Design of a Water Capturing System for Thermal Extraction of Water on the Moon

In the context of In-Situ Resource Utilisation (ISRU)

Christoph Kalis

Design of a Water Capturing System for Thermal Extraction of Water on the Moon

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Literature Study & Thesis Report

by

Christoph Kalis

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Preface

With the submission of this document, the journey as a student comes to an end. Here, I express my deep gratitude to all the people with whom I have worked or studied, and who supported me. Some of them are mentioned here.

I am grateful for the supportive and inspiring environment at DLR, where fellow students Victoria, Mart, and Kunal contributed to engaging discussions, sometimes during our lengthy lunches in the mensa. Special thanks goes to Mart for our particularly fruitful conversations, especially those about COMSOL.

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Luca who accepted me for the position, sharing his work life and office space with me for an enriching 12-month period. I extend my gratitude to Alessandra from my home university for her supervision during this time.

Philipp and Dominik, who made me aware of the DLR in Bremen and who shared the master's journey with me. This appreciation goes further to persons from Delft and my bachelor university in Hamburg.

Lastly, I would like to point out that without the support of my family and friends, especially my parents Gunhild and Robert, the journey towards a space engineer would have been extremely difficult. Also, to my beloved girlfriend Celine, who always believed in me.

Abstract

In-Situ Resource Utilisation (ISRU) is gaining prominence in space exploration due to its potential to reduce the number of costly launches from Earth. Among these resources, water holds significant importance for future space endeavours, thanks to its multiple applications e.g. as potable water, for harvesting crops, and as fuel after electrolysis to hydrogen and oxygen. While prior research has concentrated predominantly on the extraction of water from regolith, there has been a notable gap in exploring methods for capturing and liquefying the extracted water vapour. Therefore, initial concepts are presented and three experiments are executed. This resulted in a design proposal for the LUWEX experiment at the German Aerospace Center (DLR). LUWEX is an acronym for Validation of Lunar Water Extraction and Purification Technologies for In-Situ Propellant and Consumables Production. In particular, the amount of water extracted is planned to be higher compared to other publicly available experiments.

Executive Summary

The use of resources present on celestial bodies, known as In-Situ Resource Utilisation (ISRU), is becoming more and more important in space exploration due to the high cost of launching a mass into orbit. In addition, while continuous supply from Earth might be feasible for the Moon with a transportation time of about three days, the journey to Mars with around seven months is not sustainable and very expensive. ISRU would enable long-term manned operations and permanent (robotic) presence on extraterrestrial bodies.

Water is considered one of the most important resources for further space exploration and is currently being investigated for extraction and purification on the future human lunar base envisioned around 2025. Previous research focused on the extraction of water from regolith, but little work has been done to find ways to capture and liquefy the water vapour after its extraction. The first chapter aims to give a background on the condition of lunar water and the state-of-the-art of extraction, with a special emphasis on capturing the water vapour. Furthermore, it paves the way for the next chapters, which aims to develop the water vapour capturing design of the LUWEX (Acronym for Validation of Lunar Water Extraction and Purification Technologies for In-Situ Propellant and Consumables Production: `www.luwex.space`) technology demonstration.

After discussing the project boundary conditions and requirements in chapter 2, the two primary options, a cold trap and a condenser, are analysed in the following chapter 3. The trade-off favours the implementation of the cold trap. The incoming water vapour is deposited on a cold surface of which the temperature can be controlled, so that the water vapour is mainly deposited. Other specimens present in the vapour flow have solidification temperatures different from those of water. After a certain thickness of the ice, it is delaminated by heat and falls down in another section, which can have its own environment. With further heating there, the ice is liquefied.
Three experiments have been carried out to support the final design described in the last chapter. The effectiveness and general behaviour of the cold trap, the ability to control the collection surface temperature, and the demonstration of successful ice delaminations in low-pressure environments are described in chapter 4. The last chapter 5 concludes with a proposal for the water capturing design, incorporating initial simulations to estimate the thermal behaviour.

This graduation project covers the journey from understanding lunar water extraction challenges to experimental validation and final design considerations. The project contributes to the broader LUWEX objectives of increasing the TRL to 4-5, with a focus on advancing water capturing systems as part of a thermal extraction process crucial for future lunar exploration.

Contents

Nomenclature

List of Abbreviations

A Analysis

AE Aerospace

CE-Week Concurrent Engineering Week

COOL Cooling Down

CoPhyLab Comet Physics Laboratory

CRaTER Cosmic Ray Telescope For The Effects Of Radiation

D/C Direct Current

DLR Deutsches Zentrum für Luft- und Raumfahrt / German Aerospace Center

DoT Design Option Tree

EEMCS Electrical Engineering, Mathematics and Computer Science

EU European Union

HUP Heating Up

I Inspection

INIT Initial

ISRU In-Situ Resource Utilization

L-chamber Large-scale Comet Simulation Chamber

LAMP Lyman-Alpha Mapping Project

LCROSS Lunar Crater Observation and Sensing Satellite

LEND Lunar Exploration Neutron Detector

LOLA Lunar Orbiter Laser Altimeter

LRO Lunar Reconaissance Orbiter

LROC Lunar Reconnaissance Orbiter Camera

LSG Liquifer Systems Group GmbH

LUWEX Validation of Lunar Water Extraction and Purification Technologies for In-Situ Propellant and Consumables Production

NAC Narrow-Angle Camera

PROSPECT Package for Resource Observation and in-Situ Prospecting for Exploration, Commercial exploitation and Transportation

PURI Purification Temperature

ROD Review of Design

RQ Research Question

SLS Space Launch System

SMU Synergetic Material Utilization (research group at DLR)

SW Scanway sp. z.o. o.

T Test

TAS Thales Alenia Space Italia

TBD To be decided

TRL Technical Readiness Level

TUD TU Delft or Delft University of Technology

TVAC Thermal Vacuum Chamber

UNC Ice Uncoupling

V Verfication

VIPER Volatiles Investigation Polar Exploration Rover

WAC Wide-Angle Camera

WCS Water Capturing (Sub-)System

WES Water Extraction (Sub-)system

WPS Water Purification Subsystem

WUST Wroclaw University for Science and Technology

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1 Introduction and Background

Already during the second half of the last century, the abundance and use cases of resources in space have been analysed. Although major cost reductions have been achieved compared to the 60s, bringing mass into orbit is still very expensive which drives the need for the use of cheaper resources already present on celestial bodies. This approach is commonly called In-Situ Resource Utilisation (ISRU) and it is going to get more important in the future. It is currently widely discussed in the scope of space exploration, since an habitat on the Moon is envisioned for this decade. ISRU would further enable missions like long-term human operations, permanent robotic or even human presence on extraterrestrial bodies or stations. Some of the use-cases of ISRU are life-support systems (watering plants, oxygen and water, propellants, as well as walls for radiation shielding or insulation). One day, even rare resources from space could be imported to Earth; creating a new market. Using the water resources present in space is one of the first and crucial steps towards a long-term outpost.

At the German Aerospace Center in Bremen (DLR), the extraction and purification of water on the Moon is investigated within the recently formed research group Synergetic Material Utilization (SMU). The existence of water on the Moon in substantial amounts has been proven [1] [2]. Furthermore, water is considered to be one of the most important resources for future space exploration. That is why considerable research effort is put into demonstrating the feasibility of its extraction on the future human Lunar base, which would pave the way for the usage in other deep-space missions.

At the moment, the SMU group is analysing various methods for water extraction and purification. To extract water via sublimation[1], which is currently the investigated option, the water ice needs to be heated to its sublimation temperature. After that, the water vapour will outgas the regolith and can be captured in a protected environment, e.g. a dome or a reaction chamber. This capturing, also called collection, is the topic of this graduation project. The indicated lunar Water Capturing System (WCS) could be i.e. a cold trap, a membrane, or a condenser. The latter operates with the liquid phase of water, changing the requirements for the operating conditions, such as temperature and pressure. Besides, vacuum pumps might be needed to induce the flow toward the condenser and to prevent back-travel of water vapour.

[1] Sublimation is the transition of a substance directly from its solid state to the gaseous phase, hence the liquid phase is left out.

Funded under the Horizon Europe framework of the EU, the project Validation of Lunar Water Extraction and Purification Technologies for In-Situ Propellant and Consumables Production (LUWEX) has started in 2022 under the lead of the SMU group of the DLR [3]. This Literature Study and Thesis is partially embedded within this project.

In current research, there is a large emphasis on methods to extract the ice from the regolith, but so far, little work has been done on finding ways to capture this extracted water vapour. Capturing water on a larger scale has to be investigated, leading to the need for this thesis. The literature study in the first chapter aims to answer the following main question:

What is the condition of the water on the Moon and how can it be extracted, with a special emphasis on the capturing of the water vapour?

Despite challenges, including the unknown mixture of water ice with lunar regolith, advancements are necessary for a water capturing device suitable for lunar conditions. To the best author's knowledge, presently, no such device exists, and the state-of-the-art includes only technology demonstrations on Earth and design studies. They have been presented and analysed in the second chapter, the literature study, leading to the research questions in section 1.3.

The LUWEX research project, in which context this thesis has been carried out, will be introduced in chapter 2 and its high-level requirements will be shown and analysed.

With the requirements and the state-of-the-art in mind, initial concepts and ideas have been developed resulting in a trade-off for the design of the LUWEX experiment. This content is presented in chapter 3.

During the development of the final design, three experiments have been conducted to obtain a first demonstration of cold traps in low-pressure environments and to provide a proof of concept of critical functions: surface temperature control, and the ice delamination mechanism. The setup and the results of the experiment are described in chapter 4.

Consequently, the next chapter 5 describes the final design proposal for the LUWEX experiment. Simulations with COMSOL Multiphysics have been conducted to obtain initial ideas about the water capturing system's behaviour, especially regarding heating and cooling times and the temperature gradient on the collection surface.

The table 1.1 below lists the events of the LUWEX project chronologically and refers to the respective chapter of this thesis.

Month (in 2023)	Action	Reference
January	Concurrent Engineering Week	Chapter 3
February	First LUWEX-group meeting	Chapter 3
March	Hand in Literature Study	Chapter 1
March	Preliminary Experiment I	Chapter 4
April	Luxembourg Space Resources Week	Chapter 3 & 4
June	Preliminary Experiment II	Chapter 4
July	Second LUWEX-group meeting	Chapter 5
August	Preliminary Experiment III	Chapter 4
November	Project review by EU	n/a

Table 1.1: Chronological order of major events for the thesis.

One has to keep in mind that the project schedule was quite challenging leading to design decisions, although the author preferred to spend more time on the fundamentals for the decision. However, this was a valuable experience to prepare for future research or industry projects.

1.1. State-of-the-art

This section aims to give an overview of the state-of-the-art in order to identify the current gaps which will be investigated in the thesis work with the research questions discussed in 1.3. Firstly, the presence of Lunar water is described along with some missions which have lead to those findings in 1.1.1 and 1.1.2. Secondly, the methods and research done to extract and gain water in the Lunar environment are described in 1.1.3 and 1.1.4. As a side effect of the extraction and capturing, other volatiles might be worth capturing which is briefly addressed in 1.1.5. The simulation programme COMSOL probably serves as a tool to support the design process and the expected behaviour of the system, which will help to answer the second research question.

The usual research approach is either a technology demonstration in a laboratory environment corresponding to a technical readiness level (TRL) lower than 4, or a design study.

1.1.1. Presence of Lunar Water

Water ice deposits with of orders of magnitudes larger than the presence of atoms are thought to exist in craters where the temperature is constantly low, dropping below 50 K in some cases [4] [1]. Due to the very minor Lunar atmospheric pressure environment of less than 10^{-4} mbar (for most applications assumed as a vacuum) and the sunlight-dependent temperature up to around 118°C (391K), significant amounts of water are considered to exist in solid form without exposure to sunlight [5] [6].

Permanently Shaded Regions (PSR) are particular areas where the Sun or significant amounts of scattered sunlight never reach, often present at the floor of a crater. These regions are among the coldest places of our solar system and water ice could be stable there. For instance, the bottom of such a permanently shaded crater is consistently below -163 °C (110 K) [1]. The VIPER mission planned for 2024 is going to explore and go into such a crater as the first extraterrestial in-situ resource mission, as further described in 1.1.2.f. Such areas are also called natural cold traps, because free volatiles are trapped and accumulated in their solid phase. Figure 1.1 below illustrates the ice exposure at the lunar poles.

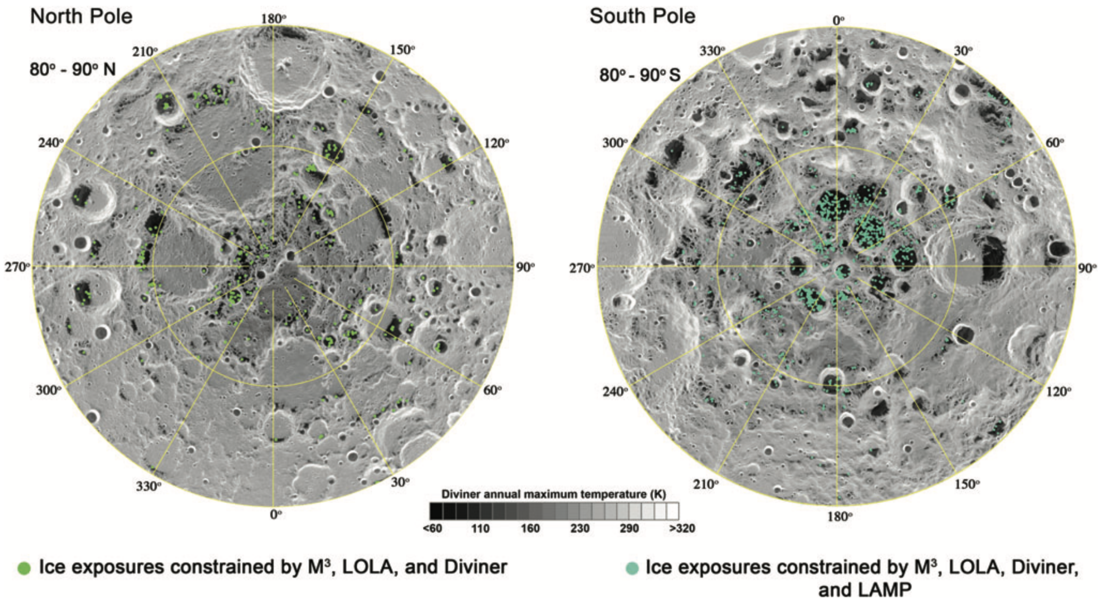


Figure 1.1: Lunar Poles water ice abundance [1].

The percentages of ice abundance in cold traps are varying: Shuai Li and Elphic [1] indicates around 30 % in weight or 20 % in volume, whereas Holquist et al. [7] refer to the data of the LCROSS mission with a total average water share of 5.6 ± 2.9 % in weight by visible mass of the ejecta plume [8]. Further details of the LCROSS-mission are explained in 1.1.2.a. Shuai Li and Elphic [1] also pointed out, that only 3.5 % of the potential cold traps at both poles have ice signatures. They concluded, that the accumulation of water ice is not only dependent on the temperature like on Mercury or Ceres.

Two reasons for the high share of dry cold traps and thus governing factors of water ice abundance are regolith gardening and true polar wander.

- **Regolith gardening:** Caused by the impact plume of smaller asteroids or comets, a layer settles upon the Lunar surface [9]. This effect is called regolith gardening. Statistically, each surface location is affected by more burying than excavation impacts [9]. The remote-sensing measurement is only able to penetrate to a certain depth, meaning deeper ice layers can not be sensed anymore.
- **True polar wander:** The PSRs have changed over time caused by the variation of the Lunar spin axis which is the second reason for dry cold traps. This phenomen alters the light distribution and as a consequence, heat reaches different areas which causes the sublimation of present water ice. There was a thermal anomaly in the Procellarum region, still persisting to date, which changed the density and consequently the moment of inertia resulting in the so-called true polar wander. [10] As indicated by Shuai Li and Elphic [1], the investigation of other influencing factors is not finished and further research is required.

A spatially condensed presence of ice would facilitate the extraction of water, like it is the case on the South Pole. Most of the water ice abundance is present at the poles, as can be seen in figure 1.1. The ice is more clustered at the south pole while it is more isolated at the north pole [1]. This patchy distribution and low abundance of surface-exposed water might be also associated with true polar wander and impact or regolith gardening [1].

Lastly, the structure of the ice and the regolith is not entirely investigated. It could be mixed on a particle level or in an order of magnitude from milimeter to meter, compare 1.2. This state clearly has an influence on the water extraction design, as described in 1.1.3.

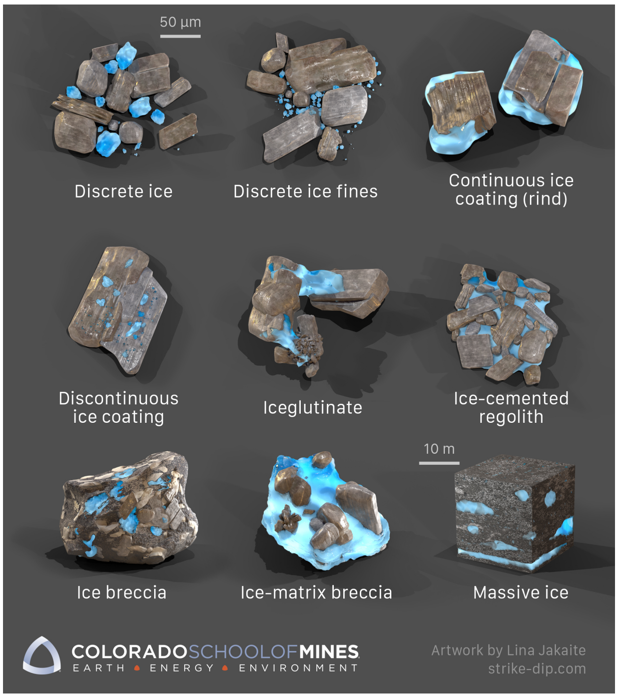


Figure 1.2: Textures of water ice and regolith on the Moon [11] [12].

In summary, the exploitation and use of water ice on the Moon has a great potential. Although most of the papers state that the total mass is unknown, an existence of around 600 million tonnes is declared by [13] and [14]. Hence, water to sustain a robotic or human presence for a longer time period is existing.

1.1.2. Lunar Missions

In this subsection, the past, current and future missions to the Moon relevant to the project are described. They are presented in chronological order.

Lunar Crater Observation and Sensing Satellite (LCROSS) flown in 2009

The Lunar Crater Observation and Sensing Satellite (LCROSS) is currently the only ground truth data point of water content available which is not gathered by remote-sensing. The satellite carried the fuel canister a rocket's upper stage (12 m) to the Lunar orbit. After enough time in space, it was found that there were no residues left in the fuel canister. During the crash of the upper stage into the Cabeus crater, a high speed, visible light photometer aboard the satellite measured the flash of impact to determine the released energy. Shortly after, the satellite flew through the plume with spectrometers as well as cameras in the infrared and visible spectrum. To achieve this trajectory, the satellite crashed into the Lunar surface shortly after collecting the data. [2] [15]

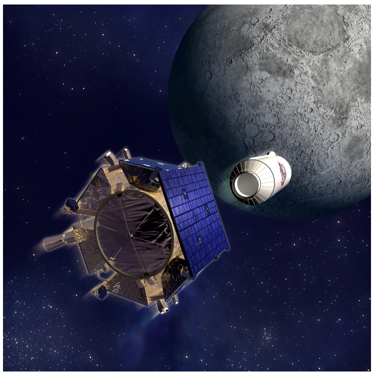


Figure 1.3: LCROSS artistic impression [16].

Lunar Reconaissance Orbiter (LRO) flying since 2009
The LRO was launched with the LCROSS mission on the 18th of June 2009 with an Atlas V rocket. Mission goal is to support future human presence on the Moon with spotting potential sites for human or robotic exploration close to resources. The results for science and exploration, enumerated under the figure 1.4, are described as "[...] legacy [...] that will be extremely useful to generations [...]." [17]
Below in figure 1.4, a 3D-CAD model can be seen showing the instruments aboard. The abbreviations are briefly described in the paragraph below starting from the top in this figure in anti-clockwise direction.

CRaTER is an abbreviation for Cosmic Ray Telescope For The Effects Of Radiation. LROC stands for Lunar Reconnaissance Orbiter Camera which is supported by WAC, a Wide-Angle Camera. LAMP is the Lyman-Alpha Mapping Project which is further described before in 1.1.1. The Lunar Orbiter Laser Altimeter (LOLA) maps the topography. Additionally, there are also two narrow-angle cameras (NACs). LEND is the abbreviation for Lunar Exploration Neutron Detector whose findings have also been described in 1.1.1. Lastly, DLRE, the Diviner Lunar Radiometer Experiment, delivered surface temperatures in a range from 40-400 K [18].

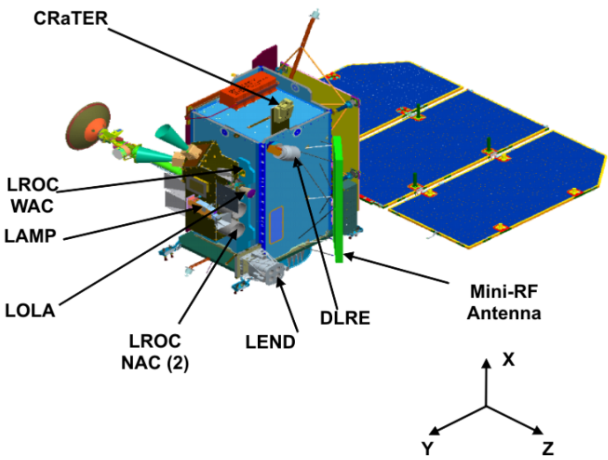


Figure 1.4: Instruments aboard LRO [18].

Some of the most important scientific findings are:

- The coldest region of our solar system, meaning below 30K, are in permanently shadowed regions of the Moon [17].
- Discovery of hydrogen under the surface in cold traps. This hydrogen could be bound to Oxygen and thus be present in the form of water ice [17].
- Contribution to the measurements of the impact cloud from the Cabeus crater of the LCROSS mission [17].
- Images of the ”Earth-rise” in high resolution and from the sites of Apollo [17].
- ”First radar measurements of the lunar farside” [17].

Artemis by NASA (first launch 2022, ongoing)
In 2022, the Orion capsule, launched by the Space Launch System (SLS), flew around the Moon as a test flight. Orion is the new spaceship for the transport of astronauts to the Moon carrying on the maiden flight only marquettes. Those were used to measure e.g. the radiation doses exposed. Envisioned is the Orbital Hub, which serves as a space-base for the transfer to the Lunar base and even for further flights, for example Mars. For the beginning, the Moon base is going to be only occoupied by humans during the Lunar day. ISRU is expected to work and help to cover the base's needs. [19]

HAKUTO-R by ispace (first launch 2022, ongoing)
HAKUTO-R, ”R” for relaunch, is a Lunar lander on a smaller scale by the Japanese company ispace. Hakuto is the translation of the ”Rabbit in the Moon”. The dry mass is 370 kg and payload mass is 30 kg. It uses a low-energy transfer orbit to the Moon. Regular flights are envisioned to build a private Lunar economy. [20] [21]
The first lander, referred to as Mission 1 (M1), failed [22]. Some rumours have been found about a collaboration between ESA and ispace in the field of Lunar water, but could not be completely verified.

ESA PROSPECT Payload for LUNA 27
This mission, Package for Resource Observation and in-Situ Prospecting for Exploration, Commercial exploitation and Transportation (PROSPECT), is especially interesting for the state of Lunar water. It has a drill of 1 m to excavate Lunar regolith. Elemental and isotopic analyses are also possible. [23] Furthermore, the lander can survive temperatures down to -150 °C, theoretically allowing him to drill inside a PSR [24].

Originally, the mission was in cooperation with Roscosmos and has been cancelled by ESA due to the Ukrainian war. Now, the cooperation is with NASA [24].

Volatiles Investigation Polar Exploration Rover” (VIPER) planned for 2024
The Volatiles Investigation Polar Exploration Rover (VIPER) is going to be the first resource mapping mission on another body, in this case the Moon. In late 2024, the launch is planned to the Nobile crater, as a part of the Artemis-program. The rover has the size of a golf cart, weighing about 450 kg and is equipped with a 1 m drill and three spectrometers. The exploration is going to last for a period of roughly 100 earth days, corresponding to three Lunar cycles of day and night. Power is supplied by a solar charged battery capable of a peak power of 450 W. Besides, mainly due to fast moving shadows, the route planning was very complicated. The data gathered is going to be most probably useful for ISRU, especially for adjusting the water extraction and capturing methods and for verification of habitat sides. [25]

Lunar Zebro Rover to be flown at the earliest in 2025

Lunar Zebro is a student-driven university project of the TU Delft, with strong footholds in the faculties of Electrical Engineering, Mathematics and Computer Science (EEMCS) and Aerospace (AE). With a team of over 60 students and multiple professors as well as PhD candidates, the team's goal is to design a small and cost-effective mobile platform on which scientific instruments can be installed. The team aims to send multiple rovers on the Moon, in order to operate them in a swarm. Zebro stands for Dutch ”Zes-Benige Robot”, or Six Legged Robot. [26]

Presently, prototypes are being built for testing on Earth. A launch of an iterated version is envisioned as a ”hitchhiking” payload to the Lunar surface where the technology can be demonstrated. After the battery is charged via solar power, it is possible to go for a one-hour ride. [27]

An application is swarming for geographic or radiation mapping as shown in the video [26]. Also, a number of terrestrial rovers have been built aimed at developing the swarming technology in parallel. [26]

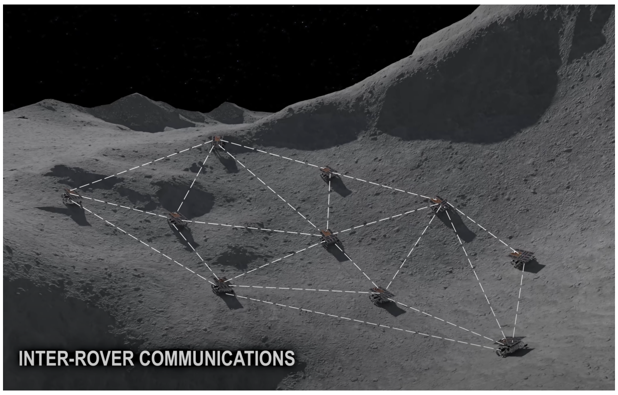


Figure 1.5: Inter-rover communication while swarming [26].

A connection to the extraction, capturing and purification of water on the Moon is discussed in 1.2 Future Work .

1.1.3. Water Extraction Designs

This project builds upon previous work conducted by the SMU-group. The extraction could be either realised in-situ or by taking the regolith away to a reaction chamber. The latter method is going to be referred as ”excavated method” or ”excavation”. Thermal mining is also an option but not further discussed here.
Examples for the in-situ method are shown in a) and b) and for excavation from c) to f) in the following figure 1.6.

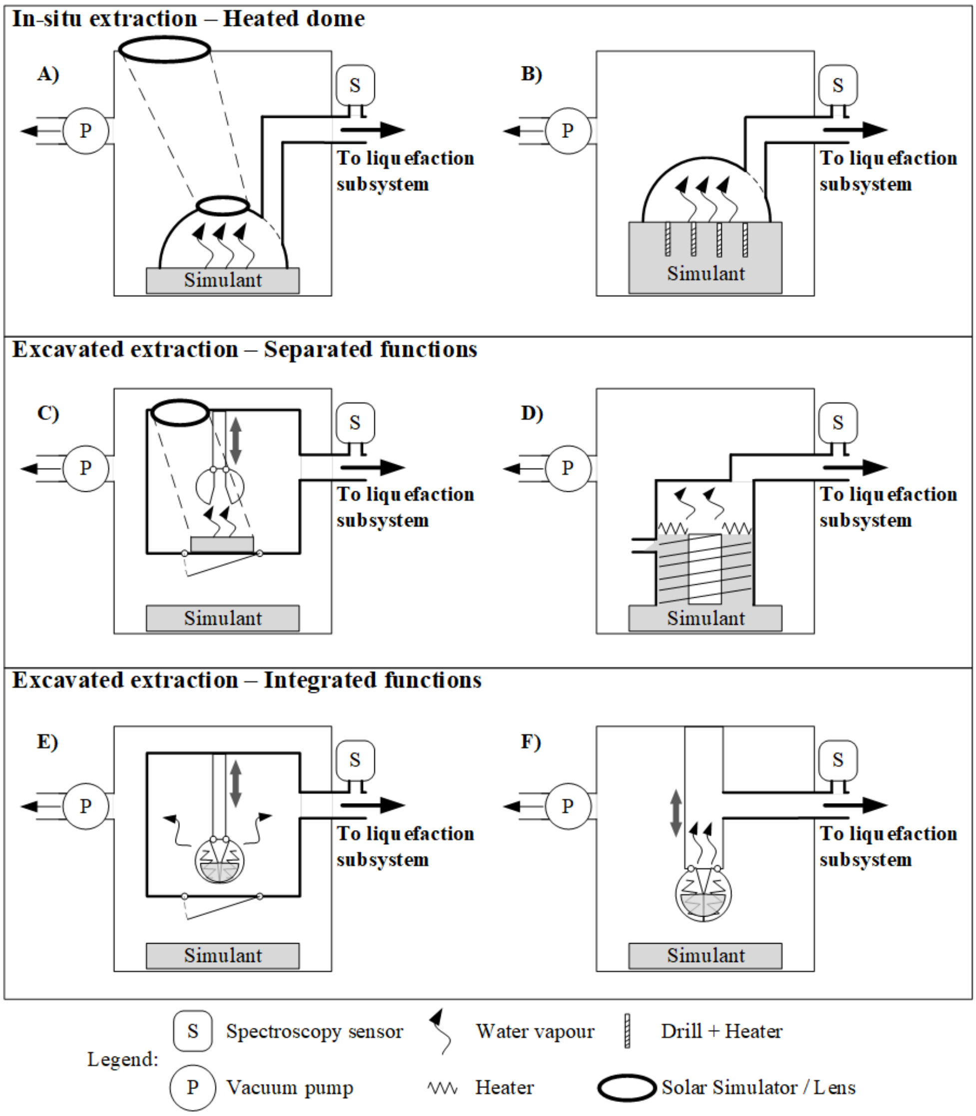


Figure 1.6: Schematic overview of possible water extraction methods [28].

For a chosen set of parameters from power available, water weight percentage (1, 5, 15 in weight %) and power density (0.5, 1, 2 sol), the excavated method is found to have always a higher extraction rate. In a certain case, the extraction rate was 10-times higher. Still, it is questionable whether the more complex system for excavation justifies the higher gain. [29]
One has to mention, that the excavation of regolith also needs energy which has not been regarded in the paper. The water capturing device, in figure 1.6 referred to as liquefaction, has an interface to the extraction system and needs to be adapted to it, respectively.

Lastly, a drill for extraction used in the laboratory environment can be found in [30] and [31].

1.1.4. Water Capturing Designs

The outgassed water could either be captured in solid or liquid state, allowing to define the phase as the governing criterium for the category. For the liquid phase, a minimum pressure of roughly 611 Pa is needed alongside sufficient temperature [32]. This is a driving requirement for the design of the capturing in liquid. In this section, the method for capturing as a solid is described with three articles. After that, the capturing in the liquid phase is presented also with two articles.

Capturing as a solid

For the capturing in the solid phase, also referred to as cold trapping, in principle only a sufficiently cooled surface is needed. Such a surface could be a plate which is partly hollow allowing the coolant to flow inside the plate. The shape and orientation to the gravitation needs to be optimised for certain needs, like available cooling power, overall desired collection rate etc.

The usage of water after its collection is mainly in the liquid phase, hence in the case of a cold trap, the ice needs to be liquefied. For that, the gathered ice needs to be in an environment where liquid water can exist. Whether this change in pressure and temperature takes places directly in the capturing system (internal liquefaction) or whether the ice is detached from the capturing system and processed in another location (external liquefaction) needs to be decided. Besides, this precedent definition of the liquefaction is different compared to figure 1.6. There, liquefaction includes the condenser and cold trap with the system to liquefy. For the purpose of this research, liquefaction is the process of transforming the captured water from its icy state to liquid. The kind of ice detachment mechanism for a cold trap needs to be investigated as well. Below, three exemplary experiments for the capturing in solid phase are shown.

Cold Trapping of Holquist et al. One possible method to gather water in the form of ice is by using a cold surface in form of a bottle, which has been used in the experiments of Holquist et al. [33] [7]. They used it with the main focus on pre-purification step besides the collection itself. At a certain pressure and temperature in the cold trap, it also accumulates aside water ice other volatiles present in the Lunar regolith like Sulfur Dioxide, Ammonia and Methanol [7]. This effect is related to the solid region, defined by pressure and temperature, in the water phase diagram which encircles triple points of other specimens - resulting in capturing of those. The article suggested and tested operational margins in terms of temperature and pressure in the cold trap and other counter-measures for avoiding the extraction of other substances than water.

Figure 1.7: Post-test cold trap photos with water ice built-up between 11.4 and 21.2 g. Bottle height is 17.6 cm [33].

Another main problem was the solubility of vapours in water ice occurring during the capturing process, which is not well recorded and has not been researched. These dissolved vapours lead to less pure water. As an upper boundary, Henry's Law of physical solubility of gases in liquids has been applied [7].

As a side-note, there was no information available for the procedure with the water-ice on the cold trap, e.g. how it was detached for storing or for liquefying. For a higher rate of water collection, the post-procedures with the ice have to be investigated thoroughly.

Below, some process parameters from Holquist et al. [33] are shown:

- Deposition between 11.4 g and 21.2 g
- Radius: 4.3 cm
- Total height: 17.6 cm
- Assumption: $\frac{2}{3}$ of the bottle act as condensing surface

Their main focus was on the purification aspect and not on the amount of mass captured.

Cold Plate of Jurado Jurado [34] also used a cold plate. In figure 1.8, the built-up of ice and the result of the delamination process are shown. The delamination was realised with a thin heating foil in 15-20 mins.

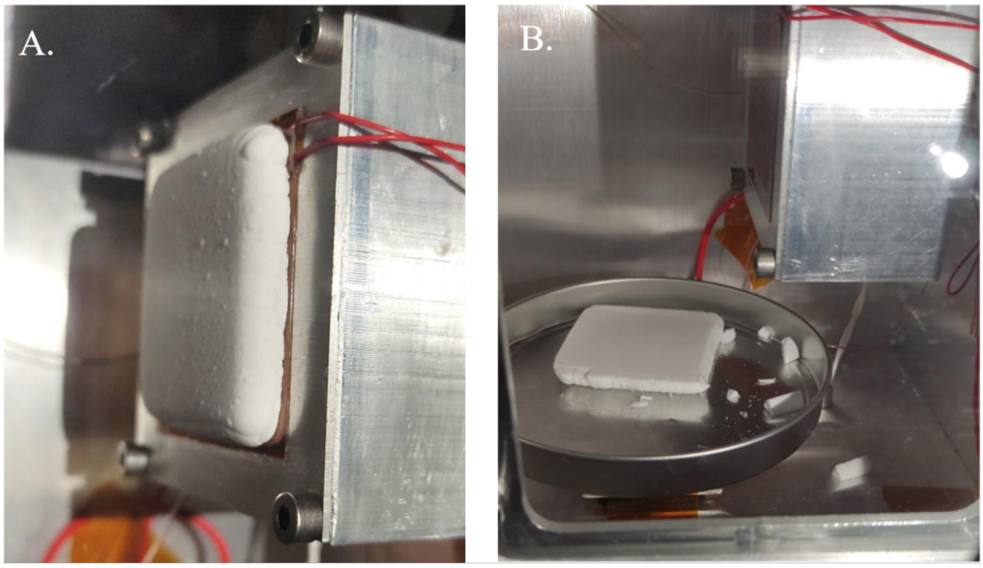


Figure 1.8: Maximum ice built-up on the cold plate (A.) and delamination induced by a thin heater (B.). Cold plate dimensions are 40x40 mm. Captured water mass is around 11 g [34].

Below, some process parameters and findings are shown:

- Ice Bulk Size: 40 x 40 x roughly 10 mm
- Time delamination: 4.3 h after vapour sublimation starts [34, p. 27]
- Time needed for delamination: less than 15 mins [34, p. 27]
- “After a certain ice thickness, the low degree of subcooling was incapable of depositing the majority of the sublimated water vapor provide resulting in an uncontrollable increase in chamber pressure.” [34, p. 44] This means also that growing an ice layer insulates the cold plate and reduces its efficiency.

Cold Trapping of Lee et al. A coil inside a tank is cooled by liquid nitrogen, as seen in figure 1.9. The vapour is guided to this coil and the system can be heated for liquefaction. [30]

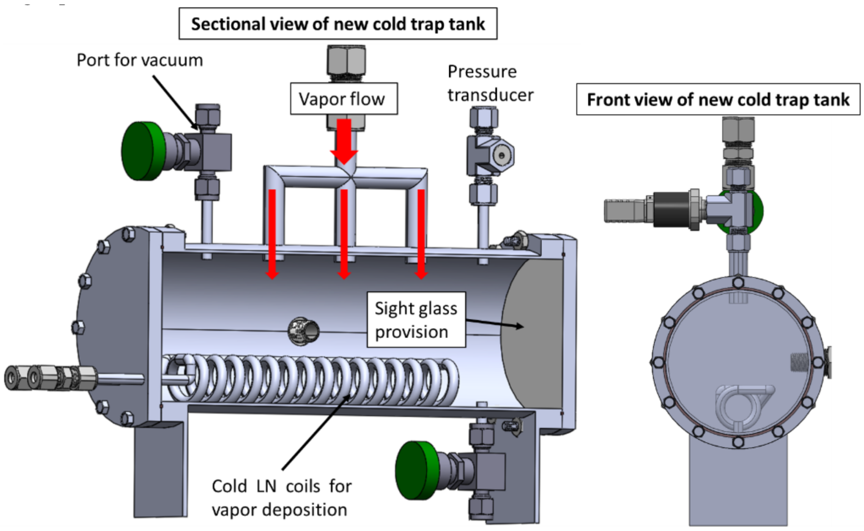


Figure 1.9: CAD-View for the experiment [30].

This design can be classified as a cold trap with internal liquefaction, since the ice is liquefied in the volume where it has been captured, as described in figure 3.5.

The next version of the cold trap with heat pipes, multiple cylindrical collection surfaces cooled by radiator panels can be seen in figure 1.10. Fabrication is ongoing and test results will come soon. [30]

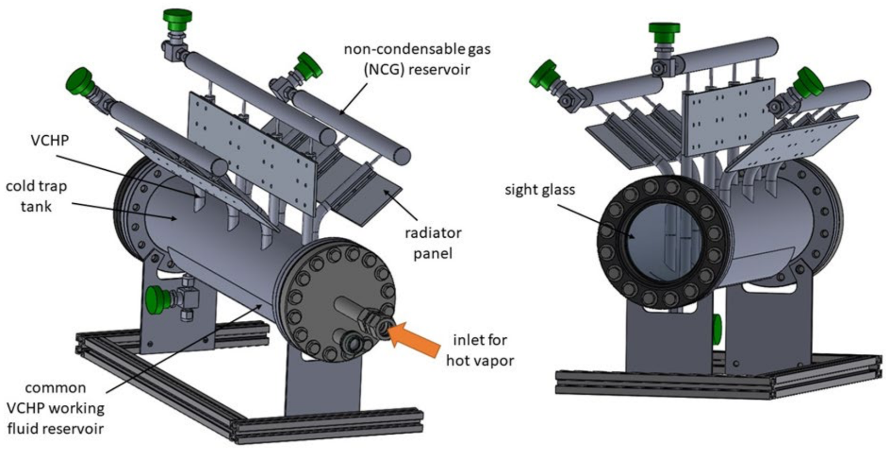


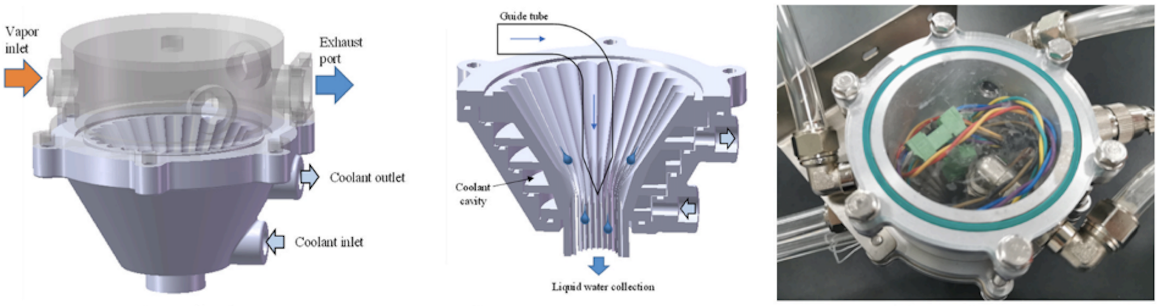
Figure 1.10: Next Iteration of the Cold Trap Chamber [30].

They aim to operate preferably at a low temperature of about -50 °C and very low pressure whose conditions are comparable to those of the design in chapter 5 [30]. The paper has been published after the baseline design was fixed in chapter 5 and fundamental difference in the assumptions made have not been found. For further development of the thesis design, this paper might be of great help.

Capturing as liquid
Condensation needs the liquid phase, respectively. The process must take place in the liquid region in the water phase diagram, meaning above the triple point (273.16 K and 611.66 Pa). Consequently, the Δp and ΔT to the TVAC or Lunar environment is higher compared to the capturing in solid form. This could lead to higher losses and has implications on complexity of the insulation and heating. Still, liquid water at the end is desired.

Condenser used by Liu et al. The authors built a pilot-scale facility in a vacuum-chamber with 1.6 m in height and a diameter of 0.6 m. A start to end system from drilling, excavation, heating, vapour collection and condensation to liquid was constructed. [31]

The cooling of the condenser, which can be seen in figure 1.11, is realised by a cooling chiller. Simply put, it consists of a metallic base part with conical shape and an even, transparent cover made of PMMA. In the base part, there are several openings for the in- and outlet of coolant and liquid. The surface for condensing is hydrophilic for achieving a better flow of the liquid water. [31]



(a) full view (b) cross-sectional view (c) real image

Figure 1.11: Condenser in CAD and in experimental setup. Captured water between 16 to 51 g [31].

The team of Yiwei Liu [31] have used a condenser starting to operate at a pressure of around 1 bar. The pressure drops during operation, but the exact pressure region has not been stored according to personal reference with the author. The condenser has a cylindrical shape tapered to the bottom, where the liquid is collected. The inlet for the water vapour is on the top left and the outlet is on the opposite side. For achieving a dispersion of the vapour stream, a rotational-symmetric spike is placed between the apertures on the middle-axis of the cylinder. The result is a higher collection efficiency of 80 to 90 %. [31]

As an important side-note, the chinese Lunar regolith simulant is made by remote-sensed data from the landing region of the Chang'E-5 mission. Intuitively, one can ask the question, if and how the results change if a simulant is used made from an actual Lunar dust sample.

To get a better insight, some of the process parameters are listed below:

Description	Value	Unit
Range of liquid water flow rates	ca. 6 - 150	$\frac{ml}{h} = \frac{g}{h}$
Condensed water per run	16 - 51	g
Energy input	308 - 607	Wh
Energy efficiency	6 - 37.9	$\frac{Wh}{g}$
Temperature of the vapour after extraction	ca. 100	°C
Operating temperature of vapour in the condenser (p. 397)	3-7	°C
Temperature of the condensing surface	0 - 5	°C
Operating presssure	1, decreasing	bar
Coolant temperature	-1	°C

Table 1.2: Process parameters for condensing taken from [31].

Autonomous atmospheric water seeping MOF matrix of Yilmaz et al.
In the work of Yilmaz et al. a passive atmospheric water sorbent is presented which uses the capillary action. In a sponge-like structure the partial pressure rises causing the water to liquefy. This concept has been proven to work on Earth. [35]

The concept could be investigated for space. The water collection unit on the Moon could be pressurised, and thus have the same pressure like on the Earth. Still, the composition of the Earth's atmosphere and the extracted Lunar gas is different. Whether this has a significant impact on the functionality needs to be investigated.

Zeolites Capturing
On Earth, zeolites can be used to absorb water from a gas stream due to its microporous capability [36]. From the author's point of view, its existence is worth mentioning, but space applications for vapour capturing have not been found.

Closing remarks for the Water Capturing Designs Section
In summary, capturing water vapour as a liquid requires higher pressure, while collection as ice requires less pressure but has challenges in post-collection handling, such as delamination from the cold surface and how to ensure continuous operations. Capturing as a solid offers the advantage of having less complexity compared to capturing in the liquid phase because there is no need to elevate the pressure above the triple point of water. However, condenser systems likely require pumps, valves, and pressure control for efficient operation, with complex insulation due to challenges in increasing the vapour enthalpy. Lastly, more examples of cold traps have been found compared to those of condenser or absorbents, indicating a possible favorisation.

1.1.5. Capturing of other present Volatiles

An important data set is the substances observed by the LCROSS-mission:

		Reported abundance with respect to water vapor detected[2]	Reported abundance with respect to soil mass[3]	Revised abundance of reported values with respect to water in lunar soil
Component	**Formula**	Moles per moles water vapor x 100% **(mol%)**	Mass per mass soil x 100% **(mass%)**	Moles per moles water per 1 kg soil x 100% **(mol%)**[c]
Hydrogen	H_2	N/R	1.4[b]	225
Water	H_2O	228.3[c]	5.6[a]	100
Carbon Monoxide	CO	N/R	0.7[b]	8.09
Hydrogen Sulfide	H_2S	16.75[a]	N/R	7.30
Ammonia	NH_3	6.03[a]	N/R	2.66
Sulfur Dioxide	SO_2	3.19[a]	N/R	1.40
Ethylene	C_2H_4	3.12[a]	N/R	1.37
Carbon Dioxide	CO_2	2.17[a]	N/R	0.94
Methanol	CH_3OH	1.55[a]	N/R	0.67
Methane	CH_4	0.65[a]	N/R	0.28
Mercury	Hg	N/R	0.22[b]	0.36

N/R: Not Reported; [a]: as reported by Ref. 2, [b]: as reported by Ref. 3, [c]: as calculated in this work

Figure 1.12: Revised abundance of volatiles in the LCROSS plume [7]. Superscript a refers to [8]. Superscript b refers to [37]. Superscript c refers to [7].

Hydrogen, Carbon Monoxide, Mercury and water are present in sufficient quantity so that it could be used to support life-support systems or rocket fuel. Hydrogen is very hard to capture. Mercury is toxic and no use-case is directly evident. Carbon Monoxide is also toxic for humans but could be split to Oxygen and Carbon.
Further investigation would be needed. The work of Hurley [38] shows more details.

1.1.6. Program and Simulation Methods

Within the SMU-group of the DLR, the software COMSOL Multiphysics is present which is going to be used for the proposed Thesis. The group posseses knowledge and experience with this program, e.g. COMSOL was used in [29].
The standard licence package with the additional heat transfer module has been bought. The special feature of the software is an easy integration and overlay of multiple physical problems in a single model.

For an overview of some physical model options which can be used see the top half of figure 1.13. The lower half shows the features of the applications builder as part of the software for an easy-to-use app.

The heat transfer module is going to be used for the design of the thesis. Possibly, the assumed laminar flow conditions are going to be superimposed over the heat transfer module, resulting in a multiphysics application.

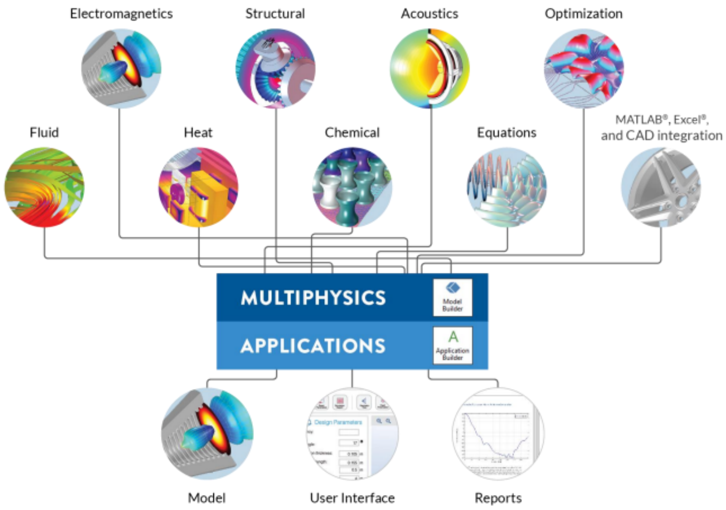


Figure 1.13: Overview of COMSOL Multiphysics features [39].

1.2. Research Plan

To begin with, the scope of this master thesis is briefly summarised. More details about the thesis are found in the next section 1.3 Research Question and Aim. The following paragraphs mention gaps found during the Literature Study for which future work may be required. The first half focusses on gaps or additional work based on the literature presented in 1.1 State-of-the-art and the second half is for research further in the future.
The thesis has the goal to significantly advance the Water Capturing Subsystem of the LUWEX project (Research Question 2). Along with the precedent tasks, an extrapolation of the gathered findings for a design study on the Moon is possible (RQ 3).

Shuai Li and Elphic [1] stated that only 3.5% of the potential cold traps at both poles have ice signatures, compare 1.1.1. The accumulation of water ice is not only dependent on the temperature and his team explained two reasons for the absence of water ice. This question is not completely solved and the underlying mechanism could be addressed in further research.

The summarised papers regarding water capturing devices do not mention material properties, forming of the ice and the process of conversion to liquid. Holquist et al. [33] have used gases for the injection in the cold trap and have not focused on the generation of vapour from the regolith-ice mixture. Furthermore, the conversion to liquid water with the precedent delamination from the cold surface has not been treated. On the one hand Jurado [34] had a delamination mechanism, a thin heating foil, but on the other hand, purification as well as the generation of vapour has not been treated.
The team of Yiwei Liu [31] has started to drill in the regolith-ice mixture at atmospheric pressure. This is not comparable to the conditions on the Moon and pressurising tons of regolith prior water extraction is likely not feasible. The reason for the pressurisation of the regolith is not clear to the author of the literature study and could not be clarified with personal correspondence. Besides, the condition of the gained water and the eventual need for a purification has not been discussed.
In summary, there is a need to demonstrate the whole process chain from excavation,

water vapour extraction, then capturing of the vapour with liquefaction and purification afterwards. This chain is investigated by the LUWEX-project.

A more in-depth review of other volatiles' capturing during the water extraction process than in 1.1.5 is needed. As an example, carbon dioxide is also present and might be worth to extract.
Also, an overview of different used simulation method for the behaviour of water vapour in a low-pressure environment with an emphasis on the conversion to liquid or solid could be conducted.

To adjust the extraction methods (and of course adapt the capturing and purification method to it), further ground data points are needed. This would also help to advance the knowledge for excavation of regolith.

Moreover, the prospecting and excavation of water ice rich regolith has been slightly treated. Possible is to use a swarm of Lunar Zebro rovers, as shown in 1.5, to scout water ice and gather samples. Their size is most likely suitable for prospecting the upper layers of the Moon's crust, for deeper layers a longer drill carried by a larger rover would be needed. A drill is also only a method.
Theoretically, the swarm could even go down a crater, to a PSR. While going down, the potential energy could be converted to electrical energy [40]. Open points are the survival of the cold temperatures and the extension of the current ability to drive one hour, but after those and further issues have been solved, the rovers could be part of an architecture value chain.

The effect's of space radiation could also be investigated. The author has not found articles on how irradiated water could be purified with a WCS of the thesis' envisioned manner. First, the dose of radiation, which is very likely dependent on the location, should be found out. Secondly, suitable purification process, conductable in space, ought to be investigated. Besides, the gained water could be used as a shielding for habitats leading to another research field.

General, further technology demonstrations on Earth to extract water, capture and purify water from icy Lunar regolith in the order of magnitude of liters are needed. The current mass scales, both on the regolith side and gained water, are not high enough to support astronauts or propellant production and need to be magnified. This would promote the way for demonstrations on the Moon. The first flight model is likely an autonomic small scale test; the next step are Lunar facilities.

Lastly, synergies with the water extraction on asteroids or Mars, maybe for other resources or even for processes on Earth could be investigated.

In summary, ISRU is a research field with many open topics. Very likely, the economic potential and future market are enormous.

1.3. Research Questions and Aim

In the previous section, open issues in the field of ISRU were discussed. In this section, the research questions defined for this thesis project are presented:

Research Question 1

Which planetary ISRU water capturing designs compatible with thermal extraction are optimal for a certain mission-scenario?

This is the baseline question and should be solved with a system engineering approach. The following two research questions will be solved with the help of the answer to the first research question.

Research Question 2

Which water capturing method is best for the EU-funded LUWEX project?

The experiment is a water extraction test with around 15 kg of regolith-water mixture, a water content of 1 to 15 % at an initial temperature of around -180 °C and an initial pressure of less than 10^{-4} mbar. The goal is the Validation of Lunar Water Extraction and Purification Technologies for In-Situ Propellant and Consumables Production (LUWEX). In order to answer the second research question, the subsequent sub-questions are posed:

2.1 What is the rate of collection of the water-vapour in the capturing device?

2.2 How does the water vapour travel in the experiment set-up and which contaminants are absorbed during its way?

2.3 How big is the pressure change in the WCD and what is the control mechanism?

The Concurrent Engineering Week (CE-Week) represents a notable tool that is utilised to address this inquiry. A CE-Week focuses on preliminary designs by combining experts from multiple disciplines. Hence, the influence of other subsystems is already regarded in an early stage of a project. Blocks of the CE-week are free working time, moderated time and presentations. The moderators, two engineers, provide an outside view of the problem. [41]

Research Question 3

How can the findings from the previous two research questions be extrapolated to a design study for a water capturing facility as part of a thermal extraction system on the Moon?

The extent of the solution of the last research question is going to be determined during the ongoing of the thesis and after the answering of the other two questions, since the latter could be enough content for a thesis on its own.

The benefit of winning water on extraterrestrial bodies would greatly facilitate outposts, especially crewed stations. This water would not needed to be transported by rockets at high costs anymore and could be used e.g. for drinking water, process water, space farming and radiation shielding. Further use-cases evolve if the water is split up in its components: hydrogen and oxygen. Clearly, the latter is needed for basically all living organisms and oxygen in combination with hydrogen could serve as rocket fuel for return or onward journeys. Also, storing electrical energy with electrolysis and recovering the electricity with a hydrogen fuel cell for e.g. the Lunar night are further possible applications.

The body on which extraterrestrial water is going to be won the first time is most likely the Moon. With the Artemis program by NASA, a crewed Lunar outpost at the south pole and in orbit are planned for around 2025. It is assumed, that local resources can be mined and used (ISRU) to cover some of the demands of the base - water included. When this technology is working on the Moon, it could be further developed or adapted for Mars or asteroids. This thesis is going to focus on the winning of water on the Moon.

Presently, the preferred method to gain water on the Moon is thermal extraction. Water can only exist as ice in permanently cold regions of the Moon. This water ice is mixed in an unknown manner with the Lunar regolith. If heat is applied, the water starts to outgas at its sublimation temperature. This vapour needs then to be captured and preferably converted to liquid which is the focus of this research.

To the author's current knowledge, a water capturing device capable of working under Lunar conditions and collecting up to kilograms of water per week is not existing yet. Hence, the state of the art are technology demonstrations on Earth in simulated Lunar conditions and design studies. The technology to extract and capture water needs to be further developed to a technical readiness level for space flight, as also discussed before and in the Introduction.

In summary, this thesis shall be a significant step to advance the capturing design for the LUWEX technology demonstration. Additionally, the findings and insight gained might be extrapolated for an actual design on the Moon. However, one has to acknowledge the challenge of this research project is the lack of data and previous research done in this field. Nevertheless, the desired outcomes are going to provide a solid foundation for LUWEX and future research.

2

LUWEX High Level Requirements

This chapter analyses the system requirements for the LUWEX project set by the project consortium which serves as the baseline for this thesis [42]. Only excerpts are shown since the document is not yet published. Less relevant requirements are summarised and non-applicable ones are left out.

As a side-note for the terminology, the procurement of water on the Moon has been split into multiple phases for this project. The most relevant areas for this thesis are extraction, capturing, and purification. Extraction means getting the water out of the regolith. Capturing means the safe containment of the extracted water in the respective phase. Then, the capturing subsystem passes the water to the purification subsystem so that it can be used further, e.g. as drinking water or for electrolysis.

2.1. LUWEX Design Requirements

In general, the project shall develop a design which can extract water from an icy-regolith mixture. At the end of the process, the gained water shall be usable for electrolysis and as potable water.
The icy-regolith shall be electrically heated in a reactor chamber leading to outgassing of the water. This decision is equivalent to an excavated extraction with separated functions, excavator and heater, as can be seen in figure 1.6 [42].

Akronym	Description
T	Test
I	Inspection
ROD	Review of Design
V	Verfication

Table 2.1: Akronyms used in the requirements tables. Partially after [42].

2.1.1. LUWEX Ambient Environment

ID	Requirement	Rationale	V
LUWEX-AE	The LUWEX design shall implement a concept where water is extracted under simulated lunar polar environmental conditions as in Table 2.3. ∗ Although vacuum residual pressure in LUWEX not as low as for Moon, this is still low enough for meeting LUWEX objectives. ***[Responsible: TUBS, DLR]"***	The ambient environment on the Moon is stated against the TVAC's values, which are close enough. The WCS shall withstand these conditions, that is the reason for stating them.	ROD

Table 2.2: LUWEX ambient environment. Requirements and verification method are taken from [42].

	Moon bulk parameter	LUWEX requirement
Polar crater cold trap	< -163 °C	-180 °C [equiv. to 93 K which is close to the 77 K boiling temperature of the nitrogen cooling under 1 atm]
Night-time atmospheric pressure	$3 \cdot 10^{-12}$ mbar	$< 10^{-6}$ mbar ∗
Highlands regolith mineralogy	$>$ 70 % anorthosite	$>$ 70 % anorthosite simulant

Table 2.3: LUWEX ambient parameters compared with the Moon [42].

2.2. LUWEX Regolith Simulant

Three requirements for the simulant are given below. In the requirement 2.2.3, a raw water simulant is mentioned. Several volatiles would harm the TVAC's pumps, that is why a raw water simulant can be inserted into the process chain after the capturing system in the TVAC and prior to the purification subsystem. Thus, some contaminants are not introduced into the TVAC volume.

2.2.1. Dry Regolith Simulant

ID	Requirement	Rationale	V
LUWEX-RS	”The dry regolith simulant to be used by LUWEX shall be based on a commercial lunar highlands simulant that shall contain > 70 Wt.-% anorthosite. *Note. Example commercial lunar highlands simulant LHS-1 from Exolith Lab with 74.4 Wt.% anorthosite, grain size distribution <0.04 µm – 1000 µm, mean particle size 90 µm. End of note.* ***[Responsible: DLR]***	This is mentioned because the simulant is mixed with water ice grains and the vapour comes from there resulting a potential source of contamination for the WCD.	I

Table 2.4: LUWEX regolith simulant. Requirement and verification method are taken from [42].

2.2.2. Ice-Regolith Simulant Physical Characteristics

ID	Requirement	Rationale	V
LUWEX-IR	The LUWEX ice-regolith simulant physical characteristics shall be as in table 2.6. ***[Responsible: TUBS, DLR]***”	The water mass which the WCS needs to handle can be inferred from the mass and its water percentage. This is useful for an initial sizing.	T

Table 2.5: Ice-regolith simulant physical characteristics. Requirement and verification Method are taken from [42].

Parameter	Value	Remarks
Ice-regolith mass	15 kg	Extraction crucible test load
Water percentage	5-20 %	Produced by mixing self-made micro-granular water ice particles with dry lunar regolith analogue. The micro-granular water ice shall have a grain size of 2.4±0.1 μm.
Initial temperature	<-180 °C	
Initial pressure	$< 10^{-6}$ mbar	

Table 2.6: LUWEX ice-regolith physical characteristics [42].

2.2.3. Raw Water Simulant Chemical Characteristics and Storage

The following table 2.7 states the components of the raw water simulant that can be inserted after the WCS. The table is needed for the requirement on the next page.

Volatile molecules in raw water simulant	
Water	H_2O
Hydrogen Sulphide	H_2S
Ammonia	NH_3
Sulphur dioxide	SO_2
Ethylene	C_2H_4
Carbon dioxide	CO_2
Methanol	CH_3OH

Table 2.7: Overview of volatile molecules present in the raw water simulant [42].

ID	Requirement	Rationale	V
LUWEX-RW	A raw water test simulant containing volatile molecules in concentration characteristic of the LACROSS plume analysis shall mimic volatile liquid composition from the cold trap in the lunar environment. Further, regolith dust simulant shall be added to the test water to verify the WPS filtering technology. The test water shall be added to the raw water prior to injection in the WPS. *Note 1. The direct introduction of all these volatiles in the TVAC ice-regolith simulant is not recommended for the TVAC chamber due to potential damage to hardware and human safety with respect to some toxic molecules.* *Note 2. Volatiles expected to stay in the vapor phase during the cold-trap process shall be neglected (CH4, H2, and CO).* *Note 3: For LACROSS plume analysis, see [...] [Table 1.12] End of notes.* ***[Responsible: DLR]***	The storage is considered to be part of the WCS hence an inlet for the raw water test simulant must be foreseen. The remaining volatile for the WCS is thus Methanol, which shall be avoided to be captured with the water vapour. This is also the closest volatile in the phase diagram, compare 2.1. In principle, the WCS for the Moon must withstand all volatiles mentioned in table 1.12 and potentially further unknown specimens.	T

Table 2.8: Raw water simulant chemical characteristics and storage. Requirement and verification method are taken from [42].

2.3. Thermal Vacuum Chamber (TVAC)

Three requirements are quoted below, after which a short summary of less relevant requirements is given.

2.3.1. Physical Characteristics

ID	Requirement	Rationale	V
LUWEX-VC-1	The thermal vacuum chamber to be used for extracting water from ice-regolith simulant shall be the L-chamber developed for the Comet Physics Laboratory (CoPhyLab). The L-chamber shall have the following physical characteristics: • Dimensions 1530 x 700 x 700 mm • Can store prepared ice-regolith samples for > 2 weeks at -170 °C • Maximum pumping rate shall be 37 $\frac{m^3}{h}$ allowing theoretically for L-chamber evacuation in minutes • Pumping rate shall be electronically controlled to reduce damage to samples • Pump system shall provide continuous ambient pressure of $< 10^{-6}$ mbar • Sample cooling system using liquid nitrogen and cold plates to reduce ambient sample temperature to -180 °C • Sample holder platform ***[Responsible: TUBS]***"	The WCS, except the storage, shares the inner volume of the TVAC with the extraction subsystem. The volume allocation is done in close cooperation with TUBS and the team for the extraction subsystem. Also, the cooling method is mentioned, which could maybe be used for the WCS.	T

Table 2.9: TVAC's physical characteristics. Requirement and verification method are taken from [42].

2.3.2. Water-volatile Cold Trap Facility

ID	Requirement	Rationale	V
LUWEX-VC-2	[The] TVAC shall provide a cold trap facility for liquefying extracted water vapour. The facility shall be accommodated within the TVAC vacuum volume. ***[Responsible: DLR,TUBS]***	This requirement has been written after the decision for cold trapping during the Concurrent Engineering Week in January 2023. At the beginning of the project, cold trap was not specified, it was just something like capturing device.	ROD, I

Table 2.10: Water-volatile cold trap facility. Requirement and verification method are taken from [42].

2.3.3. Raw Water Storage Tank Characteristics

ID	Requirement	Rationale	V
LUWEX-VC-3	The raw water storage tank shall be accommodated within the TVAC vacuum volume and have the following characteristics: • Store > 500 ml of raw water prior to purification by the WPS. • Water level sensed and monitored by the LUWEX LabVIEW control centre. • The storage tank shall be isolated as required by manual control valves from the TVAC vacuum environment and external WPS. • Tank shall be made of stainless steel. • Tank shall be sterilised prior to the test sequence to remove bacterial and fungal contamination. *Note. It is expected that several liquefaction cycles shall be performed before enough raw water is present in the storage tank for the WPS. End of Note.* *Note. It has been decided that the storage tank is placed outside the TVAC. End of Note.* ***[Responsible: DLR,TUBS]***	Since the storage tank is considered to be part of the WCS and the author worked a little bit on it, this requirement is stated here.	ROD, I

Table 2.11: Raw water storage tank characteristics. Requirement and verification method are taken from [42].

Also, the TVAC provides several sensors, e.g. a mass spectrometer, and throughputs for external sensors and heating elements are provided. [42] This brief summary of requirements is referred to as LUWEX-VC-4.

2.4. Testing

The testing phase will take place in Brunswick. All subsystems will be delivered there and integrated into the process chain. The efficiency of the process shall be monitored. [42] The efficiency is either in relation to water lost or to electricity needed for a certain amount of water.

2.5. TVAC Water-Volatile Cold Trap Interface

ID	Requirement	Rationale	V
LUWEX-IF	The TVAC L-chamber shall provide the volume for an internal cold trap to freeze the extracted gaseous water and volatiles. The cold trap shall provide facilities for extracting the frozen products as liquid and storing [them] in a stainless-steel reservoir container external to the TVAC. ***[Responsible: DLR, TUBS]***	This requirement is directly related to the WCS, although there is some overlap to the previous requirment in section 2.3.2. It is relevant for defining the electrical, fluidical and mechanical interfaces.	ROD, T

Table 2.12: Cold trap interface. Requirement and verification Method are taken from [42].

2.6. Additional Requirements

During the time at the DLR, discussions with the supervisor led to further, softer requirements summarised below:

ID	Requirement	Rationale	V
LUWEX-AD-1	No functional fluids should be introduced into the water capture system. A functional fluid, e.g. in a heat pipe, ensures the transport of latent heat through resublimation or condensation of the extracted vapours.	For a flight to the Moon, fluids in a system lead to more certifications required of a launch provider, hence a system without any fluids on the way from Earth to the Moon is desirable.	ROD
LUWEX-AD-2	The design should be robust while maintaining simplicity. It should be kept in mind that this technology should be used on the Moon. The system should operate for about six months and be able to deal with off-nominal conditions, e.g. higher vapour mass flow or other temperatures than expected.	The robustness term is due to the fact that there are still unknowns since no rover has been close to the icy-rich regolith. Simplicity also leads to less failure modes.	ROD, T

Table 2.13: Additional requirements.

ID	Requirement	Rationale	V
LUWEX-AD-3	Liquid water shall be avoided in the reactor chamber. Thus, the pressure in all connected volumes shall be kept below 600 Pa. The reactor chamber is also called the crucible or extraction chamber.	This requirement comes from the extraction subsystem and sets the upper pressure limit for the WCS, if no means to separate the pressure regions is used. The pressure leads to major design implications because of the phase diagram of water; see figures 3.2 and 3.3. Liquid water would flow to colder regions or become stuck in the regolith and is then lost for vapour extraction.	ROD
LUWEX-AD-4	The capturing subsystem should purify the extracted vapours. For capturing in the solid state, possible operational envelopes are shown below. The operational envelope should be chosen in such a way that no other specimens are deposited on the cold surface in the liquid or solid state, compare figure 2.1. Nevertheless, the purification subsystem has buffers in case all pre-purification fails.	It is desirable to have an initial purification step via destillation before the water purification system so that the latter uses less consumables. This requirement has also been written after the decision for cold trapping which is able to serve as a first purification step as shown by [33].	ROD, T

Table 2.14: Continuation of the additional requirements.

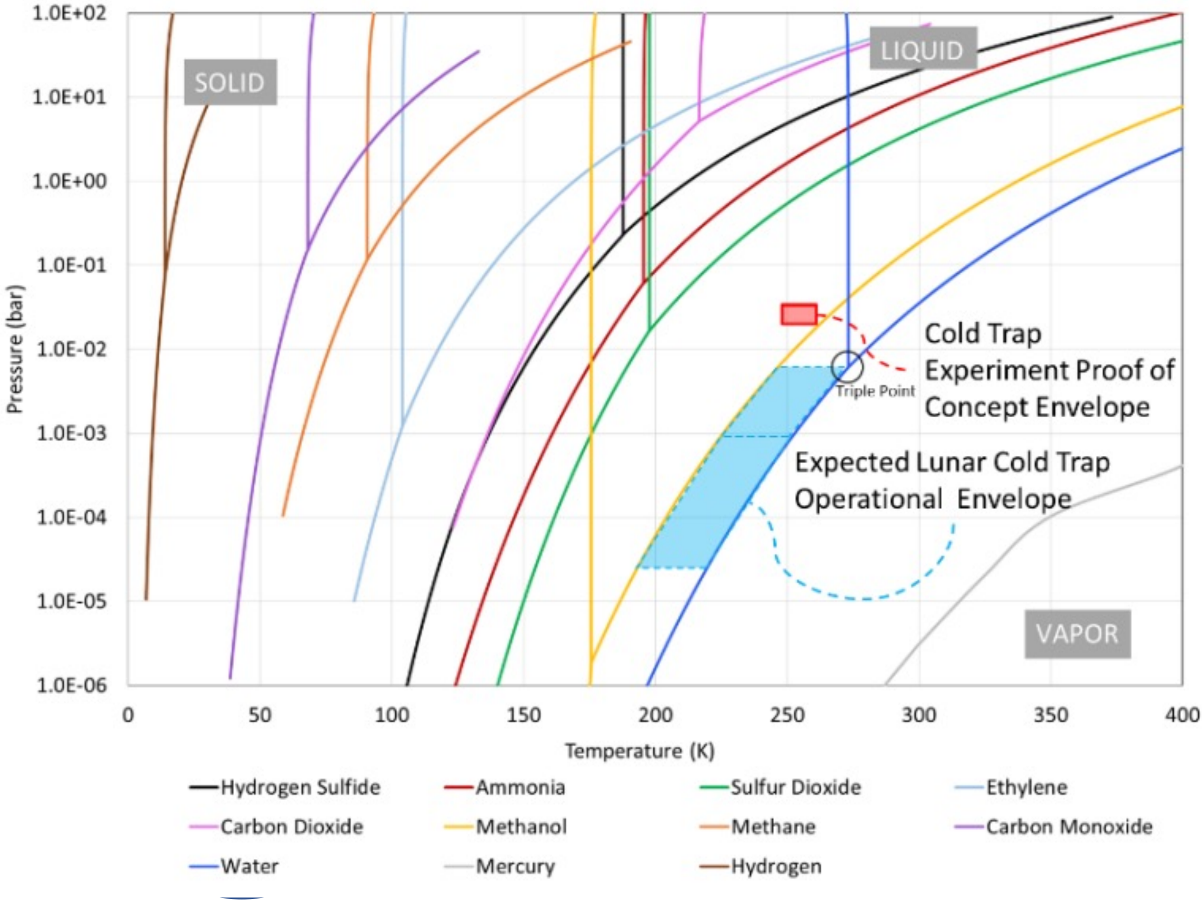


Figure 2.1: Phase Diagram with all specimen present in LCROSS with operational envelopes of cold traps [33].

2.7. Analysis of the Requirements

The requirements pose some constraints on the size of the water capturing subsystem. It must fit with the extraction system, of which the crucible occupies the most space, inside the TVAC. The TVAC's dimensions are shown in the requirement 2.3.1. Furthermore, from the mass and the water content of the batch, 5-20 % of about 15 kg, the volume of the water, either in a rather fluffy icy state or as a liquid, can be estimated. A system on the Moon would likely look differently due to other volume available and mass constraints.

In addition, some of the requirements already include a design solution because they have been revised after the initial design. The design process influenced the requirements, e.g., cold trap as the type of capturing subsystem, compare 3.3.2, which is not in line with the space systems engineering course. However, these requirements are out of the author's responsibility and are treated as given requirements from a customer.

The stated requirements are analysed against the design features in chapter 5 in a compliance matrix in 5.8, after the final design is presented.

3

Overview of Design Solutions and subsequent Choice

The most important criterion of the water capturing subsystem is reliably capturing as much water as possible during the test since the captured water will be further processed and investigated in later steps of the project. It is also relevant to design a system that reflects a future design which could be used on the Moon, but out of practicality, there might be a discrepancy between the actual design and the most optimal design. Other important criteria are its complexity, lifetime, technical readiness level, system mass, and efficiency. [40] Its functionality is defined in the flow diagram in figure 3.1. The capture subsystem shall:

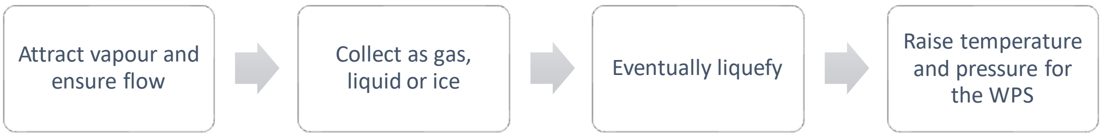


Figure 3.1: Functionalities of the WCS.

The two main methods considered for the LUWEX project are:

1. Cold trap, the water vapour is deposited as ice on a cold surface.
2. Condenser, the water vapour is condensed on a cold surface.

The difference between the two is the phase, the temperature and the pressure at which it occurs.

3.1. Water Phase Diagram Implications on the Design

The chosen path in the water phase diagram has a significant influence on the design and is therefore discussed beforehand. In figure 3.2, the phase diagram of water and possible paths of the extracted water are shown. First, the water is in a solid state at a very low temperature and pressure in the bottom left corner. Then, heat is applied and it sublimates *(1)*. After that, it is either directly liquefied *(3)*, which is basically realised with a condenser, or the vapour is deposited as ice on a cold trap *(2a)* and then liquefied with another process *(2b)*.

It is important to note the influence of the requirement that no liquid shall be in the extraction chamber, compare 2.6. A possible solution is to keep the pressure below the triple point of water, meaning below 615 Pa. That is the reason why the processes are drawn below the triple point.

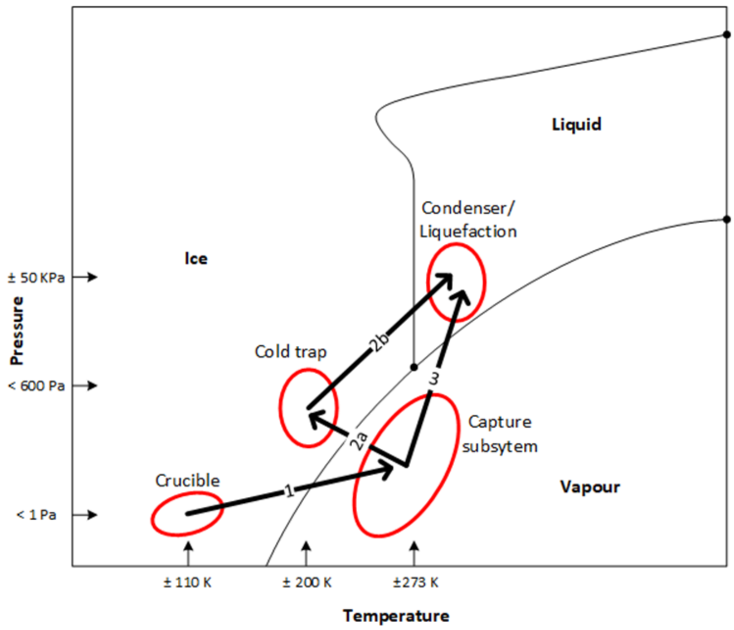


Figure 3.2: Water phase diagram. Paths are schematic; temperature and pressure regions are not exact. Figure courtesy of [43].

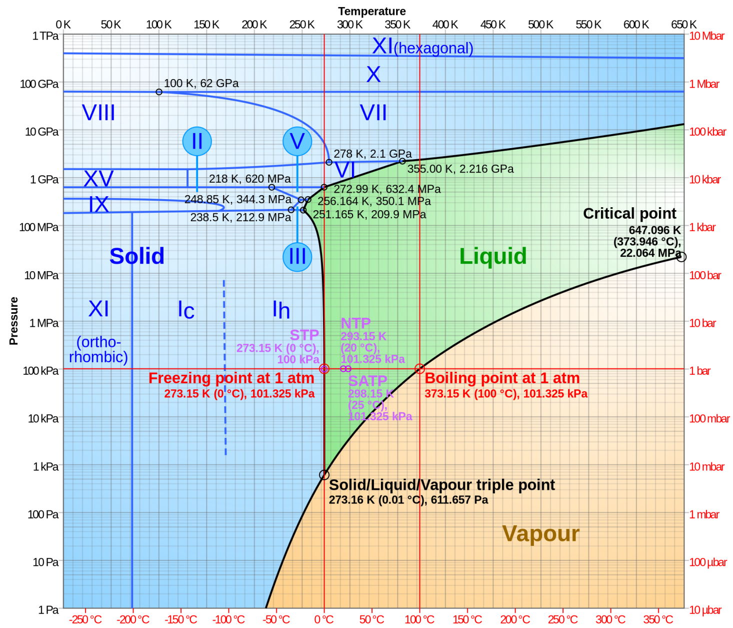


Figure 3.3: Water phase diagram [44].

One of the main differences between the two processes, compare the arrows *3* vs. *2a* and *2b* in figure 3.2 is the additional phase change to ice when using a cold trap. This has a strong influence on the complexity and pressures needed as discussed further in this chapter, compare also the elaboration in figure 3.4.

For the final purification of the sample, water in the liquid state is needed. This requires a significant pressure change above 615 Pa, either after the deposition as ice on the cold trap *(2b)* or before the condenser *(3)*. One could think to realise the pressure change in the condenser itself, for example with a piston.

The vapour could either be captured in an icy or liquid state. For both possibilities, the vapour flow needs to be induced and guided somehow, as shown in section 3.3. There, possible options for the capturing of the water vapour are shown in a Design Option Tree (DoT):

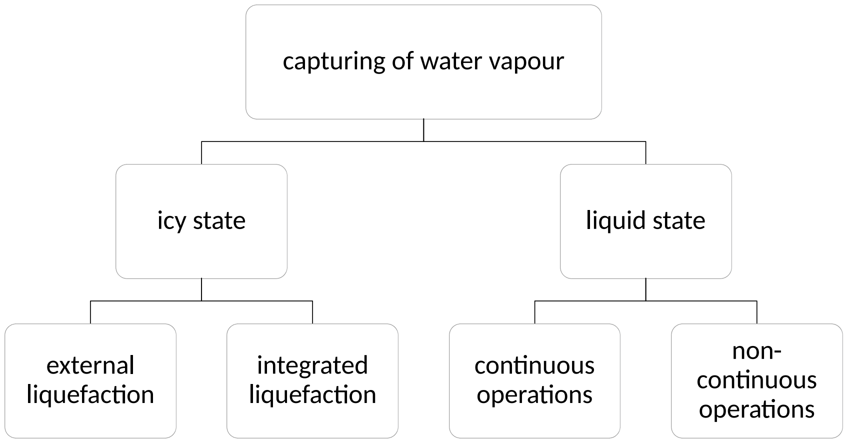


Figure 3.4: Overview of possible options for the capturing subsystem.

For the first option, the ice needs to be somehow liquefied, either directly in the cold trap itself, described as “integrated liquefaction”, or in an “external liquefaction”, whereas the ice is moved to another environment and then liquefied there. The integrated liquefaction has the drawback of stopping the collection for a longer time while the environment of the cold trap is then heated and pressurised. Also, after a liquefaction process, the containment needs to be cooled again. These factors most likely are going to have a negative impact on the collection rate and energy consumption.

With the external liquefaction, the cold trap could collect basically continuously, with only some breaks for the uncoupling of the ice or during the liquefaction cycle. If the uncoupling is realised with a staged approach, one cold surface could collect further while another cold surface continues to collect. A further requirement for better continuity is that the external liquefaction has the same rate of liquefaction in terms of mass as the cold trap’s collection rate. A scheme for a cold trap with an external liquefaction can be seen in 3.5. On the Moon, an option for an external liquefaction could be also the habitat. The water ice would melt in a pressurised and temperature-controlled environment, although the atmospheric life support system has to cover the phase change enthalpy needed.

Besides, for the cold trap, an uncoupling mechanism for the ice from the cold surface is needed. Some options for this are explored in section 3.2. Furthermore, cold traps could be realised only with valves and not with a pump or piston, leading to a lower complexity than the condenser.

The options for capturing in a liquid state can be classified into continuous and non-continuous operations. For continuity, a constant flow of water vapour to the condensing surface at sufficient pressure and temperature above the triple point is needed. This could be realised with a pump between the extraction subsystem and the capturing subsystem if the liquid phase is not allowed in the extraction subsystem. A high pressure in the crucible is unwanted since the water should only be in a solid or gaseous state during extraction. Such a system is shown in figure 3.7.

Still, the extraction subsystem and condenser could be directly connected and with sufficient heating and insulation, the pressure would most likely rise sufficiently. Furthermore, all surfaces must be kept way over 0 °C to prevent unwanted solidification or liquefaction. This could be an option for continuous condensing without a pump with the drawback of the high heating requirement and liquid occuring in the extraction subsystem.

Lastly, the water vapour could be collected in the condenser volume which is temporarily sealed off from the extraction subsystem. After that, the pressure needs to be raised, e.g. thermally or via volume reduction possibly implemented with a piston. This is an example of capturing in a liquid state with non-continuous operations.

In the next two subsections, cold trapping, meaning capturing the vapour as ice, and the condenser, are further explored.

3.1.1. Capturing in the Solid Form

This section goes into more detail and adds conceptual thoughts compared to the section in the Literature Study 1.1.4.a for capturing vapours in the solid state. One has to mention that the schematics always show multiple cylinders or "cold fingers" as the capturing surface. The shape of the surface is only exemplary as well as the dimensions of the system.

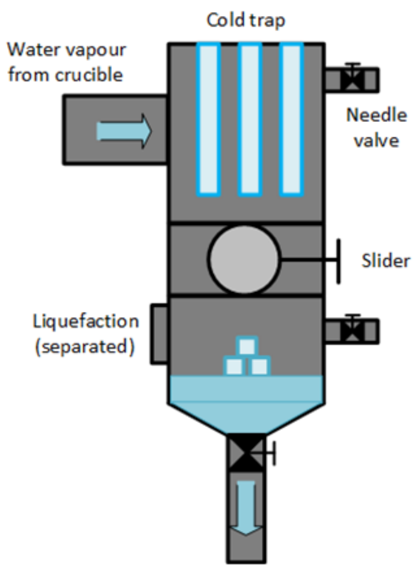


Figure 3.5: Schematic for a cold trap with external liquefaction. Figure courtesy of [43].

One advantage is that the ΔP and ΔT between the Lunar environment and the inside of the cold trap are lower compared to capturing in the liquid phase, meaning less insulation is needed and the losses are lower.

Furthermore, no solidification of the water vapour in the potential guiding tube and on the surrounding walls of the cold plate shall occur. Hence, the temperature of the walls must be controlled.

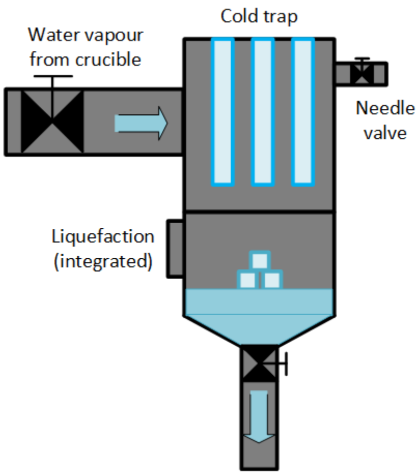


Figure 3.6: Schematic for a cold trap with internal liquefaction. Figure courtesy of [43].

Proposed concept of operations for a cold trap with external liquefaction As soon as water vapour arrives at the cold trap, the collection process starts. The water vapour is deposited on several cold surfaces. As the ice deposits on the cold trap, the heat transport capacity and thus efficiency is reduced the thicker the ice layer. After a certain point, the delamination is started to free the cold trap as described in the next section 3.2. The ice falls down through a separation mechanism into the liquefaction container. The deposition of ice and delamination can be repeated until the liquefaction container is full of ice.

Consequently, the separation mechanism is activated, so that the liquefaction is sealed and has its own environment. Heat is applied to the ice in the liquefaction leading to a pressure and temperature increase so that liquid water can exist. Meanwhile, more ice can be collected on the cold fingers. If the liquefaction process takes longer than the re-sublimation on the cold fingers, the heating in the extraction subsystem may be adapted to reduce the water vapour flow and thus minimise losses to the TVAC.

When all of the water is liquefied, it can flow to a storage tank which can also be sealed off from the liquefaction area. After all liquid water has flown out, the liquefaction volume is evacuated so that the pressure is close enough to the cold trap so that the separation mechanism can be opened. This process is repeated until the storage tank is full and sufficient liquid water is present.

3.1.2. Capturing the in Liquid Form

Obviously, the capturing process in liquid form has to take place in the liquid region of the water phase diagram, as further discussed in the literature study in 1.1.4.b.

One option for capturing in the liquid phase is the classical spiral in which the outer walls are cooled. Through the long residence time in the tube, the vapour is chilled until the phase change occurs. The number of revolutions and the diameter are the most important design criteria. Another schematic is shown below.

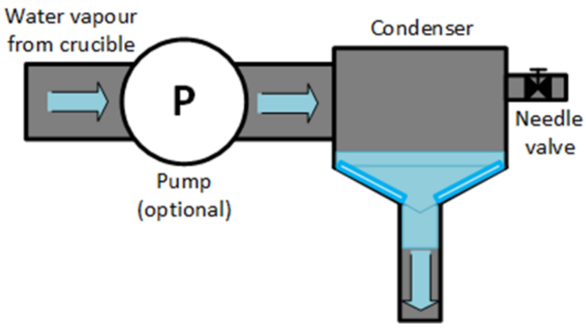


Figure 3.7: Schematic for a condenser. Figure courtesy of [43].

An example of a condenser in a laboratory setup is found in the literature study, in 1.1.4.b. There, the procedures and findings of Yiwei Liu [31] are described in detail.

This paragraph states further interpretation of Yiwei Liu [31] findings relevant for the design of the condenser. The efficiency also strongly decreases if the vapour density is too low. Continuous droplet condensation is needed. This means that the pressure must be significantly higher than circa 611 Pa. Also, his team found out that the discharge of the residual water vapour to induce the flow to the TVAC may increase pressure to around orders of magnitude of 1000 Pa in the vacuum chamber. [31]

A general advantage of the condenser is that a phase change is left out. Two phase changes are needed (ice to gas to liquid) compared to three with capturing in solid form (ice to gas to ice to liquid).

3.2. Water Ice Uncoupling from a Cold Surface

This section is specifically relevant for capturing in solid form, compare 3.1.1. The collected ice needs to be uncoupled from the collection surface for further processing which is described in this section. These options are presented in a Design Option Tree followed by schematics.

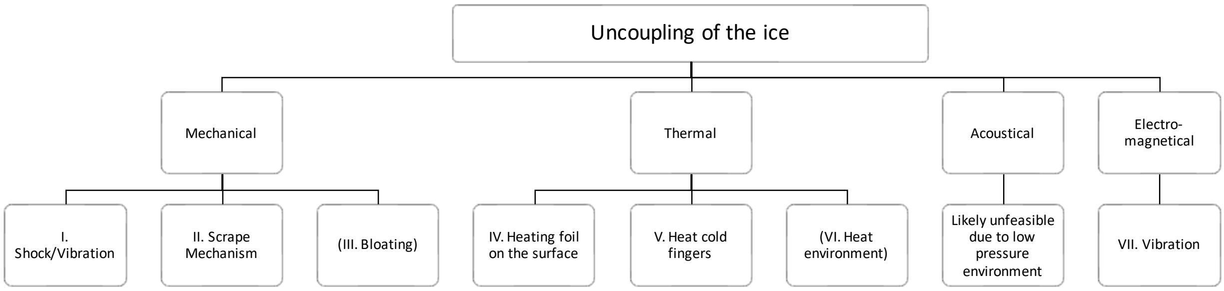


Figure 3.8: Design Option Tree for uncoupling of the ice from a cold surface.

The first level in figure 3.8 shows all type of options to change the state of the ice on the cold surface. The second level explores them further.

In all cases, the cold surface should have the lowest friction coefficient possible for less adhesion of the ice while delaminating. The preferred uncoupling options could be:

1. realised via electricity. The current induces a magnetic field and leads to shaking/vibration of the rods or cold fingers. TUBS has such a device.
2. induced by thin heating foil around or on the cold surfaces. "A total of 40 watts is supplied to the thin film heater and successfully delaminates the collected ice with minimal sublimation." [34] Jurado attached a very thin heater over the cold plate.
3. done via hand, meaning manually or preferably with a mechanism.

Nearly continuous operations with a single cold plate seem possible, since the delamination process of Jurado [34] took about 15 mins. It is questionable whether the delamination process is the same if the cold surface is significantly bigger.

3.2.1. Vibrational

Centralised Shaking Mechanism Centralised means in this context, that one actuator is sufficient for the uncoupling of the collected ice. Meaning a single mechanism is sufficient to excite the whole collection surface.

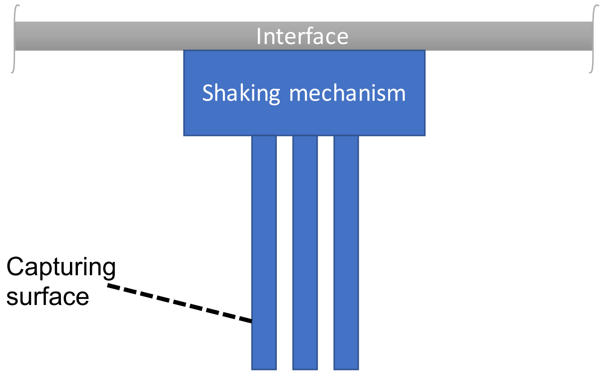


Figure 3.9: Schematic for a centralised shaking mechanism. Rods are only an example of a possible collection surface geometry.

The shaking mechanism should not hinder the heat transport due to vapour phase change and the surface temperature control. This concept refers to option I. II. VII in 3.8.

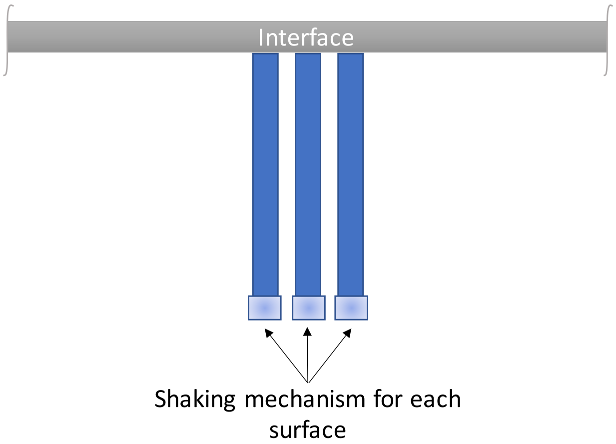


Figure 3.10: Schematic for individulised shaking mechanisms. Rods are only an example of a possible collection surface geometry.

In figure 3.10, each cold surface has an individual vibration mechanism for the delamination. This refers to option I., II. and VI in the DoT.

Options for actuators are

- a loudspeaker membrane, e.g. used in smartphones as an option for vibration besides the use of a loudspeaker. Since there is no use case in vacuum, likely no vacuum-rated version available.
- an engine with an off-balance: Also used in smartphones for vibration

- Piezo-Electric element. Proven to work by the paper [45]. Favorised for the purpose of this research project is the flexible stackable shear actuator P-1x1.0xT PICA Shear Scheraktoren (piceramic.de) . It is compatible with ultra-high vacuum and low temperatures, down to 4K.
- Excitation through Magnetic Fields

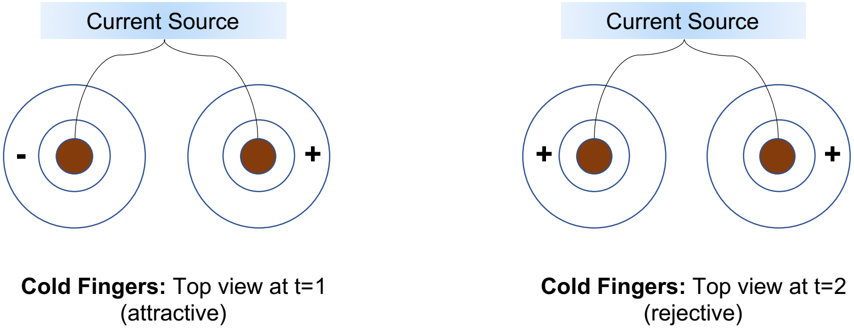


Figure 3.11: Concept for vibration induced by magnetic fields on two metal rods. (Top view)

The main disadvantage of this approach is the introduction of vibration into the whole system or lander. This might lead to a need for de-coupling of the agitator or damping.

Further general problems of the vibrational uncoupling approach are:

- Fatigue due to vibration
- Minimum amplitude and frequency needed for uncoupling
- Power needed for higher surface areas, meaning higher mass.

3.2.2. Scrape-Off

A plate scrapes-off the ice from the collection surface, which refer to II in the DoT. Another mechanism and moving parts is unwanted, compare 2.6.

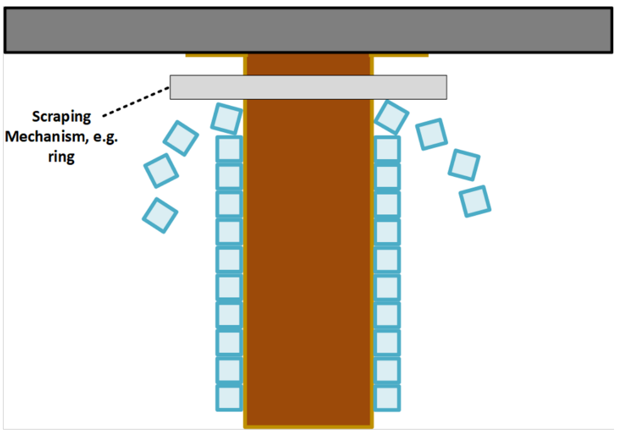


Figure 3.12: Scraping Mechanism. Brown is a cut of a collection surface.

3.2.3. Thermally

Heat is applied to the collection surface or rather the collected ice so that the ice is separated from the surface. A picture of such a system is shown in figure 1.8 which refers to IV. in the DoT.

3.3. Options to induce a Water Vapour Flow from the Crucible to the WCS

After the water vapour has been gassed out, it needs to flow towards the capturing subsystem. This could be realised with a pressure difference. The pressure inside the crucible and capturing subsystem is higher than in the TVAC. This could be used for a driving force, controlled by (solenoid) valves or a needle valve. At least valves are a possibility. Using a pump to induce the flow is an option as well, most likely in combination with the needed pressure rise for a condenser. Besides, one could think of a recirculation mechanism inside the crucible and capturing subsystem.

A control scheme for using the Δp as a driving force for the water vapour has to be designed as well. In Yiwei Liu [31] paper is some information and graphs for the pressure control in a condenser with two solenoid valves and a vacuum pump with a pressure head of at least 600 Pa.

Lastly, no additional mean might be needed. In a closed system, after sufficient time, the pressure of a gas equalises. If vapour deposits on a cold surface, the pressure decreases locally. The pressure will equalise again leading to flow towards the cold surface. Likely, this process is too slow.

3.4. Ideal Cooling Power

In this subsection, the cooling power due to the phase change enthalpy is exemplarily calculated at 600 Pa and around 0 °C. These conditions could be present in the cold trap in the baseline design.

The following assumptions are made:

- The enthalpy change due to heating or cooling in one phase is considered negligible since it is way smaller than the phase change enthalpies. This enthalpy change has to be taken into account if approximately $\Delta T \gg 20\ K$
- Water vapour flow of $\dot{m} = 100\ \frac{g}{h}$, which is quite high and thus conservative for the power requirement

The specific enthalpy of sublimation, equivalent to the enthalpy needed from gas to ice, is

$$h_s \approx 2834\ \frac{J}{g}$$

at around $p = 600\ Pa$ and below 0 °C, equivalent to below the triple point and leaving out the liquid phase. With

$$Q = h_s \cdot m \ [46]$$

and multiplying each side of the equation by the reverse value of time t

$$\Rightarrow Q = h_s \cdot m \mid \frac{1}{t}$$

$$\Rightarrow \frac{Q}{t} = h_s \cdot \frac{m}{t}$$
$$\Rightarrow P = h_s \cdot \dot{m}$$
$$\Rightarrow P = 2834\,\frac{J}{g} \cdot 100\,\frac{g}{h}$$
$$\Rightarrow P = 2834\ \cdot 100\,\frac{J}{3600 \cdot s}$$
$$\Rightarrow P = 78.7\overline{2}\,W$$

This is in an order of magnitude achievable, even though the final vapour mass flow might be lower, resulting in less power needed.

3.5. Trade-Off for the LUWEX Design

For the graphical Trade-Off Table, the score classifications are defined as the following [47]:

Excellent	Dark green
Good	Green
Correctable deficiencies	Yellow
Unacceptable	Red
Unanalysed	White

Table 3.1: Colour definitions for the graphical trade-off table [47].

In the first column, the criterion is stated. In the 2nd and 3rd columns, they are qualitatively judged via colours for the respective method, favourising cold trapping.

Criterion	**Cold Trap**	**Condenser**
Phase Change Energy needed, equivalent to cooling power	Slightly higher (about 20 %)	Lowest need, since it is only a phase change with one phase
Energy for the System Environment needed	"Only" freezing at the walls has to be prevented. Pressure and temperature difference to TVAC is lower	Liquid region of water has higher requirements for the temperature and pressure: ≫600 Pa, 0 °C vs. TVAC's pressure and temperature
Complexity of the design	Feature for the ice uncoupling is needed Pressurisation for proceeding with the captured ice is also needed	Pump needed (most likely) Condensation design is more complex effective heating method for the gas is needed
TRL / Reliability	More literature and experiments have been found	
Simulation	Likely easier	Fluid water flow might also be included
Liquefaction	Heating of the ice in a closed environment can lead to liquid water. Heat transfer is possible via conduction to the ice, which is why this environment needs less insulation to the TVAC compared to the condensing option	Gas needs to be pressurized and then heated or cooled, depending on the starting point in the water phase diagram 3.3
Resources	likely less, since system might be less complex	possibly higher
Pre-Purification	Proven possible by Holquist et al. [33]	needs to be investigated
Skill required		Most likely higher
Output Rate	Dependent on the capturing surface and post-processing to liquefy	output is a continuous flow

Table 3.2: Graphical trade-off table to determine the capturing method for the LUWEX design.

In conclusion, collecting water vapour as a liquid has the need for higher pressure. On the other hand, the collection as ice needs less pressure but has difficulties in handling after the collection process, e.g. delamination from the cold surface, if continuous operations are desired. The main advantage of capturing as a solid is less complexity since no means to raise the pressure for the liquid phase is needed. The condenser needs pumps and valves with pressure control to function efficiently and optimally. Besides, the insulation of a condenser is more complex since increasing or decreasing the enthalpy of a vapour is more difficult.

Another advantage of the cold trap is the better use of the native environment on the Moon since the condenser also operates at higher temperatures and pressures. Also, less heat and control schemes are required to achieve the desired temperature and pressure ranges. However, the cold trapping system is perhaps less controllable because pressure is more sensitive to unwanted condensation.

In future systems with cold trapping, the liquefaction might not occur directly after the capturing, so the intermediate storage could be in the icy state. This reduces the storage complexity and favours the design with a cold trap. Storing outside the TVAC would be equivalent to storage inside a habitat which includes a lot of technical hurdles still to be overcome. Furthermore, the icy regolith deposit is likely far away from the habitat resulting in a need for a transport possibility.

4

Preliminary Experiments and Investigation

During the literature study, the need for several experiments arose, which have been further refined during the design process. To the best of the author's knowledge, little content has been published to capture and liquefy several hundred grams of water under lunar conditions. Three experiments were conducted by TUBS and Luca Kiewiet assisted by the author. The author focussed on the data coming from the experiments leading to some conclusions for the design. Herewith, the author would like to express his gratitude for the use of their equipment and for the execution of the experiments.

First, the straightforward methodology is explained in 4.1, followed by the description of the experimental environment. Then, sections 4.2.1 to 4.2.3 contain the setup and the respective findings. The first experiment is executed to test whether the cold trap works effectively enough, as identified by the literature study. The following two experiments tested design functions, the temperature control and ice release through heat.
As a side note, these experiments are referred to as pre-experiments because they took place prior to the LUWEX experiment itself and serve to support the design for the LUWEX experimental campaign in the first half of 2024.

4.1. Top-Level Methodology

This section provides a description of the experimental methods employed. The aim is to assess general behaviour, control the cold trap surface temperature, and demonstrate successful ice delaminations through a series of runs. Prior to each experiment, the goal and a rough plan was developed. Also, some parts were ordered if they were absent at TUBS. Since a large inventory of vacuum parts is present at TUBS, most of the parts and tools needed were available.

The desired data collection during the experiment involved:

- Continuous monitoring of system parameters throughout the experiment's duration.
- Observation of any physical changes, anomalies, or unexpected behaviours.
- Recording of temperature data.

Furthermore, an infrared thermometer is used for measuring outside temperatures.

A controlled laboratory environment was established to replicate the conditions relevant to the research context, especially the low-pressure regime. Sensors and data acquisition equipment were strategically placed to monitor critical parameters such as temperature, pressure, as well as system responses. Only the cold trap and the ice container were cooled during the experiments, which was sufficient for proof of concept experiment and general insights.

4.2. Findings of the Pre-Experiments

4.2.1. General Behaviour of a Cold Trap in a Low Pressure Environment

Since there is little experience in capturing water vapour in low-pressure environments, specifically for the purpose of In-Situ Resource Utilisation, a small-scale test is conducted to see how effective it would be to capture water vapour on the Moon using a cold trap. Figures 4.1 and 4.2 show the setup of this experiment.

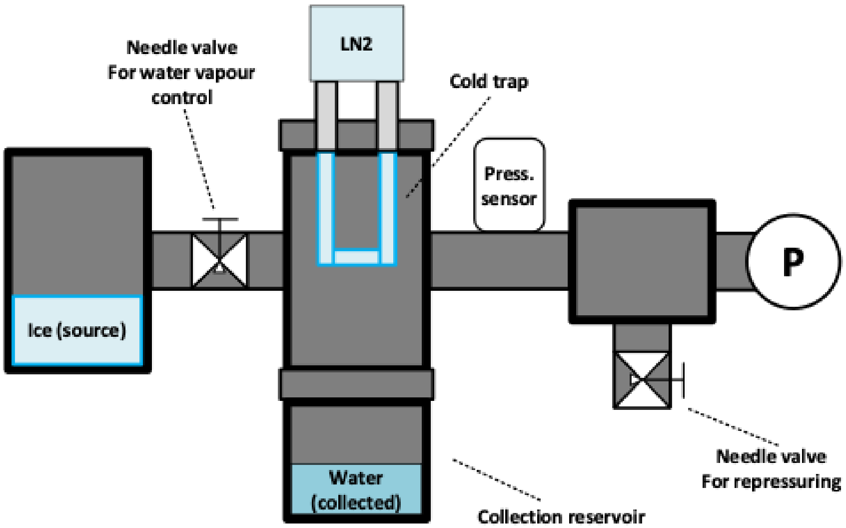


Figure 4.1: Schematic of pre-experiment I setup. Figure courtesy of [43].

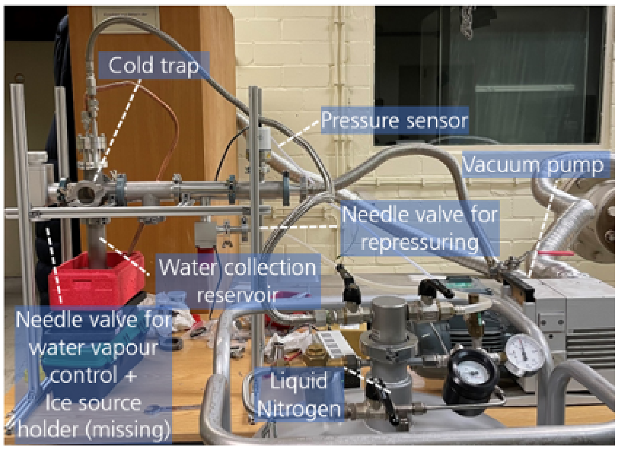


Figure 4.2: Actual pre-experiment I setup.

The experiment is designed to test the effectiveness of the cold trap when the vacuum pump is running ("constant" low pressure). This would be analogous to the cold trap being exposed to the ”atmosphere” of the Moon. In table 4.1, the results of two recorded runs are presented.

Run #	Sublimated [g]	Captured [g]	Efficiency
1	9.34	7.11	76.12 %
2	4.45	3.18	71.46 %

Table 4.1: Results of pre-experiment I.

Secondary to this, experience and insights are gained about cold traps and working with these test setups. The collection efficiency is surprisingly high, between 71 to 76 %, despite the shape of the cold trap not being optimised. The surface area blocked by the cold trap in the cross-section area rectangular to the vapour flow is lower than 50 %. To achieve an even higher collection rate in the final design, the multiple cold traps are staged and offset in view of the vapour flow direction.

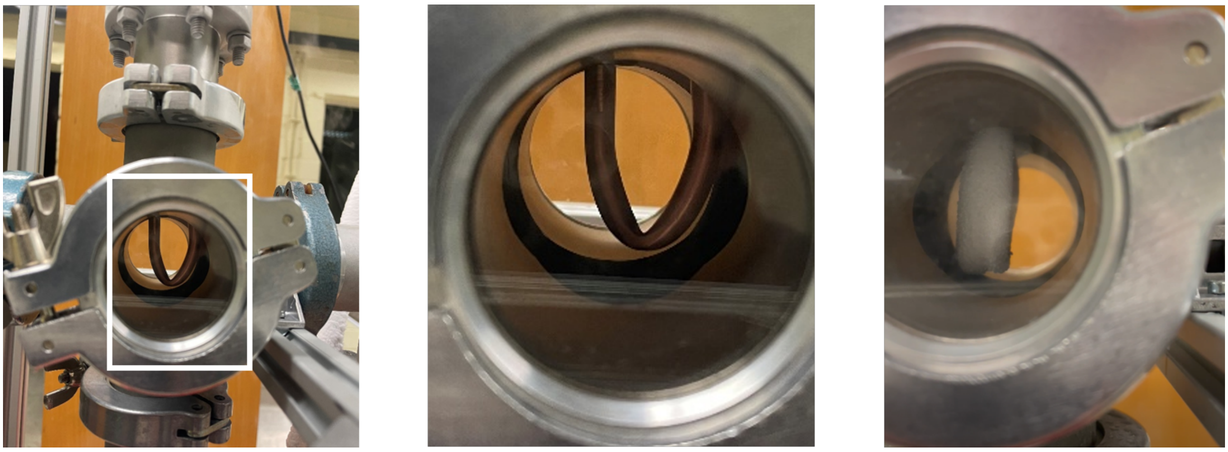


Figure 4.3: Close up views of the white rectangle of the cold trap. Middle photo is before the ice deposition which can be seen on the right photo. Glass has a diameter of around 40 mm.

4.2.2. Surface Temperature Control for Purification and Ice Uncoupling

The second experiment aimed to assess the effectiveness of surface temperature control mechanisms within the proposed design. A water vapour source has not been used in this experiment. The following steps were taken:

- The controlled thermal environment of the smaller large-scale comet simulation chamber (L-Chamber) is used and prepared for the experiment's operational context,
- Heating and cooling systems were implemented to manipulate surface temperatures,
- Temperature sensors were strategically placed on the system's surfaces for precise monitoring.

A temperature sensor is placed on the bottom heating foil (close to the base), and the other is placed just above the heaters on the copper directly. The copper stick has a thread to be screwed into the cooled surface, allowing for cooling down. The foils used were quite powerful and had a heat flux density of about 23 000 $\frac{W}{m^2}$. The schematic of the setup is shown in 4.4.

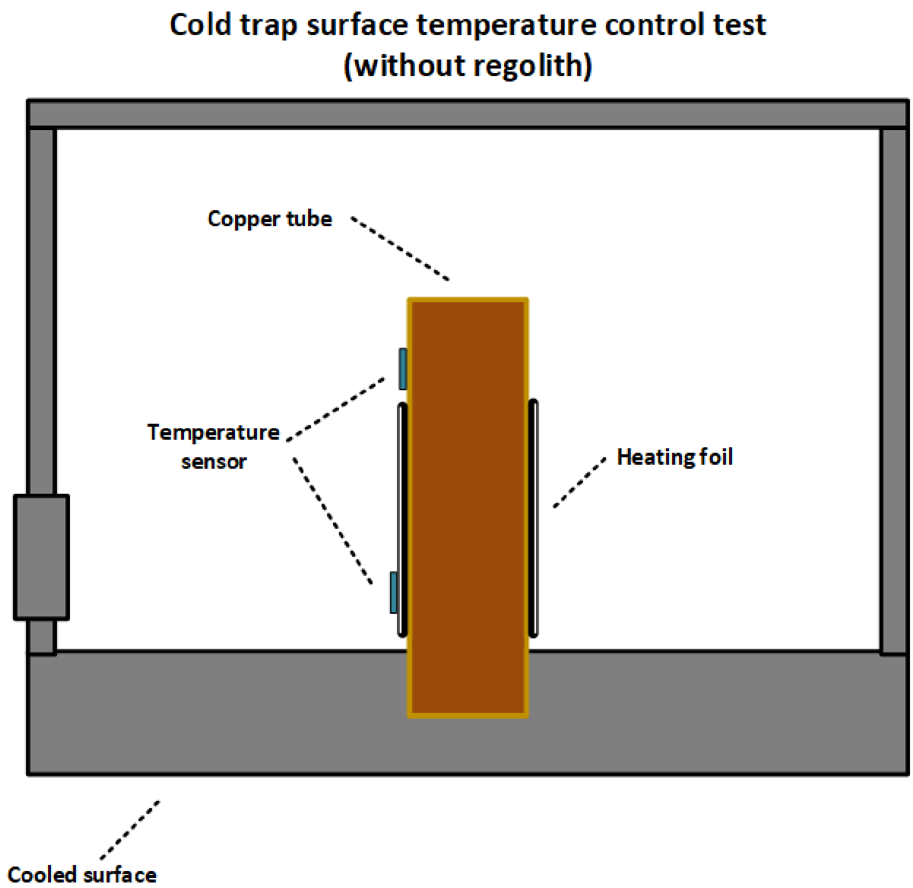


Figure 4.4: Sketch of the pre-experiment II. Figure courtesy of [43].

The temperature control process involved:

- Gradual adjustments of heating and cooling systems to achieve desired temperature profiles.
- Continuous monitoring and feedback control to maintain target temperatures.
- Data logging to record temperature variations during the experiment.

The temperature is more sensitive than expected to small power inputs. Too much power leads to melting or even burning of the foil. The foil's surface temperature is even more sensitive than the simulations anticipated. Possible reasons are the thermal connection from the heating foil to the copper and/or the connection to the cold sink hindering conductive heat transport.

The thermal connection without any spacing between the foil and the copper is crucial. It was hard to realise since the copper stick had a diameter of around 10 mm, resulting in too much bending of the foils. The foils started to bend back, worsening the thermal connection. The lessons learned support the design of the shells and inlays in the cold trap top flange.

Unfortunately, it was not possible to cool down entirely to 80 K. However, keeping the operational temperature of 200 K for over an hour, but without heating, and the delamination peek were shown.

Figure 4.5 illustrates the two temperature graphs of the sensors. The orange graph is the temperature sensor placed on copper. The blue graph represents the temperature on the heating foil.

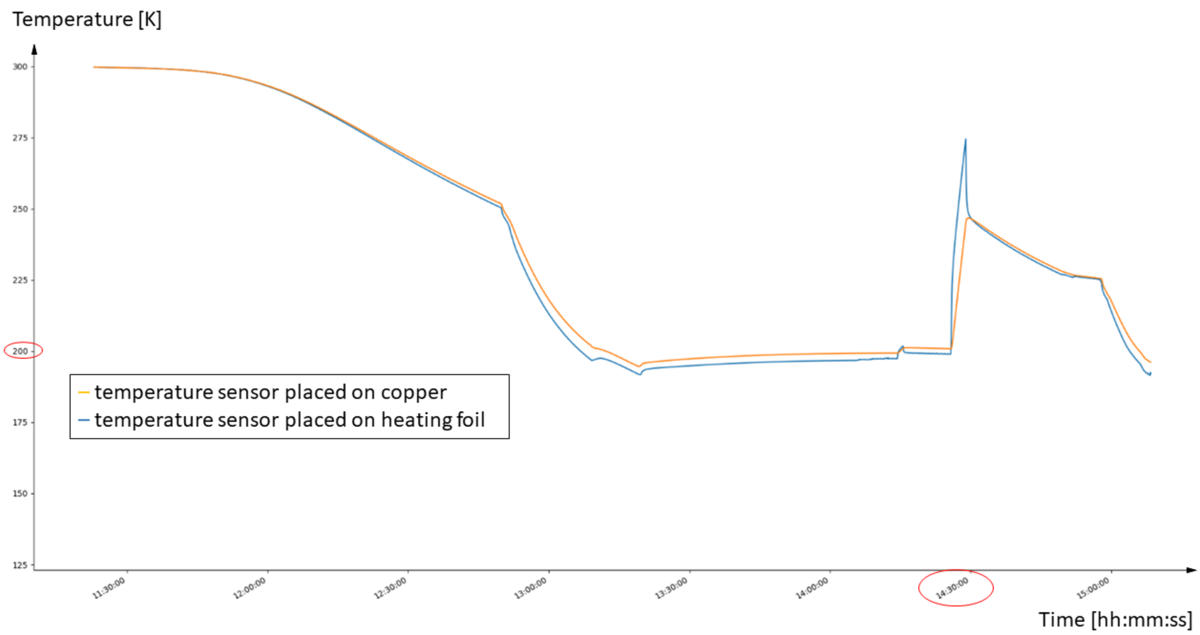


Figure 4.5: Temperature graph. Maintaining temperature at 200 K and small delamination peek at 14:30:00 h (both encircled). Based on [41] and [48].

All in all, the test did not go as expected since it was not possible to reach temperatures under 200 K. This could have been achieved with more cooling, especially by cooling the side walls of the L-Chamber. Implementing such a cooling system was too complex and the large TVAC was completely booked. The diameter of a copper rod should not be too small to avoid too much bending of the foil resulting in a worse thermal connection. Still, the surface temperature could be controlled with a heating foil and a cold surface could be used as a heat or rather cold sink. Furthermore, the setup was used for a test of the extraction subsystem.

4.2.3. Successful Ice Uncoupling

A tapered cold finger is placed in the first test setup described in figure 4.2; compare figure 4.6. The design of the cold finger is described in figure 4.9 and 4.8. The liquid nitrogen feed through from pre-experiment I, further detailed in section 4.2.1, is used again to have better control over cooling and ensures reaching 80 K.

This setup allowed multiple ice built-ups in about 45 minutes and their successful delamination in about 10 minutes. The connection to the temperature sensor could not be established, unfortunately.

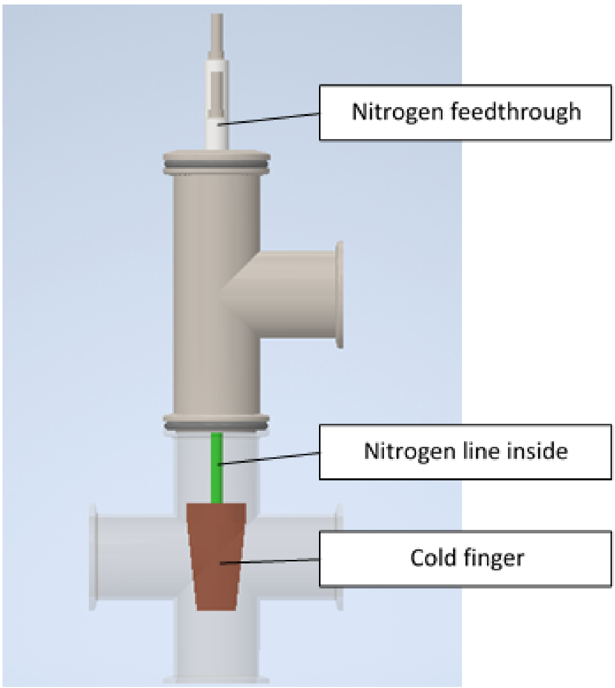


Figure 4.6: Scheme for the uncoupling experiment. Figure courtesy of [43].

The conical cold finger is cooled with liquid nitrogen. The copper lines are welded to the copper cone. The team of the Comets Physics Laboratory (CoPhyLab) TUBS has experience since the connection needs to be vacuum proven. [41]

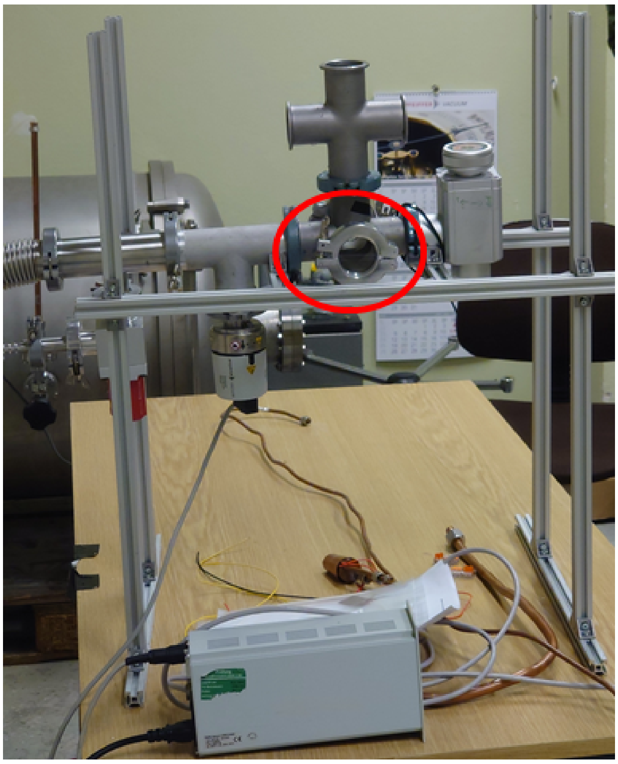


Figure 4.7: Actual test setup. Red circle is the transparent part in figure 4.6.

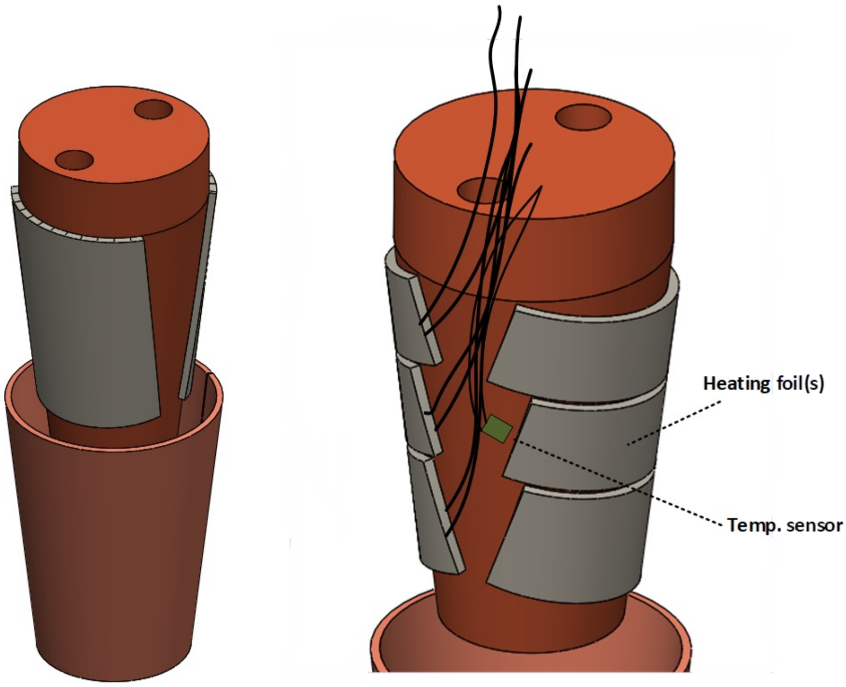


Figure 4.8: CAD-Schematic of the cold finger with channels, attached foils and sensor and shell below. Figure courtesy of [43].

Figure 4.9: Actual view of the cold finger from pre-experiment III.

Only two foils could be placed, resulting in a partial covering of the mantle‘s surface. An additional thin copper shell is placed around the heating foil to keep them in place. Grease has been used to ensure a good thermal connection of the foil to the copper. The main findings are:

1. The heating power of 40 Watts instead of 20 Watt has not significantly reduced the delamination time, but the collection efficiency. Possibly, the heat spread too slowly and was absorbed for sublimation.
2. The copper shell ensures a good thermal connection between the shell itself, the heating foil and the inner copper core.
3. The captured water ice is way denser than expected, which is good for the eventual intermediate storage in the liquefaction chamber and also for general space consumption.
4. During heating, sublimation close to the foils and re-sublimation on the bottom occurred (visible with eyes).
5. More evenly spread heat, meaning more mantle area is covered with heating foils, would lead to a quicker release.
6. Tapering facilitates the delamination process.

Ice Supply Container	Run #1 (pressurized)	Run #2	Run #3	Run #4	Run #5
Dry weight [g]	508.26	~	~	~	~
Filled weight [g]	515.15	515.65	526.23	547.75	538.02
Weight after capturing and sublimation [g]	510.03	511.13	516.21	535.30	520.76
Evaporated Ice [g]	5.12	4.52	10.02	12.45	17.26
Ice Capture Container					
Dry weight [g]	485.98	~	~	~	~
Weight after capturing and sublimation [g]	490.40	488.85	491.15	493.00	494.09
Captured Ice [g]	4.42	2.87	5.17	7.02	8.11
Efficiency	(0.86)	0.63	0.52	0.56	0.47

Figure 4.10: Results of the 3rd pre-experiment.

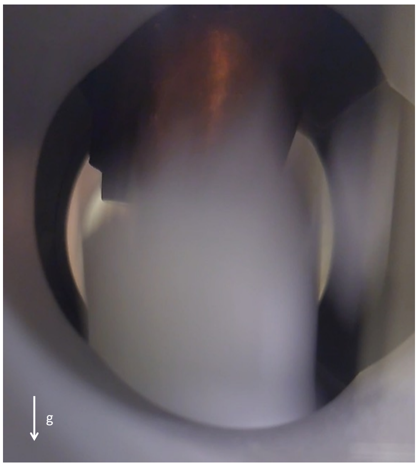


Figure 4.11: Uncoupled ice falling.

5 Resulting Design of the Water Capturing Subsystem

The water capturing subsystem is meant to collect the outgassed water vapour and pass it on to the purification system (Storage 2) in the liquid state under atmospheric conditions. The system is based on the cold trapping sketch of the previous chapter in figure 3.5.

The consortium assumes the worst-case conditions for operations: extraction and capturing of water are done inside the PSR, close to an icy-rich regolith feedstock. The system operates only on electrical power. Either it is directly generated in situ since the extraction process also needs a lot of energy, or, much more likely, electrical power lines leading from a solar farm providing the power.

The gained liquid water is then transported away in a contained and heated vessel to the purification subsystem to another location, e.g., a habitat or propellant production facility. Both should not be placed inside a PSR energy-wise, that was one reason why the purification subsystem is not placed inside the TVAC. Another reason was simply volume and budget constraints.

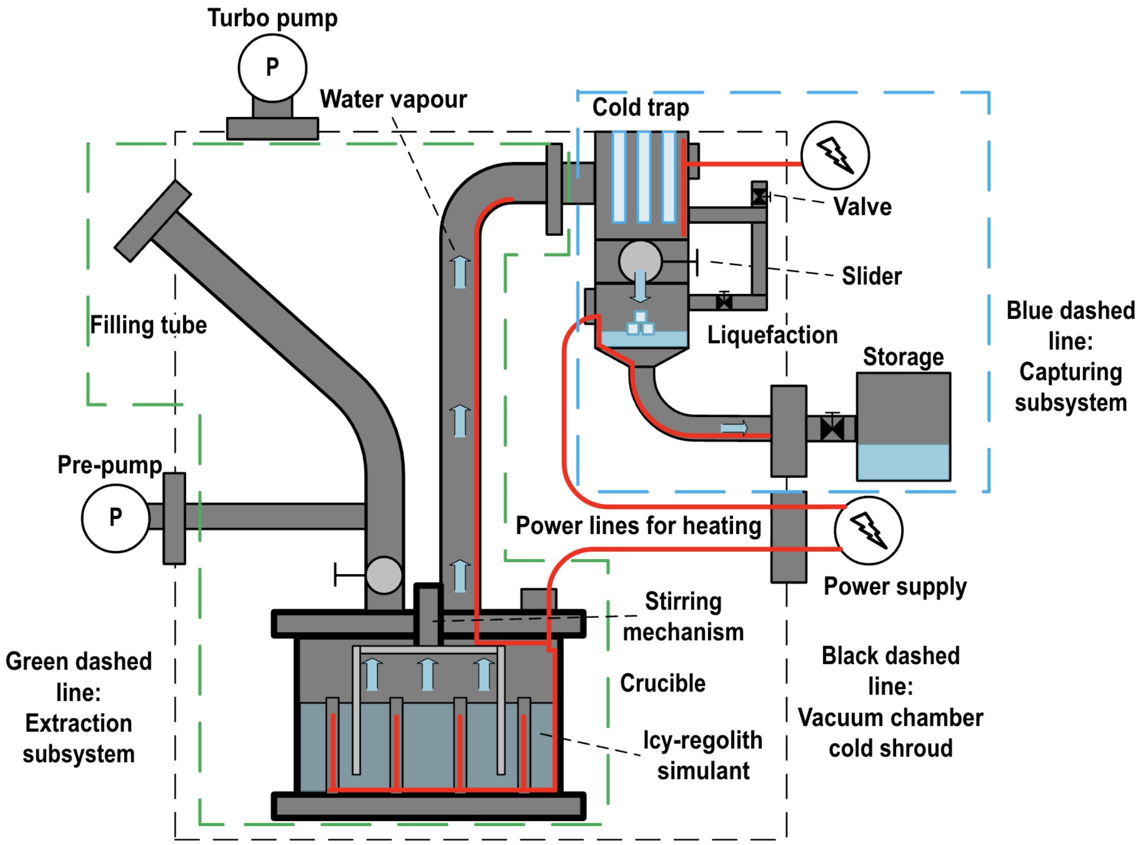


Figure 5.1: Sketch of the extraction and capturing system inside the TVAC. Figure courtesy of [43].

One can depict many tubings in the sketch shown in figure 5.1 which need to be heated. Of course, in an actual system on the Moon, tubings should be minimised. Here, this is due to the volume constraints in the chamber.

A needle valve between the cold trap chamber and the vacuum chamber controls the vapour flow toward the actual cold trap itself and prevents the pressure from rising too much should that happen. A slider separates the cold trap chamber from the liquefaction chamber. In 5.3 a preliminary CAD drawing of the relevant systems is presented. The details regarding the valves system and infrastructure have been done by TUBS.

The present volatiles in the icy-regolith sample are water ice, methanol, ethanol, CO2 (Status January 2023). The cold trap has to withstand these volatiles and is designed in such a way that these volatiles are not deposited on the cold fingers. For more information on the composition and amounts of the icy-regolith sample and its volatiles, see the website or the final report of LUWEX.

The design was driven by volume constraints of the chamber and size of the slider which separates the cold trap and the liquefaction.

The goals of this baseline design are as follows:

1. As much cold trap area as possible for maximal ice mass and thus water vapour capturing. A part of the cold trap can be seen through a window with a camera.
2. Long residence time of the vapour for lower losses leading to a higher efficiency.
3. High volume of the liquefaction to reduce the need for melting cycles for a higher total collection rate.

Cylindrical housings were proposed by the TUBS team due to their positive experience with standard parts. It should be noted that the cold trap housing has the same diameter as the circular slider to facilitate falling of the ice.

Conversion of Cooling Power to liquid Nitrogen Liquid nitrogen is available in a sufficient quantity and the flow rate inside the shroud is high enough to realise a cooling power in the order of around 1 kW. The cold fingers are conductively connected to a stainless steel plate under the liquid nitrogen inlet for the cold shroud of the chamber, leading to a high possible cooling power.

Cooling surface The cooling surface must be maximised to minimise losses of vapour through the needle valve. In the present design, the surface is as high as possible with cylindrical cold fingers while maintaining a sufficient radius for heat conduction. The cooling surface is also dependent on the sublimation rate of the crucible.

The mentioned parts are further explained and justified in the following sections.

5.1. Final Design at the 2nd LUWEX Meeting

The figure below illustrates the vapour's way through this subsystem, enclosed in blue, to the next subsystem. The collected amount of water and the discharge frequency to storage 1 are under further investigation and might be determined during the first subsystem test. With the experience gained by execution of the pre-experiments and the extrapolation in 5.2, the WCS is assumed to deal with a peak sublimation rate of 15 $\frac{g}{h}$ shown by extraction simulations of another intern.

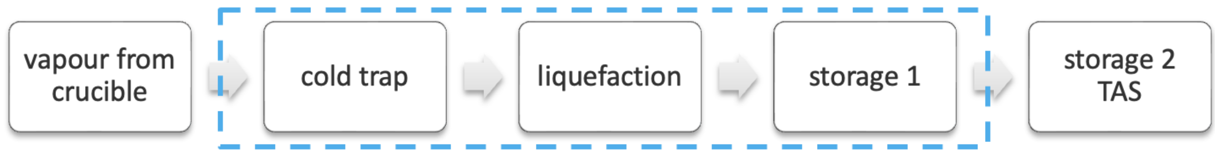


Figure 5.2: Scheme for the scope of the water capturing subsystem.

The system shown in figure 5.1 inside the black dashed line must fit inside the TVAC's cooling shield. The inner dimensions of the TVAC are 1530 x 700 x 700 mm^3 without the cooling shield. The cooling shield, in which liquid nitrogen is flowing, provides an ambient temperature of 80-90 K. Dimensions within the shield are 400 x 400 x 830 mm^3. [49]

The connection to the crucible, the subsystem before, is a DN 40 CF flange. The connection to storage 2 of the water purification subsystem of Thales Alenia Space is realised with a ¼" quick connector from hamlet and plastic tubes.

A stainless steel tube with a diameter of 40 mm guides the vapour from the crucible to the cold trap, depicted as the first arrow in figure 5.2. A slider and the extension flange connect the cold trap to the liquefaction. The water produced in the liquefaction flows through a copper tube with an outer diameter of 16 mm with the help of a TVAC throughput into storage 1, from which the purification subsystem starts pumping. These subsystem parts are further described in the following sections.

Significant to mention is the influence of the maximum pressure decision in the crucible. Liquid water shall not exist in the crucible since it would flow downward to colder regions where it would freeze again. Therefore, the pressure in the crucible and all connected volumes should always be below 600 Pa, preventing liquid water from forming. For the design of the WCS, this resulted in the decision for an external liquefaction, which can have its own environment, for further information, see sections 3.5 and 5.5. The pressure and the flow from the crucible are controlled with a needle valve connected to the TVAC volume, equivalent to the Lunar environment; see top right in figure 5.1 or figure 3.5.

Another means of controlling pressure is the sublimation rate in the crucible, which is connected to the amount of heat supplied. Besides, deposition on the cold trap also reduces the pressure, which is hard to control actively.

The WCS shall be able to be in contact with other specimens coming from the extraction subsystem, such as ethylene, carbon dioxide and methanol; compare also the section in the literature study 1.12. Further specimens can not be added without damaging the TVAC's pumps. Potentially, tiny dust particles also come with the vapour stream into the WCS. All heating foils used in the pre-experiment had the IP4 standard, and no short-circuit due to water occurred. The durability is part of the talks with the suppliers.

The concept of operations for the WCD is not repeated in this chapter; it is quite similar to the one described chapter 3 in section 3.1.1. A possible change of the liquefaction operations is described in the later section 5.8.

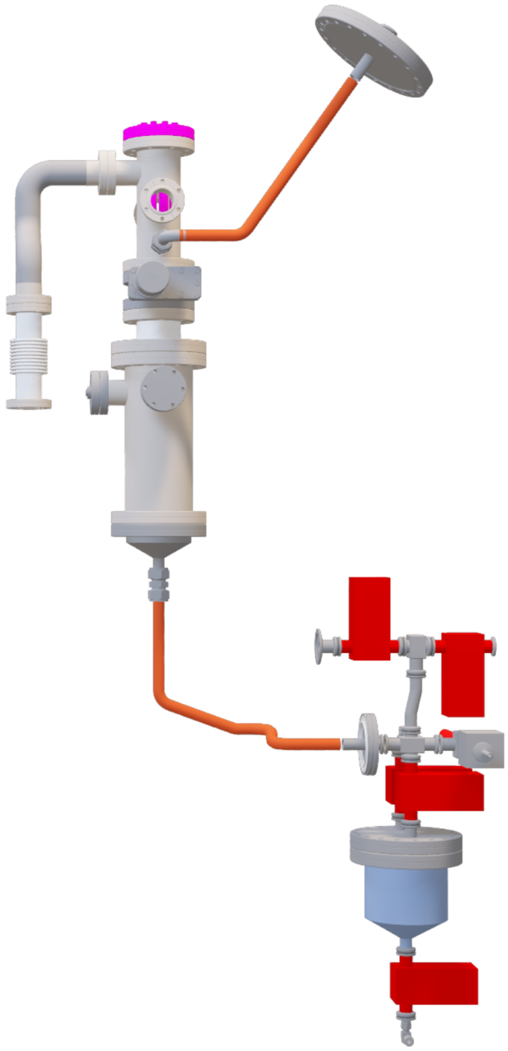


Figure 5.3: CAD-View of the capturing subsystem with Storage 1. Red boxes are valves. Figure courtesy of [48] and [50].

5.2. Piping: Crucible to Cold Trap (inside TVAC)

The piping from the crucible to the cold trap guides the water vapours. Undesired freezing is prevented by keeping the inner surface temperature of the tubes above 0 °C. This is realised with a seamless lining of heating foils.

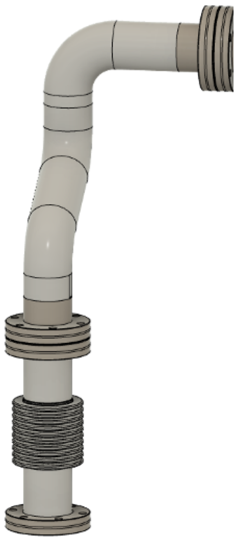


Figure 5.4: Piping from the WES to WCS with flex tube on the bottom section. [48] [50]

It is also possible to realise the connection with standard parts, resulting in multiple right-angle corners, which do not favour the vapour flow.

5.3. Cold Trap (inside TVAC)

The cold trap ensures capturing the vapours in an icy state. Except for the cold finger shells' surface, every surface is kept over 0 °C with heating foils. The cold trap also ensures pre-purification since the temperature of the deposition surface on the shell is kept between 180 and 200 K, as this possibility has been shown by Holquist et al. [33]. The temperature is kept in this range also with heating foils, as shown on the right in figure 5.5. These heating foils likely have a higher heat flux density than the others since additional power is needed for the delamination of the ice.

The main cold trap parts are the cold trap chamber, and the cold trap top flange with four shells for the insertion of the four cold fingers with heating foil from the top. The chamber, seen in figure 5.3, is attached to the slider. Then, the top flange with the four cold fingers seen in figure 5.5 and the cooling device or mechanism for the four cold fingers are attached on top.

Recently at DLR, the method of cooling the cold fingers has been changed. The cooling is realised with liquid nitrogen as in the third pre-experiment 4.2.3 and not through conductive heat transfer through the fingers to the cold shroud anymore.

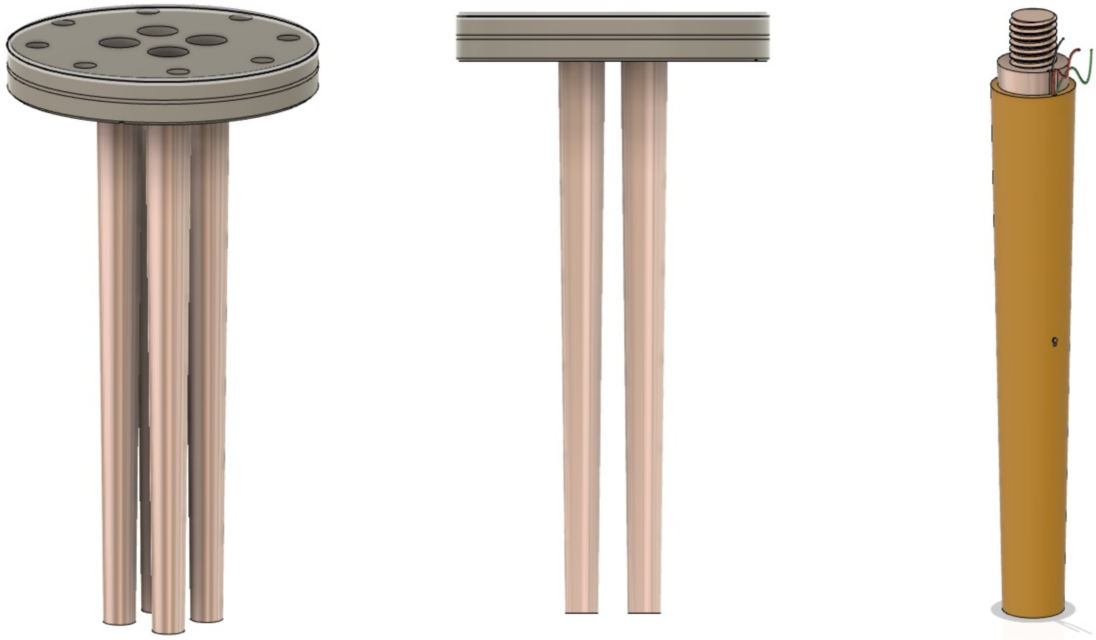


Figure 5.5: Cold trap top flange with attached cold finger shells and a cold finger for the insertion in the shell with wrapped heating foil and temperature sensor in the middle (thread outdated).

The following features are regarded in the current design:

- Smooth surface for ice forming and falling
- Tapering for easier delamination of the ice
- Tapering ratio of the cone: 15 to 10 (inner diameters, in mm)
- Thermal mass for quick cooling of the vapour
- The single temperature sensor is sufficient after the temperature profile characterisation test
- The exact length is still a point of discussion. The length shown in the above figures was maximised by assuming that a higher cold surface area yields better capturing efficiency and a higher total mass collection capacity. The possible maximum length is the distance between the slider and the cold trap top flange, roughly 227 mm.
- Length of the shells in the figure: 201 mm

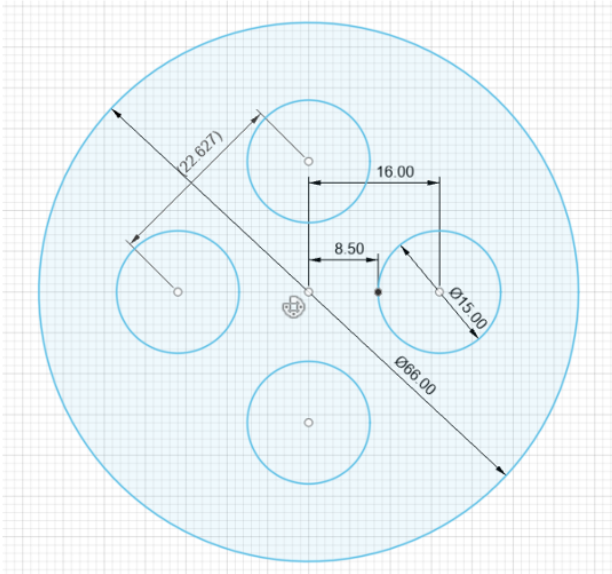


Figure 5.6: Arrangement of the cold fingers inside the cold trap chamber.

For manufacturing and assembly reasons, the diameter of a single cold finger will be around 15 mm at the cold trap top flange, leading to four cold fingers. The tip of the inserted the cold finger has around 8 mm which is still high enough to enable conductive heat transport. Also, four fingers lead to blocking and diverting of the vapour flow in three planes seen from the vapour flow direction, ensuring long contact with the collection surface. If one cold finger fails, three are still operational, and diverting of the flow is still present in two planes. With two, only one or two planes are left and this leads to significantly less blocking. The cold trap cylinder diameter is 66 mm, with the proposed setup nearly half of the diameter is used for the cold fingers itself and the remaining gap is used for the ice layer growth.

A qualitative assessment for the number of rods n and the total surface area A dependent on the diameter of the cold finger d, the minimum distance between the fingers s (remained constant for comparison) resulted in a constant A, at least in order of magnitude. The number of rods n was treated as a resulting variable of d and s.

Lastly, one option to realise the thermal connection of the cold fingers to the cold shroud is with a flexible u-profile. It could be elongated in the axis of the fingers with a spindle. The thermal connection was ensured with flexible copper ribbons, a lot of suppliers are available also stating the thermal conductivity and vacuum resistance. Another simpler option is a grub screw with nuts on the tips. This ensures that the enthalpy of the vapours phase change can be discharged in the cold shroud, the liquid nitrogen cold sink of the TVAC. The single cold fingers can be taken out allowing an substitution in case of a failure, although this should be avoided, because the cold trap cylinder needs to be unscrewed and tilted. Besides, thermal grease would have been used for all points of contact.
With such devices, the cold fingers are pressed in the shell ensuring the thermal connection and the assembly capability. These concepts have not been investigated further since the cooling method has been changed making the thermal connection obsolete. The new cooling channels can be seen from the sketch of the simulation 5.18.

5.4. Slider and Extension Flange (inside TVAC)

The slider separates the cold trap and liquefaction, resulting in both having their own environment if closed. The liquefaction needs to create sufficient pressure for liquid water. The cold trap is connected to the crucible and thus has the same pressure requirement $p < 600$ Pa, which is insufficient for liquid water to exist.

The slider needs a certain depth for opening the shutter. The depth is constrained by the dimension inside the TVAC's cold shroud. The slider chosen has the maximum diameter suitable to the dimensions available, which strongly influenced the diameter of the cold trap chamber and the liquefaction.

Heating foils on the outside heat the slider and the extension flange to a temperature of at least 273 K to avoid ice build-up.

The slider is equipped off the shelf with a hand crank. An electric motor for remote control via Lab-View will be attached in-house by TUBS.

An open point is still dust or contaminants on the shutter. These specimens should not end up in the slider mechanism. A small cylindrical inlay with a small brush might be a solution.

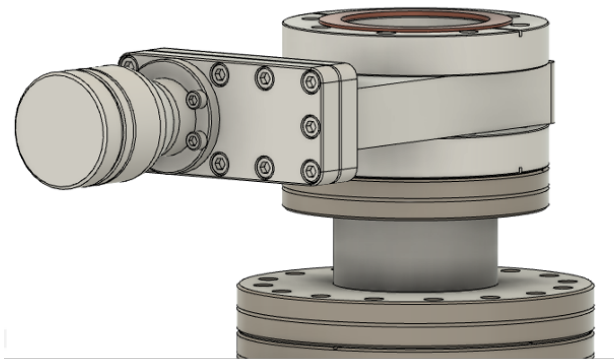


Figure 5.7: CAD-view of the slider and extension flange. [41] [48]

5.5. Liquefaction (inside TVAC)

The liquefaction's functions are to store the ice which falls from the cold trap and to liquefy it when the slider is closed. Two possible operational modes are envisioned:

1. Directly Liquefying Mode: Liquefy each ice batch instantly
2. Store multiple ice batches until the inlay is full. Then, the heating starts and multiple batches are liquefied.

The walls must be heated because there shall be no ice or liquid build-up on the liquefaction walls. The water phase diagram shows that the temperature must be above 273 K if the pressure is below 600 Pa, which is the case when the slider is open (ice collection mode). The wall temperature might increase further according to the water phase diagram for higher pressures.

Another point to mention is that the copper inlay length is longer than the cold finger length to be able to store a complete ice shape in case it stays intact while delaminating and falling.

No additional mechanisms or heat pipes with fluids are desired to keep the design simple and robust. Hence, the inlay's temperature is mainly dependent on radiative heat exchange. Conductive heat exchange through the low-pressure regime and conduction through the spacers made of isolation material are negligible. The wall temperature of the liquefaction sets the lower boundary temperature for the copper inlay, which is too high for storing ice. Thus, the inlay could only be cooled down further with ice falling from the cold trap, resulting in at least partial sublimation. This vapour could theoretically be again deposited on the cold trap.

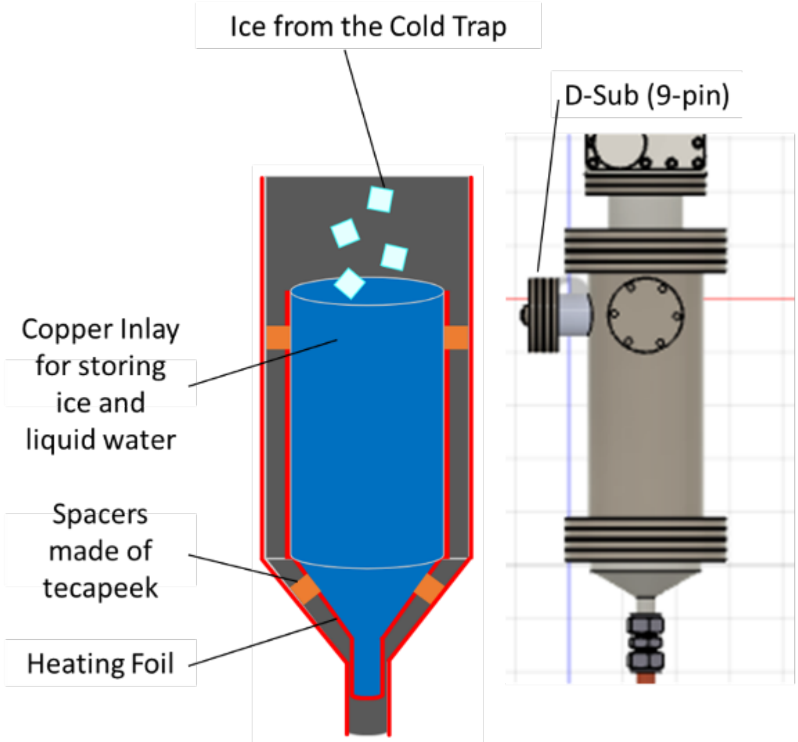


Figure 5.8: Liquefaction Sketch (left) and outside CAD view (right). Courtesy CAD of [48]

Likely, the direct liquefying mode is used in the final experiment. After the ice falls into the liquefaction, which can be determined with the cameras, the slider closes quickly since the ice directly starts sublimating. This minimises vapour losses. Also, dependent on the results of the temperature distribution in the WCS determined during preliminary tests, the slider might only open for falling ice to separate the rather "hot" temperature regime of the liquefaction from the cold fingers.

When the liquefying cycle starts, the slider is closed, and the heat is applied to the ice through heating foils on the outside copper inlay. The ice begins vaporising, creating pressure. After some time, the pressure is high enough for liquid water to exist, which then flows through the heated copper line to storage 1 outside of the TVAC. The pressure is likely below 1 bar and can be pressurised with gaseous nitrogen. As soon as storage 1 contains 500 ml of liquid water, the water purification system pumps it to storage 2. After that, the liquefaction is evacuated via the copper line.

Available Power inside the liquefaction A 9-pin d-sub for the liquefaction is sufficient for the inside of the liquefaction. Three pins are used to have at least one temperature sensor inside the liquefaction. The remaining six provide the power for three heating foils. Nominally, a single pin can handle 5 Amperes. Due to safety reasons, the maximum amperes are 4.8 A. This results in the power values shown in the following table.

Voltage [V]	Maximum power per foil using two pins [W]	Total available power inside liquefaction (Three foils) [W]
24	115.2	345.6
48	230.4	691.2

Table 5.1: Maximum available power inside the liquefaction depending on voltage.

The energy E to melt water ice of a mass m is:

$$E = Q = h_{specific,icetoliquid} \cdot m \text{ [46]}$$

15 g could be captured in roughly an hour and is taken as an example:

$E = 333\ \frac{J}{g} \cdot 15\ g$

This results in

$E = 4995\ J$

With Power

$W = \frac{J}{s}$

and supposing a desired liquefying time of 10 s results in a power of 499.5 W needed only for the liquefaction process. Heating of the inlay and radiative losses are neglected. This calculation is only to obtain an order of magnitude.

Cooling Down Estimation/Simulation for storing multiple batches The copper inlay takes at least 50 min to reach the ice storage temperature of about 220 K from a temperature of 350 K with a simulation in COMSOL based on the following assumptions:

- Only radiative heat exchange
- No conductive heat transfer to other parts
- Copper inlay is a thin cylinder, closed at one side
- A higher emissivity of 0.8 through painting
- Heating foil is not regarded in the model
- Ambient temperature of 80 K, equivalent to the liquefaction chamber temperature, which allows undesired ice deposition there

This favours the direct liquefying mode.

5.6. Concept of Mounting the WCS inside the TVAC

A plate is attached to the bottom flange of the cold trap with M8 screws. The plate is connected with an angle to the aluminium frame inside the cold shroud; compare figure 5.9 below. TUBS has used this approach before and thus, the mounting structure will be built in-house during integration.

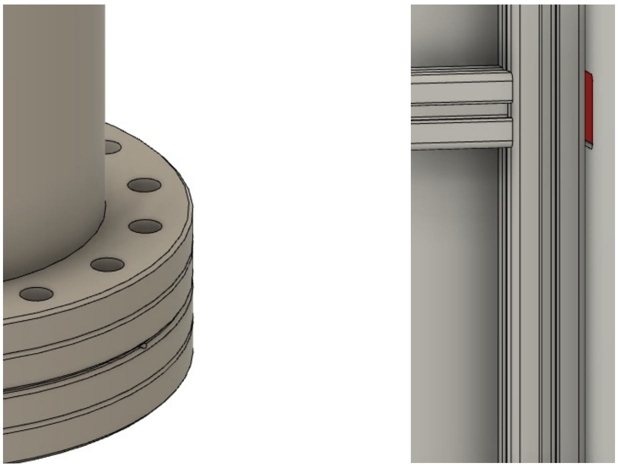


Figure 5.9: Flange (left) with holes for M8-screws and aluminium frame (right). CAD Courtesy of [48].

5.7. Extrapolation of the Collection Rate in Terms of Mass

This extrapolation is done to determine whether the cold trap might be the bottleneck of the extraction chain. Also, in case the capturing subsystem can not cope with the extraction rate it is always possible to reduce the heat supplied to the icy-regolith.

With the volume of a cylinder

$$V = \pi \cdot r^2 \cdot h,$$

the mantle surface of a cylinder

$$A = 2 \cdot \pi \cdot r \cdot h$$

and four rods assumed as cylindrical with a length of 200 mm, a radius of 6 mm and an ice thickness of 4 mm leads to the following table:

Description	**Value**	**Unit**
Volume of a rod	22 619	mm^3
Volume of a rod and ice	62 831	mm^3
Volume of the ice per rod	40 212	mm^3
Ice mass per rod ($0.92\frac{g}{cm^3}$ at 1 bar)	37	g
Surface of an empty rod	7540	mm^3
Surface A with total number of rods	30 159	mm^3
Collection surface of Jurado [34]	1600	mm^3
Ratio A to Jurado's Surface	19	$\frac{mm^3}{mm^3}$
Collection rate of Jurado [34] (appr.)	0.00076	$\frac{g}{s}$
Extrapolation of the collection rate based on the surface	0.01440 **52**	$\frac{g}{s}$ $\frac{g}{h}$
Collection time in 8 h	28 800	s
Collected water ice (delamination neglected)	**415**	g

Table 5.2: Extrapolation of capturing rates. Results are denoted in bolt.

The data of a paper and thesis of Jurado [34] allowed an initial extrapolation of the collection rate on a cold surface. The ice density reported here has a maximum of $92\frac{kg}{m^3}$ which has a strong influence on the result. By extrapolation, within 8 hours, equal to a normal working day, 415 g of ice could be collected, as can be seen in 5.2. This is of course a rough estimation based on one data point. The delamination and usage of the slider are not considered yet. This collection rate is and shall be in line with the desired probe for the purification system of 500 ml during several days.

5.8. Requirements Compliance Matrix

Req. ID	Justification
LUWEX-AE, see section 2.1.1	The WCS consists mostly of standard parts, which can withstand this environment. The grease has been used before in pre-experiment 4.2.3 in this environment, although it is not specified for it (Appendix A.6). TUBS has good experience with this grease in the environment. The pure copper parts resist this environment, as can be seen in experimental chapter 4. The heating foil has been tested on such a cold surface in the last pre-experiment 4.2.3. Procurement for integration is ongoing and a subsystem test is planned.
LUWEX-RS, see section 2.2.1	Except that the service life of the slider is significantly reduced, the WCS is likely be able to deal with a minimal contamination of regolith dust coming with the vapour. A test is foreseen.
LUWEX-IR, see section 2.2.2	This requirement are more applicable to the reaction chamber, but the maximal extracted masses can be inferred: 0.75 .. 2.25 kg. Of course, there will be a residual in the reaction chamber of the water extraction subsystem. The collection surface has been maximised for the avalailable volume. The slider limits the diameter of the cold trap cylinder. Within this cylinder, the length of the cold fingers and the surface have been maximised for collection. An extrapolation can be seen in table 5.2. A subsystem test is foreseen. In case the collection rate is lower than expected so that the extraction rate can not be met, a possibility is to reduce the heat supplied in the extraction subsystem.
LUWEX-RW, see section 2.2.3	A hose connector to a DN 16 ISO-KF flange is foreseen in the design of the storage so that the raw water simulant can be inserted in the storage tank.
LUWEX-VC-1, see section 2.3.1	The WCS is designed to the volume allocated within the TVAC. A complete CAD assembly of the whole process chain has been done by TUBS. The cooling shield is used as a heat sink for the cold fingers through conductive heat transport. In the next iteration, liquid nitrogen is used for cooling.
LUWEX-VC-2, see section 2.3.2	The design of the cold trap facility is described in this chapter 5. A subsystem test is foreseen.
LUWEX-VC-3, see section 2.3.3	The storage is present and can be seen in figure 5.3. The interfaces have been defined. It is not the author's main task and the consortium continues to work on it.

Req. ID	Justification
LUWEX-VC-4, see section 2.3.3	The WCD is able to vent water vapour to the TVAC, equivalent to venting on the Moon. The vapour will be released in case the pressure rises above 600 Pa and also to create a flow from the crucible to the cold trap. Of course, this vapour can not be collected anymore and is thus lost, hence it is aimed to have the needle valve as closed as possible most of the time. The mass spectrometer determines the specimen present in the flow to the turbo/vacuum pump. Hence, water vapour loss can be quantified. Also, it is possible to test for leakage. Temperature sensors, pressure sensors (outside the TVAC) and cameras can be used for the WCD and feedthroughs are present.
LUWEX-IF, see section 2.5	The WCS is described in this chapter 5. The connection to the extraction subsystem is a DN 40 CF flange. The connection to the water purification subsystem is a male $\frac{1}{4}$" self-locking quick connector from Hamlet.
LUWEX-AD-1, see section 2.6	The design presented in 5 works without additional fluids. The change to liquid nitrogen cooling is against this requirement, but ensures cooling as seen in the last experiment 4.2.3. The new design is briefly described in section 5.9.6.
LUWEX-AD-2, see section 2.6	Robustness and simplicity are taken into account during the design process. Tests and operations will ultimatively determine it.
LUWEX-AD-3, see section 2.6	With a needle valve, position is seen in figure 5.1, the pressure is controlled. Deposition on the cold fingers also leads to pressure decrease.
LUWEX-AD-4, see section 2.6	The surface temperature is controlled via heating foils and kept around 200 K, compare figure 2.1. Then, only water deposits on the collection surface. The heating foil can be seen in figure 5.5. The temperature distribution is visible in figure 5.12. The exact control scheme is implemented in LABVIEW by the consortium. Even if the pre-purification of the WCS is unsuccessful, the purification subsystem afterwards is able to handle the maximum amounts of contaminants.

Table 5.3: Justification of requirements with a compliance matrix.

5.9. Simulations of conductive and radiative Heat Transfer of a single Cold Finger

To assess whether the proposed design option meets the intended way of operations, simulations in COMSOL Multiphysics have been conducted. The program has been used during the design process, also influencing it.

Investigated features are the power needed and the time to reach different temperatures on the collection surface. A heat sink is needed to get rid of the phase change enthalpy of the vapour to ice. This heat sink is the cold shroud of the TVAC. Before the experiment starts, all the components inside the TVAC are cooled down to around 80 K. This is equivalent to temperatures after a lunar night or inside a relatively "hot" PSR. One goal was to proove that the system could get operational again after most of its parts cooled down. Of course, in an actual mission, some parts need to be always heated, e.g. the electronics, for example with a radionuclide element and the heat sink would be likely heat radiators.

The following sections show that the power and times needed are all acceptable with respect to the experiment schedule. Another main finding is that if the temperature gradient on the collection surface is too high, a second heating foil might be needed, referred to as "staged heating".

The influence of the radiative heat exchange on the results is negligible, it was set conservatively set to 80 K to maximize heat loss. A change to 273 K only changed the results by seconds. Another model, containing a cylinder floating in free space, was used to gain experience with radiative heat exchange supporting the minor influence compared to the conductive heat transfer to the cold shroud.

Of course, this model is an approximation and serves as a first insight. The model is partially ideal, for example, the connection of the different parts is perfect in COMSOL. In reality, because of the surface roughness and potential grease used, the thermal connection is lower. Also, the heating foil has copper wires in the middle, which change the thermal properties compared to pure polyimide. Furthermore, the cold shroud is not completely solid and gaseous or liquid nitrogen is flowing in it. According to TUBS, it is constantly at 80 K [41]. Hence, this modelling approach is sufficient. Besides, the thermal connection of the shell to the cold trap top flange is neglected in this model. The flange is shown in 5.5 and this connection is further investigated in the updated simulation model with nitrogen in 5.9.6. Lastly, the influence of vapour pressure and water ice built up is also neglected.

On the next page in figure 5.10, the setup of the model is shown. The model has three spatial dimensions and originates from a 2D sketch, which is rotated for one revolution around the central axis. A single cold finger made of copper is thermally connected to the baseplate, equivalent to the cold shroud. The baseplate is made of stainless steel and is kept at 80 K. On the cylindrical cold finger is a heating foil made of polyimide held in place by a copper shell. The conductive heat transfer and radiative exchange with the surrounding environment (assumed 80 K) are modelled. The heating foil is modelled as a volume heat source. The conductive connections are considered ideal; thus, surface textures and the influence of greases/thermal pastes are disregarded. The initial temperature of 80 K has been chosen since it is the TVAC temperature and the lowest reachable temperature when cooled with liquid nitrogen.

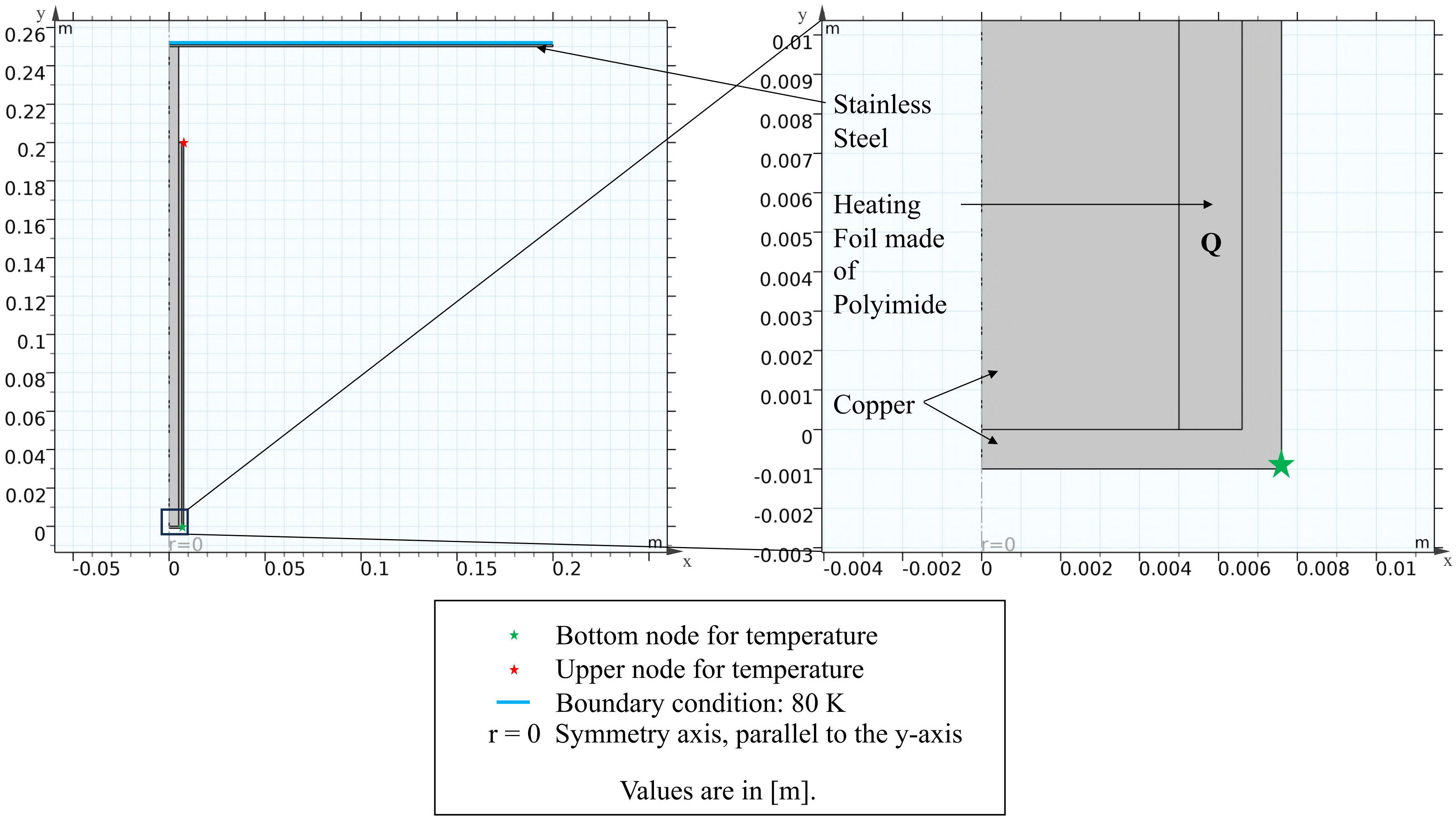


Figure 5.10: Geometry of the Simulation Model. Ambient environment temperature is set to 80 K. Heat Q is modelled as a volume heat source to the heating foil.

The cold shroud is modelled as a 2 mm thick circular plate with the boundary condition set at 80 K, equivalent to liquid nitrogen flowing over the surface. The material is stainless steel [49]. A copper rod with a total length of 25 cm and a diameter of 1 cm is connected to the plate. About 20 cm of the copper rod is inside the cold trap chamber, separated by the copper shell from the cold trap volume. The copper shell also ensures a good thermal connection between the copper rod, the heating foil and the shell itself.

5.9.1. Heating up to Purification Temperature

In figure 2.1 of Holquist et al. [33], different operational purification envelopes are shown. For the simulations, a purification temperature of 200 K has been set as a baseline. During operations, the temperatures might be directly correlated to the pressure present in the cold trap and thus crucible.

The heating foil has two goals: to control the temperature of the deposition surface to enable an initial purification step as a result of distillation. Secondly, the foil should be powerful enough to uncouple the formed ice. This ice uncoupling is further analysed in the next subsection 5.9.2. The first layers must be molten which consumes heat. Since the temperature will rise the gradient to the heat sink also increases, resulting in higher conductive heat transport. This is deducted from Fourier's law of thermal conduction in the simplified version:

$q = \lambda \cdot \frac{dT}{dx}$

with q as the heat flux density in $\frac{W}{m^2}$, λ as the conductivity coefficient in $\frac{W}{m \cdot K}$ and the temperature gradient dT along a single coordinate dx in $\frac{K}{m}$.

The increased conductive heat transfer and the sublimated ice impose high power demands on the foil. To determine an initial sizing, the simulations are conducted.

Another constraint for the foil is the available power inside the TVAC. For safety reasons and to avoid the necessity for a professional electrician, the maximum voltage is limited to 48 V as a direct current (DC). Due to national regulations, higher voltages need a professional certification. Also, the maximum amperage a single pin of the TVAC's throughput can handle is 4.8 A, with a margin of 0.2 A. With

$P = U \cdot I$

the maximum net power per foil with double wiring can be calculated, as shown in table 5.4 below. Desired is to minimise the power demand and the wiring needed; equal to a single heating foil per cold trap.

Voltage $[V]$	Resulting Power $[W]$
12	57.6
24	115.2
48	230.4

Table 5.4: Power available based on voltage shown and an amperage of 4.8 A

The heat flux density has been chosen as a variable input for the simulation, in line with the data sheets of several heating foils. Lastly, geometric dimensions can be easily scaled.

Heat flux density q $[\frac{W}{m^2}]$	**Resulting Power** $[W]$
2000	16.59
2250	18.66
2500	20.73
2550	21.15
3000	24.88
5000	41.47
8000	66.35
10000	82.94
12520	103.84
20000	165.88

Table 5.5: Exemplary peak power per cold finger dependent on the heat flux density. The gap is the region where q is not high enough to reach around 200 K.

The cold trap's surface temperature reaches circa 200 K after about 130 s if the initial temperature is 80 K with the foil's heat flux density of 12 520 $\frac{W}{m^2}$ similar to the one used in the 3rd pre-experiment. The resulting peak power is 103.84 W, which is smaller than the available power of 115.2 W per two pins at 24 V. The temperature field in the cold trap is suitable for transporting the phase change enthalpy from vapour to ice. A drawback of this model is the missing thermal connection to the cold trap top flange, resulting in a too-optimistic result. This connection is modelled in the section 5.9.6 with the updated design.

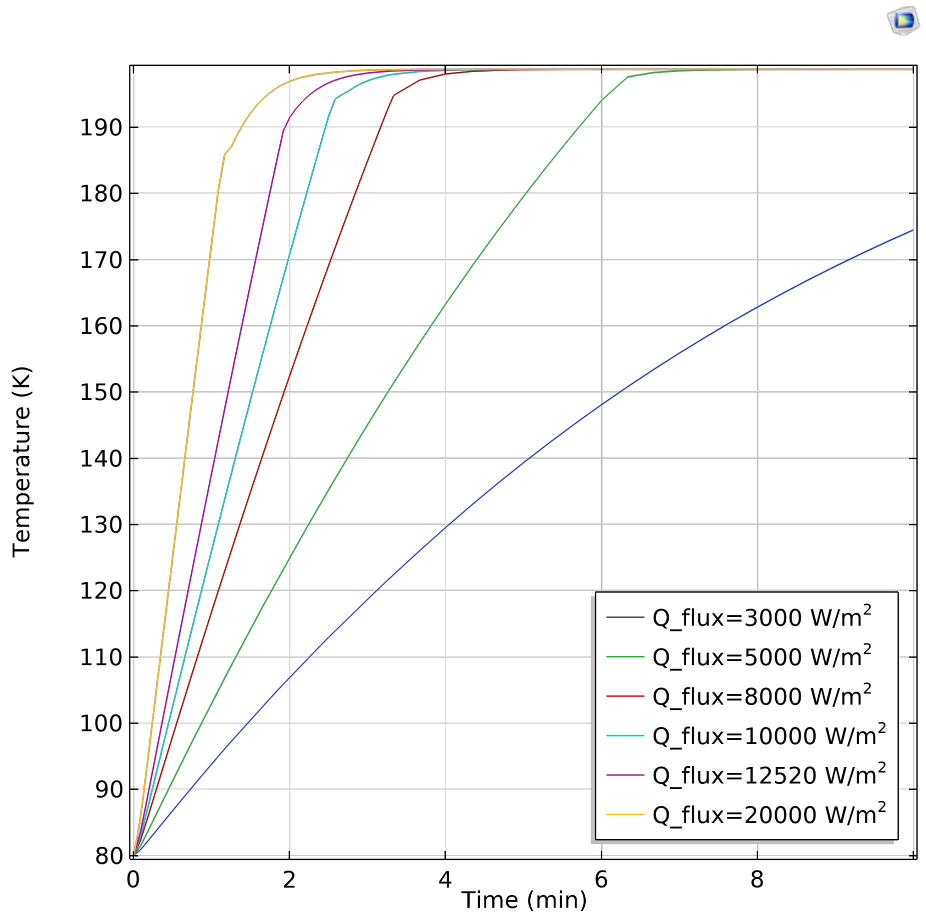


Figure 5.11: Temperature of the bottom node over time for different heat flux densities q (Q_flux).

Below, three temperature distribution graphs dependent on the time are shown for the exemplary heat flux density of $12520\frac{W}{m^2}$ are shown. It can be depicted, that this power is sufficient to reach operational temperature. Whether it is sufficient to allow for an ice uncoupling peak is discussed later in the section.

As can be seen in figure 5.12, the temperature increases from y = 0.25 m. At the tip, the temperature is 200 K for t = 200 s. At y = 0.2 m closer to the baseplate, the temperature is about 185 K. In case this difference increases or is too high, staging with a second heating foil might be a solution. As a backup option, this foil could be attached from the top close to the flange and outside of the cold trap chamber volume.

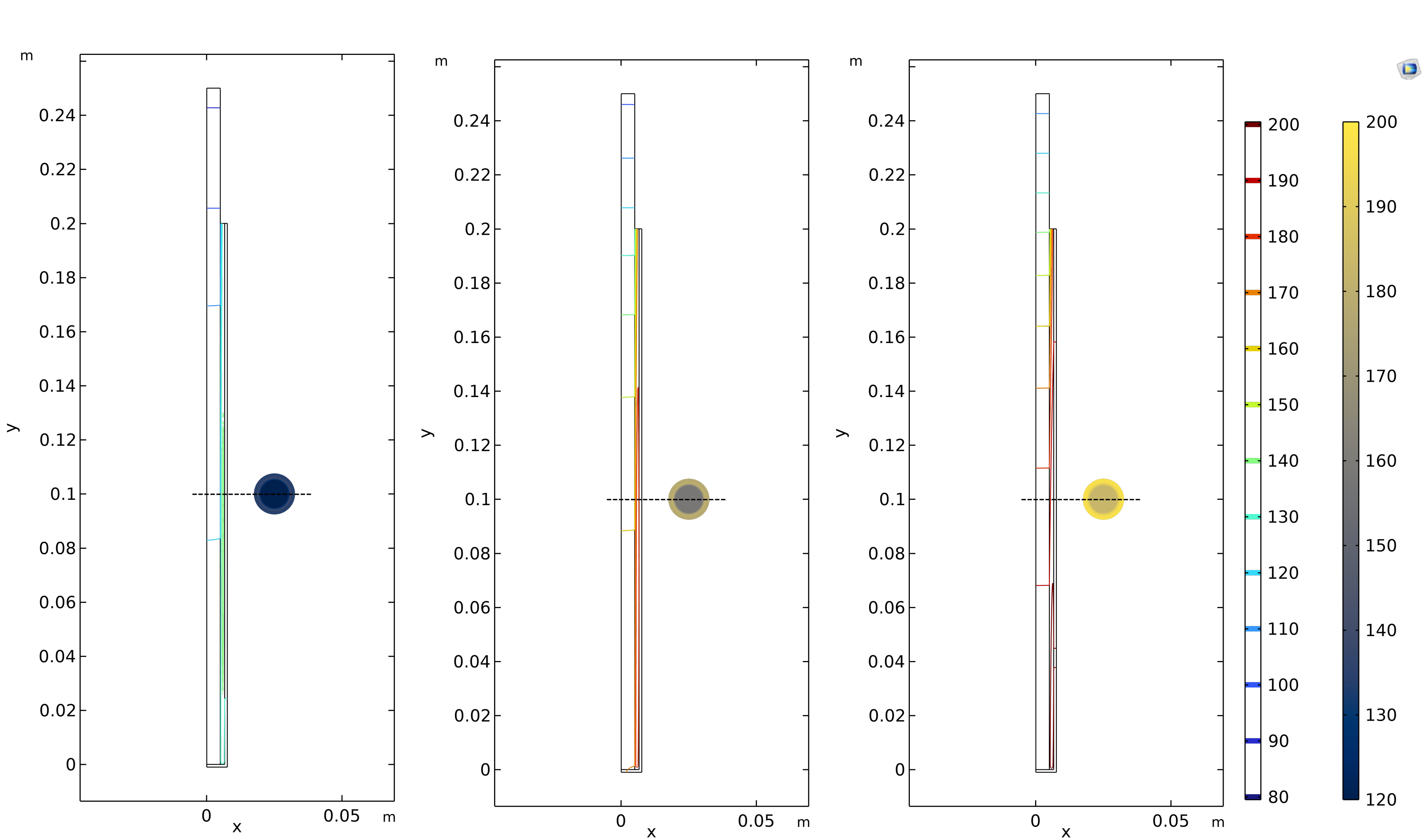


Figure 5.12: Single cold finger with cross sectional cut at y = 0.1 m at timesteps t = 60 s (left), t = 120 s (middle) and t = 200 s (right). The plate from the cooling shield has been omitted for displaying purposes.

The heating-up time needs to be minimised to ensure a high capturing rate and minimise the influence on the experimental schedule. The same applies to the cooling down time. Furthermore, the tip stays cool enough during operations. A temperature difference is needed to get rid of the latent heat due to phase change. The simulation ran long enough for a steady state.

Heat flux density too low: Below figure illustrates the behaviour if the foil has not enough power. The simulation ran for about 1000 s and no change of the temperature profile could be observed.

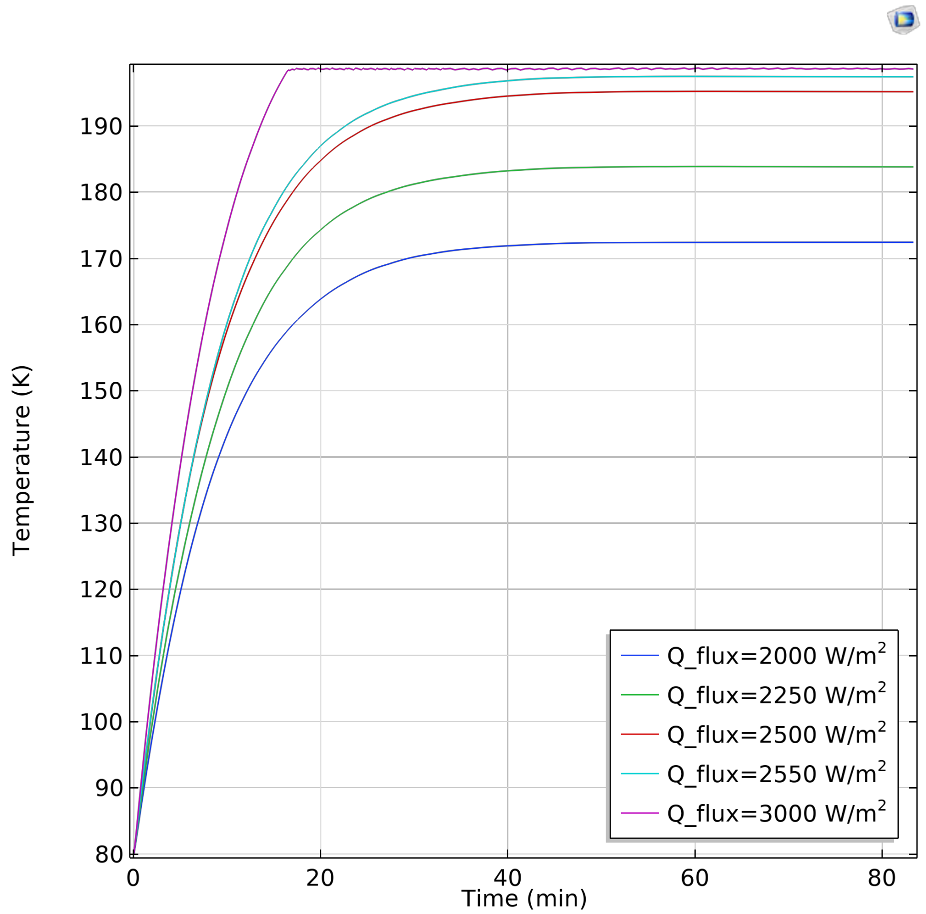


Figure 5.13: Bottom node temperature over time with too low heat flux densities q. Chatter on the purple graph is because of the on/off of the heat source to keep the temperature at 200 K.

Estimation of Power needed to maintain a temperature around 190 K: To maintain the desired temperature of 200 K, around 20 Watts are needed. This can be inferred from the figure 5.13 and the surface of a cold finger. The 20 Watts are also the maximum heat transport capacity without the system heating up further. With four cold fingers, equal to around 80 Watts, it is well in line with the ideal cooling power calculation in section 3.4.

In conclusion, the temperatures for the operations and potential delamination could be achieved with a heat flux density of the foil of around 12 520 $\frac{W}{m^2}$ within minutes. Cooling down again, also equivalent to an indication of the heat transport capability of the copper rod with the foil and shell, is also possible in reasonable time frames, shown later in figure 5.16. One has to mention that during the ice collection phase, less heating power is needed, because of the phase change enthalpy which is absorbed by the shell.

5.9.2. Heating up further to Ice Uncoupling Temperature

If the ice layer is thick enough, which is determined via a camera or when the residual water vapour content rises leaving the capturing system, an uncoupling cycle is induced. Power is applied to the heating foil without the temperature boundary of 200 K. The simulation estimates the time needed without the influence of the ice layer. Hence, the time needed might be higher. The heating process should be as quick as possible to quickly sublimate the first ice layers and not to heat the ice itself and sublimate major parts, what is observed in the third pre-experiment in 4.2.3.

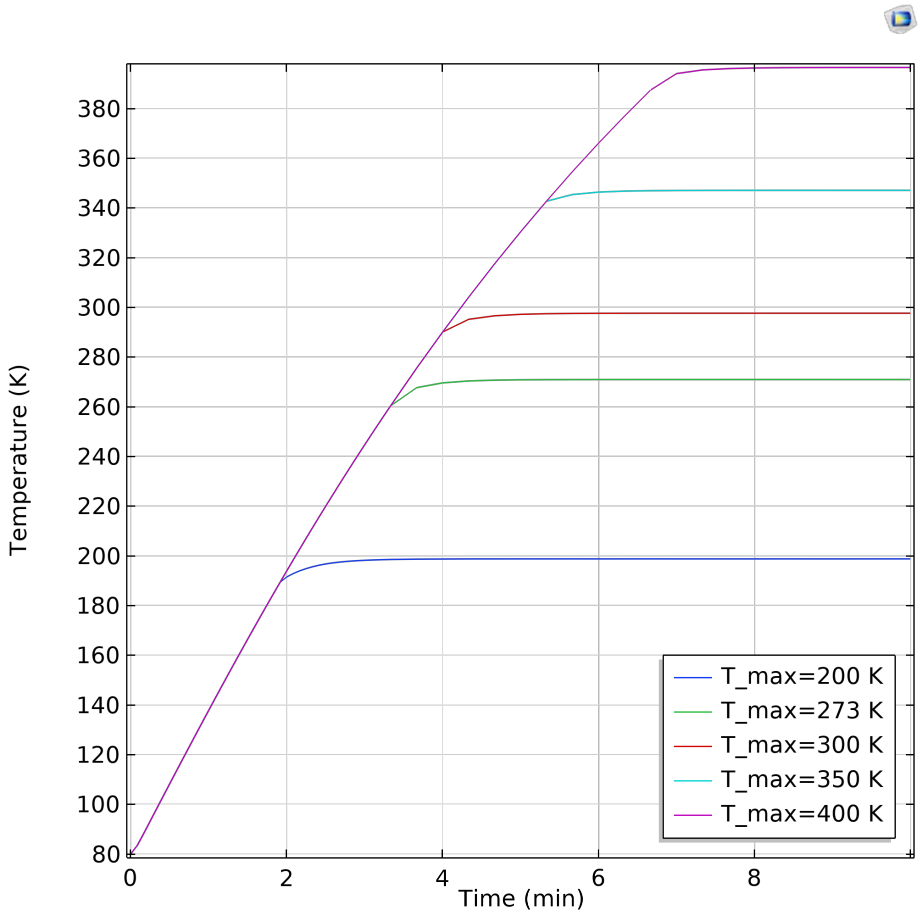


Figure 5.14: Heating up further to different ice uncoupling temperatures with $q = 12520\frac{W}{m^2}$.

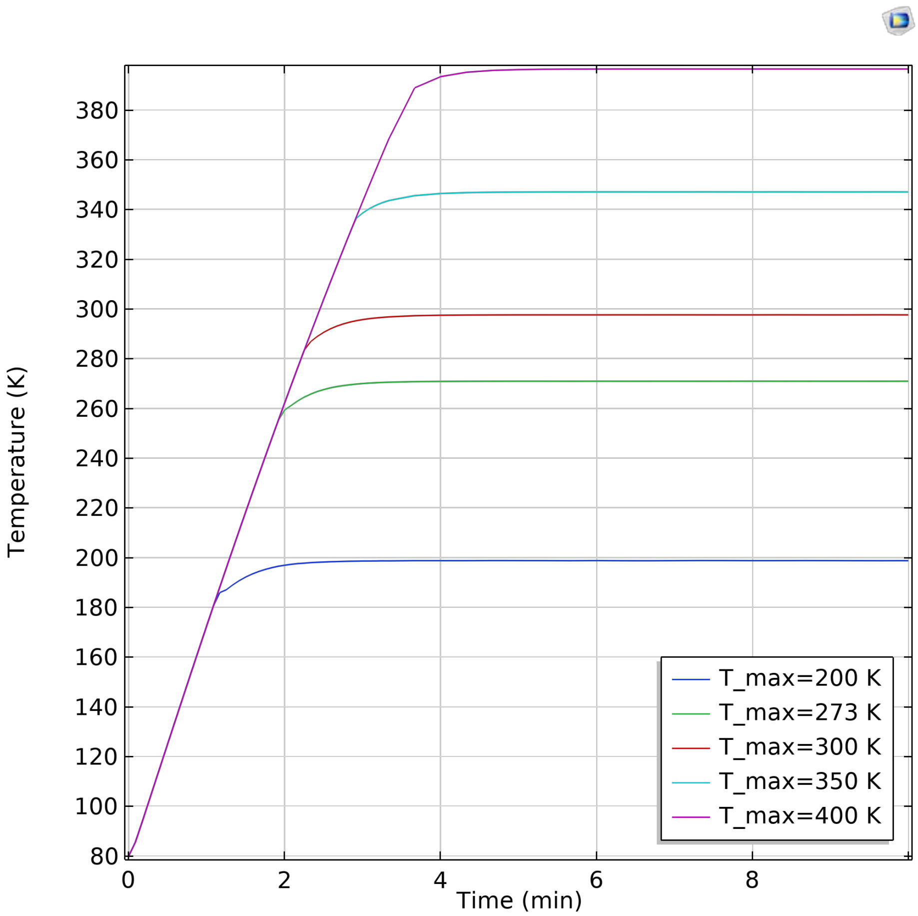


Figure 5.15: Heating up further to different ice uncoupling temperatures with $q = 20000\frac{W}{m^2}$
.

A high q is desired to sublimate the first ice layer quickly and thus preventing to heat up more ice.

5.9.3. Cooling down after an Ice Uncoupling Cycle

After an uncoupling cycle, as described in the previous subsection 5.9.2, the cold finger needs to cool down again to operational conditions.

The simulation was conducted with a conservative modelling approach. The initial values of the heating foil, the shell and the copper core have been set to different temperatures which could happen after an uncoupling cycle. In reality, parts of the copper core would have a strong temperature gradient, hence these results deliver an upper boundary for the cooling time. The cold shroud is cooled all the time and maintained at 80 K serving as the heat sink. The initial temperatures have been set to 300 K, 350 K and 400 K. The first value, 300 K, is approximately room temperature (27 °C). A higher temperature is not connected linearly with the cooling time.

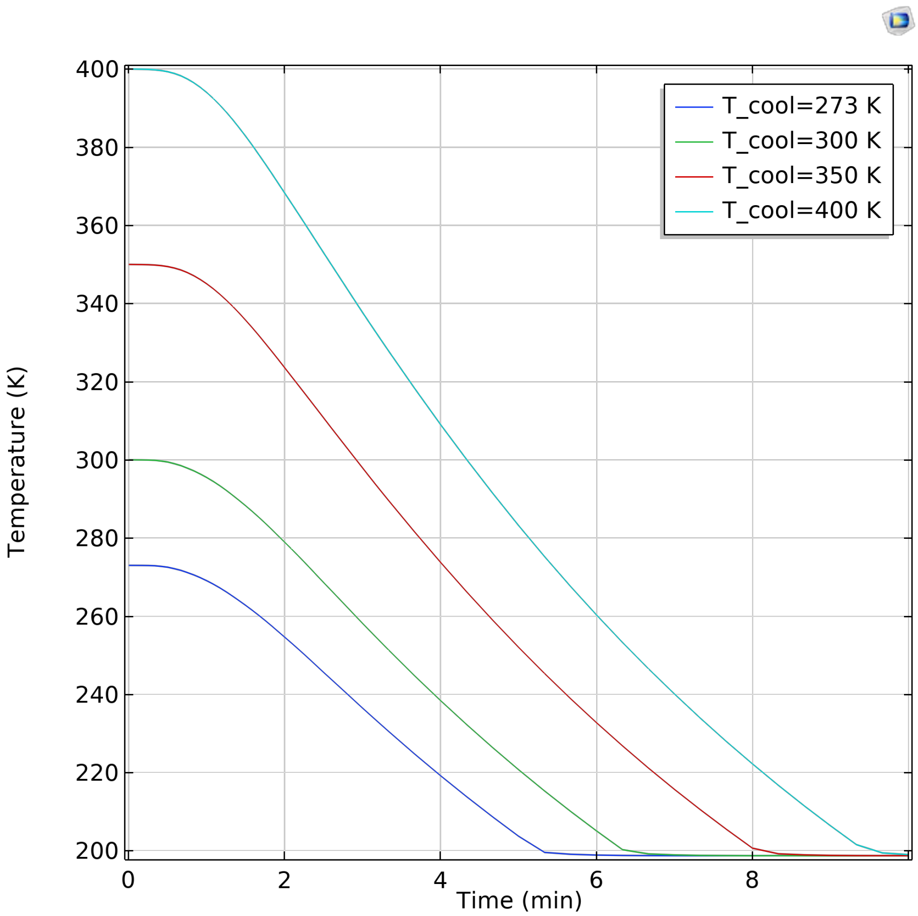


Figure 5.16: Temperature over time with different initial temperature of the copper rod, heating foil and copper shell.

5.9.4. Summarised Results

The results from the previous sections 5.9.1, 5.9.2 and 5.9.3 can be summarised in one table 5.7 to show the influence of varying heat flux density q on the times t. To account for the varying desired or starting temperatures, the variables used in table 5.7 are introduced in below figure 5.17, in which the three operational modes are plotted for the bottom and upper node.

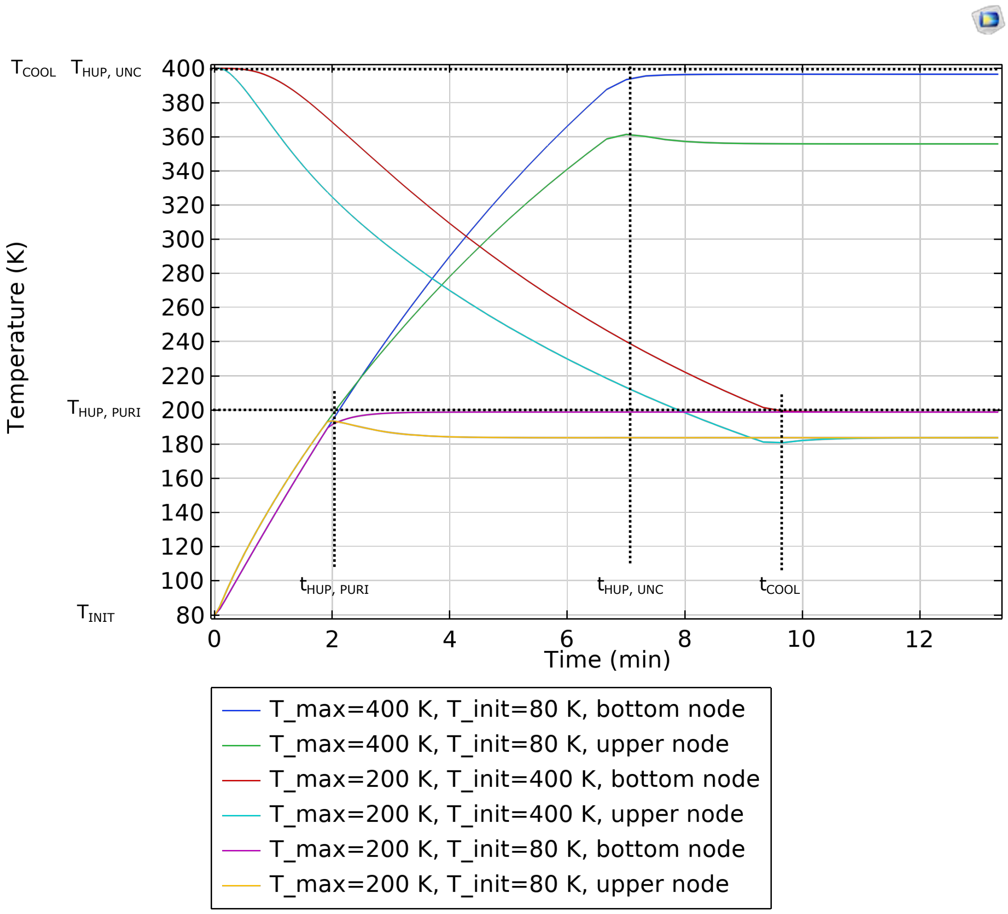


Figure 5.17: The three previously discussed modes of operations (Heating up to purification temperature, heating up to delamination temperature and cooling down) in a single plot with an exemplary heat flux power of $q = 12520\frac{W}{m^2}$. Both nodes are represented.

Akronym	Description	Process described in section
PURI	Purification Temperature	5.9.1
UNC	Ice Uncoupling	5.9.2
COOL	Cooling Down	5.9.3
HUP	Heating Up	n/a
INIT	Initial	Intro of 5.9

Table 5.6: Description of acronyms used for the summary of results.

$T_{init=0} = 80K\|$	$T_{respective}$	$q = 5000\frac{W}{m^2}$	$q = 8000\frac{W}{m^2}$	$q = 10000\frac{W}{m^2}$	$q = 12520\frac{W}{m^2}$	$q = 20000\frac{W}{m^2}$
$T_{HUP,PURI} = 200K$	$t_{HUP,PURI}$	360	190	145	110	60
$T_{HUP,UNC} = 400K$	$t_{HUP,UNC}$	n/a *	960	580	400	220
$T_{HUP,UNC} = 350K$	$t_{HUP,UNC}$	n/a *	640	440	320	165
$T_{HUP,UNC} = 300K$	$t_{HUP,UNC}$	1320	420	320	240	130
$T_{HUP,UNC} = 273K$	$t_{HUP,UNC}$	860	360	260	195	110
$T_{COOL} = 273K$	t_{COOL}	320	$\sim$	$\sim$	$\sim$	$\sim$
$T_{COOL} = 300K$	t_{COOL}	380	$\sim$	$\sim$	$\sim$	$\sim$
$T_{COOL} = 350K$	t_{COOL}	480	$\sim$	$\sim$	$\sim$	$\sim$
$T_{COOL} = 400K$	t_{COOL}	560	$\sim$	$\sim$	$\sim$	$\sim$

Table 5.7: Summarised results of the simulations. The times are in [s]. Simulation step 10 s. * denotes temperature is not reached, stabilising at 315 K over simulation time of 12 000 s.

Note: For easier comparison purposes, a certain temperature is considered to be reached as soon as one point on the collection surface has the temperature. The times sometimes deviate a little because the bottom node is plotted and the table has used the point with the highest temperature. Lastly, $t_{HUP,PURI}$ can be substracted from $t_{HUP,UNC}$ since both start at the initial temperature of 80 K. End of Note.

5.9.5. Verification

The sensitivity analysis aligns with fundamental physics principles, as shown by the steepness of the graphs in the T over t diagrams: higher heat flux density q corresponds to faster heating. Furthermore, changes of the ambient temperature lead only to a minor influence on the results.

Evaluation of the mesh structure indicated integrity, with no anomalies, e.g. sharp edges, detected along the edges. Furthermore, refining the mesh and the timesstep further has not changed the results. Also, the simulation outcomes were in line with the expected behaviour observed in the pre-experiments II and III.

Looking ahead, it may be worthwhile to validate these findings against data obtained from the final experiment.

5.9.6. New Cold Trap Cooling System with Nitrogen

At DLR, the cooling system was changed in favour for cooling with liquid nitrogen, although it is against the soft requirement of using liquids as stated in 2.6. This section provides first insights into the behaviour of the system. The decision might have been influenced by the good experience with cooling at the third pre-experiment
The heating foil between the copper shell and the finger varied between 57.6 W, 115.2 W, 172.8 W and 230.4 W, based on the available power table 5.4. The power of the flange heating foil was set at 30 W.

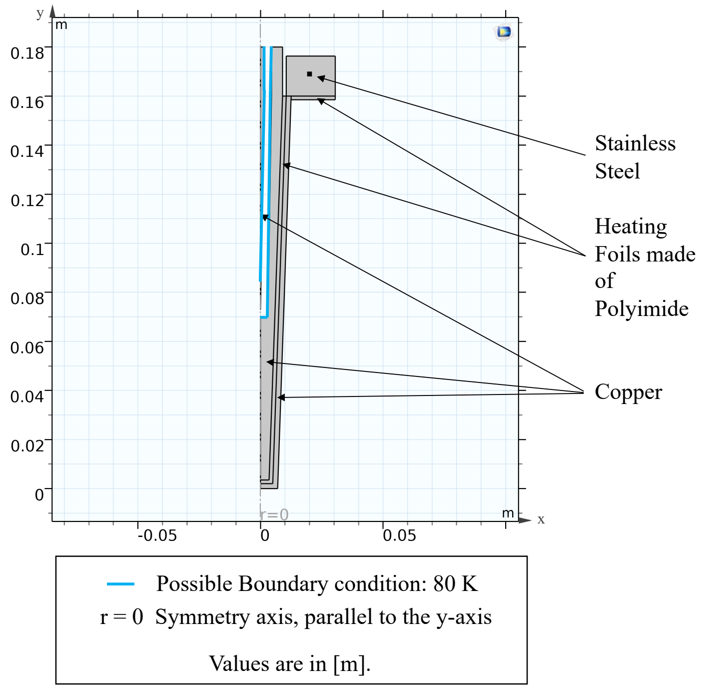


Figure 5.18: Sketch of the Geometry, which is rotated.

The figure 5.18 above shows the dimensions for the simulation, which have been roughly used for the final design. One can depict from figure 5.19 below the 3D model.

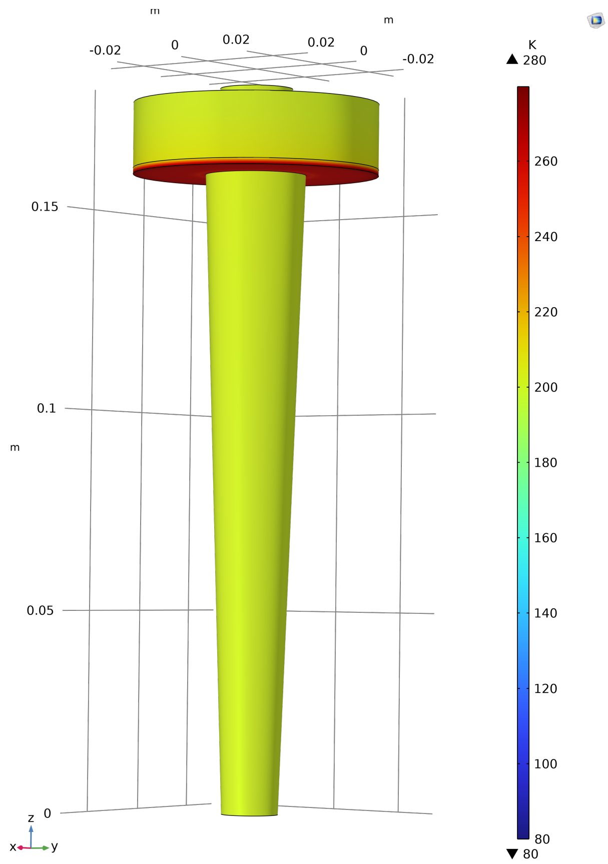


Figure 5.19: 3D-view after the revolution. Foil beneath the shell has a power of 115.2 W, compare table 5.9. 378 s were needed to reach this state.

Four use cases are analysed in this section: Heating up to the collection or operational mode from an initial temperature of 80 K. In operational mode, the shell, on which the vapour deposits itself, has a temperature of around 200 K. The heating foil on the flange has 280 K to prevent ice formation. This is simulated with nitrogen cooling still on (case 1) or nitrogen turned off (case 2).
The third case is reaching a temperature on which an uncoupling of the formed ice can be expected.
The last and fourth case is cooling down of the shell to operational mode again after the delamination cycle.

Heating up to Purification Temperature with Cooling enabled Table 5.8 states the results to reach the operational mode with 200 K on the deposition surface and ca. 280 K on the foil on the flange.

Power [W]	Time [s]
115.2	495
172.8	396
230.4	378

Table 5.8: Results of changing power to reach the operational mode.

One can depict a trend towards saturation: Double the power does not lead to half the time. The flange foil is the limiting factor. Still, the 200 K on the collection surface are reached faster the higher the power of the heating foil beneath the copper shell. A minimum power of 115.2 W is needed; with 57.6 W the 200 K on the collection surface is not reached.
Due to the high electricity consumption, the nitrogen cooling is likely gradually turned on and off during operations.

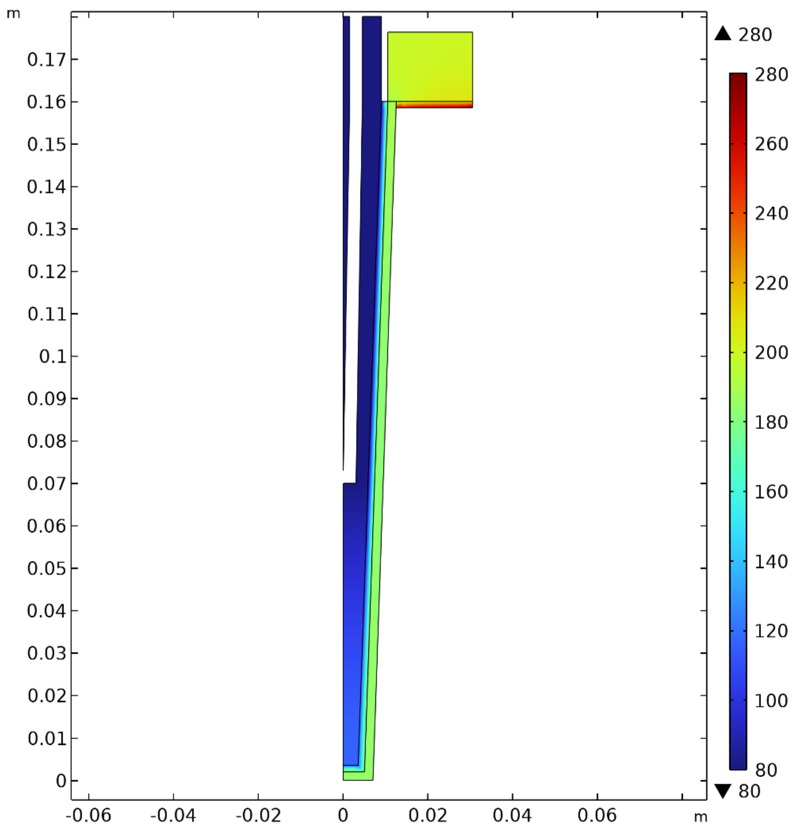


Figure 5.20: Ice Collection status with cooling still enabled with 115 W at 495 s.

Heating up with Cooling disabled Table 5.8 states the results to reach the operational mode with nitrogen turned off.

Power [W]	Time [s]
57.6	441
115.2	378
172.8	360
230.4	351

Table 5.9: Results of changing power to reach the operational mode without cooling.

As inferred below, the foils power on the flange has more influence for ready operations. the 200 K are reached quicker, e.g. already after roughly 100 s with 230.4 W

Obviously, the whole system will get hot since there is no heat sink, except for the radiative exchange, which is quite small. After a certain amount of time, every part reaches the maximum temperature of 280 K, except for the inner core.

Heating up further to Ice Uncoupling Temperature with Cooling disabled In this subsection, the delamination case is briefly analysed. After a certain thickness of the ice, the heating starts to sublimate the first ice layer. Initial insights on the times are delivered.
Of course, it is possible to reach all the temperatures of 273, 300, 350 and 400 K from the previous section on which an ice delamination supposedly occurs. Likely, the temperature will not be that high because the energy in terms of heat will go into the ice.

Roughly 300-500 s are needed with 115.2 W to reach between 273 K and 400 K The same temperatures were reached with 230.4 W within 150-300 s. Hence, sufficient power for delamination is available.

It was hard to determine an exact point of time when the copper shell has reached the temperature. The tip gets hotter quickly, then it takes way more than 100 s so that 2/3 of the collection surface reaches the desired temperature. 1/3 of the shell, the top, is about 20-30 K colder always. It is hard to put the times exactly qualitatively in a table since too much variation with the current mean of investigation.

As a side note, with the maximum available power not more than ca. 280 K could be reached when nitrogen cooling is still on.

Cooling Down after an Ice Uncoupling Cycle to reach a steady state for purification The times needed to cool from a certain temperature to operational status with the temperature distribution as in the figure 5.20 can be depicted from table 5.10. The flange temperature was set to 280 K at t = 0 s.

Temperature to cool from [K]	Time [s]
400	126
350	117
300	90
273	72 (ca.)

Table 5.10: Time to cool down from a delamination cycle to collection mode.

This cooling method is way quicker than conductively cooling in the previous section - as expected.

5.10. Critical Reflection

This section highlights some lessons learnt and criticalities of the design.

The attachment of the heating foil on the cold finger that is inserted into the copper shell is crucial. In COMSOL, it looks very easy wich is obviously not the case in reality. Talks with the supplier may lead to another solution.

Also, polyimide, the material of the heating foil, serves as a good isolator, as seen in 5.20. In reality, it has also copper in it changing the thermal properties.

The involvement of supplier talks earlier in the process might lead too less assumptions and a positive impact on the design. Other housing options than standard parts exist, although they are likely very costly.

Lastly, the conductive cooling capacity of the cold finger is relatively low which has been mitigated by the change of the cooling system to liquid nitrogen.

6 Conclusion

This thesis investigates the water capturing system as a part of a thermal extraction process from the water-ice-rich lunar regolith feedstock. This graduation project is embedded in the LUWEX project of the SMU research group of the German Aerospace Center. The overall goal of LUWEX is to develop the techniques of water procurement on the Moon in the course of In-Situ Resource Utilisation and raise them with a laboratory experiment to TRL 4 or 5.

The first chapter provides a detailed introduction and an overview of current extraction and capturing methods. After thermal extraction from the regolith, the water is in its gaseous phase and is deposited as ice (cold trapping) or liquid (condenser) on a cooled surface. The temperature and the pressure at which this process occurs determine the phase of the water. For this purpose, options to collect the vapour with membranes or with a special powder could not be found. To the best knowledge of the author, experiments designed to gain several hundreds of grams of water do not exist or have not been made publicly available. All these experiments were carried out on Earth under partially simulated lunar conditions. Additionally, the state of water on the Moon is described.
Two very promising missions were planned during the timeframe of this graduation project: A rideshare on board Artemis I and the VIPER rover. The small rideshare satellite should have investigated the water ice at the south pole in a highly elliptical orbit, but it failed due to an engine malfunction. VIPER is a golf cart-sized rover that investigates water in permanently shadowed regions, but it has been postponed by more than a year. Since there is only one ground-truth data point from LCROSS, the insights from these missions would have been thrilling. It would have been interesting to compare these new results with LCROSS, since for the latter there was an impact to obtain the plume of a PSR which might have had an influence on the results.

The second chapter summarises the high-level requirements of the LUWEX project that influence this thesis. In addition to the water mass, the available volume within the TVAC for this subsystem is specified. Also, the conditions on the Moon, which are also addressed in the literature study, are converted to the laboratory parameters. The two key options, the cold trap and the condenser, have been stated and conceptually analysed in the third chapter, resulting in a graphical trade-off favouring the cold trap. Concepts of operations and different arrangements are presented. Initial estimations regarding energy consumption are made based on enthalpy changes.

The aim of the experimental chapter is to assess the general behaviour of a cold trap in a low-pressure regime, control the collection surface temperature, and demonstrate successful ice delamination through a series of runs. The first experiment is designed to test the effectiveness and gain general insights of a cold trap when the vacuum pump is running, equivalent to constant low pressure. Despite the shape is not being optimised, the collection efficiency of evapourated vapours was above 70 %. The second experiment aimed to control the surface temperature with the help of heating foils. In the third experiment, a heating foil has been used to successfully delaminate the formed ice layer and allow for surface temperature control. Once the heating starts, the ice falls down after circa ten minutes. During this time, some collected ice evaporated, resulting in a lower collection efficiency of about 50 %. The results show that the cold trap is effective in capturing water vapour in low-pressure environments. The experiments for the surface temperature control and ice delamination are also functional validation tests for the final design.

The last chapter describes the final design for the LUWEX experiment based on the findings of the previous chapters. The housing is mostly cylindrical as it is decided to use standard vacuum parts, which leads to cost savings. Standard parts also ensure leakage resistance. The water vapour coming from the extraction subsystem is guided with tubing to the collection surface, four conical-shaped cylinders, referred to as cold fingers. After a certain thickness of the ice, the heating foil beneath the collection surface starts to heat more to enable delamination of the ice. The ice falls into another reservoir that can have its own environment thanks to a slider. With more heat applied there, the ice starts to liquefy and can be used for purification. The falling relies on gravity, which is higher on Earth than on the Moon.

The simulations with COMSOL in the second part of the last chapter focus on a single cold finger, modelling the conductive and radiative heat transfer. The investigated values are the power needed for a heating foil, the times to heat up to purification temperature or further for ice delamination and the cooling down times. Also, the temperature distribution on the surface is investigated, which is quite even, so that there is no need for another heating foil. The heating and cooling times are within minutes and thus acceptable for the overall experiment schedule.
A heat flux density greater than 10,000 $\frac{\mathrm{W}}{\mathrm{m}^2}$, equivalent to about 20 W on the chosen surface, is necessary to enable rapid heating from 80 K to the purification temperature (200 K) and significantly higher to uncoupling temperature. The cooling down to around 200 K from 273 K took 320 s; from 400 K it took 560 s.
Insights are also given for a changed cooling system with liquid nitrogen channels instead of a conductive connection to a heat sink. For a mission on the Moon, the collection surface would likely be cooled by a radiator.

Research Questions The research questions posed in Section 1.3 are repeated below for convenience and the respective outcome and the learning results are briefly stated:

Research Question 1

Which planetary ISRU water capturing designs compatible with thermal extraction are optimal for a certain mission-scenario?

A definitive answer cannot be given due to the low TRL and the lack of research in this area, as shown in the first chapter, the review of the literature. Partially, the technology is not present at all and has never been tested on the lunar surface. Chapter 3 gives an overview of design concepts and comes closest to answering this question. Two main options emerged: the cold trap and the condenser. The latter is likely favourable for an aimed production of several tons in a short time frame. Then the infrastructure needed to support liquid water to exist, and the higher insulation needs, pay off. For now, cold trapping is the preferred option since more mature laboratory designs have been found.

Research Question 2

Which water capturing method is best for the EU-funded LUWEX project?

The decision for cold trapping as the best option for LUWEX is made in the graphical trade-off Table 3.2. The final design is explained in the last chapter 5, supported by smaller experiments described in the chapter 4. The preliminary CAD design is shown in figure 5.3, the parts of which are explained in detail in the following sections. A brief summary is given in the conclusion in the second last paragraph before the research questions. Most work has been done on this question since it is the most relevant for the German Aerospace Center for which this external thesis has been conducted.
Obviously, the design would have been different on the Moon. There would likely be less tubing with fewer bendings, which is due to the inner TVAC dimensions. The cooling system with liquid nitrogen is likely also subject to change, to name a few.

The first subquestion is about the capturing rate, which should be high enough for the LUWEX experiment schedule. An extrapolation based on the surface is done in 5.2 and the available cooling power shown in 5.9.1 for the phase change enthalpy is in line with the cooling needed to freeze an assumed vapour mass flow, calculated in 3.4.
The water travel path, asked in the second subquestion, is through tubes connecting the extraction subsystem to the water capturing subsystem, the cold trap chamber, the slider, the liquefaction and the copper line to the storage. Since the volatiles determined by LCROSS shown in 1.12 would harm the chamber, mainly methanol is added to demonstrate purification through destillation. Prior to the water purification subsystem, the remaining volatiles can be added with the raw water simulant, specified in 2.7. Potentially, some regolith simulant dust particles are taken with the vapour flow.
The exact pressure change could not be determined, further tests or simulations are means for its investigation. The pressure is always kept below 600 Pa with a needle valve connected to the TVAC, equivalent to venting to the Moon. Also, through the ice deposition and thus less vapour, a pumping effect towards the collection surface occurs.

Research Question 3

How can the findings from the previous two research questions be extrapolated to a design study for a water capturing facility as part of a thermal extraction system on the Moon?

This question is given a low priority during the thesis time, since the focus lies on the LUWEX design, and a design study for the Moon could have been a thesis topic on its own. Also, results from the actual LUWEX experiment taking place after this thesis might help answer this question. Nevertheless, the author's opinion is stated. To begin with a design study, the desired produced mass should be determined. The time frame during which the product should be available is very important. The location and the next processing step also have a major influence on the design, although they might result from the desired mass over time. The capturing system is dependent on the extraction process before, e.g. whether the icy regolith is brought to the static system or the capturing system wanders with a dome-like structure.
Lastly, the kind of desired supply, continuous or one large supply, for example, to fuel a large reservoir, also impacts the solution. Such a large reservoir could be a water tank of a human mission to Mars, whereas the Lunar base presumably needs a continuous and smaller supply in batch quantity. In addition, gravity is lower on the Moon, which would lead to fewer falling forces, driving the need for further investigation of the current ice delamination mechanism and other influences.

In summary, the thesis at hand contributes to the LUWEX project by investigating possible water capturing system solutions. A design proposal for it is given based on literature, project requirements, simulations, and experiments.

7

Recommendations and Outlook

To continue this work, the following points need to be further investigated. Before figure 7.1, recommendations related to this graduation project are given. Afterwards, thoughts on future missions to the Moon are stated.

Capturing Options and Cold Trap Release The condenser and the cold trap have been identified as the main concepts. There are other options with silicat or a special gel that directly absorbs the vapour. It would be desirable that the water would drip out in liquid state by means of a consecutive process such as heating and/or pressurisation of the soaked up gel. Nevertheless, the author has not found a medium capable of such a process at low pressures and temperatures for LUWEX. It is worth mentioning that the team of Barbier et al., partially from Air Liquide, is working on something comparable, but the publications found focussed on CO_2 capturing and not on H_2O [51] [52].
Currently, the mass of growing ice is determined by a camera, which also induces the ice release process. Although likely more complex, an alternative worthy of further investigation is an eigenfrequency measurement of the collection surface to determine ice growth (additional time for a theoretical concept: >4 weeks). Another means for release related to vibration is via magnetic fields, as discussed in section 3.11. A comparable device is present in TUBS from a previous project [50]. However, a significant amount of effort is required to reactivate this device (additional time for the theoretical background and reactivation: >4 weeks).
Due to the laboratory setup for which the thesis design is made, there is a lot of tubing which is heated with many heating foils. It might be possible to use microwave heating from within the tubes with a reflective cover on the inside (concept for an experimental setup: >2 weeks).

Improvements of Experiments Several experiments have been conducted to test general behaviour, surface temperature control, and ice uncoupling. In retrospect, at least five runs of the experiments should have been documented to ensure statistical reliability (additional time to re-do and document experiments at TUBS: >1 week). An investigation for the validation of the simulation can be conducted in the future; likely only several temperature sensors need to be added, and the simulation geometry needs to be changed (additional time: >2 weeks). In addition, with exact times taken and determination of the collection surface the capturing rate could be extrapolated.
Last but not least, the theoretical background that explains the three experiments can be

examined. Interesting is the ice formation in almost vacuum, for which there is at least one paper (compare [53]). Furthermore, the ice deposition might lead to a pumping effect due to local pressure loss. Unfortunately, the ice density could not be determined with these experiments (additional time: >4 weeks).
To conclude, precise planning is needed before execution of the experiment to validate the simulations or apply the theory.

Simulations To further explore the simulation aspects, the determination of the power consumed for the heating foils and of the dissipated power in the cold sink could be implemented. In addition, attention can be devoted to modelling the phase changes of nitrogen and water vapour to ice at pressures below 600 Pa, with a focus on enthalpy monitoring. Simulations could also be used to identify the point at which the ice layer reaches sufficient thickness to effectively insulate the collection surface, so that the temperature difference is not high enough for any vapour to deposit (additional time: >3 weeks). Furthermore, simulation efforts will include the expansion to subsystems with multiple fingers and housing arrangements, enabling a comprehensive analysis of liquefaction and the flow dynamics of liquid water. Besides, the collection surface's geometry could be further optimised; maybe a better geometry than tailored cylinders exists (additional time: >4 weeks).
One has to keep in mind that the significance of simulations is deeply related to verification and validation. For an extended simulation, a more detailed sensitivity analysis and verification should be performed, as well as a validation of the baseline model.

Further steps for the Design Development For the proposed design, the next step is the supplier talks and the procurement. Exchange with suppliers might lead to new input and smaller design changes. Probably, the heating foil in the cold trap is substituted because of the wind up risk during assembly. When all the parts are procured, a subsystem test can be carried out to search for unexpected behaviour. Then, the water capturing subsystem can be integrated into the whole process chain that is planned for Q1 and Q2 2024.

Further points, which are mostly not a direct task of the graduation project, but still worth to mention are listed below:

- The dust and contaminants of the regolith sample are introduced into the whole subsystem. The influence on moving parts and possible accumulation, as well as the necessity of countermeasures, needs to be further investigated. It is also questionable whether the regolith simulant is as abrasive and as electrically charged as on the Moon.
- The slider could be blocked, for example, through ice, dust, or contaminants built up, or through ice that falls from the cold fingers. The data sheet of the slider and the possibility of these events need to be checked further.
- Since the system should run as autonomously as possible, the filling state of the liquefaction needs to be reported, most likely to Labview. This could be achieved with light barriers or with a camera. The closure of the slider and the connecting valves need to be induced for the liquefaction process, likely via labview. Furthermore, the end of the liquefaction process should also be observed. This could be implemented

in some way through pressure monitoring.

- No reliable data for the water ice density has been found (yet). This value is needed to estimate how much water can be gained during a single liquefaction. If the density is too low, it has a strong negative influence on the overall water collection rate. Maybe a value can be determined with a subsystem test.
- Interaction of the crucible (extraction system) with the capturing system. The collection rate should be adapted to the evaporation rate in the crucible.
- overall labview control scheme, sensor placement, wiring ...

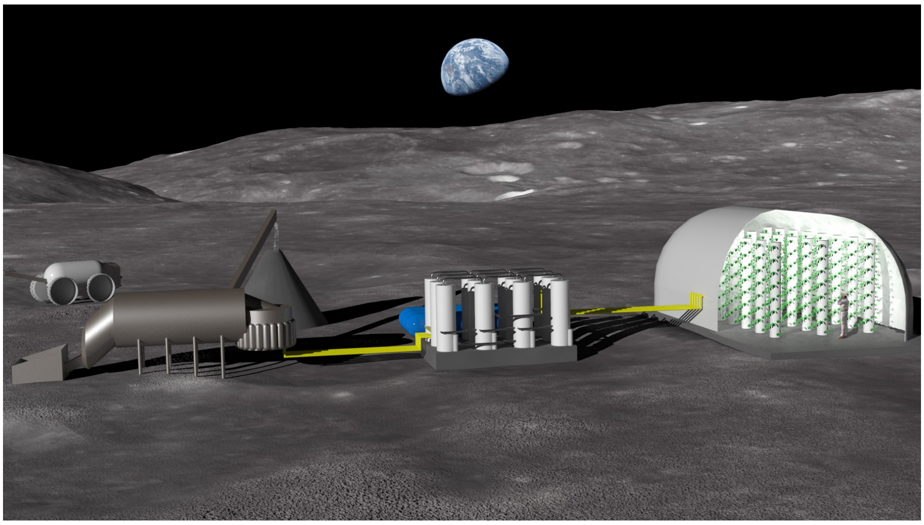


Figure 7.1: Farming on the Moon by Solsys Mining [54]

Outlook on future Lunar Water Collection and its Applications The artistic impression, seen in figure 7.1, shows a futuristic water line on the Moon. On the left, an insertion for the ice-rich regolith is visible. It must be ensured that the ice does not sublimate during transport with the rover in the left background. The residual regolith comes out of the facility after the water has been extracted, which is stored and further processed in the middle cylindrical containments. The water is then used to grow crops, likely enriched with nutrients. Heat pipes and radiators are not shown, although their use is quite certain.
Such a process line would ensure the water supply on the Moon and is crucial for a crewed base or a hydrogen / oxygen fuel depot.

This is an example of an extraction facility outside a PSR close to a consumption point. A facility inside a PSR is also feasible, as a cold trap profits from the cold environment. The surroundings also allow intermediate storage of water in an icy state without taking additional measures. The liquefying cycle would be outsourced, maybe close to where the water is needed and where it can exist, for example, a habitat.

Before such process lines are built, a small lunar lander might be the next step. With a small arm for excavation, ice-rich regolith could be inserted in the internal water extraction, capturing, and purification facilities. At the moment, the SMU group is working on an ESA proposal for a landing mission. Hopefully, the LUWEX project is a success and the results will help to realise such a mission.

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A

Appendix

A.1. Accepted Abstract for the Luxembourg Space Resources Week 2023

Review of Water Capturing Devices for Lunar ISRU

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Introduction

Since the beginning of human spaceflight, long-term human space exploration missions have always been envisioned. Recently, major technology developments have been achieved leading to the realisation of complex mission scenarios with a potential need for In-Situ Resource Utilisation (ISRU) technology. For longer duration exploration of our solar system and beyond, water is considered to be one of the most essential resources. It can be used for various life-support systems, especially oxygen and potable water, as well as for producing propellants. A water supply chain has the key elements of extraction, collection and purification. For Lunar production, thermal extraction is the preferred option, meaning the water is sublimated and separated as a vapour from the regolith. This research focusses on the method of capturing the generated vapour and aims to deliver an overview of possible technological solutions with its functionalities. A comparative review is presented along with the best choice for the respective mission scenario.

Considering the results produced by COMSOL simulations as well as the results derived from the EU LUWEX project, some concepts are proposed for achieving the collection of vapours. The research goal is to show a comprehensive analysis of existing and newly envisioned technologies or mechanisms and to work towards selection of a suitable alternative for the selected mission scenario.

In the next decade, there is a high potential for a lunar settlement to be developed [1]. Further landings and research missions on the Moon are planned by various space agencies. The long-term goal of developing such technologies is to support manned missions to Mars and beyond. Harvesting water in space would greatly enhance the potential of space exploration missions, especially for deep space exploration.

The research is embedded in the junior research group “Synergetic Material Utilization” of the German Aerospace Centre (DLR).

Keywords: ISRU, Water, Extraction, Capturing, Moon, Exploration, Space Resources, Lunar

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A.2. Poster Luxembourg Space Resources Week 2023

Review of Water Capturing Devices for Lunar ISRU

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1. Introduction

The use of resources present on celestial bodies, known as In-Situ Resource Utilization (ISRU), is becoming more and more important in space exploration due to the high cost of launching mass into orbit. ISRU would enable long-term manned operations and permanent (robotic) presence on extra-terrestrial bodies. Water is considered to be one of the most important resources for further space exploration and is currently investigated for extraction and purification on the future manned Lunar base envisioned around 2025. Previous research focused on the extraction of water from regolith but little work has been done to find ways on how to capture and liquefy the water vapour after its extraction.

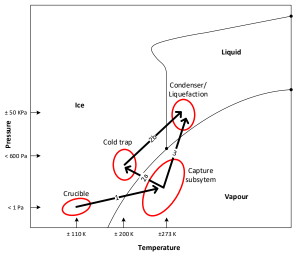

Figure 1: Schematic phase diagram with process overview. Path 2 shows how water can be captured as a solid, and path 3 as a liquid.

Thermal extraction is currently the preferred method for winning water, meaning heat is applied to the water ice regolith mixture resulting in the sublimation of ice and outgassing of the water vapour. This vapour is then captured and liquefied, as can be seen in figure 1. If sufficient temperature and pressure is present in the reaction chamber, a collection as liquid on the bottom of the chamber is theoretically possible. Unfortunately, the regolith has a high saturation with liquid water of around 16%. The residual water in the regolith would be too high and thus efficiency of the collection is likely too low. See figure 2 for the setup to test this.

Figure 2: Test-setup water in lunar regolith (saturation occurs at around 16%).

2. Potential Solutions

A cold trap is a cold surface to which the water vapour coming from the extraction system can deposit onto as a solid, after which it can be considered captured and secured. In this scenario, liquid water occurs after the capturing in a solid state. The gathered ice needs to be in an environment where liquid water can exist. Whether this change in pressure and temperature takes places directly in the capturing system (internal liquefaction) or whether the ice is detached from the capturing system and processed in another location (external liquefaction) needs to be decided.

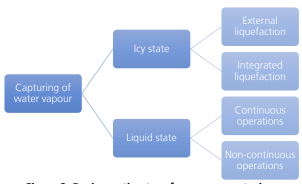

Figure 3: Design option tree for vapour capturing.

The options for capturing in liquid state can be divided in continuous and non-continuous operations. For continuity, a constant flow of water vapour to the condensing surface at sufficient pressure and temperatures above the triple point is needed. This could be realized with a pump between the extraction subsystem and the capturing subsystem, since the liquid phase is undesired in the extraction subsystem. A high pressure in the crucible is unwanted since the water should only be in solid or gas state during extraction. These options are visualized in figure 3.

3. Preliminary Design of LUWEX

In Figure 4 an overview of the entire LUWEX experiment design is presented. A needle valve between the cold trap chamber and the vacuum chamber controls the vapour flow towards the actual cold trap itself and prevents the pressure rising too much. A slider separates the cold trap chamber from the liquefaction chamber to have a contained environment during liquefaction. In Figure 5 a preliminary CAD drawing of the relevant systems is presented. In the crucible, the water vapour has a temperature of around 273K after heating the regolith. This refers to a saturation pressure of 470 Pa which is then also present in the cold trap and liquefaction. Present volatiles in the icy-regolith sample are water ice, methanol, ethanol, CO2. The cold trap has to withstand these volatiles and is designed in such a way, that these volatiles are not deposited on the cold fingers.

The design was driven by volume constraints of the chamber and size of the slider which separates the cold trap and the liquefaction.

The goals of this baseline design were as follows:

1. As much cold trap area as possible for maximal ice mass and thus water vapour capturing.
2. Long residence time of the vapour for lower losses leading to a higher efficiency.
3. High liquefaction volume to lower the need for melting cycles for a higher total collection rate.

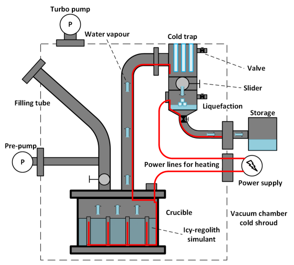

Figure 4: Schematic of the LUWEX experiment inside the TVAC.

The main reason for the decision of capturing as a solid, meaning cold trapping, was less complexity, since there is no need to rise the pressure between the crucible and the capturing system.. The condenser needs pumps and valves with pressure control to function efficiently and optimally. Besides, the condenser needs to maintain a higher temperature than the cold trap for it to work. The cold trap can make use of the cold Lunar environment. Also, less heat and control schemes are required to achieve the desired temperature and pressure ranges. Yet, the system is less controllable because pressure is more sensitive to unwanted condensation.

In future systems with cold trapping, the liquefaction might not occur directly after the capturing, so the intermediate storage could be in icy state. This reduces the storage complexity and favours the design with a cold trap.

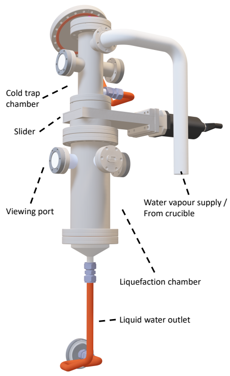

Figure 5: Model of the cold trap and liquefaction.

4. Cold Trap Experiment

Since there is little experience about capturing water vapour in low pressure environments, and specifically so for the purpose of In-Situ Resource Utilization, a small-scale test was conducted to see how effective it would be to capture water vapour on the Moon using a cold trap. Figure 6 shows the setup of this experiment.

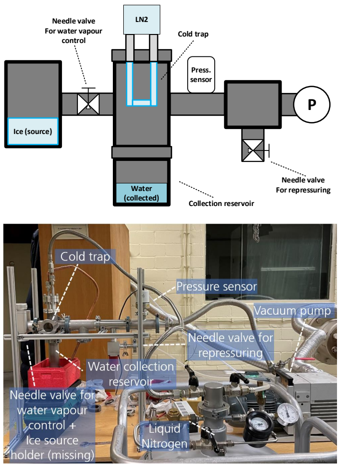

Figure 6: Schematic experiment setup above and the actual setup below.

The experiment was designed to test the effectiveness of the cold trap when the vacuum pump is running ("constant" low pressure). This would be analogous to the cold trap being exposed to the ''atmosphere'' of the Moon. In table 1 the results are presented.

Table 1: Results of the cold trap experiment under low pressure.

Run #	Sublimated [g]	Captured [g]	Efficiency
1	9.34	7.11	76.12%
2	4.45	3.18	71.46%

Figure 7: Cold trap without ice (left) and with ice (right).

Secondary to this, experience and insights were gained along the way about cold traps and working with these test setups.
The collection efficiency was surprisingly high, despite the shape of the cold trap not being optimized.

5. Conclusion

The challenge of this research project is the lack of data and previous research done in the field of water capture for ISRU. Nevertheless, these outcomes provide a solid foundation for LUWEX and future research. Many different ways to capture water vapour are envisioned, and this work provides an initial overview in some of the possibilities. Future works will investigate what the most optimal way to capture water would be for different scenarios.

Visit https://luwex.space/ or scan the QR code!

This work is part of the DLR internally funded young investigator group "Synergetic Material Utilization" (SMU) established 2021 at the Institute of Space Systems in Bremen, Germany. The group focuses on research and development of ISRU technologies for Moon and Mars exploration.

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Funded by the European Union

DLR

A.3. Data Sheet Heating Foils

Datenblatt *Datasheet*	Polyimid-Heizelement *Polyimide-heater*						
thermo Artikelnummer: *thermo item no.:*	**3626155**						
Nennspannung: *Nominal Voltage:*	24V AC/DC						
Nennleistung: *Effective Output:*	14,4W +/-10%				**Wärmestromdichte:** *Watt density:*	2,368 *15,280*	W/cm² *W/in²*
Abmessungen: *Dimensions:*	19 *7,5*	x *x*	32 *12,6*	mm *inch*	/ Dicke ca.: / *Thickness approx.:*	1,6 0,6299	mm inch
Sicherheitsthermostat (STB): *Safety thermostat:*	nicht vorhanden *N/A*						
Temperatursensor: *Temperature sensor:*	nicht vorhanden *N/A*						
Oberflächentemperatur ca.:	> 842 °C Heizelement frei in der Luft hängend, die Wärmeabgabe erfolgt nur an die Umgebungsluft (Raumtemp. ca. 20 °C)						
Surface temperature approx:	> 1548 °F *Temperature was measured with the heater suspended freely in the air, the heat was only given off to the ambient air (approx. 68 °F)*						
Beschreibungstext: *Description:*	Polyimid-Heizelement 19 x 32 mm, 24V AC/DC, 14,4W +/-10%, (inkl. Lasche 6,8 x 8 mm), Unterseite selbstklebend, PTFE-Anschlusslitzen AWG 26 x 300 mm						
Dauer-Betriebstemperatur: *Duration operating temperature:*	Bedingt durch das Klebeband ca. 120 °C - 150 °C *Due to the adhesive tape approx. 248 °F - 302 °F*						
RoHS und REACH konform: *RoHS and REACH compliant:*	ja yes						
Schutzgrad: *Degree of Protection:*	IP X4						
Bemerkung:	**Achtung:** Aufgrund hoher Heizleistung, bezogen auf die Fläche, kann die Heizfolie je nach Einbausituation, ohne ausreichende Kühlung oder Temperaturregelung, überhitzen und dadurch zerstört werden!						
Comment:	**Attention:** *Overheating and the resulting destruction, as a consequence of high heating power of the heating foil, can be prevented by providing enough cooling or temperature control, depending on the positioning of the high power heating foil.*						

Stand: 26.01.2023 - MiM   Technische Änderungen und Irrtümer vorbehalten!

Datenblatt — Polyimid-Heizelement
Datasheet — Polyimide-heater

thermo Artikelnummer: *thermo item no.:*	**3626153**		
Nennspannung: *Nominal Voltage:*	24V AC/DC		
Nennleistung: *Effective Output:*	22W +/-10%	**Wärmestromdichte:** *Watt density:*	3,761 W/cm² *24,262 W/in²*
Abmessungen: *Dimensions:*	13 x 45 mm / *5,1 x 17,7 inch*	Dicke ca.: *Thickness approx.:*	1,6 mm / 0,6299 inch
Sicherheitsthermostat (STB): *Safety thermostat:*	nicht vorhanden *N/A*		
Temperatursensor: *Temperature sensor:*	nicht vorhanden *N/A*		
Oberflächentemperatur ca.:	> 1319 °C Heizelement frei in der Luft hängend, die Wärmeabgabe erfolgt nur an die Umgebungsluft (Raumtemp. ca. 20 °C)		
Surface temperature approx:	> 2407 °F *Temperature was measured with the heater suspended freely in the air, the heat was only given off to the ambient air (approx. 68 °F)*		
Beschreibungstext: *Description:*	Polyimid-Heizelement 13 x 45 mm, 24V AC/DC, 22W +/-10%, Unterseite selbstklebend, Silikon-Anschlusslitzen AWG 22 x 300 mm		
Dauer-Betriebstemperatur: *Duration operating temperature:*	Bedingt durch das Klebeband ca. 120 °C - 150 °C *Due to the adhesive tape approx. 248 °F - 302 °F*		
RoHS und REACH konform: *RoHS and REACH compliant:*	ja yes		
Schutzgrad: *Degree of Protection:*	IP X4		
Bemerkung:	**Achtung:** Aufgrund hoher Heizleistung, bezogen auf die Fläche, kann die Heizfolie je nach Einbausituation, ohne ausreichende Kühlung oder Temperaturregelung, überhitzen und dadurch zerstört werden!		
Comment:	**Attention:** *Overheating and the resulting destruction, as a consequence of high heating power of the heating foil, can be prevented by providing enough cooling or temperature control, depending on the positioning of the high power heating foil.*		

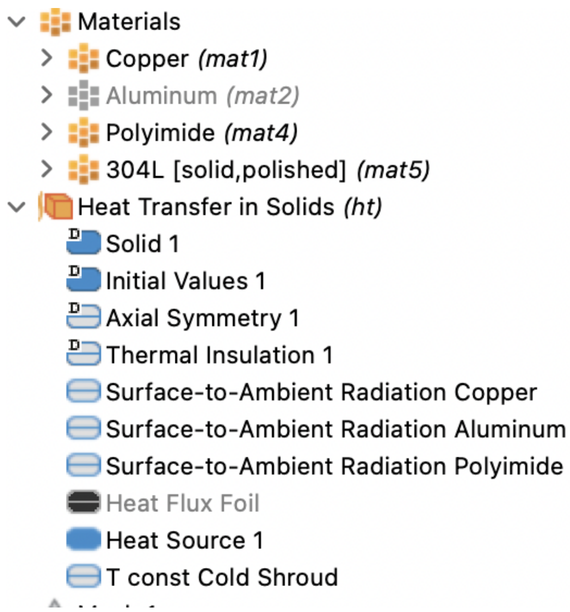
Stand: 26.01.2023 - MiM

Technische Änderungen und Irrtümer vorbehalten!

A.4. Values used for the COMSOL Simulation

Abbreviation	Value	Description
d_c	10 mm	Diameter Copper Finger
l_c	250 mm	Length of the copper finger
t	1 mm	Thickness of the baseline plate
r_b	200 mm	Radius Baseplate
t_{foil}	1.6 mm	Thickness foil
l_s	$l_c - d_s - l_t$	Length of the copper shell
d_s	50 mm	Distance shell to baseplate(cold shroud)
t_s	1 mm	Thickness of the copper shell

Table A.1: Geometry COMSOL.



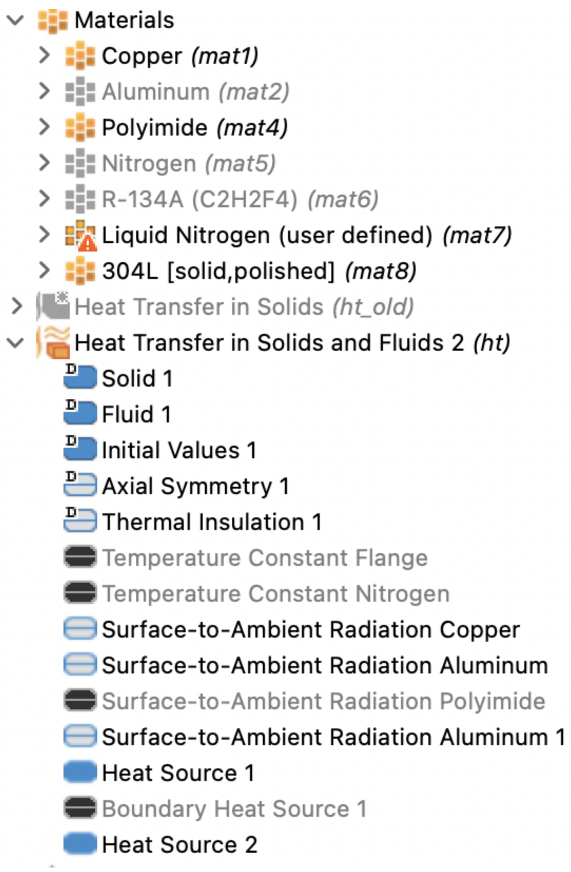
Abbreviation	Value	Description
T_{amb}	80 K	Ambient temperature
T_{init}	80 K	Initial temperature
Q_{flux}	$0.2\ \frac{W}{cm^2}$	Boundary Heat Source foil
e	0.04	Emissivity
e_{poly}	0.12	Emissivity Polyimide Foil
e_{copper}	0.035	Emissivity Copper
T_{max}	200 K	Maximum Temperature at which heating stops

Table A.2: Parameters COMSOL.

A.5. Values used for the COMSOL Simulation with Nitrogen

Abbreviation	Value	Description
d_c	18 mm	Top Diameter Copper Cone to insert
l_c	160 mm	Length of the cold finger
l_t	20 mm	Length of the cylindrical part of the cone
t	16.3 mm	Thickness of the cold trap top flange
r_b	20 mm	Radius section of the cold trap top flange
t_{foil}	1.5 mm	Thickness foil
d_b	14 mm	Diameter cold finger bottom
t_s	2 mm	Thickness of the copper shell
d_{cool}	3 mm	Diameter of the cooling channels
s_{cool}	3 mm	Distance of walls of the two cooling channels
l_{cool}	90 mm	Length of the cooling channels, seen from flange

Table A.3: Geometry with Nitrogen in COMSOL.



Abbreviation	Value	Description
T_{amb}	80 K	Ambient temperature
T_{init}	80 K	Initial temperature
Q_{flux}	$0.2\ \frac{W}{cm^2}$	Boundary Heat Source foil
e	0.04	Emissivity
e_{poly}	0.12	Emissivity Polyimide Foil
e_{copper}	0.035	Emissivity Copper
T_{max}	200 K	Maximum Temperature at which heating stops
T_{af}	280 K	Temperature to prevent freezing
T_n	80 K	Temperature of liquid nitrogen
Q_{af}	30 W	Heating Power of the foil at the flange

Table A.4: Parameters with Nitrogen in COMSOL.

A.6. Data Sheet Grease for the grease used at Pre-Experiment II & III

APIEZON

H GREASE

High Temperature Vacuum Grease

Introduction

Apiezon H grease is the ideal choice for use at higher temperatures across a wide variety of applications in both science and industry. The table opposite shows the key features of the product.

Higher temperatures

Apiezon H grease can be used over a wide range of temperatures from -10 to +240°C, while optimum consistency is retained at between +10 and +110°C.

Apiezon H grease is a relatively stiff grease which does not melt, but becomes stiffer as the temperature increases. It is not recommended as a lubricant in high temperature applications.

Apiezon H grease is specifically recommended for sealing and heat transfer applications.

Thermally conducting

Apiezon H grease is a filled hydrocarbon grease which exhibits excellent heat transfer properties.

Allowing heat to conduct away from a site of operation, Apiezon H grease will reduce the danger of overheating and hence will limit the risk of damage to heat sensitive components.

Under vacuum

Apiezon H grease exhibits good vacuum properties in the low to medium vacuum range at higher temperatures. At lower temperatures Apiezon H grease can be used in the high vacuum range.

For full information on the vapour pressure of Apiezon H grease please refer to the vapour pressure curve opposite.

Apiezon H Grease

◆ High temperatures
◆ Thermally conducting
◆ Good "stiction"
◆ Low to medium vacuum range
◆ Silicone free
◆ Easily removed

Sticking power

Apiezon H grease is a very tenacious grease exhibiting excellent cohesive strength. With Apiezon H grease, gone are the days of loose fitting glassware and mated joints working loose.

"Stiction" power makes Apiezon H grease ideal for use with laboratory glassware. Combined with properties of high thermal conductivity, this makes it the perfect choice for the electronics and space industries where heat sink media require adhesion.

Silicone free

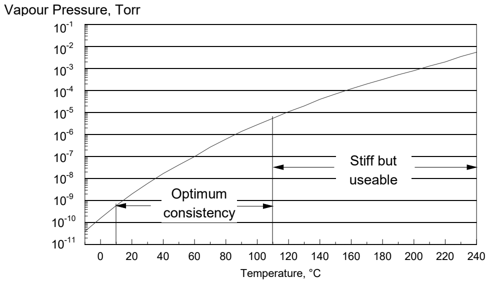
As a hydrocarbon based grease, H grease is highly resistant to "creep" or “carry over”, a phenomenon associated with silicone-based products. Silicone has a tendency to travel away from the area of application and contaminate adjacent surfaces.

The creep resistance of Apiezon H grease benefits scientific users as it reduces sample contamination and the risk of interference in analytical techniques such as infra-red and mass spectrometry.

Silicone contamination is of particular concern in surface coating applications such as industrial paint or metal deposition processes. Trace amounts of silicone on surfaces prevent the adherence of paint resulting in poor or incomplete coverage. In semiconductor manufacture, yields can be severely affected by silicone contamination.

When using silicone-free Apiezon H grease the problems associated with creep and contamination are avoided.

Vapour pressure over working temperature range



APIEZON

H GREASE

High Temperature Vacuum Grease

"Gettering" action

Apiezon H grease is manufactured from a unique feedstock containing a high proportion of branched and unsaturated hydrocarbons. These complex structures give Apiezon H grease a very high molecular weight and consequently strong powers of absorption, particularly for other hydrocarbon molecules.

Strong absorption properties ensure that Apiezon H grease has a powerful "gettering" action, i.e. the power to absorb greasy or chemical impurities on metal and glass surfaces. This is of value in the electronics industry where scrupulous cleanliness is required.

Apiezon H grease has no contaminating effect on electrical equipment and is easily removed by hydrocarbon solvents, taking with it many trace impurities which are not removed by solvents alone.

Compatibility

Apiezon H grease is compatible with a wide range of o-ring materials including:-

- Viton
- Silicone
- Nitrile (>30% nitrile content)
- Nylon
- Polyurethane
- Polyethylene
- Polypropylene

Due to its hydrocarbon base, Apiezon H grease is not compatible with:-

- EPDM (ethylene propylene diene M-class rubber)
- EPR (ethylene propylene rubber)
- Butyl rubber
- PVC seals

Typical Properties

Typical working temperature range,	*°C*	-10 to 240
	°F	14 to 464
Dropping point - ASTM.D 566		does not melt
Vapour pressure @ 20°C / 68°F, Torr		1.7×10^{-9}
Relative density @ 20°C / 68°F		0.918
Thermal conductivity @ 20°C, W/m °C		0.216
Specific heat @ 25°C, J/g		1.7
Lubricity 4 Ball Test - ASTM .D 2596, kg		250

Easily removed

Apiezon H grease is easily removed by wiping with a soft clean lint free cloth. Any residues of grease can be washed away with warm soapy water or by using any aromatic hydrocarbon solvent (toluene, xylene). For a more environmentally friendly solvent, we recommend Limonene.

Apiezon hydrocarbon greases are not soluble in alcohols (ethanol, IPA) or ketones (acetone, MEK) so these cannot be used for cleaning.

Apiezon H grease works when you want it to, but is easily removed when you don't.

Shelf life

The shelf life of Apiezon H grease is ten years from date of manufacture, providing the product is in the original unopened packaging and has been stored at ambient (10 to 30°C) temperature.

Industry approvals

Apiezon H grease is extensively used in a wide variety of applications and industries. It has gained prestigious approvals from British Aerospace, the European Space Agency, Matra Marconi and NASA.

Apiezon H grease has been approved by NASA as the only material suitable for lubricating the gold-plated threads of small variable capacitors required to operate under high vacuum from -65°C to +125°C to prevent galling.