Gas Characterization During Thermal Treatment of Regolith Simulants in a Vacuum Environment

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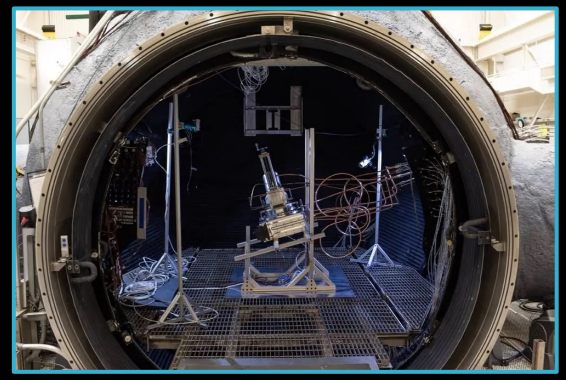
Regolith Processing at Kennedy Space Center

Lunar soil

HEAT/PROCESSING

Resource Extraction



CaRD at JSC (O_2 Extraction)

MRE (O_2/Metal Extraction)

Construction/Manufacturing

Regolith Simulants

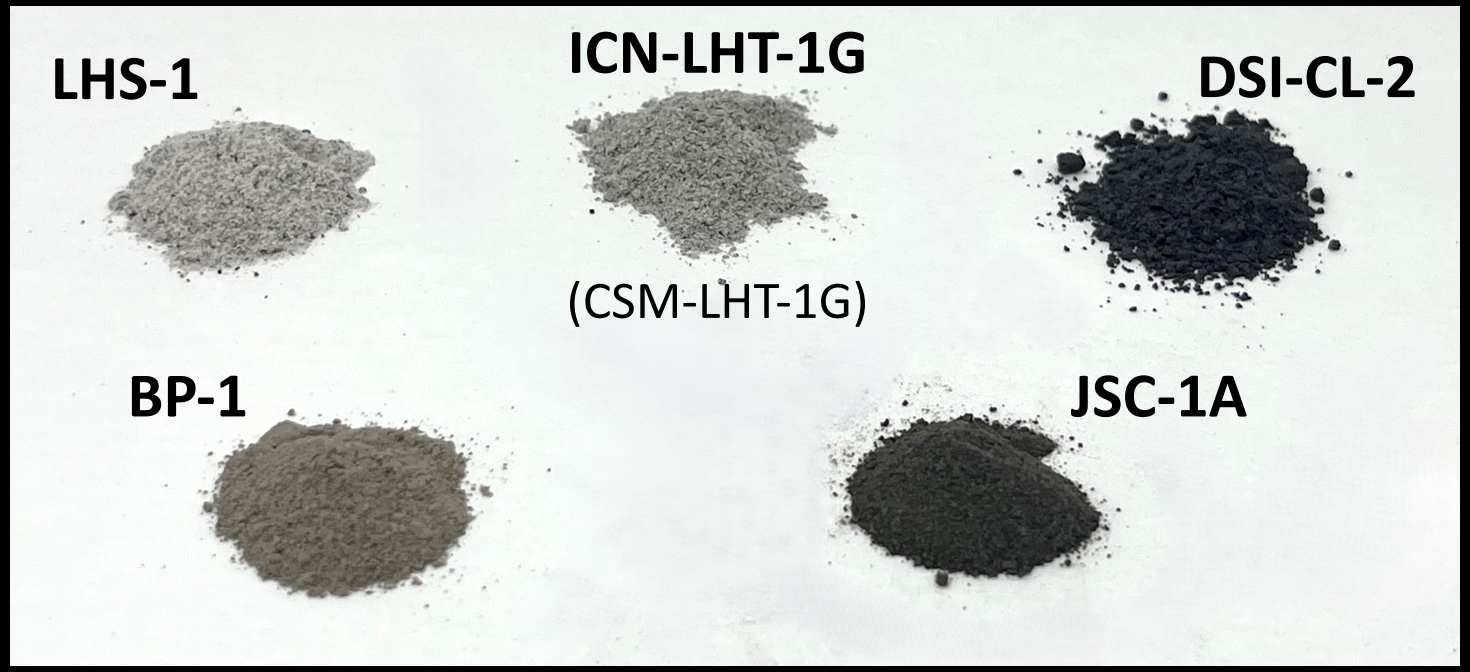
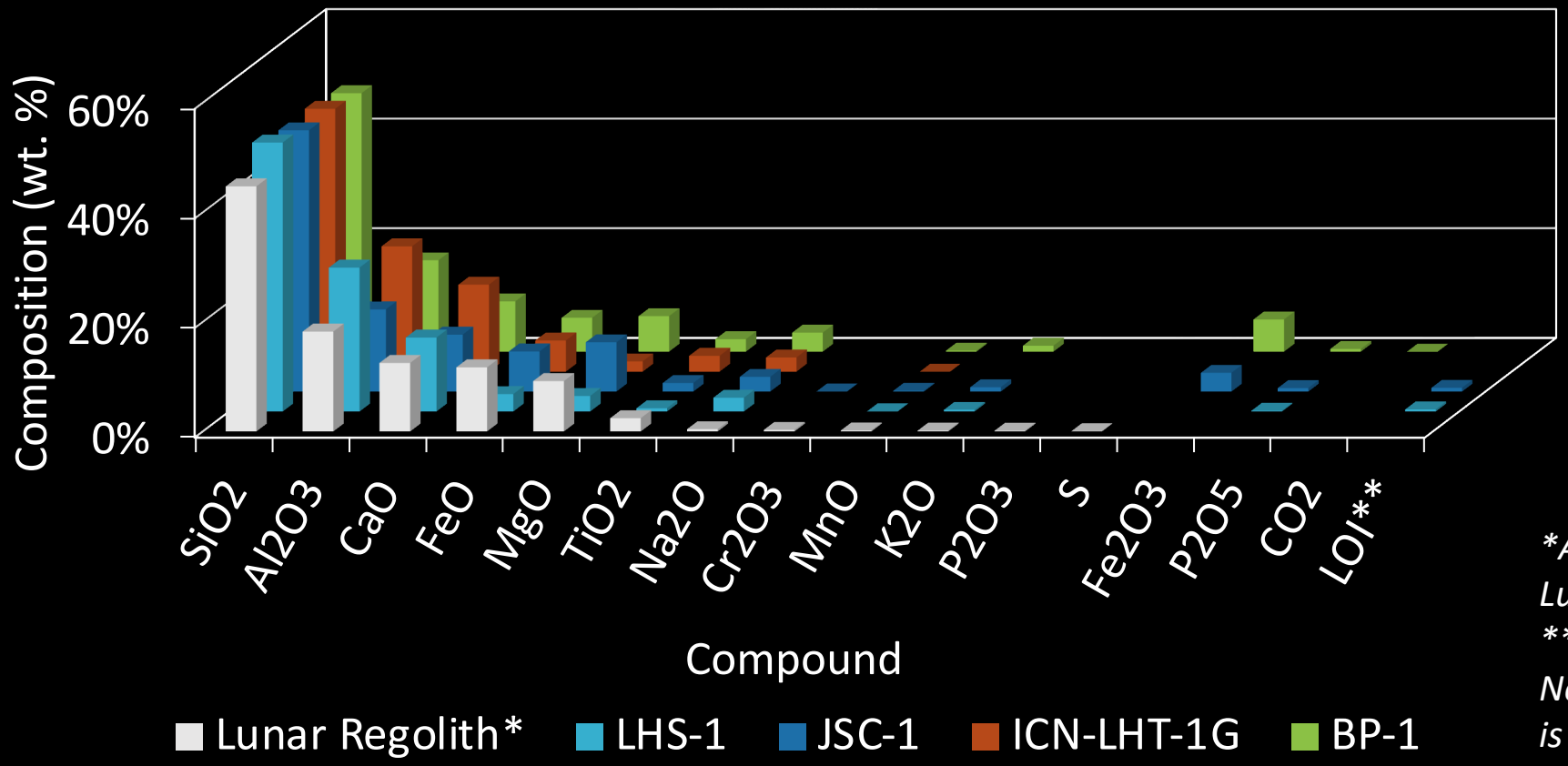


Image of regolith simulants used in study

- **LHS-1**
  A lunar highlands simulant from Exolith Labs
- **JSC-1A** (Johnson Space Center)
  Low-Ti basaltic ash
- **ICN-LHT-1G** (also known as CSM-LHT-1G)
  Sourced from the same area as JSC-1A
- **BP-1**
  Lunar simulant sourced from an aggregate quarry
- **DSI-CL-2**
  Simulant of the Orgueil asteroid obtained from Exolith Labs

[1] Jared L. and Daniel T. B. (2023) Front. Space Technol., 4:1255535. [2] David S. M. et al., (1994) Eng. Construct. and Op. in Space, 4, 857-866 [3] Laurent S. et al. (2019) Lunar ISRU Workshop [4] D. B. S. et al. (2010) NASA TM, 216444 [5] Ane S. et al. (2024) NASA STI Pro-gram [6] Philip T. M. et al. (2019) Icarus, 321, 632-646.

Lunar Simulant Chemistry Comparison



*Bulk Chemistry of **lunar** regolith simulants as provided by vendors compared to lunar regolith. [1-6]*

**Averaged American Apollo and Soviet Luna mission samples*
***LOI: Loss on Ignition*
Note: DSI-CL-2 is an asteroid simulant and is intentionally excluded from this chart

[1] Jared L. and Daniel T. B. (2023) Front. Space Technol., 4:1255535. [2] David S. M. et al., (1994) Eng. Construct. and Op. in Space, 4, 857-866 [3] Laurent S. et al. (2019) Lunar ISRU Workshop [4] D. B. S. et al. (2010) NASA TM, 216444 [5] Ane S. et al. (2024) NASA STI Pro-gram [6] Philip T. M. et al. (2019) Icarus, 321, 632-646.

Testing Apparatus

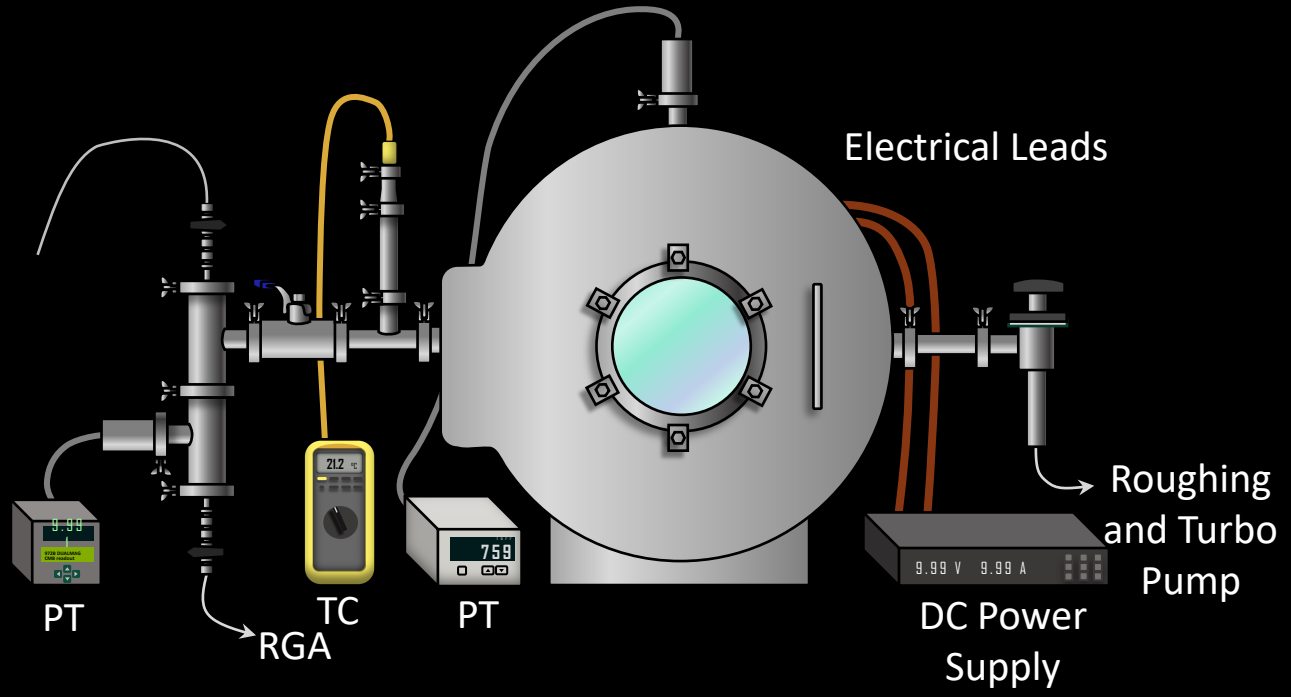


Diagram of test system setup

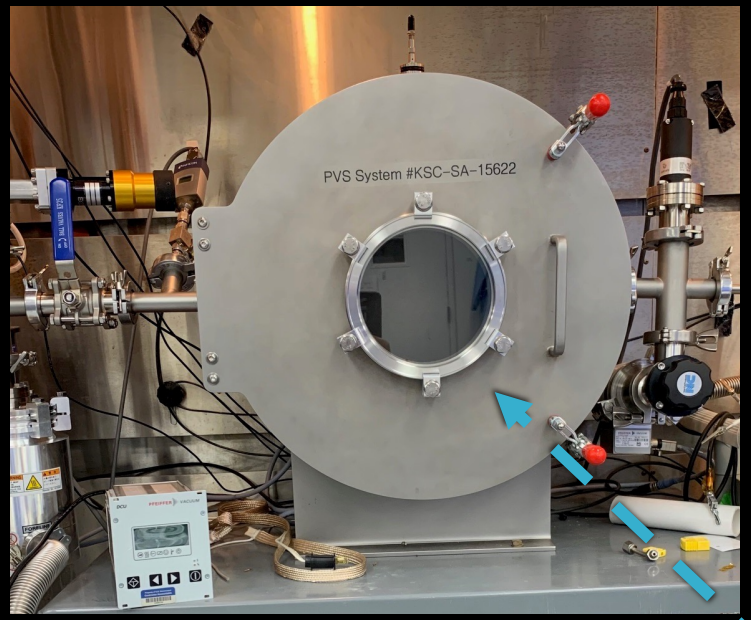
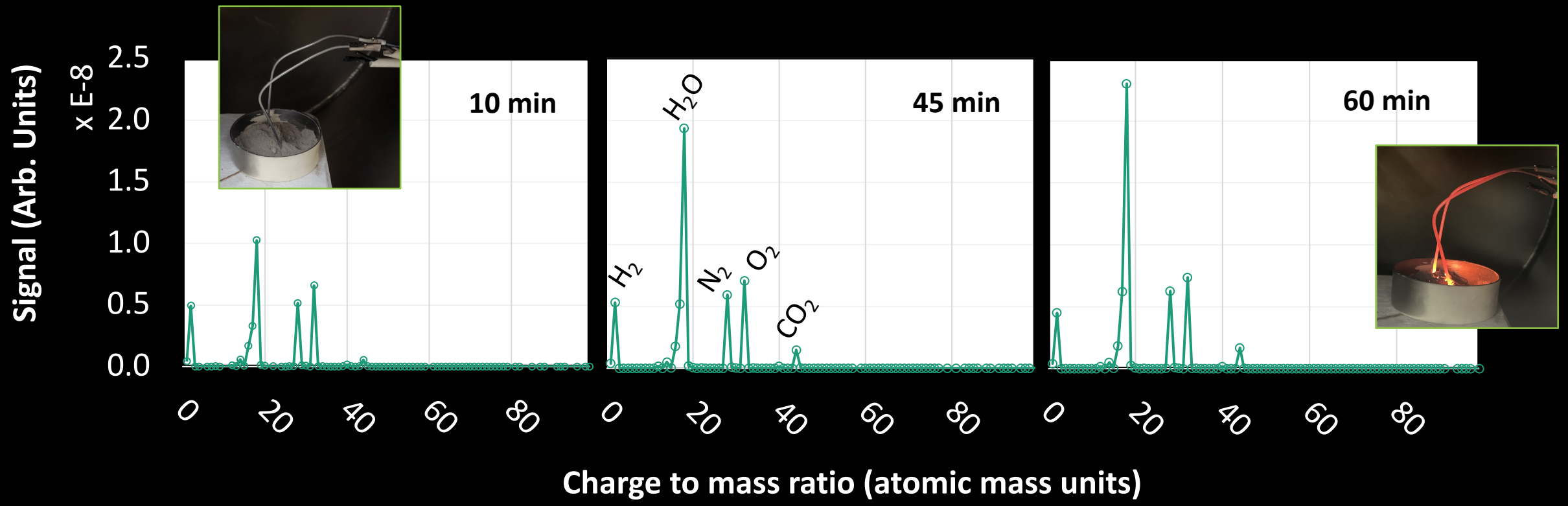


Image of vacuum chamber setup

Regolith loaded crucible during testing

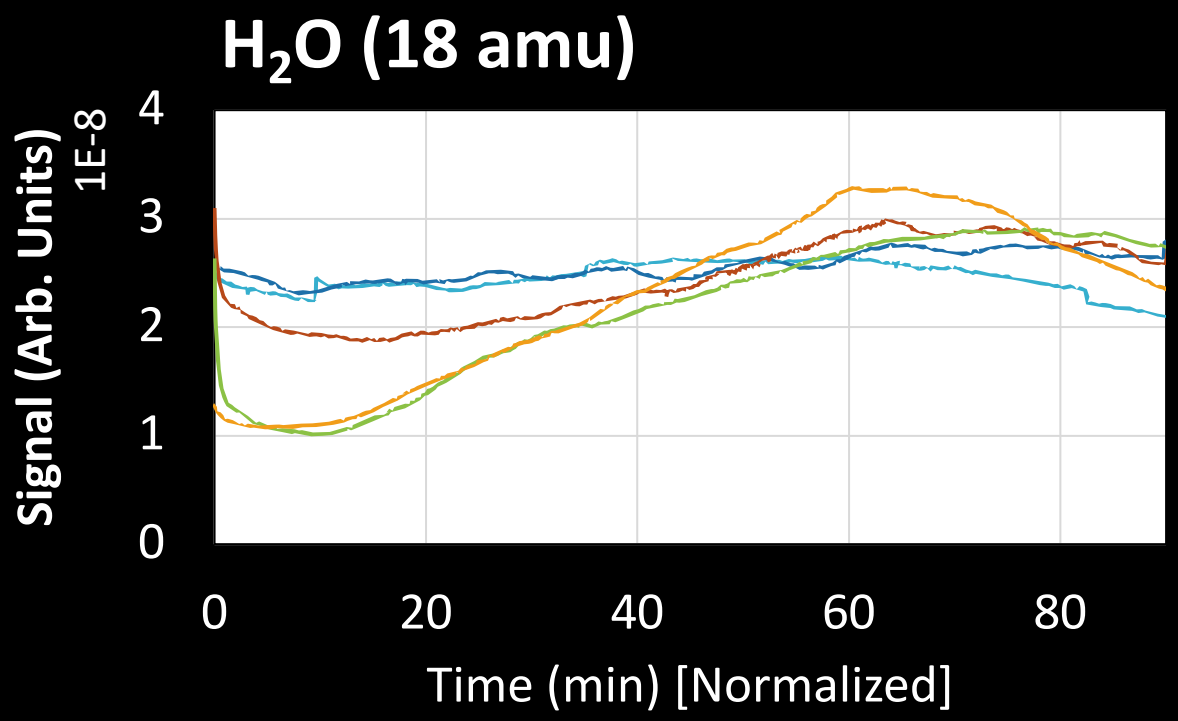
Residual Gas Analyzer (RGA)

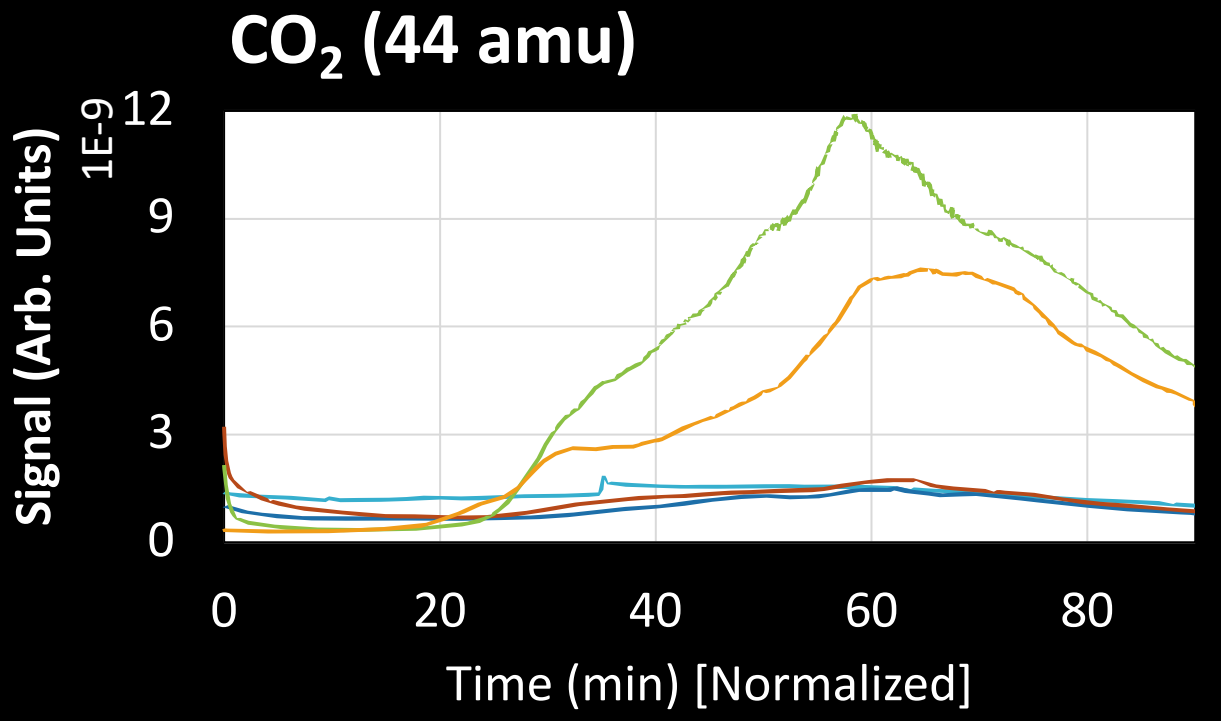
A residual gas analyzer (RGA) was used to qualitatively monitor gas constituents inside of the vacuum chamber during regolith simulant heating via charge to mass ratio.



Example of RGA spectra during thermal treatment of ICN-LHT-1G regolith. Snapshots taken at 10, 45, and 60 minutes displayed on the left, middle, and right plots, respectively.

Gas Evolution Characterization

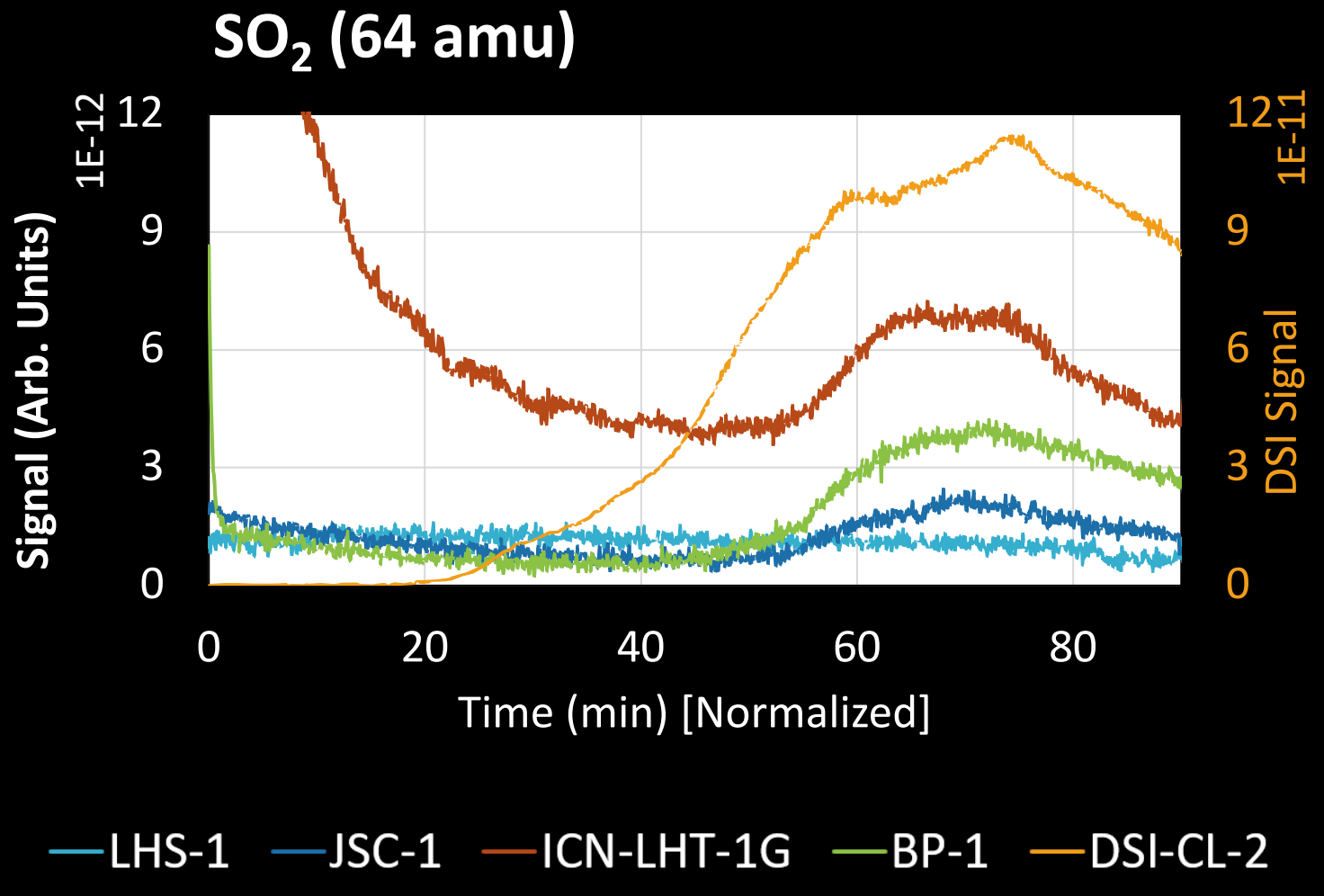




LHS-1 JSC-1 ICN-LHT-1G BP-1 DSI-CL-2

Evolution of gaseous H_2O and CO_2 during thermal treatment

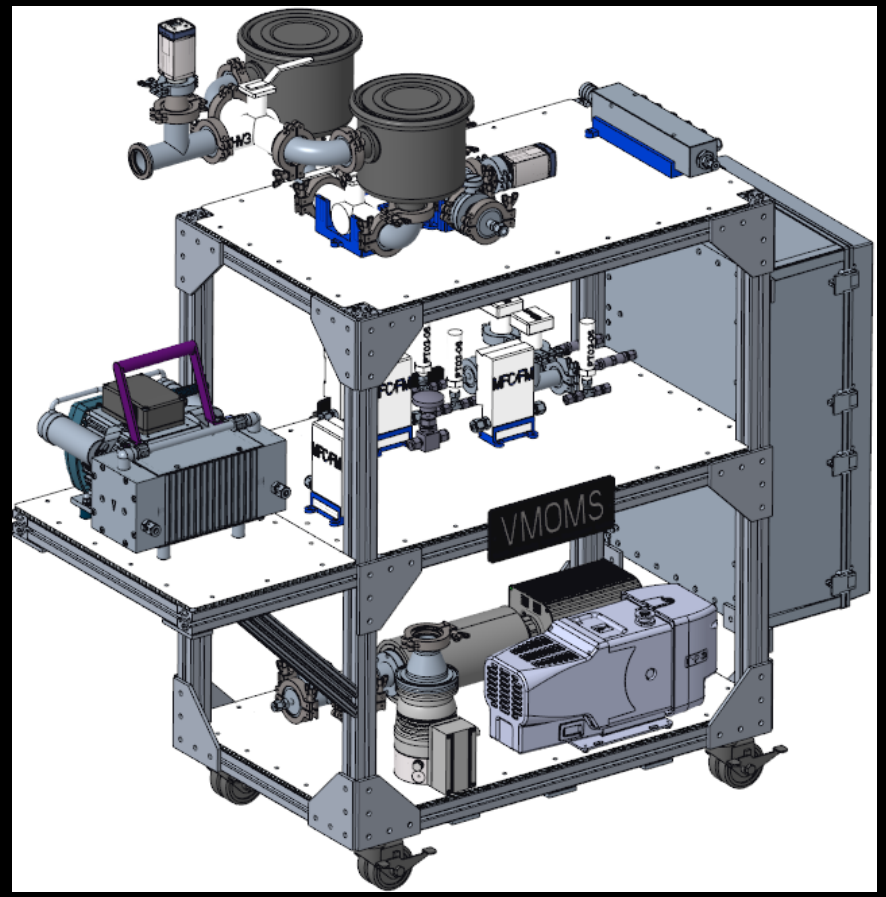
Sulfur Containing Compounds



- Sulfur compounds tend to be corrosive
- All regolith simulants displayed a peak at 64 amu
- DSI-CL-2 simulant had the largest 64 amu signal

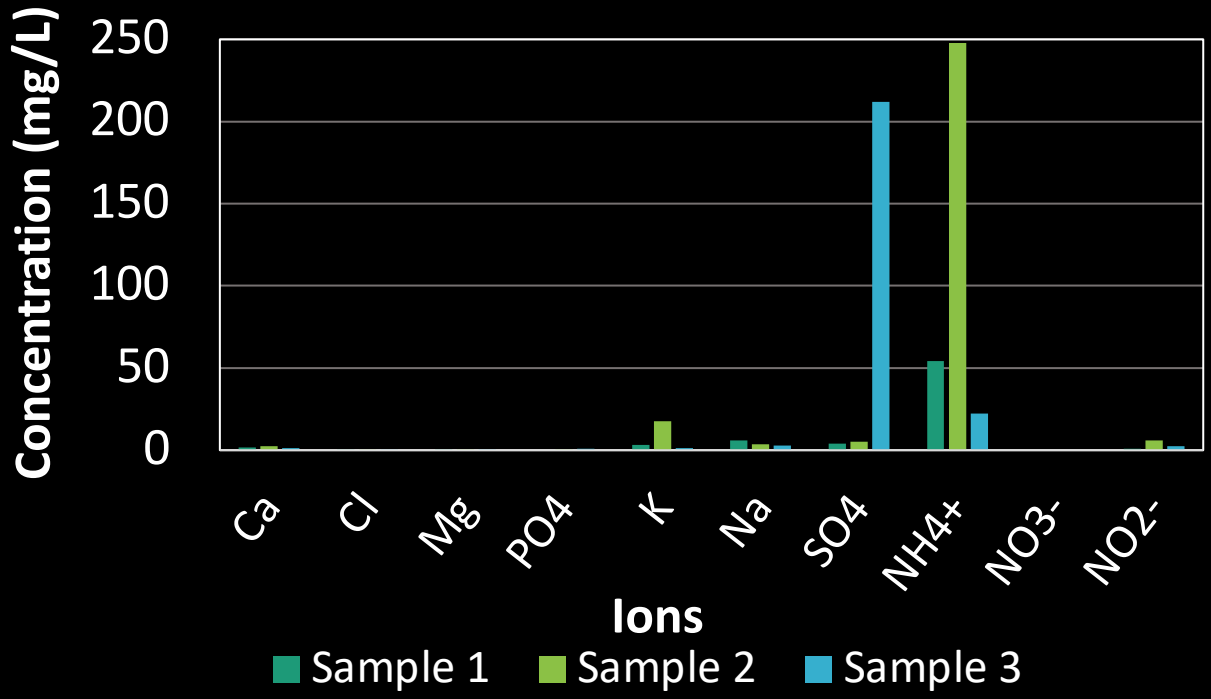
Sulfates from MRE

VMOMS



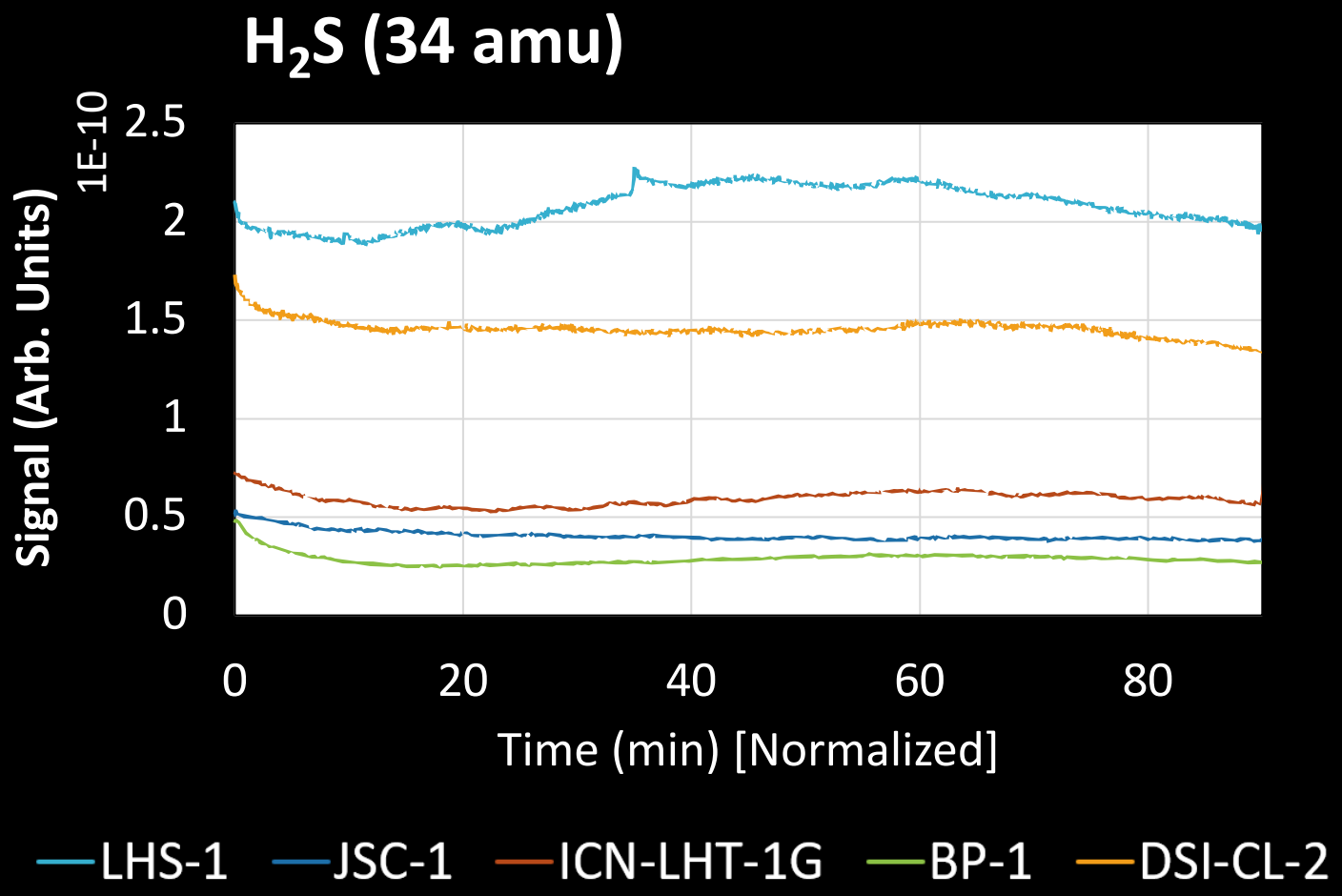
CAD of VMOMS (Volatile Monitoring and Oxygen Measurement System) design

Ion Chromatography



- Samples 1, 2, and 3 were taken chronologically
- Increasing concentration of absorbed sulfates
- Last sample contained >200 ppm

Sulfur Containing Compounds



- Signals and peaks are not as strong in comparison to SO_2
- Residual water may act as a hydrogen source to form H_2S

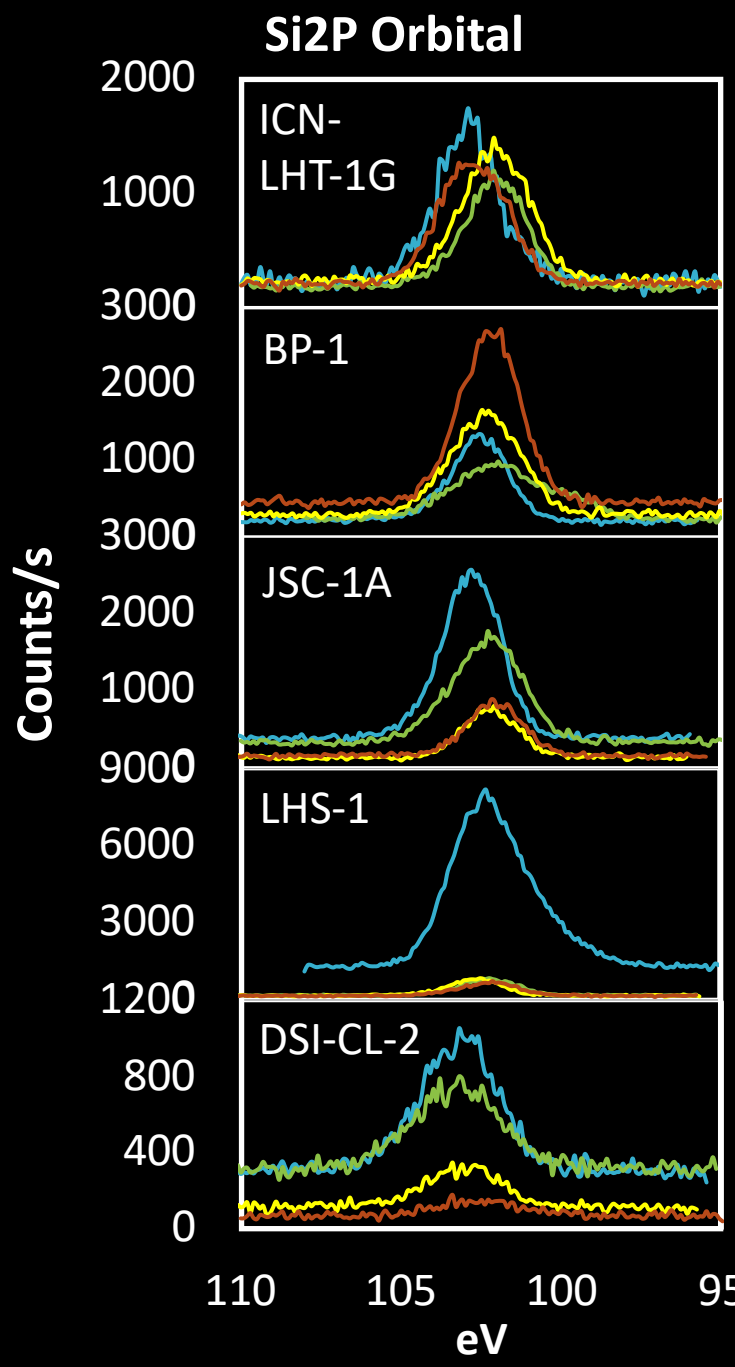
Chemical Analysis

X-ray Photoelectron Spectroscopy

- Measures surface chemistry
- Suggests silicon reduction
- Shifts in XPS data were normalized to carbon

Dissociation energy of silica, alumina, and magnesium oxide [7]

Dissociation Equations	BDE @ 0K (kJ/mol)
SiO_2 + Heat → SiO (g) + ½ O_2 (g)	707.6
Al_2O_3 + Heat → Al_2O_2 (g) + ½ O_2 (g)	1030
MgO + Heat → Mg (g) + ½ O_2 (g)	418.7



Oxidized peaks appear at 103 eV with metal peaks at 99 eV [8]

[7] John M. (2006) George Washington University
[8] https://www.thermofisher.com/us/en/home/materials-science/learning-center/periodic-table/metalloid/silicon.html

Key Takeaways

Source Material Variations

- Terrestrial sourcing has inherent limitations/differences

Sulfur

- SO_2 and H_2S were detected with varying signals between simulants

Chlorine

- Earlier recipe of LHS-1, chlorine compounds were observed (35, 37 amu)
- More recent LHS-1 recipe used in this study did not result in the detection of chlorine

LCROSS

Lunar Crater Observation and Sensing Satellite

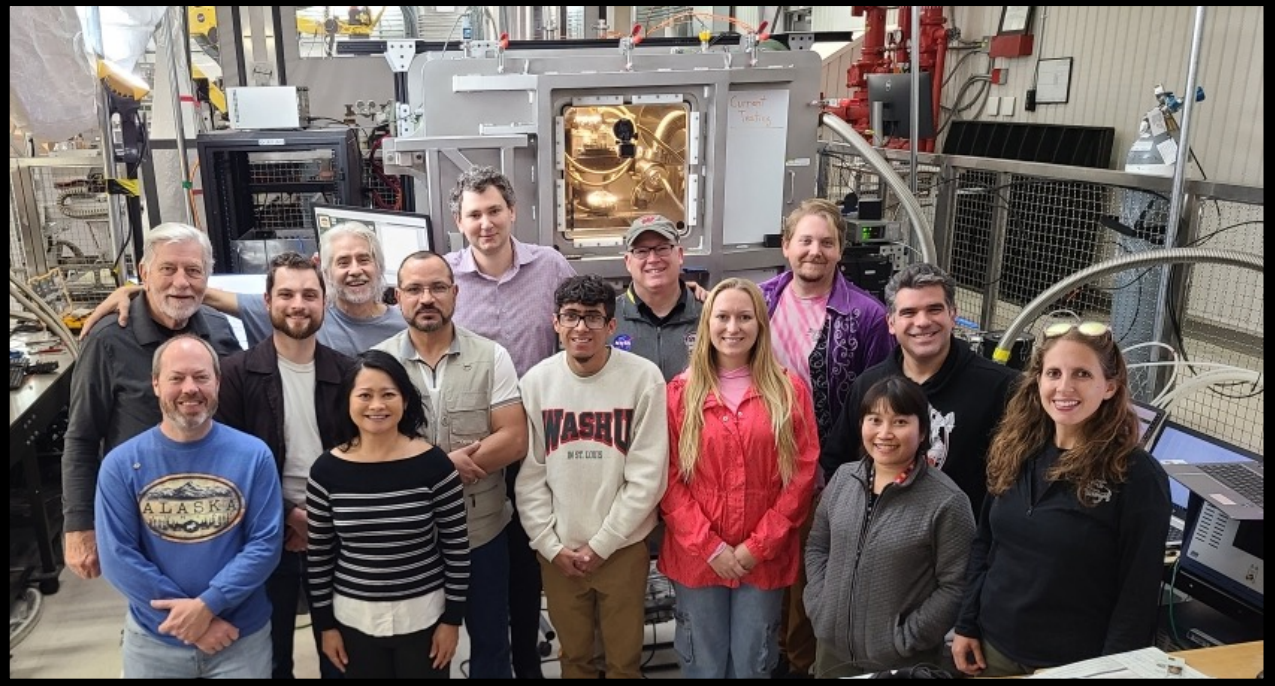
- Struck a rocket into lunar south pole crater
- Instruments monitored dust, debris, and vapor constituents
- Observed water, ice, and volatile compounds

Identified Compounds

H_2O	CO_2	OH
CH_3OH	C_2H_4	CH_4
NH_3	**H_2S**	**SO_2**

Acknowledgements

KSC MRE team members during system setup



KSC MRE team members with Lunar Resources during MRE demonstration

NASA Space Technology Mission Directorate, Game Changing Development Program, Molten Regolith Electrolysis team, Applied Chemistry Laboratory, NICL, MAL, MUREP

Questions

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