MEASUREMENTS OF SILICOSIS FACTORS IN LUNAR AND MARTIAN SIMULANTS

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Introduction:

Simulants are geologically complex materials that are developed to represent the physical and/or compositional characteristics of a planetary surface (e.g., a naturally occurring soil or regolith). There are dozens of commercially available simulants that have been developed over the years; each simulant exhibits unique physical, chemical, and mineralogical characteristics. Simulants are derived from either natural or synthetic sources (i.e., "feedstocks") of glass, minerals, and rocks. These feedstock components are processed by crushing, pulverizing, melting, etc., and then combined in the appropriate proportions to represent a particular site, surface, or region (e.g., Lunar Highlands Regolith).

The process of creating simulants therefore requires the mechanical breakdown and reincorporation of feedstock components which may contain crystalline silica minerals such as quartz, cristobalite, and tridymite. Certain crystalline silica particles of the respirable fraction (<10 µm in diameter) are of great concern; chronic and acute exposure to these respirable crystalline silica (RCS) can lead to permanent damage and scarring of lung tissue, incurable lung diseases (i.e., silicosis), lung cancer, COPD (chronic obstructive pulmonary disease), and kidney disease[1].

Planetary simulants are used extensively as test materials in the in scientific and engineering communities (e.g., testing of dust mitigation technologies[2], *in situ* resource utilization[3], rover mobility[4], hardware[5], soft goods[6], etc.). As such, this assessment was developed to serve as a guide for simulant users, local Safety and Occupational Health professionals, and Industrial Hygienists to evaluate the risk of silicosis across a wide variety of Lunar and Martian simulants. The goal of these works is to ensure that those working with simulant can do so safely and with an informed understanding of potential health risks.

Materials and Methods:

22 Lunar and 5 Martian simulants were analyzed by the commercial lab DCM Science Laboratory of Wheat Ridge, CO. Samples were analyzed using methods from NIOSH 7500, OSHA ID-142, and MSHA. A modified version of the NIOSH 7500 method was used to determine percent passing and to remove interferences. Percent passing of the respirable fraction (<10 µm) was determined by wet sieving samples through a 10 µm sieve. Compounds that interference with quartz, cristobalite, and tridymite (e.g., silicates such as plagioclase) were eliminated by a phosphoric acid treatment. Samples were weighed with a Mettler XP56 microbalance with an estimated limit of detection of 0.030 mg. The balance is certified within instrument specifications traceable to National Institute of Standards and Technology. X-ray diffraction was used for analysis, with a slow scan rate to determine the phases of crystalline silica present in the samples. Identified crystalline silica polymorphs were scanned over principal peaks to determine concentration. The samples were analyzed in conjunction with prepared standards of crystalline silica using NIST and NIOSH standards. The quantitative detection limit of crystalline silica for this method is 0.005mg quartz and 0.010mg cristobalite and tridymite. The coefficient of variation as stated by NIOSH is 0.09 for concentrations between 0.025mg and 2.5mg.

Results:

Summary Tables of Total Percent Crystalline and Respirable Silica Contents in Select Lunar and Martian Simulants and Feedstock Components shown to the right.

Lunar Highlands Simulant. Lunar highlands simulants tend to have higher overall silica contents when compared to lunar mare simulants and Martian simulants. GRC-1, GRC-3, and GreenSpar contain the highest fraction of total percent crystalline silica by weight at 96.32%, 29.8%, and 6.37 wt.%, respectively. All other highlands simulants analyzed contained <4.0 wt.% total crystalline silica with an average of 1.6 wt.%. Further, lunar highlands simulants contain the highest fractions of total respirable crystalline silica (RCS) by weight when compared to both lunar mare and Martian simulants, with GRC-3, LHS-1D, and GRC-1 containing 0.66 wt.%, 0.42 wt.%, and 0.39 wt.% RCS respectively. All other highlands simulants contain <0.39 wt.%.

Lunar Mare Simulant. Lunar mare simulants tend to contain lower overall silica contents compared to lunar highlands and select Martian simulants. The three simulants with the lowest total percent crystalline silica content by weight include the mare simulants JSC-1A (0.13, 0.21 wt.%), MLS-1 (0.14 wt.%), and LMS-1 (0.18 wt.%). Additionally, lunar mare simulants tend to contain lower total RSC contents when compared to highlands simulants, with all mare simulants containing <0.06 wt.% RCS.

Lunar Simulant Feedstocks. Simulant feedstocks selected for analysis contained total percent crystalline silica contents similar to that of the highlands simulants, with values ranging from 0.65 to 0.9 wt.% with an average of ~0.75 wt.%. Total RCS contents reflected similar values as well with maximum values of 0.19 wt.% RCS with an average of ~0.11 wt.% RCS for all feedstocks.

Martian Simulants. Martian simulants contained variable total percent crystalline silica contents that ranged from 0.2 wt.% to ~4.5 wt.%. Total RCS values ranged as well from 0.01 wt.% RCS (lowest content measured in all simulants) to 0.10 wt.% with an overall average of 0.052 wt.% RCS.

Lunar Highlands Simulant	*Total Percent Crystalline Silica (wt%)	†Percent Passing (<10 µm) Respirable Fraction	Total Respirable Crystalline Silica (wt%)	Analysis Source
CSM-LHT-1	2.56	13	0.33	§
CSM-LHT-1G	3.21	11.4	0.37	§
GreenSpar (Greenland Anorthosite)	6.37	3.33	0.16	§
GRC-1	96.32	0.4	0.39	§
GRC-3	29.8	2.2	0.66	§
LHS-1	3.05	7	0.21	§
LHS-1D	2.77	15.2	0.42	§
LHS-2	3.68	5.1	0.19	§
NU-LHT-2M	0.67	10.1	0.07	§
NU-LHT-2M	0.82	No data	No data	‡
NU-LHT-4M	0.92	8.1	0.07	§
NU-LHT-4M	1.94	No data	No data	‡
NU-LHT-4M	1.23	No data	No data	§
NUW-LHT-5M	0.84	13.9	0.13	§
OB1A	0.84	3	0.03	§
OB1A	0.61	No data	No data	§
OPRH4W30	1.6	16.3	0.26	§
OPRH4W30	1.73	No data	No data	‡
OPRH2N-J1	0.9	9.8	0.09	§
OPRH3N	0.87	11.5	0.1	§
OPRH3N-J1	1.18	11.9	0.14	§

Lunar Mare Simulant	*Total Percent Crystalline Silica (wt%)	†Percent Passing (<10 µm) Respirable Fraction	Total Respirable Crystalline Silica (wt%)	Analysis Source
BP-1	1.89	No data	No data	¤
BP-1	0.36	No data	No data	‡
BP-1	0.52	11.5	0.06	§
CSM-LMT-1	0.29	12.1	0.04	§
JSC-1A	0.13	3.4	<0.01	§
JSC-1A	0.21	No data	No data	§
LMS-1	0.18	10.2	0.02	§
LMS-2	2.31	2.2	0.05	§
MLS-1	0.14	4.2	0.01	§
OPRL2N	0.29	16.8	0.05	§

Lunar Simulant Feedstocks	*Total Percent Crystalline Silica (wt%)	†Percent Passing (<10 µm) Respirable Fraction	Total Respirable Crystalline Silica (wt%)	Analysis Source
Stillwater Anorthosite	0.65	No data	No data	§
Stillwater Norite	0.9	No data	No data	§
Stilwater Mill Sand	0.67	6.4	0.04	§
Stillwater Waste Rock	0.77	25.6	0.19	§

Martian Simulant	*Total Percent Crystalline Silica (wt%)	†Percent Passing (<10 µm) Respirable Fraction	Total Respirable Crystalline Silica (wt%)	Analysis Source
Fillite	4.52	2	0.09	§
JSC Mars-1	0.49	1.1	0.01	§
JSC Rocknest Mars Soil	0.5	20	0.1	§
JPL Mojave Mars Simulant (MMS)	0.24	20.5	0.05	§
M90	4.19	0.2	0.01	§

*	Total Percent Crystalline Silica (wt%) = Quartz (wt%) + Cristobalite (wt%) + Tridymite (wt%).
§	DCM Science Laboratories. The respirable fraction (<10µm) was removed by wet sieving through a 10µm sieve to determine percent passing.
‡	Herndon Solutions Group
¤	Innovative Health Applications - Industrial Hygiene Office; RJ Lee Group
†	Percent passing values are associated with only DCM analyses. Percent passing of the respirable fraction (<10 µm) was determined by wet sieving samples through a 10 µm sieve.
<	Indicates below the limit of detection for the analytical method used.
p	Indicates samples that were washed in phosphoric acid to remove interferences.

Discussion and Recommendations:

Health risks from crystalline silica in simulants is highly dependent on the simulant and what is done with the simulant. For example, large-sized particles of crystalline silica (i.e., > 100 µm) may break, generating respirable crystalline silica particles (i.e., < 10 µm). Individuals are advised to work closely with their local Safety and Occupational Health Professionals and Industrial Hygienists when simulants are involved to accurately assess the level of risk that is associated with their specific use-case scenario.

References:

[1] Merchant J. A. et al. (1986) US Dep HHS. No. 86-102. [2] Zanon P. et al. (2023) Acta Astronautica (2023). [3] Zhang P. et al. (2023) Space: Science & Tech 3, 0037. [4] Edwards M. B. et al. (2017) Journal of Terramechanics, 70,13-26. [5] Barkó G. et al. (2023) Lubricants 11.8, 334. [6] Black J. and Fritz A. (2023) IEEE Aerospace Conf.

Once ready, the latest version of the **Simulant User Guide** will be available on the SDL's ARES website. Contents of Guide include – Lunar Regolith; Lunar Regolith Simulants; Figures of Merit; Working Safely with Simulants; Preparing Simulants for Testing.