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Space systems — Lunar simulants

Systèmes spatiaux — Simulation de la poussiére lunaire

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Foreword

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The committee responsible for this document is ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Introduction

This International Standard provides lunar systems developers and operators with a specific quantitative measure for lunar regolith simulants in comparison to other simulants and with relation to sampled lunar materials from Apollo and Lunakhod missions. Developers of lunar systems will use simulants as test materials. This International Standard is a reference for quantitative measures of lunar simulants finer than 10 cm. It describes four properties (composition, size, shape, and density) which are the minimum number of properties needed for such uses as comparative testing involving simulants or civil engineering. The quantitative measures of lunar dust simulants are based on the quantitative measures of lunar regolith samples collected at multiple lunar landing sites of the Apollo missions.

This International Standard provides communication of the geological quality of the simulant between developing organizations and systems operations organizations.

Space systems — Lunar simulants

1 Scope

This International Standard is a reference for quantitative measures of lunar simulants.

2 Terms and definitions and abbreviated terms

2.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1.1
agglutinate
vesiculated glass bonded particle containing other particles (lithic fragments), of which the bonding glass contains spherical particles of iron

Note 1 to entry: The lunar spherules are typically 3 – 100 nanometers in diameter and formed contemporaneous with the glass.

Note 2 to entry: Six features characterize lunar agglutinates: size, surface area with relation to volume, composition, nanophase iron content, flow banding, and multiple generations.

2.1.2
angularity
an expression of roundness

EXAMPLE A poorly rounded grain is described as angular.

Note 1 to entry: This definition has been taken from the *Glossary of Geology* (see Reference [5]).

2.1.3
aspect ratio
ratio of the maximum Feret diameter divided into the orthogonal Feret diameter

Note 1 to entry: Values range from > 0 to 1 and equal to 1 for a circle.

2.1.4
Feret diameter
distance between two parallel lines which are tangent to the perimeter of a particle

Note 1 to entry: The maximum Feret diameter is defined as the greatest distance between two parallel lines which are still tangent to the perimeter of the particle.

2.1.5
figure of merit
degree to which a sample matches a reference

Note 1 to entry: Scaling (normalization) forces the norm of the difference of two composition vectors to lie between 0 and 1, and subtraction from unity results in a figure of merit of 1 for a perfect match and 0 for not match at all.

2.1.6
Heywood circularity factor
expression of the complexity of a particle's perimeter

Note 1 to entry: Formally, the Heywood circularity factor is equal to 1 divided by particle perimeter divided by the circumference of a circle with the same area as the particle. This is numerically equal to the "circularity" defined by Waddell (1933). It is expressed in this manner to make it apparent that the Heywood factor is the inverse of a common definition of "circularity", another common measure.

Note 2 to entry: Values range from > 0 to 1 and equal 1 for a circle.

2.1.7
lithic fragments
physically discrete solids of any rock type whose normative composition is within the range of the target terrain

Note 1 to entry: Lithic fragments have texture and mineralogy. Texture is a more important feature than mineralogy for lithic fragments. Texture describes the grain to grain connectivity boundary. Lunar textures cannot be replicated on Earth.

2.1.8
lunar terrains
mare and highlands

2.1.9
regolith
all particulate surface material including rocks, soils, and dust

Note 1 to entry: As stated in the Introduction, this International Standard is limited in scope to regolith 10 cm and smaller. Rocks, soils, and dust are not differentiated on the basis of size.

2.1.10
re-use
after a simulant volume is used (any sequence of events in which a simulant volume is removed from a storage container) then placed back into storage, any future use constitutes re-use

2.1.11
sphericity
degree to which the shape of a particle approaches a sphere

2.2 Abbreviated terms

c_x concentration or portion of a sample for the x^{th} item in the sample

FoM Figure of Merit

RFD Relative Frequency Distribution

w_i weighting factor. *w* is a value between one and zero. *i* is an index which refers to the characteristic being weighted, such as glass (a grain type)

3 Characteristics of lunar regolith previously defined in the Lunar Sourcebook©

3.1 Minerologies

The lunar surface mineralogy is variable across major terrain. These properties are qualitative; they cannot be described in a quantitative manner related to any known spatial distribution across the lunar surface. The listing of the primary minerologies in Reference [3] includes

— Silicate minerals such as Pyroxene, Plagioclase Feldspar, Olivine (Fo_{80}), and Silica minerals,
— Oxide minerals such as Ilmenite, Spinels, and Armalcolite,
— Sulfide Minerals such as Troilite,
— Native Fe, and
— Phosphate Minerals.

3.2 Physical and chemical properties

3.2.1 General

Reference [3] provided a compilation of properties from Apollo and Lunakhod lunar samples of use to the scientific community. These properties are listed since a large amount of data exists for lunar regolith characterization using these properties. As demanded by scientific definitions, these properties are qualitative and quantitative. This means some properties can be measured directly while others are descriptive and are not readily measurable. While these properties are of value to planetary or lunar scientists, they do not address the needs of lunar systems developers and operators with a specific quantitative measure for lunar regolith simulants in comparison to other simulants and with relation to sampled lunar materials.

3.2.2 Physical properties

3.2.2.1 Geotechnical properties

a) particle size distribution;
b) particle shapes;
c) specific gravity;
d) bulk density;
e) porosity;
f) relative density;
g) compressibility;
h) shear strength;
i) permeability and diffusivity;
j) bearing capability;
k) slope stability;
l) trafficability.

3.2.2.2 Electrical and electromagnetic properties

a) electrical conductivity;
b) photoconductivity;
c) electrostatic charging;
d) dielectric permittivity.

3.2.3 Chemical properties

a) major elements;

b) incompatible trace elements;

c) miscellaneous minor elements;

d) siderophile elements;

e) vapor-mobilized elements;

f) solar wind implanted elements.

4 Quantitative measurement properties of lunar simulants

4.1 General

Lunar simulants can be measured as lunar samples were measured and published using 22 listed properties (see Clause 3). However, the quality of lunar simulants measured in this way cannot be readily compared to lunar source material nor communicated across development and operational communities. Comparison of these measures for simulants for other than scientific purposes is not recommended.

The more useful qualification of lunar simulants is tied to lunar minerologies and is expressed most concisely in four figures of merit: composition, size, shape, and density. The figures of merit for lunar simulants range from zero to one. A figure of merit value of zero indicates no useful correlation to a comparative sample. A figure of merit value of one indicates exact correlation as defined by the standard measurements to a comparative sample. A specific quantitative measure for lunar regolith simulants is made only in comparison to other simulants or with relation to sampled lunar materials from Apollo and Lunakhod missions. Data from existing lunar samples are necessary to use these figures of merit to establish a real baseline from the lunar surface.

4.2 Comparative baseline

Comparative (quantitative) measures shall be stated for lunar simulants. Figures of merit for a simulant shall be stated against a single baseline. If multiple baselines are referenced for a simulant, a complete set of figures of merit shall be calculated for each reference.

4.3 Impurities and contamination

Simulants can not be completely defined by these figures of merit for reasons of mineralogical impurity and contamination of the simulant by organic/inorganic materials.

Impurity of the sample/simulant measured shall be stated in percent of the sample mass.

Contamination of the sample/simulant shall be stated in percentage of the sample volume. Characterization of the sample contamination and the nature of that contamination shall be stated if an analysis is performed.

4.4 Validation of figures of merit

Calculation of figures of merit for a simulant shall be performed and recorded for each use. In the event a volume of simulant is re-used, the figures of merit shall be recalculated in accordance with this standard. Scaling (normalization) forces the norm of the difference of two composition vectors to lie between 0 and 1, and subtraction from unity results in a figure of merit of 1 for a perfect match and 0 for not match at all.

4.5 Composition figure of merit

4.5.1 Composition figure of merit formula

The figure of merit definition is

$$FoM = 1 - \frac{\left\| w_{adjusted} \left(c_{adjustedreference} - c_{adjustedsimulant} \right) \right\|_1}{\left\| \left[\max_1 \left(w_{adjusted} \right) \max_2 \left(w_{adjusted} \right) \right] \right\|_1} \quad (1)$$

where w_i is used to adjust the figure of merit for a particular grain type (see 4.5.3) and $\max_i(w)$ is the i^{th} largest element of w. This form of the figure of merit is not useful in actual calculation. The figure of merit formula for calculation shall be

$$FoM = 1 - \frac{\sum_i w_{adjusted} \left| \left(c_{adjusted\,reference_i} - c_{adjustedsimulant_i} \right) \right|}{\sum_i w_{adjusted} c_{adjusted\,reference_i} + \sum_i w_{adjusted\,reference_i} c_{adjusted\,simulant_i}} \quad (2)$$

For example, in the constituent example table below, normalized concentrations for basalt are given for both the sample and the simulant (approximately 0,015 and 0,120, respectively). In the difference table, it is further shown that the basalt difference is 0,105 with a higher concentration in the simulant.

Table 1 — Constituent example table

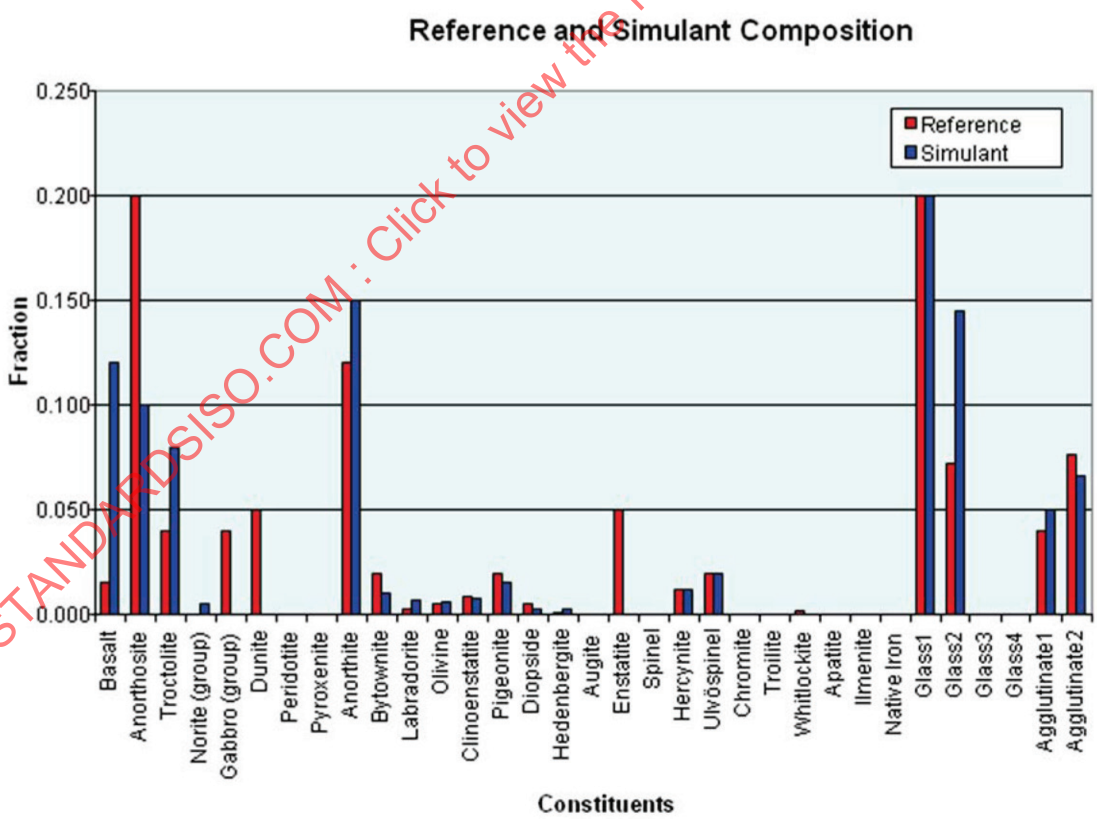
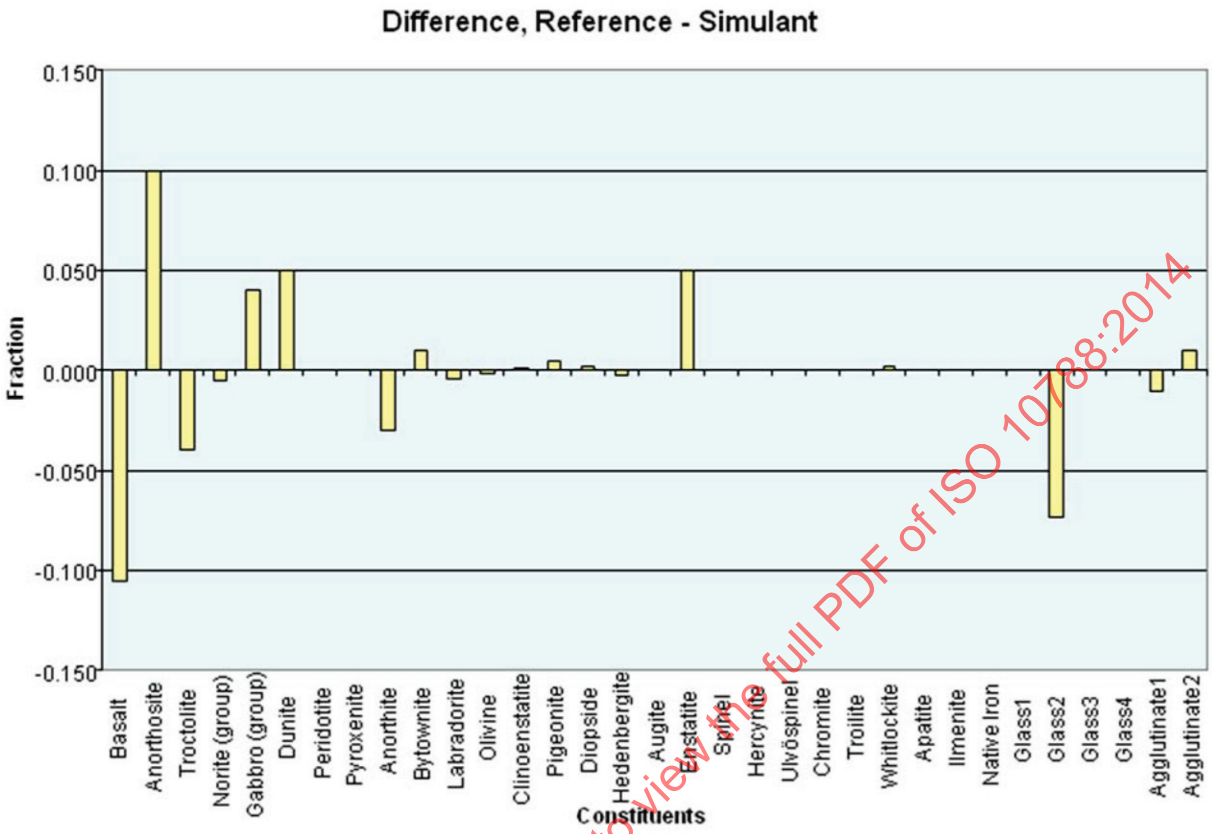


Table 2 — Difference table



4.5.2 Particles

Compositions are defined for particles. A particle may be made up of one or more grains. A particle may be composed of a combination of crystalline solids, glass, or a mixture of these and may contain voids. The smallest particle is a single grain of material.

4.5.3 Grain types

Grain types shall be described as crystalline solids (agglutinates, lithic fragments) or glass.

4.5.3.1 Crystalline solids

Crystalline solids shall have structure at the level of an X-ray.

4.5.3.2 Glasses

Glasses shall be made from the rest of the material in the simulant

Glasses shall have a normative mineralogy within the range of the moon.

4.6 Size distribution figure of merit

4.6.1 Size distribution figure of merit formula

The calculation of the size distribution figure of merit shall be

$$FoM_{before-constraints} = 1 - \frac{\sqrt{\int w\left(RFD_{reference} - RFD_{simulant}\right)^2}}{\sqrt{\int wRFD^2{}_{reference} + \int wRFD^2{}_{simulant}}} \quad (3)$$

with the further constraint

$$FoM = \begin{matrix} FoM_{before-constraints} \ if \left|RFD_{reference} - RFD_{simulant}\right| \leq \max RFDdifference \\ 0 \qquad\qquad\qquad\qquad\qquad otherwise \end{matrix} \quad (4)$$

In the reference and simulant size distribution example table below, RFD values for reference and simulant are given for the 0,1 cm size at 0,08 and 0,02 respectively.

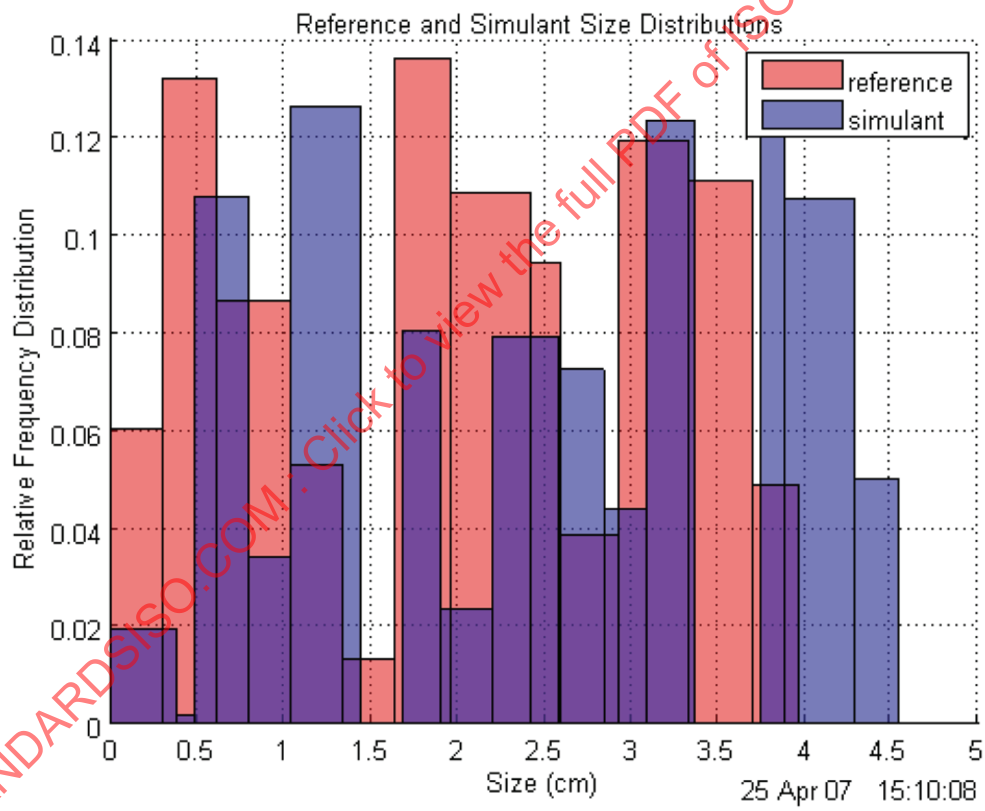


Figure 1 — Reference and simulant size distributions

4.6.2 Particles from 4 cm to 75 microns

Particles from 4 cm to 75 microns shall be measured by the method of sieving.

4.6.3 Particles from 100 microns to 1 micron

Particles of Apollo and simulant materials between 100 microns and 1 micron shall be analysed by the method of optical imaging.

4.6.4 Particles finer than 2 microns

Particles finer than 2 microns shall be measured by the method of aerosol dispersion.

4.7 Shape figure of merit

4.7.1 Shape figure of merit formula

The calculation of the shape figure of merit shall be the product of the FoM for sphericity (Heywood circularity factor using automated systems) and FoM for angularity (aspect ratio using automated systems).

$$FoM_{before-constraints} = 1 - \frac{\sqrt{\int w\left(RFD_{reference} - RFD_{simulant}\right)^2}}{\sqrt{\int wRFD^2{}_{reference} + \int wRFD^2{}_{simulant}}} \tag{5}$$

with the further constraint

$$FoM = \begin{matrix} FoM_{before-constraints} \; if \left|RFD_{reference} - RFD_{simulant}\right| \le \max RFDdifference \\ 0 \qquad\qquad\qquad otherwise \end{matrix} \tag{6}$$

4.7.2 Shape

Shape shall be determined by the combined sphericity and angularity of the particles.

Shape is conventionally defined on a particle by particle basis by shape specialists in the scientific field of Geology using a combination of sphericity and angularity of the particles. An equivalent method for determining shape of a large number of particles in a sample by automated devices and computer analysis use the Heywood circularity factor and aspect ratio (dependent on the Feret diameter).

4.7.2.1 Sphericity

Sphericity shall be determined to define particle shape. If automated devices and computer analysis are used, this distribution shall use the Heywood circularity factor.

4.7.2.2 Angularity

Angularity shall be determined to define particle shape. If automated devices and computer analysis are used, this distribution shall use the aspect ratio.

4.8 Density figure of merit

4.8.1 Density FoM formula

The figure of merit for how closely a simulant matches a reference is proportional to the ratio of the densities. Ratios of less than (1-density quotient limit) or greater than (1+density quotient limit)