

Water Extraction and Purification on Moon and Mars

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Abstract

Establishing long-term sustainable habitats on celestial bodies like the Moon and Mars requires overcoming the challenge of obtaining and purifying water from the ground. Water is essential for various purposes such as human hydration, crop cultivation, in-situ manufacturing, fuel production, and diverse applications. A comparative assessment of various water extraction and purification techniques is presented where factors such as resource availability, efficiency, and scalability are considered to identify the most viable approaches. The proposed technologies are examined in the context of their compatibility with lunar and Martian conditions. Furthermore, this study develops a scalable model that integrates the technologies studied during the analysis. The model combines the strengths of the extraction and purification methods to optimize water production and quality. Additionally, the study acknowledges the theoretical limitations of the proposed model, highlighting the challenges and potential areas for improvement.

Keywords: H_2O thermal extraction, In-situ resource utilization, nano-particle filtration, perchlorate, Acoustic Nanotubes

1. In-Situ Resource Utilization

In-Situ Resource Utilization, commonly referred to as ISRU, is the use of local resources to support space exploration rather than transporting those from the Earth as that becomes prohibitively expensive. In the case of water as a resource, it is found both on the moon and on Mars. While the price per kilogram of payload to low-earth orbit has dropped significantly over the years, the current cost to bring a kilogram to orbit around the moon or even land on the surface is 300k \\$ and 1.2Mio \\$ respectively (<https://www.astrobotic.com/lunar-delivery/landers/>). This would imply

paying millions just to satisfy the drinking requirements of a single astronaut in one day, without considering any other water needs. Aside from financial reasons, ISRU also becomes essential when considering the time-frame of delivery in case a shipment is needed from Earth. While in the case of the Moon it takes a couple of days to reach (assuming the launch window is favorable), for a base on Mars a shipment may take years. Therefore, using the resources found in-situ is indispensable for upcoming space exploration missions such as NASA's Artemis mission, in particular the extraction of Water and other volatiles from the lunar regolith.

1.1. Water presence on Moon and Mars

1.1.1. Water on the Moon

Using previous and current missions, it is known that water is present in permanently shadowed regions (PSRs) and polar regions of the moon but its composition and structure are unknown. Here, it is expected to be mixed with other volatiles such as carbonates, ammonia etc., which are generally toxic even for the potential machine that is intended to electrolyze it. In 2009, a second stage of an Atlas rocket was purposefully crashed into the moon in order to study the composition of the ejected plume produced, giving insight on the subsurface abundance of various molecules [1]. Upon impact, the plume was analyzed using the Lunar Reconnaissance Orbiter (LRO), which until today is measuring the composition of the lunar surface as well as the temperature in the different regions on the moon. The relative abundances that were measured are summarized in Table 1.1.1, taken from [1].

The relative abundance of various volatiles present in a sample of lunar regolith from the PSR obtained by analyzing the ejecta plume of a rocket stage that was crashed into crater are presented in Table 1. below:

The aforementioned PSRs are typically the bottom of craters on the poles of the moon, where the sunlight never reaches. Using the Lunar Crater Observations and Sensing Satellite (LCROSS) spacecraft the presence of water ice was confirmed in the Cabeus crater. The more water-abundant regions are shown to have a mass component of around 6% H₂O. It is worth noting that near the polar regions is also the location with the most sunlight hours, making it a convenient option to have prolonged solar power availability. Also, using the moon mineralogy mapper water ice has been detected on the exposed surface, but this finding is not supported by other studies using

Compound	Molecules cm ⁻²	% Relative to H ₂ O(g)*
H ₂ O	5.1(1.4)E19	100.00%
H ₂ S	8.5(0.9)E18	16.75%
NH ₃	3.1(1.5)E18	6.03%
SO ₂	1.6(0.4)E18	3.19%
C ₂ H ₄	1.6(1.7)E18	3.12%
CO ₂	1.1(1.0)E18	2.17%
CH ₃ OH	7.8(42)E17	1.55%
CH ₄	3.3(3.0)E17	0.65%
OH	1.7(0.4)E16	0.03%

radar and laser reflectance [2]. Therefore, this paper will focus on methods targeted at extracting the water from the ice contained in frozen lunar regolith in the PSRs [3].

1.1.2. Water on Mars

Mars has about 15% of the water of Earth. If looked at as a homogeneous mass, around 36-72 ppm (based on meteorite samples) [4]. However, the distribution of water on Mars is not homogeneous. Mars has abundant ice fields located at its poles created by atmospheric condensation [4]. Below these fields are hundreds of layers of ice sheets mixed with Martian dust, up to a content of 15% [4]. Ice is also located at mid-latitudes, in craters and other formations, which are thought to be remnants of a recent ice age. It is estimated that the quantity of water on Mars is enough to cover the planet in a 20-40m layer. However, most of this water is located on the poles and underground in the form of ice [5].

Water on Mars can also be found in the form of hydrated minerals throughout the surface of the planet. These hydrated minerals are thought to contain between 2-13% water content [6]. This water could be extracted by heating the regolith to a suitable temperature which would depend on the concentration of each type of hydrated mineral.

When heating hydrated minerals to release water, perchlorates are released [7]. Perchlorates are particles made of one chlorine atom and four oxygen atoms [7]. They are very soluble in water and also very stable meaning that their removal is often challenging. Moreover, perchlorates can be very harm-

ful to humans as they have been shown to interfere with thyroid function, cause development issues during pregnancy and certain types of cancer when exposure is prolonged [8]. For these reasons, it is imperative that they are removed from the water extracted.

1.2. Aim

This research aims to provide a comprehensive overview of the current water extraction methods under study for lunar and martian regolith. The focus is on summarizing and evaluating the efficiency, technology readiness level, and scalability of these methods. The ultimate goal is to identify the most promising and suitable technologies that offer potentially viable and scalable solutions for extracting and purifying water in extraterrestrial environments. The proposed final design will combine select components from different methods to optimize water production rates while minimizing power requirements.

While there are two general extraction philosophies, elaborated in section 2, the focus of the systems discussed in the subsequent section 3 (water excavation and extraction processes) will mostly focus on the 'in-situ' extraction. Following the extraction method, various types of purification methods will be reviewed in section 4. Considering those, a complete setup using a combination of two of the most suitable extraction methods integrated along with two appropriate purification techniques is suggested in section 5. The operating conditions for each step will be outlined in sections 5.2.1, 5.2.2, and 5.3, providing a more detailed understanding of the proposed approach. The projected water production and power consumption rates are extrapolated as a function of the size of the setup, specifically the surface area of the indirect solar receiver, in section 5.4. Finally, in section 6, the current technology readiness level of each of the stages suggested in the complete setup is discussed along with the challenge of applying these technologies in lunar and martian environment that differs in terms of atmosphere and level of gravity to the terrestrial environment.

2. Extraction and Purification

Two main types of mining and extraction techniques:

Firstly, the "drilling and extraction" method which drills into the lunar regolith in the PSR at an environment temperature of around 40 Kelvin

and subsequently transports it to a separate site where the water ice is extracted (type "A"). Typically this extraction occurs by heating the drilled regolith until sublimation of the water ice occurs at around 220 Kelvin (the optimal heating temperature has been highly investigated as too high a melting temperature starts becoming less energy efficient [9]). The water vapor formed is then condensed and collected. However, the transport of the regolith that contains the water ice also contains many other substances that are not wanted and therefore represent ballast weight, making this method very energy-demanding.

On the other hand, the second popular method involves the in-situ heating of the regolith such that the water ice is sublimated at the source (type "B"). In this scenario, the water vapor is collected and cooled back into water ice for transportation to the storage destination, which more than a magnitude lighter than transporting compared to the first method. The mathematical models elaborated for the two techniques can be found in [10].

3. Water Excavation and Extraction Process

3.1. Thermal-drilling Technique

The extraction of water from icy lunar regolith has been investigated for various decades now, as it represents a major frontier to enabling a prolonged mission on the Moon. One of the main pilot plants proposed to obtain water is using a drill equipped with a heating coil. Here, it is important to create a sealed chamber where pressure can build up such that the H₂O molecules in the regolith are captured and sublimated. A design implementing this method is shown in Figure 1 below.

Here, the drill has a drop rate in the $z - axis$ and a load rate that transports the regolith fragments into the chamber. After the drilling process, a heating coil is used to raise the temperature of the collected sample to bring it to sublimation. The vapor produced is then channelled to a funnel for condensation to occur, by channelling a cooling liquid inside the walls. However, not only does this method contain multiple complicated steps in the process, but initial pilot-plants tested by the Chinese Academy of Science as well as NASA show small water production rates (18 mL/h) as well as high power consumption (8.6 Wh/g), especially associated with the heating of the

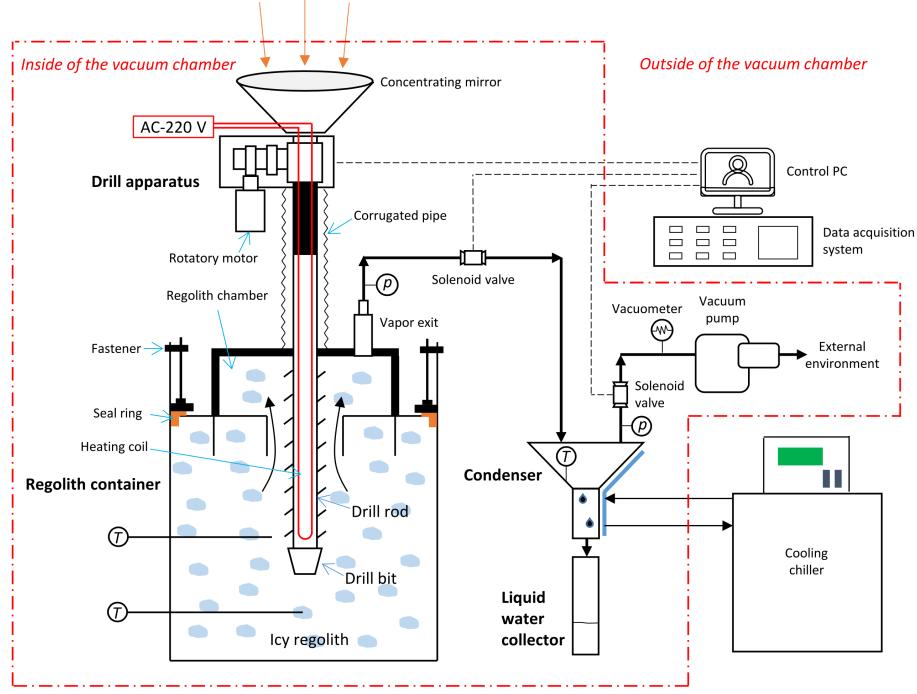


Figure 1: Chinese Academy of Science pilot plant schematics, Liu et al. 2023

sample by passing current through the coil inside the drill [11].

3.1.1. Challenges applying terrestrial mining techniques in low-gravity environments

When aiming to replicate the conditions on Moon and Mars in testing scenarios, there are some aspects such as the temperature and pressure which can be manipulated in a controlled environment. However, the main factor that is hardly reproducible on Earth is the level of gravity experienced at those locations. The Moon, for example, only has around 17% of the Earth's gravity making the drilling methods that rely on generating a strong normal force very difficult to apply.

Many attempts to simulate similar reduced gravity environments by having the rover/machine be suspended to the point where the remaining weight matches its total weight on the Moon or Mars respectively. Another method that was applied to resemble the reduced gravity for the thermal drilling

technique was to set the whole system on an incline, again with the same final aim. Nonetheless, neither of those methods is able to create a perfectly resembling environment of the Moon or Mars as the simulated regolith still acts and has the properties of being under Earth's gravity. The reduced reaction force that is generated with the mass of the excavator on Moon and Mars combined with the higher bulk density of the regolith material encountered causes traditional excavation blades to not function properly and render useless.

A passive thermal heating approach on the other hand does not have the issue of requiring to produce significant normal force in order to drill into the regolith but rather aims to extract water from the surface layers of the lunar regolith without excavating it.

3.2. Counter-rotating Drum Excavation Technique

This technique, implemented by NASA's Regolith Advanced Surface Systems Operations Robot (RASSOR), ensures that the force used is minimally in the vertical direction hence addressing the issue of having very little normal force at disposal due to the low gravity present on Moon and Mars [12].

As can be seen in Figure 2, the vast majority of the force is exerted in opposite directions of the horizontal plane leading to a net zero force on the machine. This method seems to be promising in various types of low-gravity environments as compared to other methods such as hammering that might be commonly used in terrestrial material extraction applications but are not viable for rovers on the moon. It is worth noting that drilling into the surface also appears to be a potential solution when the drill bits are anchored into the soil thus providing resistance against the vertical normal force on the rover. However, unlike in this counterrotating bucket drums system, in the very beginning, the drills essentially only exert a perpendicular force to the surface (vertical). Hence, studying the feasibility of this technique might be worth looking into, particularly for the initial drilling phase. Moreover, the RASSOR excavates pieces of regolith which then need to be transported to a site specialized for water extraction. This makes it part of the first technique discussed in section 2 meaning that a lot of mass needs to be excavated and transported to a distant site (most likely outside the PSRs in order to exit the cold and dark environment) in order to obtain small amounts of water.



Figure 2: NASA’s Regolith Advanced Surface Systems Operations Robot (RASSOR) Excavator, Patent: KSC-TOPS-7

3.3. Powered Microwave heating

A potential method to extract water from a sample that may be applied once lunar regolith is already excavated, using the aforementioned methods, is by heating it using microwaves. As opposed to a heated coil which uses the friction of the current passing through a wire (relying on conductive heat transfer), this technique is based on aligning polar molecules such as water in the sample to align with the electric field applied. This alignment process produces heat as the excited polar molecules experience friction while changing orientation. This allows to uniformly heat a sample as opposed to other techniques which produce a thermal gradient in the sample due to the nature of their heat transfer. Using a 250 Watt microwave heating unit (MHU) shown in Figure 3, this technique was found to achieve an extraction yield of around 67% in a heating time of 25 minutes [13]. However, the subsequent steps of water collection using a condenser similar to Figure 1 is not discussed in detail in the study.

Moreover, the sample size used in the three runs were of 40 grams and showed a negative correlation between specific water content and the extraction percentage. This can be derived back to the grains in which the frozen

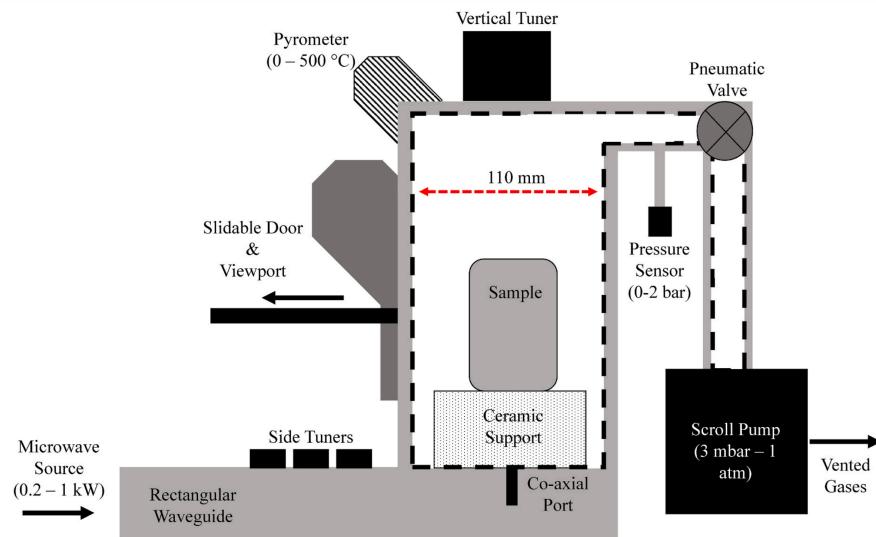


Figure 3: Schematic of the microwave heating unit (MHU), using side and vertical tuners to maximize absorption of microwaves into the regolith sample (Not to scale), J.D. Cole et al. 2023

water is trapped being pushed further apart the more ice is between them which leads to a reduces contact area between the grains as well as increasing the space of free ice. While in the study the 250 Watt MHU is considered a 'low power', when considering a prolonged heating time to scale the operation for larger water production, the grams per watt-hour of this method is around $0.02304g/Wh$. This value is significantly lower compared to the other methods discussed in this work and is hence not considered a viable method to produce significant amounts of water for a temporary or permanent crewed mission on the Moon or Mars. Moreover, the complexity of the MHU in combination with the need of a separate excavator and condenser unit makes this an unrealistic approach.

3.4. Indirect Solar Receiver

A more optimized design, aiming to diminish the higher power consumption required by the heating coil from [3], is the "Solar Extractor of Volatiles Indirect Receiver" (SEVIR) [14]. This design uses sunlight that is redirected and concentrated from the edge of the crater towards the PSRs. In this paper, the well-developed and efficient components of the drilling technique's pilot plant draft, namely the condenser and water collector, are incorporated

into the SEVIR, in order to produce a complete design able to extract, condense and collect water out of the regolith using efficient methods for each of those steps.

The SEVIR set-up consists of a solar concentrator, a receiver vessel containing the lunar regolith, and a heat exchanger. The solar concentrator focuses solar energy onto a small area, providing high-temperature heat to the receiver vessel. This is done through heliostats set up at the edge of a crater. The lunar regolith is placed inside the receiver vessel and heated by concentrated solar energy. The heat exchanger is then used to transfer the heat from the heated regolith to a working fluid, which is then used to extract the water vapor from the regolith. A tentative design of the setup is shown in Figure 4 below.

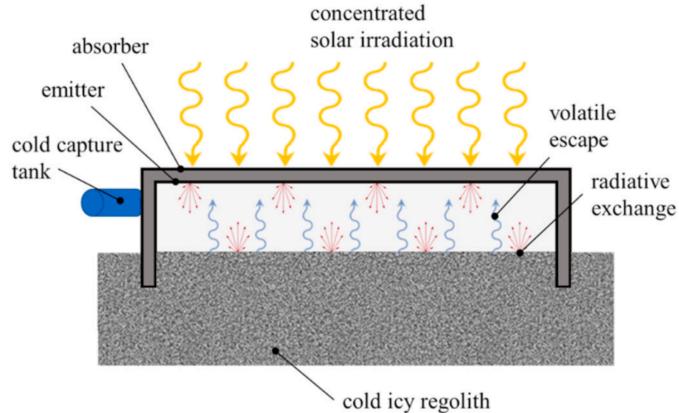


Figure 4: Conceptual depiction of the Solar Extractor of Volatiles Indirect Receiver using opaque, highly conductive, and absorptive solar receiver, Schieber et al. 2022

3.4.1. Thermodynamic Scheme

In this method, there is no drilling process as the sealed volume is directly heated using indirect sunlight concentrated from heliostats. For the proposed design a concentration ratio of around 10 is needed in order to extract significant quantities of water from the icy lunar regolith. Over a 10 hour exposure period the inner wall temperature reaches temperatures above 900 Kelvin as shown in the temperature distance profile in Figure 5 below.

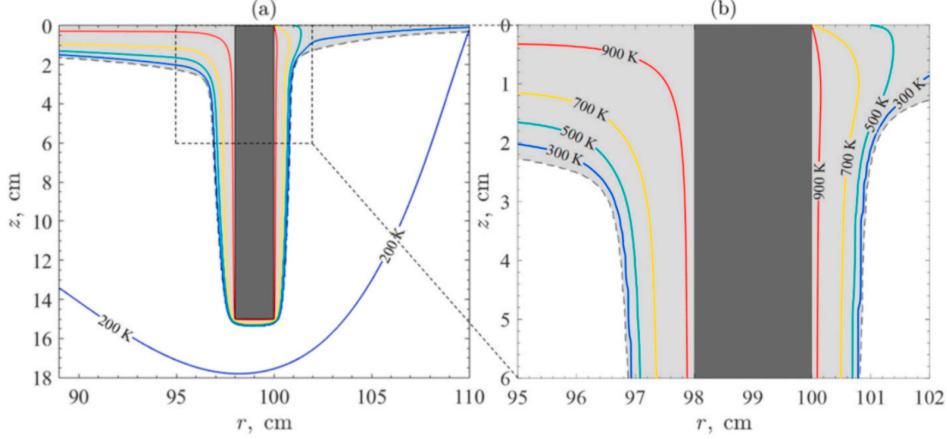


Figure 5: temperature contours at the embedded portion of the wall for the solar selective receiver with a (a) full and (b) zoomed in view, including the zone of desiccation (light gray), from which the water is extracted, and SEVIR (dark gray)

Here, a solar selective receiver which is coated on the outside of the SE-VIR will absorb the redirected and concentrated sunlight from the heliostats. Subsequently, through thermal conduction, this heat is transferred to the emitter on the inside wall where the heat is then radiatively exchanged to the regolith. Naturally, the regions right adjacent to the walls will be heated the most as they have direct exposure. This creates a thermal gradient within the regolith depicted in Figure 5. In the regions where the regolith is significantly heated the majority of the water is evaporated up to the point where saturation pressure is reached in the sealed volume. The temperature gradient inside the SEVIR is modeled according to:

$$P_{sat,i} = e^{\left(9.550426 - \frac{5723.265}{T} + 3.53068 \ln T - 0.00728332T\right)} \quad (1)$$

The region from which the water is extracted is called the 'desiccation' zone and has less favourable thermal properties as the heat is not passed further down into the regolith as efficiently. The water vapor saturation pressure is calculated using equation 1. At this point, the vapor is brought to condensation by passing taken at a distance of 1 cm from the wall into a condenser similar to the one depicted in Figure 1. Here, a cooling liquid will be passed inside the funnel walls to condense the vapor and collect it in the 'non-treated' water concentrator shown in Figure 9.

3.4.2. Technological Requirements

There are several different technological requirements for this design that concern the different material and thermophysical properties in order to enable efficient heat transfer to the regolith. In Schieber et al. 2022 an absorber surface composed of SiC with a solar selective coating using spectral properties of a commercially available Mo-SiO₂ coating was used for this purpose. The same materials are also used to compute the extrapolated water production rates for this paper. The thermophysical properties of the Silicon carbide as well as the spectral properties of Mo-SiO₂, required to heat the lunar regolith as simulated (including the solar selective coating denoted as 'sel') are summarized in Table 2. below:

Parameters	Value
ρ_{SiC}	3210 kg·m ⁻³
$c_{p,SiC}$	690 J·kg ⁻¹ ·K ⁻¹
k_{SiC}	150 W·m ⁻¹ ·K ⁻¹
ε_{SiC}	0.9
α_{sel}	0.94
ε_{sel}	0.13

4. Water Purification

As humans continue to explore and establish colonies on planets like Mars or natural satellites, the need for a reliable and sustainable water supply becomes paramount. The availability of water is a crucial factor in determining the survival and success of these settlements. However, the importance of water quality cannot be overlooked. The water extracted must not only be sufficient in quantity but also be of suitable quality, depending on the intended use.

For instance, the quality of water utilized for human consumption must meet high safety standards to ensure that it is free from harmful contaminants. Waterborne illnesses can cause devastating consequences in isolated and resource-limited settings. As such, rigorous monitoring and treatment of water sources are essential to protect the health and wellbeing of the inhabitants [15].

On the other hand, the quality requirements for water used in agriculture or industrial applications may differ. Water used for irrigation or manufacturing processes may have a lower standard of quality compared to water intended for human consumption. Nevertheless, it is still essential to ensure that the water used is safe and free from pollutants that could affect the plants or the environment [15].

4.1. Method Discussion

When it comes to purifying water, there are several methods available that are effective in removing contaminants and impurities. However, to determine the most appropriate method, certain requirements for the purification system must be established. These requirements should consider both the quality of the purified water and the environmental factors that will affect the system.

One of the significant constraints to consider is the size and weight of the purification system. For an offshore establishment, it is crucial to select a compact and lightweight model that does not require heavy machinery, such as cranes or excavators. The system should be easily transportable and able to fit within the limited space available on the offshore platform.

Another important consideration is the amount of purified water required to sustain the population. According to WHO standards [16], an average person requires a daily intake of between 1.7 and 2.8 liters of water, depending on their body weight. Therefore, for a population of 70 kg individuals, the purification system must be capable of filtering at least 2.4 liters per day per person, which equates to 27.78 mm^3 per day per person for human consumption alone. If the water is intended for other purposes, such as irrigation or industrial use, the system's requirements would increase accordingly.

This section discusses various methods that employ innovative ideas that can provide adequate performance for the stated requirements.

4.2. Carbon acoustic Nanotubes

This water filtering technology uses an acoustic molecular sieve containing small diameter carbon nanotubes. Upon entering the device, the water initially comes into contact with the filter matrix, which, depending on the

end-use requirements, may consist of polymeric, ceramic or metallic compounds. Therefore, only water molecules can pass through the carbon nanotubes in the matrix; all other molecules and impurities are left out [17],[18].

At first glance, acoustic nanotube technology was originally developed for water filtration on the space station. But, today it is available for development in larger arrays and export to a more industrial environment [19].

One of the advantages of this technology is its efficiency in terms of energy. Also the currently established models have problems of pressure to be able to drive the water through the filters. On the other hand, with this technology, filtration can be done regardless of the gravity. This makes it very convenient to use this technology in extraterrestrial environment [17],[18].

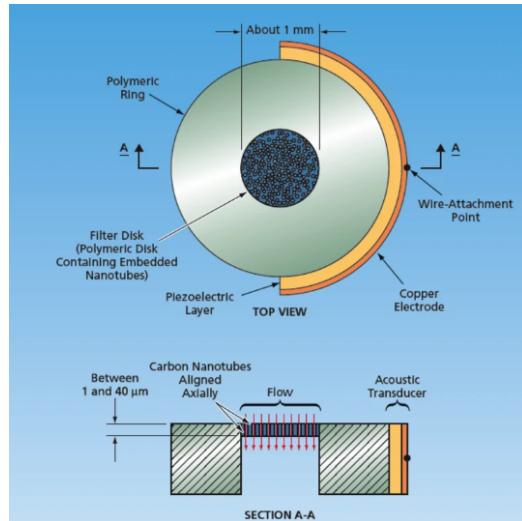


Figure 6: Carbon acoustic nanotubes blueprint illustration [19]

4.3. Nanoparticle Filtration

One method of dichlorination or perchlorate detection and removal is the use of nanoparticles. Nano particles have been shown to be capable of removing pharmaceuticals, endocrine-disrupting compounds, hormones, disinfection byproducts, perfluorinated compounds, brominated flame retardants, pesticide degradation products, perchlorate, benzotriazoles, naphthenic acids, dioxane, algal toxins and microorganisms [20]. This versatility makes them a suitable option for water purification on Mars.

A method that has shown promising results in perchlorates from the water extracted from the Martian surface is using Chitosan (CS) stabilised Zero Valent Iron-nanoparticles (ZVI). Experiments have shown that CS-nZVI prepared by reduction of ferrous ions with borohydride in the aqueous phase are able to degrade up to 55 per cent of perchlorates within an hour at a concentration CS-stabilised nZVI, the nanoparticles were prepared by reducing ferrous ions with borohydride in the aqueous phase [20]. The degradation of perchlorates was then tested in a series of duplicated batch experiments. These experiments tested ZVI, nZVI and CS-nZVI at the same concentration (15 g/L) [20]. The size of the particles produced is 98.5 ± 7.9 nm [20].

The efficacy and speed of this purification can be sped up by increasing the concentration and the temperature of the solution. When the concentration was increased to 200 mg/L and the temperature to 95 °C the purification efficacy increased to around 99% [20].

A downside of this method will be the continuous preparation of nanoparticles to be used for purification. This, therefore, means that nanoparticle production equipment will be required on-site. CS-nZVI nanoparticles are produced by the reduction of ferrous ions with borohydride in the aqueous phase as mentioned above.

CS-nZVI particles were prepared in a 1 L three-necked flask with a mechanical stirrer under a nitrogen atmosphere. The flask was immersed in water at 21 °C [20]. From there, chitosan was dissolved in an acetic acid solution at a concentration of 2% [20]. This solution was degassed using ultrasound and was allowed to dissolve completely by being left to stand for 12hrs. From there 60 mL of FeSO₄·7H₂O solution was mixed with 67.5mL of the afore prepared Chitosan solution and mixed at 180 RMP for 15 minutes,

135 mL of anhydrous ethanol was then added to the mixture under constant stirring [20]. After 5 minutes, the NaBH₄ solution at a concentration of 0.8 M was added to the system slowly, at a rate of 0.15mLs⁻¹ [20]. This caused the reduction of ferrous ions to form nZVI nanoparticles. This mixture was stirred for a further 20 minutes until the release of hydrogen gas stopped [20]. From there, the CS-nZVI particles could be separated using a magnet and washed with deoxygenated water to remove any residual chemicals [20]. This process is quite involved, requires numerous auxiliary chemicals and different equipment, as well as trained scientists produce the nanoparticles.

4.4. Zero valent Iron naonoparticles stabilised with CMC

Another nanoparticle that could be used to remove contaminants is CMC-stabilised ZVI.

Since ZVI nanoparticle effectiveness is affected by their surface area, there is extensive research on how to stabilise the particles in order to maintain their SA during their operation. This is because the particles tend to agglomerate rapidly and become less effective. In order to reduce the agglomeration stabilisers have been tested. One of these is sodium carboxymethyl cellulose (CMC) or food grade water soluble starch. [21]. The stabilised particles display a greater surface area and are able to maintain their surface area for longer.

4.4.1. Preparation method

The stabilised ZVI nanoparticles were prepared in a 500mL flask attached to a vacuum line [21]. A solution of 1.2% CMC was prepared and then purged with N₂ for 30 minutes to remove any dissolved oxygen that may be present [21]. From there a solution of 0.2 M FeSO₄·7H₂O was also prepared and slowly added to the starch solution until a final concentration of 2 g/L was reached [21]. This solution was then purged again with N₂ to remove any dissolved oxygen. From there the Fe(II) ions were then reduced to form Fe(o) nanoparticles by adding a stoichiometric amount of sodium borohydride to the mixture [21]. This reaction was operated under inert conditions in a continuous vacuum as well as shaken intermittently during preparation. The

end of the release of hydrogen marked the completion of the preparation of the nanoparticles. [21] The study also prepared other stabilised bimetallic nanoparticles to test the effect of their metal catalysis. This was done by adding another metal solution of 0.3% (w/w) of another metal such as aluminium, copper, cobalt, nickel or palladium [21].

The nanoparticles were then analysed using transmission electron micrograph photography to determine the particle size. The minimum particle size was 1 nm with the average size of the freshly prepared CMC-stabilised being 11.2 ± 7.9 nm [21].

4.4.2. Experimental results

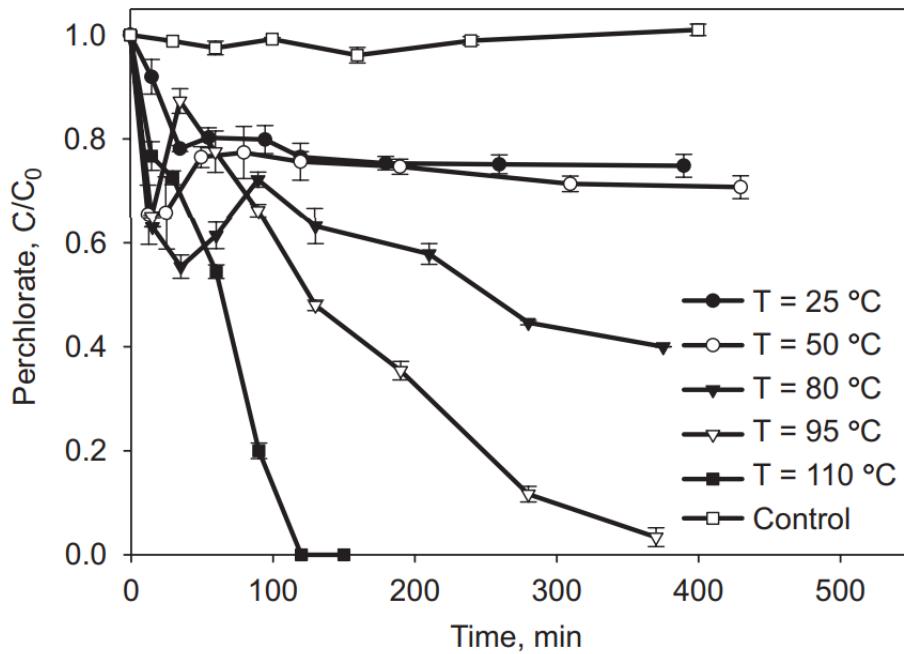


Figure 7: Perchlorate concentration reduction on time depending on the temperature of the water for Zero valent iron nanoparticles (ZVI) with 0.9% CMC. [21]

Figure 7 shows the results of the distinct kinetics of perchlorate concentration using Zero valent iron nanoparticles with 0.9% CMC in water, as influenced by temperature. As the temperature rises, the concentration of

perchlorates gradually decreases over a six-hour period, ultimately reaching a final concentration of $0.02C_0$ at 95°C . Notably, at 110°C , complete removal of perchlorates is achieved in approximately two hours.

This particular case holds significant interest due to the potential for water decontamination within a relatively short time frame. Furthermore, it is important to highlight that the experiment was conducted with an initial pH of 6.5, which increased to 7.5-7.8 during the process. The performance of the filtration process, reliant on the ferrous nature of these nanoparticles, is susceptible to corrosion and degradation of perchlorates based on the pH of the initial water. Therefore, a high initial pH, ranging from 8.5-8.6, can detrimentally impact the filtration performance by up to 60% at 95°C .

4.4.3. CMC-ZVI use analysis

To optimise the filtration performance based on the findings of Zhong Xiong et al. [21], several key ideas can be implemented to enhance both velocity and efficiency. Firstly, maintaining a high temperature is crucial, with an ideal target of 110°C , as this enables the complete removal of perchlorates within a remarkably short duration of two hours.

Additionally, controlling the pH within a specific range is vital for maximising the effectiveness of the nanoparticles. It has been empirically demonstrated that an initial pH value between 7.0 and 7.4 yields the highest efficiency in perchlorate reduction. By carefully managing the pH, the filtration process can achieve optimal performance.

Furthermore, the experiment conducted by Zhong Xiong et al [21]. also reveals the influence of high concentrations of NaCl (up to 6% w/w) on perchlorate reduction rates. Intriguingly, it was observed that such high concentrations can enhance the reduction rate by an impressive 53%. Consequently, when operating at a temperature of 110°C , it is possible to achieve a complete elimination of perchlorates in a mere 53 minutes.

4.4.4. Discussion of use of CMC-ZVI particles:

CMC-ZVI particles have shown to be effective in removing perchlorates in fresh water and brine [21]. The effectiveness of starch or CMC as a stabiliser is a promising factor when considering the use of these particles as purifying agents for water extracted in-situ. As the stabiliser is food-grade water-soluble starch, it would have to be initially taken to site but could later be derived from food production as it is often derived from potato, tapioca and wheat [21]. This process would have to be investigated further to determine the viability of the process, the equipment required and the realistic volume of production.

Production of the nanoparticles is a long process that can be challenging. This will be even more challenging under conditions different to earth. If these nanoparticles are to be used as part of a purification system they would first need to be produced on Earth and stored during the voyage to Mars or the Moon. Further work would be required to determine if the particles will last the long journey to Mars and determine the optimal storage conditions. Eventually, the nanoparticles will have to be produced on in-situ if prolonged habitation of Mars and the Moon is to take place. This will also pose further technical challenges as the conditions of Mars and the Moon are vastly different to those of Earth. One of these factors is gravity, which is different in the three locations. For this reason, experiments will have to be performed under the conditions of each location to determine if the particles can be created.

Although, further research is required to determine the viability of using CMC-ZVI as part of a purification system they show promising results when removing contaminants.

5. Combined Setup

As was seen in this paper, there are many different methods that may be applied in order to extract water from wet regolith and subsequently purify it. Here, a combined setup is proposed which intends to take advantage of the low-power consumption of the SEVIR, the well-established condensation funnel from the Chinese Pilot Plant to maximize the efficient extraction of

water in terms of production rate and power demands. Finally, in order to treat the water, the carbon nanotubes and nanoparticles filtration techniques are suggested, due to their efficiency and their simplicity.

5.1. Suitable Extraction System

As mentioned before, this technique leverages the light received from the sun and redirected using heliostats which can be located at the edge of the crater as illustrated in the computer-generated Figure 8 below. The power from the sun is not only reflected to the required location by the heliostats but is also concentrated onto the surface of the SEVIR. This is done in order to maximize the power per meter squared at the bottom of the crater which heats up the lunar regolith and hence causes the water to evaporate as described in section 3.4.



Figure 8: Heliostats redirecting and concentrating sunlight to the SEVIR unit in the bottom of the crater, credit: James Vaughan

Moreover, as the SEVIR system is focused on extracting the water from the regolith and by itself does not have a suitable condenser stage, the condensation funnel presented in section 3.1 is suggested. This condenser runs a cooling liquid in the funnel walls to ensure that the vapor condenses and is gathered in the 'liquid water collector' from Figure 1. Since in the following filtration and purification steps, the water is also required to be at a specific temperature, it may be beneficial to pass the water that is being collected

straight into those as it is still much warmer than the ambient conditions.

For the purposes of allowing free scalability, no predetermined surface area of the SEVIR is suggested as that will depend on the water needs.

5.2. Suitable Water Purification System

As discussed in the preceding sections regarding 4.2 and 4.3, the construction of a water purification system will involve the utilization of two distinct technologies that operate in different manners. Therefore, it is proposed to amalgamate these two technologies in order to attain a more effective solution. The purification process commences with untreated water, which is initially at very low temperature of -203 degrees Celsius. To enhance the water quality, the aforementioned water will be subjected to the inclusion of CMC-ZVI nanoparticles, with a concentration of 1.8 g/L having an efficiency of a 99% as elucidated in the preceding section. Furthermore, once the particles have been completely dissolved within the water, they will be directed through a stack of acoustic carbon nanotubes conforming a microporous membrane. The pores of this membrane have a maximum diameter of 20 Å (2nm) ([22],[23]) and an area of 1mm of diameter. Thus, this membrane serves the purpose of eliminating nanoparticles carrying contaminants from the water solution, having a size of 98.5 ± 7.9 nm.

5.2.1. Input Conditions

On one hand, as the water exits the condenser and is stored in the untreated water collector it will begin to cool down. This water will eventually reach the ambient temperature of the permanently shadowed regions (70 K or -203 °C). As the optimum working temperature of the CS-nZVI nanoparticles is 110 °C, this water must be heated to that temperature prior to entering the first phase of purification [20]. A heater has been added for this purpose in between the stages. Moreover, the flux ratio of the Heater will be considered the same of the extractor. Additionally, it is needed to pressurize the water to reach a pressure of 206.8 KPa for water not to boil at 120°C.

On the other hand, it is crucial to carefully control the pH of the extracted water. As highlighted in section 4.4.3, reaching a pH range of 7.0 to 7.4 as input condition is imperative to ensure optimal performance. However, the exact pH value of the extracted water remains unknown. Consequently, further investigations are needed to explore the theoretical use of a pH regu-

lator. This regulator will play a main role in achieving the pH levels, and its specific characteristics and parameters will be defined in subsequent studies.

5.2.2. Output conditions

The output flow rate of the water purification system can be adjusted depending on the requirements. The carbon nanotubes, as shown in Figure 6, can be easily stacked according to [22] and [23] to achieve the desired flow rate.

Regarding the outlet temperature in the water filtration process, there is no significant heat dissipation other than what may occur through radiation, which is a slow process, and conduction with the atmosphere. In the case of Mars it is not negligible, as it has a tenuous atmosphere approximately 100 times less dense than that of Earth. Therefore, it is expected that the temperature at the outlet of the filter will be around 105 °C.

The pH of the water as mentioned in section 4.4.2 is expected to increase one unity, specifically, from 7.0-7.4 to 8.0-8.6.

Finally, regarding the pressure, as the filtration system does not depend on pressure difference, as it uses acoustic waves to drive the water, it will be maintained the same.

5.3. Overall Process Review

In Figure 9, the process of the system is depicted, starting with the water extraction method utilizing the solar concentrator, as shown in section 3.4. Subsequently, the water passes through a condenser and is collected within the concentrator. Additionally, the Flux Rate of the system(represented as R) is dependent on the surface area (A) of the solar concentrator, as indicated.

Furthermore, considering that the extracted temperature of the water is 70K and the optimal performance of the nanoparticles (NZ-nZVI) requires a temperature of 383K, the water is heated to meet this requirement. Finally, the nanoparticles are introduced into the water for between 53 minutes and subsequently directed through the acoustic Nanotubes filters, resulting in a remarkable 99% removal of contaminants for the 53 minutes.

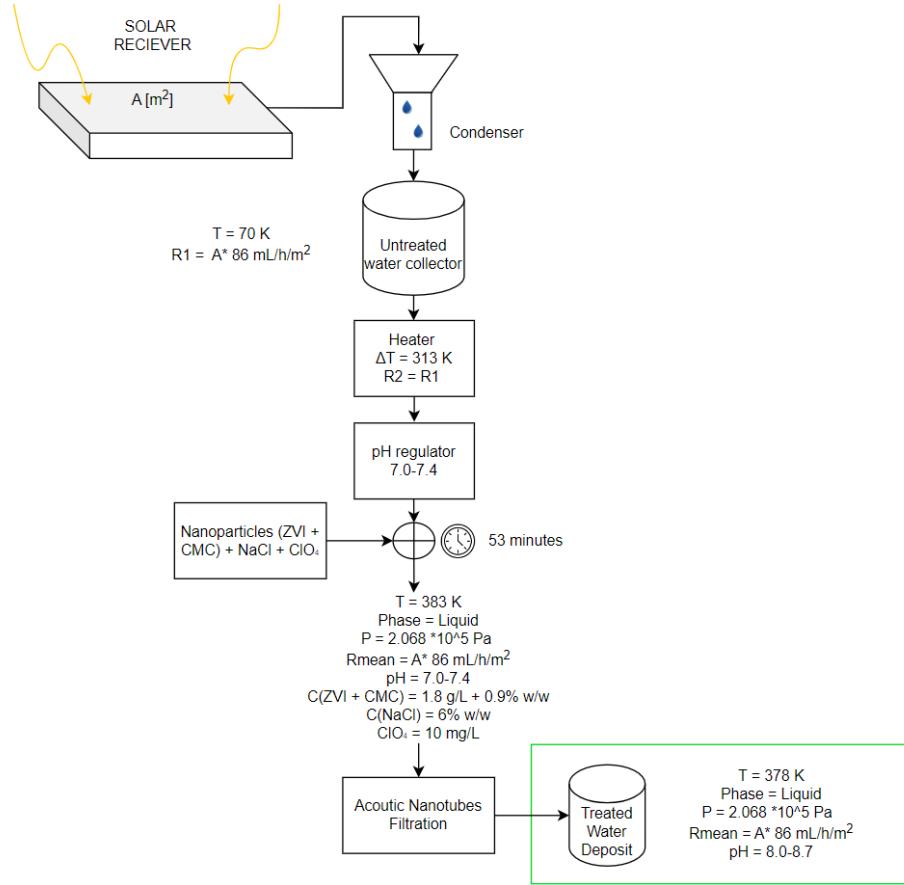


Figure 9: Diagram of the entire process system for extraction and purification of water

5.4. Summary & Projected Results

The pressure is modeled according to equation 1 in the picture but the whole system has a temperature gradient according to Figure 5. Assuming the condensation occurs 1 cm away from the walls, i.e. at a local temperature of $T = 400$ Kelvin) a pressure of about 700 kPa is obtained. Since the water condenses and then flows out of the system it can be frozen in a collection container at the environment temperature of 70 Kelvin. The collection ambient temperature as well as the aforementioned pressure are then taken as the output parameters of the extraction system which will subsequently enter the purification and filtration as input parameters. Using a simulated SEVIR device of radius $r = 1$ meter and a concentration ratio of 8 providing a surface

power density of $I = 10,000W/m^2$ (at the receiver), the water production rate is $r_{H2Oproduction} = 0.27L/h$. This gives a final water collection rate of $R = 0.085987261L/h/m^2$, which can be scaled appropriately to produce the total amount of H₂O desired. Considering NASA's target for in-situ water collection of over 10 tons per year, this method in the tested size alone would be able to produce almost 1200 kg assuming it only operates 50% of the time.

The filtration device has been designed to undergo a three-step main process. Firstly, the water heated up to a temperature of 368 Kelvin, ensuring that the nanoparticles employed in the system can exhibit optimal performance. This specific temperature range has been identified as the point at which the nanoparticles are most effective, successfully eliminating up to 99% of water contaminants. This level of filtration is achieved within eight hours of exposure of nanoparticles to the contaminated water.

Furthermore, to facilitate the removal of these nanoparticles from the water, the use of acoustic nanotubes has been implemented. These nanotubes guide the water through a series of carbon nanotube stacks featuring a minuscule pore size of 2 Å ([22],[23]). This pore size is approximately 50 times smaller than that of the nanoparticles, ensuring their efficient separation from the water stream. It is noteworthy that the design of this device removes the effect of the gravity, pressure while maintaining the same production rate of the extraction method.

6. Discussion

6.1. Current TRL assessment

In the initial water extraction phase the main components required to construct the SEVIR device have mostly been tested and proven to work in terrestrial conditions. Moreover, the heliostats required, while they are producible on earth, can also be produced using the product of the lunar regolith, making the equipment to extract the water themselves ISRU built. This redundancy as well as the simplicity of the sunlight redirection may give a lot of confidence in the passive thermal approach at first. However, it is worth considering the cost-benefit of producing the reflective layer on the moon as the production equipment itself will have a notable mass. Additionally, the absorptive solar receiver on the outside in combination with the emitter on the inside wall of the SEVIR has not been physically tested in the

expected PSR environment conditions. Moreover, in order to establish the initial set-up of constructing a sealed volume, the walls of the SEVIR need to be inserted in cutouts in the lunar regolith that need to be precut before. The challenges involved with this process such as the cutting device required for this process as well as the issue of cutting out the right shape have not been properly assessed thus far.

6.2. Challenges applying the techniques on the Moon and Mars

As the regolith found on bodies other than the earth is very different in terms of its natural properties, our commonly used methods such as the use of blades (which may be used to produce the initial cutouts of the SEVIR walls in the regolith) will render themselves ineffective in for example the lunar or martian environment. This is due to the higher density of the regolith as well as the limited amount of gravity that only allows for a reduced reaction force. Hence any regolith extraction reactor attempting to use terrestrial methods which are developed for lower density applications and with a significantly higher reaction force available will face difficulties.

Nonetheless, the very cold environment temperature in the PSRs, of around 70 Kelvin, will be a technical difficulty that needs to be mastered as most testing occurs at temperatures above the expected. Electronics within the devices and in particular a local battery supply, such as the inclusion of a portable battery, will have significantly reduced efficiency as compared to their optimal operating temperature and pressure.

Mars: One of the challenges of the method selected to extract water from Mars is the production of nanoparticles. As seen above, the process takes several hours, and requires different equipment and several auxiliary chemicals, as well as trained scientists to prepare it. This equipment would have to be taken to Mars adding additional weight to the spacecraft. Chemicals would also have to be taken to Mars, again, adding additional weight to the spacecraft until they could be produced onsite. Production of the required chemicals for the process on-site would propose another large logistical challenge and would be dependent on the availability of chemicals on Mars.

Carbon nanotube filtration technology necessitates the transportation of components from Earth. As we look ahead to the future, with the growth of settlements and the subsequent rise in demand for treated water, it becomes

imperative to establish a manufacturing plant for these components. However, such a facility would require not only the establishment of the physical infrastructure but also the recruitment of skilled and specialized personnel to oversee the manufacturing process.

The implemented filtration device combines two independently validated systems. However, it is crucial to acknowledge that this study presents a theoretical scenario, wherein certain considerations may deviate from real-world circumstances. Consequently, the creation of mock-ups becomes imperative to thoroughly investigate the actual behavior of the filtration device under simulations mirroring realistic conditions.

Furthermore, the compatibility of the device is contingent upon the temperature of the incoming water, necessitating that the output conditions of the extraction device align with those of the filtration device. Failure to meet this requirement would necessitate the inclusion of a preliminary heating or cooling mechanism as in figure 9.

In order to calculate the weight of nanoparticles needed for the purification of water NASA's 10-ton production per year target was used. As the concentration of CS-nZVI nanoparticles used to purify water is 200mg/L one can calculate that 2 Kg of nanoparticles would be needed for a year. Although it doesn't appear like a large quantity, producing 2 Kg of CS-nZVi would require significant time and resources.

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