Research Development for Lunar Volatile Extraction at KIGAM.

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Introduction: Volatile extraction on the Moon is an important task for the future aspect of in-situ resource utilisation, regardless of the location on the Moon. Many experiments have been carried out on the Apollo return samples in a laboratory environment. At present, 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.

Data of Lunar Volatile Extraction: Since the LRO and LCROSS missions, our knowledge of lunar volatiles has been enhanced by new data from LAMP[1] and thermal image from the impact event at the Cabeus [2]. Not only the volatiles themselves, but also the volatile extraction techniques have been re-examined in conjunction with ISRU prospects for future apllications. The updated volatiles in the lunar volatiles on the polar region of the Moon can be important to make a lunar simulant on the polar regions for technological development in ISRU applications. The lunar volatiles available in various publications [3,4] provide a guide to the components of lunar volatiles for volatile extraction in a laboratory environment. The two aspects of volatile extraction with respect to its location associated landing sites are linked for our preparation of lunar simulant towards extraction of volatiles in a laboratory environment.

Experimental Settings on Volatile Extraction: The volatile extraction experiment conducted at KIGAM to design a lunar volatile extraction demonstrator (LUVED) for the Korean lunar lander planned for 2032. We conducted volatile experiments using few lunar simulants and temperature settings associated with solar wind extraction of the lunar regolith. The experimental results were compared with data from volatile extraction experiments performed on the Apollo samples. Our data show that the amount of sample required for the LUVED can be confirmed as the range of sample weights from approximately 200 to 500 mg mg studied with the Apollo samples [3,4]. The initial melting points ranged from 1130°C~1150°C [4]. 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 [5]. Considering these reference temperatures, the heating temperature required for LUVED could be as low as 700°C if no other in situ experiment (such as hydrogen reduction temperatures for Apollo samples at 1050°C [5]) is going to be attempted.

Preliminary Data of Volatile Extraction at KIGAM: Our experiments were conducted on volatile extraction by setting of a heating temperature at 700°C using various lunar simulants and chemical oxides. An IR lamp with a quartz crucible was used to heat samples of either a lunar simulant or a chemical oxide, with a sample weight of approximately 1 g (Figure 1). Figure 2 shows the pressure changes as a function of time during the volatile extraction experiment. Sample heating was initiated when the pressure reached 2.6 x 10^{-7} mbar. The heating rate was set at 20.0°C/min. The temperature was maintained at 700°C for 10 minutes. After that, the chamber was allowed to cool down at the same rate. During this process, 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 (Figure 2).

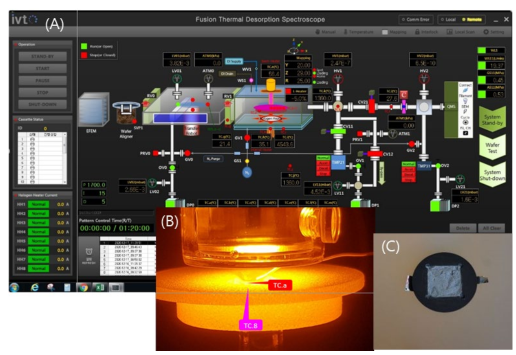

Figure 1. Experimental setup for volatile extraction

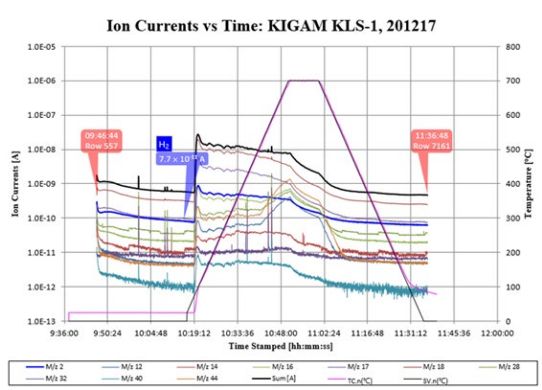

Figure 2. Ion current of gas release as a function of time and temperatuare.

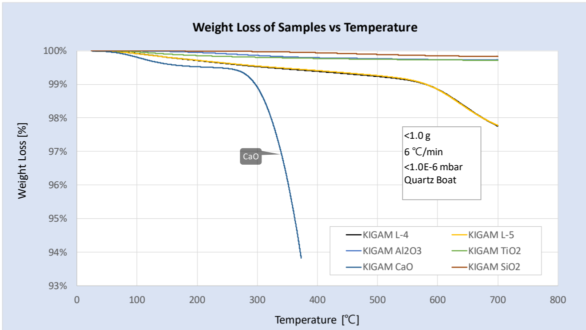

Figure 3. Weigh loss of samples as a function of temperature.

Table 1. Gas release with respect to initial heating periods.

Sample ID	Sample Type	Weight(g)	H_2 (amb ~500°C)	H_2 (500 ~700°C)	O_2 (amb ~500°C)	O_2 (500 ~700°C)	H_2O (amb ~500°C)	H_2O (500 ~700°C)
KIGAM L-4	Lunar Simulant (LH)	0.9486	9.88E+00	1.90E+01	7.27E-01	4.43E-01	6.09E+02	5.01E+02
KIGAM L-5	Lunar Simulant (LH)	0.9367	3.12E+00	2.08E+01	2.36E-01	8.31E-01	2.21E+02	7.65E+02
KIGAM Al_2O_3	Oxides	0.9687	3.79E+00	5.37E-01	1.75E-01	2.07E-02	1.06E+02	3.46E+00
KIGAM TiO_2	Oxides	0.9788	3.88E+00	5.69E-01	3.44E-01	3.16E-02	1.67E+02	4.49E+00
KIGAM CaO	Oxides	0.9746	3.58E+01	0.00E+00	1.91E+00	0.00E+00	4.52E+03	0.00E+00
KIGAM SiO_2	Oxides	0.9594	1.26E+00	1.41E+00	1.02E-01	5.86E-02	3.94E+01	2.27E+01

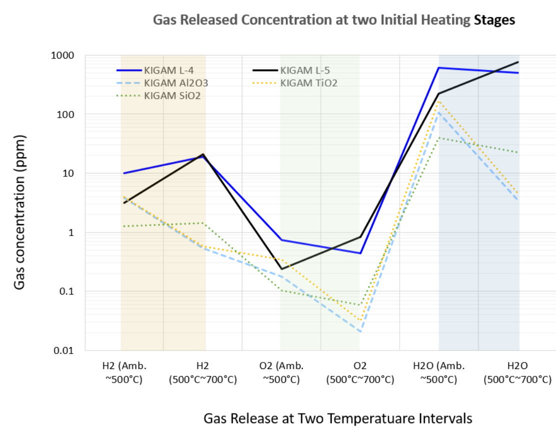

Figure 4. Gas released at two initial heating stages.

The results of the preliminary volatile extraction work demonstrated that heating lunar simulant up to 700°C would release volatiles implanted in fine rock materials (Table 1, Figures 3 & 4). The gas release from lunar highland simulant and chemical oxides showed distinct differences in the release of H_2, O_2 and H_2O (Table 1, Figure 4). Gas release due to moisture absorbance was clearly demonstrated by weight loss at temperatures below 400°C, as seen with the CaO sample (Figure 3). The weight losses observed in KIGAM LS-4 and LS-5 samples are interpreted as the mineral component of olivine. 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 700°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.

The main purpose of the LUVED, if selected as a payload of the lander is to demonstrate the identification of lunar volatiles at the landing site and applying filtration techniques for gases, such as oxygen, hydrogen, and water. Additionally, testing hydrogen storage capabilities with nanomaterials is planned. This method can be used for future In-Situ Resource Utilization (ISRU) applications at any location on the Moon.

Ion Implantation for the Development of Lunar Simulants: In a laboratory, an extraction of synthetic volatiles can be feasible using a lunar simulant that closely resembles the lunar regolith on the Moon in terms of its location. Therefore, lunar simulants at both mid-low latitudes and polar regions could be studied separately. We propose lunar simulants that include ion implantation, mimicking the implantation of various solar-wind particles. This activity will allow a more accurate lunar volatile extraction experiment in a laboratory environment prior to the event of in-situ resource extraction on the Moon. The 500 MV ion implanter at KIGAM has been used for various space and materials science applications for ion implantation on a surface material [6]. The ions available for this experiment are H^+, H_2^+, $^4He^+$, $^3He^+$, C^+, N^+, O^+, Ar^+, Kr^+, and Xe^+, in the energy range of 300 keV to 8 MeV ions, depending on the ion source, with the desired implantation taking into account the irradiation time and flux. The ion-implanted lunar simulant could provide new insights in a more efficient and accurate experimental settings in in-situ volatile extraction with respect to the factors of solar wind particle implantation on the lunar surface. Both composition and environmental characteristics can be considered in developing ion implanted lunar simulant for future ISRU research applications.

Future Plans: Volatile implanted lunar simulants are useful for resource extraction in a laboratory environment. The production of lunar simulants for different landing sites in terms of resource extraction and utilization is invaluable for the development of both small ISRU payloads and larger ISRU extraction devices. We propose this work for the near future.

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.

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