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

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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 LHT highland simulant series aims to be the best lunar highland simulant to date.

Background: Current lunar sample testing lacks the high-temperature depth needed to fully assess the thermophysical merit of lunar simulants, but NUW-LHT-5M emerges as a promising lunar simulant. This joint product by NASA, USGS, and Washington Mills closely mimics the Moon's soil in density, mineral content, and chemistry while tackling past production issues [1][2]. Although its iron content is a little low, NUW-LHT-5M's glassy composition and iron redox state are on par with lunar soil, indicating high potential to mirror the thermophysical behavior of Apollo soils.

Results: The study characterized NASA-USGS-Washington Mills Lunar Highland Type 5 Medium (NUW-LHT-5M) lunar simulant and its high-quality 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).

Density bulk powder measurements were made using helium pycnometry showing the NUW-LHT-5M average of test 1 and test 2 to be 2819 ± 11kg/m³. Glass density utilizing Archimedes' principle in ethanol shows NUW-LHT-5M when melted and quenched into a bulk glass average to 2729±18kg/m³. The NUW-LHT-5M HQ glass component as received was 2731 ± 3kg/m³. When remelted the density of the bulk glass is 2753±4kg/m³.

Loss on Ignition (LOI) when heated to 1050°C for 1hr, NUW-LHT-5M loses 0.509 ± 0.029wt% on average. The -5M HQ glass component gained 0.044 ± 0.187wt% but was essentially zero.

XRF Fused disks for major element analysis were prepared by mixing the sample with lithium tetraborate and analyzed using a Rigaku Primus II WD-XRF.

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[1]
SiO_2	45.71	47.05	47.10	45.09
TiO_2	0.58	0.28	0.28	0.56
Al_2O_3	27.70	25.81	25.92	27.18
MgO	6.10	7.75	7.78	5.84
FeO(T)	3.22	2.93	2.90	5.18
MnO	0.04	0.05	0.05	0.065
CaO	16.67	14.61	14.68	15.79
Na_2O	0	0.86	0.80	0.47
K_2O	0.003	0.05	0.04	0.11
P_2O_5	0.02	0.02	0.02	0.12
Cr_2O_3	-	-	-	0.107
S	-	-	-	0.064
LOI	-0.044	0.578	0.44	-
Sum	100.00	100.00	100.00	100.58

Table 1. [1]NASA 1982 Conf. Pub 2255 [3]. XRF reveals incredible similarity to the Apollo 16 average as designed.

Fe-Redox Iron oxidation state in 10-20mg of simulant was analyzed using colorimetry concurrently with the USGS BIR-1a standard. Results show the simulant and its glass component contain essentially no Fe^{3+}, with the NUW-LHT-5M test 1 and test 2 FeO(T) average being 3.33 ± 0.34% and Fe_2O_3 being 0 ± 0.07%.

Differential Scanning Calorimetry (DSC) experiments were performed on the simulant using a Netzsch® 404F1 Pegasus calorimeter under argon where ~20-35mg samples were heated and cooled at 30K/minute in a PtRh pan measured using the ratio method and a sapphire of known heat capacity.

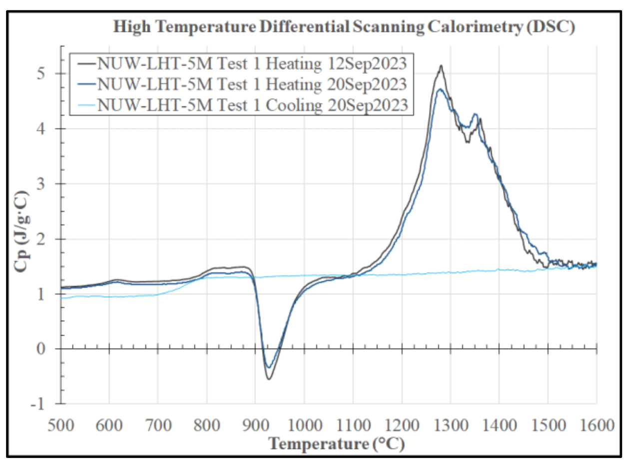

Fig 1. Apparent heat capacity ($Jg^{-1}K^{-1}$) against temperature for two aliquots of 5M test 1 powder.

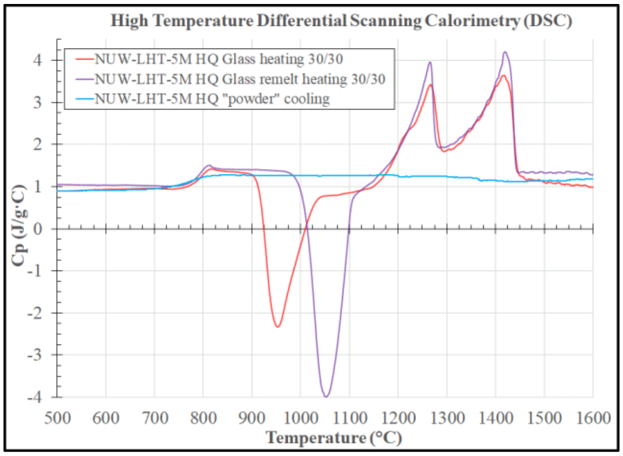

Fig 2. Apparent heat capacity against temperature for -5M HQ glass across 500-1600°C. Note the crystallization delay.

Viscosity was measured in air using a rotating spindle Orton RSV-1700 viscometer. A PtRh crucible contains the melt whereby a rotating spindle is immersed and the required torque measured. Viscosity is displayed on an Arrhenian diagram.

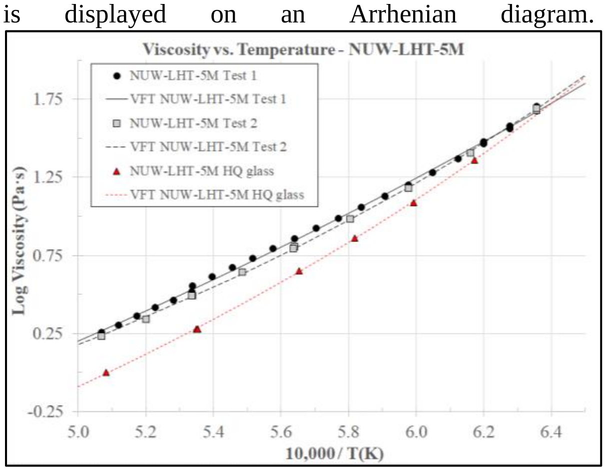

Fig 3. Log viscosity vs inverse temperature of NUW-LHT-5M and its glass component.

Thermal diffusivity & conductivity were measured and calculated for 5M glasses using a Netzsch 467HT light-flash apparatus (LFA) in an argon atmosphere to 1250°C. Data consists of at least three measurements at each temperature, processed using the Netzsch software. Each sample was run with a Pyroceram 9606 standard for accuracy. The resulting diffusivity data were fitted to the formula $D(T)= FT^{(-G)} + HT$ with F and G being dimensionless parameters, T the temperature in Kelvin, and H being $mm^2s^{-1}K^{-1}$ [4]. The average measured liquid diffusivity (α) for NUW-LHT-5M HQ remelt glass was 0.485±0.037mm^2s^{-1} with the NUW-LHT-5M melt glass 0.451±0.052mm^2s^{-1}. Thermal conductivity (*k*) was calculated using measured, thermal diffusivity, heat capacity, and glass density data of the -5M HQ remelt glass [4]. Its conductivity increases gradually, ~12%, from 1.33 $J \cdot s^{-1}m^{-1}K^{-1}$ at 75°C to 1.50 $J \cdot s^{-1}m^{-1}K^{-1}$ at 700°C.

Rhyolite-Melts v1.0.x equilibrium crystallization modeling applied a QFM buffer at 1atm. Since the content of NUW-LHT-5M is 40% of the 5M glass component [1], a 40% liquid calculated in MELTS was examined. Applying CIPW norm analysis reveals approximately 20% less plagioclase volume than the initial CIPW norm of the 5M glass [12].

Discussion: The -5M glass component crystallizes at 900°C, but after remelting is delayed to 1000°C hinting at impurity-driven nucleation points. The -5M glass component, even with unintended iron specks and bubbles from its production [5], is more faithful to the Moon better resembling heterogeneous glasses.

Chemically, NUW-LHT-5M aligns well with the Apollo 16 average with redox showing iron existing mostly as Fe^{2+} consistent with the Moon. However, our findings indicate an iron deficiency in the simulant [3][7]. To accurately represent lunar regolith, particularly from aged areas like the South Pole-Aitken basin, the simulant's iron content should be increased to at least 4wt% [8][9].

Decomposition of volatile minerals in the simulant occurs at 620°C to 700°C, suggesting an ideal baking temperature of 700°C. This is below T_g and does not compromise the glass integrity, but is notably lower than NASA's standard of 750°C [10]. Annealing at 750°C may still be useful for simulating lunar heterogeneity, and further experiments are warranted.

Rhyolite-MELTS v1.0.x modeling shows that the composition of the 5M glass component does not match the composition a residual liquid produced from the bulk simulant during crystallization [11]. This disparity between compositions aligns with expectations, as the component was not designed as a partial melt. However, this finding has implications for sintering and other thermal applications.

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