Water Extraction Experiment Assuming Lunar Icy Regolith for In-situ Resource Utilization on the Moon

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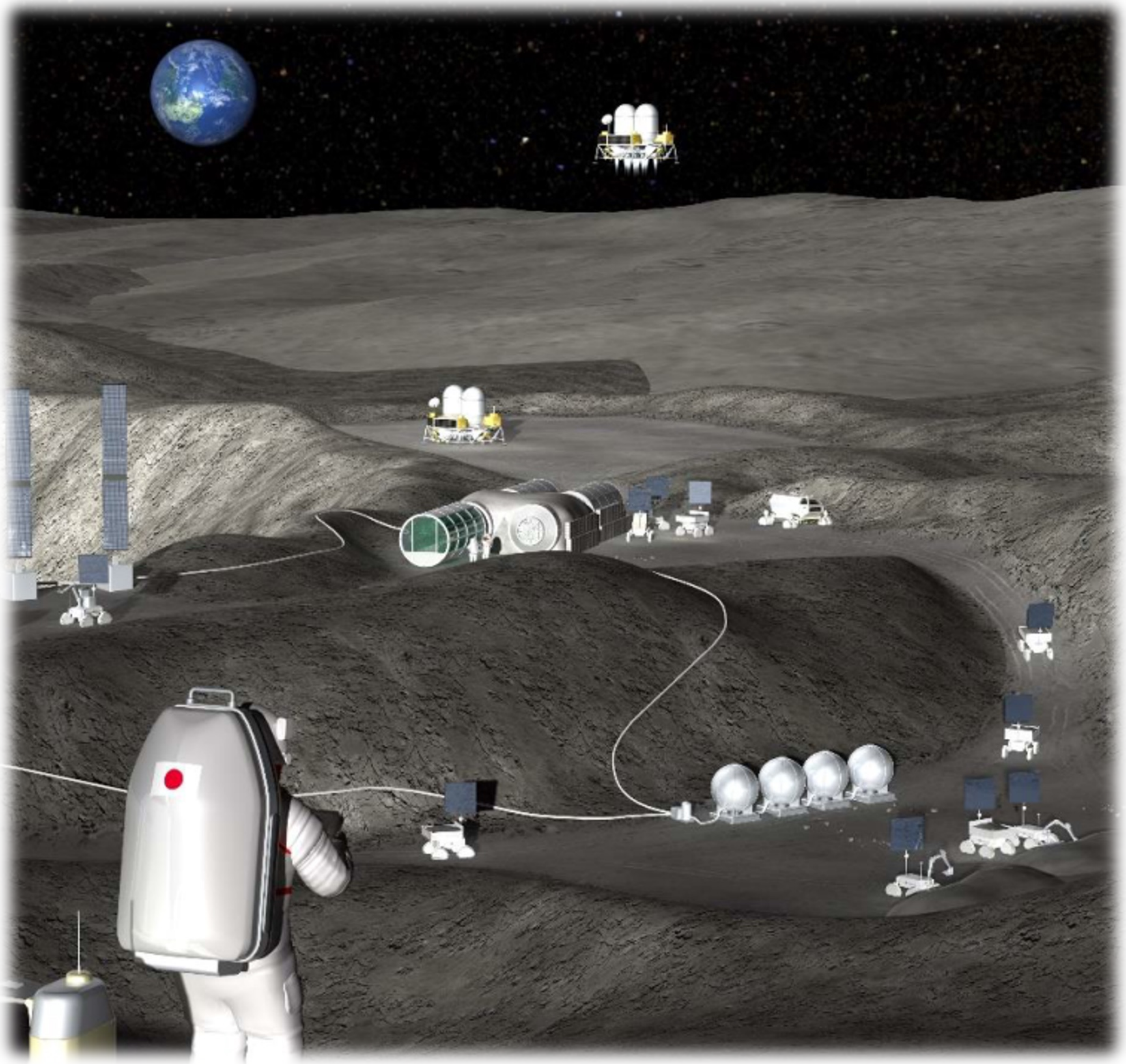
25th Space Resources Roundtable

Highlights

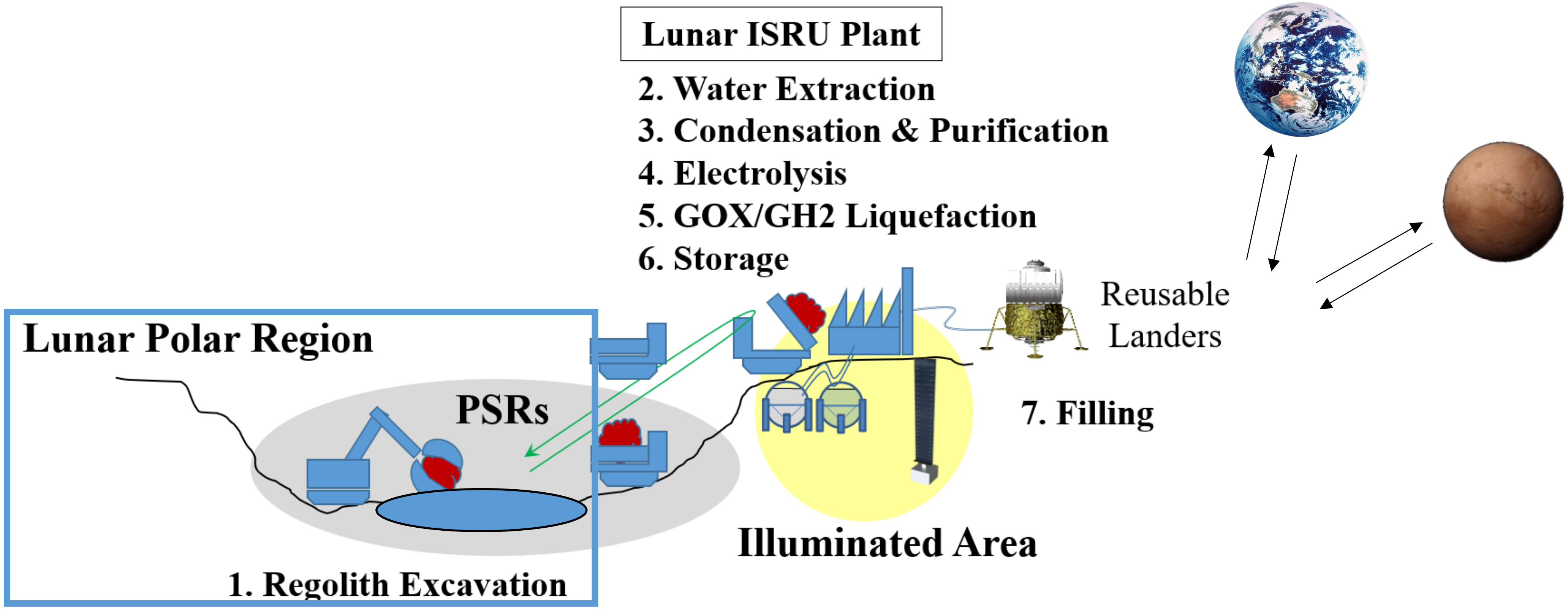


1. Water extraction experiment from hydrous regolith simulant was succeeded in Japan

2. The Water recovery rate of the experiment reached 85% with microwave heating

Hydrous regolith is likely to be present in the permanent shadow of the lunar polar regions in the form of ice.

To reduce the cost of transportation and increase the sustainability of space exploration, propellant production using this resource on the Moon is being considered.



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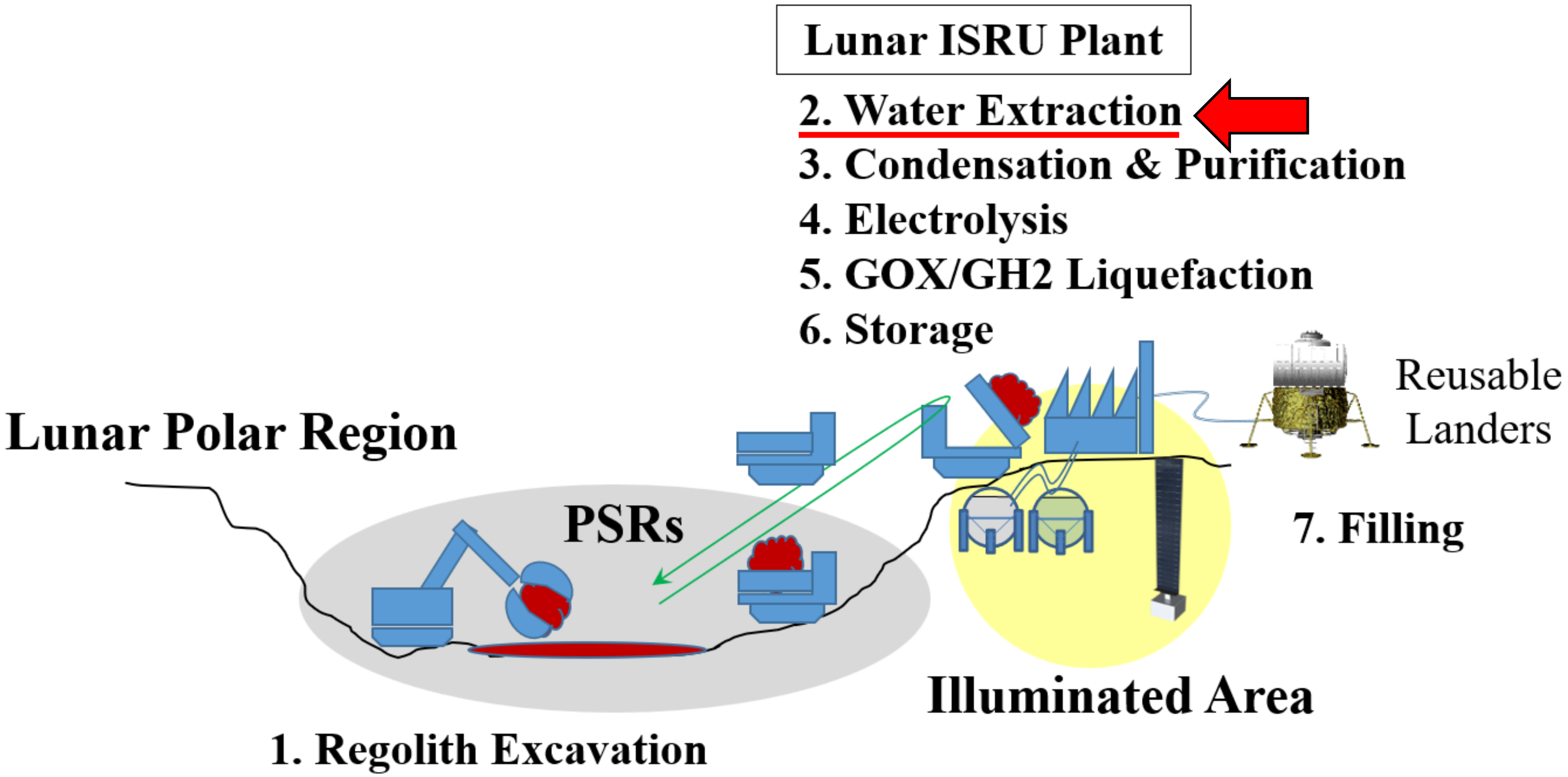
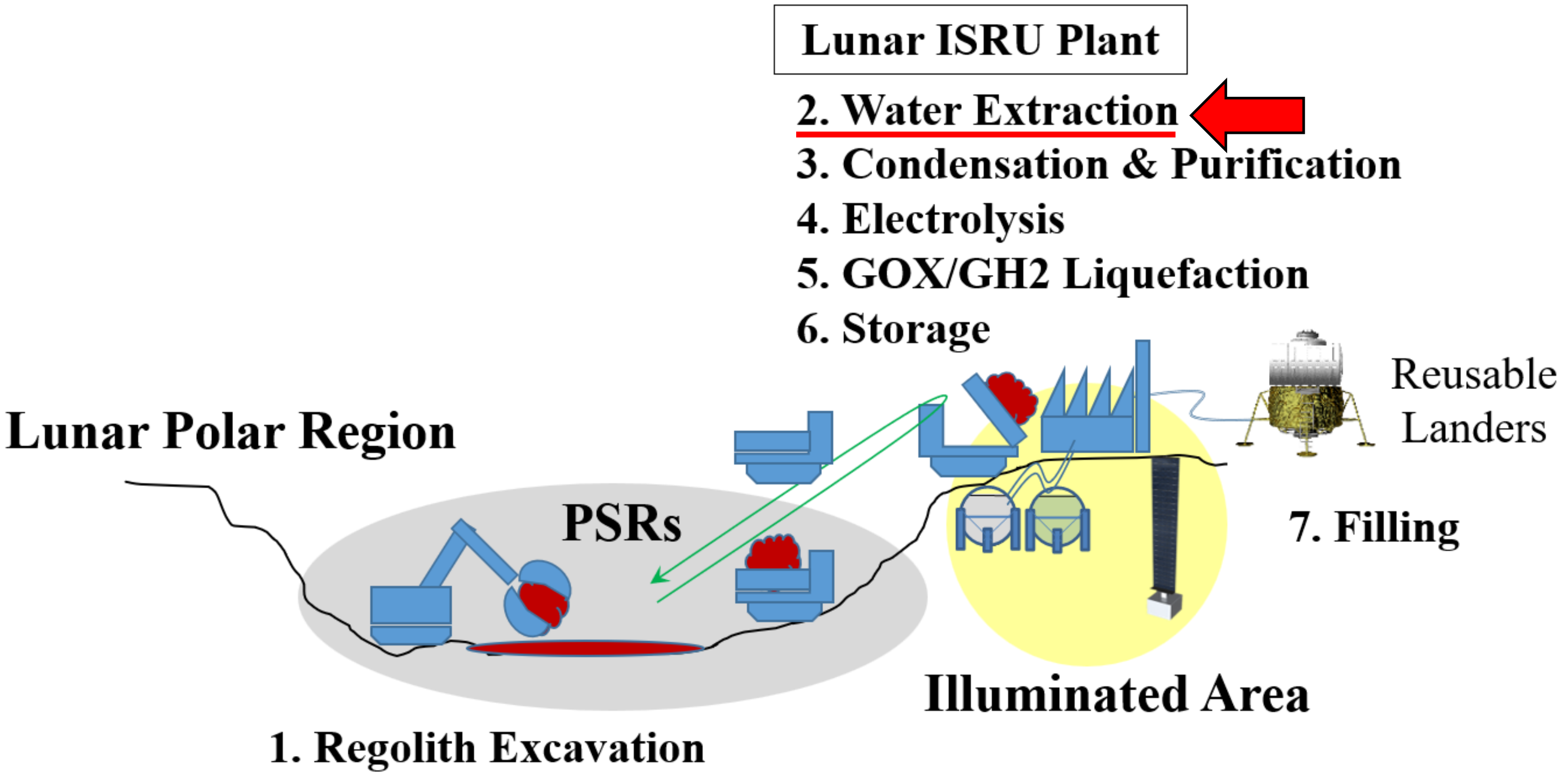
Water extraction from lunar icy regolith is regarded as one of the key technologies for the following reasons.

- Technology that has not yet been operated on Earth
- Essential technology for the utilization of water resources

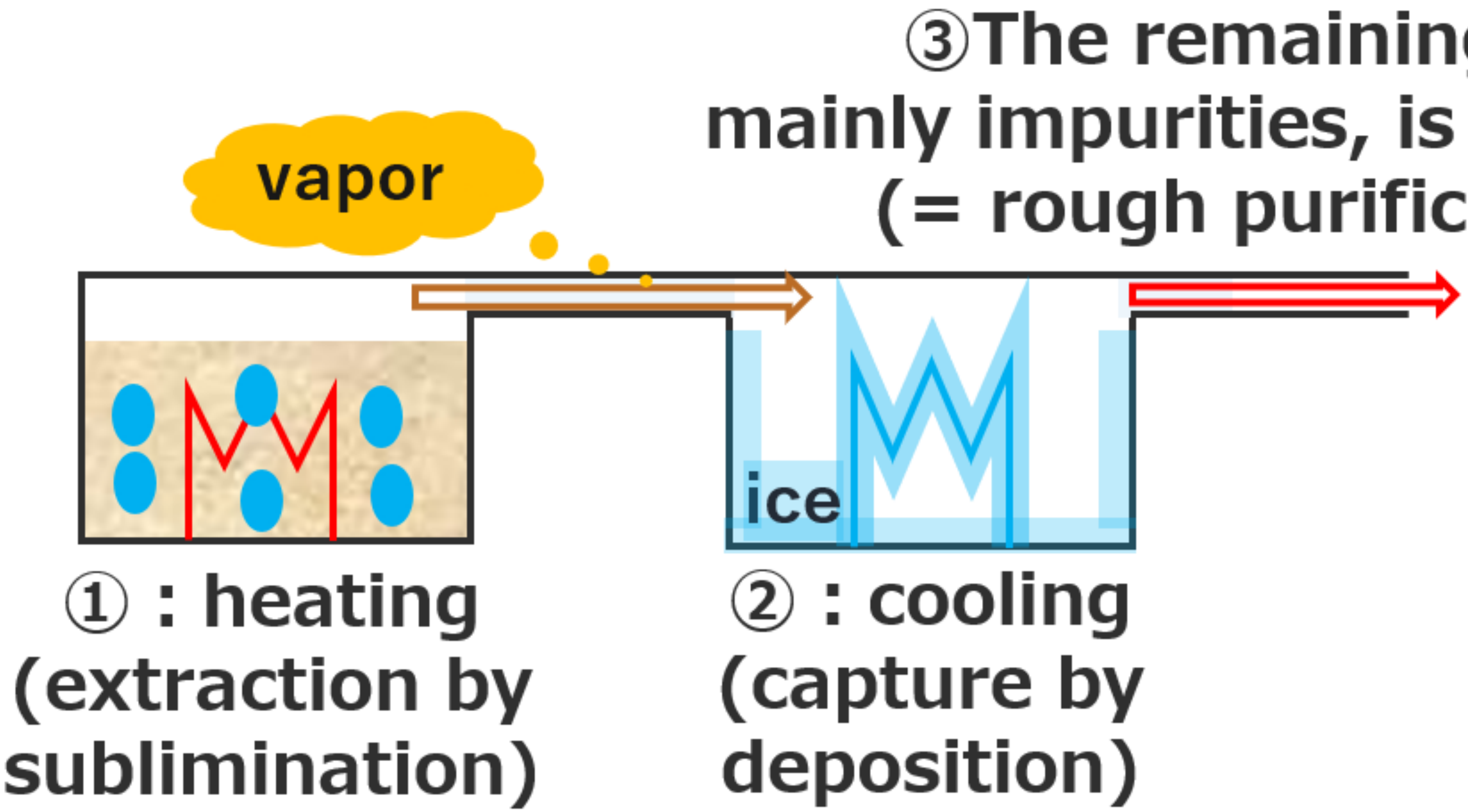


Research Purpose

- Demonstrating a method for separating water from a sample mixture of water and regolith simulant
- Obtaining the characteristics of the heating method to improve the extraction process



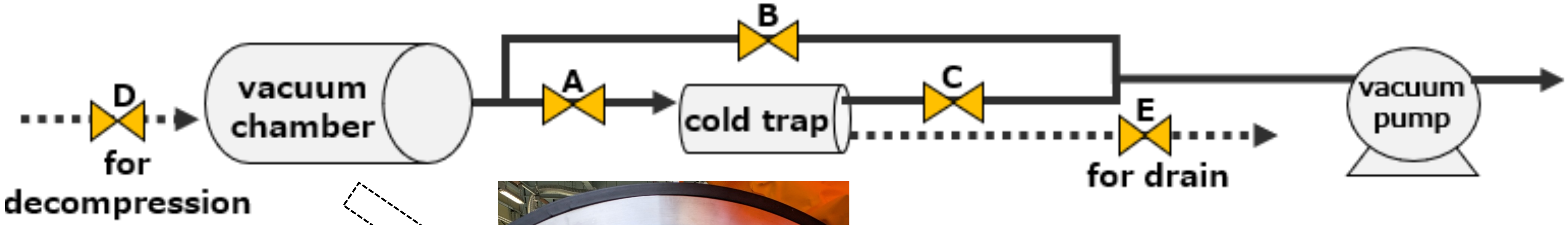
The ConOps of this experiment is to collect water in the hydrous regolith simulant by manipulating the state change of water with heat.

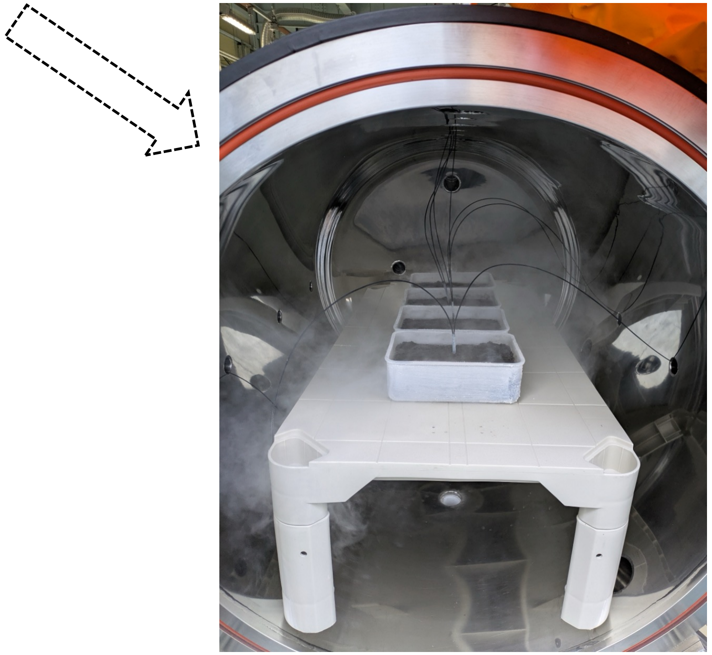


Method -System-

The overview of the experimental apparatus is the following.

The samples are heated in a vacuum chamber that simulates the space environment, and water is collected in a cold trap.





Method -Heating-

For the heating process, 3 methods were compared and electric heating wire and microwave were elected.

	Electric Heating Wire	Microwave	Sunlight
Simplicity	○	×	○
Precision of temperature control	△	○	×
Conversion efficiency to heat	△ 25% Breakdown Sunlight→Electricity: 25% Electricity→Heat: 100%	× 15-18% Breakdown Sunlight→Electricity: 25% Electricity→Microwave: 60-70% Microwave→Heat: 100%(*1)	○ 80-90% Breakdown Sunlight→Heat: 80-90%
Usability at night	○	○	×
Uniformity of heating	×	○	×

*1 in case sufficient heating path length can be secured.

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*1 in case sufficient heating path length can be secured.

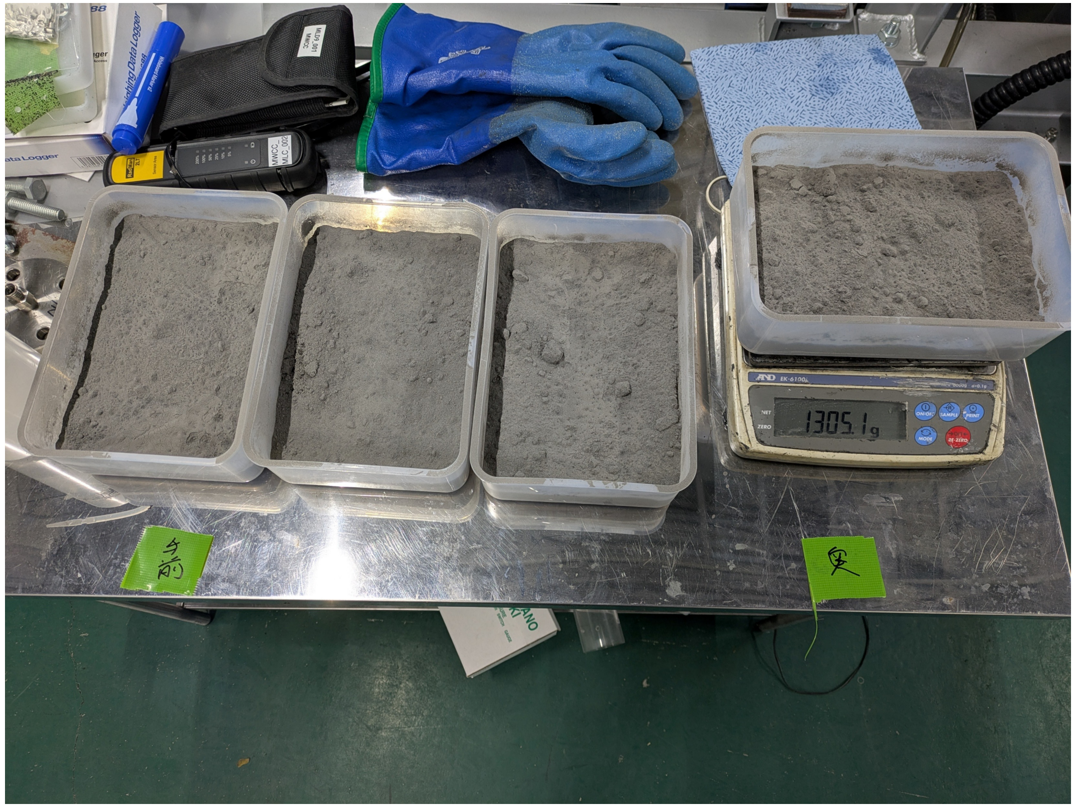
There are multiple ways to prepare samples because the state of water resources on the Moon is still unclarified. Since it was the first time, the following simple recipe was used.

① Heating regolith simulant for 6 hours to remove the unnecessary contained water and impurities

② Mixing regolith simulant with the aqueous solution of impurities

③ Freezing samples in the freezer

④ Pouring liquid nitrogen over the samples until they no longer boil, and cooling to approximately -196°C



Method -Sample-

Impurities were also mixed to simulate lunar water resources.

They were selected based on the data from the LCROSS mission.

Methanol and ammonia were chosen for the following reasons;

- Not present in the atmosphere and thus less susceptible to atmospheric effects
- Difficult to purify and have a big impact on downstream purification equipment.

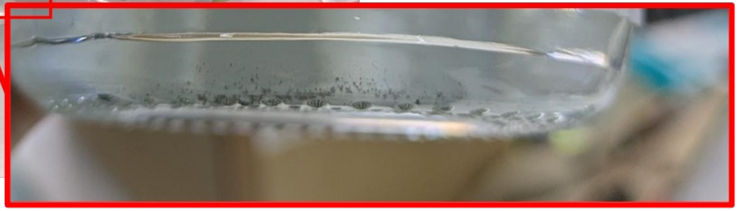
Category	
be miscible rather than dissolve as a solute	CH_3OH
dissolve in water mainly as ions	NH_3 H_2S SO_2 CO_2
dissolve without ionization	C_2H_4 CH_4

A. Colaprete et al (2010). Detection of Water in the LCROSS Ejecta Plume, Vol 330, Issue 6003, pp. 463-468, ISSN 0036-8075.

Result

- Water with impurities was extracted from samples by 2 heating methods, electric heating wire and microwave.
- During the 1st experiment with electric heating wire, a large amount of regolith was mixed in due to unfamiliarity with the operation, but during the 2nd experiment with microwave, almost no regolith was mixed.

1st experiment with electric heating wire



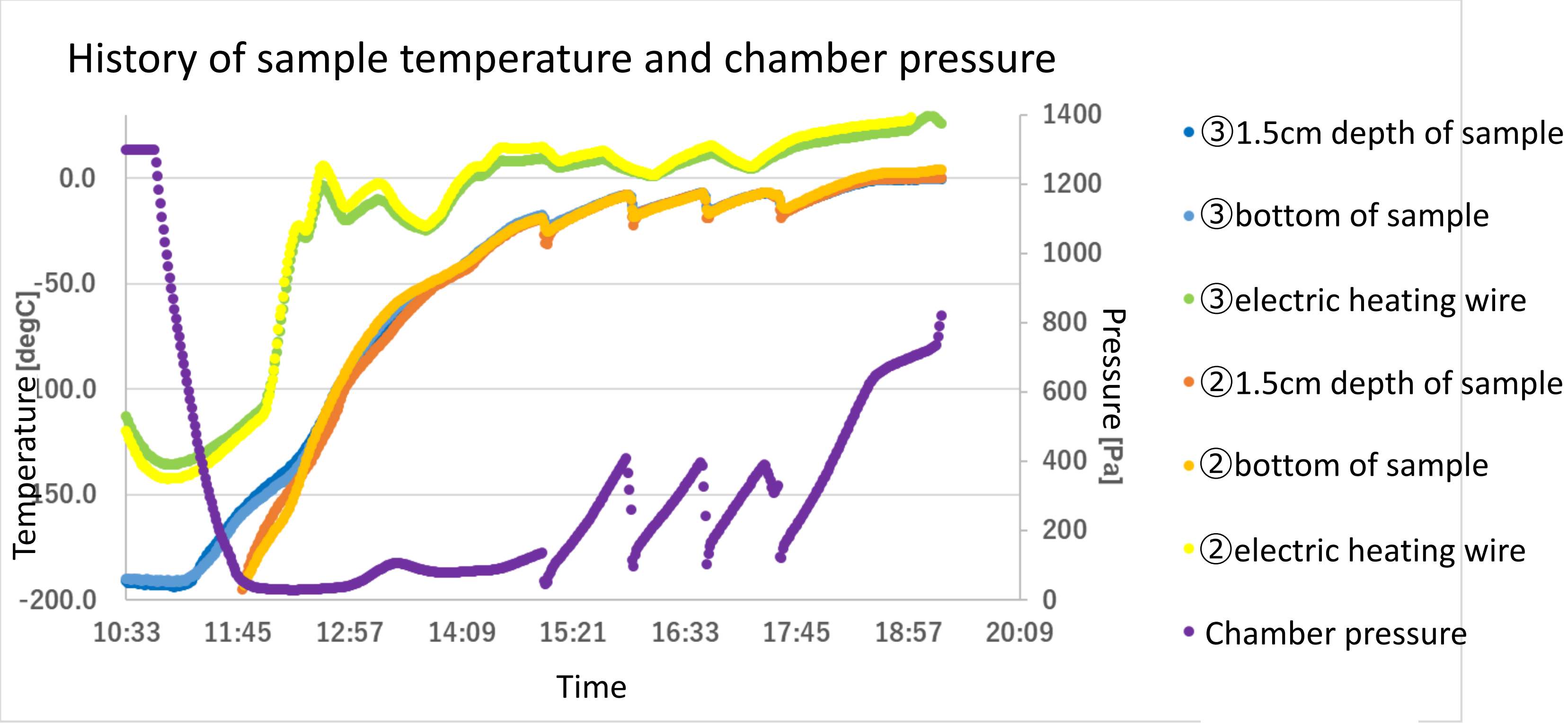
2nd experiment with microwave

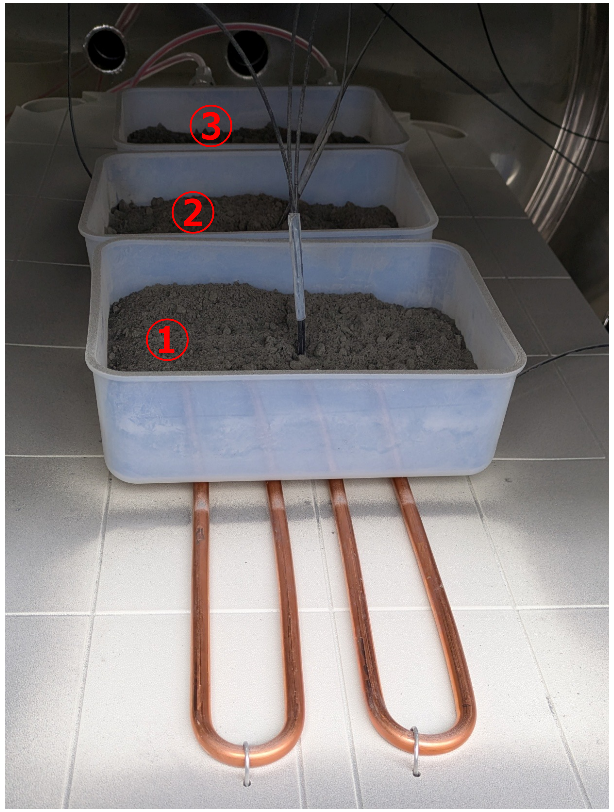
Result

- The water recovery rates are 85.4% for microwave and 22.75% for electric heating wire.
- The process of extraction was also found to be purify impurities such as ammonia and methanol.

		Microwave	Electric Heating Wire
Water recovery rate[wt%]		85.4	22.75
Ammonia	Added to the simulant [g]	11.6	11.6
	Extracted with water (extraction rate) [g (%)]	0.35 (3.0%)	0.13 (1.1%)
	Concentration in the extracted water [mg/L]	2,062	2,795
Methanol	Added to the simulant [g]	5.6	5.6
	Extracted with water (extraction rate) [g (%)]	0.22 (4.0%)	0.04 (0.7%)
	Concentration in the extracted water [mg/L]	1,307	876

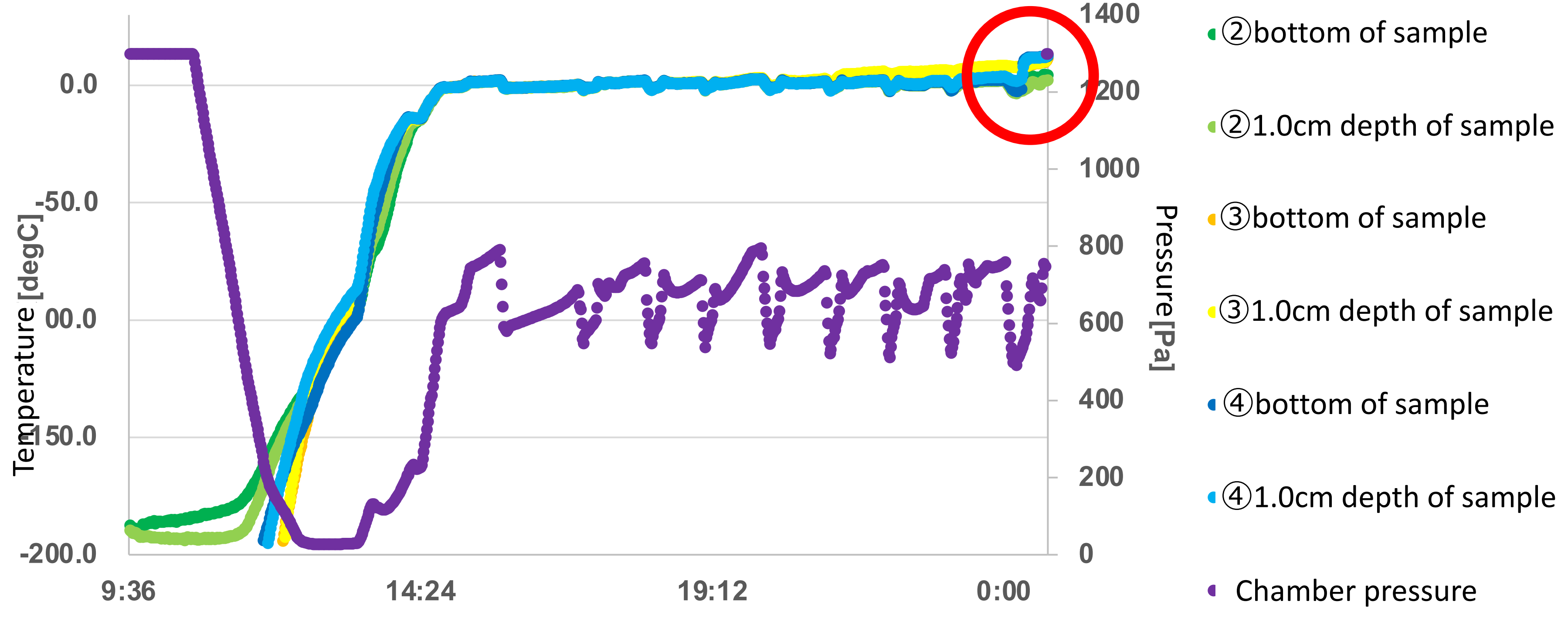
In the case of the electric heating wire, the recovery rate was low because the operation proficiency was not enough to extract until the end of the process. The history of samples' temperature shows that samples could be heated even though they have low thermal conductivity.

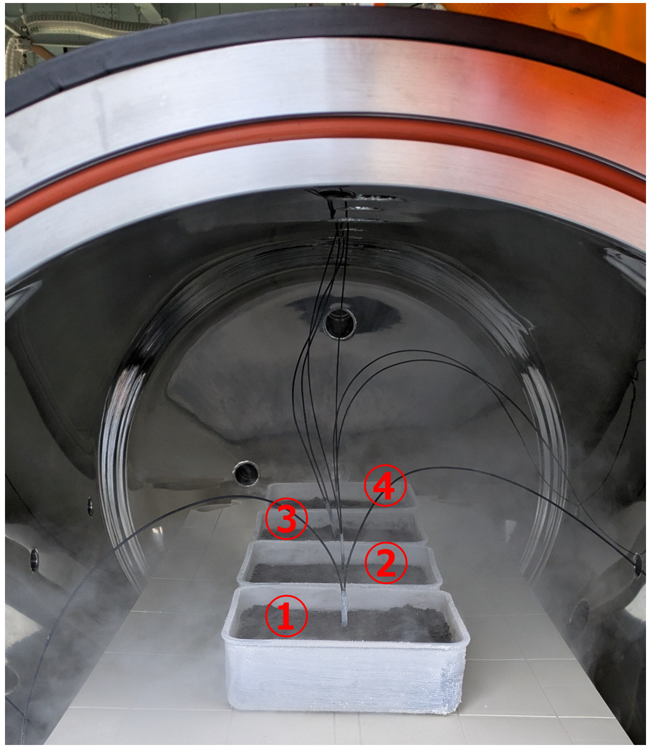




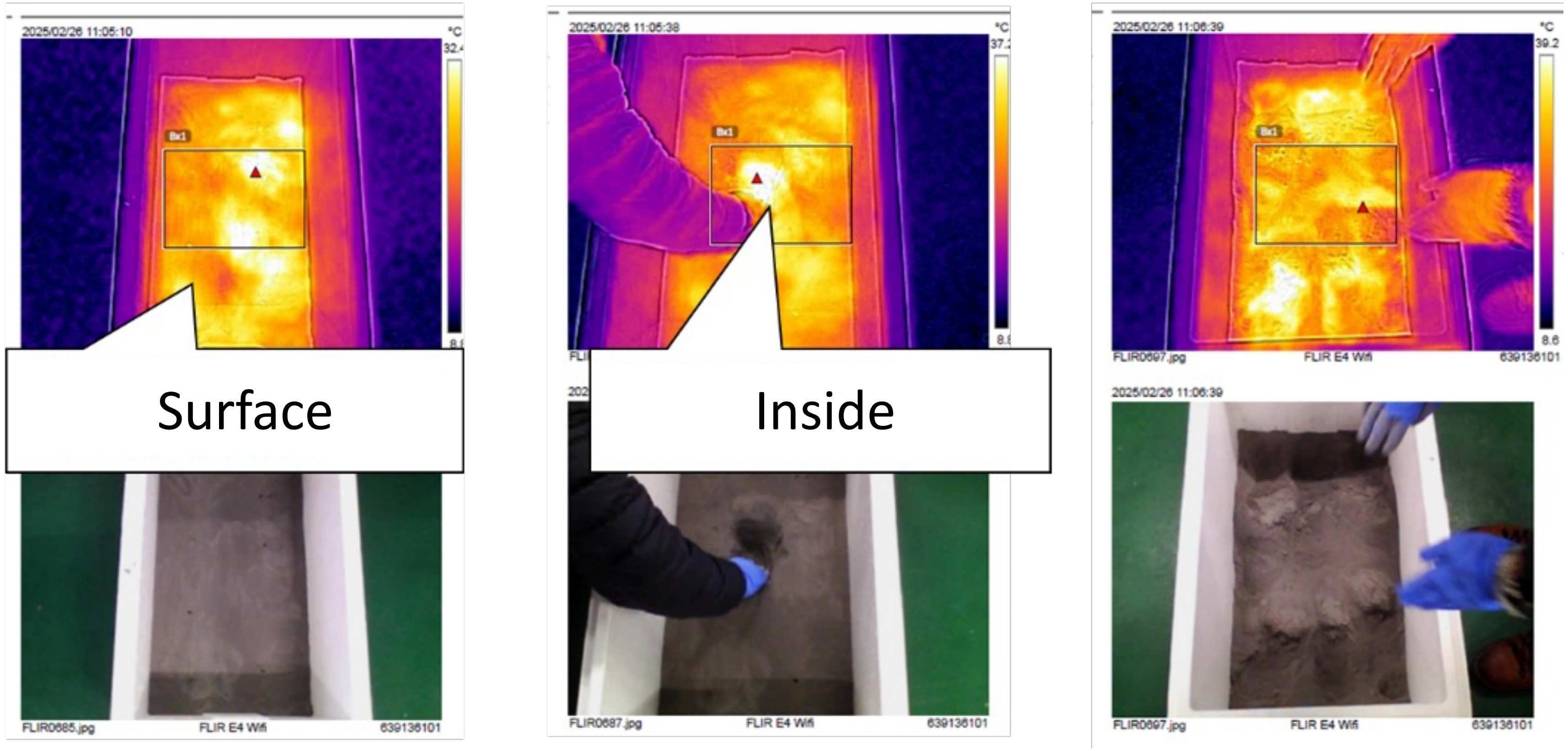
In the microwave experiment, the history of pressure and temperature shows that extraction has occurred up to the area circled in red.

History of sample temperature and chamber pressure





In terms of the uniformity of microwave heating, it was found that only 1~2°C of unevenness occurred in the depth direction up to a depth of 10 cm. In the horizontal direction, a difference of about 10°C was observed.

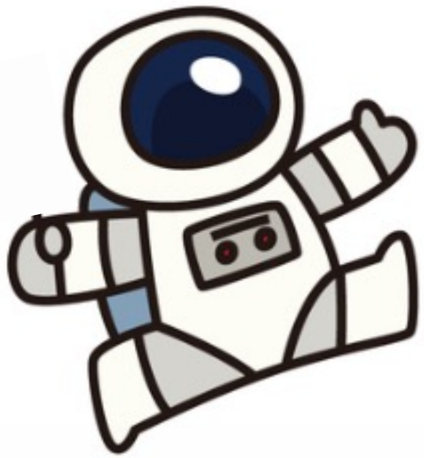


Conclusion

- Water with impurities was separated from samples of water, impurities and regolith simulant frozen mixture in a vacuum environment by heating with electric heating wire and microwave.
- The recovery rate of water by microwave heating reached 85%.
- The temperature characteristics of microwave heating were obtained.

This study will be continued with various parameters comparing heating methods.

The results of these experiments will be utilized in the overall system for the ground demonstration and the future operation.



https://www.ac-illust.com/

Future Work & Questions

- Studying methods of producing samples of lunar icy regolith
  - Which of the following methods can be considered appropriate as the existing state of water on the Moon?

    Mixing water and freezing / Mixing frost / Spraying water on cooled regolith and freezing it
  - Are there any other production methods?

- Brushing up experimental methods
  - Are there any measures to reduce the contained regolith in the extracted water?
  - How can the amount of unrecovered water and volatile impurities be measured?
  - How can the efficiency of heat transfer from the electric heating wire to the regolith be improved?

- Investigating effects of impurities
  - What should be employed as impurities?

参考

表 7.2-31 推薬プラントの水生成/電解・液化能力の要求整理

	生成ΔV量 [m/s]	全体質量 [ton]	推薬 [ton]	水 [ton] 混合比考慮[*1]	水生成期間[日]	水電解・液化期間[日]	備考
有人月離着陸機	5600[*2]	51.0	36.8 (LH2:5.3) (LOX:31.5)	48.0	365日	42日[*5] or 365日[*6]	・ESA-HSO-K-TN-0008より、有人月離着陸機に必要なモジュールを選定の上、ΔV量の生成に必要な推薬量をJAXAにて算出
曝露ホッパー	5905[*3]	28.2	20.8 (LH2:3.0) (LOX:17.8)	27.1	365日	～365日（明確な定めはない）	・ESA-HSO-K-TN-0008より、曝露ホッパーに必要なモジュールを選定の上、ΔV量の生成に必要な推薬量をJAXAにて算出 ・月面を合計4回離着陸する際の重力損失についてJAXAにて考慮（AAX-16029：153頁に掲載の通り）
合計	-	-	57.6 (LH2:8.3) (LOX:49.3)	75.1[*4]			

参考

月面実証用パイロットプラント全体のリソース推算値

項目	単位	概算値
装置質量	kg	240
装置体積	m^3	2
ラジエータ面積	m^2	5
消費電力	kW(ピーク)	2
排熱量	kW(ピーク)	1

日本の国際宇宙探査シナリオ（案）2021

・ JAXAは「日本の国際宇宙探査シナリオ（案）2021」を2022年4月に公開
（JAXA国際宇宙探査センターWebサイトで全文公開中）

国際宇宙探査シナリオ（案）とは

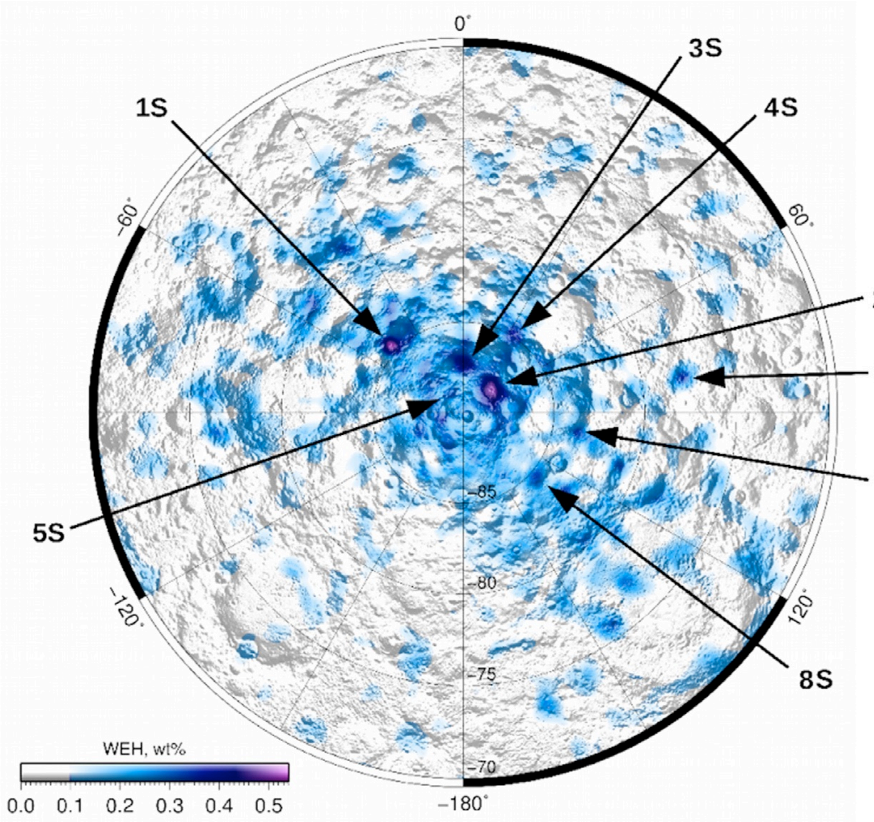
- 目的「政府の国際宇宙探査政策・計画に対し，宇宙機関としての提言をまとめる」
- 宇宙基本計画工程表（2017年改訂時）やJAXA 第 4 次中期目標の国際宇宙探査に関する政策議論に JAXAからの提案として資された

第3版（2021年度版）作成の背景

- 米国主導のアルテミス計画の取り込み
- 2020年8月に国際宇宙探査協働グループ（ISECG）が公表した国際宇宙探査ロードマップの最新版（GER Supplement）にも対応

日本の国際宇宙探査シナリオ（案）2021

月面における水資源



月南極域の水素分布

- 米国月周回衛星LROの中性子観測データをもとに推定された月南極域の水素分布。
- 水素の存在量を水の量に換算して示している。図の中心は南極点、外側の円は緯度70度。

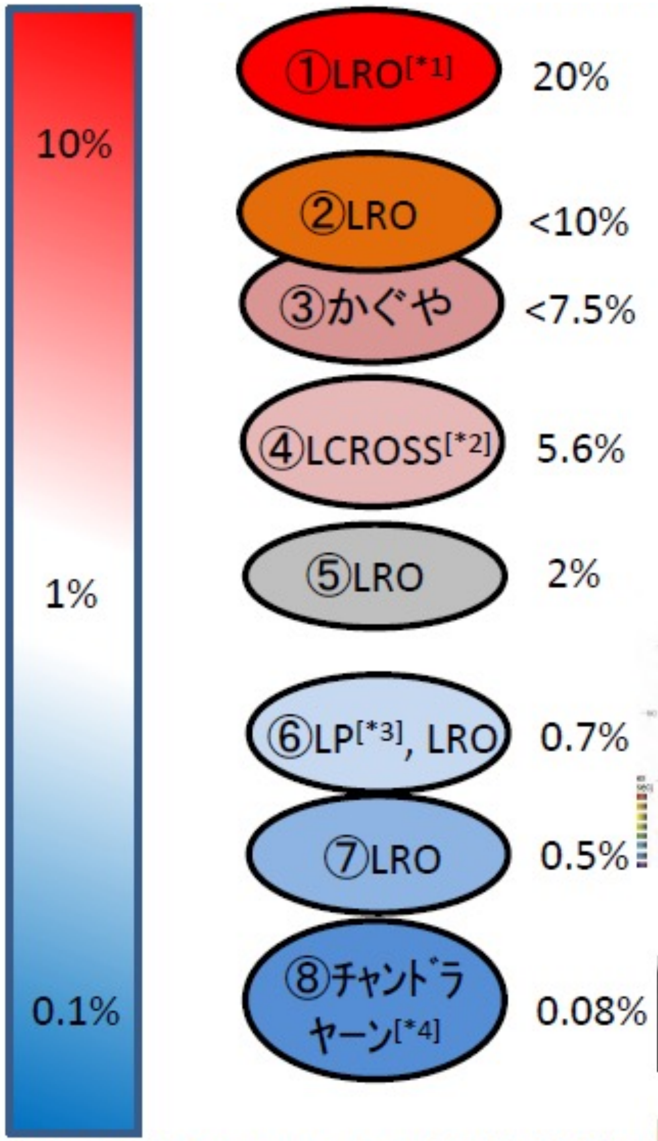
A.B. Sanin et al., Hydrogen distribution in the lunar polar regions, Icarus 283 (2017)より引用。

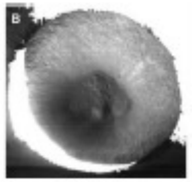
- ❑ 月極域には彗星・小惑星・太陽風によりもたらされた水氷（あるいは水素）が保存されていると考えられている。
- ❑ 月極域の水氷関連データは、リモートセンシング観測データに基づく多くの研究が報告されている。
- ❑ 観測波長・データ解析手法により結果が異なることや、データの解釈において意見が分かれるなどの理由から、量・分布・形態（塊、吸着など）について決定的な結論はまだ得られていない。

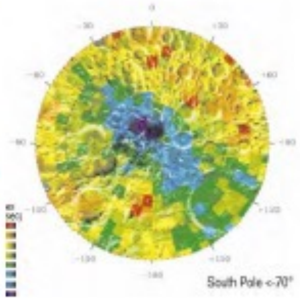
月面における水資源利用の実現には一定程度の水の存在確認が必要！

グランド・トゥルースデータの獲得に向け、我が国の月極域探査機（LUPEX）を含め、各国で水資源探査に向けた活動が本格化している。

月面における水資源





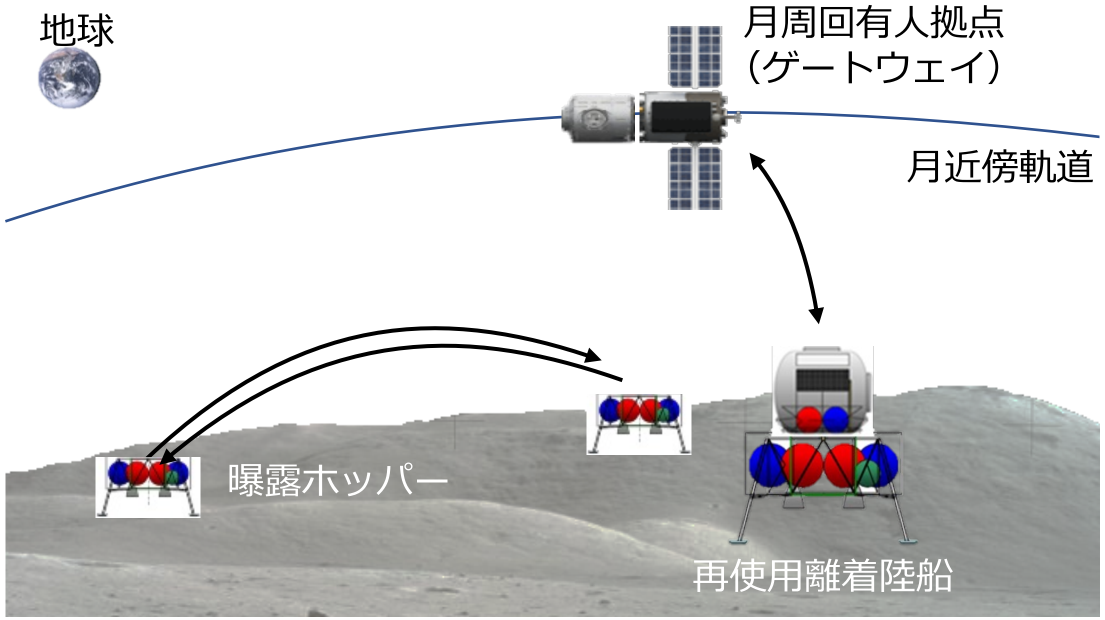


月南極域の水氷の質量比率（推定値）

① シャックルトンクレータ内は太陽風による月表面の変化が小さいか、又は水氷が存在（Zuber et al., 2012）
② 永久影領域に水氷が存在（Thomson et al., 2012）
③ シャックルトンクレータ（南極の永久影）内の地表に大量の氷は存在しない（Haruyama et al, 2009）
④ 飛翔体の衝突による放出物を観測（Colaprete et al., 2010）
⑤ 表層に水の霜が存在（Gladstone et al., 2012）
⑥ 極域の永久影領域に水氷または水素が存在（Miller et al., 2012）
⑦ 水に換算すると最大0.5%程度が存在する(A.B. Sanin et al., 2017)
⑧ 高緯度地域にOH基もしくは水が存在（Pieters et al., 2009）

[*1] Lunar Reconnaissance Orbiter（米国，2009年打上）
[*2] Lunar CRater Observation and Sensing Satellite（米国，2009年打上）
[*3] Lunar Prospector（米国，1998年打上）
[*4] Chandrayaan-1（インド，2008年打上）

年間推薬生成量の要求



将来的な月面広域探査のイメージ図

年間推薬生成量の要求案

	ΔV量	必要推薬量		
		LH2	LOX	計
曝露ホッパーによる飛翔移動（1000km往復分）	5,900 [m/s]	5.3 [ton]	31.5 [ton]	36.8 [ton]
再使用離着陸船による降下・離陸（Gateway-月面 1往復分）	5,600 [m/s]	3.0 [ton]	17.8 [ton]	20.8 [ton]
合計	-	8.3 [ton]	49.3 [ton]	57.6 [ton]

⇒ 年１回の有人月探査に必要な推薬量は **57.6 ton/year**

⇒ 液体酸素と液体水素の混合比を 1:5.9 とすると、必要量はそれぞれ

LH2: 8.3 ton/year、 LOX: 49.3 ton/year