Influence of Powder Type on Aerosol Emissions in Powder-Binder Jetting with Emphasis on Lunar Regolith for In Situ Space Applications

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ABSTRACT: Powder-binder jetting is an additive process with applications for manufacturing complex geometric structures, such as lightweighting, mold making, and in situ resource utilization (ISRU) for space applications. With this technique, a powder feedstock is spread across a bed during which aerosol may be released leading to human health implications. This study characterizes airborne powder emissions for three powders of varying particle diameters and composition: Hydroperm gypsum plaster, Lunar Highland Simulant regolith (LHS-1, a lunar soil simulant), and Zeolite 13X (a molecular sieve). Bulk powder $D_{50}$ values were 22 μm for Hydroperm, 304 μm for LHS-1, and 3.85 μm for Zeolite. Total particle emission rates were $(5.4 \pm 0.96) \times 10^3$ min$^{-1}$ for Hydroperm, $(1.0 \pm 0.28) \times 10^4$ min$^{-1}$ for Zeolite, and $(2.2 \pm 0.82) \times 10^3$ min$^{-1}$ for LHS-1. An emission factor was developed normalized to the volume of powder spread resulting in emission factors of $(2.8 \pm 0.85)$ mm$^{-3}$ for Hydroperm, $220 \pm 72$ mm$^{-3}$ for LHS-1, and $5.0 \pm 0.24$ mm$^{-3}$ for Zeolite. This indicates that particle emissions from powder-binder jetting machines with a constant spreading mechanism can vary widely depending solely on powder type. In the experimental enclosure where testing took place, LHS-1 PM$_{10}$ concentrations exceeded 8 h TWA PEL OSHA standards for crystalline silica by sixfold, indicating that air quality should be a strong design consideration for 3D printing for lunar ISRU. With lower gravitational settling effects, Lunar particulate concentrations 20 m away from the printer were modeled to be 330% higher than on Earth. This study suggests that powder size, morphology, and composition should be considered holistically when determining emission concerns for new powders in powder-binder jetting. This study also suggests particular attention should be paid to aerosol emissions in a Lunar environment.

KEYWORDS: Powder-Binder Jetting, Particulate Matter, Emission Rate, Additive Manufacturing

INTRODUCTION

Additive manufacturing has become a significant approach for the fabrication of complex, functional parts. With a total market growth of 18% in 2018, additive manufacturing has become a $9.3-billion dollar industry. In addition to manufacturing for industry, additive manufacturing also has consumer users. For hobbyists, 3D printing, especially fused-deposition modeling (FDM), has become increasingly prevalent in various settings. With increased availability comes the potential for increased inhalation, dermal, and optical exposure to particulate matter (PM) and volatile organic compound (VOC) emissions, leading to potential adverse health effects.

Recent research has identified air quality degradation via additive manufacturing for both commercial manufacturing and hobbyist use, especially for fused-deposition modeling (FDM). The present work focuses on powder-binder jetting (PBJ), extending a well-developed research base for FDM printer emissions to the powder printing domain. Powder-binder jetting was first developed by an MIT team led by Emmanuel Sachs in 1989. In this process, a layer of powder (e.g., plaster of Paris) is spread over the work surface, and a solution (primarily water) is selectively ejected using an inkjet process that binds the powder to form the solid regions of the part. This process is then repeated for each layer, before the completed part is removed and cleaned using an air jet to mechanically remove unbound powder. Advantages of this technique include improved resolution and faster throughput as the time to complete a layer is largely independent of the number of parts in a build. Powder-binder jetting is used in manufacturing by companies such as Hewlett-Packard Inc., ExOne, and Desktop Metal for developing large-scale machines.

As powder-binder jetting becomes more prevalent in manufacturing, it is reasonable to expect increased use of these machines by human operators extracting parts, filling...
powder beds, and sintering parts. Little is known about air pollutant emissions from these machines due to their higher cost and procurement difficulty. In fact, to the authors’ knowledge, one paper has been published to date describing powder-binder jetting emissions from the standard Zcorp gypsum-based powder (PXL),\textsuperscript{15} which determined that aerosol emissions occur in the micrometer size range with mass concentrations that can be 10× and 3× greater than PM2.5 and PM\textsubscript{10} USEPA\textsuperscript{16} standards, respectively. Other powder bed additive techniques could not be compared (laser sintering, electron beam melting) as the fusing mechanism was expected to influence emissions. Current research on powder-binder jetting machines has focused on print quality, binding techniques, process parameters, and material selection to produce higher quality parts.\textsuperscript{17–19}

We have identified a need to determine how different powder grain sizes and types influence the emission rate leading to operator risk. As this technique can use any flowable powder feedstock, a wide variety of materials can potentially be used such as metal powder,\textsuperscript{18} ceramics,\textsuperscript{20} cellulose,\textsuperscript{21} and silicone.\textsuperscript{22} Widely varying materials are expected to have varying emissions, yet little is understood about how changing the powder type and other physical parameters influence printer emissions during normal operation. This is especially true for extraterrestrial manufacturing using in situ resource utilization.

The goal of this work was to determine the influence of the powder feedstock on the particle emission rates. The specific objectives were to characterize the influence of the powder size, morphology, and other powder properties on emission rates focusing on powders that may lead to future adverse exposure in real-world applications. In this work, we present emission rates for Hydroperm gypsum plaster, simulated lunar regolith (LHS-1), and Zeolite 13X (a molecular sieve) in a Zcorp 650 powder-binder jetting printer. Specific emphasis is placed on lunar regolith. We present normalized emission rates allowing estimation with similar printers of varying bed size, as well as average number concentrations during each stage of printing and during depowdering. This work identifies not only the particle size but also the morphology and powder composition as factors indicating potential occupational risks.

**MATERIALS AND METHODS**

**Printer Characteristics.** We used a powder-binder jetting machine (ZPrinter 650, Z Corporation, Burlington, MA) for this study. This printer was selected for its large build volume of 254 mm × 381 mm × 203 mm (10 in × 15 in × 8 in) with 5 printheads allowing custom ink and powder development. This printer processes 2–4 layers per minute with a thickness of 100 μm at a resolution of 600 × 540 dots per inch. The printer uses 5 thermal inkjet heads (HP 11, Hewlett-Packard, Corvallis, OR) to deposit binder and is depicted in Figure S1.

**Powder Selection.** Three different powders were investigated (Table S1): Hydroperm,\textsuperscript{23} a gypsum-based powder that sets with water and is capable of withstanding casting with water and is capable of withstanding casting and to cover a variety of particle sizes and compositions. Hydroperm was selected due to its ability to set with water and to provide a high temperature casting mold. Furthermore, Hydroperm is representative of gypsum-based powders. LHS-1 was selected for its potential application to in situ resource utilization missions on printing in extraterrestrial environments. NASA’s Artemis Mission has the goal of long duration human presence on the Moon which will require in situ resource utilization. Powder binder jetting of the lunar regolith can create ceramic and metal parts usable by astronauts to reduce the need for Earth resupply missions. Therefore, ISRU may increase astronaut exposure to regolith through printing. Understanding these emissions will be vital for operating printers safely in lunar or martian environments as these powders often have angular morphologies that may pose an inhalation risk. Zeolite was chosen for its small particle size and its use as a molecular sieve which has the potential for application in gas sorption systems. Selecting these three powders allows an analysis of both the particle size and the morphology while characterizing materials that have the potential for broad future applications.

**Bulk Powder Characterization.** Bulk particle size distributions (PSDs) of all powders were obtained using a laser diffraction particle size analyzer (Mastersizer 3000, Malvern, U.K.) and a sample dispersion unit for wet dispersion control of large volumes (Hydro LV, Malvern, U.K.). To avoid agglomeration, samples were both continuously stirred at 2800 rpm and sonicated during the experiment. The D\textsubscript{50} and D\textsubscript{90} values define the sizes for which 50% and 90% of all particles are smaller, respectively, and were calculated for each powder type.

The morphology and qualitative major elemental composition of the powder samples were assessed using a scanning electron microscope (SEM, Hitachi SU3500, Krefeld, Germany) with an energy dispersive spectroscopy (EDS, Oxford Instruments, Concord, MA) detector. Samples were cast in epoxy resin and hand polished with 3000-grit sandpaper. Afterward, samples were sputter-coated using a platinum target. Imaging was conducted at 15 keV at a working distance of 10.4 mm.

Bulk powder density was obtained gravimetrically using a known volume of powder and determining the mass of the given volume on a laboratory scale (±0.001 g).

**Emissions Enclosure.** To contain particulate matter emissions in a controlled volume of air for emission rate calculations, a rectangular enclosure was built surrounding the printer. The enclosure was made using polycarbonate greenhouse plastic [6 mil (0.15 mm), AA Grower Supply] and measured 1.9 m × 1.4 m × 2.3 m (77 in × 56 in × 90 in) for a volume of 6.4 m\textsuperscript{3}. A 9 mm air sampling port was cut into the plastic and sealed with tape. A representative schematic is presented in Figure S2. A duct of 0.2 m (8 in) diameter was connected to an inline HEPA filter (GrowBright 8 in. CleanFlow) and blower (Vivohome 720 cfm 8 in. inline duct fan) to provide a known exhaust flow rate and to provide negative pressure to the enclosure to prevent PM from exiting the enclosure to the indoor environment without first passing through the HEPA filter. The exhaust air velocity was determined experimentally using a hot wire anemometer.
(Lutron AM-4224SD, Taipei, Taiwan). The blower was operated with a flow velocity of 0.2 m/s providing an air exchange of 3.7 ACH or one air change at every 16 min.

**Aerosol Characterization.** Aerosol size distributions were measured using a Scanning Mobility Particle Sizer (3938 SMPS, TSI, Shoreview, MN), set up with a long differential mobility analyzer to capture size distributions with electrical mobility sizes of 0.010–0.400 μm every 2 min and an Optical Particle Sizer (3330 OPS, TSI), set up to capture a size distribution with optical particle sizes between 0.300 and 10.0 μm at every minute. An Aerodynamic Particle Sizer (APS, TSI) was used to capture aerosol size distributions in the 0.500–20.0 μm aerodynamic particle size range for the Zeolite powder due to instrument availability constraints. For mass calculations, we assumed spherical particles. The APS and OPS were placed inside the enclosure while the SMPS sampled through a conductive inlet line of 0.8 m length and 6.35 mm inner diameter.

**Aerosol Emission Rate Calculations.** Particle emission rates were calculated following a procedure similar to that described by Afshar-Mohajer et al., who first reported emissions data for powder binder jetting of a ZCorp machine. The printing process was separated into four main printing regimes including background, filling the bed, printing, and a decay period. The different printing regimes are represented schematically in Figure 1.

![Figure 1. Schematic of printing air quality regimes.](image)

To determine the emission rate, we model the enclosure using a time varying mass balance as depicted in eq 1.

\[
C_i(t) = C_{i_{\text{past}}} e^{-L_i/t} + \left( C_{i_{\text{bg}}} + \frac{E_R}{V/L_i} \right) \left( 1 - e^{-L_i/t} \right)
\]

where \(C_i(t)\) is the instantaneous concentration of \(i\)th particle size bin at time \(t\), \(C_{i_{\text{past}}}\) is the concentration of \(i\)th bin at time printing starts, \(C_{i_{\text{bg}}}\) is the concentration of \(i\)th bin at background measurement, \(V\) is the volume of enclosure, \(L_i\) is the particle wall loss rate at the \(i\)th bin, and \(t\) is the elapsed time of decay. Equation 1 requires a known wall loss rate \((L_i)\) to solve for emission rate \((E_R)\). Regime 4, the decay period, was used to determine the total loss rate, where the emission rate is assumed to be zero as no printing occurs. As a result, \(E_R = 0\) and the total loss rate is expressed as a first-order decay process, as seen in eq 2.

\[
L_i = \ln \left( \frac{C_i(t) - C_{i_{\text{bg}}}}{C_{i_{\text{bg}}} - C_{i_{\text{bg}}}} \right)/t
\]

where \(C_i(t)\) is the instantaneous concentration of \(i\)th particle size bin at time \(t\), \(C_{i_{\text{bg}}}\) is the concentration in the \(i\)th size bin at background measurement, \(C_{i_{\text{fg}}}\) is the concentration in the \(i\)th bin at the end of print, and \(t\) is the time between samples. The total loss rate was calculated for every particle size bin denoted by \(L_i\). Equation 2 is the result of fitting a straight linear regression line on the time varying log plot of the decay period.

**Lunar Application Simulations.** To understand how these particle emissions would behave in an assumed lunar space station module, we performed computational fluid dynamics simulations of particle transport using the commercial software Flow 3D, considering similar order-of-magnitude physical characteristics as the international space station. We assumed this lunar module to be a rectangular prism of 50 m in length and 3 m × 3 m height and width for a volume of 450 m³. We modeled the air flow moving from one end to the other as a plug-flow reactor with a velocity inlet and pressure outlet. All other sides were considered as walls. Air exchange rates of 0.7 ACH and 4.4 ACH were considered, leading to air velocities of 0.01 m s⁻¹ and 0.06 m s⁻¹, respectively. A value of 4.4 ACH is used on the ISS in crew cabins. We considered scenarios in which one and two printers were used at one end of the module.

A total of 2.2 million particles were tracked under an emission source scenario where the maximum particle concentration is reached within 5 s. The particle release rate was given for 10 particle sizes, and the rate was determined from emissions data. We considered particle coagulation effects to be negligible and did not incorporate it into this model. This is a reasonable assumption given coagulation is a second-order effect and only significant in highly concentrated plumes. A dynamically coupled \(k-\epsilon\) model was used to resolve local turbulence features in the developing flow \((Re = 2112)\). Mass concentrations at discrete positions 0–49 m away from the printer were assessed under Earth and Lunar gravity. A schematic and more complete description of the CFD setup can be found in Figure S15.

For in situ resource utilization, Lunar highland regolith simulant (LHS-1) can be sourced directly from the Moon to alleviate the need for Earth resupply missions for needed parts. This material can be used as a form of cement for producing lunar structures. However, this lunar soil contains highly angular silica-laden particles closely aligned with crystalline silica. Significant cell toxicity and DNA damage was found in neuronal and lung cell lines exposed to lunar regolith simulant. Furthermore, during the Apollo mission, electrostatically charged lunar dust clung to astronauts’ spacesuits and was brought into living areas. Harrison Schmitt, an astronaut on the mission, described his reaction to the dust as “lunar hay fever” with sneezing, watery eyes, and sore throat.

**Uncertainty and Data Quality Assurance.** All bulk powder samples were analyzed 10 times to ensure the measurement repeatability. In order to account for uncertainty in PM emission experiments, two to three print cycles were...
performing for each powder type. Airborne particle number and mass concentrations were verified visually using heatmaps after each experiment. Uncertainty in emissions calculations was quantified via standard error.

**RESULTS AND DISCUSSION**

**Bulk Powder Size Distributions and Bulk Particle Density.** Bulk powder \(D_{50}\) values were 3.85 \(\mu m\) for Zeolite, 22 \(\mu m\) for Hydroperm, and 304 \(\mu m\) for LHS-1. Bulk particle density values were 2.96 g cm\(^{-3}\) for Hydroperm, 1.30 g cm\(^{-3}\) for LHS-1, and 0.43 g cm\(^{-3}\) for Zeolite. Table S2 presents \(D_{50}\), \(D_{90}\) and density results for each powder type, and Figure S11 shows the PSDs for all powders.

**Electron Spectroscopy Analysis.** Figure 2 shows SEM micrographs of the tested powders and Figures S3–S5 show corresponding EDS spectra. Hydroperm particles appeared angular in shape (Figure 2a), and the sizes observed in the SEM images agree with particle size distribution (PSD) analysis. Hydroperm was shown to be composed of calcium and sulfur—this is expected as this powder is a plaster, which tends to be composed of gypsum (calcium sulfate dihydrate and CaSO\(_4\)·2H\(_2\)O). The LHS-1 lunar simulant was relatively heterogeneous in size with both large (mm scale) and small (\(\mu m\) scale) angular particles as seen in Figure 2b.

The LHS-1 is primarily composed of silica and alumina, in agreement with the literature as it was made from volcanic rock.\(^{24,32}\) Its high silica content creates unique respiratory concerns over powder aerosol due to increased risk of silicosis.\(^{29}\) Lastly, micrographs of Zeolite X-13 show mostly homogeneous sub-100 \(\mu m\) particles (Figure 2c), which correlates well with PSD results. EDS showed that Zeolite samples were primarily composed of magnesium, silica, sulfur, and calcium, indicating the presence of impurities and absence of the expected sodium and aluminum peaks. While reference Zeolite 13X has no magnasia or sulfur, synthetic and commercial forms have presented magnesia.\(^{33}\) Additionally, this material shows high affinity for sulfur-containing compounds (hydrogen sul
de and mercaptans),\(^{34}\) which can explain the sulfur signal.

**Particle Concentrations During Printing.** Particle number concentrations were used as a means to compare each powder under the specific air exchange conditions in the enclosure. A heatmap was generated from the OPS/APS data depicting the relative particle concentrations in each bin size throughout each time step. A corresponding cumulative mass concentration plot is shown in Figure 3 indicating PM\(_1\), PM\(_{1.5}\), PM\(_{10}\), and PM\(_{10p}\). SMPS data indicate no discernible ultrafine (\(\leq 100 \text{ nm, or nanoscale}\)) particle number concentrations from the printer, which can be seen in Figure S6. The highest number concentration was observed for LHS-1, along with high particle counts across the entire 0.4–10 \(\mu m\) size span with a maximum number concentration of \(\approx 166 \text{ cm}^{-3}\) and a particle mode of 1.3 \(\mu m\). Zeolite depicted low particle counts between 0.5 and 7.6 \(\mu m\) with a maximum number concentration of 5.8 \(\text{ cm}^{-3}\), which is above the background level of 0.8 \(\text{ cm}^{-3}\) and a particle mode of 1.2 \(\mu m\). Printing activities with Hydroperm resulted in periodic particle counts in the 0.4–4.0 \(\mu m\) size range, with a maximum number concentration of \(\approx 6.6 \text{ cm}^{-3}\), slightly above the \(\approx 3.3 \text{ cm}^{-3}\) background level, and a particle mode of 0.5 \(\mu m\). The initial spike in mass concentration is due to the filling process in which powder is continuously spread onto the bed.

**Airborne Particle Emission Rates.** Emission rates in total particles per minute and emission factors normalized by the power bed drop volume are depicted in Figure 4, respectively. For all powder types, particle emissions under 0.2 \(\mu m\) were negligible due to no discernible difference between background and printing regimes; therefore, emission rates and reported data are reported using the OPS data in the 0.3–9.0 \(\mu m\) size range and for the APS data in the 0.5–8.3 \(\mu m\) size range. For all powders, emission rates were of the same order of magnitude across the measured particle size range without a drop at larger particle sizes as traditionally seen. This is atypical, and data accuracy was confirmed via comparisons between modeled and experimental mass and number concentrations (Figures S7–S9).

Total particle emission rates were \((5.4 \pm 0.96) \times 10^5 \text{ min}^{-1}\) for Hydroperm, \((1.0 \pm 0.28) \times 10^6 \text{ min}^{-1}\) for Zeolite, and \((2.2 \pm 0.82) \times 10^5 \text{ min}^{-1}\) for LHS-1. The emission rates for Zeolite and Hydroperm were similar, except for particles between 2 \(\mu m\) and 6 \(\mu m\) in size, where Zeolite had 2–4 times the
emission rate of Hydroperm. This indicates that particle emissions from powder-binder jetting machines with a constant spreading mechanism can vary widely depending solely on powder type. There are multiple hypotheses for the observed variability in particle emission rates among different powder materials. One hypothesis is the relative quantity of fine powder in each material and size dependent particle–particle interactions. Logically, a powder with a higher percent of fine components (indicated by a D$_{50}$ value below 10 μm) is expected to have higher emission rates. Under this hypothesis, the Zeolite should have a higher emission rate than Hydroperm and LHS-1 as it has the smallest D$_{50}$ value (3.85 μm, as compared to 22 μm for Hydroperm, and 304 μm for LHS-1). One possible explanation is that particle–particle interactions also play a role in airborne particle emissions. Smaller particles are more likely to agglomerate due to higher cohesive forces as particles attempt to minimize their Gibbs free energy. Furthermore, Zeolites have a high affinity for moisture; therefore, liquid-bridging and cohesion are stronger than for the other powders, which may reduce their respirable powder emission rate. Liquid bridging and agglomeration are often seen in food manufacturing such as in diary powder and lactose. Numerical studies suggest that a fine powder particle fraction of <4.0% is associated with lower flowability and increased agglomeration. Finally, Van der Waal forces become dominant as the effective powder diameter decreases because the effect of the gravitational force decreases with decreasing particle diameter.

Given these assumptions, powders with a larger particle size span and a sufficient percentage of fine particles are expected to emit the most repairable powder aerosol. This can be seen in the LHS-1 powder. Additionally, due to a high concentration of millimeter-sized particles for LHS-1, there is a potential for agitation in the powder collection bin as larger particles impact the finer particles resulting in a powder aerosol.

Mohajer et al. evaluated the standard PXL gypsum-based powder and found a peak PM emission rate of $2 \times 10^2$ min$^{-1}$ for particles of 0.3–1.5 μm in size, with emissions decreasing for particles approaching 10 μm in size. In this study, Hydroperm and Zeolite had peak emission rates 2 orders of magnitude higher at $3.0 \pm 0.91 \times 10^4$ min$^{-1}$ and $5.4 \pm 0.25 \times 10^4$ min$^{-1}$, respectively.
10^4 min⁻¹, respectively. PXL has a D₅₀ value twice that of Hydroperm and, therefore, is expected to have lower emissions in the upper particle size ranges. In contrast, Hydroperm has a D₅₀ of 21.7 μm, indicating a larger number of particles in the measurable range. Obviously, powder size has a large influence in emissions within the respirable range. PXL has 16% less powder by mass in the respirable range from 0.3–19 μm than Hydroperm. Furthermore, the presence of Portland cement changes the material properties of Hydroperm and helps explain why both gypsum-based powders yielded different emission rates.

In order to extrapolate these data to powder-binder jetting machines of different bed sizes, an emission factor was developed for each powder. The emission factor is defined as the emission rate divided by the volume of powder spread into the bed. Therefore, it is given in number of particles per minute per cubic millimeter of powder spread (Figure 4b). Volume spread is estimated as 10% greater than the volume of the bed after the stage drops 100 μm. The value is greater than the drop volume because extra powder is spread to ensure complete coverage of the build bed. The emission factors were 2.8 ± 0.85 min⁻¹ mm⁻³ for Hydroperm, 220 ± 72 min⁻¹ mm⁻³ for LHS-1, and 5.0 ± 0.24 min⁻¹ mm⁻³ for Zeolite.

**Influence of Depowdering.** The largest increase in particle emissions occurred during the depowdering process. During the depowdering process an air wand is used to remove extra powder from the part. This post processing unit is attached to the printer. Although there are bristles to prevent the bulk powder from blowing out, the depowdering station is not sealed, resulting in powder escaping from the machine during depowdering. As a result, a large powder cloud is released to the environment and results in the highest emissions seen in Figure S12. Only Hydroperm was tested in depowdering due to concern over large dust clouds of potentially harmful powders. Depowdering data from Hydroperm was used to infer its influence on any other powder type with the same air wand setup. The maximum total number concentration was 540 cm⁻³ compared to the 3.9 cm⁻³ background concentration. The number concentration decayed to background levels within 30 min equivalent to 3.5 air changes. The mass concentration (Figure S13) of PM₁₀ increased 24× that of background concentrations (0.516 to 12.2 μg m⁻³) and PM₁₀ rose 69× the background levels (1.17 to 80.72 μg m⁻³).

**Particulate Matter Mass Concentration by Printing Regime.** Understanding when emissions occur in the powder-binder jetting process is vital to limiting exposure as well as designing lower emission printers. PM concentrations by printing regime and percent increase from background concentrations are reported in Figure S14. The highest emission occurs during the spreading phase as the roller agitates the powder. The second highest PM concentrations were seen in the printing stage where both a spread layer is done and the roller agitates a powder mass. During spreading, Hydroperm PM₁₀ was 1.2 μg m⁻³, PM₁₅ 5.4 μg m⁻³, and PM₁₀ 19 μg m⁻³. For LHS-1, PM₁₀ was 68 μg m⁻³, PM₁₅ 440 μg m⁻³, and PM₁₀ 1560 μg m⁻³. For Zeolite, PM₁₀ was 1.5 μg m⁻³, PM₁₅ 19 μg m⁻³, and PM₁₀ 43 μg m⁻³. For comparison, office laser printers⁴⁰ have a PM₁₀ of 36 μg m⁻³ and PM₁₀ of 53 μg m⁻³, PM₁₀ for inkjet printers¹⁴ of 20–38 μg m⁻³; and PM₁₀ for photocopy machines¹¹ of 19–22 μg m⁻³.

### LUNAR MISSION CONSIDERATIONS

In situ resource utilization (ISRU) is the gold standard for manufacturing in an off-Earth environment. OSHA recently lowered the permissible 8-h TWA PEL of crystalline silica to 50 μg m⁻³.⁴² In this study, powder-binder jetting LHS-1 in a 6.4 m³ enclosure with a high AER has a 24 h exposure nearly 6× that of the recommended exposure limit set by OSHA. Although astronaut spacewalks and working hours are typically less than 8 h, the OSHA 8-h TWA PEL for printer emissions was used as both a reference value and a worst case scenario. This indicates proper emission controls should be in place if powder-binder jetting of regolith is to be considered for in situ resource utilization on a lunar base. From simulation results, we found that in a lunar environment with 1/6 the Earth’s gravity (1.62 m/s²), particles settle slower, resulting in higher concentrations than on Earth at distances away from the printer (Figure 5). In a simulated lunar module of a 3 m × 3 m × 50 m rectangular duct at an ACH of 0.7 with one printer, the lunar mass concentration 1 m from the printer was 46 μg m⁻³. This is 5.5% higher than on
Earth and just below the OSHA 8-h TWA PEL of 50 μg m⁻³. At 20 m away from the printer, the lunar mass concentration was 22 μg m⁻³ which was 330% higher than on Earth. The settling effect is pronounced at higher distances from the printer as seen in Figure 5. If two printers are operated in the same module, emissions exceed PEL in a lunar module for 16.4 m downstream. Flow is transitional for an air exchange rate of 0.7 with a Reynolds’s number of 2112, and velocity profiles can be found in Supporting Information Figure S16. Simulations were conducted at a higher ACH of 4.4 (Re ≈ 12 600), which is representative of a crew cabin on the ISS. In this scenario, flow is well within the turbulent regime verified through its velocity profile in Supporting Information Figure S17. The mass concentration declined sharper for a higher air exchange rate for the first 5 m, most likely due to turbulent effects. However, after 5 m, mass concentrations were greater than at 0.7 ACH.

A higher air exchange rate usually yields lower mass concentrations in a controlled volume. Due to modeling as a plug flow reactor, a larger air exchange rate yields a larger velocity and lower particle residence time (823 s compared to 5000 s). As a result, gravitational settling effects are lower at higher exchange rates leading to larger overall mass concentrations at equivalent distances away from the printer(s). This model highlights the influence of gravitational settling yet is limited in realistic applications. Future work taking into account full HVAC parameters would improve model utility. Further limitations to this model include no coagulation, overly simplified geometries, assumed particle and wall loss coefficients, and consideration of emissions as a source block across the entire cross section. The emission rates can be generalized for any lunar module shape and volume to predict mass or number concentration for more realistic lunar modules. Additional occupational exposure analysis can be found in Supporting Information Figure S18 for Hydroperm and Zeolite powders.

CONCLUSIONS

This paper identifies aerosol emissions in powder-binder jetting as highly dependent on powder properties as well as the powder spreading process. This paper also identifies emission concerns as powder-binder jetting enters new manufacturing use cases such as mold-making, life support systems, and in situ resource utilization. The main conclusions of this paper are as follows:

1. Aerosol emissions from powder-binder jetting depends on a combination of size, morphology, and composition. This suggests attention to emissions should be taken in powder development for powder-binder jetting printers.
2. The greatest aerosol emissions result from the powder spreading process. This study used a counter-rotating roller, and different emissions are expected for different spreading mechanisms.
3. LHS-1 exhibited the highest emission rate with a total emission rate of (2.2 ± 0.82) × 10⁷ min⁻¹, 2 orders of magnitude higher than Hydroperm [(5.4 ± 0.96) × 10⁵ min⁻¹] and 1 order of magnitude greater than Zeolite [(1.0 ± 0.28) × 10⁶ min⁻¹].
4. Aerosol emissions in lunar gravity have a lower settling time due to reduced gravity which may result in higher mass concentrations at distances away from the printer. In a simulated plug flow reactor at 0.7 air changes per hour 20 m away from the printer, the mass concentration of regolith was 330% higher in simulated Lunar gravity than for Earth.

This study highlights the need for further research on the interplay between powder chemistry or morphology and aerosol emissions. Furthermore, as metal powder-binder jetting enters the manufacturing industry on a greater scale, research on metal powder aerosol emissions is needed. For space applications, this paper identifies differences in aerosol emissions in Lunar gravity compared to Earth. Additive manufacturing of regolith for in situ resource utilization is important for improved extra-terrestrial self-sufficiency, yet greater research is needed on determining the human health impact as well as emission controls necessary for safety.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsestengg.0c00045.

EDS spectra, enclosure schematics, nanosized particle heat maps and concentrations, graphical PSD results, depowdering data, and simulation velocity profiles as well as a more thorough description of the simulation model and CFD approach (PDF)

Particulate simulation in the 3 m × 3 m duct at 0.01 m s⁻¹ velocity depicting particle spread (AVI)

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Notes

The authors declare no competing financial interest.

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