

VOLATILE TRAPPING BY LUNAR REGOLITH: EXPERIMENTAL RESULTS AND SUGGESTIONS FOR FUTURE MISSIONS. E. L. Patrick, K. E. Mandt, B. D. Teolis, Southwest Research Institute (6220 Culebra Rd., San Antonio, TX 78238 epatrick@swri.edu).

We compare results of the exposure of Apollo 11 lunar sample #10084, lunar regolith simulant JSC-1A, and mineral oxides SiO and CaO to various gases under ultrahigh vacuum (UHV) conditions to monitor and compare retention effects relevant to the trapping of volatiles at the lunar surface. Gases used included He, Ne, Ar, Kr, Xe, CO, CO₂, O₂, N₂ and CH₄.

Introduction: The measurement of volatiles ejected from the lunar South Pole by the LCROSS impactor[1] contrasted sharply with decades-old assumptions regarding volatiles at the lunar near surface from Apollo-era measurements. Gas behavior on the Moon was first observed by video recording of vernier engine plumes of Surveyor 5 impinging upon the lunar surface nearly two years prior to the Apollo 11 landing[2]. However, observation of gas escaping the lunar surface did not preclude the possibility that rocket exhaust could have become trapped long term in the exposed regolith. In fact, experiments on lunar samples taken from near the Apollo 11 Lunar Module (LM)[3,4] released N₂ that we have been unable to trap under laboratory conditions using the simulant JSC-1A. Here we also report results for volatile exposure to Apollo 11 sample 10084, SiO, and CaO that supplement our previous investigations of volatile exposure to JSC-1A[5,6].

Investigations of Returned Samples: In the temperature programmed desorption (TPD) experiments of Gibson & Johnson[3], returned A11 lunar “soil” sample 10086 taken from near the landed LM produced a gas evolution peak for N₂ not observed in similarly-treated A12 sample 12023 taken from over 150 meters away. Furthermore, the characteristic mass 28 peak for N₂ in the scan of the quadrupole mass spectrometer (QMS) occurred immediately upon heating above room temperature[3]. Simultaneous occurrence of a mass 14 peak distinguished the 28 signature from possible interfering mass peaks of CO and C₂H₄.

Henderson et al.[4], seeking to identify organic compounds in lunar samples, also observed mass 28 in 10086 using a gas chromatograph mass spectrometer (GCMS) and revealing the concentration of N₂ to be 35 times higher than that of CO in the 28 mass channel. Trace ethylene (C₂H₄) at mass 28 was also identified. The Henderson et al. GCMS technique used hydrogen fluoride gas (HF) to “demineralize” the sample. In contrast to the N₂ peak quickly released upon heating during the TPD of Gibson & Johnson[3], the release of N₂ was the result of a destructive chemical process during the GCMS analysis of Henderson et al.[4] Amino acids

were also detected. Results from recent more sensitive LCMS and GCMS experiments by Elsila et al.[7] characterized the detection of amino acid contamination in lunar samples. Both of these investigations suggested contamination from the Apollo spacecraft as a likely source for a number of observed signatures.

No Gas Detection from Lunar Orbit: In December 2013, the Chinese Chang’E-3 lunar spacecraft landed and deployed its Yutu rover during operation of the Neutral Mass Spectrometer (NMS) aboard NASA’s orbiting Lunar Atmosphere and Dust Experiment Explorer (LADEE). A lack of detection by the LADEE NMS of any gas signature from the Chinese Chang’e-3 spacecraft not only suggested that closer scrutiny of earlier Apollo-era gas detection at and above the lunar surface was warranted, but also introduced the possibility that gases transported across the lunar surface may experience significant interaction and retention with the highly-active surfaces of regolith grains.

Gas Detection from the Lunar Surface: The Cold Cathode Gauge Experiment (CCGE), deployed to the lunar surface during Apollos 12, 14 & 15, measured the pressure of that tenuous ambient atmosphere[8]. The A12 CCGE failed to saturate during venting of the cabin, but did saturate as astronaut Pete Conrad walked away from it, a pressure signature likely due to water vapor from his backpack beaming into the ion source inlet of the gauge as we have previously reported[6].

Results: Previously, we presented results that included a time analysis of the pressure response of the Apollo 12 CCGE[6], as well as pressure profiles resulting from exposure of JSC-1A lunar soil simulant to multiple gases. Here we include recent observations of gas dosing of the curated lunar sample 10084, and the mineral oxide phases SiO and CaO.

Although the mass 28 peak produced during the TPD of Gibson & Johnson[2] was identified as contamination and attributed to N₂, no source of contamination was identified, nor was any mechanism suggested for retention of N₂ within the sample. Furthermore, we have found no retention of N₂ in JSC-1A lunar soil simulant in numerous laboratory experiments[5,6].

Recent results produced curious pressure responses in other materials (Figure 1) that could be related to sample composition, grain size, or sample properties not yet elucidated. Preliminary results for gas dosing of lunar sample 10084 will also be presented and compared to results from JSC-1A, SiO, and CaO.

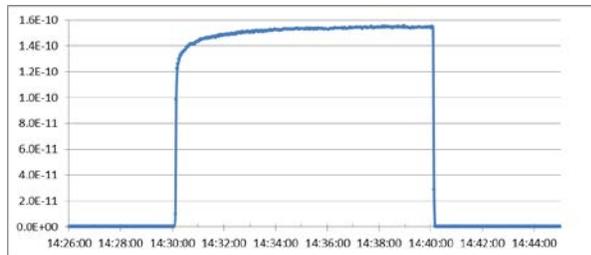


Figure 1. Ten minute He gas pulse exposure to CaO. The unexpected time constant required to achieve equilibrium pressure suggested some gas retention feature, yet no subsequent gas release feature is observed upon immediate removal of the He at the 10 minute mark.

Discussion & Conclusions: Questions concerning how regolith functions to trap gases from both above and below the lunar surface motivated our experiments, and the gases used included those expected to represent contamination byproducts from spacecraft (exhaust, outgassing, etc.), those delivered to the lunar surface by impactors (comets, meteoroids), and those escaping from the lunar interior (radiogenic Ar).

Sources of Contamination: The potential for sample contamination from artificial sources at each Apollo site during the missions was significant. Potential sources included engine exhaust products, outgassing spacecraft components and surfaces, deployed instrumentation, multiple cabin atmosphere depressurizations, and water “coma” from astronaut backpacks. We summarize these and what their impact may mean for future missions to the lunar surface.

Suggestions for Future Missions: Supplementing our results, we conclude with recommendations for future investigations of the lunar surface with implications for further in situ resource utilization (ISRU) studies of lunar volatiles and their potential contribution to long-term human presence on the Moon.

1. **Regolith Contamination Control:** Contamination factors for regolith surfaces need to be elucidated. Samples are not pristine if sprayed by rocket exhaust, cabin air, and water vapor.
2. **Remote Sensing of Past Landing Sites:** Does any evidence remain of spacecraft volatiles transported to the lunar surface? If N_2 can become trapped in lunar regolith, how long can it survive? Investigations of old landing sites (Surveyor 1), or recently discovered impact sites (A17 LM ascent stage), could reveal secrets of volatile retention with implications for the preserved paleoc cosmic record and its contamination by artificial sources.

3. **Artificial Impactor Lesson from LCROSS:** Impacts by known masses and materials could produce plumes indicative of the true lunar surface composition and aid in the study of impacts from comets, asteroids and meteors. A 1 kg impactor of pure Cu and known velocity could be used to produce a crater of predictable size and ejecta volume and provide unambiguous detail of the inventory of near subsurface volatiles to previously-deployed sentinel instruments at the surface.
4. **Investigate Lunar Skylights:** These natural entrances into the lunar interior now number over two hundred[9]. Are these a means of access to more refractory volatiles within the Moon’s interior that have survived its formation history?
5. **High Resolution Mass Spectrometry:** Analytical chemistry of the lunar exosphere from orbiting spacecraft began with the Lunar Atmospheric Mass Spectrometer Experiment (LOMSE) aboard A15[10] & A16[11]. Data included measurements of Ne, CO_2 & H_2O . The LADEE NMS more recently measured the presence of a number of atomic species (O, Na, Cl, K)[12]. Fast, high-resolution mass spectrometers can separate interfering peaks of atoms and molecules in the lunar exosphere to unambiguously reveal such sputtered atomic species as Al, Si, S & Ca.
6. **Return Mass Spectrometry to the Lunar Surface:** The A17 Lunar Atmospheric Composition Experiment (LACE) remains the only mass spectrometer[13] placed at the lunar surface. In light of current knowledge regarding lunar volatiles, it is surely past time for returning such an instrument to the Moon.

References: [1]Gladstone, G. R., et al., *Science* 330, 472 (2010). [2]Christensen, E. M., et al., *JGR* 73, 7169-7192 (1968). [3]Gibson E. K. and Johnson S. M., *LPS II*, 1351-1364 (1971). [4]Henderson W. et al., *LPS II*, 1901-1912 (1971). [5] Patrick et al. *Icarus* 255, 30-43 (2015). [6]Patrick et al., *LPSC 47*, 2649 (2016). [7]Elsila, et al., *Geochim. Cosmochim. Acta* 2, (Suppl. 4), 2241-2248. [8]Johnson F.S. et al. (1970) *A12 PSR*, 93-97. [9]Wagner R. V. and Robinson M. S., *Icarus* 237, 52-60 (2014). [10]Hoffman J.H. et al. (1972) *A15 PSR* 19-1. [11]Hodges R.R. et al. (1972) *A16 PSR*, 21-1. [12]Hurley D.M. (2014) *LPSC 45*, 2160. [13]Hoffman J.H. et al. (1973) *A17 PSR*, 17-1.

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