

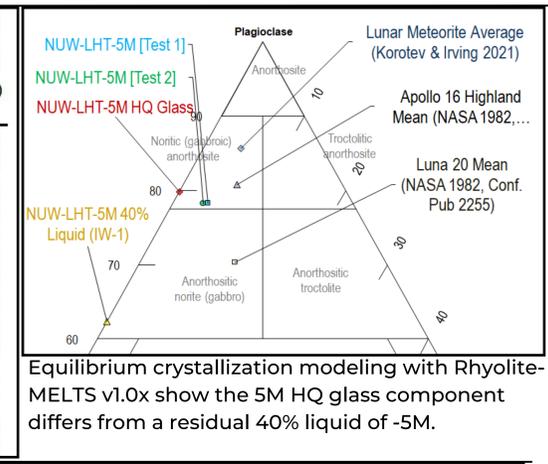
THERMOPHYSICAL CHARACTERIZATION OF NUW-LHT-5M LUNAR HIGHLAND SIMULANT

A. M. PATRIDGE¹, A. WHITTINGTON¹, A. MORRISON¹, D. RICKMAN², J. E. GRUENER³.

¹UNIVERSITY OF TEXAS SAN ANTONIO (UTSA CIR 1, SAN ANTONIO 78249, AUSTIN.PATRIDGE@MY.UTSA.EDU, ALAN.WHITTINGTON@UTSA.EDU), ²JACOBS (JACOBS SPACE EXPLORATION GROUP/NASA MARSHALL SPACE FLIGHT CENTER, HUNTSVILLE, AL, 35812, DOUGLAS.L.RICKMAN@NASA.GOV), ³NASA-JSC/JACOBS (2101 NASA PARKWAY, XI4-JETS, HOUSTON, TX 77058, JOHN.E.GRUENER@NASA.GOV)



FeO(T) Normalized XRF	NUW-LHT-5M HQ Glass (UTSA 07Jun2022)	NUW-LHT-5M Test 1 (UTSA 17SEP2023)	NUW-LHT-5M Test 2 (UTSA 11MAY2023)	Apollo 16 Average[3]	5M 40% Residual Liquid (IW-1)
SiO ₂	45.71	47.05	47.10	45.09	50.95
TiO ₂	0.58	0.28	0.28	0.56	0.70
Al ₂ O ₃	27.70	25.81	25.92	27.18	19.08
MgO	6.10	7.75	7.78	5.84	10.39
FeO(T)	3.22	2.93	2.90	5.18	5.20
MnO	0.04	0.05	0.05	0.065	0.10
CaO	16.67	14.61	14.68	15.79	12.73
Na ₂ O	0	0.86	0.80	0.47	0.69
K ₂ O	0.003	0.05	0.04	0.11	0.10
P ₂ O ₅	0.02	0.02	0.02	0.12	0.05
Cr ₂ O ₃	-	-	-	0.107	-
S	-	-	-	0.064	-
LOI	-0.044	0.578	0.440	-	-
Sum	100.00	100.00	100.00	100.58	100.00



INTRODUCTION

NASA's imminent return to the Moon with the Artemis III program necessitates efficient lunar construction and habitation technologies, prompting development of in situ resource utilization (ISRU). Lunar ISRU depends on high-fidelity lunar regolith simulants that must be thermophysically faithful to the Moon. The 5th iteration of the highland simulant series aims to be the best lunar highland simulant to date.



NUW-LHT-5M simulant

NU/NUW-LHT Series of Lunar Simulants [2]		1M ²	2C ³	2E ⁴	2EG ⁴	2M ²	3M ³	4M ⁶	5M ⁷
Stillwater Norite	⁸ Plagioclase _(-An85) , Orthopyroxene, Clinopyroxene	✓	✓			✓	✓	✓	✓ (17.6%)
Stillwater Anorthosite	⁹ Plagioclase _(-An89) , Clinopyroxene	✓	✓			✓	✓	✓	✓ (37.7%)
Stillwater Hartzburgite	Olivine, Orthopyroxene, Chromite	✓							
Twin Sisters Dunite	Olivine, Chromite		✓			✓		✓	
Commerical Turkish Olivine ⁹	⁹ Olivine (F ₆₈)								✓ (4.7%)
	Natural Ilmenite (beach sand)	✓	✓			✓		✓	
	Synthetic Whitlockite (β-tricalcium phosphate)		✓			✓		✓	
	Natural F-Apatite		✓			✓		✓	
	Natural Pyrite		✓			✓		✓	
Stillwater Mill Sand (dump source material)				✓	✓		✓		
Agglutinate Glass ⁴		✓ (16%)	✓ (2%)		✓ (2%)	✓ (30%)		✓ (35%)	
Zybeck 'Good Glass'		✓ (4%)	✓ (2%)			✓ (5%)			
Washington Mills glass									✓ (40%)
Manufacturing Year		2006		2007			2010	2020	Present

¹Stillwater 'mill sand' was used as the feedstock for all NUW-LHT glass components (see Stoesser et al 2010); feldspathic norite composition (Stoesser et al 2010) Design and specifications for the Highland Regolith Prototype Simulants NU-LHT-1M & 2M, NASA/TM-2010-216438; based on Apollo 16 Regolith USGS-NASA Preliminary Certificate of Information, "Prototype"; and Schrader et al. (2010) Lunar Regolith Simulant User's Guide, NASA/TM-2010-216446
⁴Label on 5-gallon buckets read, "Stillwater dump source material, engineering grade" (2E); "Stillwater dump source material + agglutinate, engineering grade" (2EG)
⁵Information gleaned from a 2011 email chain between Steve Wilson (USGS) and Allen Wilkerson (NASA-JSC), and a 2020 Email chain by Doug Rickman (NASA-MSFC)
⁶The olivine and Pyrite for -4M have a different, and higher quality source material than -2M (Steve Wilson email 01DEC2020)
⁷Email communication with Doug Rickman NASA-MSFC 14AUG2023
⁸Rickman et al. (2014) Benefaction of Stillwater Complex Rock for Production of Lunar Simulants, NASA/TM-2014-217502
⁹Email communication with Doug Rickman NASA-MSFC 26FEB2024

METHODOLOGY

The study characterized NASA-USGS-Washington Mills Lunar Highland Type 5 Medium (**NUW-LHT-5M**) lunar simulant and its **Washington Mills glass component (NUW-LHT-5M HQ glass)**, both supplied by NASA Marshall Spaceflight Center. Reproducibility was ensured by testing two separate provided aliquots of NUW-LHT-5M powder (labeled test 1 and test 2).

- Composition - by X-ray fluorescence (XRF)
- Iron redox -by wet chemistry and uv-vis spectroscopy
- Bulk powder density - by helium pycnometry
- Remelted glass density - by the Archimedeian method
- Heat capacity, glass transition, and enthalpy of crystallization - by differential scanning calorimetry (DSC)
- Viscosity of molten simulant - by concentric cylinder viscometry
- Thermal diffusivity of remelted glass - by light-flash analysis (LFA)
- Grain size Analysis via Anton Paar Litesizer 500 Dynamic image Analyzer

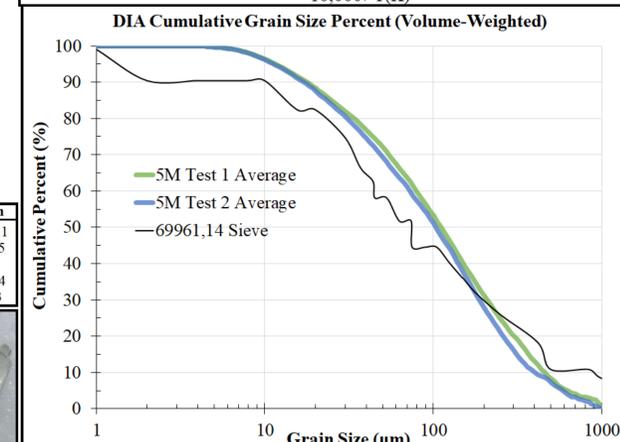
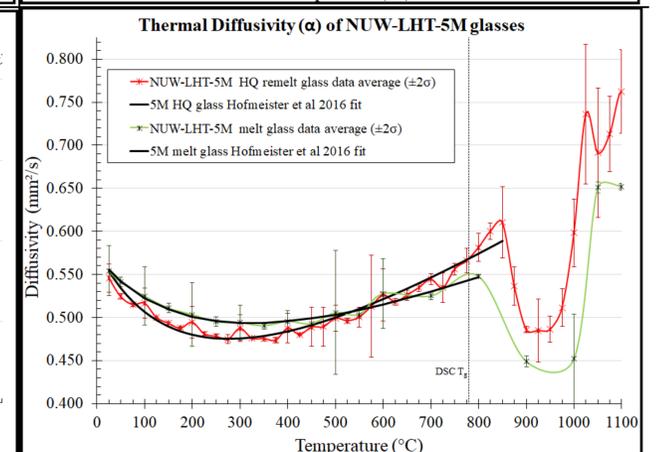
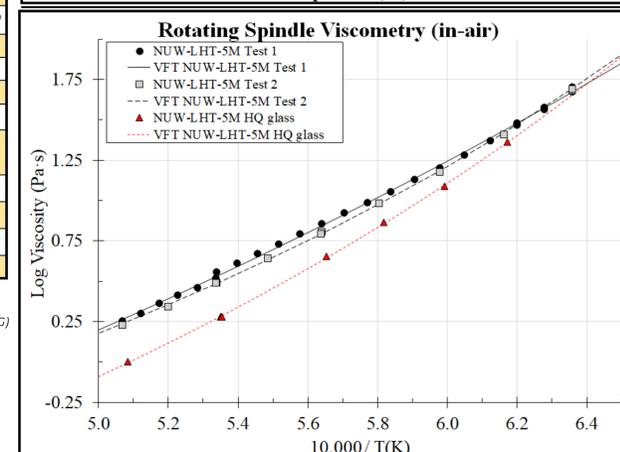
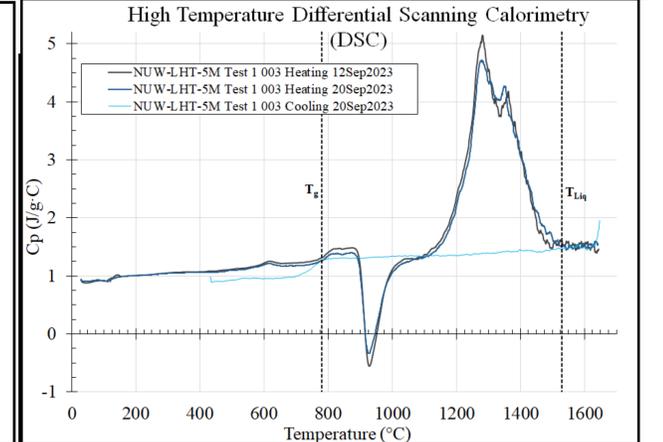
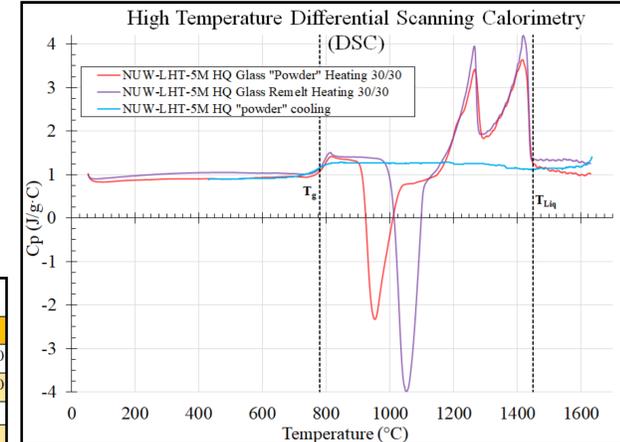


Dr. Aaron Morrison (L) and Austin Patridge (R) Pouring Molten NUW-LHT-5M Washington Mills Glass Component

Bulk Powder Density	kg/m ³	±2σ	n
NUW-LHT-5M Average	2819	11	211
NUW-LHT-5M HQ glass	2731	3	15
Glass Density (Archimedeian in Ethanol)			
NUW-LHT-5M melt glass Average	2729	18	14
NUW-LHT-5M HQ remelt glass	2753	4	3



NUW-LHT-5M Glass component with iron beads from manufacturing [5] (grains ~1mm)



A Litesizer 500 Dynamic Image Analyzer (DIA) to assessed grain size and shape (1mm to 0.8µm) of NUW-LHT-5M Test 1 and 2 aliquots showing no significant differences in size, form factor, solidity, or elongation.

CONCLUSION

- Iron beads and vesicles likely cause early crystallization on heating -5M glass, resembling heterogeneity of lunar glasses.
- NUW-LHT-5M mostly matches Apollo 16's major element composition and reduced Fe²⁺ state
- Recommended to increase simulant's iron content to 4wt% in-line with lunar samples and the ancient south pole [7][8][9].
- Ideal baking temperature for simulant is 700°C, below the standard 750°C [10]
- Rhyolite-MELTS modeling shows 5M glass composition differs from expected residual liquid, implications for sintering applications.

ACKNOWLEDGEMENTS

Thank you Dr. Alexis Godet for running my XRF samples and teaching me how to prep them. Thank you Brian Rodenhausen and Anton Paar for your DIA analysis and interpretations.

REFERENCES

[1] Rickman et al. (2022). 1146. 53rd LPSC. [2] Gruener et al. (2023). 2238. 54th LPSC. [3] NASA (1982). Conference Publication 2255. [4] Hofmeister et al. (2016). J Volc Geotherm Res 327, 330-348. [5] Creedon et al. (2023). LSIC. [6] Stoesser, Rickman, & Wilson (2010). NASA. [7] Korotev & Irving (2021). Meteoritics & Planetary Sci., 56, 206-240. [8] Pasckert et al. (2018). Icarus. 299, 538-562. [9] Fortezzo et al. (2020). USGS. [10] Wilkerson et al. (2023). Icarus 400, 115577. [11] Ghorso & Gualda (2015). Contribs. Min. & Petro., in press. [12] Hollocher K. T. (2022). Norm Calculation Program. V4.