$[C_{16}mim][Cl]$	Pt(IV)	AE	HCl (0.8 M)	Pt(IV), >95%	Hydrazine: Pt(IV) >90%	[112]
$[C_8mim][NTf_2]$	Pt(IV)	AE	HCl (0.8 M)	Pt(IV), >53%	Hydrazine: Pt(IV) >90%	[112]
$[C_1C_8IM][NTf_2]$	Pt(IV)	AE	HCl (1 M)	Pt(IV), D=18.4	-	[113]
$P_{88812}Cl$	Pt(IV), Pd(II), Rh(III)	AE	HCl (1 M)	Pt(IV), 100%; Pd(II), 100%; Rh(III), >80%	5 mol L^{-1} HNO_3 Pt>74%> HCl (5 M): Rh>70% $CS(NH_2)_2$ (1 M): Pd>91%	[89c]
$[C_4mim][PF_6]$	Cd(II), Co(II), Ni(II), Fe(II), Hg(II)	AE	KSCN (0.5 M)	Cd(II), D = 5.4; Co(II), D= 49; Ni(II) D= 0.26 ; Fe(II),D=0.89; Hg(II),D= 0.90	-	[89b]
$[C_4mim][PF_6]$	Cd(II), Co(II), Ni(II), Fe(II), Hg(II)	AE	NaCN (0.5 M)	Cd(II),D= 0.19; Co(II),D 0.015; Ni(II), D= 0.76; Fe(II),D= 0.52; Hg(II),D= 140	-	[89b]
Cyphos IL101/chloroform	Fe (III), Ni(II)	-	HCl (6 M)	Fe (III)>99%; Ni(II)<1%	HCl (<0.5M): Fe (III)>80%	[114]
$[BMIM]PF_6$	Ni(II), Pb(II), Cu(II)	proton transfer and redox	2-aminothiophenol (ligand),	Ni(II)> 99% ; Pb(II)> 80%; Cu(II)>99%	(H_2O_2 inHNO_3 (3 M)): Ni(II)>99%; (HNO_3 (0.5 M)): Pb(II)>99%; Cu(II)>99%	[89a]
[A336][TS]	Pt(II), Ni(II)	-	-	Pt(II)=85%; Ni(II)<1%	-	[115]
[A336][SCN]	Pt(II), Ni(II)	-	-	Pt(II)=95%; Ni(II)<1%	-	[115]
[PR4][MTBA]	Pt(II), Ni(II)	-	-	Pt(II)97%; Ni(II)<1%	-	[115]

[a] IE: Ion Exchange,
[b] AE: Anion Exchange
[C] IP: Ion Pairing

Extraction selectivity

As on Earth, there is a co-existence of metals in ores common in Space mining, and so a selective extraction process is needed, i.e. favouring one metal over the other. This constitutes an important and difficult hydrometallurgical problem [116]. Many conventional solvent-based studies have focused on the extraction of Co(II) in the presence of Ni(II) by using an organic solvent with a complexing agent. These systems can be applied to both chloride and sulphate solutions, but the selectivity is relatively low [117]. However, more recent works have considered the ILs for the extraction of these metals. Table 6 summarizes the solvents commonly used to extract the Co(II) and Ni(II) selectively.

Table 6 *Comparison of the performance of ILs and conventional solvents in metal selectivity*

Solvent	**Medium**	**Concentration of Co in feed (g L^{-1})**	**Concentration of Ni in feed (g L^{-1})**	**Selectivity Co/Ni**	**Reference**
Na-D2EHPA/Kerosene and (TBP)	NaCl, (1 M)	0.5	2	13	[117c]
Na-PC88A/Kerosene and (TBP)	NaCl, (1 M)	0.5	2	26	[117c]
Na-Cyanex 272/Kerosene and (TBP)	NaCl, (1 M)	0.5	2	1848	[117c]
Cyphos IL 101	NaCl, (4 M)	5	5	12000	[102]
$[P_{8888}][Br]$	HCl, (8 M)	5	5	98000	[102]
$[P_{44414}][Cl]$	HCl , (8 M)	5	5	420	[102]
$[P_{66614}][Br]$	HCl, (8 M)	5	5	58000	[102]
$[P_{66614}][Cl]$	HCl, (8 M)	5	5	52000	[102]
Aliquat 336	HCl, (8 M)	5	5	2500	[102]
[Dibutyl IM][Br]	NH_4SCN, 2 M	0.05	0.05	2000000	[96]

Based on Table 6, ILs can be several thousand times more selective than a conventional solvent when applied for the separation of Co from Ni. Wellens et al. [102] introduced an efficient solvent extraction process for the separation of cobalt and nickel using phosphonium hydrophobic IL as an undiluted extractant. They scaled up the process to a 250 mL batch reactor and reported the process is more efficient than those industrial processes currently in use. Separation factors higher than 50000 for cobalt/nickel were achieved. Eyupoglu et al. used four imidazolium-based ionic liquids with different alkyl groups in mild acidic aqueous solutions containing thiocyanate as the complexing agent [96]. They reported 1,3-dibutyl imidazolium bromide can extract Co with pivotally high selectivity of 2,000,000 even in mild acidic media. ILs enable process simplification, i.e. they can be used without any scavenging agent, whereas organic solvents need some complex agent(s) to extract metal ions. Table 2 also shows that the operational window of ILs is higher; whereas organic solvents only separate well at Co:Ni ratios >> 1, ionic liquids show high selectivity even where the Co:Ni ratio equals one.

Recycling

After stripping off the metal, the ionic liquids can be recycled for reuse. Acetone, 2-propanol, supercritical CO_2 and water were used successfully for recovery of ionic liquids after extraction [118].

13. Automation and communication challenges

13.1. Asteroid communication

Previous Asteroid missions provided guidance on automation and communication issues, in particular during the JAXA Hayabusa 1 and 2 missions, NASA OSIRIS-Rex and those that were designed for Asteroids [119]. For Asteroid mining, the communication challenges involve ground support for the mission, trajectory corrections, remote control in case of emergencies, and the transmission of data for

analysis [120].

On the Spacecraft side, the Hayabusa Spacecraft has two high-gain directional antennas for the X band and the Ka band. Bit rates are 8 bit/s–32 kbit [120]. The telecommunications system employed by OSIRIS-REx consists of a large directional high-gain antenna, a single medium-gain antenna and a pair of omnidirectional low-gain antennas. The heart of the communications system is the Small Deep Space Transponder (SDST) and the Traveling Wave Tube Amplifier [121]. The SDST is a NASA/JPL design for deep Space missions, used to unify a number of communications functions in a single unit – receiver, command detection, telemetry modulation, exciters, tone generator, and control. Each unit has a mass of 3 kilograms and supports command reception in the X-Band and data transmission in both the X- and Ka Band (two bands being of importance for gravity science applications needed by many Space probes). The antenna is a 2.1-meter diameter dish with a dual-reflector X-Band system to achieve downlink data rates of up to 914kbit/s.

The Prospector-1 mission from DSI (Deep Space Industries) proposes the use of X-band communication. In their studies, they also define some link budget characteristics, such as the transponder's power, to ensure continuous communication [122]. Considering the data volume, the prospection phase is the system driver; however, no real-time communication is needed. For a similar application, the ESA MarcoPolo mission included three antennas for communications: a high gain antenna, a medium gain antenna, and two low gain antennas, basing their design on the Bepi Colombo and Solar Orbiter missions [123]. A typical communication module weighs around 10 kg and requires a power of 120 W (around 10% of the typical power consumption in an aircraft) [120].

For the ground control side, large antennas are needed on the ground, such as those at the Usuda Deep Space Center, Uchinoura Space Center, NASA Deep Space Network and ESA's Malargü Station [124]. The Radio Science team will use the high and low gain antennas, part of the Telecommunications Subsystem, to communicate with the Deep Space Network (DSN) on Earth in order to obtain accurate Doppler and range measurements of the Spacecraft.

Significant communications challenges for Asteroid mining include the low data rate and high latency of communication links. This makes remote control applications requiring sub-millisecond delay practically impossible. Most importantly, all of the existing missions rely on the large, multi-billion dollars of public ground stations such as the Deep Space Network, for communications. There are about 12 antennas available at the DSN [125]. At any one time, each antenna is steered towards a Spacecraft, limiting the number of Space crafts that can be served simultaneously to 12. These will create a bottleneck as the number of Asteroid missions increases. Perhaps such a problem could be solved when greater commercial interests are focused on deep space discovery, which would enable the expansion of the current network.

13.2. Asteroid automation

The long distances between the Earth and the selected Asteroid are the main obstacles for the automation approach. The latency might take up to several minutes for a round-trip communication to and from the Earth. Highly automated or AI embedded equipment would be required, while humans should also be available for troubleshooting and equipment maintaining. Yet previous missions to Mars were successful despite minute delays due to deep space distance. It is obvious that modern automated systems will be developed to adapt to the need for instant communication [62].

14. Outlook: The final frontier - Asteroids as the 'Americas' of today

14.1. Asteroids – the 'Americas' of today

Christopher Columbus, Marco Polo, and Neil Armstrong felt a desperate need to know the unknown. The diversity of human history has been written by explorers, adventurers, and dreamers, driven by a vision to push the boundaries of our collective beliefs and expand our presuppositions about corporeal limits.

Seen from the disruption of the technology, mining the Asteroids is not entirely a new frontier yet, in a way, it is like getting old wine in a new bottle. About 500 years ago, the economic challenge to mankind was similar, as the Americas were discovered. The lesson of history is that the economics and logistics of American colonisation might encompass a future solution for Space discovery.

14.2. Learning from the past: hubs and supply chains

What can be learned from this masterpiece of history, is:

- The need to develop supply chains
- The need to develop hubs enabling multi-lateral economic connectivity
- The chance to develop product innovations through new hubs and supply chains.

Figure 4 shows the supply chains established between England as the mother country and the new colonies (New England). The critical point is that the initial business model was solely based on exploiting resources from the colonies, in a one-directional supply chain. Yet even for this simple business model, a production co-location was needed, i.e. hubs in the islands of the West Indies and in West Africa, see Figure 4.

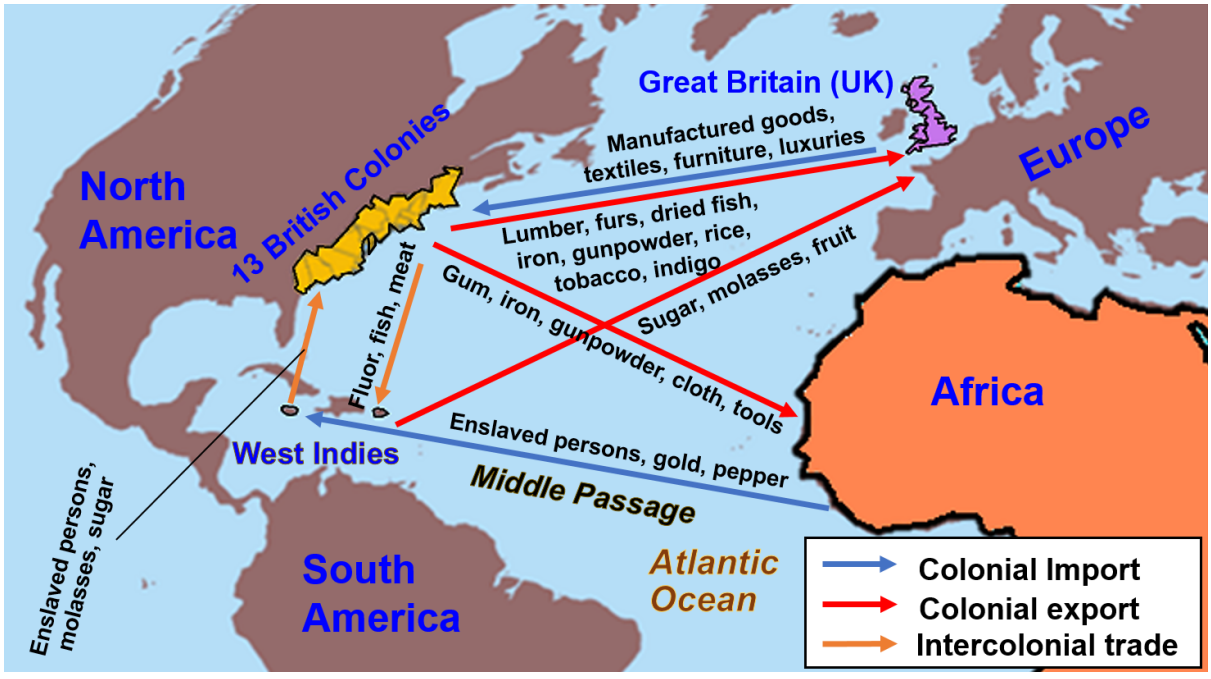


Figure 4 *Trading map between Europe and New England in 1700*

Such a supply chain model awaits development for resource business exploitation in Space. This paper cannot give that vision; it is too far-reaching and complex. Yet, it can recommend learning from the past. The Moon is a likely hub for all Asteroid resourcing matters, as will be the Earth. Another historical learning is to implement product vision into Space resource matters. This implies the transformation of the 'colonies' from resource delivery to goods delivery and to create innovation

precincts, which will make them autonomous and thus a vital economic player. Disruptive technologies have a major role in industry transformation. The following two examples may throw light on this.

14.3. From resources to finished goods: the story of the beaver hat

The beaver hat marked the transformative change in the industries of the new colonies from resources to finished goods and is one of the first examples of an economic product success story. For centuries, hats were a mandatory part of everyday dress, for both men and women, of which beaver wool was the favourite. In 1700, the potential market for hats in England alone was nearly 5 million per year. The depletion of European beaver populations coincided with the establishment of European colonies in North America. England, France, and the Netherlands had all established North American colonies by the early-to-mid 17th century. 21 million beaver hats were exported in 1700-1770. In 1750, the export to Germany was 16,500, to Spain 110,000, and to Portugal: 175,000. The exchange of goods inhabited a realm that tied two cultures together economically, symbolically and politically.

14.4. Product innovation by modularisation: the story of Eli Whitney

Any colonisation will start with resource harvesting/exportation, and move from there towards manufacturing of finished products at the site. The history of the Americas also teaches us of the invention and very first commercialisation of the concept of modularisation.

In 1801, Eli Whitney introduced a manufacturing method based on interchangeable parts. He assumed that if all the individual pieces of a machine are produced identically, then the final products should be identical copies of each other, and replacing a single broken part is as easy as ordering the replacement. While weapons were not a driving factor of the Industrial Revolution, the idea of interchangeable parts certainly was. This process transformed America from an artisan-based manufacturing nation to an unskilled, assembly-line style producer.

14.5. A modern approach to space mining

Based on the past lessons, the Fishbone or Ishikawa diagram, as seen in Figure 5, shows a proposed approach that might be applied for future Asteroid mining. The supply chain and communication management techniques should be developed in advance on Earth to enable the establishment of the first space colony/hub on Moon or Mars. Specifically, the cost of the supply chain from Earth should be significantly reduced while communication and information management techniques should be speeded up to minimise the latency to and from the targeted Asteroid objects [126]. In the meantime, Earth-based space technologies such as spacecraft design, exoplanet telescopes, lightsails, solar surfing, etc. should also be brought up to a state-of-the-art level, enabling cheap, fast, stable and reliable transportation between the mining sites and the space colony/hub centre [127].

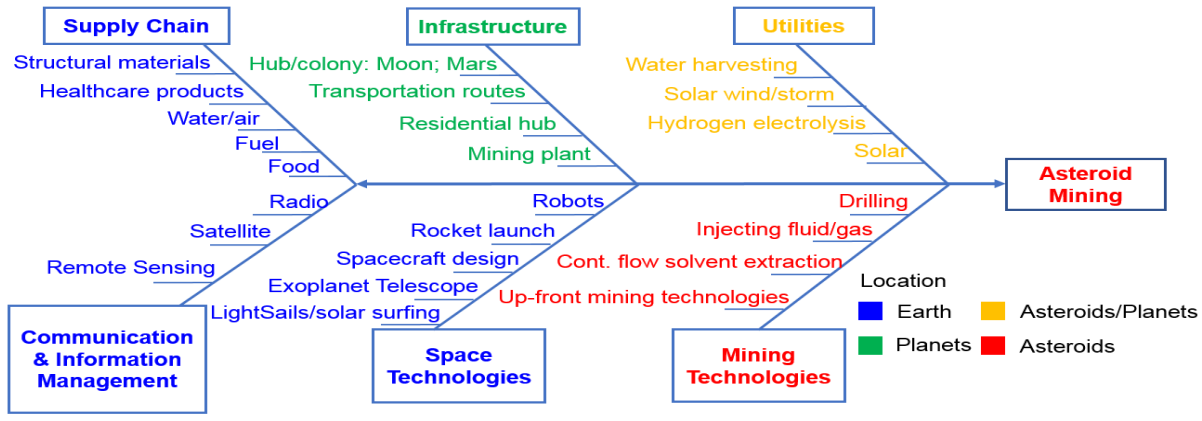


Figure 5 *Asteroid Mining supply chain: from Earth to Space*

On the other hand, on-site ISRU technologies appear to be the most important factors that will decide the success of a space mining mission [128]. Although mining technologies have been developed and well studied on Earth, most of them will be out-dated in space due to harsh conditions such as zero-gravity, extreme heat or ice-cold temperatures, etc [62, 65a, 129]. Thus, a completely new mining approach, procedure, and knowledge might need to be developed on-site to achieve the expected performance. Many other factors, including size, velocity, the composition of Asteroids, etc., should also be taken into account when considering the construction of on-site mining plants. The key success for this new model of business will be inter-disciplinary cooperation, which will gather together state-of-the-art technologies from the ground floor on Earth and take them up to outer-space on the Moon, Mars or Asteroids.

15. Conclusions

This feature paper started with the likely assumption that, as on Earth, disruptive technologies are needed for industrial start-ups and transformations in Space. The example of continuous-flow metal solvent extraction considered here, which is one step among mining/metallurgical processing, confirms this. The use of continuous-flow solvent extraction can hasten, simplify, and intensify the process. There is very early evidence that this technology can process metal flows of extraordinarily high concentrations (10 mol/l), which are believed to be needed for Space processing. More studies and more evidence is, however, needed to substantiate this first hypothesis. If this is achieved, then process intensification can save massive amounts of water, possibly by three orders of magnitude. Likewise, this holds for other materials that are used in large volumes (e.g. solvents; or, in our case, kerosene). This might finally make it possible to launch water and other materials from Earth or from the Moon to the Asteroids, under economic conditions. Yet, we cannot give proof here that this would be successful. Many more studies and calculations are needed. Our mission is to make suggestions and generate motivation within Space and flow communities, to initiate a new kind of interdisciplinary research. We also aim to consider more modern chemical engineering approaches (process intensifications) in the concept of Space manufacturing (ISRU). Knowledge of electrical, mechanical, Space and other forms of engineering is well covered in the ISRU studies reported, yet the potential for chemical engineering is largely unexploited.

Returning to the concrete example chosen, the final solution for Space metal purification might be solvent-free processing, which is one of the green chemistry principles for Earth pharmaceutical manufacture [130]. It should also be pointed out that water harvesting is only part of the whole mining issue. Greater capability development and deployment trade are needed, including resource prospecting and acquisition; water filtering, storage, and transfer; and reusable vehicles moving between the lunar surface and the mineral processing location [18a]. Thus, only a first step has been made, yet it is a step with a top-down view from the economic side.

Acknowledgments

Volker Hessel and Nam Nghiep Tran acknowledge funding from a start-up fund of the University of Adelaide. Michael Goodsite acknowledges the Faculty's support for the ISRU Laboratory and conceptual approach. Hung Nguyen acknowledges the Faculty's support for the Space Theme.

Author Biography



Prof. dr. Volker Hessel studied chemistry at Mainz University (PhD in organic chemistry, 1993). In 1994, he entered the Institut für Mikrotechnik Mainz GmbH (1996: group leader microreaction technology). In 2002, Prof. Hessel was appointed Vice Director R&D at IMM and in 2007 as Director R&D. In 2005 and 2011, Prof. Hessel was appointed as part-time and full professor at Eindhoven University of Technology, respectively, for the chair of "Micro Flow Chemistry and Process Technology". He is honorary professor at TU Darmstadt, Germany, and guest professor at Kunming University of Science and Technology, China. Currently, Prof. Volker is the Deputy Dean (Research) in the Faculty of Engineering, Computer & Mathematical Sciences (ECMS), The University of Adelaide.



Dr Nam Nghiep Tran finished his PhD study in Chemical Engineering at The University of Adelaide in early 2018. He is currently a postdoc researcher in Hessel's group. His research interests include process design and optimization, process simulation, renewable energy, and life cycle assessment.



Dr. Sanaz Orandi hold a PhD in Chemical Engineering, specialising in water treatment technologies. She is passionate about environmental challenges, exploring sustainable remedies for contaminated lands and water. Her experience is gained through working with industry and academic institutions, collaborating with research organizations, (e.g. Research & Development centre at Sarcheshmeh copper mine, the largest porphyry copper mine in Iran and Middle East), and supervising research students and PhD candidates at the University of Adelaide.



Prof. Michael Evan Goodsite is a civil- and environmental engineering full professor and Head of School for Civil, Environmental and Mining Engineering (CEME); Head (ad interim) the Australian School of Petroleum (ASP) & Director of Commercialisation at the University of Adelaide Faculty of ECMS. An MBA in global management with experience as an appointee (by the elected Regional Council) as the Region of Southern Denmark's Chief Operating Officer with responsibility for regional development which included environment and natural resources. Experienced Board member: currently appointed by the Danish Minister of Energy to the Board of the Danish National Energy Technology Development and Demonstration Programme (EUDP) as well as other associations and businesses.



Dr Hung Nguyen has a PhD in Computer Science and Telecommunications from the Swiss Federal Institute of Technology, Lausanne, Switzerland (EPFL). Prior to that, he received the B.Eng. degree in Information Technology and Telecommunications Engineering from the University of Adelaide, Australia and completed the Pre-Doctoral school in communication systems at EPFL. He is currently the theme leader for the Space and Defence theme, the faculty of Engineering, Computer and Mathematical Sciences (ECMS), the University of Adelaide.

References

[1] G. B. Sanders, K. A. Romig, W. E. Larson, R. Johnson, D. Rapp, K. R. Johnson, K. Sacksteder, D. Linne, P. Curreri, M. Duke, **2005**.

[2] G. B. Sanders, **2018**.

[3] B. A. Cohen, **2015**.

[4] aG. Craig, S. Saydam, A. Dempster, *Journal of the Southern African Institute of Mining and Metallurgy* **2014**, *114*, 1039-1047; bA. M. Hein, R. Matheson, D. Fries, *Acta Astronautica* **2019**; cH. H. Schmitt, *Popular Mechanics* **2004**, *12*.

[5] P. Knights, G. Yeates, in *Proceedings of the IEEE International Conference on Industrial Technology, Vol. 2019*, Institute of Electrical and Electronics Engineers Inc., **2019**, pp. 27-32.

[6] K. Fong, *The Lancet* **2019**, *394*, 205-207.

[7] W. R. Stahel, *Nature News* **2016**, *531*, 435.

[8] aG. Sanders, T. Peters, R. Wegeng, W. TeGrotenhuis, S. Rassat, K. Brooks, S. Stenkamp, in *39th Aerospace Sciences Meeting and Exhibit*, **2001**, p. 939; bR. S. Wegeng, M. K. Drost, D. L. Brenchley, in *Microreaction Technology: Industrial Prospects*, Springer, **2000**, pp. 2-13; cA. Stankiewicz, T. Van Gerven, G. Stefanidis, *The Fundamentals of Process Intensification*, John Wiley & Sons, **2019**.

[9] D. J. am Ende, M. T. am Ende, *Chemical Engineering in the Pharmaceutical Industry: Drug Product Design, Development, and Modeling* **2019**, 1-17.

[10] H. R. Sahoo, J. G. Kralj, K. F. Jensen, *Angewandte Chemie International Edition* **2007**, *46*, 5704-5708.

[11] D. Flett, D. Spink, *Hydrometallurgy* **1976**, *1*, 207-240.

[12] L. Zhang, V. Hessel, J. Peng, Q. Wang, L. Zhang, *Chemical Engineering Journal* **2017**, *307*, 1-8.

[13] D. Sivolella, in *The Space Shuttle Program*, Springer, **2017**, pp. 215-249.

[14] M. J. Sonter, *Acta Astronautica* **1997**, *41*, 637-647.

[15] P. Thomas, J. W. Parker, L. McFadden, C. T. Russell, S. Stern, M. Sykes, E. Young, *Nature* **2005**, *437*, 224.

[16] F. Marchis, M. Kaasalainen, E. Hom, J. Berthier, J. Enriquez, D. Hestroffer, D. Le Mignant, I. De Pater, *Icarus* **2006**, *185*, 39-63.

[17] aV. Reddy, T. L. Dunn, C. A. Thomas, N. A. Moskovitz, T. H. Burbine, *Asteroids IV* **2015**, 43-63; bA. Mastrobuono-Battisti, H. B. Perets, *Monthly Notices of the Royal Astronomical Society* **2017**, *469*, 3597-3609.

[18] aK. Zacny, M. M. Cohen, W. W. James, B. Hilscher, in *AIAA SPACE 2013 Conference and Exposition*, **2013**, p. 5304; bM. Cohen, W. W. James, K. Zacny, J. Craft, P. Chu, **2018**.

[19] aJ. Borovička, P. Spurný, P. Brown, *Asteroids IV* **2015**, *257*; bA. W. Harris, G. D'Abramo, *Icarus* **2015**, *257*, 302-312.

[20] T. C. Taylor, W. Grandl, M. Pinni, H. Benaroya, in *AIP Conference Proceedings, Vol. 969*, AIP, **2008**, pp. 934-941.

[21] D. G. Andrews, K. Bonner, A. Butterworth, H. Calvert, B. Dagang, K. Dimond, L. Eckenroth, J. Erickson, B. Gilbertson, N. Gompertz, *Acta Astronautica* **2015**, *108*, 106-118.

[22] J. Sanchez, C. McInnes, *Journal of Spacecraft and Rockets* **2011**, *48*, 153-165.

[23] V. Badescu, *Asteroids: Prospective energy and material resources*, Springer Science & Business Media, **2013**.

[24] L. Zhang, V. Hessel, J. Peng, *Chemical Engineering Journal* **2018**, *332*, 131-139.

[25] J. Sponable, *DARPA public release statement* **2016**.

[26] H. E. McCurdy, *Space Policy* **1994**, *10*, 277-289.

[27] M. Benna, D. Hurley, T. Stubbs, P. Mahaffy, R. Elphic, *Nature Geoscience* **2019**, *12*, 333.

[28] aS. Li, P. G. Lucey, R. E. Milliken, P. O. Hayne, E. Fisher, J.-P. Williams, D. M. Hurley, R. C. Elphic, *Proceedings of the National Academy of Sciences* **2018**, *115*, 8907-8912; bD. Needham, M. Siegler, S. Li, D. Kring, **2019**.

[29] J. Dino, L. C. Observation, S. S. Team, *NASA, November* **2009**, *13*.

[30] P. Mishra, S. Kumar, D. Singh, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* **2014**, *8*, 30-38.

[31] aC. McLemore, J. Fikes, K. McCarley, J. Good, J. Kennedy, S. Gilley, in *Earth & Space 2008: Engineering, Science, Construction, and Operations in Challenging Environments*, **2008**, pp. 1-11; bM. D. Hogue, R. P. Mueller, P. E. Hintze, L. Sibille, D. J. Rasky, in *Earth and Space 2012: Engineering, Science, Construction, and Operations in Challenging Environments*, **2012**, pp. 526-536.

[32] D. S. McKay, G. Heiken, A. Basu, G. Blanford, S. Simon, R. Reedy, B. M. French, J. Papike, *Lunar sourcebook* **1991**, 285-356.

[33] H. Brown, M. Robinson, A. Boyd, in *Lunar and Planetary Science Conference, Vol. 50*, **2019**.

[34] R. Zimmerman, *Astronomy Jan* **2014**, *50*, 52-54.

[35] R. Jedicke, J. Sercel, J. Gillis-Davis, K. J. Morenz, L. Gertsch, *Planetary and Space Science* **2018**, *159*, 28-42.

[36] T. Okada, R. P. Binzel, H. C. Connolly, T. Yada, K. Ohtsuki, *Earth, Planets and Space* **2017**, *69*, 31.

[37] S. Stern, J. W. Parker, P. Feldman, H. Weaver, A. Steffl, M. F. A'Hearn, L. Feaga, E. Birath, A. Graps, J.-L. Bertaux, *The Astronomical Journal* **2011**, *141*, 199.

[38] A. S. Rivkin, F. E. DeMeo, *Journal of Geophysical Research: Planets* **2019**, *124*, 128-142.

[39] O. Abramov, S. J. Mojzsis, *Icarus* **2011**, *213*, 273-279.
[40] A. Morbidelli, J. I. Lunine, D. P. O'Brien, S. N. Raymond, K. J. Walsh, *Annual Review of Earth and Planetary Sciences* **2012**, *40*.
[41] S. Graham, C. Parkinson, M. Chahine, *NASA Earth Observatory* **2010**.
[42] H. Jones, 48th International Conference on Environmental Systems, **2018**.
[43] K. Cheyns, C. B. L. Nkulu, L. K. Ngombe, J. N. Asosa, V. Haufroid, T. De Putter, T. Nawrot, C. M. Kimpanga, O. L. Numbi, B. K. Ilunga, *Science of the Total Environment* **2014**, *490*, 313-321.
[44] B. Zeuner, *Frontiers in Energy Research* **2018**, *6*, 123.
[45] M. Flynn, **2016**.
[46] R. Zubrin, D. Baker, *The Political Economy of the Space Age: How Science and Technology Shape the Evolution of Human Society* **2018**, 153.
[47] E. Musk, *The Political Economy of the Space Age: How Science and Technology Shape the Evolution of Human Society* **2018**, 121.
[48] aM. Willbold, T. Elliott, S. Moorbath, *Nature* **2011**, *477*, 195; bJ. M. Brenan, W. F. McDonough, *Nature Geoscience* **2009**, *2*, 798.
[49] aS. K. Mondal, E. A. Mathez, *Journal of Petrology* **2006**, *48*, 495-510; bR. Schouwstra, E. Kinloch, C. Lee, *Platinum Metals Review* **2000**, *44*, 33-39.
[50] W. Herschel, *Philosophical Transactions of the Royal Society of London* **1801**, 265-318.
[51] L. Levskij, *Meteoritics* **1979**, *14*, 475-476.
[52] A. L. Graps, P. Blondel, G. Bonin, D. Britt, S. Centuori, M. Delbo, L. Drube, R. Duffard, M. Elvis, D. Faber, *arXiv preprint arXiv:1612.00709* **2016**.
[53] H. F. Levison, W. F. Bottke, M. Gounelle, A. Morbidelli, D. Nesvorný, K. Tsiganis, *Nature* **2009**, *460*, 364.
[54] T. SONG, N. ZHENG, Y. LIU, H. KUANG, N. PENG, C. LI, Q. YAN, J. TANG, L. GAO, Z. ZHU, *Acta Geologica Sinica-English Edition*.
[55] S. Riley, J. Rich, *Environmental geology* **1998**, *34*, 203-213.
[56] J. S. Kargel, *Icarus* **1991**, *94*, 368-390.
[57] J. Baez, *Physics World* **2009**, *22*, 22.
[58] E. R. Scott, *Asteroids* **2002**, *3*, 697-709.
[59] S. Harris, *The Engineer* **2016**.
[60] D. G. Yárnoz, J.-P. Sánchez, C. R. McInnes, *Celestial Mechanics and Dynamical Astronomy* **2013**, *116*, 367-388.
[61] J. R. Brophy, L. Friedman, F. Culick, in *2012 IEEE Aerospace Conference*, IEEE, **2012**, pp. 1-16.
[62] T. James, in *Deep Space Commodities*, Springer, **2018**, pp. 81-92.
[63] aA. Sommariva, *The Political Economy of the Space Age: How Science and Technology Shape the Evolution of Human Society*, Vernon Press, **2018**; bS. Covey, J. Lewis, P. Metzger, D. Britt, S. Wiggins, in *Earth and Space 2016: Engineering for Extreme Environments*, American Society of Civil Engineers Reston, VA, **2016**, pp. 112-120; cK. Zacny, P. Metzger, K. Luczek, J. Mantovani, R. P. Mueller, J. Spring, in *AIAA SPACE 2016*, **2016**, p. 5279.
[64] aJ. S. Lewis, **1992**; bP. Jenniskens, B. Damer, R. Norkus, S. Pilotz, B. Grigsby, C. Adams, B. Blair, in *Spacecraft Reconnaissance of Asteroid and Comet Interiors, Vol. 1829*, **2015**, p. 6039; cP. Jenniskens, B. Damer, R. Norkus, S. Pilorz, J. Nott, B. Grigsby, C. Adams, B. R. Blair, *New Space* **2015**, *3*, 36-43.
[65] aP. T. Metzger, *Space Policy* **2016**, *37*, 77-91; bP. T. Metzger, A. Muscatello, R. P. Mueller, J. Mantovani, *Journal of Aerospace Engineering* **2012**, *26*, 18-29.
[66] S. Fornasier, B. Clark, E. Dotto, A. Migliorini, M. Ockert-Bell, M. Barucci, *Icarus* **2010**, *210*, 655-673.
[67] V. Hellgren, *Student thesis series INES* **2016**.
[68] T. Milligan, *Commercial Space Exploration: Ethics, Policy and Governance* **2016**, 123.
[69] R. Graczyk, *arXiv preprint arXiv:1711.03813* **2017**.
[70] W. R. Kramer, *Environmental Practice* **2017**, *19*, 128-138.
[71] J. S. Lewis, **2016**.
[72] aE. Wikramanayake, R. Hale, J. Elam, A. Shahriari, V. Bahadur, A. R. Alvarez-Hernandez, N. Howard, in *ASME 2018 International Mechanical Engineering Congress and Exposition*, American Society of Mechanical Engineers, **2018**, pp. V007T009A019-V007T009A019; bY. Chen, S. Pei, L. Yan, X. Qiu, R. Li, S. Yu, A. Lodhi, B. Li, R. Manzoor, P. Zhang, *Acta Astronautica* **2019**.
[73] R. McAree, *AusIMM Bulletin* **2018**, 48.
[74] K. Jähnisch, V. Hessel, H. Löwe, M. Baerns, *Angewandte Chemie International Edition* **2004**, *43*, 406-446.
[75] V. Hessel, A. Renken, J. C. Schouten, J.-i. Yoshida, *Micro Process Engineering, 3 Volume Set: A Comprehensive Handbook, Vol. 1*, John Wiley & Sons, **2009**.

[76] W. Hymer, T. Salada, R. Cenci, K. Krishnan, G. Seaman, R. Snyder, H. Matsumiya, S. Nagaoka, Elsevier, **1996**.
[77] S. Choi, A. Ronca, D. Leveson-Gower, C. Gong, K. Stube, D. Pletcher, C. Wigley, J. Beegle, R. Globus, **2016**.
[78] M. Roberts, I. Deputy Chief Scientist, **2018**.
[79] E. Seedhouse, *Lunar Outpost: The Challenges of Establishing a Human Settlement on the Moon* **2009**, 151-182.
[80] L. P. C. Gómez, P. Bollgruen, A. I. Egunov, D. Mager, F. Malloggi, J. G. Korvink, V. A. Luchnikov, *Lab on a Chip* **2013**, *13*, 3827-3831.
[81] M. Mridha, K. Nigam, *Chemical Engineering Science* **2008**, *63*, 1724-1732.
[82] I. V. Gürsel, S. K. Kurt, J. Aalders, Q. Wang, T. Noël, K. D. Nigam, N. Kockmann, V. Hessel, *Chemical Engineering Journal* **2016**, *283*, 855-868.
[83] D. Scranton, W. Lindberg, *The Physics of Fluids* **1983**, *26*, 1198-1205.
[84] aY. Su, N. J. Straathof, V. Hessel, T. Noël, *Chemistry–A European Journal* **2014**, *20*, 10562-10589; bT. Illg, P. Löb, V. Hessel, *Bioorganic & medicinal chemistry* **2010**, *18*, 3707-3719; cV. Hessel, C. Hofmann, P. Löb, J. Löhndorf, H. Löwe, A. Ziogas, *Organic Process Research & Development* **2005**, *9*, 479-489.
[85] V. A. Cocalia, J. D. Holbrey, K. E. Gutowski, N. J. Bridges, R. D. Roqers, *Tsinghua science and technology* **2006**, *11*, 188-193.
[86] A. P. De Los Rios, F. J. H. Fernandez, *Ionic Liquids in Separation Technology*, Elsevier, **2014**.
[87] aZ. Fei, D. Zhao, D. Pieraccini, W. H. Ang, T. J. Geldbach, R. Scopelliti, C. Chiappe, P. J. Dyson, *Organometallics* **2007**, *26*, 1588-1598; bV. M. Egorov, D. I. Djigailo, D. S. Momotenko, D. V. Chernyshov, I. I. Torocheshnikova, S. V. Smirnova, I. V. Pletnev, *Talanta* **2010**, *80*, 1177-1182.
[88] P. T. Anastas, P. Wasserscheid, A. Stark, *Green solvents: ionic liquids, Vol. 6*, John Wiley & Sons, **2010**.
[89] aR. Lertlapwasin, N. Bhawawet, A. Imyim, S. Fuangswasdi, *Separation and Purification Technology* **2010**, *72*, 70-76; bA. E. Visser, R. P. Swatloski, S. T. Griffin, D. H. Hartman, R. D. Rogers, *Separation Science and Technology* **2001**, *36*, 785-804; cM. L. Firmansyah, F. Kubota, M. Goto, *Journal of Chemical Technology & Biotechnology* **2018**, *93*, 1714-1721.
[90] aF. Pena-Pereira, J. Namieśnik, *ChemSusChem* **2014**, *7*, 1784-1800; bJ. Płotka-Wasylka, M. Rutkowska, K. Owczarek, M. Tobiszewski, J. Namieśnik, *TrAC Trends in Analytical Chemistry* **2017**, *91*, 12-25.
[91] aP. Kubisa, *Progress in Polymer Science* **2004**, *29*, 3-12; bJ.-f. Liu, G.-b. Jiang, J. Å. Jönsson, *TrAC Trends in Analytical Chemistry* **2005**, *24*, 20-27; cR. Rodriguez, R. Herrera, L. A. Archer, E. P. Giannelis, *Advanced Materials* **2008**, *20*, 4353-4358.
[92] A. Marciniak, *International journal of molecular sciences* **2010**, *11*, 1973-1990.
[93] Y. Zhou, S. Boudesocque, A. Mohamadou, L. Dupont, *Separation Science and Technology* **2015**, *50*, 38-44.
[94] J. Flieger, M. Tatarczak-Michalewska, E. Blicharska, A. Madejska, W. Flieger, A. Adamczuk, *Separation and Purification Technology* **2019**, *209*, 984-989.
[95] M. Coll, A. Fortuny, C. Kedari, A. Sastre, *Hydrometallurgy* **2012**, *125*, 24-28.
[96] V. Eyupoglu, E. Polat, A. Kunduracioglu, H. I. Turgut, *Journal of Dispersion Science and Technology* **2015**, *36*, 1704-1720.
[97] D. Parmentier, T. Vander Hoogerstraete, D. Banerjee, Y. A. Valia, S. J. Metz, K. Binnemans, M. C. Kroon, *Dalton Transactions* **2016**, *45*, 9661-9668.
[98] P. Diabate, L. Dupont, S. Boudesocque, A. Mohamadou, *Metals* **2018**, *8*, 412.
[99] B. Onghena, S. Valgaeren, T. Vander Hoogerstraete, K. Binnemans, *RSC Advances* **2017**, *7*, 35992-35999.
[100] B. Onghena, T. Opsomer, K. Binnemans, *Chemical Communications* **2015**, *51*, 15932-15935.
[101] T. Vander Hoogerstraete, S. Wellens, K. Verachtert, K. Binnemans, *Green Chemistry* **2013**, *15*, 919-927.
[102] S. Wellens, B. Thijs, K. Binnemans, *Green Chemistry* **2012**, *14*, 1657-1665.
[103] W. Wei, C.-W. Cho, S. Kim, M.-H. Song, J. K. Bediako, Y.-S. Yun, *Journal of Molecular Liquids* **2016**, *216*, 18-24.
[104] C. Zhang, K. Huang, P. Yu, H. Liu, *Separation and Purification Technology* **2013**, *108*, 166-173.
[105] S. Boudesocque, A. Mohamadou, A. Conreux, B. Marin, L. Dupont, *Separation and Purification Technology* **2019**, *210*, 824-834.
[106] Z. Xu, Y. Zhao, P. Wang, X. Yan, M. Cai, Y. Yang, *Industrial & Engineering Chemistry Research* **2019**, *58*, 1779-1786.
[107] N. Papaiconomou, L. Svecova, C. Bonnaud, L. Cathelin, I. Billard, E. Chainet, *Dalton Transactions* **2015**, *44*, 20131-20138.
[108] V. T. Nguyen, J.-c. Lee, A. Chagnes, M.-s. Kim, J. Jeong, G. Cote, *RSC Advances* **2016**, *6*, 62717-62728.
[109] W. Liu, Q. Wang, Y. Zheng, S. Wang, Y. Yan, Y. Yang, *Dalton Transactions* **2017**, *46*, 7210-7218.

[110] Y. Yan, Q. Wang, Z. Xiang, Y. Zheng, S. Wang, Y. Yang, *New Journal of Chemistry* **2017**, *41*, 8985-8992.
[111] S. Katsuta, Y. Yoshimoto, M. Okai, Y. Takeda, K. Bessho, *Industrial & Engineering Chemistry Research* **2011**, *50*, 12735-12740.
[112] Y. Tong, C. Wang, Y. Huang, Y. Yang, *Industrial & Engineering Chemistry Research* **2015**, *54*, 705-711.
[113] N. Papaiconomou, L. Cointeaux, E. Chainet, C. Iojoiu, I. Billard, *ChemistrySelect* **2016**, *1*, 3892-3900.
[114] D. Kogelnig, A. Stojanovic, F. Jirsa, W. Körner, R. Krachler, B. K. Keppler, *Separation and Purification Technology* **2010**, *72*, 56-60.
[115] L. Fischer, T. Falta, G. Koellensperger, A. Stojanovic, D. Kogelnig, M. Galanski, R. Krachler, B. K. Keppler, S. Hann, *Water research* **2011**, *45*, 4601-4614.
[116] K. C. Sole, A. M. Feather, P. M. Cole, *Hydrometallurgy* **2005**, *78*, 52-78.
[117] aP. Tsakiridis, S. Agatzini, *Hydrometallurgy* **2004**, *72*, 269-278; bB. R. Reddy, D. N. Priya, *Journal of Power Sources* **2006**, *161*, 1428-1434; cK. Sarangi, B. Reddy, R. Das, *Hydrometallurgy* **1999**, *52*, 253-265; dJ. S. Preston, *Hydrometallurgy* **1982**, *9*, 115-133.
[118] N. L. Mai, K. Ahn, Y.-M. Koo, *Process Biochemistry* **2014**, *49*, 872-881.
[119] D. R. Wibben, R. Furfaro, *Acta Astronautica* **2015**, *115*, 147-159.
[120] P. Calla, D. Fries, C. Welch, *arXiv preprint arXiv:1808.05099* **2018**.
[121] M. Grott, J. Knollenberg, B. Borgs, F. Hänschke, E. Kessler, J. Helbert, A. Maturilli, N. Müller, *Space Science Reviews* **2017**, *208*, 413-431.
[122] G. Bonin, C. Foulds, S. Armitage, D. Faber, **2016**.
[123] P. Michel, M. Barucci, A. Cheng, H. Böhnhardt, J. Brucato, E. Dotto, P. Ehrenfreund, I. Franchi, S. Green, L.-M. Lara, *Acta Astronautica* **2014**, *93*, 530-538.
[124] aN. Chahat, R. E. Hodges, J. Sauder, M. Thomson, Y. Rahmat-Samii, *IEEE Antennas and Propagation Magazine* **2017**, *59*, 31-38; bT. Kosugi, K. Matsuzaki, T. Sakao, T. Shimizu, Y. Sone, S. Tachikawa, T. Hashimoto, K. Minesugi, A. Ohnishi, T. Yamada, in *The Hinode Mission*, Springer, **2007**, pp. 5-19; cJ. Goodwin, **1986**.
[125] J. Lad, M. Johnston, D. Tran, D. Brown, K. Roffo, C.-A. Lee, in *2018 SpaceOps Conference*, **2018**, p. 2579.
[126] U. Apte, G. Ferrer, I. Lewis, R. Rendon, NAVAL POSTGRADUATE SCHOOL MONTEREY CA GRADUATE SCHOOL OF BUSINESS AND PUBLIC …, **2006**.
[127] J. Guillochon, A. Loeb, *The Astrophysical Journal Letters* **2015**, *811*, L20.
[128] aD. Linne, G. Sanders, J. Kleinhenz, L. Moore, **2019**; bB. Khoshnevis, A. Carlson, M. Thangavelu, **2017**; cJ. Kleinhenz, J. Collins, M. Barmatz, G. E. Voecks, S. J. Hoffman, **2018**.
[129] G. B. Sanders, **2015**.
[130] J. L. Tucker, *Organic Process Research & Development* **2006**, *10*, 315-319.