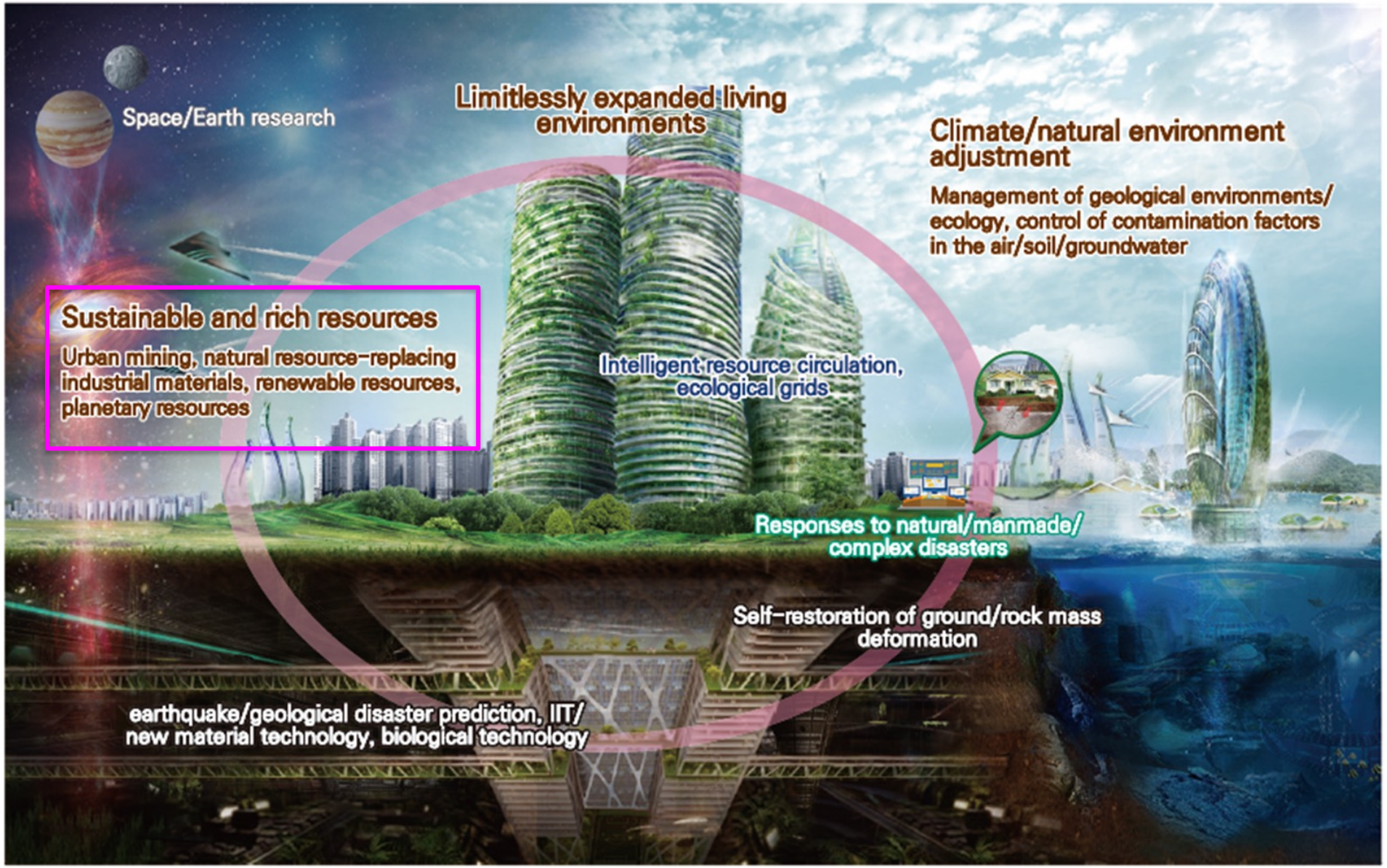
KIGAM

Research Development for Lunar Volatile Extraction at KIGAM

Kyeong Ja Kim[1], Jong-Yeon Lim[2]

[1]Space Resource Exploration and Utilization Center, Geology and Space Division, KIGAM, [2]IVT

KIGAM's Vision of Geo-Technology in 2050



Contents

- ✓ Introduction to volatile extraction
- ✓ Volatile extraction results at KIGAM
- ✓ ISRU payload proposed for Korean Lunar Mission
- ✓ Ion Implantation Facility at KIGAM

Introduction

- ✓ **Volatile extraction on the Moon is an important task** for the future aspect **of in-situ resource utilization**, regardless of the location on the Moon.
- ✓ Many experiments have been carried out on the **Apollo return samples** in a laboratory environment.
- ✓ The data obtained with **the Apollo samples are invaluable** when these results are **referenced for the development of an ISRU payload** to extract volatiles on the Moon as part of lunar surface exploration.
- ✓ We present our preliminary research project on **volatile extraction using the lunar simulant samples** and indicate some aspects and directions of future research on this topic towards volatile extraction on the Moon.
- ✓ Our goal is to develop **an volatile extraction demonstrator in mid-low latitude of the Moon**

Experimental Settings on Volatile Extraction

- ✓ Considering the payload mass budget, the amount of sample required for the LUVED can be confirmed as the range of sample weights from approximately **200 to 500 mg studied with the Apollo samples** [Gibson & Johnson (1971), Gibson and Moore (1972)].
- ✓ **The initial melting points ranged from 1130°C~1150°C** [Gibson and Moore (1972)].
- ✓ The temperature required for **solar wind volatile extraction** is known as **700°C**, at this temperature, **H_2, ^4He, ^3He, H_2O, N_2, CH_4, CO, and CO_2** are released [Allen et al. (1996)].
- ✓ Considering these reference temperatures, the **heating temperature required for LUVED could be as low as 700°C** if no other in situ experiment
  - ✓ hydrogen reduction temperatures for Apollo samples at 1050°C [Allen et al. (1996)

Heating Temperature for Volatile Extraction

Table 1. Volatiles Products of Heating Mare Regolith t

700°C Volatile	Mass evolved per tonne of regolith mined (g)*	Mass evolved per kg of ^{3}He evolved (kg)	Mass extracted (tonnes/yr) **
H_2	43	6100	201
^{4}He	22	3100	102
^{3}He	0.007	1	0.066
H_2O	23	3300	109
N_2	4.0	500	16.5
CH_4	11	1600	53
CO	13.5	1900	63
CO_2	12	1700	56
*After beneficiation, 450 kg of regolith is heated			
** With 20 ppb and 1258 tonnes/hr excavation			

The heating temperature required for LUVED could be as low as 700°C if no other in situ experiment
- hydrogen reduction temperatures for Apollo samples at 1050°C [Allen et al. (1996)]

Table 1

Volatile Elements in Apollo 11 Regolith (Lunar Sourcebook)

Element	Wt. ppm*
H	60
C	154
N	78
He	46
S	1240
*Average values	

https://fti.neep.wisc.edu/fti.neep.wisc.edu/neep602/9301/node2.html

Volatile Extraction (Apollo 11, 12 samples)

Gibson and Johnson 1971

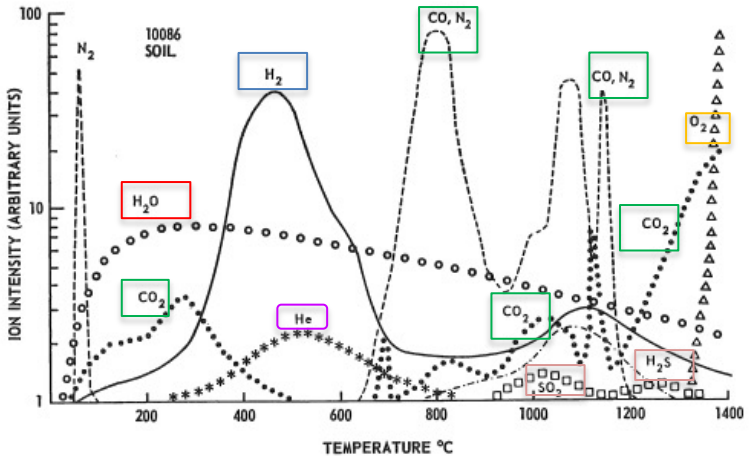


Fig. 1. Gas release pattern for Apollo 11 soil 10086,16. Sample weight 242.94 mg. Heating rate 4°C/minute.

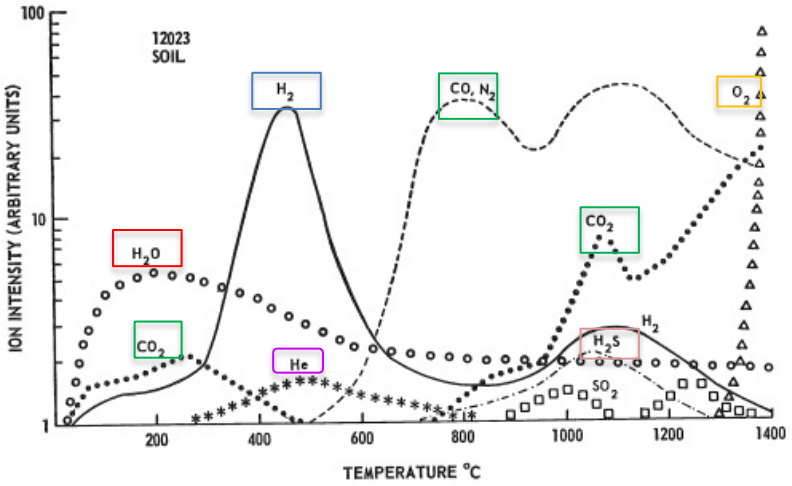


Fig. 2. Gas release pattern for Apollo 12 soil 12023,9. Sample weight 208.50 mg. Heating rate 4°C/minute.

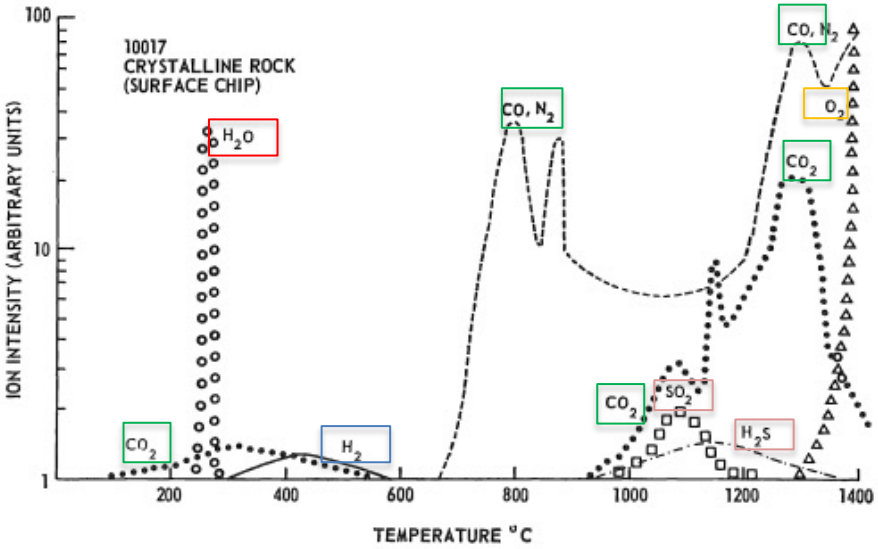


Fig. 3. Gas release pattern for a surface chip of Apollo 11 crystalline rock 10017,57. Sample weight 400.45 mg. Heating rate 4°C/minute.

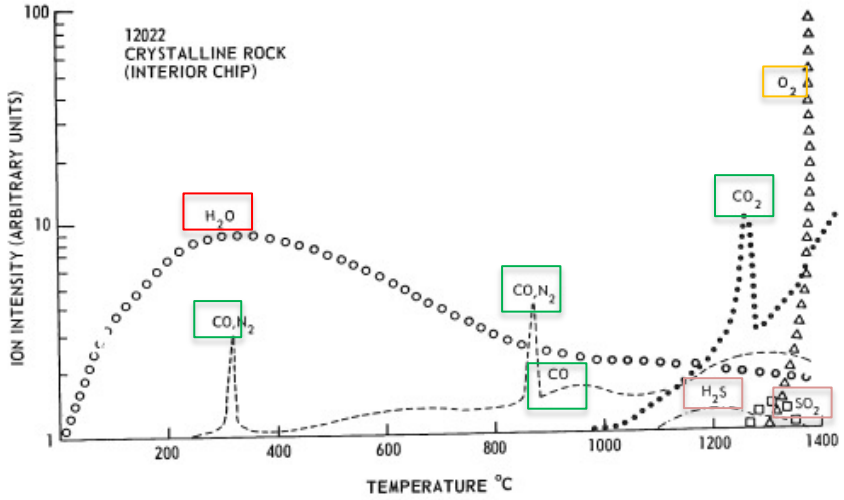
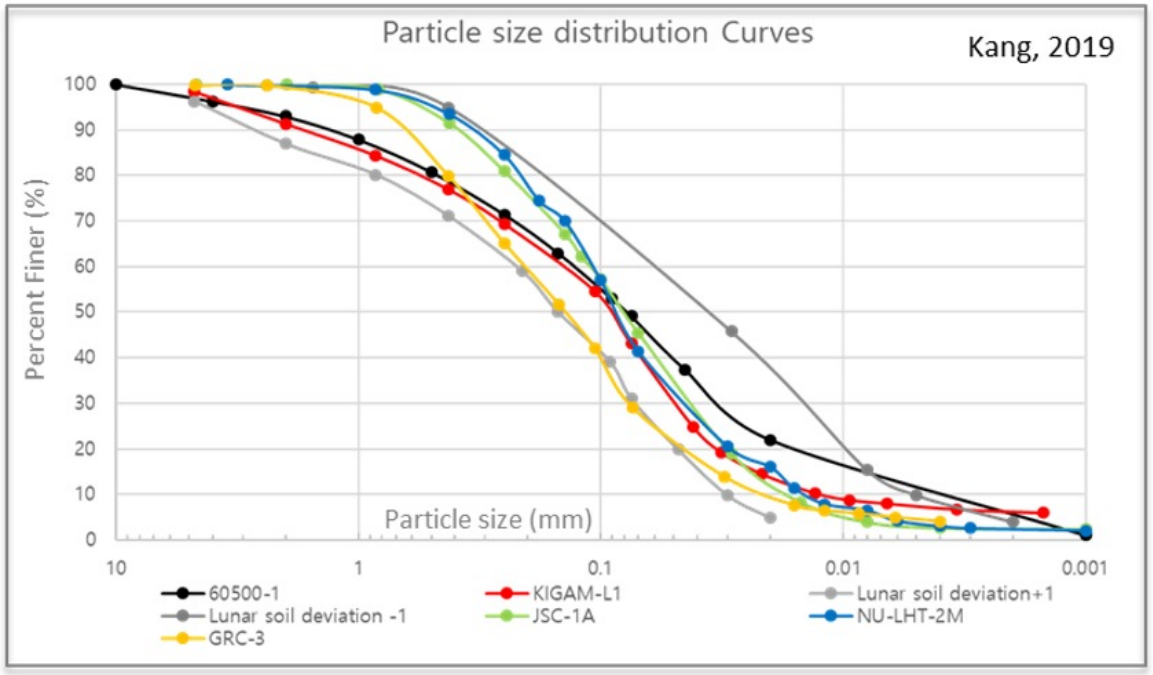


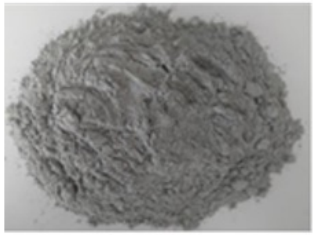
Fig. 4. Gas release pattern for an interior piece of Apollo 12 crystalline rock 12022,38. Sample weight 500.65 mg. Heating rate 4°C/minute.

KIGAM Lunar Simulant for This Study



KIGAM-L1
(KLHS-1)

<Preliminary work>

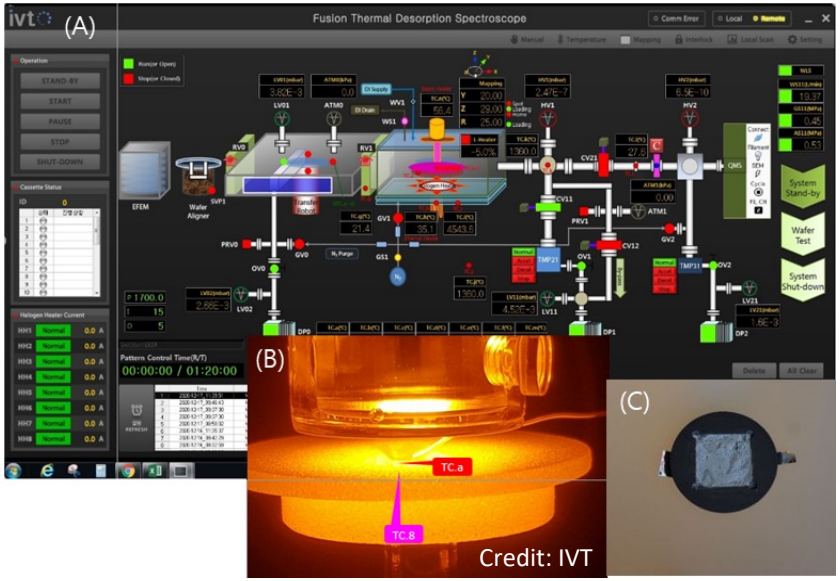


- ✓ Particle size distribution
- ✓ Composition

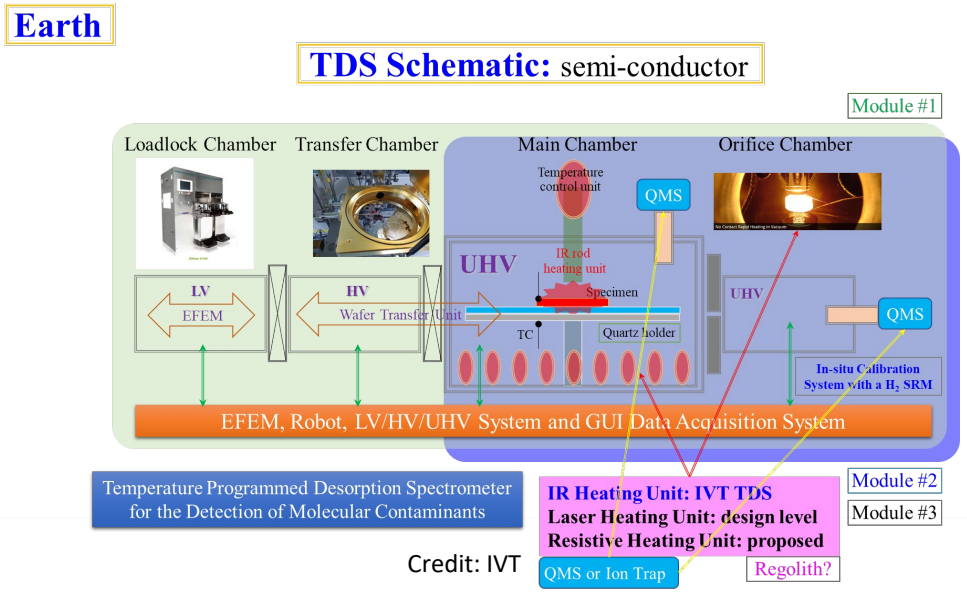
Sample name	SiO_2	$Al2O_3$	FeO (total)	Fe_2O_3 (Total)	CaO	MgO	K_2O	Na_2O	TiO_2	MnO	P_2O_5	Igloss	total
Olivine	40.18	0.36	0	11.22	0.28	47.78	0.02	0.02	0.03	0.15	0.01	-0.47	99.58
Anorthosite	52.59	28.18	0	0.57	11.92	0.52	0.5	4.16	0.13	0.02	0.02	1.18	99.77
KLHS-1	52.1	23.82	0	2.47	10.9	5.14	0.46	3.78	0.12	0.04	0.02	0.86	99.71
Apollo 16	45.16	27.66	4.39	0.00	15.63	5.85	0.13	0.48	0.48	0.10	0.11		99.98

Experimental Settings on Volatile Extraction

- ✓ The volatile extraction experiment conducted at KIGAM and IVT in Korea
- ✓ Payload of a lunar volatile extraction demonstrator (LUVED) for the Korean lunar lander planned for 2032.
- ✓ Volatile extraction experiments using few lunar simulants and chemical oxides at a temperature range up to 700°C.
- ✓ An IR lamp with a quartz crucible to heat
- ✓ A sample weight of approximately 1 g



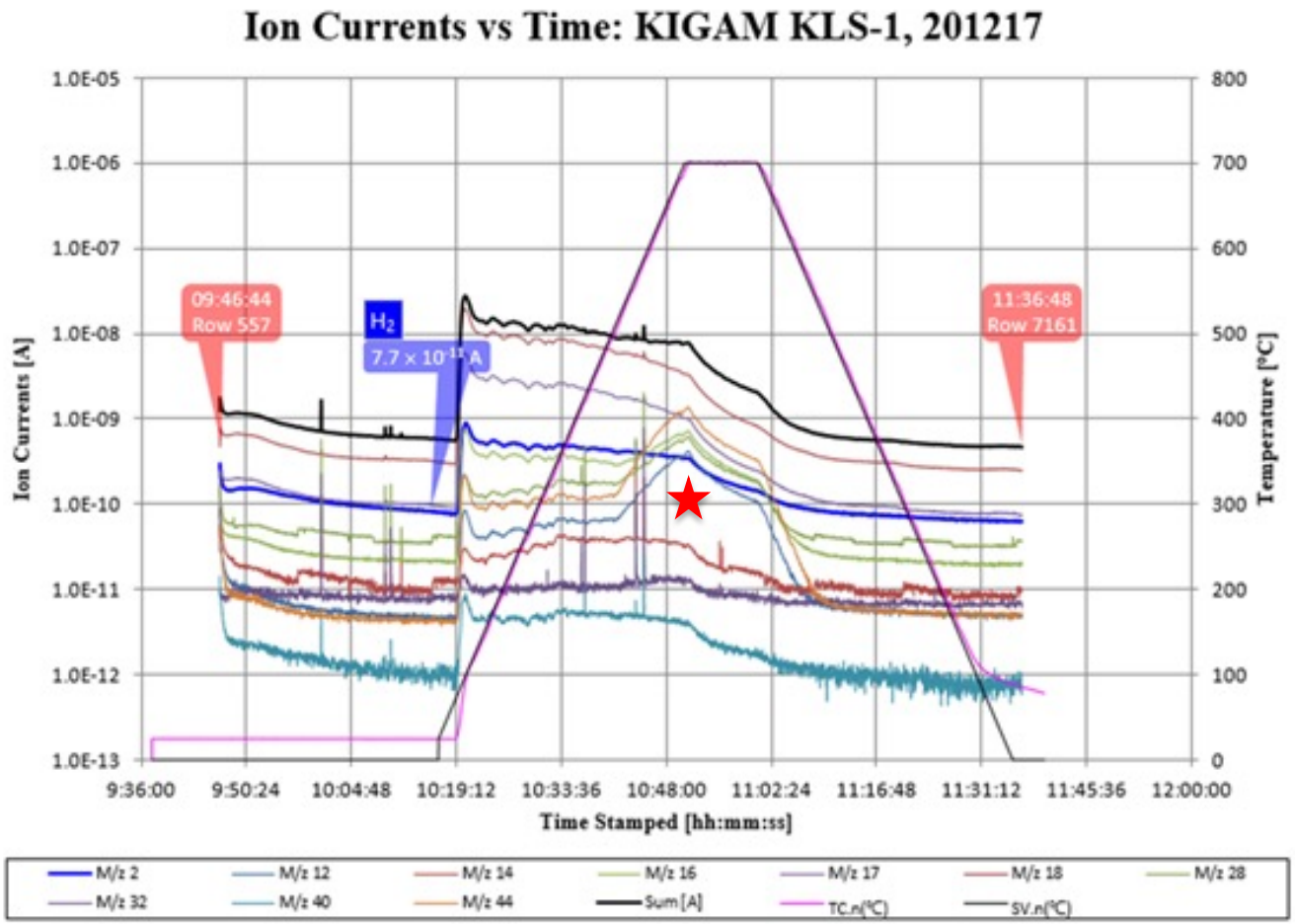
Kim and Lim 2024 (unpublished)



Preliminary Data of Volatile Extraction

- ✓ Heating started when the pressure reached 2.6 x 10^{-7} mbar (the base pressure of the TDS system ~5 x 10^{-9} mbar)
- ✓ The heating rate was set at 20.0°C/min.
- ✓ The temperature was maintained at 700°C for 10 minutes
- ✓ The chamber was allowed to cool down at the same rate.
- ✓ The released gas was monitored using a RGA.
- ✓ This preliminary investigation demonstrated that initial gas extraction could be accomplished after heating for 30 to 40 minutes
- ✓ The experimental system (IVT uTDS) was calibrated with a NIST SRM 2453a (126.8 mg/kg, H).

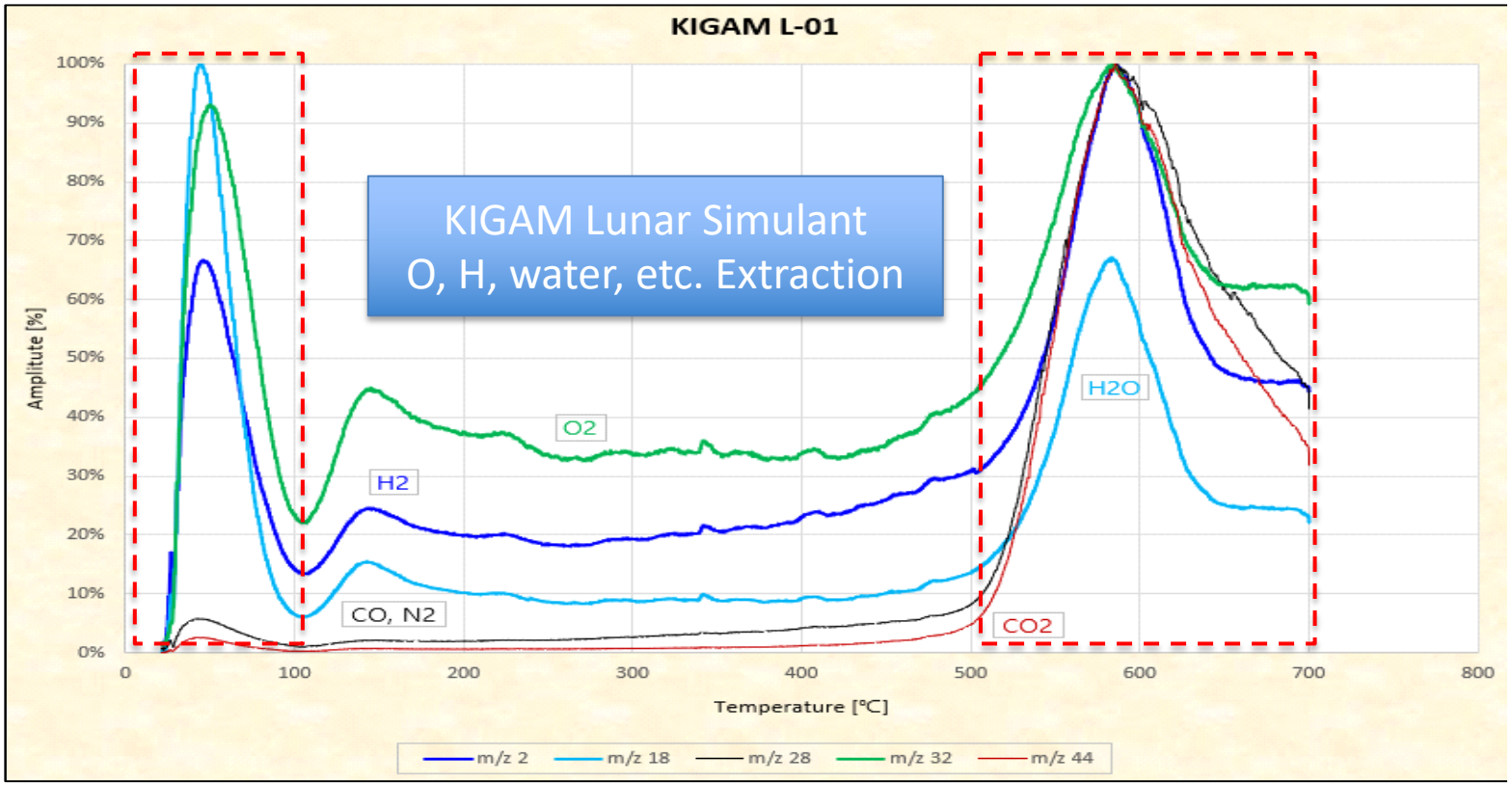
Ion Current vs Time



Kim and Lim 2024 (unpublished)

Ion current of gas release as a function of time and temperature.

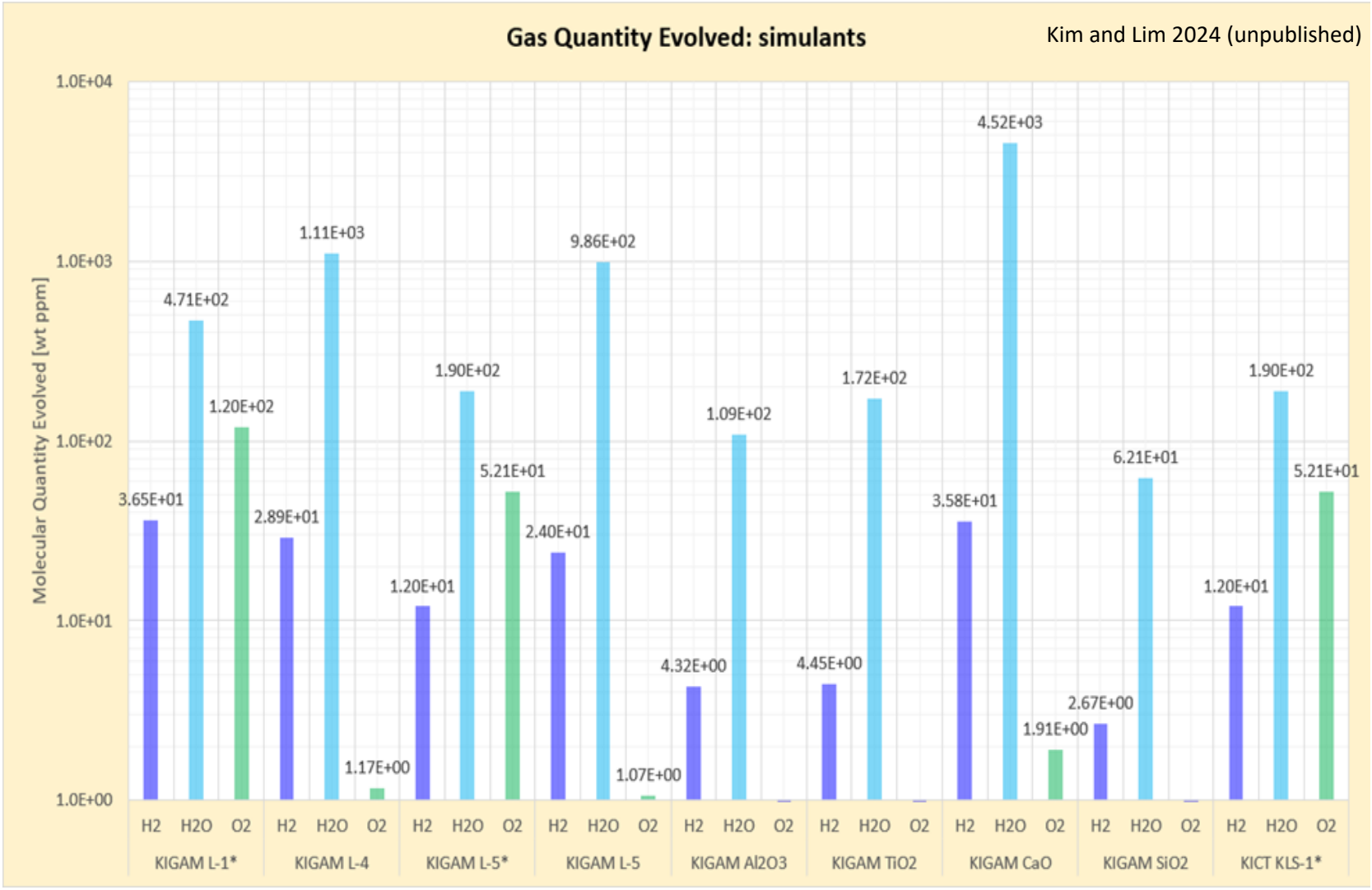
Gas Release vs Temperature



Moon Simulants		Molecular Quantity Evolved*				Sample Weight [g]
		[wt ppm]			[molecules]	
		Amb. ~ 500 ℃	(500 ~ 700) ℃	Sum	Sum	
KIGAM L-1*	H2	1.5780E+01	2.0670E+01	3.6450E+01	4.9933E+18	0.4588
	H2O	2.1279E+02	2.5822E+02	4.7101E+02	7.2216E+18	
	O2	5.8828E+01	6.1277E+01	1.2011E+02	1.0367E+18	

Kim and Lim 2024 (unpublished)

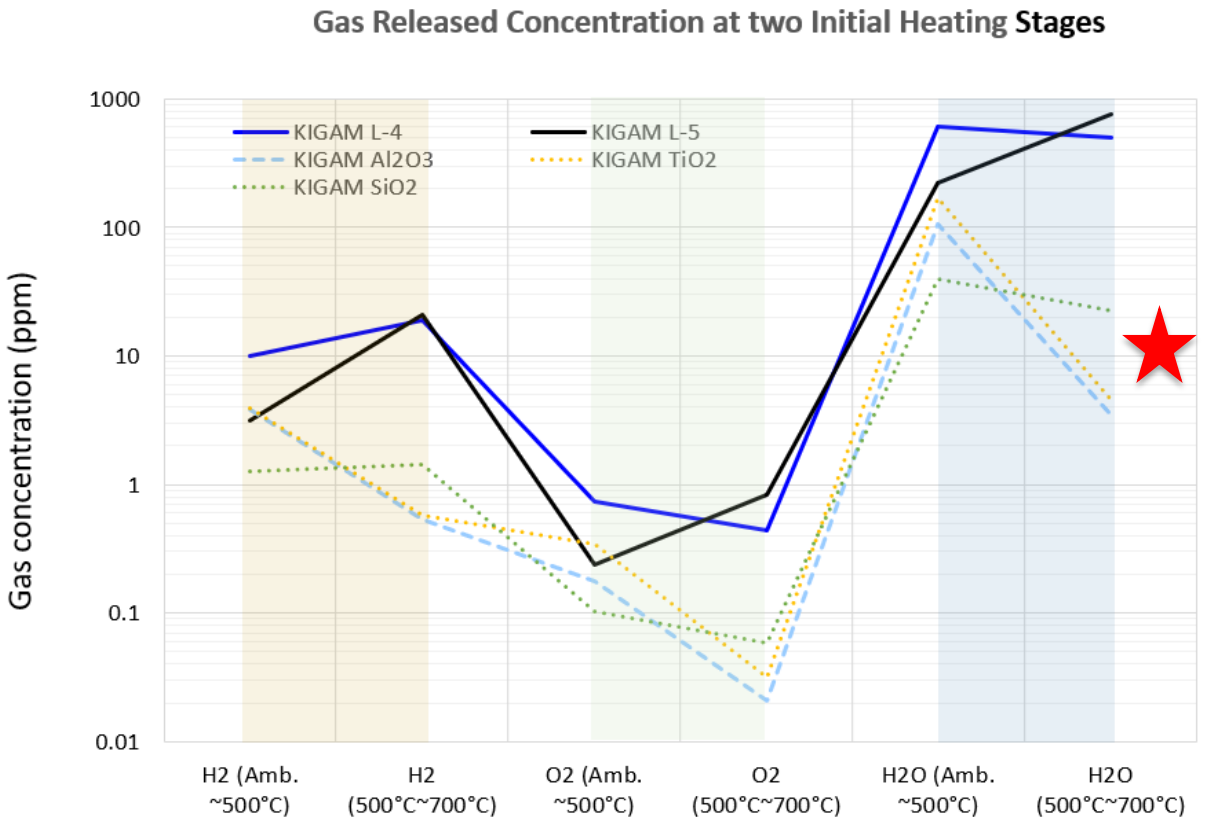
Gas Evolved Amount for Various Samples



Gas Concentrations

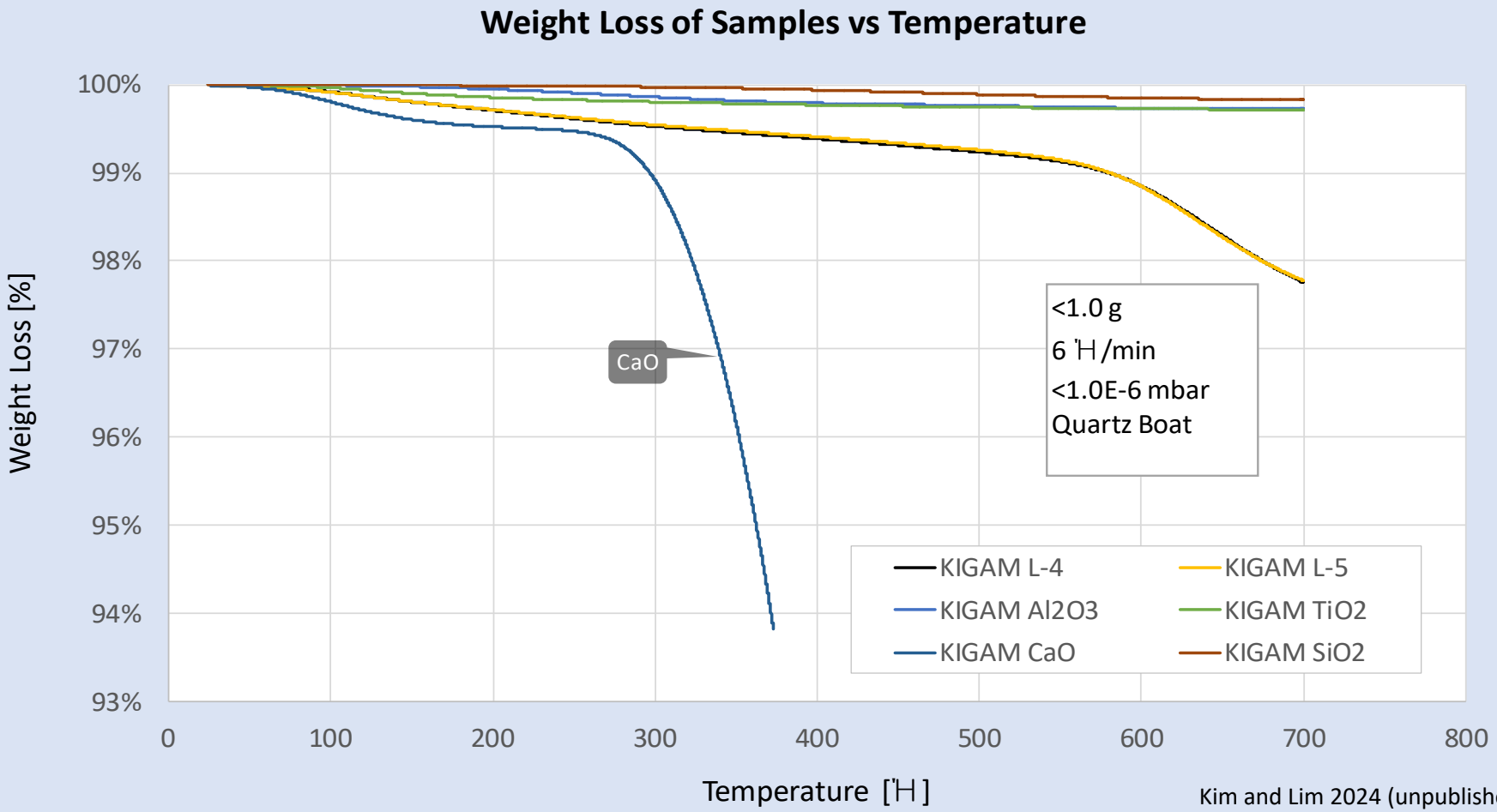
(ppm)

··)° , (! :’	··)° , (! :5, !	! %$0#	⌐·:·)°	·: ⌐W	⌐·:· : ⌐W	⌐·:·)°	·: ⌐W	⌐·:· : ⌐W	⌐·:·)°	·: ⌐W	⌐·:· : ⌐W
⌐·:	1* .:% 1(*0:	⌐·:·	·:··	·:·	·:·	·:·	·:·	·:·	·:·	·:·	·:·
⌐·:	1* .:% 1(*0:	⌐·:·	·:·	·:·	·:·	·:·	·:·	·:·	·:·	·:·	·:·
⌐::(⌐.	4%! /	⌐·:·	·:·	·:·	·:·	·:·	·:·	·:·	·:·	·:·	·:·
⌐:%⌐	4%! /	⌐·:·	·:··	·:·	·:·	·:·	·:·	·:·	·:·	·:·	·:·
⌐: ¸ °	4%! /	⌐·:·	·:··	·:·	·:·	·:·	·:·	·:·	·:·	·:·	·:·
⌐:%⌐	4%! /	⌐·:·	·:·	·:·	·:·	·:·	·:·	·:·	·:·	·:·	·:·



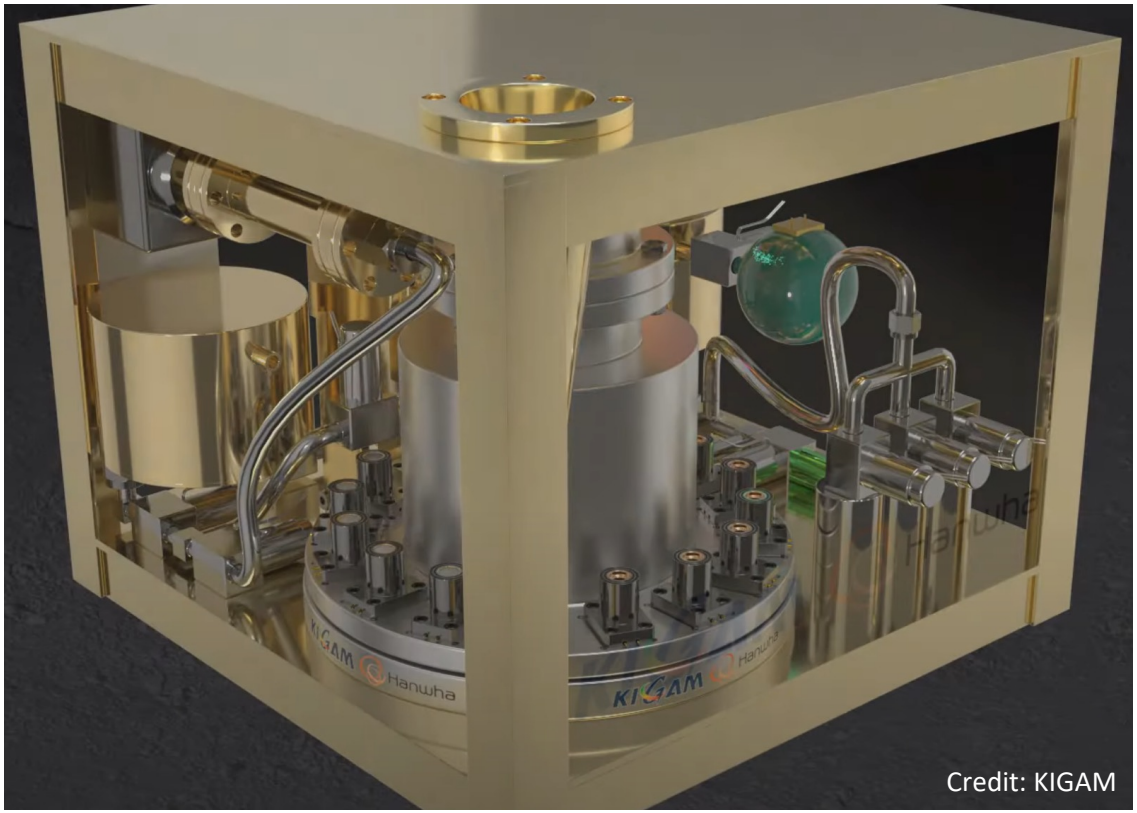
Kim and Lim 2024 (unpublished)

Weight Loss vs Heating Temperature



Kim and Lim 2024 (unpublished)

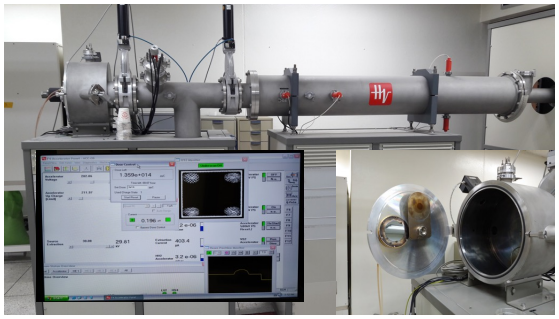
LUnar Volatile Extraction Demonstrator (LUVED)

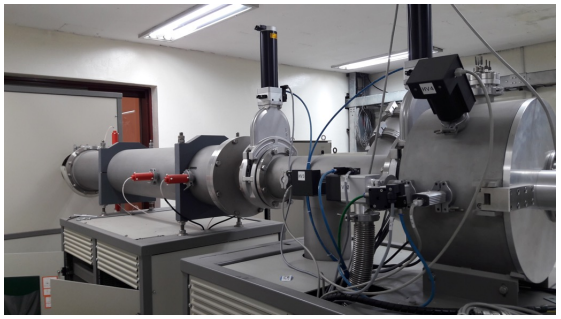


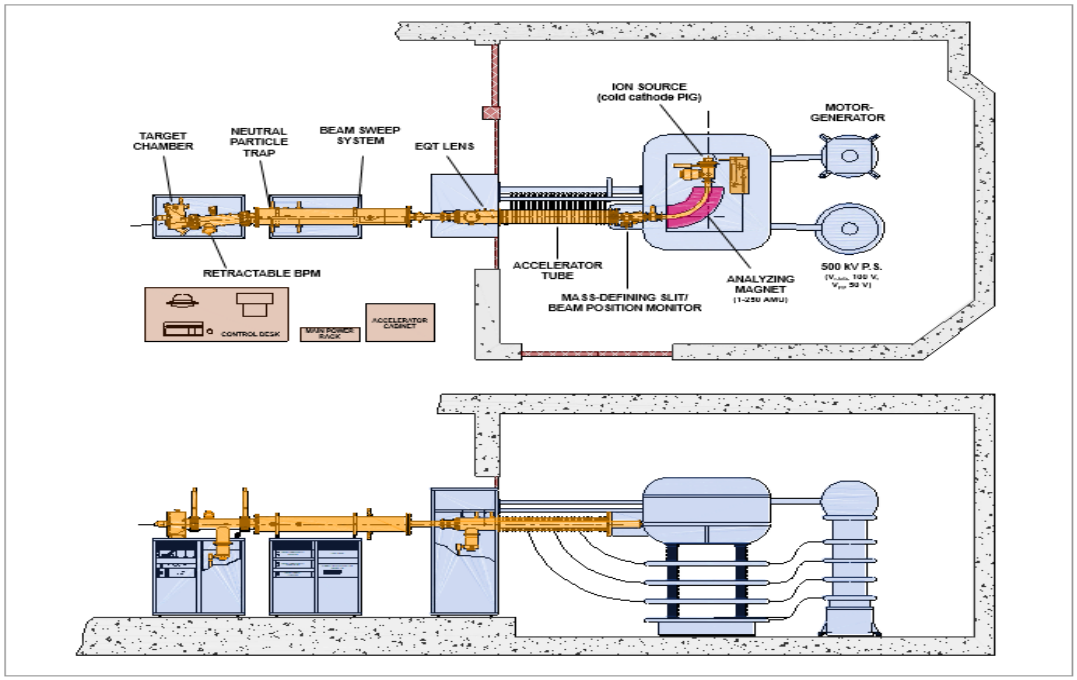
< Major Steps >

- ❖ Heating lunar regolith
- ❖ Analyzing evolved gases
- ❖ Separation techniques for gases, such as oxygen, hydrogen, and water.
- ❖ Testing hydrogen storage capabilities with nanomaterials
- ❖ Capability of In-Situ Resource Utilization (Future Investigation)

500 keV Ion Implanter System at KIGAM







Specifications

Mass range : 1 - 250 amu

Terminal voltage : 10 - 500 kV
- ✓ stability : 100 V
- ✓ ripple : 50 V

X-ray level : < 5 μSv/hr
(with 100 μA Ar beam at max. voltage)

Beam currents (eμA at max. voltage)
- ✓ H^+ : 10
- ✓ H_2^+ : 100
- ✓ He^+ : 150 (He^{2+} : 2)
- ✓ C^+ : 25 (C^{2+} : 1)
- ✓ N^+ : 80 (N^{2+} : 2)
- ✓ O^+ : 65 (O^{2+} : 3)
- ✓ Ar^+ : 150 (Ar^{2+} : 15)
- ✓ Kr^+ : 70 (Kr^{2+} : 8)
- ✓ Xe^+ : 20 (Xe^{2+} : 5)

Metal Beam: Be, B, C, Al, Fe (50~100 μA)

Applications

- ✓ Characterization of space materials and electronics parts
- ✓ Implantation of ions into polymers for reformation
- ✓ High performance test for semiconductors
- ✓ Carbon nanotube reformation

Space Applications

- ✓ Simulation Solar Wind Interactions
- ✓ Produce ion implanted lunar simulant

Preliminary Experiment

Kim and Kim 2024 (unpublished)

- ❖ Energy : 200 keV proton, 1E+18/cm^2
- ❖ Beam Current : 10-20 μA/cm^2
- ❖ Irradiation : 6 hr, 3E+14/cm^2/s
- ❖ Beam Size ID : 2.5 cm
- ❖ Target Thickness: 1 mm

→ **Ion-implanted lunar simulant**

Summary

- ✓ The temperature required for volatile extraction for **LUVED can be <800°C**.
- ✓ **A few lunar simulants for landing site candidates** are needed to be developed.
- ✓ For effective volatile extraction developing **ion-implanted simulant** is useful.
- ✓ The initial melting temperature of Apollo samples were known as over 1000°C [3,4] and refractory minerals require even higher temperatures as ~1600°C [6].
- ✓ However, for volatile extraction from lunar regolith, the required temperature could be approximately 700°C.
- ✓ The experimental data of this study confirms the <800°C, a temperature requirement of the LUVED, which is to extract volatiles from the lunar soil in a mare region of either mid or low latitudes on the Moon.

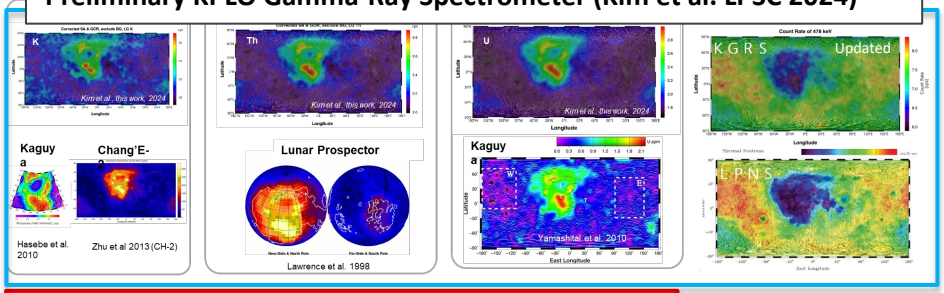
KIGAM's ISRU Research Areas

Credit: KIGAM

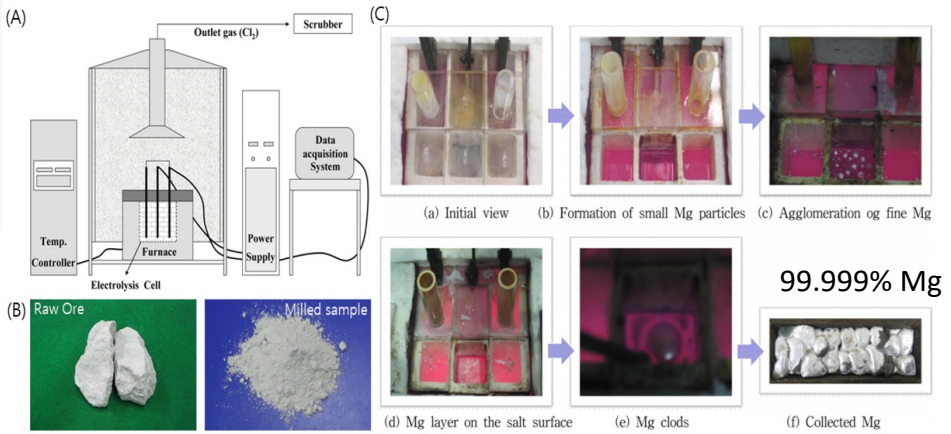
New Developments at KIGAM

KIGAM

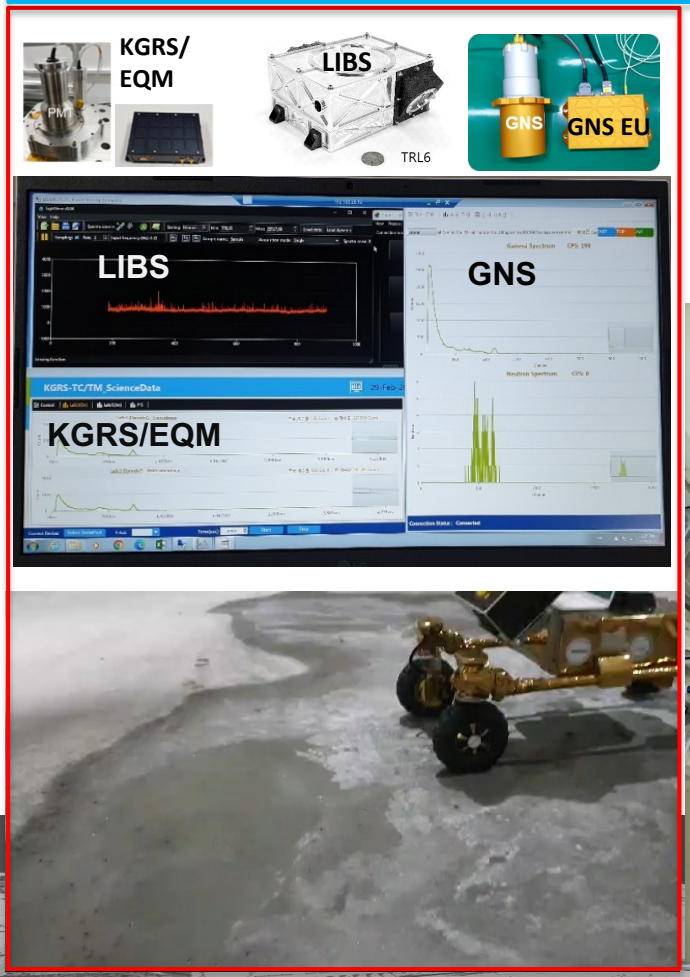
Preliminary KPLO Gamma-Ray Spectrometer (Kim et al. LPSC 2024)

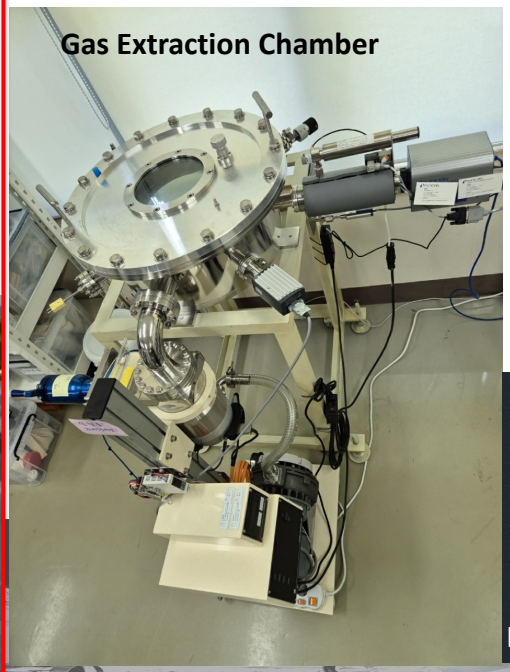


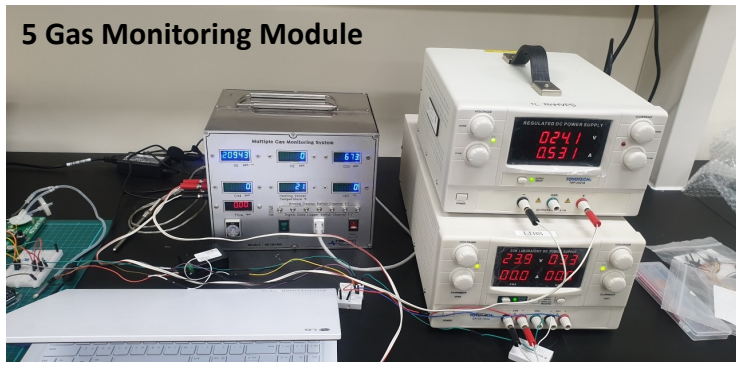
MRE (Molten Regolith Electrolysis)-> Mg production at KIGAM's Lab

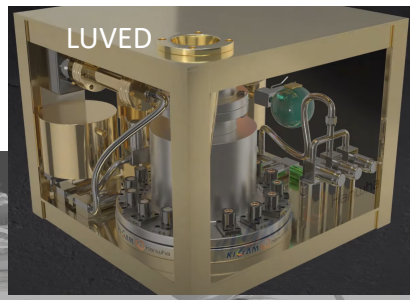


Lee, Tae-Hyuk et al. 2020









References

[1] Gladstone et al. (2010) *Science 330*, 472-476.

[2] Colaprete et al. (2010) *Science 330*, 463-468

[3] Gibson & Johnson (1971) *Proc. LPSC 2*. 1351-1366.

[4] Gibson and Moore (1972) *Proc. LPSC 3*. 2029-2040.

[5] Allen et al. (1996) *JGR 101*. 26,085-26,095.

[6] Schluter and Cowley. (2020) *PSS 181*. 104753.

[7] KIGAM's facility internal document.

[8] Kang et al. (2019). MSc Thesis, CNU.