Health Hazard Evaluation Program

Evaluation of Metals Exposure in a Metal Powder Additive Manufacturing Facility

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Authors: **Aleksandr B. Stefaniak, PhD, CIH**
Elizabeth D. Brusak
Lauren N. Bowers
Sherri Friend
Christopher Barnes, MS
Chaolong Qi, PhD, PE

Analytical Support: Bureau Veritas North American, Inc.

Industrial Hygiene Field Assistance: Aleksandr Stefaniak, Elizableth Brusak, Lauren Bowers

Data Support: Brian Tift

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Disclaimer

The Health Hazard Evaluation Program investigates possible health hazards in the workplace under the authority of the Occupational Safety and Health Act of 1970 [29 USC 669a(6)]. The Health Hazard Evaluation Program also provides, upon request, technical assistance to federal, state, and local agencies to investigate occupational health hazards and to prevent occupational disease or injury. Regulations guiding the Program can be found in Title 42, Code of Federal Regulations, Part 85; Requests for Health Hazard Evaluations [42 CFR Part 85].

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Introduction

Request

The director of operations and control at a metal powder additive manufacturing facility requested a health hazard evaluation concerning dermal and inhalation exposures to metals in the workplace.

Workplace

The facility was comprised of a main production area and a separate non-production (office) area. The production area was a main hallway with access to the powder bed fusion, directed energy deposition, and post-processing rooms. Each area had its own dedicated ventilation system. During our visits, the employees performed a variety of tasks including printing metal parts, sieving powder, de-powdering printed parts, and post-processing of printed parts. Approximately 8 to 12 employees spent the majority of their time in the production area performing these tasks.

To learn more about the workplace, go to Section A in the Supporting Technical Information

Our Approach

We visited the facility on two separate occasions. The first visit was in March 2023, and we did the following activities:

- Completed a walkthrough survey of the facility.
- Observed employees as they performed specific tasks to prepare and finish a print.
- Collected wipe samples of surfaces and employee outer clothing, personal protective equipment (gloves, coveralls), and skin.
- Obtained bulk samples of feedstock metal powders to determine particle morphology and composition.

The second visit was in May 2023. During this visit, we did the following activities:

- Collected personal air samples for metals and/or organic gases during preparation, printing, post-processing, cleaning, and maintenance.
- Collected area air samples for metals throughout the facility during the workday.
- Monitored task-based levels and spatial distribution of particles using real-time instruments.
- Performed assessment on the ventilation system in the powder bed fusion printing area. Captured face velocities of the exhaust air vents in the area and took pressure readings of the interlock room located between the powder bed fusion room and main hallway.

To learn more about our methods, go to Section B in the Supporting Technical Information

Our Key Findings

Employees in the powder bed fusion room were exposed to airborne particles.

- Particle number concentration measurements showed that work tasks increased particle concentrations to some degree in the powder bed fusion room whether an employee was working directly with powders or not.
- Particle number concentration measurements did not show a clear consistent spatial difference that supports deviating from the current company policy to wear respiratory protection when someone else in the room is handling powder or when directly handling powder.

Employees in some production areas were exposed to airborne metal particles.

- Personal breathing zone sampling demonstrated exposure to multiple metals in the powder bed fusion and post processing rooms.
- The personal breathing zone concentrations of some elements were similar in the powder bed fusion room where bulk powders were handled and post-processing room where only solid forms of metal were handled.
- None of the personal breathing zone concentrations of elements exceeded their respective occupational exposure limits.

Feedstock metal powders have migrated throughout the facility.

- Particles with shape and composition consistent with feedstock powders were seen in nearly all areas of the facility.
- Measurable amounts of metals were present on surfaces in the powder bed fusion, directed energy deposition, and post-processing rooms.
- Levels of metals on surfaces were barely measurable in non-production areas such as administrative offices and breakrooms.

Employee's skin and clothing was contaminated with metals during work.

- Measurable amounts of metals were present on the wrist skin of employees, some who were working directly with metal powders and others who were not.
- Measurable amounts of metals were present on the shirts of employees, some who were working directly with metal powders and others who were not.

Particle migration was affected, in part, by airflow patterns in the facility.

- Particles generated by the wire electrical discharge machine in the post-processing room migrated into the air throughout the production area and were drawn into the powder bed fusion room.

To learn more about our results, go to Section B in the Supporting Technical Information

Our Recommendations

The Occupational Safety and Health Act requires employers to provide a safe workplace.

Benefits of Improving Workplace Health and Safety:

- ↑ Improved worker health and well-being
- ↑ Better workplace morale
- ↑ Easier employee recruiting and retention
- ↑ Enhanced image and reputation
- ↑ Superior products, processes, and services
- ↑ May increase overall cost savings

During the March 2023 site visit, management expressed interest in ways to possibly improve ventilation. In May 2023, NIOSH ventilation experts visited the facility. The recommendations below are based on the findings of our industrial hygiene sampling and ventilation evaluation and are offered to you for consideration if you wish to further control emissions and exposures to hazardous substances, even though measured exposures of these substance are below available occupational exposure limits where they exist. For each recommendation, we list a series of actions you can take to address the issue at your workplace. The actions at the beginning of each list are preferable to the ones listed later. The list order is based on a well-accepted approach called the "hierarchy of controls." The hierarchy of controls groups actions by their likely effectiveness in reducing or removing hazards. In most cases, the preferred approach is to eliminate hazardous materials or processes and install engineering controls to reduce exposure or shield employees. Until such controls are in place, or if they are not effective or practical, administrative measures and personal protective equipment might be needed. Read more about the hierarchy of controls at About Hierarchy of Controls | Hierarchy of Controls | CDC.

We encourage the company to use a health and safety committee to discuss our recommendations and develop an action plan. Both employee representatives and management representatives should be included on the committee. Helpful guidance can be found in "*Recommended Practices for Safety and Health Programs*" at https://www.osha.gov/shpguidelines/index.html.

Recommendation 1: Implement ventilation controls to minimize the migration of metals and gases throughout the facility and prevent them from being inhaled.

If hazardous metals and gases migrate among rooms in the production area, employees can unknowingly come into contact with them during work. Several of the metals in the feedstock powders can cause adverse effects if breathed into the lung. The effects of breathing these metals include lung irritation, fibrosis, respiratory symptoms (cough, breathing difficulty, or wheezing), asthma, respiratory hypersensitivity, and neurological symptoms. Several gases released during wire electrical discharge machining can cause eye, nose, throat, or lung irritation. Measurable levels of metals and gases were present in employees' breathing zones (the area around their face) throughout the production area, but these levels were below occupational exposure limits. Recommendations herein are based on the company's request for ways to improve ventilation.

How? At your workplace, we recommend these specific actions:

Enhance performance of the existing ventilation system.

- Evaluate the seals in the high efficiency particulate air (HEPA) filter boxes outside the PBF room to verify no fugitive emissions are escaping into the *in situ* bay.
- Implement local exhaust ventilation, e.g., capturing hood or negative pressure enclosure with HEPA filtration, for the tasks in the post-processing room that may release powder/particles to the air as noted in the previous section of the report. NIOSH can provide additional guidance on designing proper local exhaust ventilation.
- Increase the air change rate of the general ventilation in the post-processing room and/or put the room under negative pressure to minimize the airborne migration of particles, metals, and aldehydes to other spaces of the facility. A desired air exchange rate (ACH) can be set to the number of exchanges necessary to reduce concentrations to a level acceptable to the company. NIOSH can provide additional guidance on calculating and selecting a desired ACH.
- Close the access doors in the main hall to minimize air exchange and contaminants migration between the areas of the PBF room and the post-processing room.
- Increase the clearance in front of the exhaust vents in the PBF room (e.g., by moving storage cabinets) to allow improved airflow into the vents and convenient access for maintenance.
- Ensure airflow direction from supply air vents in the ceiling is not blowing particle-laden air into employees' breathing zones during tasks, e.g., setting up desirable positions for the workers and/or providing trainings to workers to always position themselves upstream of the process in terms of airflow.

Evaluate whether the company wants to augment existing ventilation controls.

- Consider implementing portable local exhaust ventilation with HEPA filtration in the PBF room to capture the airborne particles near the source of release during routine and non-routine tasks (NIOSH can provide additional guidance).
- Consider implementing local exhaust ventilation on the wire electrical discharge machine to capture particles, metals, and aldehyde near their sources and lower their concentrations in the post-processing room and potentially throughout the entire production-side of the facility (NIOSH can provide additional guidance).
- Consider implementing portable local exhaust ventilation for the grinding process in the post-processing room to capture the airborne particles near the source and minimize exposures (NIOSH can provide additional guidance).

Recommendation 2: Enclose or isolate dusty processes to minimize the migration of metals throughout the facility and prevent metals from being inhaled or getting on the skin.

Several of the metals in the feedstock powders can cause adverse effects if breathed into the lung or are hazardous to the skin. The effects of breathing these metals include lung irritation, fibrosis, respiratory symptoms (cough, breathing difficulty, or wheezing), asthma, respiratory hypersensitivity, and neurological symptoms. Employees can come into contact with metals by touching a surface contaminated with metal particles that have settled from air or that escaped from a process. If an employee gets these metals on the skin, it is possible they could develop skin irritation or an allergic reaction. These health effects could require absence from work and/or medical treatment and costs. Measurable levels of metals were present in employees' breathing zones (the area around their face) throughout the production area, but these levels were below occupational exposure limits. Measurable amounts of metals were present on surfaces throughout the facility.

How? At your workplace, we recommend these specific actions:

Redesign the depowder process to further enclose this dusty process.

- Evaluate the feasibility of a two-step depowdering process, i.e., current depowdering in the glove box followed by vacuuming or washing in an enclosure to remove more powder from parts and build plates prior to transport out of the powder bed fusion room.

Redesign the printing process to contain dust.

- Continue to implement process design changes that reduce skin exposure such as the enclosed powder handling process (version 2 printers) compared with the manual handling process (version 1 printers).

Implement dust control measures to minimize the release of powder particles into air.

- For version 2 machine tasks (wet vacuuming, residual powder cleaning within build chambers, opening access doors, and powder cleaning) allow several build chamber air exchanges to occur before opening the door to reduce the amount of dust released into the PBF room air.
- Perform manual powder scooping in a ventilated hood or cabinet.
- For depowdering, allow several chamber air exchanges to occur before opening the door to reduce the amount of dust released into the PBF room air.
- Avoid activities that might suspend powder from surfaces into air such as hammering on items (e.g., powder sieves) or machines.
- Evaluate the dust generating potential of handling parts and testing activities in the quality control laboratory to determine if controls are necessary.

Provide an added barrier to movable items prior to transport.

- Thoroughly clean build plates and place in a sealed plastic bag before transporting from printer rooms to non-powder areas of the facility (e.g., post-processing room, quality control laboratory, part testing area).
- Clean the exterior, and to the extent feasible, interior surfaces of items and place in a sealed plastic bag before transporting to the maintenance cage for repair.
- Place ground build plates inside clean, sealed plastic bags before storing on shelves in the post-processing room or transporting back to printing rooms.

Increase use of tacky mats by all doors in production areas.

- Frequently replace tacky mats (whenever they become visibly dusty or the surface appears dull) in front of doors in both the clean and dirty sides of the personal protection equipment (PPE) change out room to collect particles from shoes.
- Frequently replace tacky mats in front of person doors leading out of the directed energy deposition (DED) room to the small hallway and the post-processing room; in front of the doors leading from the production area to the administrative suite,

individual offices, and engineering suite; and narrow hallway leading to the backside of the PBF room.

Recommendation 3: Implement administrative controls to prevent metals from getting on employees' skin and migrating in the facility.

Some of the hazardous metals in feedstock powders were present on work surfaces. If an employee contacts these surfaces, metals could get on their skin. An employee can also get metals on their skin when handling feedstock powders. Once on skin, an employee could develop skin irritation or an allergic reaction. If they develop these reactions, it could result in lost workdays and medical costs for treatment. Measurable levels of metals were present on work surfaces, PPE, and employees' street clothing that could result in contact with skin. Measurable levels of metals were present on employees' wrist skin.

How? At your workplace, we recommend these specific actions:

Perform periodic maintenance on the depowdering station.

- Replace the seal for the glove box in accordance with the manufacturers' specifications and visually inspecting it periodically for signs of ageing, cracking, crimping or other compromises that could affect integrity.
- Periodically monitor the seal around the glove ports to ensure its integrity remains intact.

Encourage hand washing to remove metals from skin.

- Encourage staff to wash their hands with soap and warm water throughout the work day and dry thoroughly. This recommendation is especially important for any task that involves powder handling or touching build plates.

Use wet cleaning to remove metals from surfaces.

- Continue regular cleaning of work surfaces and room surfaces such as walls and floors (mopping devices with single-use damp cleaning pads could be useful for walls and floors).
- Pay particular attention to surfaces that employees' skin might contact. These could range from high touch surfaces (e.g., door handles, machine touch screens and keypads, locker handles, computer equipment; transport cart handles; and vacuums and hoses and brooms) to less frequently touched surfaces (e.g., bench tops, cabinets, and filter boxes; and outer surfaces of containers such as powder cans and waste buckets).

- Clean the inner surfaces of the neoprene gloves on the depowdering station (or have staff wear oversleeves if wearing short sleeves and disposable gloves) prior to use.
- Clean surfaces of powered air purifying respirators (PAPRs) using wet wipes after every use.
- Clean all floors in production areas with particular attention to areas in front of the DED room roll-up garage door (where not feasible to put tacky mats down) and in front of doors leading into non-production areas.
- Wrap the wheels of the Artie robot in a disposable cover (or tape) while in powder areas and remove the protective layer (or thoroughly wet clean) before traveling to non-powder areas.
- Clean items before placing in storage cabinets and frequently wet clean interior cabinet surfaces.

Cover office equipment and personal items with easily cleanable materials.

- Cover the fabric portions of any chairs with a smooth material that is easy to clean or replace with chairs that have an easy to clean hard surface.
- Place personal items such as backpacks in a clean sealable plastic bag if brought into the production area.
- For employees with desks in the production area (e.g., offices opening to main hall or in the post-processing room), use a keyboard cover made of a smooth material that is easy to clean.
- For employees with desks in the administrative and engineering suites, consider offering the option to use a keyboard cover made of a smooth material that is easy to clean.

Dedicate equipment.

- Dedicate the vacuum in the DED room and avoid moving it to other areas of the facility.

Prevent metals from settling on respiratory protection.

- Do not store respirators out in the open in areas where feedstock powder is handled such as the DED room.

Prevent skin contact with contaminated PPE.

- Remove cloth laboratory coats in the dirty side PPE change out room while wearing nitrile gloves and place in a plastic bag before entering the clean side.
- Provide wet wipes (such as a disposable towel wetted with isopropyl alcohol or water) and nitrile gloves in the clean-side change out room and follow the instructions at How

to Safely Put on PPE, Selected Equipment: PAPR and Coverall - YouTube when putting on PPE. Note that these instructions were developed for healthcare settings but can be adapted to your workplace as the types of PPE in use are similar. Briefly, the procedure is: 1) inspect boot covers, Tyvek® suit, gloves, and powered air-purifying respirator (PAPR) to ensure physical integrity, and the PAPR battery is fully charged; 2) clean hands with a wet wipe and dry; 3) put on boot covers; 4) put on nitrile gloves; 5) put on Tyvek® suit; 6) attach PAPR to belt and clip belt around your waist; 7) put on outer gloves; and 8) attach hose to PAPR helmet/hood and put on.

- Provide wet wipes, nitrile gloves, and plastic bags in the dirty side change out room and follow the procedure prescribed at How to Safely Take off PPE, Selected Equipment: PAPR and Coverall (youtube.com) to remove potentially contaminated PPE (the same procedure should be used when taking off PPE worn in the DED room). Note that these instructions were developed for healthcare settings but can be adapted to your workplace as the types of PPE being removed are similar. Briefly, the procedure is: 1) clean your outer gloves with a wet wipe; 2) remove one outer glove by pinching at the wrist and rolling it off the hand into a ball, place the balled glove in the other hand then slide a finger or thumb under the other outer glove and roll down the hand and around the previously balled glove; 3) inspect the inner layer glove for tears or signs of visible powder contamination and either clean contaminated gloves with a wet wipe or place clean gloves over them if torn; 4) detach the hose from the PAPR hood, unclip the belt, and take of the helmet/hood and place in plastic bag for storage in the clean side; 5) clean gloves with a wet wipe; 6) remove Tyvek® suit by unzipping and rolling down toward the feet; 7) clean gloves with a wet wipe; 8) remove boot covers; 9) remove gloves using procedure described earlier; and 10) wash hands with wet wipes or with soap and water, if available. Use a wet wipe to clean the door handle before opening to enter the clean side.

Launder fabrics that come into contact with skin.

- If shirts worn by employees in production areas are personally owned, substitute for company-issued work shirts or require changing into a clean shirt before leaving the facility.
- Provide a service to appropriately launder either company-issued or personal outer work clothing worn in production areas.
- Launder cloth over gloves used in the post-processing manual finishing area if they become contaminated (or disposed of).
- Launder cloth laboratory coats if they become contaminated.

Monitor employee exposures.

- Continue to monitor exposures to staff when performing routine and non-routine tasks.
- Encourage employees to report new, persistent, or worsening symptoms, particularly those with a work-related pattern, to their personal healthcare providers and, as instructed by their employer, to a designated individual in their workplace.

Recommendation 4: Use PPE to keep metals and gases out of employees' lungs and metals off their skin and to prevent migration throughout the facility.

Small particles and gases that are breathed in can get trapped in the lung. Once in the lung, they can induce adverse health effects. The type of health effect will depend on the chemistry of the exposure, and for some people, on their individual susceptibility to the chemical. Several of the metals in the feedstock powders can cause adverse effects if breathed into the lung. These effects include lung irritation, fibrosis, respiratory symptoms (cough, breathing difficulty, or wheezing), asthma, respiratory hypersensitivity, and neurological symptoms. Several gases released during wire electrical discharge machining can cause eye, nose, throat, or lung irritation. These effects could require absence from work and/or medical treatment and costs. Particle count measurements in the powder bed fusion room show that all tasks could increase particle levels whether an employee was working directly with powders or not. Measurable levels of metals and gases were present in employees' breathing zones (the area around their face) but were below applicable occupational exposure limits. Some of the hazardous metals in feedstock powders were present on work surfaces. If an employee contacts these surfaces, metals could get on their skin. An employee can also get metals on their skin when handling feedstock powders. Once on skin, an employee could develop skin irritation or an allergic reaction. If they develop these reactions, it could result in lost workdays and medical costs for treatment. Measurable levels of metals were present on work surfaces, PPE, and employees' street clothing that could result in contact with skin. Measurable levels of metals were present on employees' wrist skin.

How? At your workplace, we recommend these specific actions:

Use respirators to keep dusts out of the lungs.

- For version 1 machine sieving, consider directing employees to wear PAPRs if an error message is displayed on a sieve station and requires resolution or if two or more stations are operating simultaneously.
- For version 1 machine sieve flow bin uncoupling, powder vacuuming, and opening access door tasks, continue company policy to wear PAPRs to minimize breathing in particles.

- All staff present in the PBF room should wear PAPRs because particle number concentration measurements did not show a clear consistent difference that supports deviating from the current company policy to wear respiratory protection when someone else in the room is handling powder or when directly handling powder.

Use gloves to prevent particle contact with skin and particle migration throughout the facility.

- Frequently change nitrile gloves while working in the PBF room, especially between tasks at different printers, sieve stations, and other areas.
- Encourage all production staff to consistently wear nitrile gloves and frequently change them, especially when leaving a room or after handling build plates.
- Increase staff awareness to remove nitrile gloves before entering the employee lounge.
- Require all administrative employees to wear nitrile gloves while in production areas, no matter how brief, and remove them before returning to non-production areas.
- Increase awareness among production staff to wear nitrile gloves while installing a new printer since there might already be metals on surfaces.
- Increase awareness among staff to always wear nitrile gloves when contacting cart handles or other items that might be contaminated with metals.
- Increase awareness among staff to change nitrile gloves before using office equipment or contacting other surfaces on desks.
- Remind staff to always wear clean nitrile gloves under over gloves such as the cloth gloves in the manual part finishing area.
- Always wear clean nitrile gloves when putting on a cloth laboratory coat or taking it off.
- Always wear nitrile gloves when handling build plates brought into the quality control laboratory for testing.
- Thoroughly clean shop packets before they leave a room, do not store them directly in contact with build plates on shelves, and replace them with a clean cover whenever brought into any administrative area.
- Remind staff to wash their hands with soap and water or wet wipes when removing gloves and before putting on new gloves.

Use shoe covers to prevent particle migration.

- Consider requiring staff to wear shoe covers out of the clean side of the PPE change out room.

- Require boot covers (provide boot scrubbers) whenever leaving a production area and entering a non-production area.

Use arm sleeves to keep metals off wrists and arms.

- Reinforce the importance of covering exposed skin (wrists, forearms) using long sleeve shirts or protective arm sleeves.

Supporting Technical Information

Evaluation of Metals Exposure in a Metals Additive Manufacturing Facility

HHE Report No. 2023-0034-3409

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Section A: Workplace Information

Building

The 18,000 square foot building is a product sales demonstration facility for powder bed fusion (PBF) and directed energy deposition (DED) additive manufacturing machines, allowing potential customers to evaluate the capabilities of equipment and processes involved in manufacturing parts prior to purchasing. The facility was divided into a production area and an office area. The production area had an open floor plan main hall (consisting of an *in-situ* production bay (area with computer monitors to track build progress without entering the printer rooms), shipping area, and small laboratory area), from which there were access doors to non-production areas (administrative and engineering suites), the PBF room, the DED room, and a post-processing room. The PBF room contained two rooms for personal protective equipment (PPE) change out: a "clean" side room where employees entered and donned their PPE before accessing the PBF room and a "dirty" side room where the employees doffed their PPE before exiting to the clean side room then the main hall. The PBF room was under negative pressure and had an inter-lock door system leading to the main hall to prevent metal powder from escaping into other areas of the facility. The post-processing room included a maintenance cage, a space with work benches and pneumatic hand tools, and employee desks as well as doors to access the DED room, a quality control laboratory, and an employee break room.

Employee Information

At the time of our visits, there were 38 employees at this facility that work 8-hour shifts, 5 days per week. Approximately 8 to 12 employees spent the majority of their shift in the production area, and the remaining employees worked in the non-production areas.

Background about the Request

Employees wore street clothes in work areas. This facility had an established policy for PPE use during work that was revised in Fall 2023. The revised policy indicated that employees must always wear steel toed shoes, eye protection, and nitrile gloves when in the production area. If an employee was not directly handling or agitating powder but was in a room where someone else was doing these activities, they must also wear a powered air-purifying respirator (PAPR), laboratory coat (can be cloth), and shoe covers. When an employee was directly handling or agitating powder, they must replace the laboratory coat with a hooded Tyvek® suit. One goal of management was to verify the efficacy of these existing policies and learn of any improvements to better protect their staff and potential customers.

Process Description

Powder Bed Fusion Room

The PBF room was served by general room ventilation that consisted of supply air vents in the ceiling and return air vents in the walls with HEPA filters; the room air turnover reported by the company was 1 air exchange per 1.25 minutes. PBF machines at this facility used a laser in an inert atmosphere to selectively melt metal powder in a moveable bed. Once a layer was fused, the bed lowered slightly, and a powder roller pushed a new layer of powder over the fused material (Figures A1 and A2). This process repeated itself until completion of the printed part. The PBF process required preparation before the print and a post-processing sequence once the print was complete. The printers themselves were enclosed and sealed during the printing process which minimized potential exposure to feedstock powders or particles that became suspended in the atmosphere inside the build chamber.

There were two versions of PBF printers in use at this facility at the time of the site visits. The (older design) version 1 printer had a powder sieving station separate from the printer so an employee must manually move containers of sieved powder to/from the printer. The (newer design) version 2 printer had a sieving station connected to it that automatically transported powder to the printer. Once printing was complete, the final part was immersed in powder that needed to be removed to retrieve the part. For version 1 printers, the access doors had to be opened so that an external vacuum could be used to remove excess powder. Version 2 printers had a built-in vacuum to remove as much powder from the part as possible before opening the printer door. Once a version 2 printer door was opened, a separate external vacuum (specific to the feedstock powder) was connected to a container to extract the excess powder for recycling or disposal. The inside and outside of the printers were cleaned with paper towels and isopropyl alcohol to remove residual metal powder prior to next use.

Regardless of printer design, after the vacuuming, the part was placed into a depowdering station. This station was a glove box under negative pressure with a compressed argon gas gun to dislodge loose powder in difficult to reach areas of the printed part (e.g., inside crevices). After depowdering, the part (still attached to a build plate) was transferred onto a cart for transport to the testing laboratory area, shipping, or the post-processing room.

Figure A1. A powder bed fusion machine on standby. Photo by NIOSH.

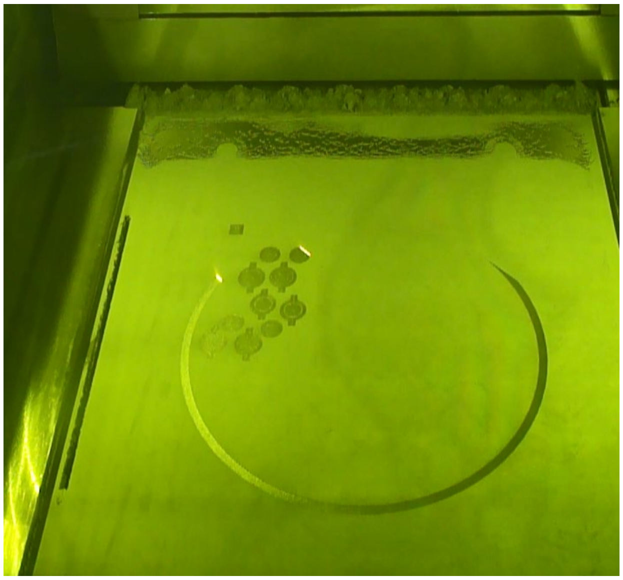


Figure A2. The powder bed fusion process of sintering metal powder with a laser to form the part. Photo by NIOSH.

Directed Energy Deposition Room

DED additive manufacturing machines had a nozzle that used a focused energy source such as a laser to simultaneously melt the metal powder as it was deposited onto the build platform to make an object (Figures A3 and A4). Since the metal powder was being melted directly onto the bed or metal part, the final product did not have to go through an extensive powder removal process, though some powder remained in the build chamber. Before the part was removed, a wire brush was used to scour the surface of the metal part to dislodge any unsintered powder. A vacuum dedicated to the type of metal powder used to make a part was used to remove any residual powder. The build plates for DED machines were smaller compared with those used for PBF machines so they were manually removed from a printer and placed onto a cart for transport to shipping or the post-processing room.

Figure A3. A directed energy deposition machine on standby. Photo by NIOSH.

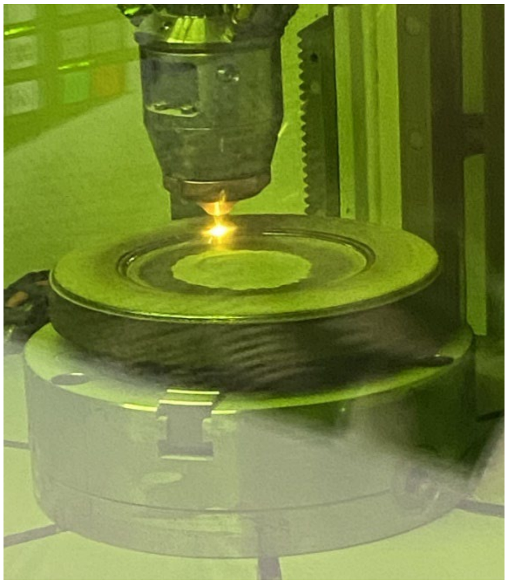


Figure A4. The directed energy deposition nozzle depositing melted metal powder onto a build platform. Photo by NIOSH.

Post-Processing Room

In this room, parts were cut from their build plate using a wire electrical discharge machine (EDM) (Figure A5) and could be further processed by grinding or sand blasting to reach the desired finish. The other major activity in the room was wet grinding build plates after part removal to achieve dimensional tolerance prior to reuse.

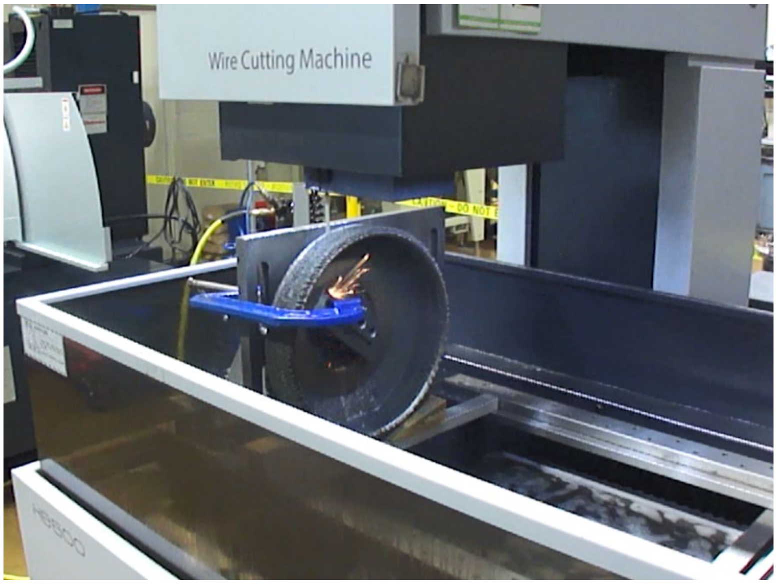


Figure A5. Wire electrical discharge machine cutting a metal part from a build plate. Photo by NIOSH.

Section B: Methods, Results, and Discussion

Our objectives were to

- Study whether migration of feedstock powders occurs from the powder handling rooms to other rooms in the facility (post-processing room, main hall, and non-production areas).
- Evaluate potential and actual skin and inhalation exposures to metals and gases.
- Evaluate particle levels in proximity to, and a distance from, production activities.
- Assess effectiveness of ventilation and offer potential improvements to ventilation systems.

Methods: Bulk Feedstock Samples

The company provided NIOSH with a few grams of four virgin (never printed) feedstock powders in use at the facility. A sample of each powder was prepared for analysis by scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDX). A scanning electron microscopy (SEM) is a microscope that allows us to visualize individual particles at high magnification. EDX is a chemical analysis technique that tells us the composition of a particle. Double-sided carbon tape was attached to a SEM pin stub sample mount and a fine layer of powder sprinkled onto the tape. A separate sample was prepared for each powder. These samples served as references for the shape and composition of feedstock powders in use at the facility. The particles were imaged at magnifications of typically 500× to 10,000×. These powder samples were also used as recovery spikes as quality control for wipe and air samples.

Results: Bulk Feedstock Powders

Appearance of powders

Figure B1 is SEM images of the four feedstock powders used at the facility. All powders were used in both the powder bed fusion (PBF) and directed energy deposition (DED) printers, except AlSi10Mg which was only used in PBF printers. Many powder particles had spherical shape with occasional particles that were longer than they were wide. Some particles had smaller "satellite" particles on their surface, though SEM cannot determine how strongly attached they were to one another. The scale bar on all images is 100 micrometers or 0.1 millimeter. Comparing particles among images, the 316L stainless steel (panel a) and (b) Inconel 718 (panel b) powder particles appeared smaller than the Ti64 (panel c) and AlSi10Mg (panel d) powder particles.

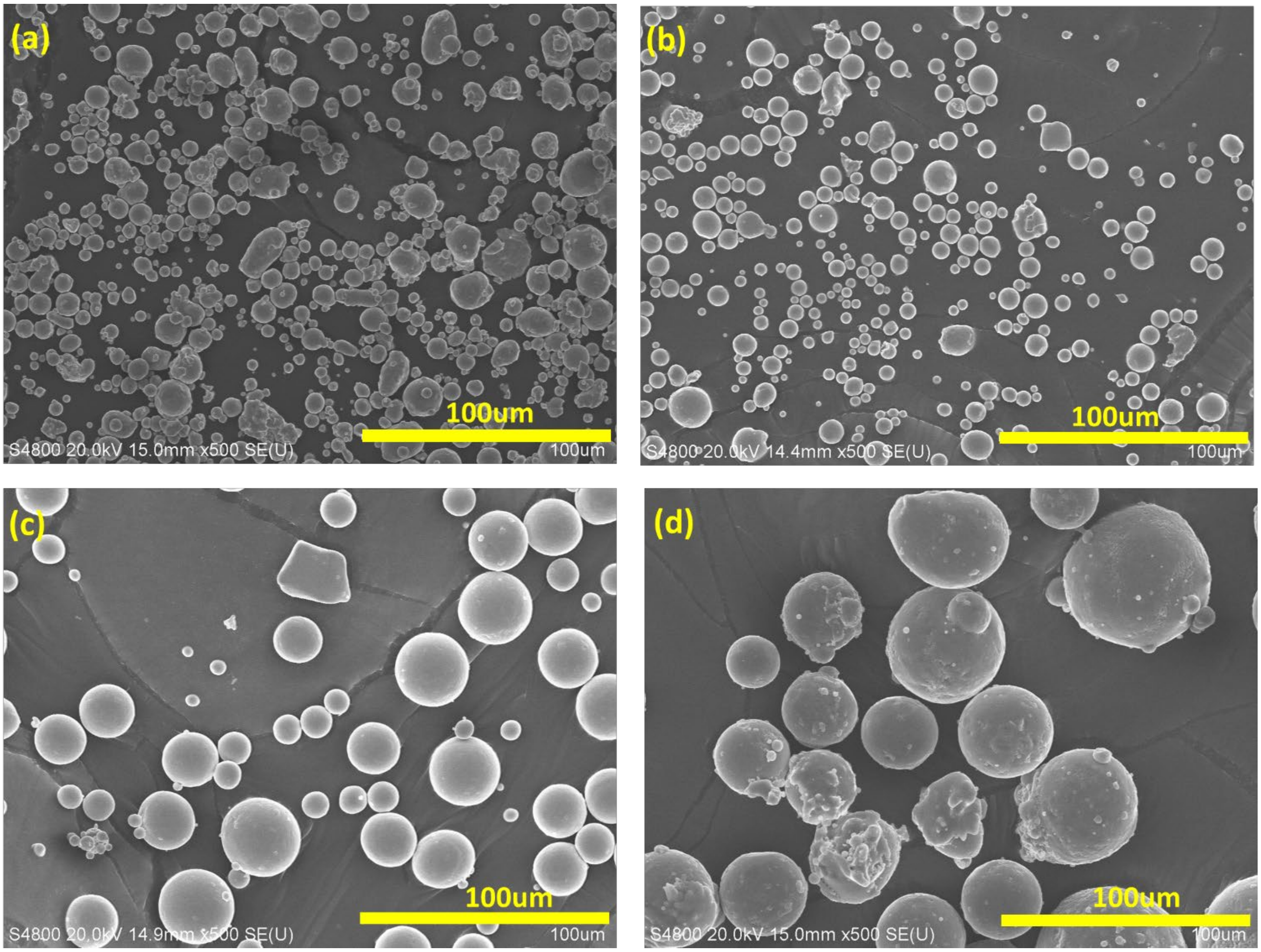


Figure B1. Scanning electron micrograph images of bulk feedstock powders used for printing: (a) 316L stainless steel powder, (b) Inconel 718 powder, (c) Ti64 powder, (d) AlSi10Mg powder.

Composition of Powders

Figure B2 shows the EDX pattern of each bulk feedstock powder. An EDX pattern is like a fingerprint. An element produces one or more peaks at distinct energy levels that are unique to the element so it can be used to identify it. The chemical composition of each powder determined by its EDX pattern was consistent with its safety data sheet (SDS) provided by the company.

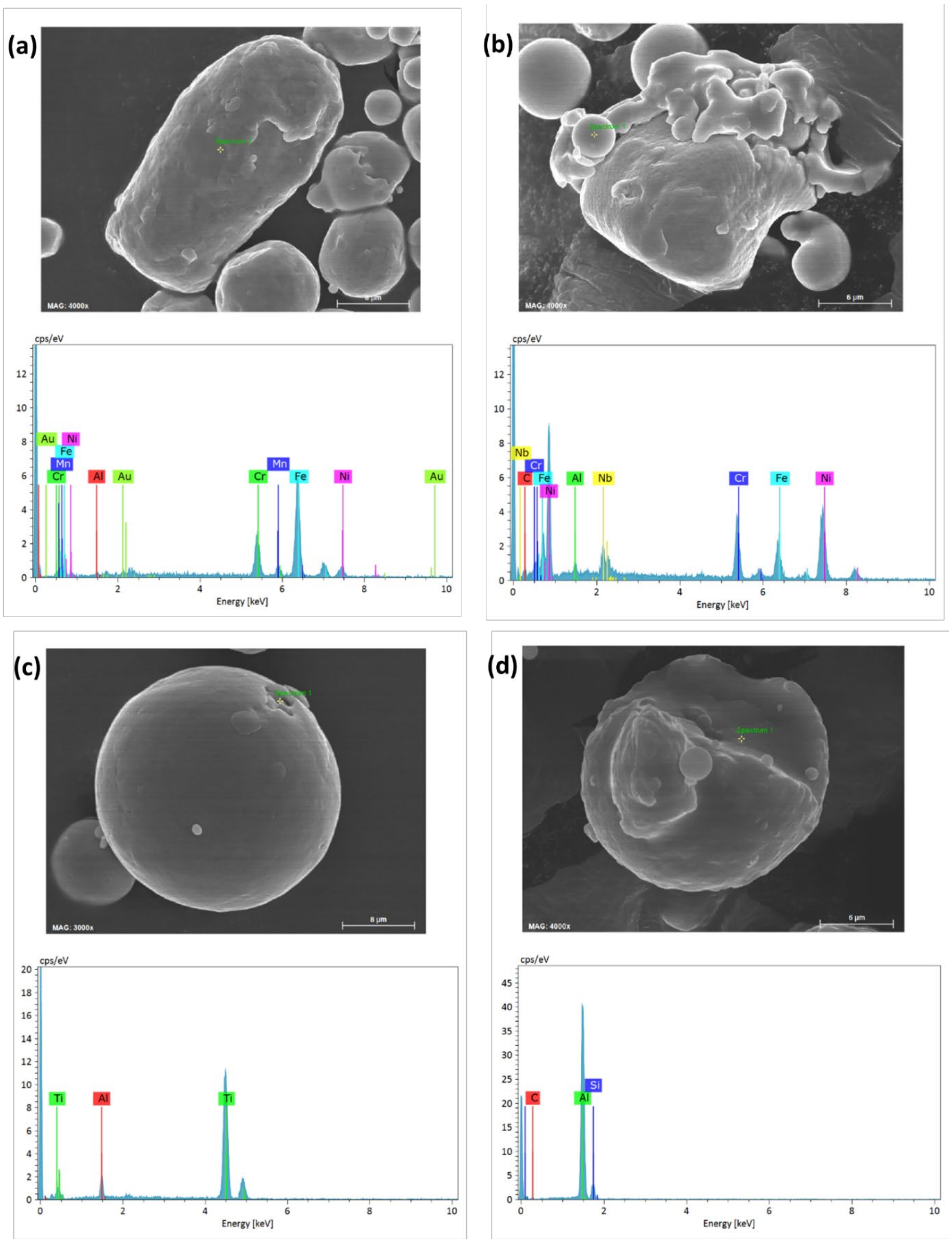


Figure B2. Energy dispersive X-ray patterns of bulk feedstock powders used for printing: (a) micron-scale 316L stainless steel powder particle consisting of chromium, iron, nickel, aluminum, and manganese; (b) micron-scale Inconel 718 powder particle consisting of chromium, iron, nickel, niobium, and aluminum; (c) micron-scale Ti64 powder particle consisting of titanium and aluminum; (d) micron-scale AlSi10Mg powder particle consisting of aluminum and silicon.

Methods: Surface Sampling

We collected SEM pin stub and surface wipe samples to understand whether migration of powders occurs from the PBF and DED rooms to other rooms in the facility. Pin stub samples were used to identify the presence of particles on surfaces, and wipe samples were used to quantify the amount of metals on surfaces.

We used SEM pin stubs with double-sided carbon tape to collect samples of particles on surfaces throughout the facility for analysis by SEM-EDX for comparison with the feedstock powders (Figures B1 and B2). For each SEM stub sample, several different locations or "fields" were inspected to get an overview of the particles. Magnification of images are typically 500× to 10,000×.

We used square paper sampling templates (10 cm × 10 cm) to demarcate a known area to wipe using a Ghost Wipe™ (Environmental Express, Charleston, South Carolina) pre-moistened wet wipe material for collection of particles from surfaces [NIOSH 2022]. A template was placed on a surface and held securely while a fully unfolded wipe was used to wipe the entire surface in an S-shaped pattern from left to right. The wipe was folded in half and used to wipe the surface inside the template in an S-shaped pattern from top to bottom. The wipe was folded in half once more and used to wipe the surface in an S-shaped pattern diagonally, from corner to corner. Each wipe was placed in a clean individual labeled bag until analysis. We used a new template for each sample. If a template could not be used because the surface had an irregular shape (e.g., a door handle), the dimensions of the surface were measured using a ruler to calculate the area. All Ghost Wipe™ samples were analyzed using NIOSH Method 7303 to quantify the amount of aluminum (Al), total chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), molybdenum (Mo), nickel (Ni), tin (Sn), titanium (Ti), and vanadium (V) [NIOSH 2003]. Additionally, we used polyvinyl chloride (PVC) filters with templates in the same manner as outlined above to sample for hexavalent chromium [Cr(VI)] which is one type of chromium. These samples were analyzed using OSHA Method W4001 [OSHA 2001]. We selected those elements because they were constituents in the feedstock powders that have capacity to cause adverse skin reactions. The presence of metals on surfaces is not evidence of exposure (material on skin) rather it is indicative of potential for exposure (material is available and could get on skin).

Table C1 summarizes the types of surfaces that were wiped, including desks, tabletops, keyboards, workers' personal items (such as a backpack), handles, machine touch panels, floors, chairs, and other frequently touched items.

Results: Surface Sampling

PBF Room

Figure B3 shows a printed part made of Inconel 718, after vacuuming and removing it from a printer (before depowdering), and the SEM-EDX results. The shape and composition of the particles were consistent with Inconel 718 (compare to Figures B1(b) and B2(b)) feedstock powder.

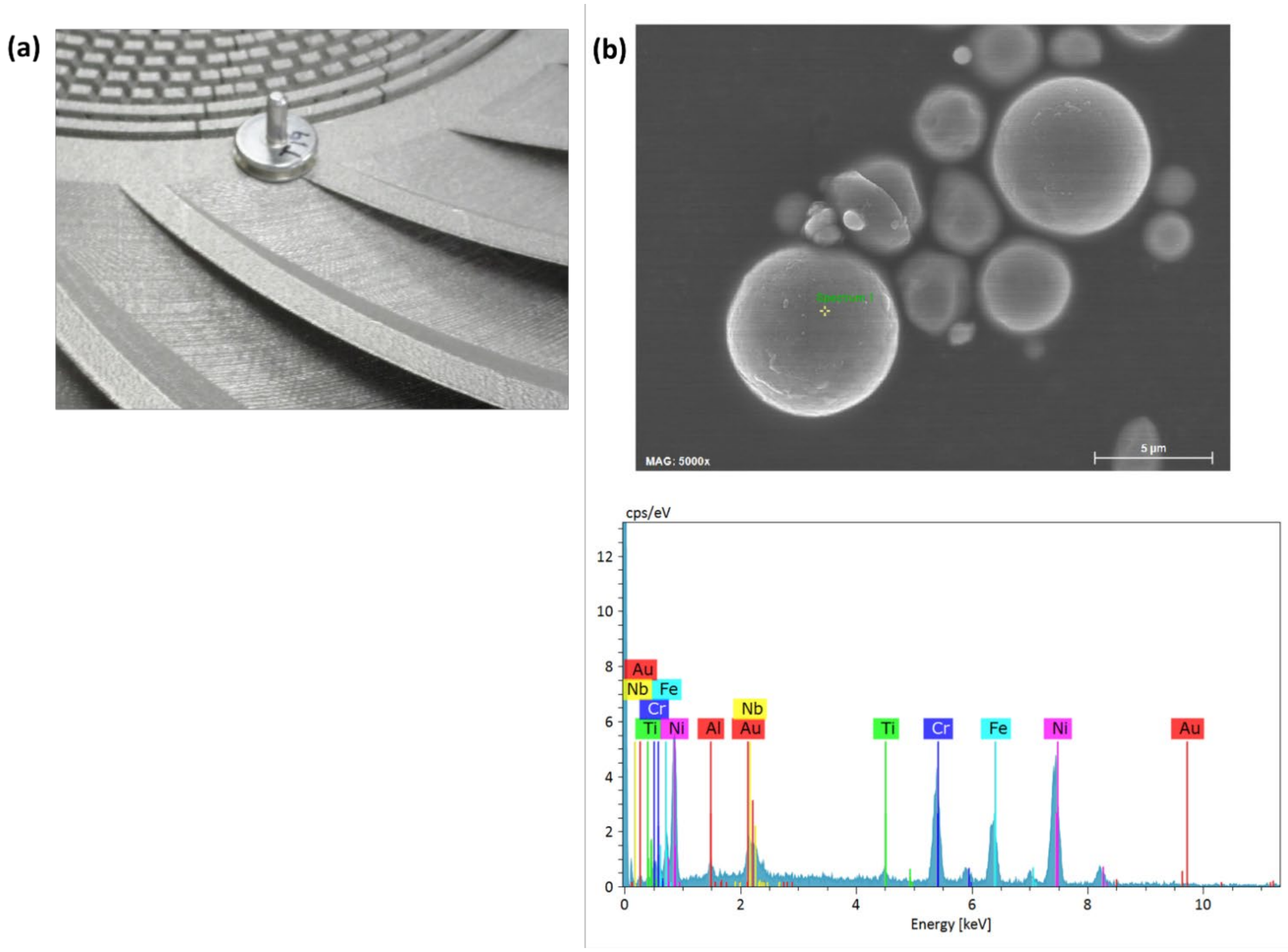


Figure B3. Energy dispersive X-ray pattern of particles on an Inconel 718 printed part just removed from a PBF printer: (a) scanning electron microscopy stub on the printed part, (b) micron-scale particle of aluminum, chromium, iron, nickel, niobium, and titanium consistent with Inconel 718 powder.

The PPE clean side change out room contains lockers for employees to store personal belongings before entering the PBF room. Figure B4 has results for a SEM stub from one of the lockers that shows particles with shapes and compositions consistent with ambient dust or possibly fused AlSi10Mg feedstock powder (compare to Figures B1(d) and B2(d)).

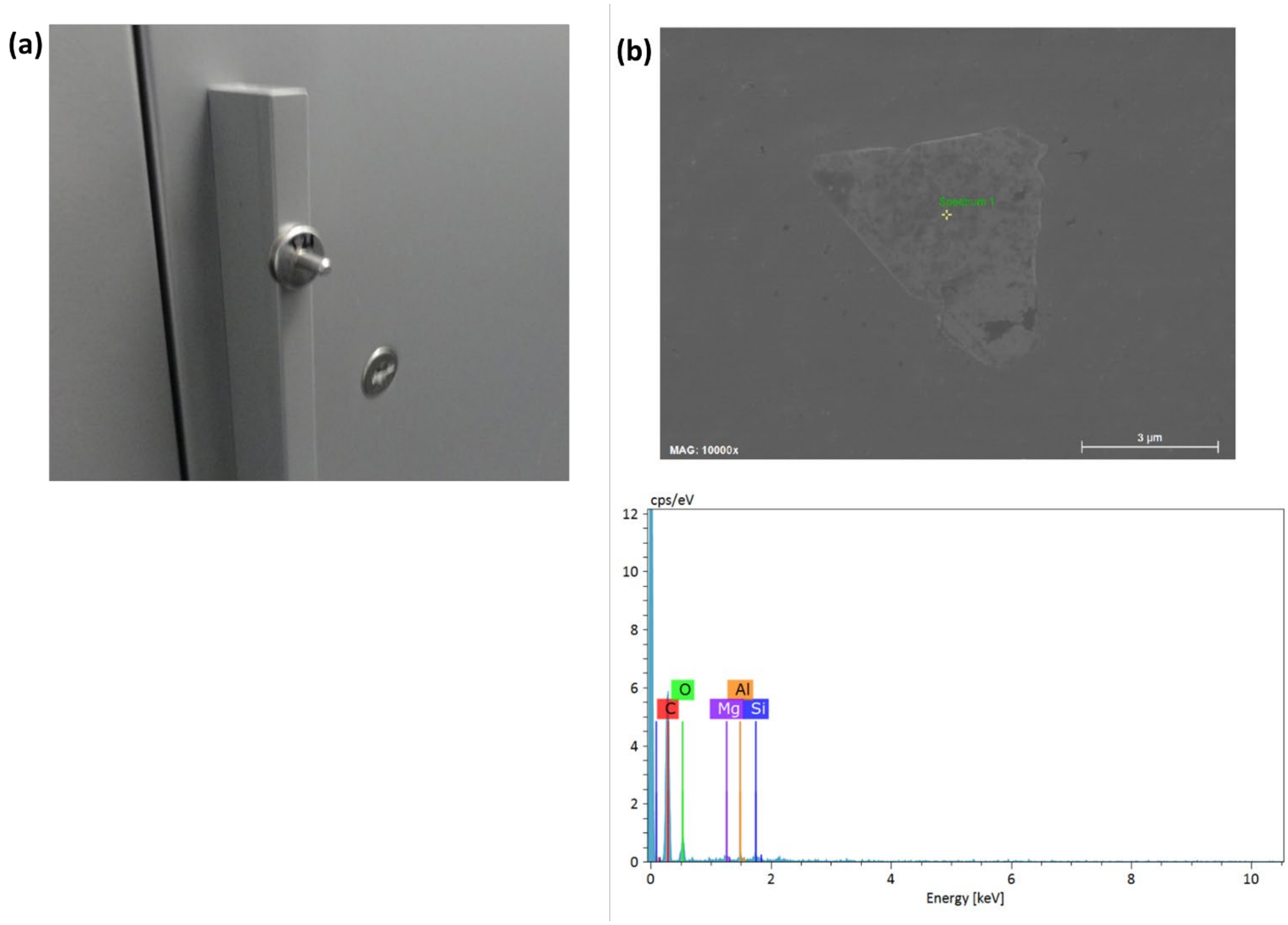


Figure B4. Energy dispersive X-ray pattern of a particle on a locker handle in the powder bed fusion clean-side personal protective change room: (a) location of the SEM stub on the locker handle, (b) micron-scale chip of aluminum, magnesium, and silicon consistent with AlSi10Mg powder.

Figure B5 is a sample collected on the floor in the main hall where the clean-side PPE change room door exited to the main hall and shows particles with shape and composition consistent with stainless steel feedstock powder (compare to Figures B1(a) and B2(a)). Particles in some other fields were consistent with ambient dust and in other fields they were consistent with Ti64 feedstock powder (images not shown).

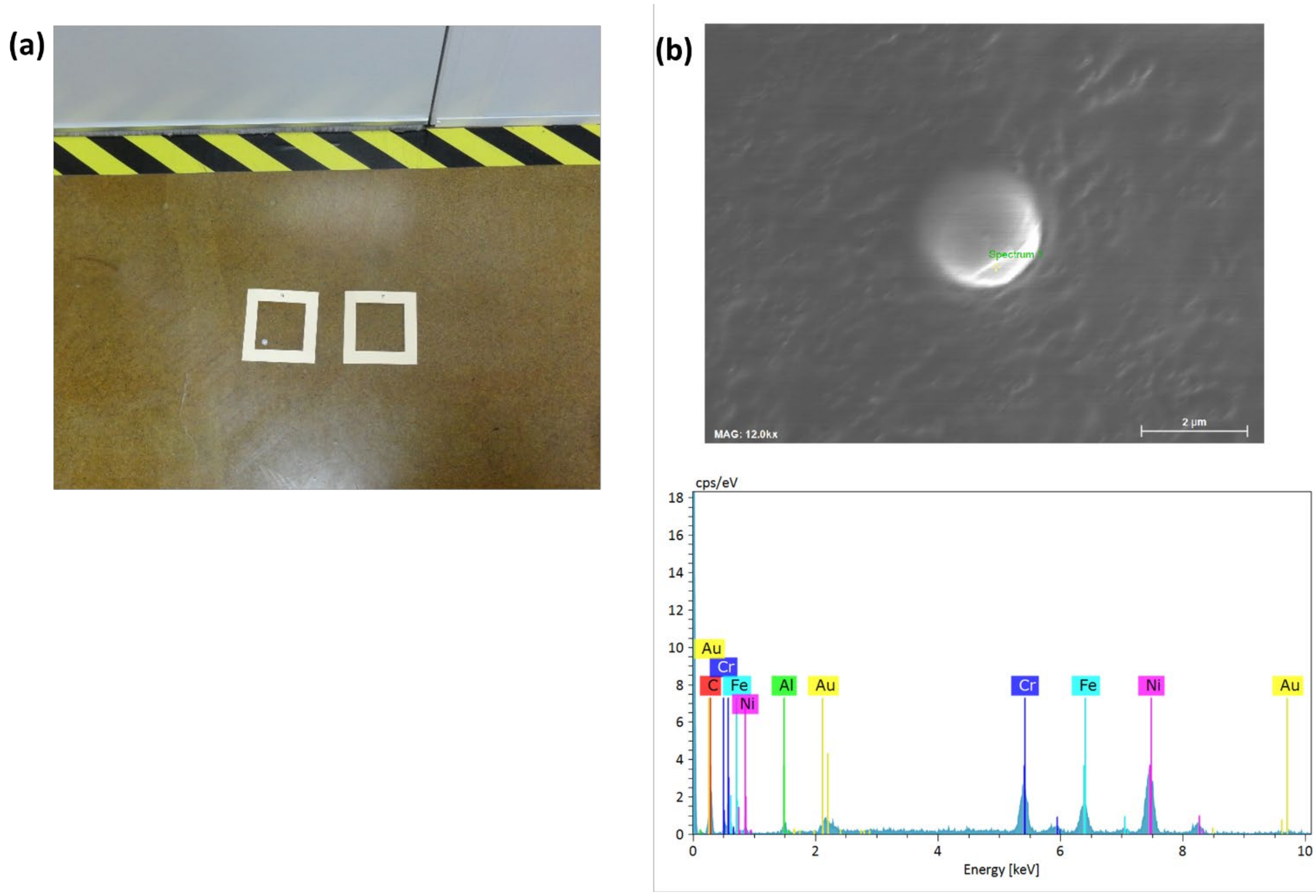


Figure B5. Energy dispersive X-ray pattern of a particle on the main hall floor in front of the exit from the PPE clean-side change out room: (a) sampling location of the SEM stub, (b) micron-scale particle of aluminum, chromium, nickel, and iron consistent with stainless steel or Inconel 718 feedstock powders.

Table C2 presents results of surface wipe samples to quantify amounts of metals on surfaces in the PBF room. Levels of Cu, Sn, and V were below the analytical limit of detection on 26, 32, and 24 of 34 samples, respectively. A result below the analytical limit of detection means if the element is present, it is at a level too low to be measured by our analytical technique (indicated by a "<" symbol). A value above the limit of detection (measurable) but below the limit of quantification (level above which there is high confidence in the result) is considered a semi-quantitative value (indicated by italic font). The M306 (version 2) printer used Ti64 feedstock powder, and the SDS for this material indicated it was made of titanium Ti, Al, and V. Among the three samples collected at this printer, Ti and Al were quantified on all of them, but V was only measurable on one. Several metals not used to make Ti64 feedstock powder, including Cr, Co, Mo, and Ni were present on the printer door handle, powder station glove port, and shop packet which indicates cross-contamination from other feedstock powders. The mechanism of cross-contamination could be from gloves used for tasks involving other feedstock powders in the PBF room that were worn when a person contacted the M306 printer surfaces.

The M307 (version 2) printer used feedstock powders made of mostly Al, magnesium (Mg), and silicon (Si) with traces of Cu, Ni, and Ti. Consistent with the feedstock, high levels of Al were present on the printer door and powder station door port (Mg and Si were not included in our measurements of samples because they did not present a risk of skin disease). Both Ni and Ti were present on these surfaces. Cu was below the limit of detection. For the sample collected from the touch screen, levels of metals were below the limit of the detection which indicates effective housekeeping.

The M319 (version 2) printer used Ti64 or stainless-steel powder, and all metals present on the printer door and powder station door port were consistent with the ingredients listed on the SDSs for these feedstocks.

At the time of our visit, a new (version 2) PBF printer was being installed prior to shipment to a customer. In general, samples from the door handle, touch panel, and build chamber had measurable levels of all metals except Cu and V. Additionally, Cr(VI) was quantified on the edge underneath the printer glove box door. There were a few possible sources of these metals: 1) residues from when the printer was assembled at the parent company in Europe and tested using unknown feedstock, 2) cross-contamination from gloves used for tasks involving other feedstock powders in the PBF room that were worn when a person contacted these surfaces; 3) and/or migration of dust in air that settled on printer surfaces.

Several wipe samples were taken from the M26 (version 1) printer and sieve station that used Inconel 718 feedstock powder. From the product SDS, this powder was primarily Ni, Cr, Fe, Mo, and niobium with traces of Al and Ti. All these metals, except niobium (not included in our measurement of samples) were present on surfaces of the M26 printer and its dedicated sieve station (including external walls). Some of the Cr on these surfaces was in the form of Cr(VI). Metals were present on the M26 printer and sieve station touch screens, which contrasts the finding from the M307 printer, and could reflect differences in system design (i.e., more manual interaction for version 1 printers in the form of a separate powder sieve station compared with version 2 printers) and/or less effective housekeeping.

The M27 (version 1) printer and its sieve station only used stainless steel powder that, according to the product SDS, was primarily Fe, Co, Ni and Cr. All these metals were present on surface samples from the printer and sieve station. A portion of Cr was in the form of Cr(VI). Additionally, Al, Mo, and Ti were present on surfaces which might reflect cross-contamination from gloves used for tasks involving other feedstock powders in the PBF room that were worn when a person contacted these surfaces.

Powder vacuums were dedicated to specific printer/feedstock powder combinations to prevent cross-contamination of material during recovery for re-use or disposal. Wipe samples were collected from vacuums dedicated to the M306/M307 version 2 printers (Ti64 and Al feedstock powders), M26/M15 version 1 printers (Inconel 718 and 17-4 PH stainless steel feedstock powders), and M27/M13 version 1 printers (316L stainless steel and maraging steel feedstock powders). For the M306/M307 vacuum hose nozzle attachment, Al, Ni, and Ti were present, consistent with the SDS ingredients lists for these feedstock powders. Additionally, Fe, Cr, and Mo were present which suggests cross-contamination from Inconel 718 and/or 316L stainless steel feedstock powders. For the M26/M15 vacuum hose nozzle, Cr(VI) was present which is consistent with Inconel 718 powder. For the M27/M14 hose nozzle Cr, Ni, and Co (but not Fe) were present on the surface. Additionally, Al and Mo were present, which was consistent with Inconel 718 and might reflect cross-contamination.

All parts, regardless of printer and feedstock powder were depowdered so it was possible that any metal in the feedstocks could be present at this station. The amounts of Fe, Mo, and Ni on the depowdering station handle (right side) were higher than all other samples from surfaces in the PBF room. The level of Cr was second highest among samples collected in the PBF room. The high levels of these metals reflect the dusty nature of this task. Parts were vacuumed prior to transfer to the depowdering station, though they still contained residual powder in cracks, crevices, holes, etc. Additionally, though powder was dislodged using an argon gas gun inside the ventilated depowdering chamber, there was still potential for airborne powder to settle back onto the build plate and part before transferred to a cart. Wipe samples from the inner surfaces of the neoprene gloves attached to the depowdering station ports had metals present which indicated contamination from placing a dirty disposable nitrile gloved hand inside them. Some employees wore short sleeved shirts so there was potential for skin contact with metals on the insides of the neoprene gloves. Samples were collected from the same location of a part after vacuuming at the printer and after depowdering. For all metals (except tin which was not measurable), the amounts on the vacuumed part (including the highest level of Cr among any sample in the PBF room) were higher compared with after depowdering which supports a reduction of powder on parts by the depowdering task. Though depowdering reduces the amount of loose powder on the part and build plate, the amounts of many metals including Cr and Ni were still appreciable and support the need for further removal treatment and/or housekeeping.

After depowdering, because of its weight, the build plate with part was slid via rollers onto a cart (dedicated to the type of feedstock powder used to make the part) for transport out of the PBF room. Al, Cr, Co, Fe, Mo, Ni and Ti were present on the handle of an orange cart dedicated to the M27 (version 1) printer that used 316L stainless steel powder. If not cleaned before moving outside the PBF room, contaminated cart handles could be sources of metals migration to other work areas such as the post-processing room where employees were not required to always wear nitrile gloves. Al, Cr, Co, Cu, Fe, Mo, Ni, Ti, and V were present on the handle of the pneumatic lift cart used to move powder bins between version 1 printers and their respective sieve stations. This lift was dedicated to the PBF room, though more frequent cleaning could lower levels of metals on the handle and reduce movement of metals among areas in the PBF room. A shelf inside a storage cabinet near the M27 (version 1) printer was wiped and all metals except Cu and Sn were present on the surface. The presence of these metals on the shelf indicates contaminated items were placed in the cabinet and when removed could serve as sources of metals that are spread to other areas.

Wipe samples collected from walls above three of the return air high-efficiency particulate air (HEPA) filter screens all showed the presence of Al, Cr, Co, Mo, Ni, and Ti. The presence of these metals on wall surfaces near the HEPA screens suggested air currents were carrying dust toward the return air vents, though some dust was adhering to walls. More frequent housekeeping of vertical surfaces as well as containment of powders at the source could help reduce spread of metals throughout the PBF room.

Several wipe samples collected from surfaces in the personal protective equipment (PPE) change out room showed the presence of metals on both the dirty and clean sides. On the dirty side, Al, Cr, Cr(VI), Co, Fe, Mo, Ni, and Ti were present on the floor. These same metals plus Cu were on the dirty side handle of the door that led to the clean side. On the clean side, levels of metals were present on the floor but at levels higher than the dirty side. Further, all metals except Ti and V were on the clean side handle of the door that led into the PBF room. On the clean side, PPE was donned before entering the PBF room or doffed before entering the main hallway to access other areas of the facility. The presence of metals on the clean side at levels higher than the dirty side indicates a need for improved housekeeping as well as renewed efforts for controls (existing or new) to prevent particle migration.

Based upon the results of the SEM and surface wipe samples collected in the PBF room, we recommend the following:

- Frequently change nitrile gloves, especially between working at different printers, sieve stations, and areas to minimize cross-contamination of metals.
- Frequently wet clean surfaces of printers and sieve stations (e.g., door handles, touch screens, and other high touch surfaces) using a disposable towel and isopropyl alcohol or water to reduce surface contamination.
- Increase awareness among staff to always wear nitrile gloves during installation of a new printer to reduce opportunity for skin exposure to metals that might be on surfaces.
- Frequently wet clean the inner surfaces of the neoprene gloves on the depowdering station or have staff wear oversleeves if wearing short sleeves to reduce opportunity for skin exposure.
- Further depowder parts and build plates before removal from the PBF room, e.g., by a two-step depowdering process, i.e., current depowdering task followed by vacuuming in an enclosure (could be the depowdering station, if feasible, or another adjacent glove box to permit transfer of the part without opening the depowdering station).
- Frequently wet clean transport cart handles, surfaces, and wheels to minimize migration of metals out of the PBF room to other areas of the facility.
- Change nitrile gloves before and after using the pneumatic lift and frequently wet clean its handles, surfaces, and wheels to minimize cross-contamination of metals among areas in the PBF room.
- Wet clean items before placing in storage cabinets and frequently wet clean interior cabinet surfaces to reduce contamination of surfaces and spread of metals throughout the PBF room.
- Frequently wet clean the floors, door handles and locker handles and frequently replace tacky mats (whenever they become visibly dusty or the surface appears dull) in front of doors in both the clean and dirty sides of the PPE change out room to reduce contaminant migration.
- Consider requiring staff to wear boot covers out of the clean side of the PPE change out room until the source of metals contamination in the clean side is identified and mitigated.

DED Room

Figure B6 is a SEM stub sample from the door sill of the Modulus 800 DED printer and shows a particle with shape and composition consistent with Inconel 718 feedstock powder (see Figures B1(b) and B2(b)). All other particles viewed in fields of this sample had shape and elements consistent with 316L stainless steel or Inconel 718 feedstock powders.

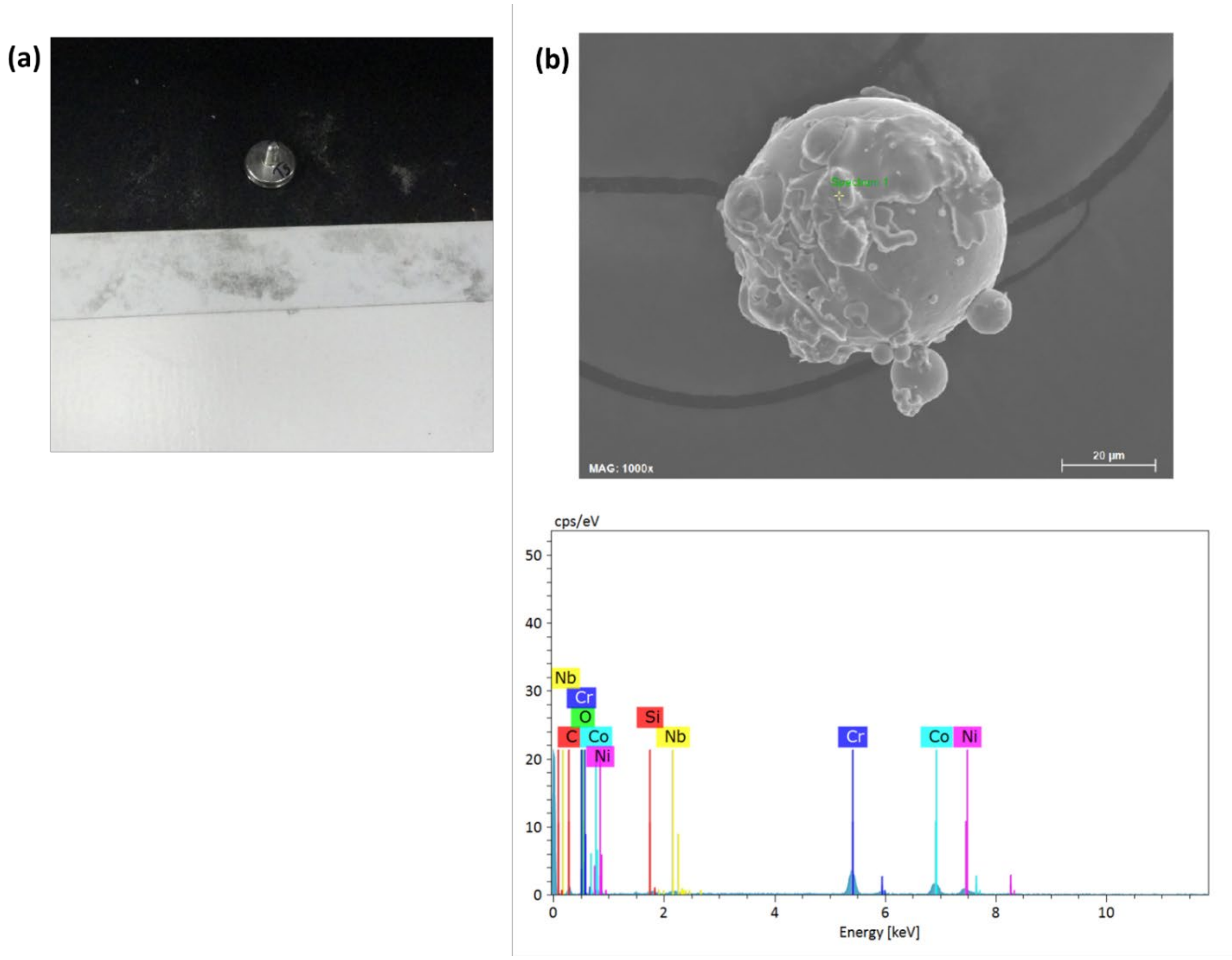


Figure B6. Energy dispersive X-ray pattern of a particle from the floor at the door to the Modulus 800 printer in the DED room: (a) location of the SEM stub, (b) micron-scale particle consisting of chromium, cobalt, nickel, niobium, and silicon consistent with Inconel 718 feedstock powder.

Table C3 presents results of the wipe samples to quantify amounts of metals on surfaces in the DED room. Sn was below the analytical limit of detection on all samples, and levels of Cu and V were mostly below the analytical limit of detection (these results are indicated by a “<” symbol). Semi-quantitative values are denoted by italic font.

There were two DED printers in this room, though neither was operating during the March 2023 site visit. For the Modulo 400 printer, a keypad on the left side of the machine was wiped before and after cleaning by an employee and results show a reduction in levels of all metals. Frequent cleaning could help to further lower levels of metals on this surface. For both the Modulo 400 and 800 printers, wipe samples were taken from the touch screen of their powder loaders and computer keyboards. All samples had measurable levels of metals which indicates potential for skin exposure. Additionally, the tubes on the powder loaders had several metals present on the external surfaces which again indicates potential for skin exposure.

A sample from the black bench near the garage door leading to the main hall had many metals present at measurable levels, indicating the need for more housekeeping.

Several samples collected from handles and external surfaces of waste and feedstock powder containers had some of the highest levels of Cr, Fe, Mo, Ti, and V among all samples collected in the DED room.

Multiple samples were collected from floors, doors, and transport carts to assess potential for metals migration from the DED room to other areas in the facility. Several metals were quantified on the floor in the DED room in front of the hinged doors that led to the small hallway or the post-processing room. Samples from the handles of the doors leading to the small hallway and post-processing room were mostly below the analytical limit of detection which supports good housekeeping. The handle of a transport cart had among the highest levels of Al, Cr, Co, Fe, and Ni for samples collected in this room. Cr in the form of Cr(VI) was also present on the cart handle. Collectively, these samples indicate opportunity for metals migration from the DED room to other areas in the facility.

Samples from a wet vacuum indicated surface contamination with all metals except Sn and V. Given the dusty nature of vacuuming, efforts should be made to thoroughly clean the external surfaces of the vacuum and its attachments after each use and wear skin protection when operating.

Two fabric surfaces were sampled. The chair for a computer desk showed measurable levels of Al, Cr, Co, Fe, Mo, Ni, and Ti from a wipe sample of the seat area. Al, Cr, Co, Ni, and Ti were present at varying levels on a cloth backpack. Particles strongly adhered to fabric and were difficult to remove even by vacuuming.

Based upon the results of the SEM and surface wipe samples collected in the DED room, we recommend the following:

- Frequently change nitrile gloves to minimize potential for skin exposure to metals on surfaces.
- Frequently wet clean surfaces of printers and powder loading stations (e.g., keypads, touch screens, door handles, touch screens, and other high touch surfaces) to reduce surface contamination and opportunity for skin exposure.
- Frequently wet clean work surfaces such as bench tops to reduce surface contamination and opportunity for skin exposure.
- Increase awareness among staff that external surfaces of feedstock and waste metal powder containers can have high levels of metals and to frequently wet clean containers and change nitrile gloves before and after contacting containers to reduce opportunities for skin exposure.
- Frequently wet clean floors and person door handles and replace tacky mats in front of person doors leading out of the DED room to the small hallway and the post-processing room to minimize migration of metals to other work areas in the facility.
- Frequently wet clean transport cart handles, surfaces, and wheels to minimize migration of metals out of the DED room to other areas of the facility.
- Thoroughly wet clean the external surfaces of the vacuum and its attachments after each use and wear skin protection when operating to minimize opportunity for skin exposure.
- Do not move the vacuum from the DED room to other areas of the facility to minimize migration of metals out of the DED room to other areas of the facility.

- Cover the fabric portions of the chair with a smooth material that is easy to wipe clean such as a plastic film and place personal items such as backpacks in a clean sealable plastic bag if brought into the DED room. Always wash hands or wear clean nitrile gloves when handling personal items brought into the DED room.

Post-Processing Room

As a part of the evaluation of powder migration, an SEM stub sample was collected from the floor in the post-processing room just front of the person door that went to/from the DED room. All particles viewed in all fields of this sample had shape and elements consistent with ambient dust (images not shown).

Figure B7 is a SEM stub sample collected from the grey bench used for manual grinding and sanding activities. Particles from this sample showed shape and composition consistent with AlSi10Mg feedstock powder that was sintered and fractured but could also be from sandpaper grit.

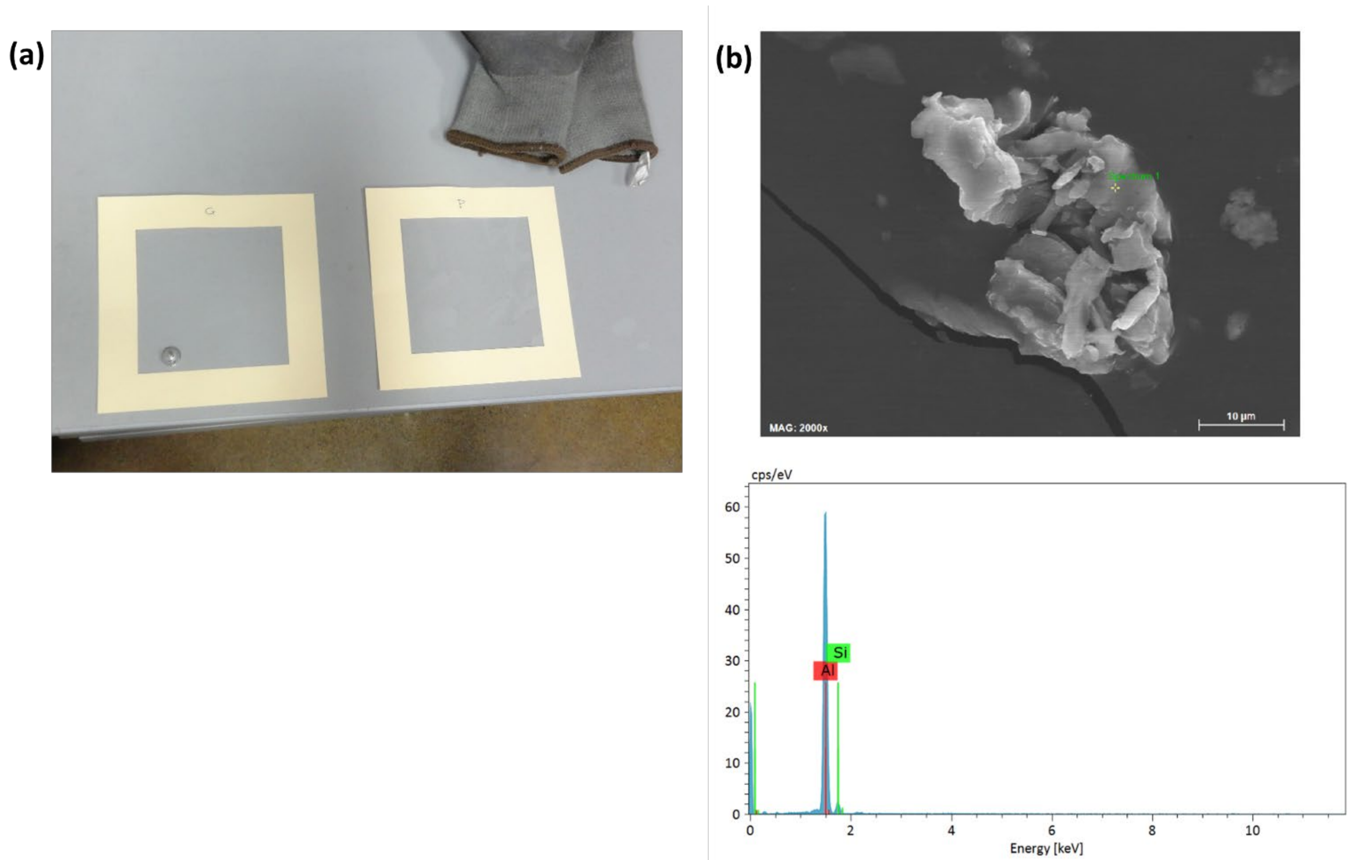


Figure B7. Energy dispersive X-ray pattern of particles on the grey bench where grinding and sanding are performed: (a) SEM stub on the surface of the grey bench, (b) micron-scale particle cluster composed of aluminum and silicon with unknown origin.

A downdraft table for grinding and sanding parts was directly beside the grey grinding bench. Figure B8 shows where the SEM stub sample was collected from the downdraft table and the corresponding EDX pattern of a particle that was likely Ti64 (note that the EDX spectra of Ti64 feedstock powder in Figure B2(c) does not include a peak for vanadium (V), though it was a constituent listed on the powder SDS). Other particles in this sample contain Al and Si which could be from AlSi10Mg powder, grinding wheel debris, or ambient dust (images not shown).

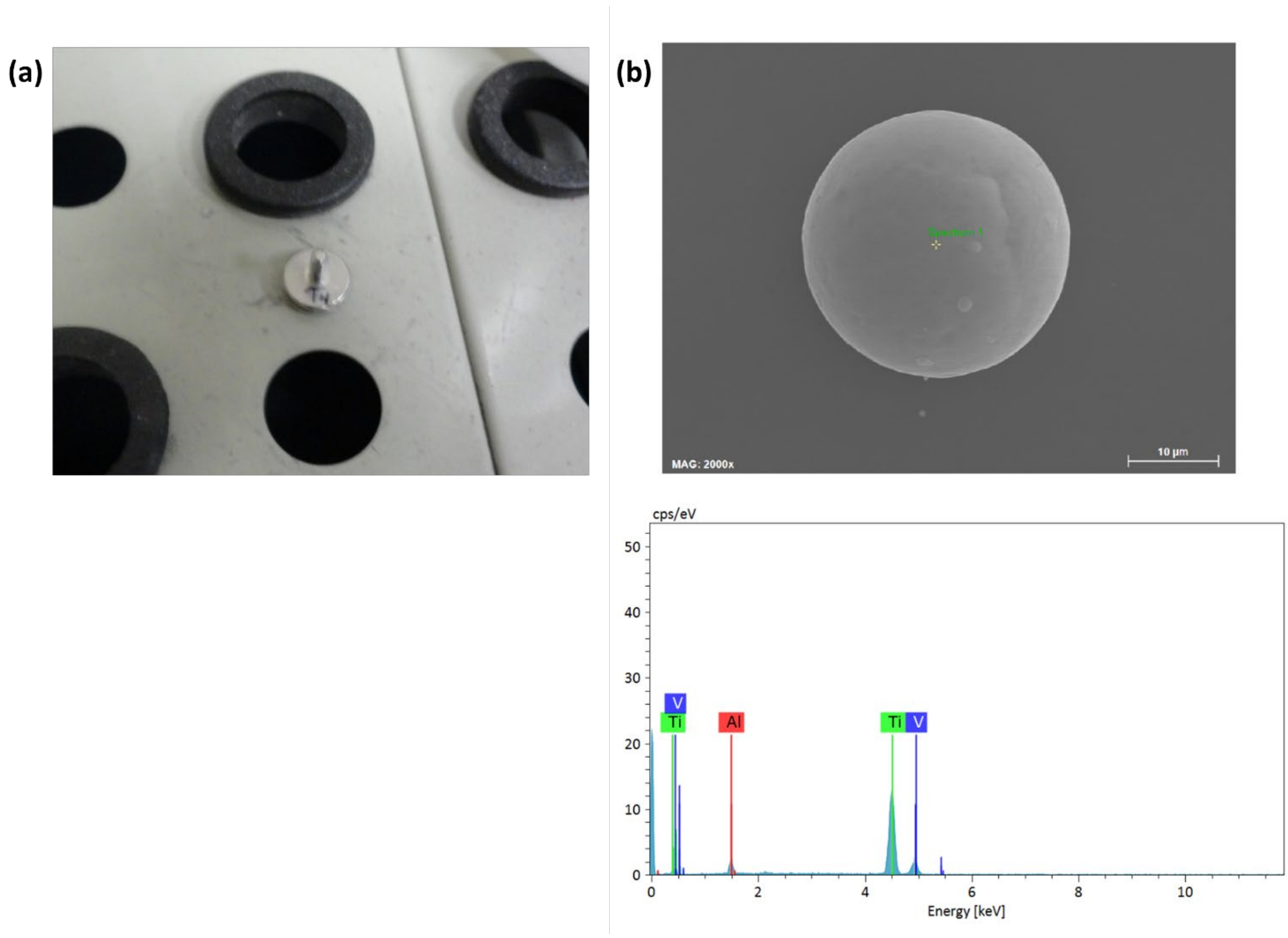


Figure B8. Energy dispersive X-ray pattern of particles on the downdraft table for grinding and sanding parts: (a) location of SEM stub on downdraft table, (b) micron-scale particle composed of aluminum, titanium, and vanadium that was likely Ti64 powder.

Samples were collected from a computer mouse of an employee's desk in the post-processing room and a trigger handle on a cart used to transport parts. Both samples showed particles with shape and elements consistent with ambient dust (images not shown).

Figure B9 is a SEM stub sample collected from a cardboard box of nitrile gloves located in the maintenance cage area. As shown, particles in this sample have shapes and composition consistent with ambient dust, though in other fields, particles consistent with stainless-steel are present (not shown).

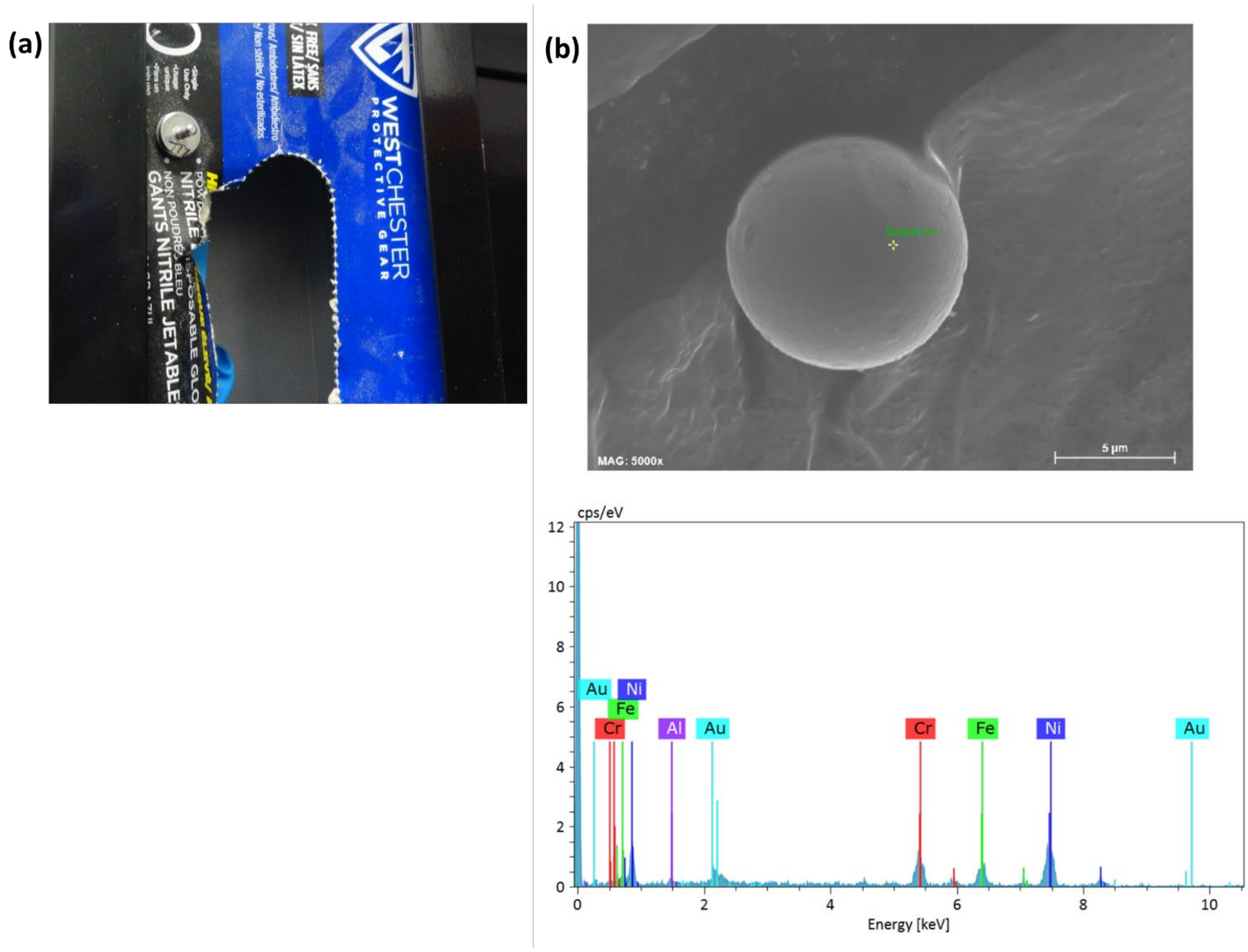


Figure B9. Energy dispersive X-ray pattern of a particle on a cardboard box of nitrile gloves in the maintenance cage: (a) location of SEM stub on glove box, (b) micron-scale particle composed of aluminum, chromium, iron, and nickel.

Figure B10 show the location of an SEM stub sample collected from a table in the employee lounge. Particles in this field were made up of Cr, Fe, and Ni. Particles in other fields had shapes and metals consistent with ambient dust or sweat salt crystals (images not shown).

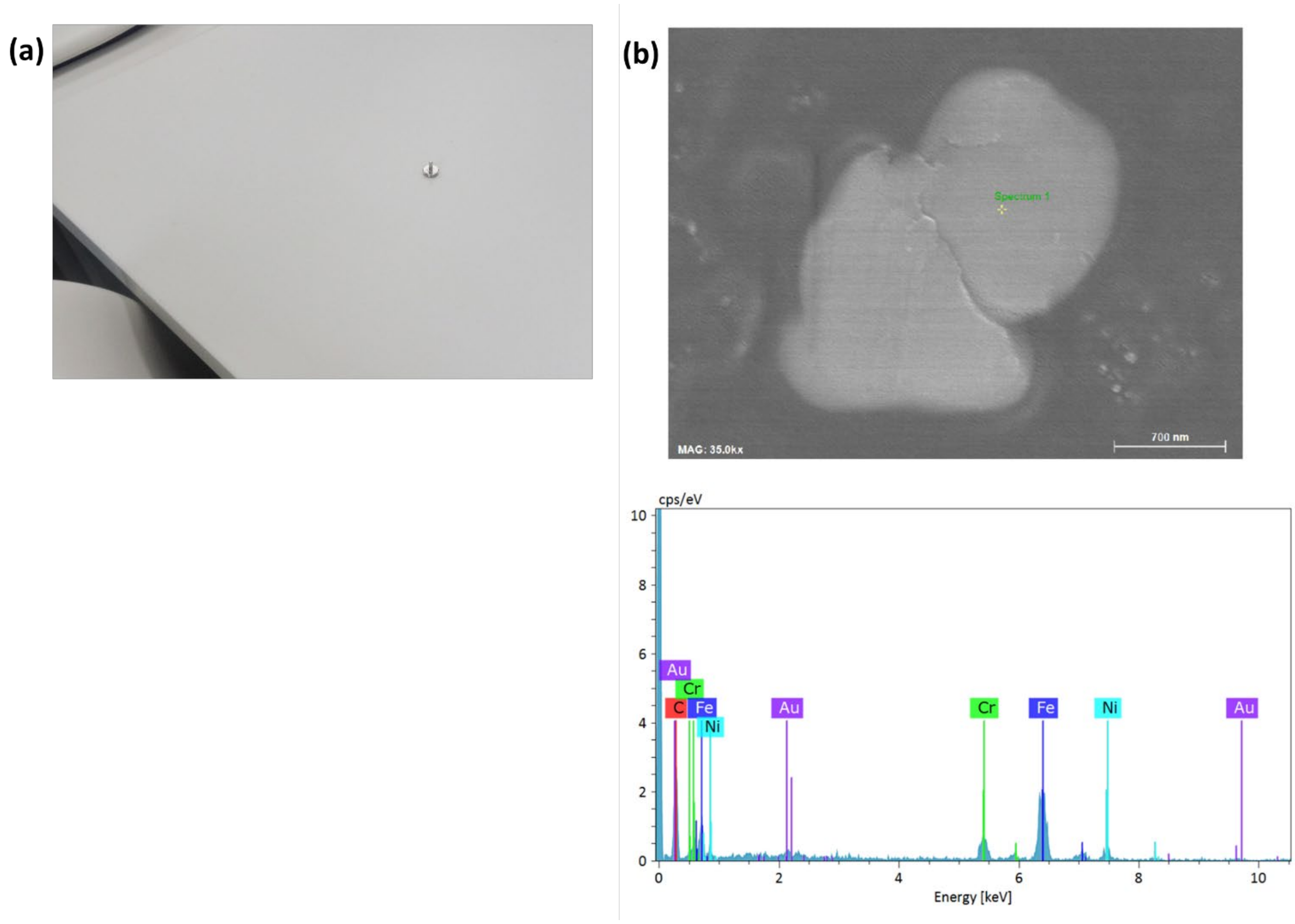


Figure B10. Energy dispersive X-ray analysis pattern of a particle sampled from a table located in the employee lounge (a) location of SEM stub sample, (b) particles composed of chromium, iron, and nickel.

In the quality control laboratory, there was a variety of testing equipment to ensure the parts met customer specifications. Figure B11 shows the location of the SEM stub on a computer mouse of a tensile testing machine and the corresponding EDX pattern indicates the particle was likely AlSi10Mg. All other particles viewed in different fields of this sample had shape and composition consistent with ambient dust (images not shown).

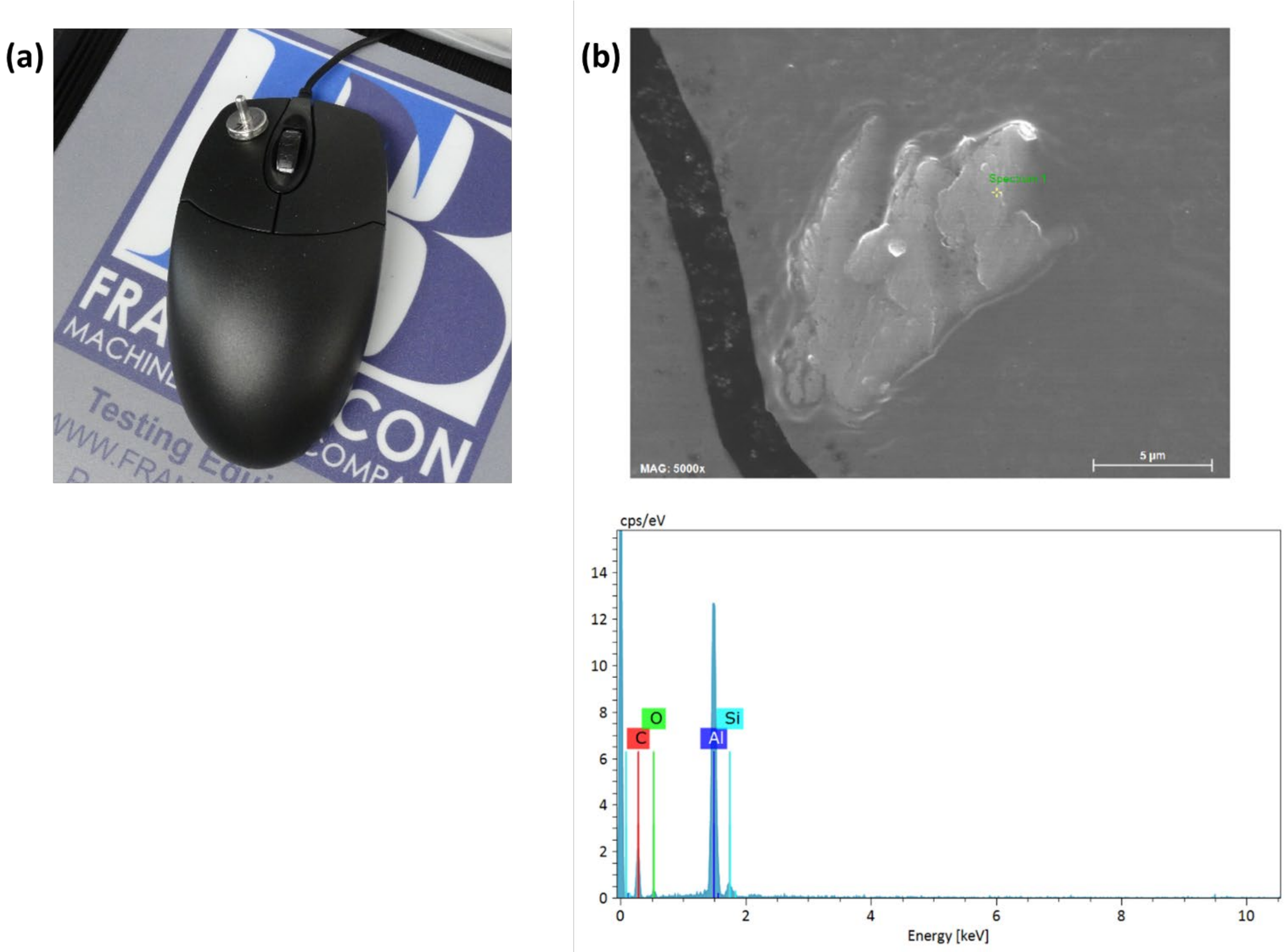


Figure B11. Energy dispersive X-ray pattern of particles on a computer mouse used to operate a tensile testing machine in the quality control laboratory: (a) sample location of SEM stub on the mouse, (b) micron-scale particle composed of aluminum and silicon.

Table C4 presents results of the wipe samples to quantify amounts of metals on surfaces in the post-processing room and adjacent areas. Sn was below the analytical limit of detection on all samples collected in this room. Levels of Cu and V were below the analytical limit of detection on 14 and 12 of 23 samples, respectively (these results are indicated by a "<" symbol). Semi-quantitative values are indicated by italic font.

A wire electrical discharge machine (EDM) was used to cut parts from build plates in the post-processing room. Since the EDM was used to remove parts made of any feedstock powder, it was likely many metals were present in this work area. A wipe sample of the cover for the computer keyboard used to operate the machine had the highest levels of Co and Mo and second highest levels of Cr and Ni among all samples collected in this room. A corded control panel for the EDM had measurable levels of several metals, including Al, Cr, Co, Fe, Mo, Ni, and Ti. The black table near the grinder and EDM had quantifiable levels of Al, Cr, Cr(VI), Co, Fe, Mo, Ni, and Ti on its surface. During the site visit, employees were observed to clean work surfaces in this area.

Carts were used to transport items among the PBF, DED, and post-processing rooms. Handles of two carts in the post-processing room were wiped and shown to have measurable levels of all metals except Cu, Sn, and V.

Once a part was cut from its build plate; the plate was ground to tolerance for reuse. All metals except Sn were measurable on shelves used to store these ground build plates and shop packets. These results indicated the potential for contaminant migration through the facility by movement of build plates or shop packets.

A set of work benches for manual finishing tasks were in the post-processing room. During the site visit, we sampled metals on the surface of the grey bench. Later that day, an employee cleaned the bench, so it was sampled again in the same location. Results indicate that cleaning was effective in reducing levels of all metals, and we recommend continued housekeeping to minimize surface contamination. Pneumatic tools at these work benches had measurable levels of all metals (except Sn) which indicates the need for more housekeeping. A cloth over-glove in this area was turned inside out to wipe the inner lining; several metals were present which indicates contamination.

Metals were present on the floor in the post-processing room which reflects migration of contaminants from powder handling areas of the facility (e.g., on cart wheels or boots). The metals could also be from suspension of dusts on build plates during movement and released during grinding and machining.

Several employee desks were situated in the post-processing room. The computer keyboard on one desk was wiped, and results showed measurable levels of all metals except Cu and Sn.

A maintenance cage area was present in the post-processing room, where according to management, items from around the facility might be brought for repair. Wipes of the work bench in this area showed quantifiable levels of all metals (except Sn).

From the main area of the post-processing room, separate doors lead to an employee lounge and a quality control laboratory. Wipe samples were collected from a chair, table tops, and handle of the refrigerator in the lounge. For the chair and table tops, levels of most levels were close to or below detection limits which indicated good housekeeping and contaminant migration prevention. The refrigerator door handle had measurable levels of all metals except Sn and V.

The quality control laboratory received parts for testing physical and other properties. General practice was that a part attached to its build plate was placed on a shelf outside the laboratory door. When ready for testing, the build plate with part was brought into the laboratory. A wipe sample of a build plate for a part made with Inconel 718, on the shelf outside the laboratory, had the highest levels of Cr, Fe, and Ni among all samples collected in the post-processing room. Inside the laboratory, surfaces such as the marble table for the 3-D scanner, door handle for the tensile testing instrument, and the desk for roughness testing instruments all had measurable levels of metals (except Sn).

Based upon the results of the SEM and surface wipe samples collected in the post-processing room, we recommend the following:

- Frequently and thoroughly wet clean high contact surfaces such as computer keyboards and control panels for cutting and grinding machines and tabletops near these machines to reduce surface contamination levels and minimize opportunity for skin exposure.
- Encourage staff to consistently wear nitrile gloves and frequently change nitrile glove, especially after handling build plates to minimize opportunity for skin exposure.
- Frequently wet clean surfaces on work desks such as computer keyboards and peripherals.
- Frequently wet clean transport cart handles, surfaces, and wheels to minimize migration of metals into the post-processing room from other areas of the facility.
- Increase awareness among staff to wear nitrile gloves when using carts to minimize opportunity for skin exposure.
- Frequently and thoroughly wet clean shelving used to store build plates to reduce surface contamination levels and minimize opportunity for skin exposure.
- Consider placing ground build plates inside clean plastic bags before storing on shelves or transporting out of the post-processing room to minimize contaminant migration.
- Thoroughly wet clean shop packets before they leave a room, do not store them directly in contact with build plates on shelves, and replace them with a clean cover whenever brought into any administrative area to minimize contaminant migration.
- Continue to wet clean work surfaces such as the bench and downdraft hood for manual part finishing.
- Remind staff to always wear clean nitrile gloves under over gloves such as the cloth gloves in the manual part finishing area and appropriately launder cloth over gloves (or disposed of properly) at feasible intervals to minimize potential for skin exposure.
- Frequently wet clean floors and person door handles and replace tacky mats in front of person doors leading out of the post-processing room to the small hallway or DED room to minimize migration of metals to other work areas in the facility. Mopping devices with single-use damp cleaning pads could be useful for cleaning floors.
- For employee desks in the post-processing room, use a keyboard cover made of a material that is easily cleanable and increase awareness among staff to change gloves before using office equipment or contacting other surfaces on desks.
- For the maintenance cage, wet clean the exterior, and to the extent feasible, interior surfaces of items before bringing them to this area to minimize migration of metals to other work areas in the facility.
- Always wear nitrile gloves when performing maintenance work to minimize potential for skin exposure.

- Avoid any activities that might suspend powder from surfaces into air such as hammering on items to minimize potential for inhalation exposure and spreading metals throughout the cage area.
- For the employee lounge, continue housekeeping to maintain cleanliness, renew efforts to clean high contact surfaces such as handles and knobs, and increase staff awareness to remove nitrile gloves and wash hands before entering the lounge to minimize migration of metals into break areas.
- For the quality control laboratory, thoroughly wet clean build plates and if feasible, place in a plastic bag, before leaving printer rooms and arriving at the laboratory to minimize migration of metals to non-powder handling areas.
- Always wear nitrile gloves when handling build plates brought into the quality control laboratory to minimize opportunity for skin exposure.
- Evaluate the dust generating potential of handling parts and testing activities in the quality control laboratory to determine if additional steps are necessary to minimize potential skin and inhalation exposures.

Note that in the post-processing room, the EDM for cutting parts from their build plates used a triethanolamine-based solution as the dielectric fluid. Triethanolamine is a known skin irritant [Anderson et al. 2009; Goh and Ho, 1993; Lessman et al., 2009] and can possibly cause a weak skin allergic reaction [Almeida et al., 2020; Geir et al., 2004]. During our site visits, it was observed that the dielectric fluid often splashed on the EDM surfaces and nearby control panels and tables. To protect skin from effects of triethanolamine, we recommend that nitrile gloves be worn whenever working at the EDM and when cleaning the machine.

Main Hall and Non-powder Handling Areas

Figure B12 shows the SEM stub sampling location on the floor in front of the door to the administrative suite. The particles contained Al, Cr, Fe, Mn, Ni, and sulfur that could be from several feedstock powders used in the facility.

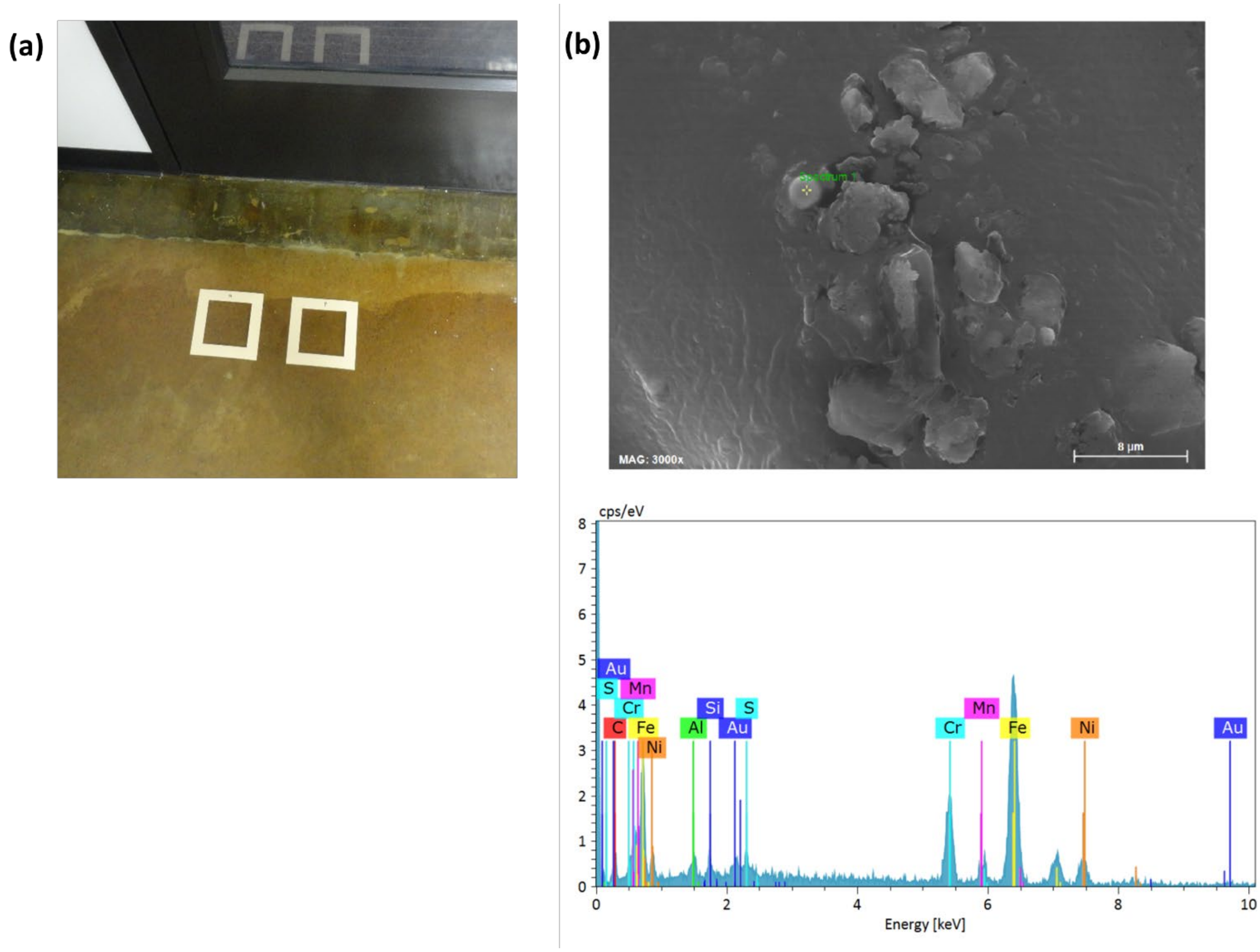


Figure B12. Energy dispersive X-ray analysis pattern of particles on the floor before entering the administrative suite: (a) location of sample area for the SEM stub, (b) micron-scale particles composed of aluminum, chromium, iron, manganese, nickel, and sulfur.

Across from the PBF room roll-up door was a black bench and the part testing laboratory. Figure B13 showed the sampling location on the bench and the corresponding EDX pattern. Particles viewed in this sample and other fields had shapes and compositions consistent with AlSi10Mg or dust (compare to Figures B1((d) and B2(d)). Some particles in other fields contained barium and zirconium which were not elements in the feedstock powders (images not shown).

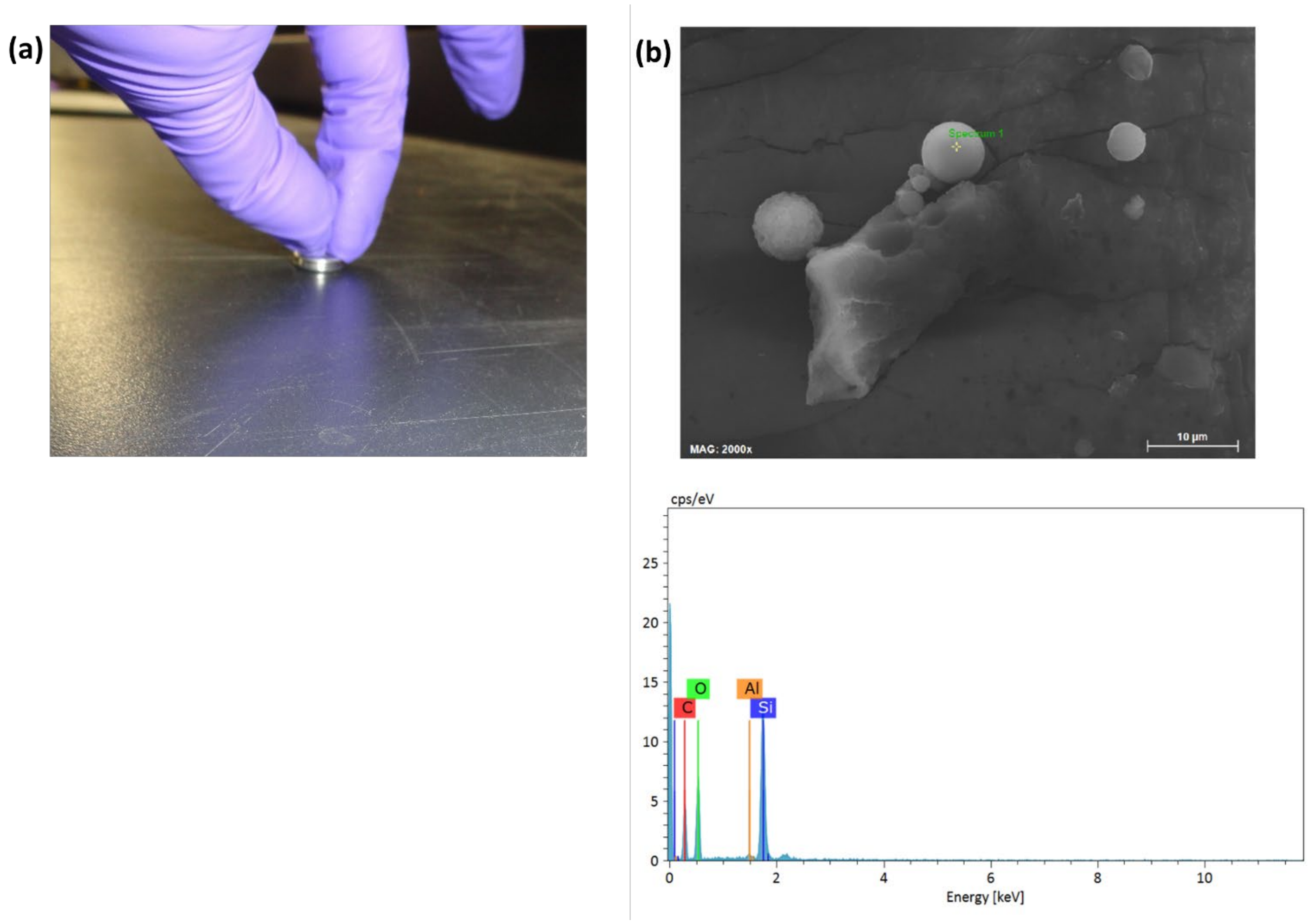


Figure B13. Energy dispersive X-ray analysis pattern of particles sampled on a black bench in the final part testing area across from the PBF room roll-up door: (a) location of SEM stub on the black bench, (b) micron-scale particles composed of aluminum and silicon.

An SEM stub sample was collected from the floor in front of an individual office that opened to the main hall. This sample contained particles with shape and composition consistent with ambient dust, though the possibility of a particle from Ti64 alloy was also present (images not shown).
SEM stub samples were collected in an individual office that opened to the main hall, the administrative suite, and the engineering suite. Figure B14 shows the EDX pattern of a particle on the desk in an individual office. The particle had shape and contained metals consistent with stainless steel or Inconel 718 feedstock powders. All other fields viewed in this sample contained particles with shape and elements consistent with ambient dust or salt crystals from sweat (images not shown).

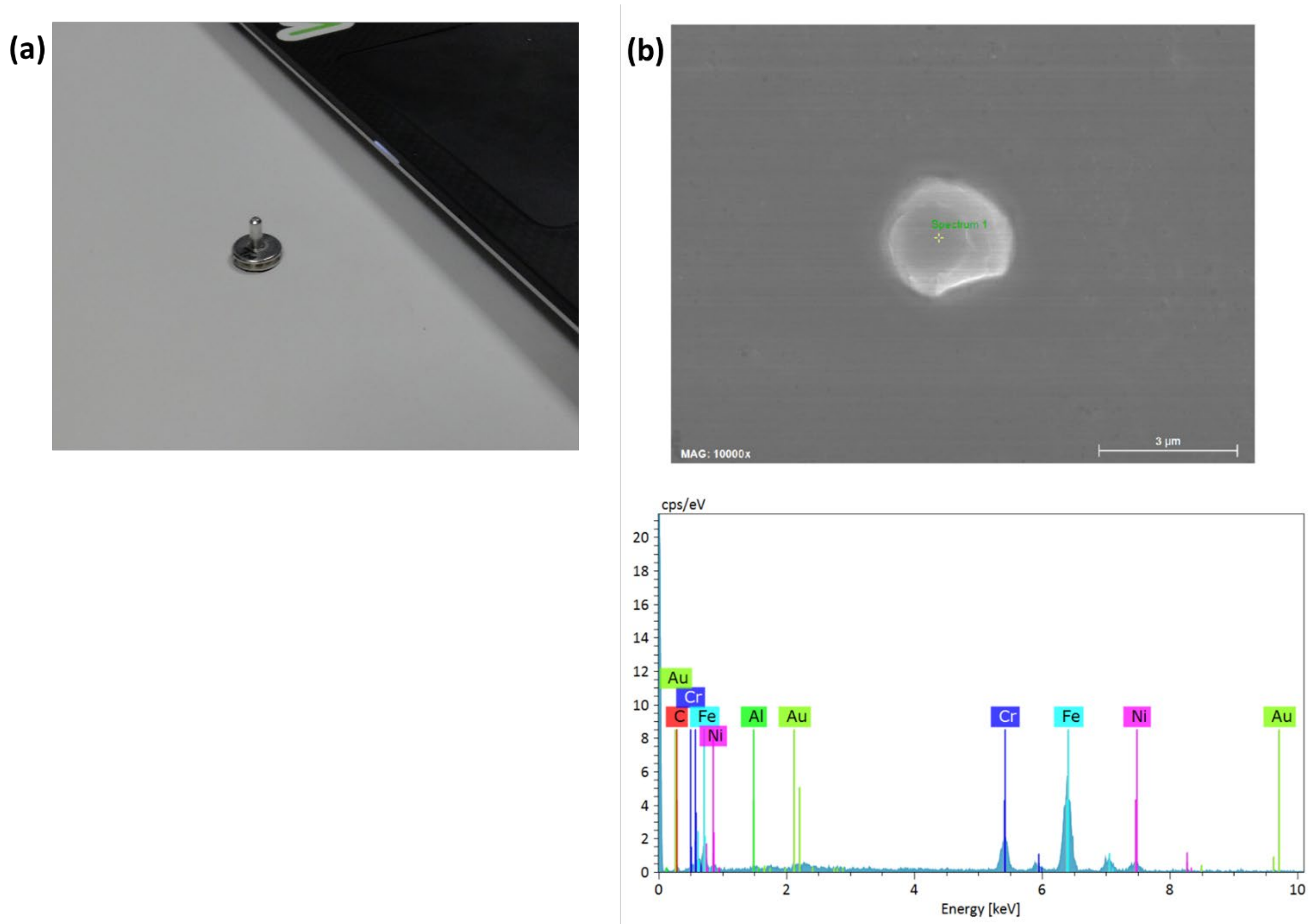


Figure B14. Energy dispersive X-ray analysis pattern of a particle on a desk in an individual office: (a) location of SEM stub sample location on the desk, (b) micron-scale particles composed of aluminum, chromium, and iron.

The SEM stub sample in the engineering suite was collected from a computer mouse (Figure B15). This particle was made of Al, Fe, Ni, Si, and calcium and might have originated from stainless steel or Inconel 718 feedstock powders. Most of the other fields viewed in this sample contained particles with shapes and composition consistent with ambient dust or sweat salt crystals, though a few particles that contained Ni were also present (images not shown).

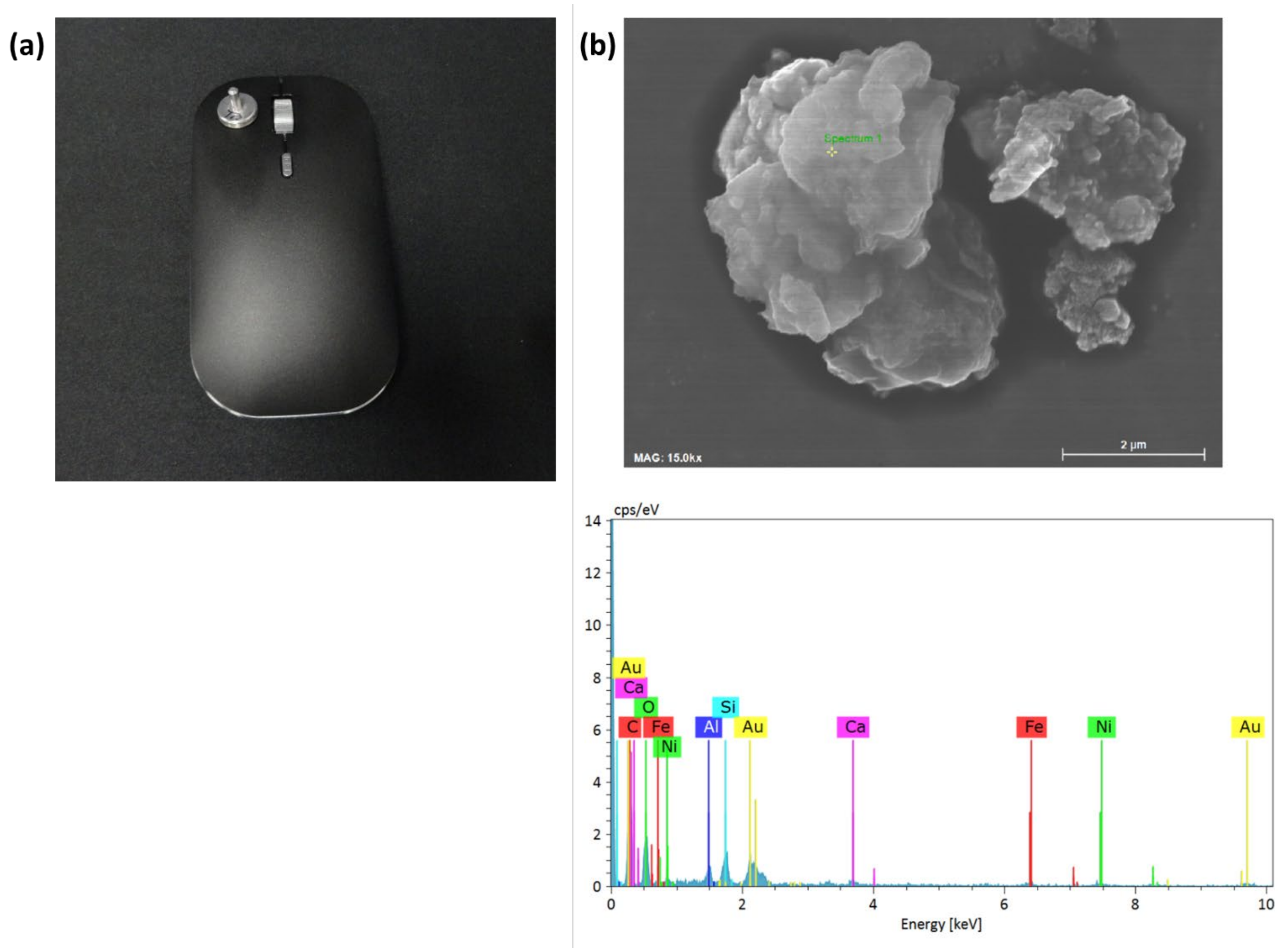


Figure B15. Energy dispersive X-ray analysis pattern of a particle sampled from a computer mouse in the engineering suite: (a) location of SEM stub sample, (b) micron-scale particles composed of aluminum, calcium, iron, nickel, and silicon.

A SEM stub sample was collected from the handle of the refrigerator in the front breakroom. All fields viewed in this sample contained particles with shapes and compositions consistent with ambient dust or sweat salt, though particles that could be AlSi10Mg were also present (images not shown).

Table C5 presents results of the wipe samples for metals on surfaces in the main hallway and other non-powder handling work areas. Sn was below the analytical limit of detection on all samples collected in these areas. Levels of Cu, Fe, and V were below their analytical limits of detection on 16, 12, and 16 of 26 samples, respectively (these results are indicated by a "<" symbol). Semi-quantitative values are indicated by italic font.

Four samples were collected in the *in-situ* bay area. A wheel of the "Artie" robot that streams meetings from work areas had some of the highest levels of metals among all GhostWipe® samples from the main hallway. This robot traveled throughout the facility. The top surface of the HEPA box on the left side (when facing the PBF printer room) had quantifiable levels of all metals (except Sn). It is unknown whether these metals were from dust in the room air settling on the box or fugitive emissions from the PBF room. Several metals were present on the floor in front of the door that led to the administrative office suite which indicated potential for tracking contaminants into the suite (samples were not collected from the floor inside the suite to verify if there was migration).

Some printed parts bypassed post-processing and were sent instead to the part testing laboratory in the main hall. Wipe samples were collected from a white "slide plate" on the bench across from the PBF inter-lock door and from the bench itself. The slide plate reduced friction between a build plate and surface, so it was used to facilitate transfer of heavy PBF build plates off a cart. Comparison between these samples showed higher levels of metals on the slide plate compared with the bench. This observation was consistent with contamination of slide plates with metal dust from build plates. As noted in Table C2, depowdering was insufficient to remove all loose powder from build plates. A wipe sample of the touch panel for a polisher machine had measurable levels of several metals.

When an employee needed PPE such as boot covers or a Tyvek® suit or cleaning supplies such as disposable paper towels they accessed these items from a vending machine in the main hallway. A wipe sample of the touch pad on the vending machine showed measurable levels of several metals. Several samples were collected from the floor at various locations in the main hall and within the short hall that led to the post-processing and DED rooms. One pair of floor samples was collected in the main hallway, in front of the tacky mat before the door to the short hall. The other floor samples were collected directly in front of doors because none had tacky mats. Measurable levels of metals were present on all floor samples. As shown in Table C2, levels of metals on the floor in the clean side PBF change out room were often higher compared with the dirty side. It is unknown if this observation was due to metals being tracked in from the main hall into the clean side room, from the dirty side to the clean side room, or a combination of both pathways. Reducing levels of metals on the floor in the main hall should help to determine if this pathway contributed to accumulation of metals in the clean side change out room.

Wipe samples were collected from computer equipment and desktops in an individual office that opened to the main hall, two workstations in the administrative suite, and one work station in the engineering suite. In the individual office, Al, Cr, Co, Cu, Mo, Ni, and Ti were measurable on a keyboard, mouse, and desktop. In the administrative suite, Al was measurable on all samples and Cr, Co, Mo, Ni, and Ti on most keyboards and desktops. In the engineering suite, levels of Al, Cr, and Ni were close to their analytical limits of detection, and all other metals were not measurable.

Two wipe samples were collected from surfaces in the front office area breakroom. Levels of all metals were close to, or below, their respective analytical detection limits which supports good housekeeping practices. We encourage continued vigilance in preventing migration of metals to eating areas and frequent cleaning of surfaces.

From the *in-situ* bay area, a door led to a narrow hallway between the side of the PBF room and an exterior building wall. This hallway dead ended at shelves used for storing powder containers and a door to the PBF room. The top surface of the HEPA box at the end of the hall (near shelves with powder containers) had quantifiable levels of all metals (except Sn). The concentrations of Cu and Ti were highest among all samples collected in the main hall and adjoining non-powder handling areas. The level of Cr(VI) was the highest in the facility. It is unknown whether these metals were from dust in the room air settling on the box or fugitive emissions from the PBF room. Several metals were quantifiable on the floor in the narrow hallway in front of the door to the PBF room. At the time of the survey, a tackey mat was positioned to the right of the door, and we recommended moving it in front of the door. Two brooms near the HEPA filter box were wiped, and both had Al, Cr, Co, Mo, Ni, and Ti at measurable levels.

Based upon the results of the SEM and surface wipe samples collected in the main hall and adjacent areas we recommend the following:

- Wrap the wheels of the Artie robot in a disposable cover (or tape) while in powder areas and removing the protective layer (or thoroughly wet clean) before traveling to non-powder areas.
- Frequently wet clean horizontal surfaces in the *in-situ* bay such as the HEPA boxes to minimize surface contamination with metals.
- Evaluate the seals in the HEPA filter boxes to verify no fugitive emissions are escaping from the PBF room into the *in-situ* bay.
- Frequently wet clean and place tacky mats in front of the doors leading to the administrative suite, individual offices, and engineering suite to minimize potential for migration of metals into non-production areas.
- For the part testing area, if feasible, place build plates in a plastic bag, before leaving printer rooms to minimize migration of metals to non-powder handling areas.
- Frequently wet clean horizontal surfaces such as slide plates and bench tops as well touch pads and other machine interfaces in the part testing area to minimize migration of metals to non-powder handling areas.
- Frequently wet clean buttons on the PPE vending machine and wear clean nitrile gloves when touching buttons to reduce surface contamination levels and minimize opportunity for skin exposure.
- Frequently wet clean all floors in the main hall and the short hall leading to the post-processing room to reduce contamination and minimize opportunity for migration of metals. This recommendation is particularly important for the wide DED room roll-up garage door where it is not feasible to put tacky mats down.
- Place tacky mats in front of the person doors (before short hall to the post-processing and DED rooms, entrance/exit for clean side PBF change out room, the main hall, and within the short hall in front of the door to the DED room) to help intercept metals on shoes and minimize migration of metals.
- Require any administrative employee to wear nitrile gloves while in production areas, no matter how brief to minimize migration of metals from production areas to non-production areas.
- Increase awareness among all employees to wash hands before leaving production areas and entering non-production areas to minimize migration of metals.

- If not already in use, encourage administrative staff to use a keyboard and mouse cover made of a smooth easily cleanable material and frequently wet clean to minimize opportunity for skin exposure.
- Frequently wet clean door handles leading to the administrative suite, individual offices, and engineering suite to minimize potential for migration of metals into non-production areas.
- Frequently wet clean horizontal surfaces in the narrow hall along the back wall of the PBF room such as the HEPA boxes to minimize surface contamination with metals.
- Evaluate the seals in the HEPA filter boxes to verify no fugitive emissions are escaping from the PBF room into the narrow hall.
- Frequently wet clean floors in the narrow hall to minimize potential for migration of metals from the PBF room to other areas in the facility.
- Frequently wet clean surfaces in the narrow hall such as the brooms near the HEPA filter box and wear nitrile gloves to reduce surface contamination.

Methods: Dermal Exposure Assessment

Wipe samples were collected from surfaces of PPE (respirators, laboratory coats, Tyvek® suits, gloves, boots), employees' shirts, and employees' skin using Ghost Wipe™ media. The presence of metals on protective equipment and shirts is indicative of potential for exposure (material is available and could get on skin if contacted) whereas metals on skin is evidence of exposure.

For protective equipment and employees' shirts, a template was used in accordance with the procedure previously outlined for surface sampling to obtain each sample [NIOSH 2022]. For wipe samples from one or both gloved hands, the surface of a palm was wiped in an S-shaped pattern from wrist to base of fingers. The wipe was folded and used to wipe the palm diagonally in an S-shaped pattern. The wipe was folded once more and used to wipe the palm-side of each finger vertically.

To obtain wrist wipe samples, a sampling template was placed and held securely on the forearm side of an employees' wrists, directly above the hand. Each wrist filled approximately one half of the template. Wipe sampling was completed as previously detailed for surfaces: a fully unfolded Ghost Wipe™ wipe was first used to wipe the entire surface in an S-shaped pattern from left to right. The wipe was folded in half and used to wipe the surface inside the template in an S-shaped pattern from top to bottom. The wipe was folded in half again and used to wipe the surface in an S-shaped pattern diagonally, from corner to corner. The wipe was folded again, and the same procedure was completed on a template held securely on the opposing wrist to complete one wipe sample. All Ghost Wipe™ samples were analyzed for Al, Cr, Co, Cu, Fe, Mo, Ni, Sn, Ti, and V following NIOSH Method 7303 [NIOSH 2003].

Results: Dermal Exposure Assessment

Protective equipment and employees' shirts

Table C6 shows levels of metals on protective equipment and employees' shirts. Cu, Sn, and V were mostly below their respective analytical limit of detection. Results below an analytical limit of detection are indicated by a "<" symbol. Semi-quantitative values are indicated by italic font.

Wipes were collected from surfaces of powered air-purifying respirators (PAPRs) in the clean side of the PPE change out room and in the DED room. All samples showed contamination with metals.

A wipe sample collected from the exterior side of a blue cloth laboratory coat hanging in the clean side PPE change out room revealed the presence of all metals (except Cu and Sn). As noted previously, particles strongly adhere to fabric.

On two different days, the external surface of a Tyvek® suit was wiped before and after a cleaning task. The post-task levels of metals were much higher compared with the pre-task samples.

At the end of the site visit, NIOSH staff wiped the bottom of their boots and results show measurable levels of all metals. The presence of metals on boot treads indicates that shoes could be a source of contaminant migration throughout the facility. During time in the facility, shoe covers were worn as required by company policy.

Multiple pairs of wipe samples were collected from the abdomen area of employees' shirts before and after performing normal job tasks during their work shift in the PBF room. Shirts worn by employees appeared to be personal clothing not company-issued work shirts. The first sample was collected near the start of their shift (baseline), and results showed the presence of metals. It is unknown if these levels reflect accumulation from prior to time of sample collection or if any employees wore the same shirt multiple days in a row, and the baseline reflects accumulation over several days. The second sample was collected near the end of their shift, and results showed levels of metals were sometimes higher or lower compared with baseline. The presence of metals on clothing indicated potential for exposure to employees through skin contact. Additionally, if worn out of the facility, there is potential for migration to vehicles and home.

Tables C7 and C8 show levels of metals on a single gloved hand and both gloved hands, respectively. Note that because gloves frequently contact surfaces, levels of metals were much higher compared with surfaces and clothing. For this reason, units in Tables C7 and C8 are in micrograms per gloved hand or both gloved hands. 1 microgram = 1000 nanograms. Results below an analytical limit of detection are indicated by a "<" symbol. Semi-quantitative values are indicated by italic font.

Regardless of whether one or both gloved hands were wiped, there was a clear accumulation of metals at the end of the cleaning tasks. The employee in the DED room wore multiple layers of gloves. On the first occasion, after cleaning, the employees' left hand outer glove had nicks and tears, but the right hand was intact. Results show measurable levels of several metals on the left hand under the layer glove, but levels were at or near analytical detection limits on the right hand under the layer glove (see Table C7). On the second occasion, both outer gloves remained intact during cleaning, and levels of metals were at or near analytical detection limits on both under the layer gloves (see Table C8).

Based upon the results of the PPE and clothing wipe samples we recommend the following:

- Frequently wet clean (after every use) PAPRs while wearing nitrile gloves to minimize potential for skin exposure.
- Do not store PAPRs in open areas where powder is handled such as the DED room to minimize opportunity for contamination with metals.
- Follow the instructions at https://www.cdc.gov/hai/pdfs/ppe/ppe-sequence.pdf for putting on PPE. Note that these instructions were developed for healthcare settings but apply to your workplace as the types of PPE in use are similar.
- Always wear clean nitrile gloves when putting on a cloth laboratory coat or taking it off to minimize potential for skin exposure.
- Remove worn cloth laboratory coats in the dirty side PPE change out room and place in a plastic bag or other barrier (e.g., open-ended bag used by dry cleaners) before entering the clean side to minimize migration of metals.
- Frequently launder cloth laboratory coats appropriately.
- Provide wet wipes, nitrile gloves, and plastic bags in the dirty side change out room and follow the procedure prescribed at How to Safely Take off PPE, Selected Equipment: PAPR and Coverall (youtube.com) to remove potentially contaminated PPE (the same procedure should be used when taking off PPE worn in the DED room). Note that these instructions were developed for healthcare settings but can be adapted to your workplace as the types of PPE being removed are similar. Briefly, the procedure is: 1) clean your outer gloves with a wet wipe; 2) remove one outer glove by pinching at the wrist and rolling it off the hand into a ball, place the balled glove in the other hand then slide a finger or thumb under the other outer glove and roll down the hand and around the previously balled glove; 3) inspect the inner layer glove for tears or signs of visible powder contamination and either clean contaminated gloves with a wet wipe or place clean gloves over them if torn; 4) detach the hose from the PAPR hood, unclip the belt, and take of the helmet/hood and place in plastic bag for storage in the clean side; 5) clean gloves with a wet wipe; 6) remove Tyvek® suit by unzipping and rolling down toward the feet; 7) clean gloves with a wet wipe; 8) remove boot covers; 9) remove gloves using procedure described earlier; and 10) wash hands with wet wipes. Use a wet wipe to clean the door handle before opening to enter the clean side.
- Require shoe covers whenever leaving a powder handling area to minimize migration of metals to other areas of the facility.
- If shirts worn by employees are personally owned, substitute for company-issued work shirts or require changing into a clean shirt before leaving the facility to minimize migration of metals and reduce potential for skin exposure.

- Provide a laundry service to appropriately wash either company-issued or personal work clothing. It is highly likely that metals also accumulate on pants during work (though they were not sampled), and they should be treated the same as shirts.

Skin exposure

Table C9 shows levels of metals on skin of both wrists of employees working in the PBF room. As noted, a 10 x 10 cm^2 template was used to guide skin sampling; however, to capture individual differences, measured levels of metals are in units of micrograms per both wrists. 1 microgram = 1000 nanograms. Most measurements of Cu and Sn were below their respective analytical limit of detection, and all results for V were below its analytical detection limit. Results below an analytical limit of detection are indicated by a "<" symbol. Semi-quantitative values are indicated by italic font.

Pairs of wipe samples were collected from employees' wrists before and after performing normal job tasks during their work shift. The first sample was collected mid-morning (baseline), and results showed the presence of metals. It is unknown how long these metals were on skin prior to the time of sample collection. The second sample was collected near the end of their shift. Results showed post-task levels of metals were sometimes higher or lower compared with baseline. There are several reasons that could explain this inconsistency. All employees reported wearing nitrile gloves at times during their work on the day of sampling (we did not ask how many times they changed gloves). One employee was observed to put on disposable arm sleeves after collecting the baseline sample. Two employees reported washing their hands two to three times between collecting the baseline and post-task samples. Other factors could also affect results such as if employees wiped hands with a rag during work (we did not ask if they practiced any hand hygiene other than washing).

Potential adverse effects from skin exposure to these metals are:

- Aluminum metal dust – skin irritation (temporary inflammation of the skin that is not from an allergy) [NIOSH 2019a].
- Chromium metal dust – skin irritation [NIOSH 2019b] and skin sensitization (an allergy that once developed, can result in a reaction when exposed to the agent again) [Iyer et al. 2002; Forte et al. 2008, Lansdown 1995; Bregnbak et al. 2015; ATSDR 2023].
- Cobalt metal dust – skin symptoms (dermatitis) [NIOSH 2019c].
- Copper metal dust – skin symptoms (dermatitis) [NIOSH 2019d].
- Iron metal dust- in rare cases, can cause skin sensitization [Davis et al. 2011; Nonaka et al. 2011; Lansdown 1995].
- Molybdenum metal dust – skin irritation and in rare cases, sensitization [Lansdown 1995; Navarro-Triviño et al. 2021].
- Nickel metal dust – skin sensitization [NIOSH 2019e].
- Tin metal dust – skin irritation [NIOSH 2019f].
- Titanium metal dust – in rare cases, titanium can cause skin sensitization [Davis et al. 2011].

- Vanadium metal dust – skin irritation [NIOSH 2019g].

There are no occupational exposure limits for metals on skin, so it is unknown whether the levels reported in Table C9 present a health risk. It is important to recognize that individuals respond differently to exposure to metals that have potential to cause an allergic reaction (skin sensitization). Some persons can be exposed throughout their lives without ever developing allergy, whereas others are very sensitive and can develop allergy even after a brief exposure. We recommend minimizing skin exposure to all metals in Table C9, with vigilance for those that can cause an allergic response.

Based upon the results of the skin wipe samples, we recommend the following:

- Reinforce to staff the importance of protection for any exposed skin (hands, wrists, and forearms) such as gloves and long sleeve shirts or arm sleeves to minimize skin exposure.
- Encourage staff to wash their hands with soap and warm water throughout the workday to minimize skin exposure.
- Continue to identify process improvements that reduce opportunities for skin exposure such as the version 2 printer enclosed powder handling process compared with the version 1 printer manual handling process.

Methods: Inhalation Exposure Assessment

The approach to inhalation exposure assessment included complementary real-time monitoring and time-integrated sampling.

Real-time Monitoring

A model 8525 Ultrafine Particle Counter (P-TRAK, TSI Inc., Shoreview, MN), a model 3910 Scanning Mobility Particle Sizer (SMPS, TSI Inc., Shoreview, MN), and a model 3300 Optical Particle Sizer (OPS, TSI Inc., Shoreview, MN) were used to monitor airborne particles. All instruments were within factory calibration. The P-TRAK measures number concentration for particles in the size range 20 nanometers to 1000 nanometers. The SMPS measures particle number concentration and size distribution in the range 10 nanometers to 420 nanometers. The OPS measures particle number concentration and size distribution in the range 0.3 micrometers to 10 micrometers. There are 1000 nanometers in 1 micrometer, so the OPS range is equivalent to 300 nanometers to 10,000 nanometers. For the post-processing room only, photoionization detector (PID) instruments (Tiger, Ion Science Inc., Stafford, TX) were used to measure total volatile organic compounds (TVOC) in air.

The real-time instruments were used in both task-based assessments and assessments involving spatial variability. The instruments were placed in the near field (NF) and far field (FF) positions during work tasks to ascertain the variability of particle counts close to and at a short distance (typically approximately 2 meters) from work tasks, respectively. Only one SMPS instrument was available at the time of this site visit, and it was always positioned in the NF location.

Time-Integrated (Filter-Based) Sampling

The real-time instruments are not able to determine the composition of particles or gases in air. As such, air sampling pumps (AirChek® XR5000, SKC, Inc., Eighty Four, PA) were connected via inert tubing to the following sampling media: mixed cellulose ester (MCE) filter cassettes, PVC filter cassettes, track-etched polycarbonate (TEPC) filter cassettes, glass fiber filter (GFF) cassettes, and sorbent tubes with silica gel coated with 2,4-dintrophenylhydrazine (DNPH). These pumps and sampling medias were used in NF/FF task-based assessments and were also attached to sampling belts for use in personal breathing zone (PBZ) sampling. The sampling pumps were calibrated within ± 0.05 L/min to the stated flow rates. Post-sampling calibrations were also recorded. MCE filter sampling pumps were calibrated to 3.0 L/min for sample collection, and the filters were analyzed for Al, Cr (total), Co, Cu, manganese (Mn), Mo, Ni, Sn, and Ti according to NIOSH Method 7303 [NIOSH 2003]. PVC filter sampling pumps were calibrated to 2.0 L/min, and the filters were analyzed for Cr(VI) following OSHA ID215 V2 [OSHA 2006]. Air was drawn through TEPC filters at 4.0 L/min and collected particles were imaged and their elemental composition identified via SEM-EDX. GFF sampling pumps were calibrated to 1.0 L/min, and the filters analyzed for triethanolamine by OSHA PV2141 [OSHA 2008]. The pumps used to sample with DNPH-treated tubes were calibrated to 1.5 L/min and analyzed for 11 different aldehydes according to EPA TO-11A [EPA 1999]. Results for crotonaldehyde are not reported as this chemical can react with the DNPH sampling media resulting in analytical bias [Ho et al. 2011].

Results: Inhalation Exposure Assessment

PBF Room

Management and workers identified 20 tasks with potential for exposure to metal powder and ranked them by exposure potential from highest (task 1) to lowest (task 20). During the May 2023 site visit, tasks identified in **bold** font were monitored using a NF/FF sampling strategy. Each of these tasks was monitored at least twice. The remaining tasks were not evaluated because they were not performed at the time of the site visit.

1. Cleaning/bag swap on dry tiger vacs
2. **V1 machine sieving**
3. V1 flow bin virgin powder loading from small bins
4. V1 flow bin scooping out and into can
5. **V1 powder vacuuming**
6. **AM-Pro Depowdering machine de-inerting**
7. **Wet vacuum cleaning**
8. **V1 sieve uncoupling flow bins**
9. Opening V1 sieve interior
10. V2 sieve maintenance/AZO maintenance
11. **V2 cleaning of residual powder within build chamber**
12. V2 powder glovebox opening/cleaning
13. **Opening Am-Pro depowdering machine door**
14. Removing V2 oversized bin from sieve
15. **Opening v1/v2 access doors**
16. V1/v2 changing dust bin on herding system
17. **V2 powder vacuuming**
18. V2/v1 build production

19. V2 powder handling inside the glovebox
20. **AM-Pro Depowdering process**

Version 1 machine sieving (task 2)

The version 1 (older design) PBF printers had a powder sieving station housed in a metal cabinet that was physically separate from the printer. Sieving involved an employee using a pneumatic lift cart to position a bin that contained used powder at the top of the sieve stack in a station and an empty bin at the bottom. Used powder flowed onto the sieve stack by gravity feed, and size separation was assisted by forced air and vibration. Powder with the desired size distribution was collected in the bottom bin and stored for later use or transferred to a printer for making a part. The door to the sieve station cabinet did not form an air-tight seal and was ajar at times. Each version 1 printer had its own dedicated powder sieve station to prevent cross-contamination of feedstock powders. At the time of this site visit, three sieve stations were installed in a row near the center of the PBF room, though only two were in use. This task was monitored on three occasions for the M27 printer sieve (316L stainless steel), once for the M26 printer sieve (Inconel 718), and once while the M27 and M26 sieves were operating simultaneously. As shown in Figure B16, during all sieving tasks, the NF basket was placed by a sieve station cabinet, and the FF basket was placed on the pneumatic lift parked between the inter-lock system door and the PPE change out room door. Periodically, the P-TRAK and OPS instruments were removed from the NF basket and used to monitor particle counts along the perimeter of the sieve station cabinet and inside the cabinet.

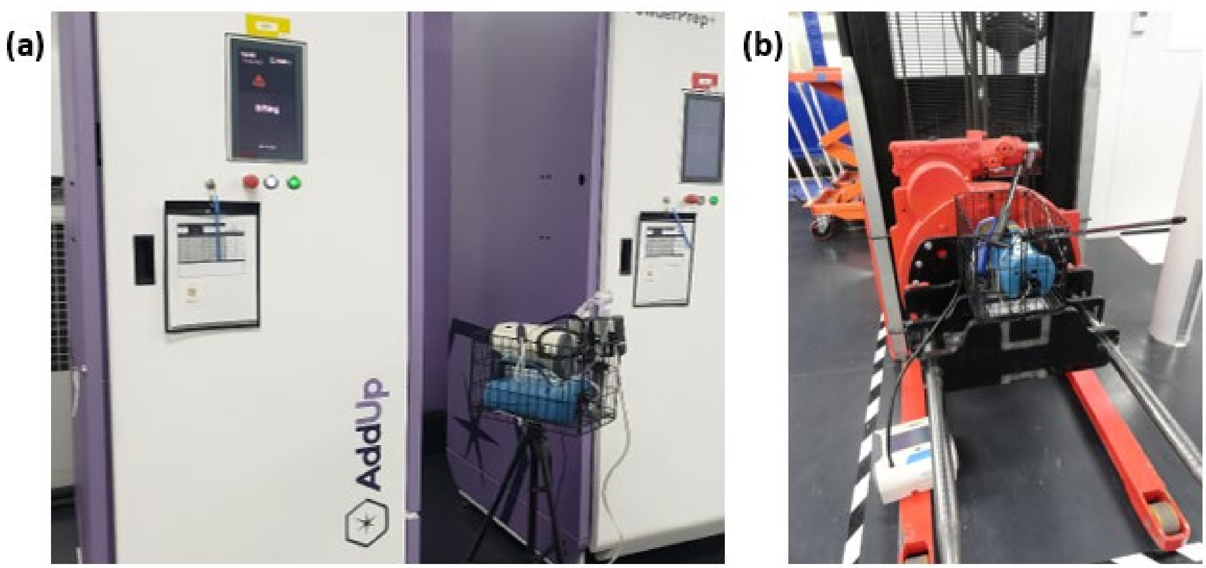


Figure B16. Sampler placement for version 1 printer powder sieving task: (a) location of near field (NF) basket, (b) location of far field (FF) basket.

Figure B17 contains plots of particle concentrations in the NF and FF during the first replicate of the M27 sieve station with 316L stainless steel powder. For the P-TRAK, particle concentrations ranged from 4,000 to 14,000 particles/cm^3 of air. Levels were steady initially, increased from approximately minute 12 to 22 (there was no observable change in the process during this time to explain the rise), and then slowly return to their initial level. When the operator used a mallet to dislodge powder (event 8), there was a small increase in concentration. For the OPS, except for an initial spike in concentration (likely suspension of dust from vibration in the cabinet), levels ranged from 500 to 1,000 particles/cm³ of air and remained steady during this task. The higher concentration recorded by the P-TRAK compared with the OPS indicated that on a number basis, most airborne particles had sizes below 300 nanometers. In general, particle concentrations were similar in the NF and FF locations.

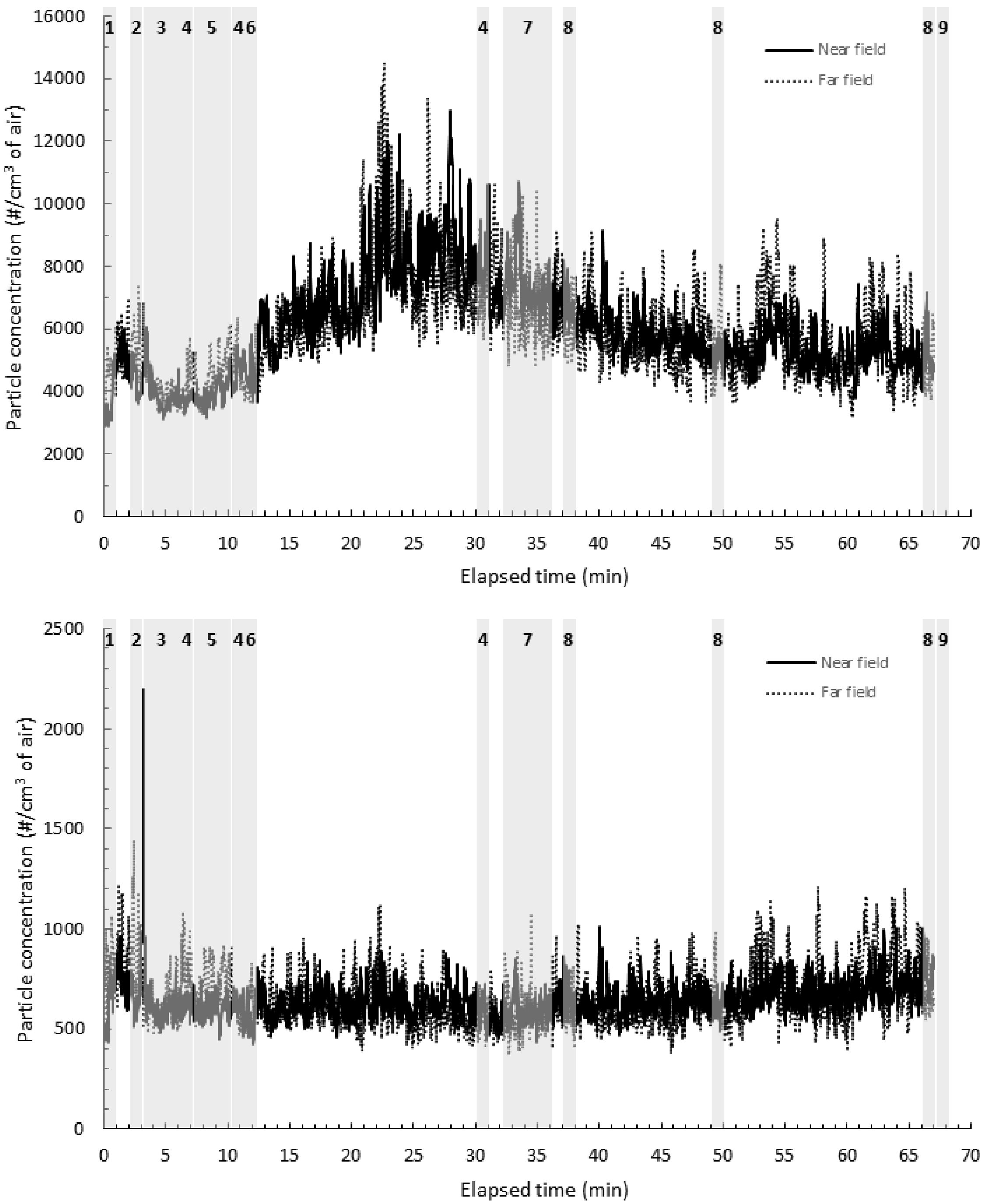


Figure B17. Plots showing no appreciable changes in airborne particle concentrations during operation of the M27 printer sieve station with 316L stainless steel powder on 16 May 2023 (morning): P-TRAK data (top panel), OPS data (bottom panel).

Time	Event	Description
0	1	NF instruments used to monitor inside M27 sieve station
2	2	Began sieving 316L stainless steel powder (front door open)
3	3	Closed front door/NF instruments moved along door frame
6	4	Opened front door/NF instruments moved from top to bottom inside cabinet
7	5	Closed front door/NF instruments moved along door frame and back of cabinet
10	4	Opened front door/NF instruments moved from top to bottom inside cabinet
11	6	Closed front door/NF instruments placed near door
30	4	Opened front door/NF instruments moved from top to bottom inside cabinet
32	7	Closed front door/NF instruments moved along door frame, back of cabinet, door frame
37	8	Front door opened/operator used mallet to dislodge powder in top bin
49	8	Front door opened/operator used mallet to dislodge powder in top bin
66	8	Front door opened/operator used mallet to dislodge powder in top bin
67	9	End task

Figure B17 (continued). Plots showing no appreciable changes in airborne particle concentrations during operation of the M27 printer sieve station with 316L stainless steel powder on 16 May 2023 (morning): P-TRAK data (top panel), OPS data (bottom panel). Similar particle concentrations were seen in the near field and far field sampling locations for both instruments.

Figure B18 is plots of particle concentrations for the second replicate of the M27 sieve station. Particle concentrations measured using the P-TRAK are approximately 5,000 particles/cm^3 of air until minute 70 when there was a rapid increase in levels. The plot for the OPS shows the same pattern. During minutes 69 to 70, there was an error message displayed on the sieve station, and the inter-lock door was opened which resulted in an increase in particle concentration. As with the first replicate, particle concentrations were similar in the NF and FF locations.

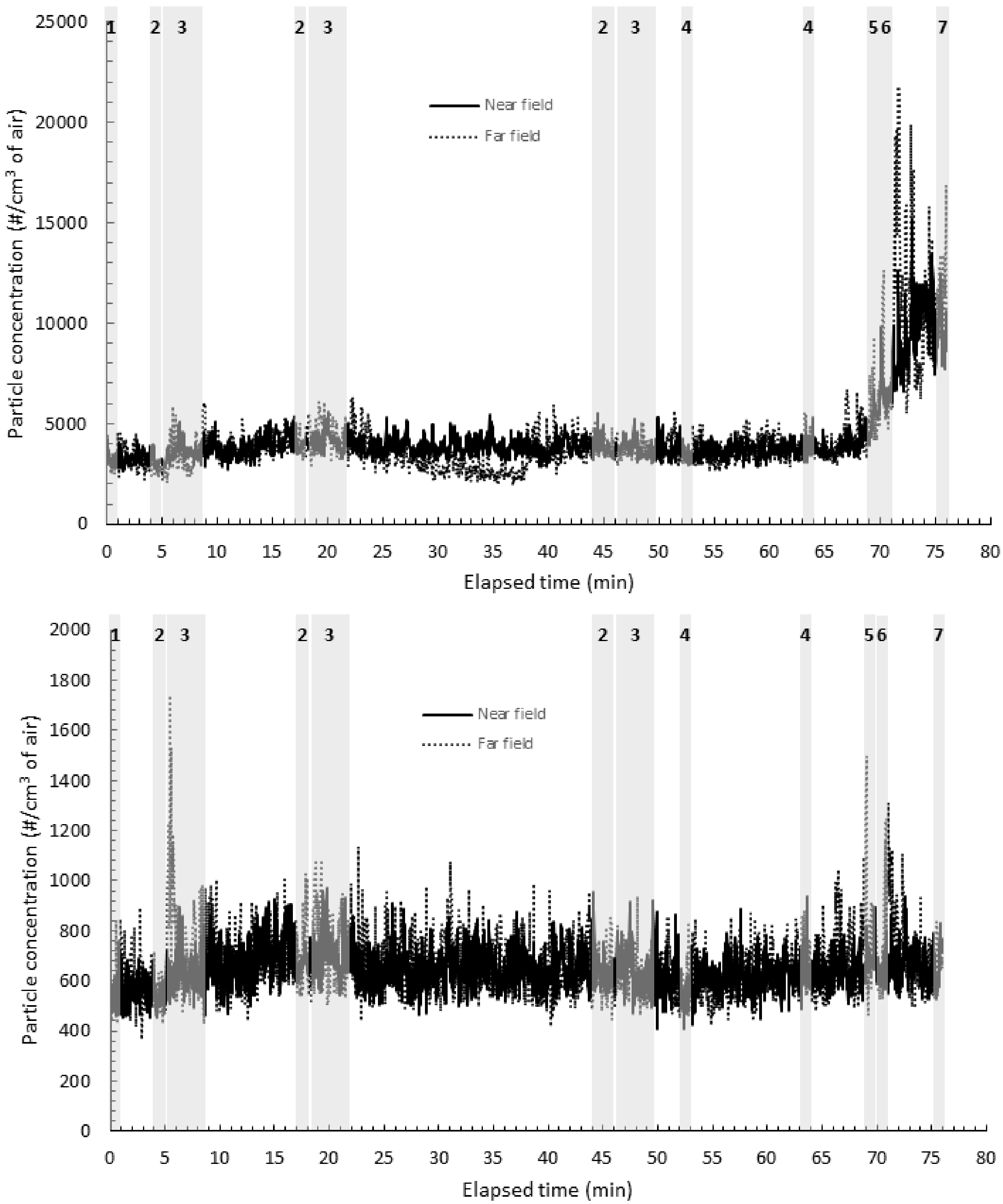


Figure B18. Plots showing stable airborne particle concentrations except for a machine error during operation of the M27 printer sieve station with 316L stainless steel powder on 16 May 2023 (mid-day): P-TRAK data (top panel), OPS data (bottom panel).

Time	Event	Description
0	1	Began sieving 316L stainless steel powder (front door open)
4	2	Opened front door/NF instruments moved from top to bottom inside cabinet
5	3	Closed front door/NF instruments moved along door frame, back of cabinet, door frame
17	2	Opened front door/NF instruments moved from top to bottom inside cabinet
18	3	Closed front door/NF instruments moved along door frame, back of cabinet, door frame
44	2	Opened front door/NF instruments moved from top to bottom inside cabinet
46	3	Closed front door/NF instruments moved along door frame, back of cabinet, door frame
52	4	Front door opened/operator used mallet to dislodge powder in top bin
63	4	Front door opened/operator used mallet to dislodge powder in top bin
69	5	"Machine faulted" message on M27 display
70	6	Inter-lock door opened and closed
76	7	End task

Figure B18 (continued). Plots showing stable airborne particle concentrations except for a machine error during operation of the M27 printer sieve station with 316L stainless steel powder on 16 May 2023 (mid-day): P-TRAK data (top panel), OPS data (bottom panel). Similar particle concentrations were seen in the near field and far field sampling locations for both instruments.

Figure B19 is plots of particle concentrations for the third replicate of the M27 sieve station. For this replicate, particle concentrations were measured using an SMPS, P-TRAK, and OPS. Particle concentrations monitored with the SMPS (NF only), and P-TRAK were approximately 8,000 particles/cm^3 of air, whereas for the OPS, the level was approximately 1,000 particles/cm^3 of air. Occasionally, particle concentrations increased while monitoring along the seams of the sieve station door, the side panels, and back panel or inside the cabinet, though in general, these locations did not appear to be major sources of fugitive emissions. Consistent with the first two replicates, particle concentrations were similar in the NF and FF locations.

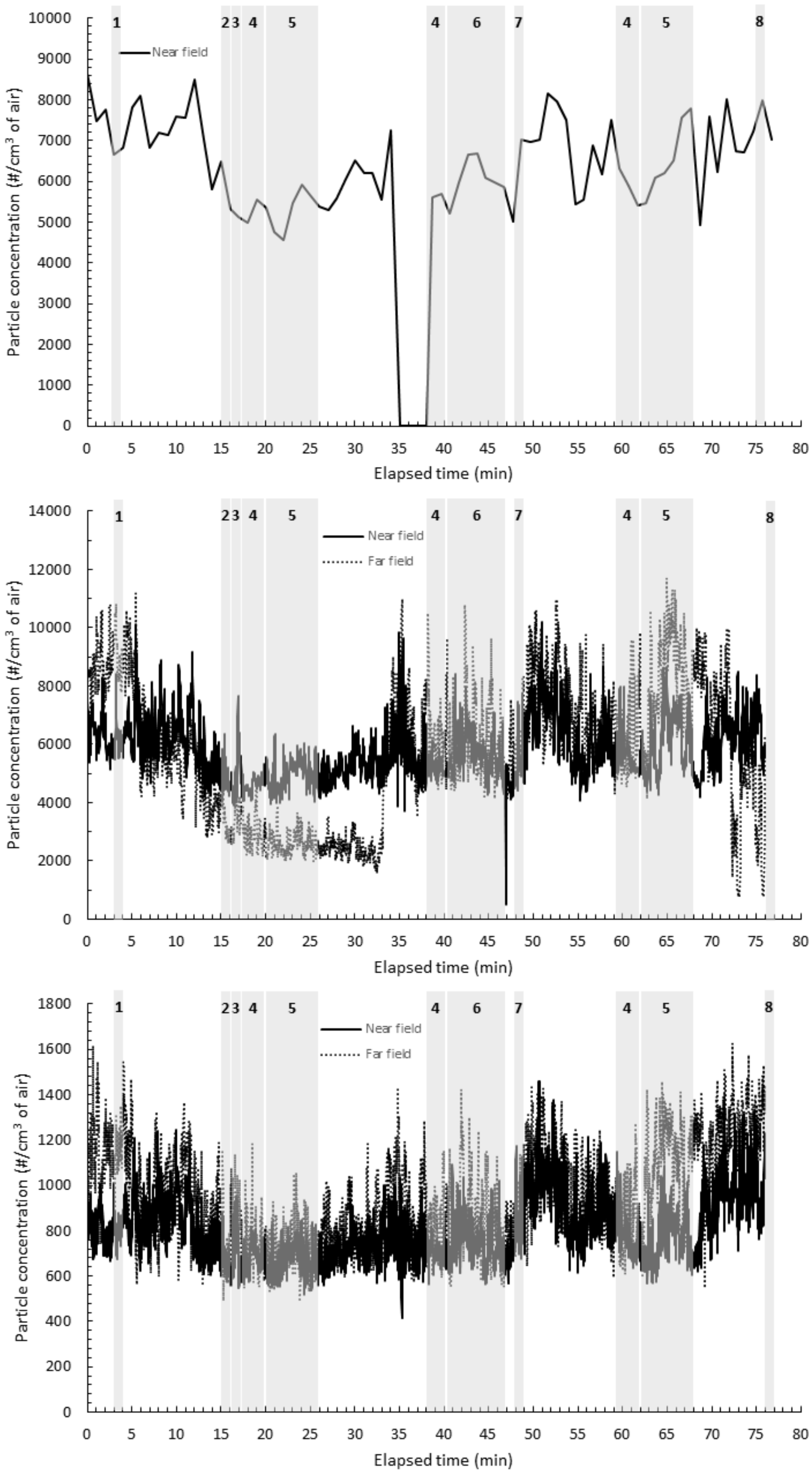


Figure B19. Plots showing no appreciable changes in airborne particle concentrations during operation of the M27 printer sieve station with 316L stainless steel powder on 16 May 2023 (afternoon): SMPS data (top panel), P-TRAK data (middle panel), OPS data (bottom panel).

Time	Event	Description
3	1	Began sieving (front door closed)
15	2	Opened front door
16	3	Closed front door
17	4	Opened front door/NF instruments moved from top to bottom inside cabinet
20	5	Closed front door/NF instruments moved along door frame, back of cabinet, door frame
38	4	Opened front door/NF instruments moved from top to bottom inside cabinet
40	6	Closed front door/NF instruments moved along door frame and back of cabinet
48	7	Front door opened/operator used mallet to dislodge powder in top bin
59	4	Opened front door/NF instruments moved from top to bottom inside cabinet
62	5	Closed front door/NF instruments moved along door frame, back of cabinet, door frame
76	8	End task

Figure B19 (continued). Plots showing no appreciable changes in airborne particle concentrations during operation of the M27 printer sieve station with 316L stainless steel powder on 16 May 2023 (afternoon): SMPS data (top panel), P-TRAK data (middle panel), OPS data (bottom panel). Similar particle concentrations were seen in the near field and far field sampling locations for all instruments.

Figure B20 is plots of particle concentration in the NF and FF at the M26 sieve station with Inconel 718 powder. In the NF, particle concentrations measured with the SMPS, and P-TRAK are approximately 6,000 to 10,000 particles/cm^3 of air. For the OPS, particle concentrations in the NF and FF are approximately 250 particles/cm^3 of air. For all instruments in the NF, slight transient increases in particle concentration were seen when moving them along the door frame and back of cabinet (events 3 to 5). For the P-TRAK, particle concentration was higher in the NF compared with the FF, whereas for the OPS, particle concentration was intermittently higher in the NF compared with the FF.

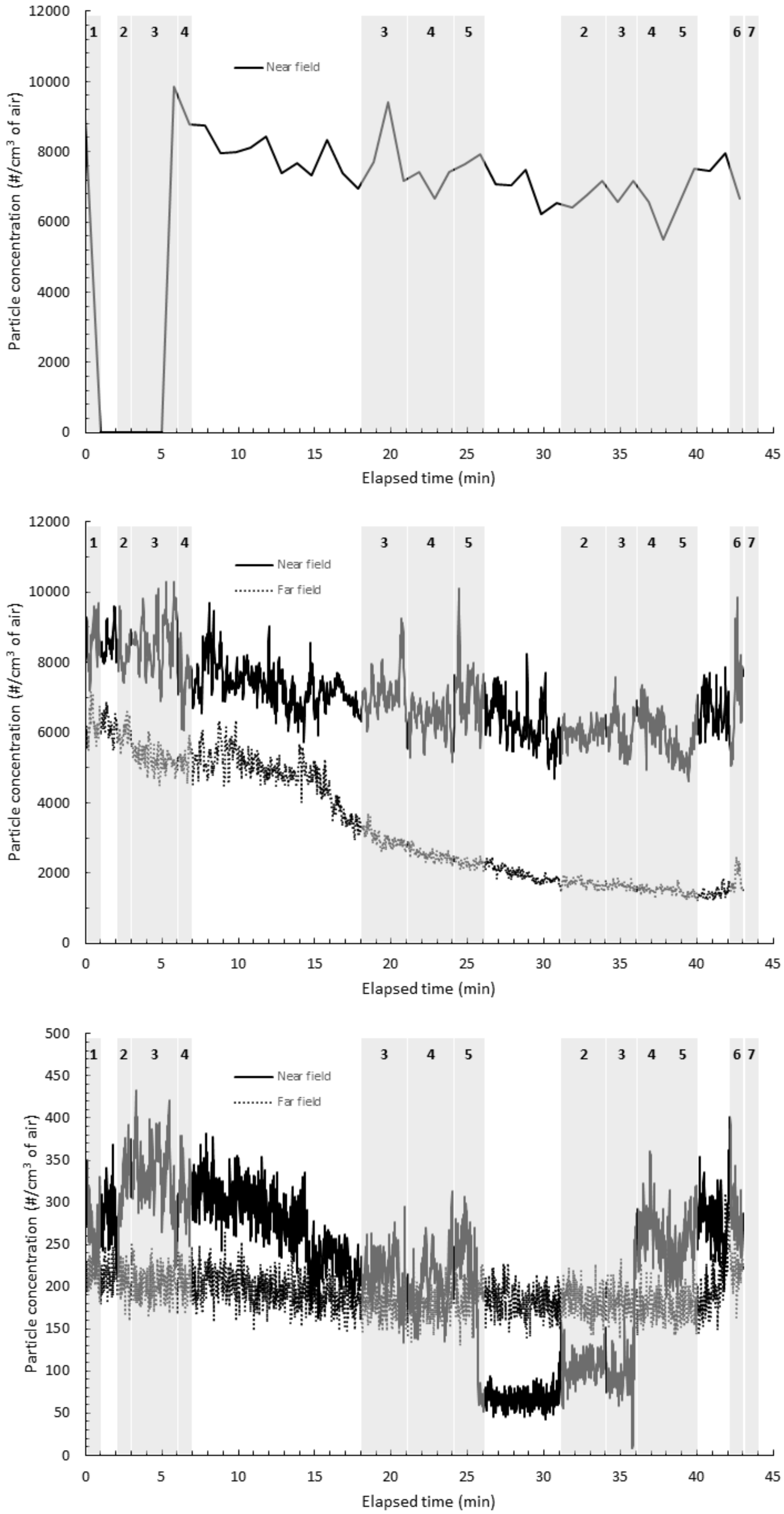


Figure B20. Plots showing no appreciable change in airborne particle concentration during operation of the M26 printer sieve station with Inconel 718 feedstock powder on 17 May 2023 (afternoon): SMPS data (top panel) – no values from 0 to 5 minutes because of an instrument error, P-TRAK data (middle panel), OPS data (bottom panel).

Time	Event	Description
0	1	Began sieving Inconel 718 powder (front door open)
2	2	Opened front door/NF instruments moved from top to bottom inside cabinet
3	3	Closed front door/NF instruments moved along door frame
6	4	NF instruments moved along back of cabinet
18	3	Closed front door/NF instruments moved along door frame
21	4	NF instruments moved along back of cabinet
24	5	NF instruments moved along door frame
31	2	Opened front door/NF instruments moved from top to bottom inside cabinet
34	3	Closed front door/NF instruments moved along door frame
36	4	NF instruments moved along back of cabinet
38	5	NF instruments moved along door frame
42	6	Used hammer on top powder container
43	7	End task

Figure B20 (continued). Plots showing no appreciable change in airborne particle concentration during operation of the M26 printer sieve station with Inconel 718 feedstock powder on 17 May 2023 (afternoon): SMPS data (top panel) – no values from 0 to 5 minutes because of an instrument error, P-TRAK data (middle panel), OPS data (bottom panel). Higher particle concentrations were seen in the near field compared with the far field sampling location for the P-TRAK, but levels were similar for the OPS instrument.

Figure B21 shows particle concentration during simultaneous operation of the M26 sieve station with Inconel 718 powder and M27 sieve station with 316L stainless steel powder. In the NF, particle concentrations measured using the SMPS and P-TRAK were stable at approximately 8,000 to 10,000 particles/cm^3 of air. At minute 25, the NF basket was relocated to between the two sieve stations (event 5), and particle concentrations increased up to approximately 16,000 particles/cm^3. The SMPS and P-TRAK both showed a slight increase in particle concentration again at minute 27 when the M27 sieve station began operating (event 6). OPS concentration measurements were approximately 250 particles/cm^3 and relatively stable throughout the task. Particle concentration measurements with the P-TRAK and OPS instruments showed levels were slightly higher in the NF compared with the FF; however, FF basket instruments only ran for a portion of the task.

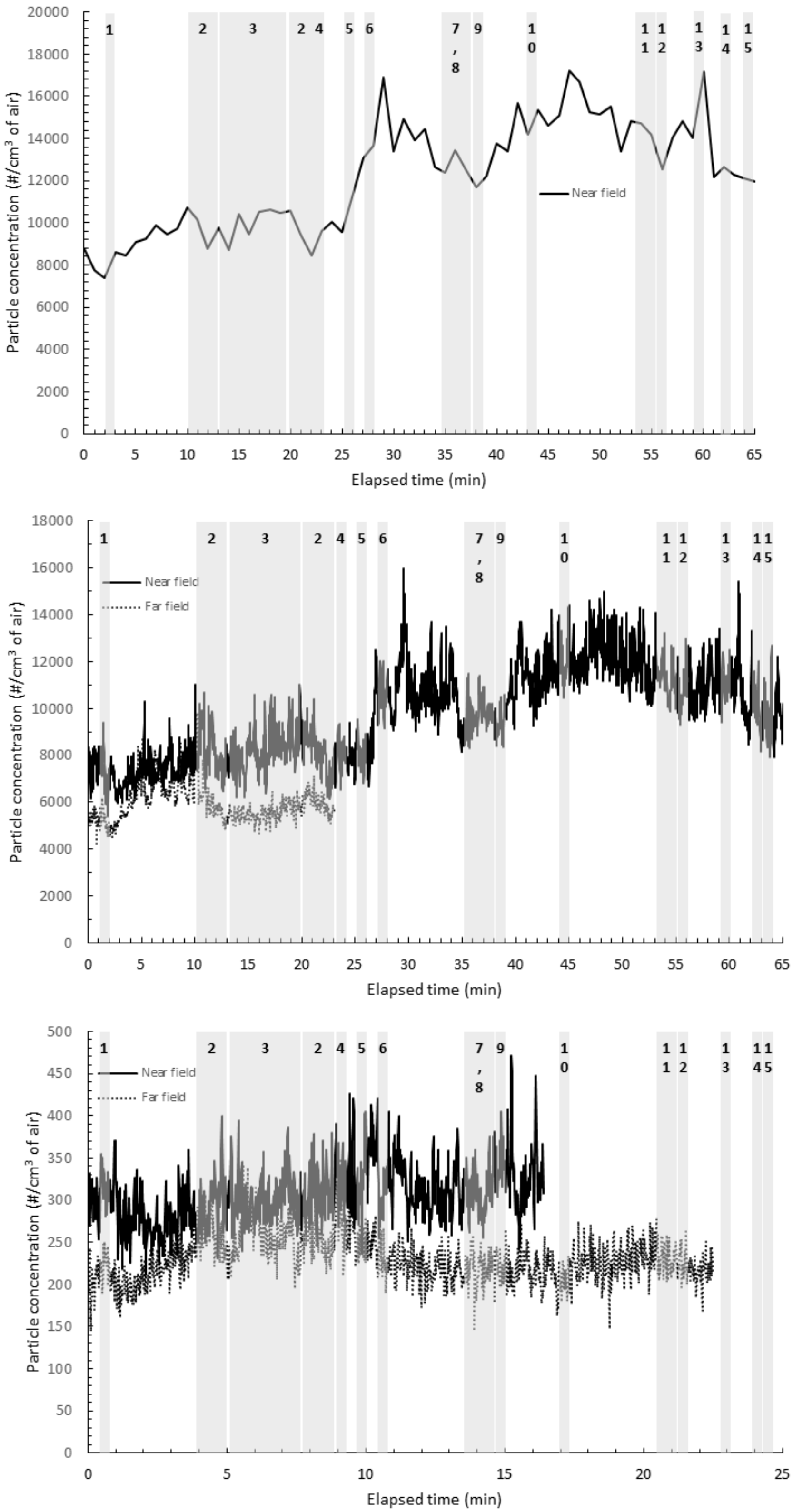


Figure B21. Plots showing particle concentrations during simultaneous operation of the M26 printer sieve station with Inconel 718 powder and M27 printer sieve station with 316L stainless steel powder on 17 May 2023 (afternoon): SMPS data (top panel), P-TRAK data (middle panel), OPS data (bottom panel).

Time	Event	Description
2	1	Began sieving Inconel 718 powder on M26 printer sieve station (door closed)
10	2	Opened door on M26 printer sieve station
13	3	Closed door on M26 printer sieve station
20	2	Opened door on M26 printer sieve station
23	4	Turned off FF basket
25	5	Moved NF instruments between M26 and M27 printer sieve stations
27	6	Began sieving 316L powder on M27 printer sieve station/Still sieving Inconel 718
35	7	Opened doors on both M26 and M27 printer sieve stations
35	8	Used hammer on top powder container inside M26 printer sieve station
38	9	Closed doors on both M26 and M27 printer sieve stations
44	10	End sieving Inconel 718 powder on M26 printer sieve station
53	11	Opened door on M27 printer sieve station
55	12	Closed door on M27 printer sieve station
59	13	Dry sweeping in room (mostly near PBF printers)
62	14	Used hammer on top powder container inside M27 printer sieve station
64	15	End sieving 316L stainless steel powder on M27 printer sieve station

Figure B21 (continued). Plots showing particle concentrations during simultaneous operation of the M26 printer sieve station with Inconel 718 powder and M27 printer sieve station with 316L stainless steel powder on 17 May 2023 (afternoon): SMPS data (top panel), P-TRAK data (middle panel), OPS data (bottom panel). The SMPS and P-TRAK both showed a slight increase in particle concentration at minute 27 when the M27 sieve station began operating (event 6). The far field P-TRAK and near and far field OPS instruments were turned off before the end of the task.

From the SMPS, geometric average particle sizes ranged from approximately 35 to 45 nanometers. The OPS senses larger particles than the SMPS; geometric averages were approximately 335 to 435 nanometers.

In summary, there was no apparent influence of powder sieving on particle concentrations in the PBF room except for when an error occurred (Figure B18) and two stations operate simultaneously (Figure B21). For the three replicates of the M27 sieve station with 316L stainless steel feedstock powder, particle concentrations in the NF and FF were similar. For the M26 sieve station with Inconel 718 feedstock powder, particle concentration was higher in the NF compared with the FF for the P-TRAK, though levels were similar for the OPS instrument.

Version 1 sieve uncoupling flow bins (task 8)

The powder bins in the version 1 printer powder sieve station were connected to the sieve stack by flexible collars. Once sieving was complete, the operator must detach the powder bins from the sieve stack so they can be removed using a pneumatic lift. This task was monitored four times, twice for the M27 printer sieve station (316L stainless steel) and twice for the M26 printer sieve station (Inconel 718). The NF and FF baskets were placed at the same locations as for the sieving task (see Figure B16) but moved aside as necessary to avoid interfering with access to the stations while employees performed their work. Particle concentrations measured using the SMPS and P-TRAK were higher compared with the OPS which indicates that most particles had sizes smaller than 300 nanometers.

Figures B22 and B23 show that during the two replicates for the M27 sieve station with 316L stainless steel powder, P-TRAK and OPS measurements revealed slight increases in particle concentration during powder bin decoupling and when placing bins inside or removing them from the station. For both replicates, particle concentrations were similar in the NF and FF locations.

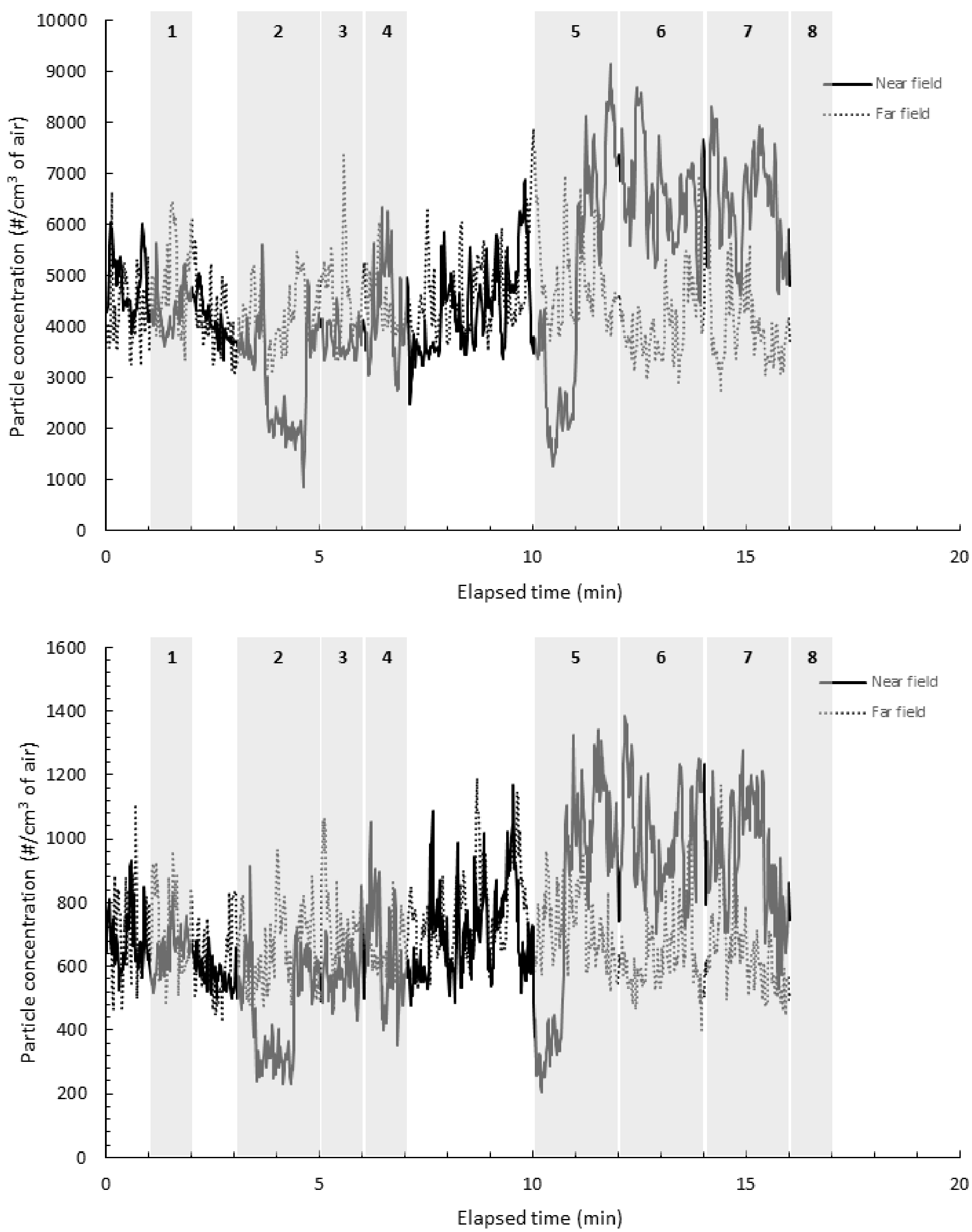


Figure B22. Plots of particle concentrations during powder bin decoupling and when placing bins inside or removing them from the M27 printer sieve station with 316L stainless steel powder on 16 May 2023 (morning): P-TRAK data (top panel), OPS data (bottom panel).

Time	Event	Description
1	1	Uncoupled top powder bin inside sieve cabinet
3	2	Used pneumatic lift to move top bin in sieve to bottom of M27 PBF printer
5	3	Uncoupled bottom powder bin
6	4	Vacuumed exterior of bottom powder bin
10	5	Used pneumatic lift to move bottom bin in sieve to top of M27 PBF printer
12	6	Used pneumatic lift to place new powder bin in bottom position in sieve
14	7	Used pneumatic lift to place new powder bin in top position in sieve
16	8	End task/inerting system for next sieving task

Figure B22 (continued). Plots of particle concentrations during powder bin decoupling and when placing bins inside or removing them from the M27 printer sieve station with 316L stainless steel powder on 16 May 2023 (morning): P-TRAK data (top panel), OPS data (bottom panel). Slight increases in particle concentration were seen during decoupling on both the P-TRAK and OPS instruments. Particle concentrations were similar between the near field and far field sampling locations.

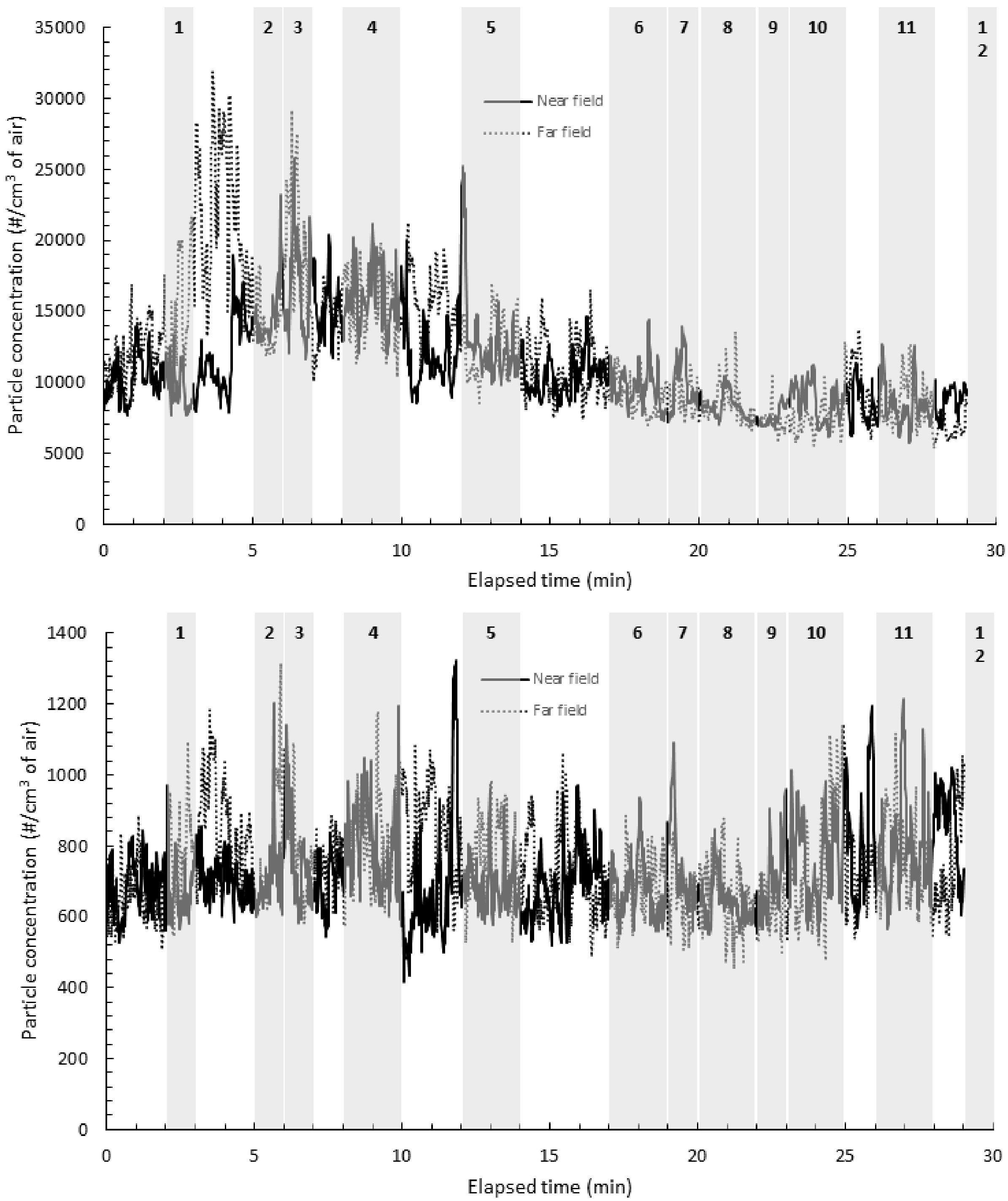


Figure B23. Plots of particle concentrations during powder bin decoupling and when placing bins inside or removing them from the M27 printer sieve station with 316L stainless steel powder on 16 May 2023 (afternoon): P-TRAK data (top panel), OPS data (bottom panel).

Time	Event	Description
2	1	Uncoupled bottom powder bin inside sieve cabinet
5	2	Detached bottom powder bin inside sieve cabinet
6	3	Used pneumatic lift to remove bottom powder bin from sieve cabinet
8	4	Vacuumed bottom powder bin after it was placed next to M27 PBF printer
12	5	Dry sweeping near M27 printer sieve station
17	6	Used pneumatic lift to remove top powder bin in sieve cabinet
19	7	Vacuumed where top powder bin was inside of M27 printer sieve station
20	8	Vacuumed where bottom powder bin was inside of M27 printer sieve station
22	9	Closed sieve station cabinet door
23	10	Used pneumatic lift to place top powder bin into bottom position in sieve station
26	11	Dry sweeping near M27 sieve station/placed bottom powder bin into top position
29	12	End task

Figure B23 (continued). Plots of particle concentrations during powder bin decoupling and when placing bins inside or removing them from the M27 printer sieve station with 316L stainless steel powder on 16 May 2023 (afternoon): P-TRAK data (top panel), OPS data (bottom panel). Plots show slight increases in P-TRAK and OPS particle concentrations during decoupling. Particle concentrations were similar between the near field and far field sampling locations.

Figure B24 illustrates that for the M26 sieve station with Inconel 718 powder, SMPS, P-TRAK, and OPS measurements there was no appreciable increase in particle concentration during powder bin decoupling (events 1 and 10). Particle concentration measurements with the SMPS and P-TRAK instruments increased from approximately 6,000 particles/cm^3 when the pneumatic lift was first used to move the bottom powder bin in the sieve station to the top of the M26 printer (event 3) and continued to increase thereafter to approximately 12,000 particles/cm^3. OPS concentration measurements were relatively stable at approximately 300 to 400 particles/cm^3 throughout this task. P-TRAK and OPS particle concentrations measurements were consistently higher in the NF compared with the FF location.

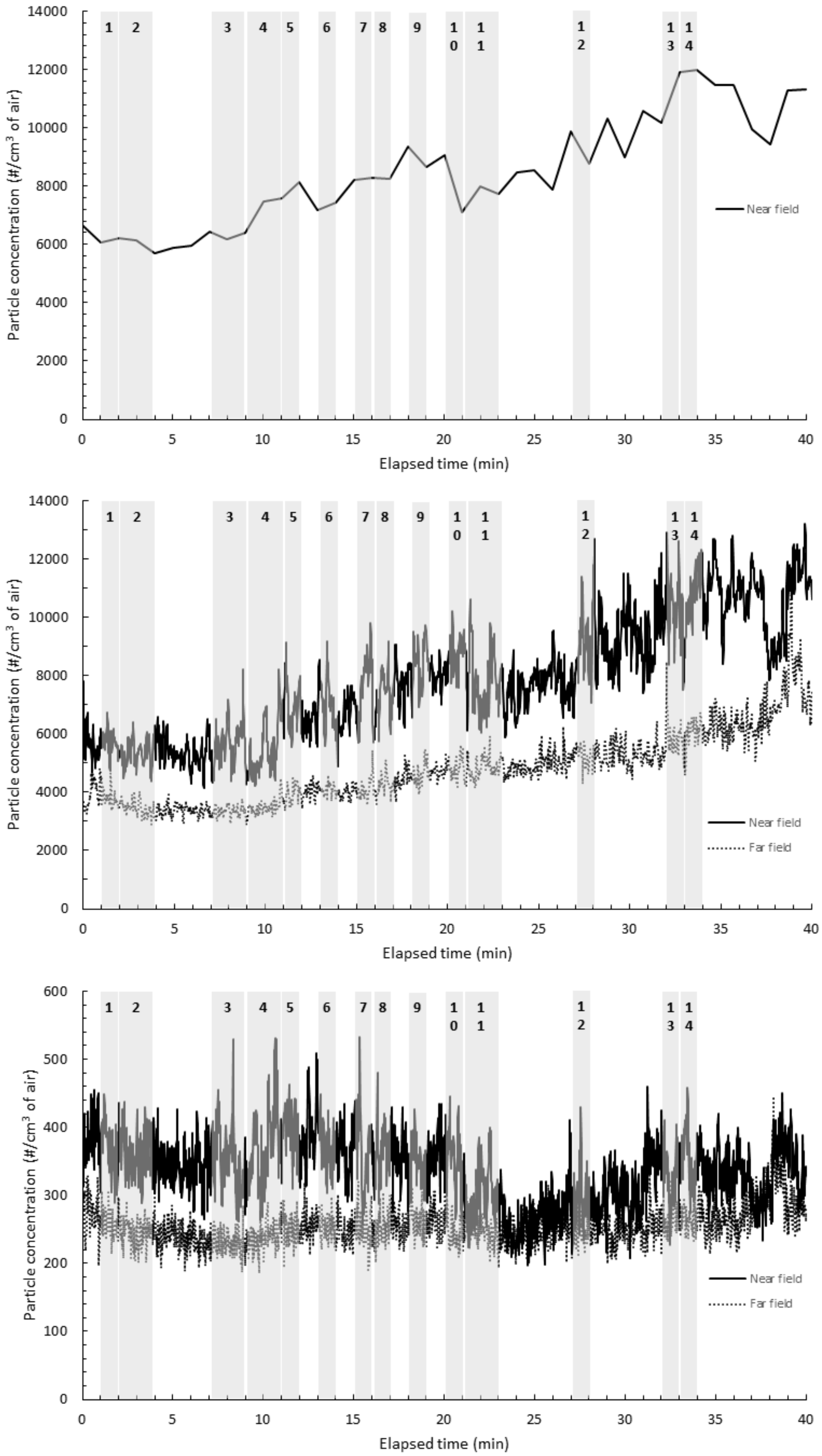


Figure B24. Plots of particle concentrations during powder bin decoupling in the M26 printer sieve station with Inconel 718 powder on 17 May 2023 (morning).

Time	Event	Description
1	1	Uncoupled bottom powder bin inside M26 sieve station/used pneumatic lift to remove
2	2	Vacuumed bottom powder bin after it was placed next to scale
7	3	Used pneumatic lift to move bottom bin from sieve to top of M26 PBF printer
9	4	Used pneumatic lift to remove top powder bin from sieve cabinet
11	5	Used pneumatic lift to move top bin from sieve to bottom of M26 PBF printer
13	6	Vacuumed inside of M26 printer sieve station
15	7	Added new powder container to top of M26 printer sieve station
16	8	Added new powder container to bottom of M26 printer sieve station
18	9	Connected hose to bottom container inside M26 printer sieve station
20	10	Uncoupled bottom powder bin inside M26 sieve station/used pneumatic lift to remove
21	11	Vacuumed bottom powder bin after it was placed on scale
27	12	Removed bottom container from scale
32	13	Hammered on bottom powder container
33	14	End task/began inerting M26 printer sieve station

Figure B24 (continued). Plots of particle concentrations during powder bin decoupling in the M26 printer sieve station with Inconel 718 powder on 17 May 2023 (morning): SMPS data (top panel), P-TRAK data (middle panel), OPS data (bottom panel). No appreciable increase in particle concentration were observed on any instrument during decoupling (events 1 and 10). P-TRAK and OPS particle concentrations measurements were consistently higher in the near field compared with the far field.

Figure B25 illustrates that for the second replicate monitoring of the M26 sieve station with Inconel 718 powder, none of the instruments showed an appreciable increase in particle concentration during powder bin decoupling (events 1, 2, and 7). Particle concentration measurements for all instruments slowly increased when the operator began to inert the sieve station (event 5). P-TRAK particle concentration measurements were generally higher in the NF compared with the FF throughout this task, whereas for the OPS, particle concentrations were mostly similar between sampling locations.

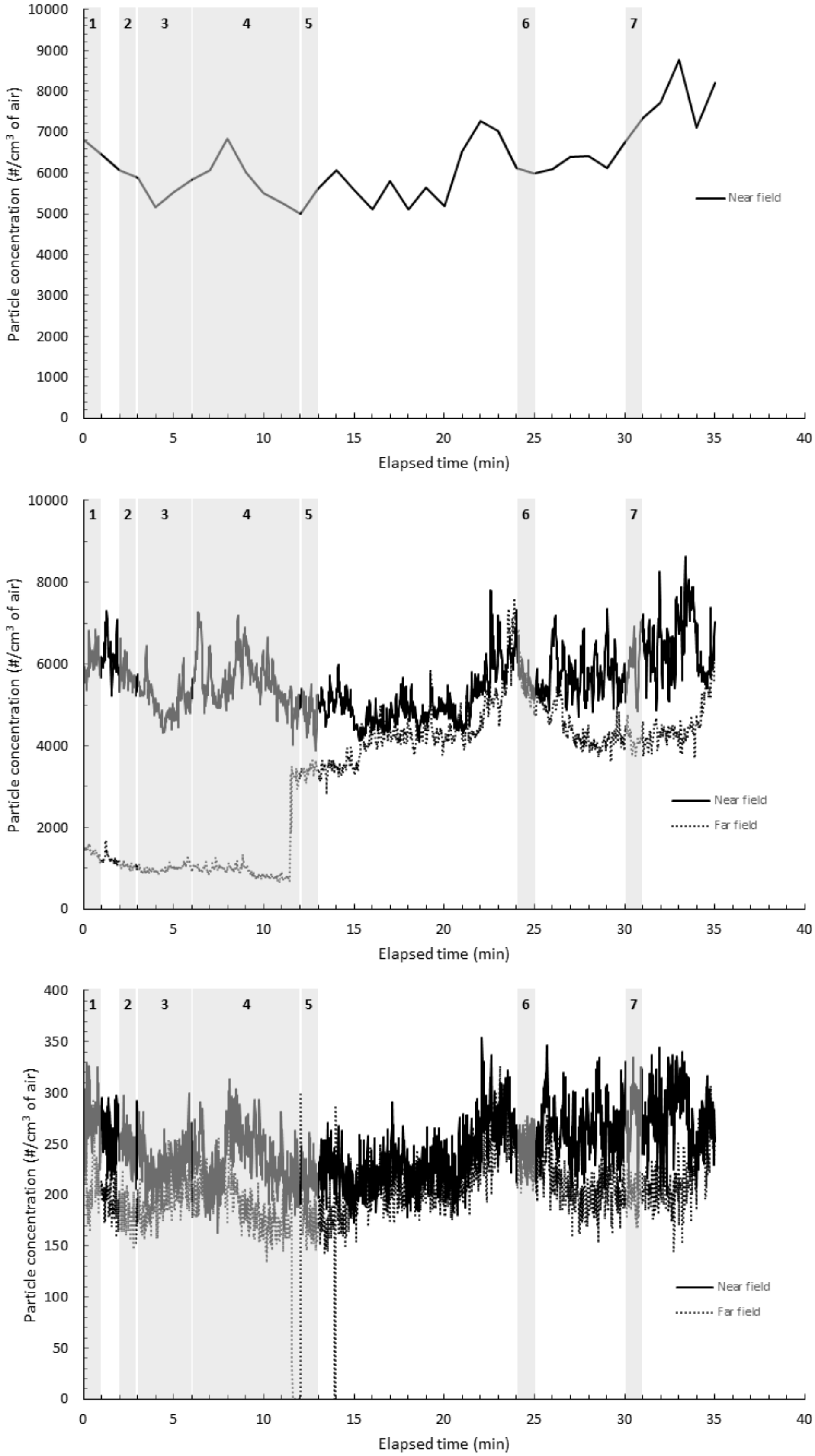


Figure B25. Plots of particle concentrations during powder bin decoupling in the M26 printer sieve station with Inconel 718 powder on 17 May 2023 (afternoon).

Time	Event	Description
0	1	Uncoupled and removed top powder bin inside M26 printer sieve station
2	2	Uncoupled and removed bottom powder bin inside M26 printer sieve station
3	3	Wet vacuuming inside M26 printer sieve station and powder containers
6	4	Used pneumatic lift to swap top and bottom powder containers in sieve station
12	5	End task/began inerting M26 printer sieve station
24	6	Using electric drill at M14 machine
30	7	Uncoupled and removed powder bins from M26 PBF machine

Figure B25 (continued). Plots of particle concentrations during powder bin decoupling in the M26 printer sieve station with Inconel 718 powder on 17 May 2023 (afternoon): SMPS data (top panel), P-TRAK data (middle panel), OPS data (bottom panel). No appreciable increases in particle concentration were seen during decoupling (events 1, 2, and 7). Particle concentrations area was generally higher in the near field sampling location compared with the far field for the P-TRAK instrument but not the OPS instrument.

In summary, for the M27 sieve station with 316L stainless steel feedstock powder a slight increase in particle concentration was seen during powder bin decoupling, whereas for the M26 sieve station with Inconel 718 feedstock powder, there is no appreciable change in particle concentration during decoupling. Interestingly, though a change in particle concentration during decoupling was seen at the M27 station; levels were similar between the NF and FF locations. No influence of bin uncoupling was seen at the M26 sieve station; however, particle concentrations were higher in the NF compared with the FF for the P-TRAK but mostly similar for the OPS instrument.

Version 1 powder vacuuming (task 5) and Opening v1 access doors (task 15)

With PBF machines, upon completing a build, the part was immersed in powder. The version 1 (older design) printers had two access doors to the build chamber. On the broad size of the printer, there was a door with glove ports (glove door), and on the narrow side, there was a door where the build plate was loaded into/removed from the printer (front door). For version 1 printers, the removal of excess powder was done manually using an external dry vacuum connected by a hose to a cyclone that, in turn, was attached to a powder bin. We this monitored this task twice for the M26 printer (Inconel 718 feedstock powder). Figure B26 shows that NF monitors were held by a NIOSH staff person at the face of the M26 printer doors while an employee was vacuuming, and the FF basket was placed on a black tool box approximately 4 meters behind the printer. The P-TRAK and OPS instruments in the NF were moved to follow the employee while dry vacuuming at the glove and printer access doors.

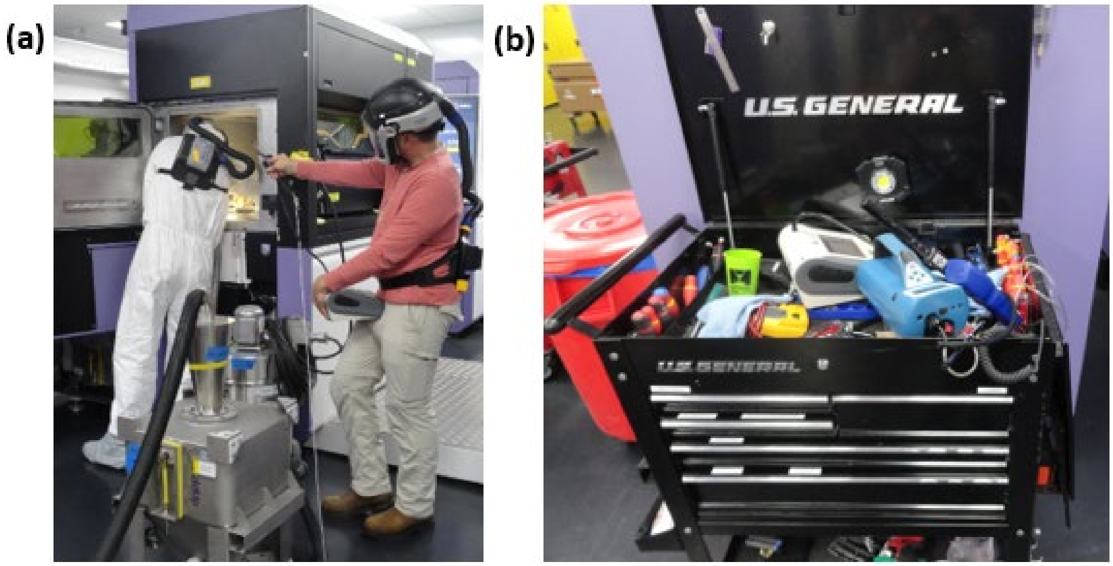
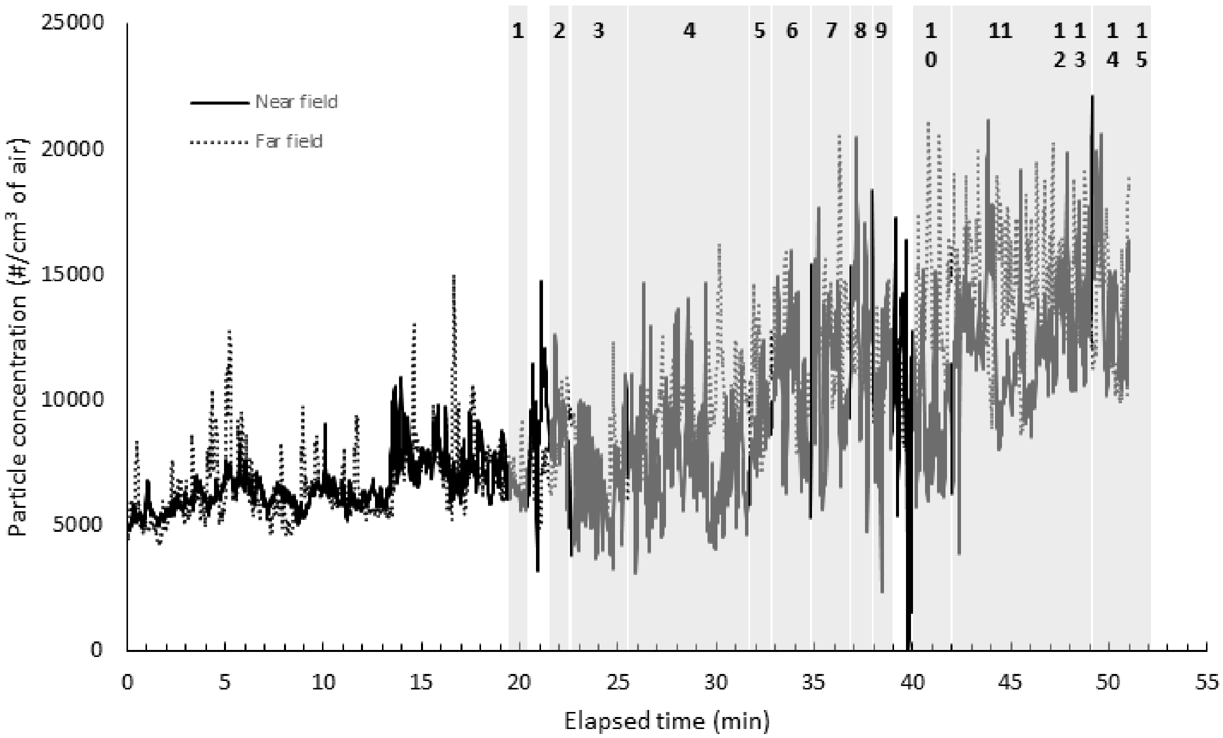


Figure B26. Sampler placement for version 1 printer powder vacuuming task: (a) near field monitors held by a NIOSH staff person, (b) far field basket location approximately 4 meters behind the printer.

Figure B27 illustrates that during the first session, turning on the vacuum caused P-TRAK particle concentrations to increase in both the NF and FF, and levels continued to rise thereafter. These particles were likely from the vacuum itself and Inconel 718 powder, but the P-TRAK instruments could not discern between these sources. Notable increases in P-TRAK concentration measurements were seen during opening/closing access doors (events 5 to 8). OPS particle concentration values were much lower compared with the P-TRAK and relatively constant in the NF and FF locations during activities.



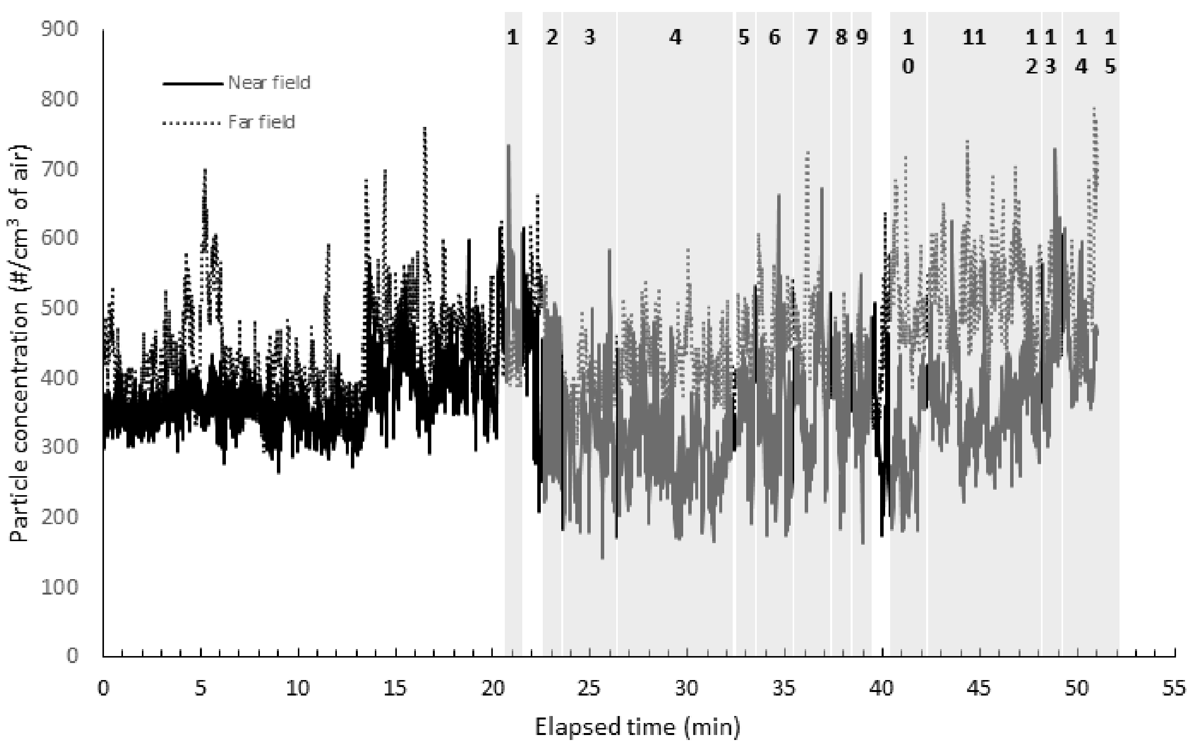
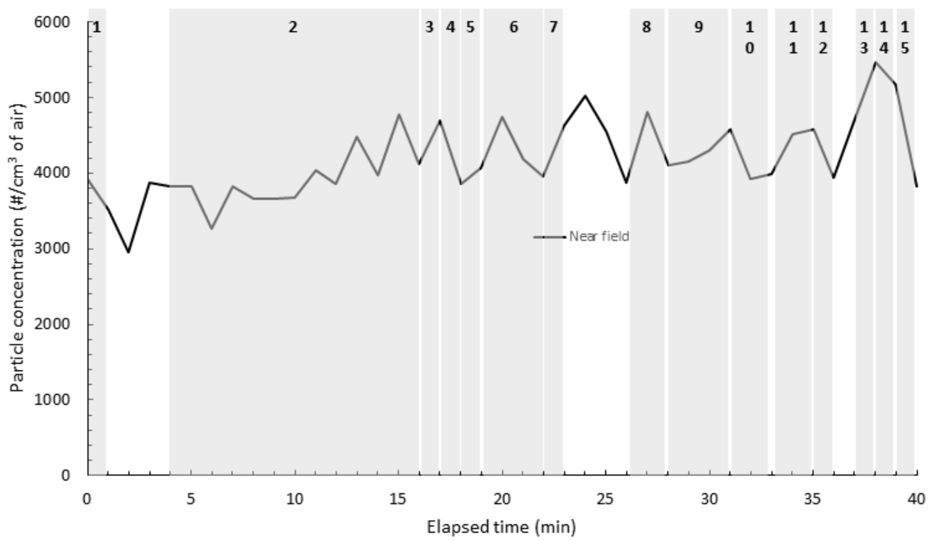


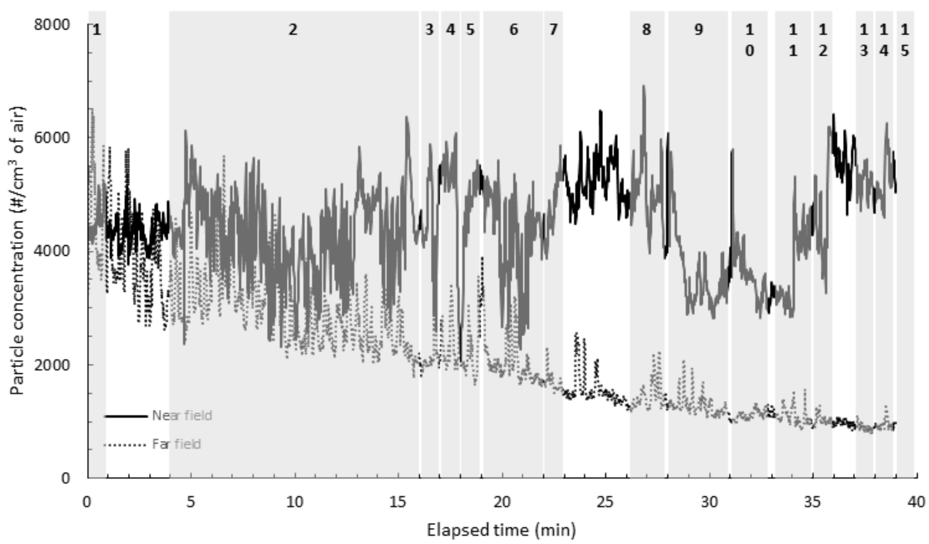
Figure B27. Plots of airborne particle concentrations during vacuuming of excess Inconel 718 powder at the M26 PBF printer on 15 May 2023 (morning).

Time	Event	Description
20	1	Attached vacuum to waste powder bin/vacuum turned on
22	2	Began vacuuming at glove door using small hose adapter
23	3	Changed to larger vacuum hose adapter/still at glove door
26	4	Reattached small hose adapter/still at glove door
32	5	Stopped vacuuming/closed glove door/raised build platform
33	6	Opened glove door/began vacuuming build plate
35	7	Opened access door/vacuuming build plate (glove door open)
37	8	Closed access door/vacuuming at glove door again
38	9	Stopped vacuuming/closed and opened glove door
40	10	Slid build plate onto transport cart/vacuuming part at glove door while still in printer
42	11	Stopped vacuuming/opened access door/vacuuming part on cart outside of printer
47	12	Used scraper to loosen powder while vacuuming part
48	13	Stopped using scraper and stopped vacuuming
49	14	Vacuum on/tightened funnel screws attaching it to hopper
51	15	Stopped tightening screws/vacuum off/end task

Figure B27 (continued). Plots of airborne particle concentrations during vacuuming of excess Inconel 718 powder at the M26 PBF printer on 15 May 2023 (morning): P-TRAK data (top panel), OPS data (bottom panel). Plots show an increase in P-TRAK and OPS levels when the turning on the vacuum (event 1) and for the P-TRAK when opening and closing access doors (events 5 to 8). P-TRAK and OPS concentration levels are similar in the near field and far field sampling locations.

Figure B28 shows that during the second session, turning on the vacuum (event 2) caused SMPS and P-TRAK particle concentrations to increase from slightly below 4,000 particles/cm^3 of air to approximately 5,000 particles/cm^3 of air in the NF. There was another increase in concentration about the time when the screws that attach the vacuum to the cyclone were loosened. OPS measurements showed many short peaks during vacuuming (events 2, 6, 8, and 8) though levels were generally lower compared with the SMPS and P-TRAK measurements. During this task, particle concentration measurements with the P-TRAK showed a steady decrease in the FF location from 4,000 to 1,000 particles/cm^3 of air. OPS values were slightly higher or generally similar in the NF compared with the FF location. Since the version 1 printers did not have a built-in vacuum, the employee had to manually remove all excess powder while one or more printer access doors were open. As a result, there was potential for exposure to metal powder throughout this vacuuming task. Additionally, depending on the geometry and size of the printed part and where it was positioned on a build plate, the employee might need to place their head and/or torso inside the printer build chamber to vacuum the excess powder. This scenario can potentially yield a high concentration of airborne particles within the build chamber. Given the highly variable nature of this task, some differences in particle concentration are expected each time this task is performed by an operator and between operators.





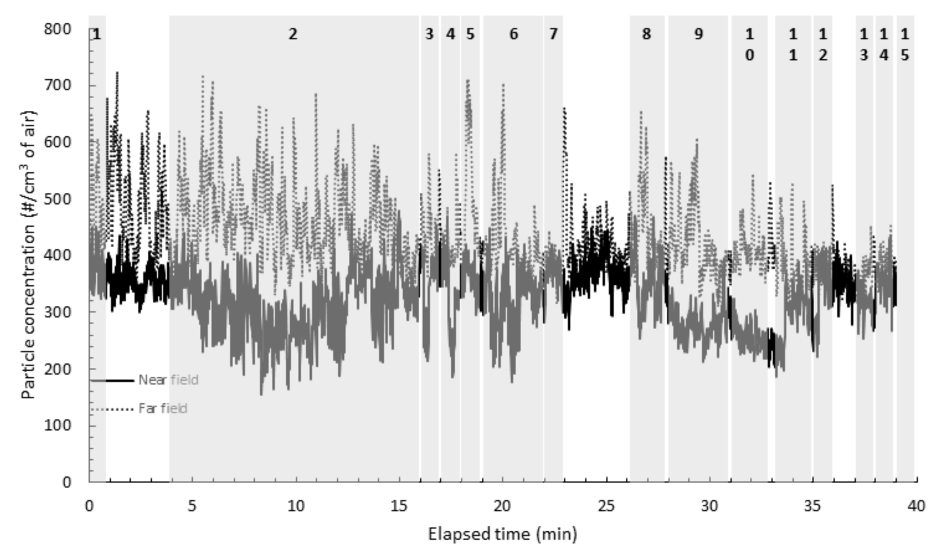


Figure B28. Plots of particle concentrations during vacuuming of excess Inconel 718 powder from the M26 PBF printer on 17 May 2023 (morning): SMPS data (top panel), P-TRAK data (middle panel), OPS data (bottom panel).

Time	Event	Description
0	1	Attached vacuum cyclone to waste powder bin
4	2	Began vacuuming inside build chamber
16	3	NF instruments moved closer to vacuum
17	4	Resumed vacuuming in build chamber
18	5	NF instruments moved closer to vacuum
19	6	Vacuuming inside build chamber and part on cart in room
22	7	Vacuum off/moved part to depowdering station
26	8	Vacuum on
28	9	Operator torso inside build volume while vacuuming at access door
31	10	Vacuuming at glove door
33	11	Vacuuming without attachment nozzle
35	12	Vacuum off
37	13	Loosening screws on vacuum cyclone attached to waste powder bin
38	14	Removed vacuum cyclone from waste powder storage bin
39	15	End task

Figure B28 (continued). Plots of particle concentrations during vacuuming of excess Inconel 718 powder from the M26 PBF printer on 17 May 2023 (morning): SMPS data (top panel), P-TRAK data (middle panel), OPS data (bottom panel). SMPS and P-TRAK data showed increases in particle concentration when turning on the vacuum (event 2) and when loosening screws that attach the vacuum to a cyclone (event 13). OPS data showed many short peaks during vacuuming (events 2, 6, 8, and 8). P-TRAK concentrations were higher in the near field compared with the far field, whereas for the OPS instrument, concentrations were slightly higher or mostly similar between these sampling locations.

In summary, dry vacuuming at version 1 printers increased particle concentrations in the PBF room, though it was unclear what proportion of particles might be from the vacuum and what proportion was feedstock powder. This task was highly manual so there was much variability in the concentration data, and there was no clear consistent difference in levels between the NF and FF sampling locations.

Depowdering station de-inerting (task 6), Opening depowder station door (task 13), and Depowdering process (task 20)

After vacuuming powder from a part built on a version 1 or version 2 printer, the part (still attached to its build plate) was moved by cart to the depowdering station. This station was a square glove box with a door that opened vertically and built-in glove ports on one side wall. There was a polymer seal around the perimeter of the door. The build plate was slid off a cart onto the platform in the depowder station and secured in place. After closing the depowdering station door, the chamber volume was made inert with argon gas. Next, an employee used a pressurized argon gas gun to dislodge powder from crevices, small openings, and other fine features in the part as well as holes and channels in the build plate. During this process, an opaque dust cloud formed inside the chamber. Periodically, the operator paused to allow the dust to settle and scrape dust off the chamber walls using a plastic scraper (stored inside the chamber). The dust fell to the bottom of the chamber which had angled walls to funnel the powder into a collection container. Once depowdering was complete, the chamber was de-inerted by replacing argon with air, opened, and the part slid back onto a cart before moving out of the room.

Depowdering activities were monitored on five occasions, twice for parts made of Inconel 718 feedstock powder and three times for parts made from Ti64 feedstock powder. Figure B29 showed the locations of the NF and FF monitors during depowdering. The NF monitors were held by a NIOSH staff person who periodically traced the perimeter of the door seal, and the glove port seals during work. The FF basket was approximately 4 meters behind the depowdering station.

Figure B29. Sampler placement for the depowdering task: (a) near field monitors were held by a NIOSH staff person, (b) location of far field basket. Photos by NOISH.

Figures B30 and B31 show plots of particle concentration measurements during the two depowdering runs with parts made of Inconel 718 feedstock powder. For both runs, particle concentration measurements using a P-TRAK and OPS increased at the start of depowdering. When the chamber was de-inerted, for run 1 an increase in OPS but not P-TRAK levels was observed, whereas for run 2, a pronounced spike in concentration was observed with the P-TRAK but only a small increase was observed for the OPS. When opening the chamber door, the OPS instruments showed increases for both runs, but the P-TRAK only showed an increase for run 1. For both runs, increases in particle concentrations with both the P-TRAK and OPS were observed whenever surveying the seal along the door which indicated the seal was not fully intact. Particle concentration measurements with the P-TRAK were higher in the NF compared with the FF for both runs, but for the OPS, it was similar during run 1 and higher during run 2.

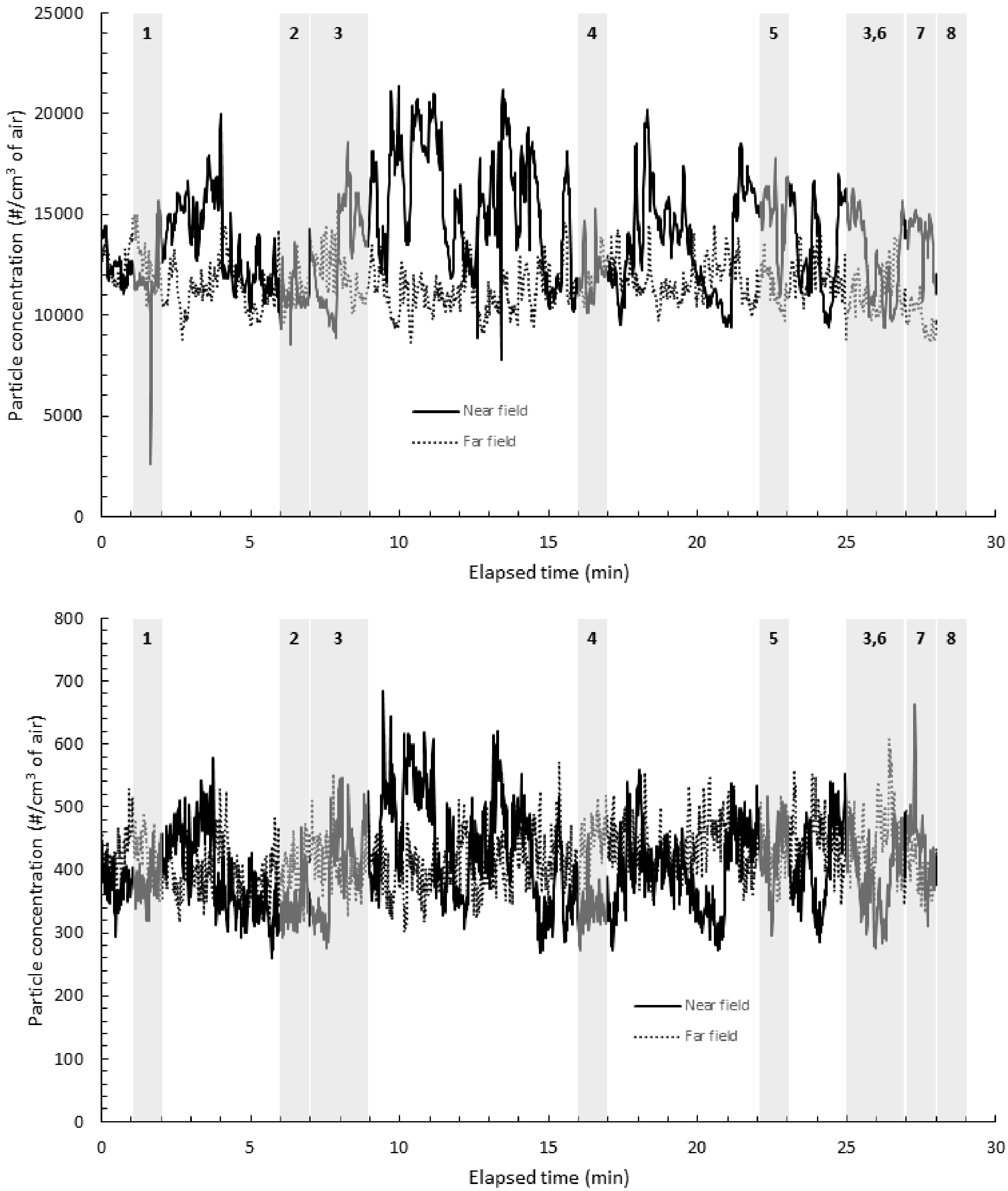
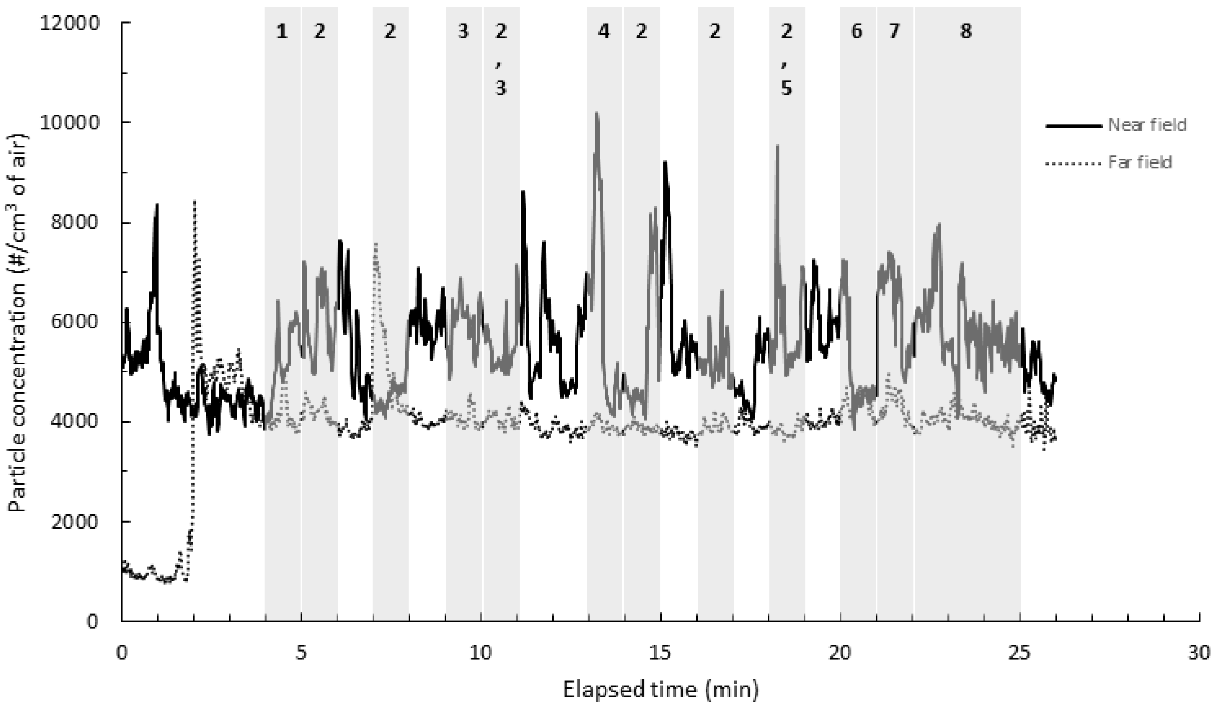


Figure B30. Plots of particle concentrations during depowdering of a part made from Inconel 718 feedstock powder on 15 May 2023 (mid-day). P-TRAK data (top panel), OPS data (bottom panel).

Time	Event	
1	1	NF instruments moved around glove ports while inerting
6	2	Began depowdering (NF instruments at glove ports)
7	3	NF instruments moved around chamber door seals
16	4	Scraping down inside walls of depowdering station
23	5	NF instruments moved around glove ports
25	3	NF instruments moved around chamber door seals
25	6	Task finished/de-inerting chamber
27	7	Opened depowder station/part moved onto cart
28	8	Depowder station door closed

Figure B30 (continued). Plots of particle concentrations during depowdering of a part made from Inconel 718 feedstock powder on 15 May 2023 (mid-day). P-TRAK data (top panel), OPS data (bottom panel). Particle concentrations measurements for the P-TRAK and OPS increased at the start of depowdering (event 2). Particle levels were observed to rise during de-inerting on the OPS instrument only (event 6). Both P-TRAK and OPS levels rose when opening the depowdering station door (event 7). Increases in particle levels also occurred when moving the P-TRAK and OPS instruments along the door seal, indicating it was compromised at certain points. P-TRAK concentrations were higher in the near field compared with the far field, whereas for the OPS instrument, concentrations were similar between these sampling locations.



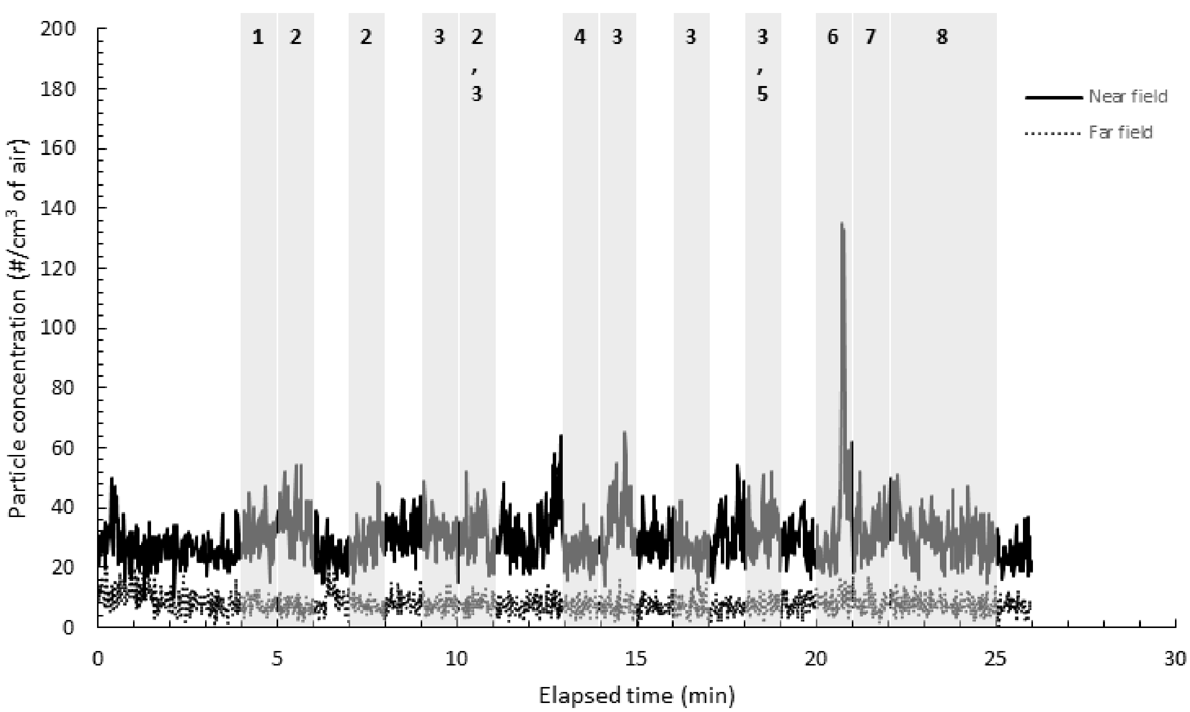
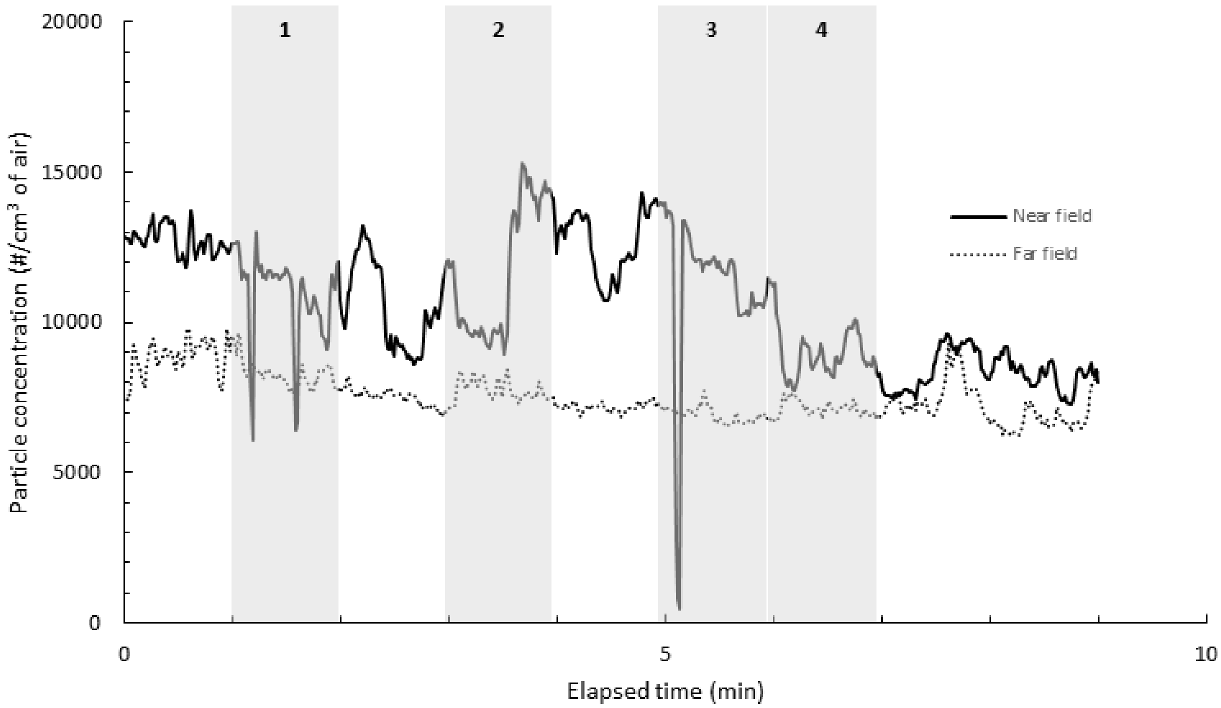


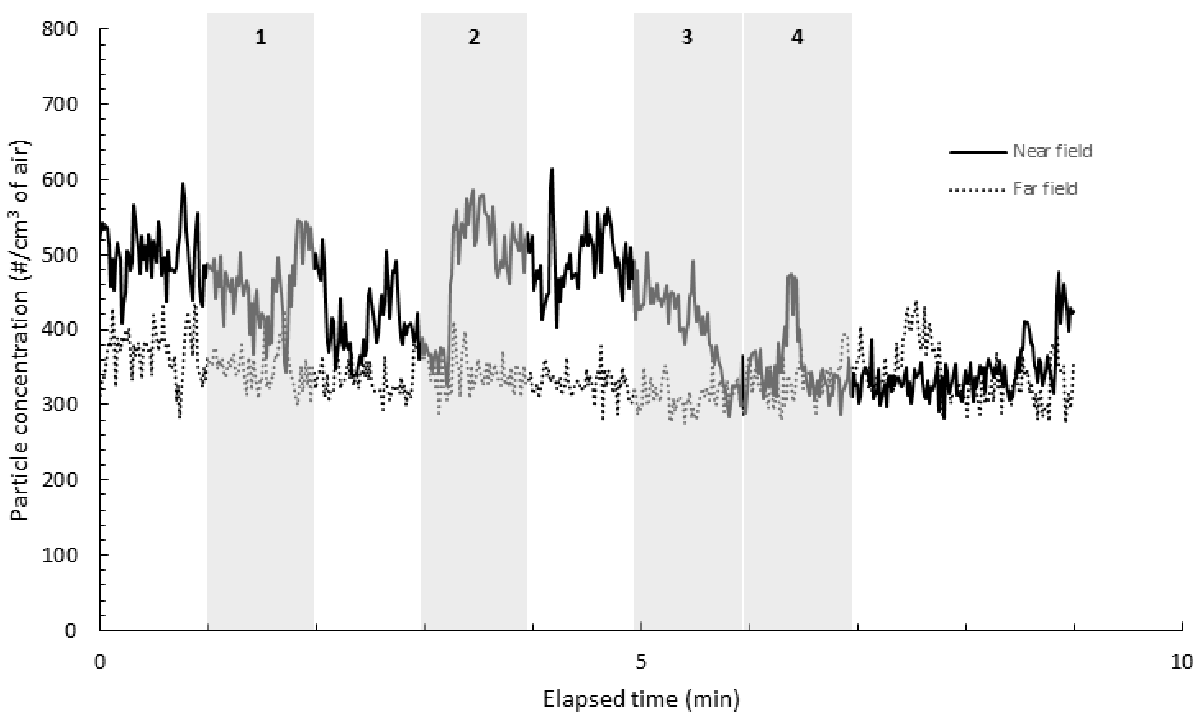
Figure B31. Particle concentrations during depowdering a part made from Inconel 718 powder on 17 May 2023 (morning): P-TRAK data (top panel), OPS data (bottom panel).

Time	Event	Description
4	1	Began depowdering
5	2	NF instruments moved around chamber door seals
7	2	NF instruments moved around chamber door seals
9	3	Scraping down inside walls of depowdering station
10	2,3	NF instruments moved around door seals/scraping down inside walls
13	4	NF instruments moved around glove ports
14	2	NF instruments moved around chamber door seals
16	2	NF instruments moved around chamber door seals
18	2	NF instruments moved around chamber door seals
18	5	Task finished/de-inerting
20	6	Opened depowder station
21	7	Part moved onto cart/closed door
22-25	8	Handled build plate to wet wipe

Figure B31 (continued). Particle concentrations during depowdering a part made from Inconel 718 powder on 17 May 2023 (morning): P-TRAK data (top panel), OPS data (bottom panel). Particle concentration measurements for both instruments increased at the start of depowdering (event 1). Particle levels were seen to spike on the P-TRAK during de-inerting but only a small rise was observed on the OPS instrument (event 5). Particle levels spiked on the OPS when opening the chamber door but remained steady for the P-TRAK instrument (event 6). Increases in particle levels also occurred when moving the P-TRAK and OPS instruments along the door seal, indicating it was compromised at certain points (events 2 and 4).

Figures B32 to B34 show plots of particle concentrations for three runs of depowdering parts made from Ti64 powder. When depowdering began, particle concentrations (P-TRAK and OPS instruments) remained stable during run 1 (Figure B32) but increased during run 2 (Figure B33) and run 3 (Figure B34). De-inerting was only captured during run 2 (transient increase) and run 3 (no change). For all runs, particle concentrations increased during door opening as seen for the P-TRAK and OPS measurement results. Both the P-TRAK and OPS data showed an increase in particle levels when the operator scraped excess powder off the chamber. We observed a decrease in particle concentration when surveying the glove port seals (Figure B32). For all replicate runs, particle concentrations in the NF were higher or similar compared with the FF sampling location.





Time	Event	Description
1	1	Began depowdering
3	2	Scraping down inside walls of depowdering station
5	3	NF instruments moved around glove ports
6	4	Opened depowder station/part moved onto cart/closed door

Figure B32. Particle concentrations during depowdering of a part made from Ti64 powder on 15 May 2023 (afternoon): P-TRAK data (top panel), OPS data (bottom panel). Particle concentration measurements for both instruments showed little change in levels at the start of depowdering (event 1) but increased when opening the chamber door (event 4). Increases in particle levels also occurred when scraping powder off the chamber walls (event 2). When moving the P-TRAK and OPS instruments along the glove port seals, there was a decrease in concentration, indicating an intact seal (event 3). Particle concentrations for both instruments were higher in the near field location compared with the far field sampling location.

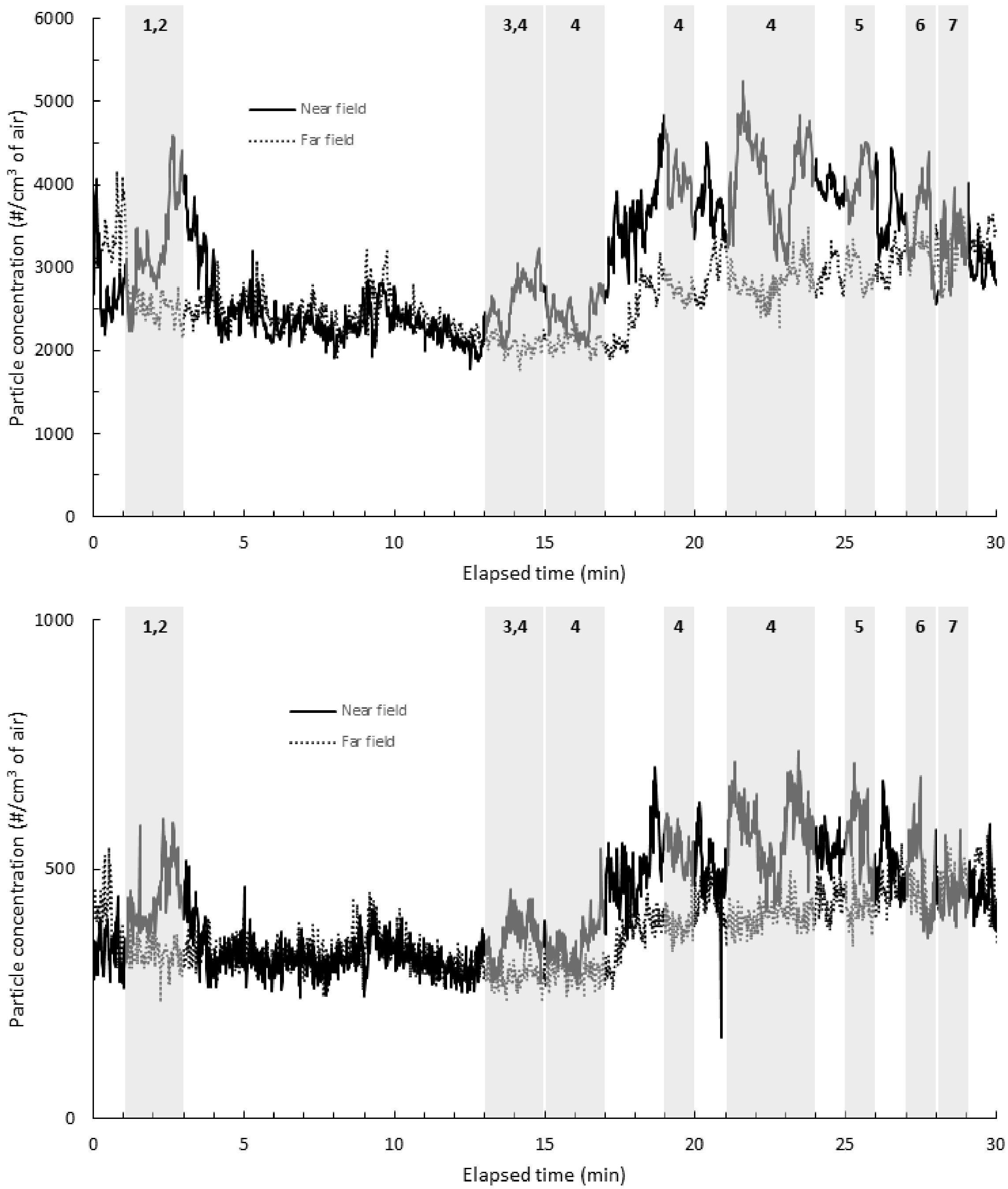


Figure B33. Particle concentrations during depowdering of a part made from Ti64 powder on 16 May 2023 (morning): P-TRAK data (top panel), OPS data (bottom panel).

Time	Event	Description
1-3	1	Began inerting depowdering station
1-3	2	NF instruments moved around chamber door seals
13-15	3	Began depowdering
15-17	4	NF instruments moved around glove ports and chamber door seals
19-20	4	NF instruments moved around glove ports and chamber door seals
21-24	4	NF instruments moved around glove ports and chamber door seals
25	5	Scraping down inside walls of depowdering station
27	6	Task finished/de-inerting
28	7	Opened depowder station door/part moved onto cart

Figure B33 (continued). Particle concentrations during depowdering of a part made from Ti64 powder on 16 May 2023 (morning): P-TRAK data (top panel), OPS data (bottom panel). Particle concentration measurements for both instruments show transient increases at the start of depowdering (event 3), during de-inerting (event 6), and when opening the chamber door (event 7) Increases in particle levels also occur when moving the P-TRAK and OPS instruments along the door seal (event 4) and when scaping excess powder off chamber walls (event 5). For both instruments, particle concentrations are similar and higher in the near field compared with the far field sampling location.

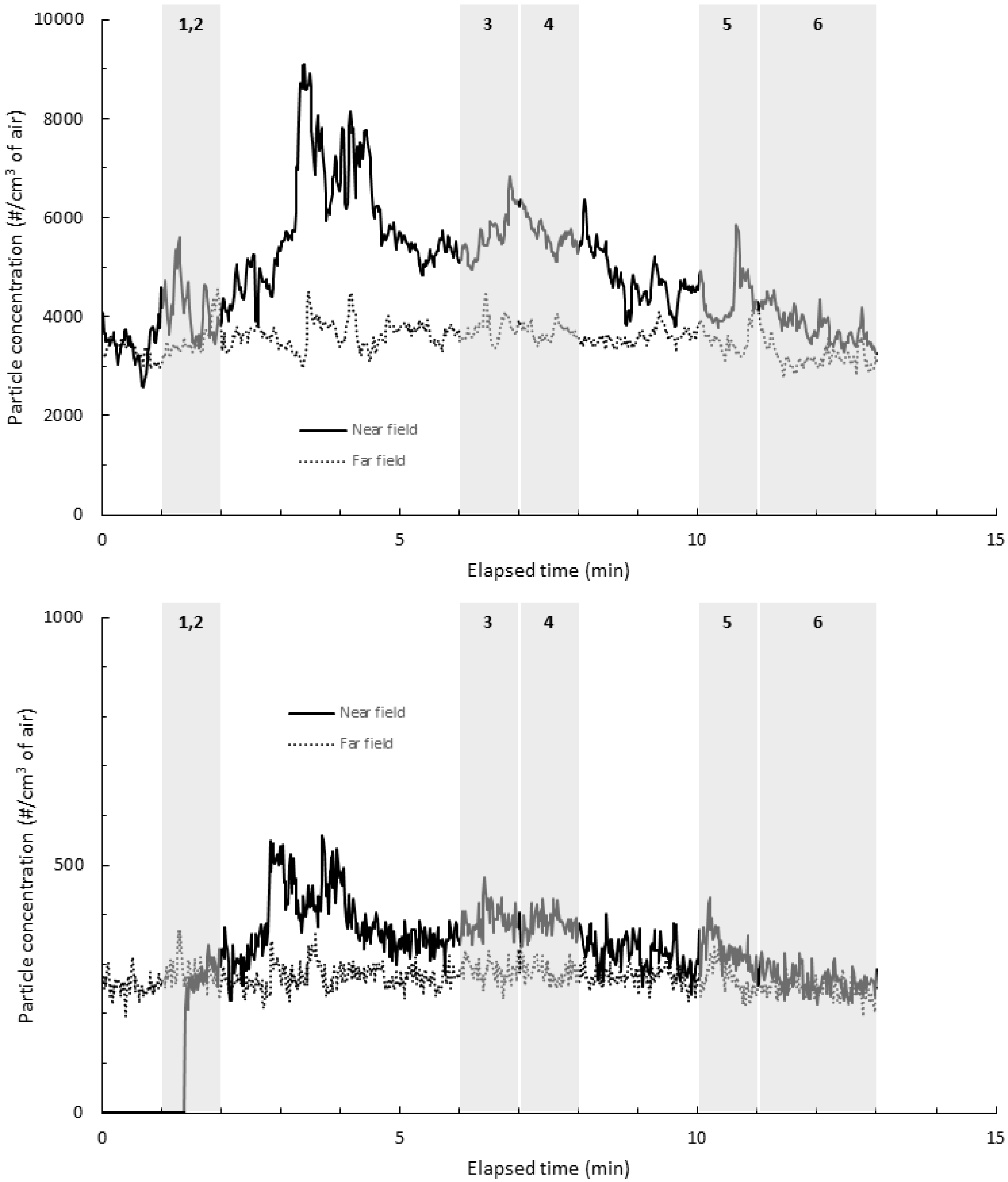


Figure B34. Particle concentrations during depowdering of a part made from Ti64 powder on 17 May 2023 (morning): P-TRAK data (top panel), OPS data (bottom panel).

Time	Event	Description
1	1	Began depowdering
1	2	NF instruments moved around chamber door seals
6	3	Scraping down inside walls of depowdering station
7	4	Task finished/de-inerting
10	5	Opened depowder station door/part moved onto cart
11-13	6	Handled build plate to wet wipe

Figure B34 (continued). Particle concentrations during depowdering of a part made from Ti64 powder on 17 May 2023 (morning): P-TRAK data (top panel), OPS data (bottom panel). Particle concentration measurements showed a transient increase for the P-TRAK but not the OPS instrument at the start of depowdering (event 1). There was no noticeable change in levels for either instrument during de-inerting (event 4) though increased slightly when opening the chamber door (event 5). A slight increase in concentration also occurred when scaping excess powder off chamber walls (event 3). For both instruments, particle concentrations were higher in the near field compared with the far field sampling location.

In summary, depowdering was a highly dusty task. Though a large amount of powder was removed by vacuuming to recover a part inside a printer build chamber, much powder remained as evidenced by the opaque dust cloud that formed inside the depowdering chamber. The particle concentration measurement data indicated that the glove box seal was not fully intact and outward leakage occurred when starting depowdering, scraping chamber walls, de-inerting, and opening the chamber door. Dust settled onto a part and its build plate while the chamber was de-inerting which presents an opportunity for migration out of the PBF room. As noted previously in Table C3, a wipe sample of a build plate for a part made with Inconel 718 that had come directly from the PBF room and was placed on the shelf outside the quality control laboratory had the highest levels of Cr, Fe, and Ni among all wipe samples collected in the post-processing room.

Version 2 wet vacuum cleaning (task 7), cleaning of residual powder within build chamber (task 11), Opening v2 access doors (task 15), and V2 powder cleaning (task 17)

The (newer design) version 2 printers had a built-in dry vacuum that the operator used to remove most powder from around a printed part without unsealing the machine. On the broad size of the printer was a door with glove ports (glove door) and on the narrow side was a door where the build plate was loaded into/removed from the printer (front door). After dry vacuuming, the chamber was de-inerted, the doors opened, and the part removed by sliding onto a cart. At this point, the operator switched to a wet vacuum to further remove powder from the part while on the cart and for final cleaning of the printer build chamber. Disposable cloths wetted with isopropyl alcohol were used to remove residual powder from the surfaces of the printed part and build chamber. This task was monitored on three occasions for the M306 printer (Ti64). As shown in Figure B35, the NF monitors were held at the face of the access doors, and the FF basket was placed on a nearby flammables storage cabinet.

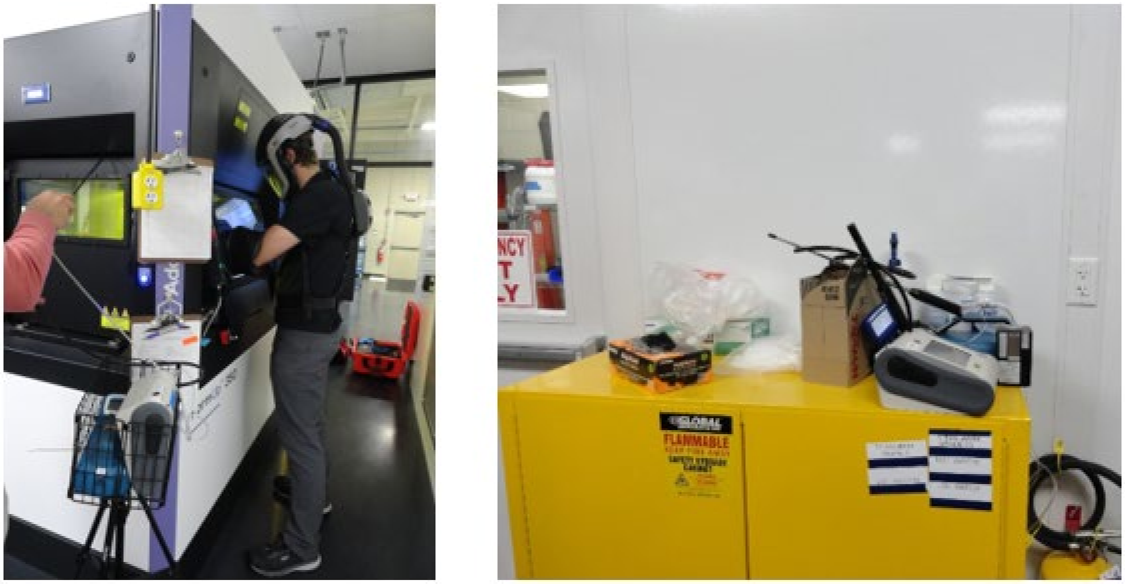


Figure B35. Sampler placement for version 2 printer powder vacuuming and access door opening tasks: (a) near field monitors were held by a NIOSH staff person, (b) location of far field basket.

Figures B36 to B38 show the particle concentration values in the NF and FF for each repeated measure of the version 2 machine vacuuming and cleaning tasks. The duration of each task varied, but all showed the same pattern: stable particle concentrations outside the build chamber while it was enclosed and sealed during dry vacuuming, a rapid spike in particle concentration when opening machine access doors, and generally stable levels thereafter (similar to before opening the doors) during wet vacuuming and cleaning tasks. During the first run (Figure B36), the P-TRAK measurements showed increases when the part was moved from the build chamber to a cart (event 9) and when the cart was moved to the depowdering station (event 12). These increases were likely resuspension of dust from movement onto the cart and vibration as the cart crossed the room.

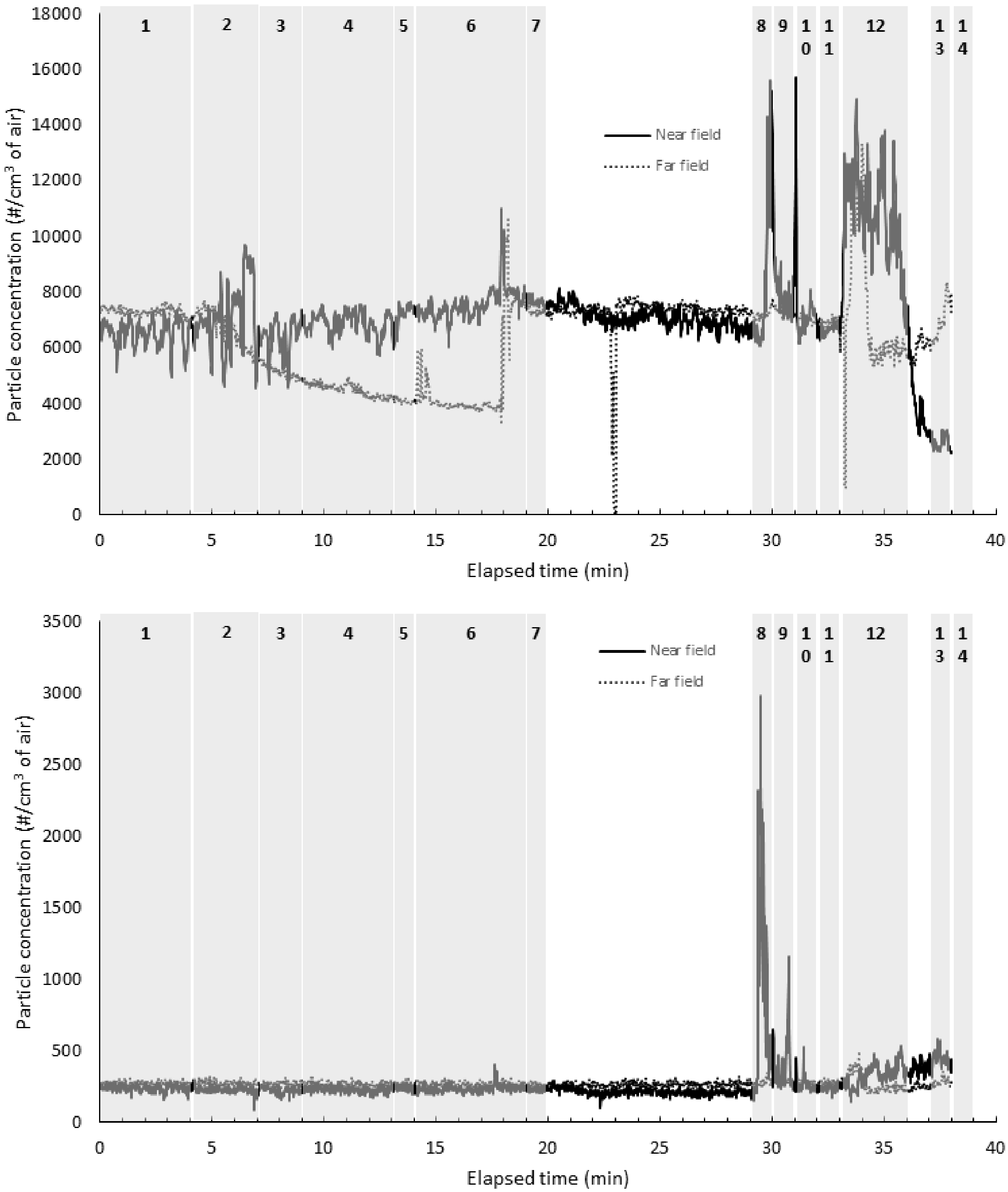
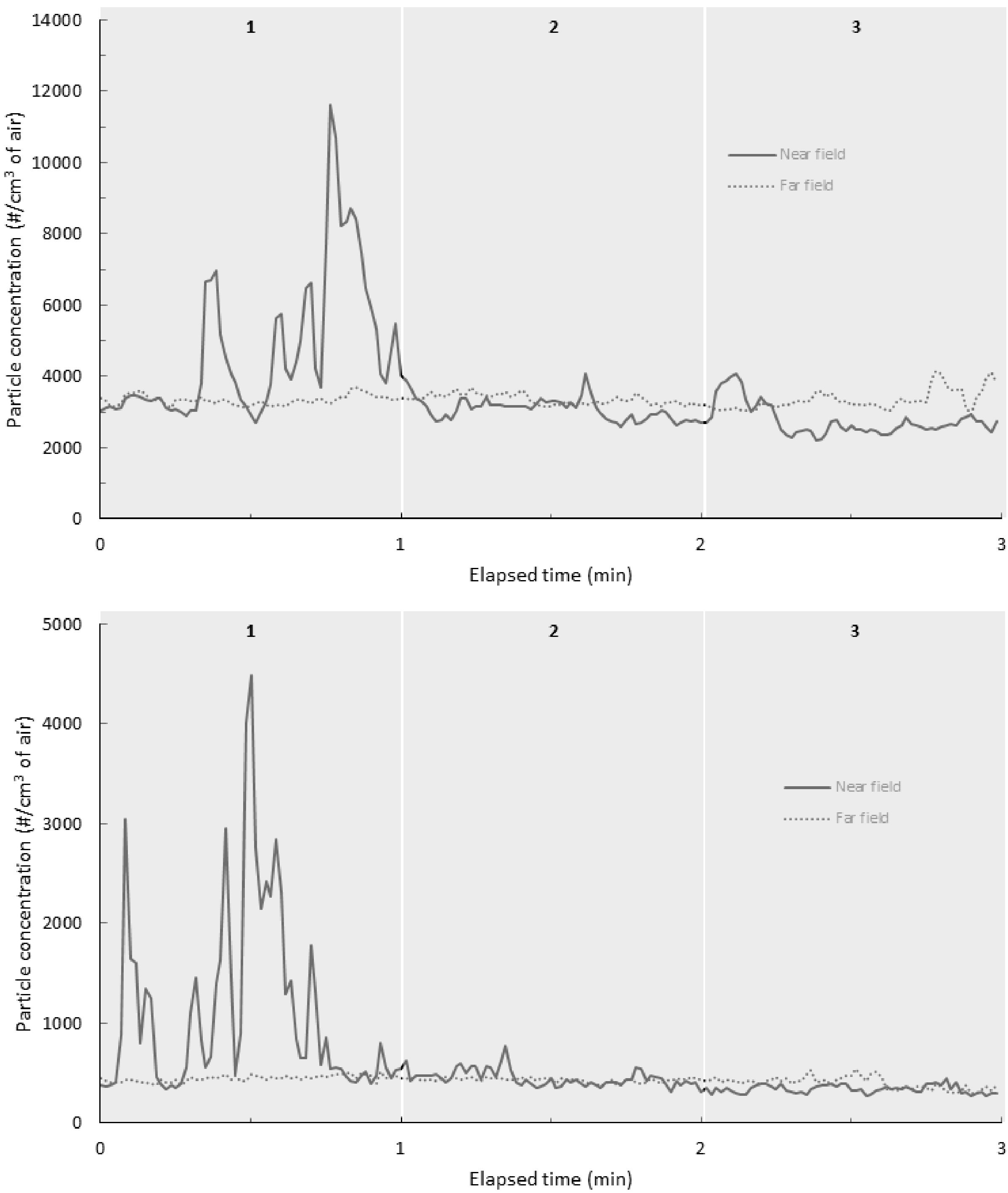


Figure B36. Particle concentrations during vacuuming of excess Ti64 powder in a version 2 printer on 15 May 2023 (morning): P-TRAK data (top panel), OPS data (bottom panel).

Time	Event	Description
0	1	Began dry vacuuming inside enclosed build chamber (NF basket at glove door)
4	2	Moved NF instruments to front door
7	3	Moved roller arm/dry vacuuming inside build chamber
9	4	Raised build platform/dry vacuuming inside build chamber
13	5	Moved NF instruments to front door
14	6	Dry vacuuming inside build chamber
19	7	Stopped dry vacuuming
29	8	Opened M306 front door/began wet vacuuming
30	9	Moved part from build chamber onto cart
31	10	Wet vacuuming part on cart outside machine/vacuuming inside build chamber
32	11	Stopped wet vacuuming
33	12	Moved part to depowdering station
37	13	Cleaning M306 build chamber with wetted wipes
38	14	End task

Figure B36 (continued). Particle concentrations during vacuuming of excess Ti64 powder in a version 2 printer on 15 May 2023 (morning): P-TRAK data (top panel), OPS data (bottom panel). Particle concentration measurements were stable while dry vacuuming in a sealed printer, rapidly increased when the printer door was opened (event 8) and returned to baseline during wet vacuuming and cleaning. Spikes were also seen when moving the part from the printer onto a cart (event 9) and moving the cart to the depowdering station (event 12). For both instruments, particle concentrations were generally similar in the near and far field sampling locations.



Time	Event	Description
0	1	Began wet vacuuming build chamber at glove side with front door open
1	2	Moved part from build chamber onto cart/continued wet vacuuming at glove side
2	3	Wet vacuum off/moved part to depowdering station

Figure B37. Particle concentrations during vacuuming of excess Ti64 powder in a version 2 printer on 16 May 2023 (morning): P-TRAK data (top panel), OPS data (bottom panel). Particle concentrations levels rapidly increased when the printer door was opened (event 1) and returned to baseline during wet vacuuming and cleaning. For both instruments, particle concentrations were generally similar and higher in the near field compared with the far field sampling location.

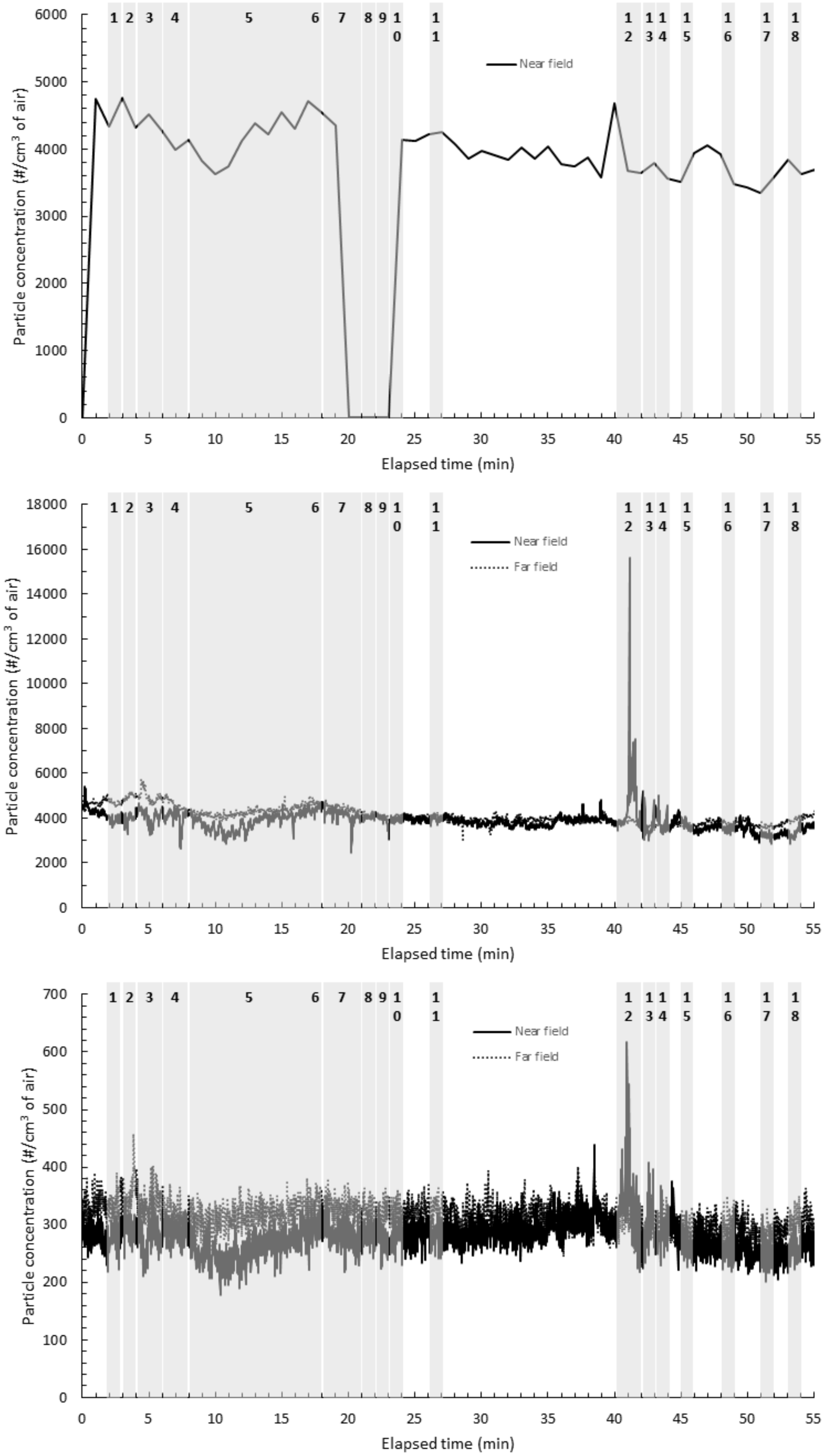


Figure B38. Particle concentrations during vacuuming of excess Ti64 powder in a version 2 printer on 17 May 2023 (morning): SMPS data (top panel – no data, minutes 21 - 23), P-TRAK data (middle panel), OPS data (bottom panel).

Time	Event	Description
2	1	Began dry vacuuming inside sealed build chamber
3	2	Moved SMPS to front door
4	3	Moved SMPS to glove door
6	4	Moved SMPS to front door
8	5	Moved SMPS to glove door
17	6	Moved SMPS to front door
18	7	Moved SMPS to glove door
21	8	Stopped dry vacuuming inside sealed build chamber
22	9	Started dry vacuuming inside sealed build chamber
23	10	Stopped dry vacuuming inside sealed build chamber
26	11	Began de-inerting build chamber
40	12	Opened front door/began wet vacuuming build chamber
42	13	Moved part onto cart/wet vacuuming inside chamber and part on cart
43	14	Stopped wet vacuuming/began wiping part with alcohol
45	15	Closed front door
48	16	Opened front and glove doors
51	17	Began wet vacuuming build chamber
53	18	Closed front and glove doors/end task

Figure B38 (continued). Particle concentrations during vacuuming of excess Ti64 powder in a version 2 printer on 17 May 2023 (morning): SMPS data (top panel – no data, minutes 21 - 23), P-TRAK data (middle panel), OPS data (bottom panel). Particle concentration was level but rapidly increased when the printer door was opened (event 12) and returned to baseline during wet vacuuming and cleaning (events 13, 14, and 17). For both instruments, particle concentrations were similar in the near field and far field sampling locations.

In summary, door seals on the version 2 printers were highly effective in preventing fugitive emissions from escaping the build chamber while dry vacuuming; however, once the printer doors were opened, there was rapid burst of particle released into the PBF room. For two of the three runs, particle concentrations in the NF and FF sampling locations were similar for the P-TRAK and OPS instruments. For one run, NF levels tended to be higher than FF levels for both instruments. Consideration could be given to mitigating this burst through a change in printer design, such as maintaining local exhaust ventilation in the build chamber during door opening.

Manual powder scooping

In addition to the 20 tasks identified by management and employees, we also monitored airborne particle levels during manual powder scooping. For this task, an operator brought a cart into the PBF room with a large container of 316L stainless steel powder. The operator manually scooped the powder from this container into a smaller container. The NF basket instruments were positioned a few inches from the larger powder container during this task. The FF basket was located approximately 1.5 meters away (on the pneumatic cart near the PPE change out room). P-TRAK readings remained stable at approximately 9,000 particles/cm^3 of air during scooping with minor fluctuations. The OPS measurements were also stable with a few minor fluctuations during this task. The FF values were higher than the NF values.

PBF room air flow and particle concentrations

Throughout the course of air monitoring in the PBF room, it was observed that the real-time particle monitor readings often increased when the inter-lock door was opened. Explanations for this increase in PBF room particle concentration could include: 1) ceiling ventilation supply vents were bringing particle-laden air into the room; 2) there was an incursion of particle-laden air from the inter-lock room into the PBF room, or 3) there was adisturbance of dust in the PBF room by air currents created during door movement.

To investigate the first possibility, a P-TRAK was used to monitor the particle concentration in supply air from five different vents. Figure B39 shows the measurement results. The particle concentration at the ceiling supply vent closest to the inter-lock room was approximately 10,000 particles/cm^3 of air whereas for supply vents at other locations in the room, concentrations were approximately 4,000 to 7,000 particles/cm^3 of air.

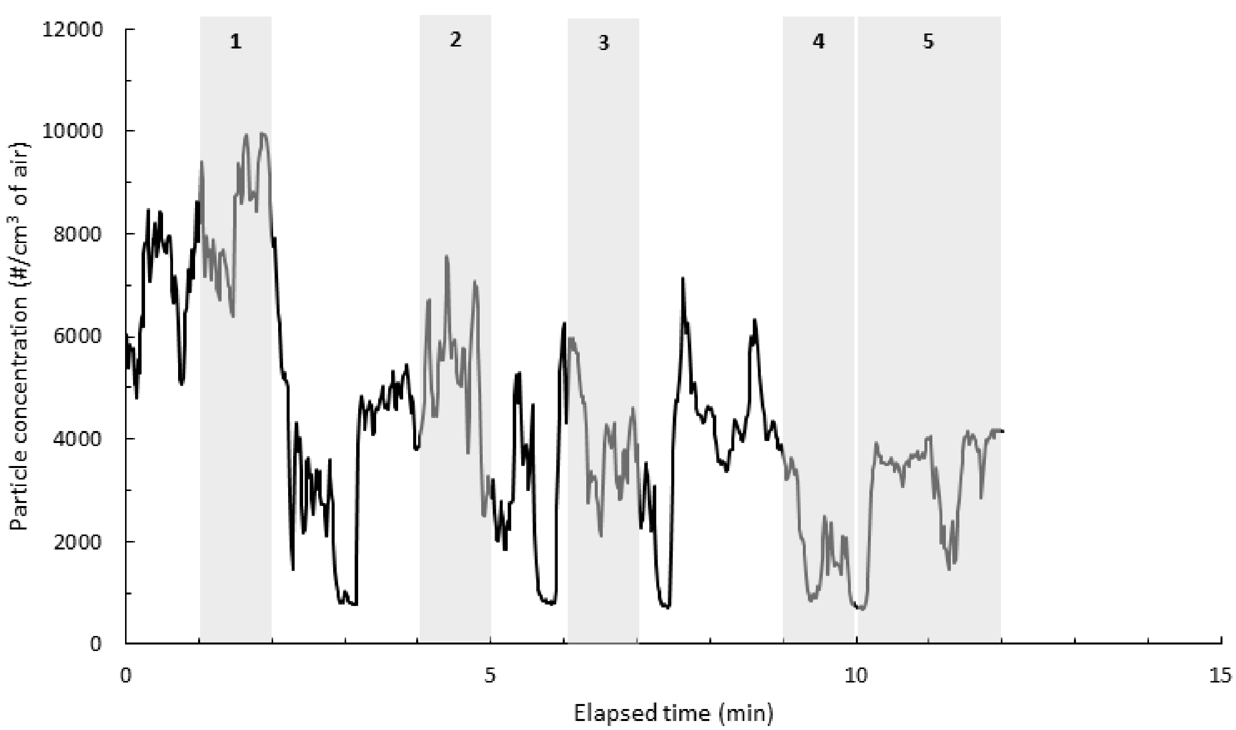
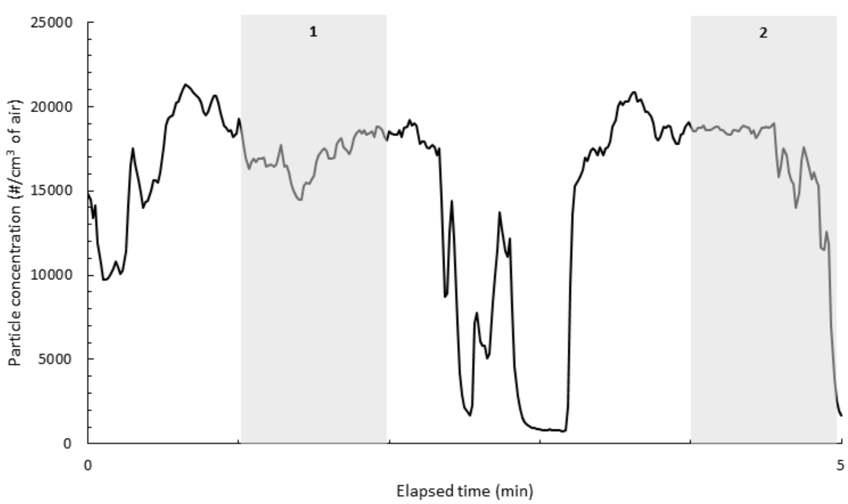


Figure B39. Particle concentration (P-TRAK data) in PBF room supply air at five different vents.

Time	Event	Description
1	1	Ceiling supply in PBF room near inter-lock door
4	2	Ceiling supply above depowdering station
6	3	Ceiling supply between the M27 and M316 printers
9	4	Ceiling supply above M316 printer
10	5	Ceiling supply between M306 and M319 printers

Figure B39 (continued). Particle concentration (P-TRAK data) in PBF room supply air at five different vents. Particle concentration was highest at the ceiling supply vent closest to the inter-lock room compared with other locations in the room.

Based on the observation that particle concentration was highest at the ceiling supply vent nearest to the inter-lock room, we used the P-TRAK to monitor particle concentration in the supply air from the only vent in the inter-lock room. Figure B40 gives the results of repeat measurements of the same vent in the inter-lock room. Notably, the concentration exceeded 20,000 particles/cm^3 both prior to and during the supply vent monitoring period (compare to no more than approximately 10,000 particles/cm^3 of air in the PBF room). This observation suggested that particle concentration was elevated in the inter-lock room in general and not localized at the supply vents. Further inspection of the inter-lock room revealed that the door frame on the main hallway side was not sealed to the wall (see Figure B40).



Time	Event	Description
1	1	Inter-lock room supply
4	2	Inter-lock room supply (replicate)

Figure B40. Particle concentration (P-TRAK data) at the inter-lock room supply vent. Photo illustrating cracks between the inter-lock door and the door frame on the main hallway side of the room.

Based on the observations in the inter-lock room, a series of P-TRAK and OPS measurements were made simultaneously in the inter-lock room and the PBF room and main hallway at different times throughout the day. Figures B41 illustrates that each time the inter-lock door to the PBF room was opened (main hallway inter-lock door remained closed during all measurements), there was a decrease in particle concentration in the inter-lock room and a corresponding increase in particle concentration in the PBF room. The same pattern was seen when the test was repeated the same day in the afternoon (plots not shown).

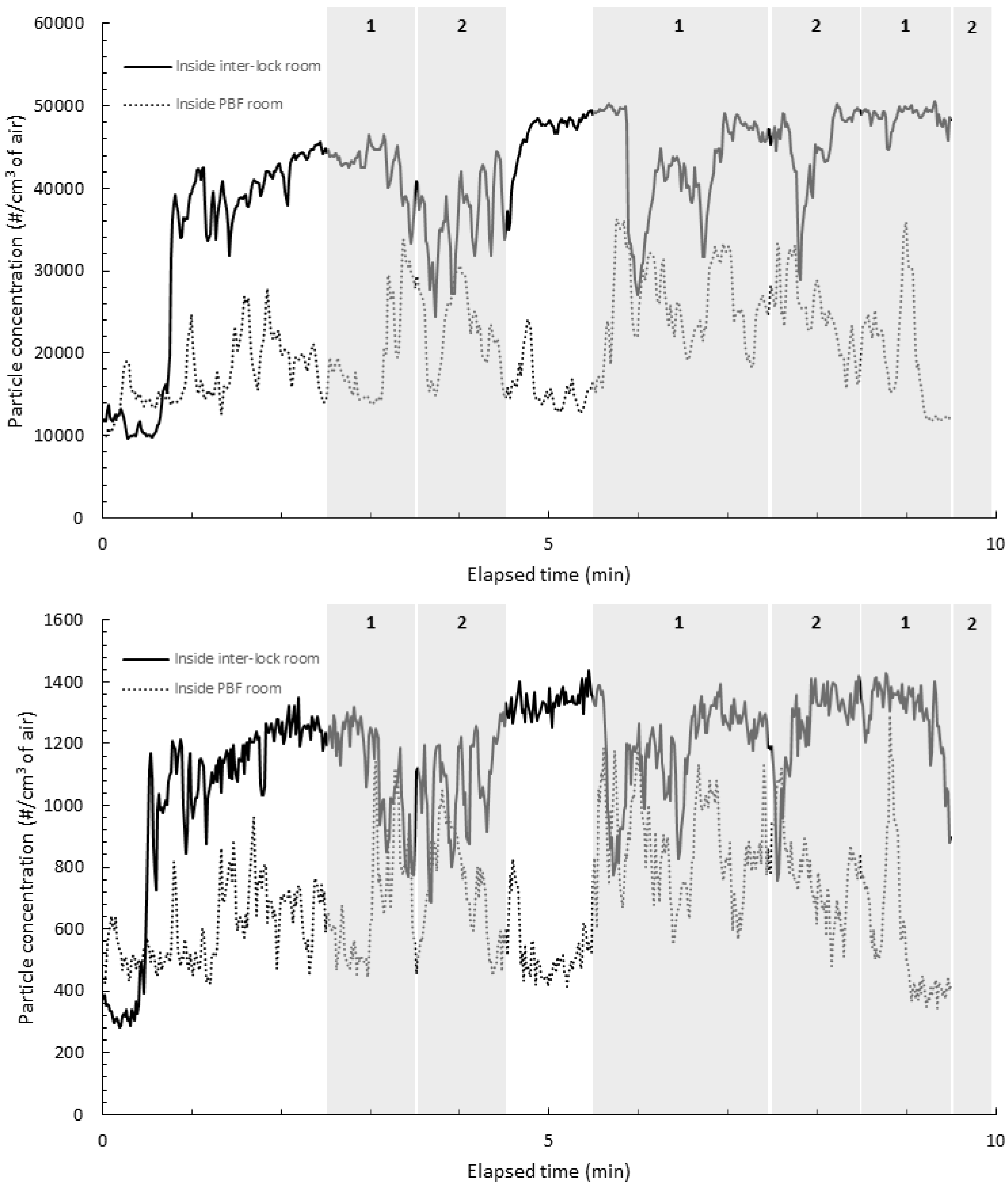


Figure B41. Particle concentrations measured simultaneously inside the PBF room and inside the inter-lock room.

Time	Event	Description
2.5	1	Opened PBF-side inter-lock door
3.5	2	Closed PBF-side inter-lock door
5.5	1	Opened PBF-side inter-lock door
7.5	2	Closed PBF-side inter-lock door
8.5	1	Opened PBF-side inter-lock door
9.5	2	Closed PBF-side inter-lock door

Figure B41 (continued). Particle concentrations measured simultaneously inside the PBF room and inside the inter-lock room. The PBF-side inter-lock door was opened and closed three times on 15 May 2023 (morning): P-TRAK data(top panel), OPS data(bottom panel). Data show an incursion of particles from the inter-lock room into the PBF room each time the door was opened.

As shown in Figure B42, each time the inter-lock door to the main hallway was opened (PBF-side inter-lock door remained closed during all measurements), the particle concentration was the same in the inter-lock room and main hallway. Subsequent air monitoring revealed that particle concentrations ranged from 50,000 to 150,000 particles/cm^3 in the post-processing room (see discussion below). Hence, rather than particles in ceiling supply air or a disturbance of dust in the PBF room by air currents created during door movement, it is believed that particles from the post-processing room entered the main hallway air by open doors and infiltrated into the inter-lock room air through cracks between the door frame and wall. Each time the inter-lock door was opened on the PBF-side, the negative pressure of the PBF room drew particle-laden air in, thereby increasing particle concentration in the room. These particles were subsequently filtered out by the PBF room ventilation system.

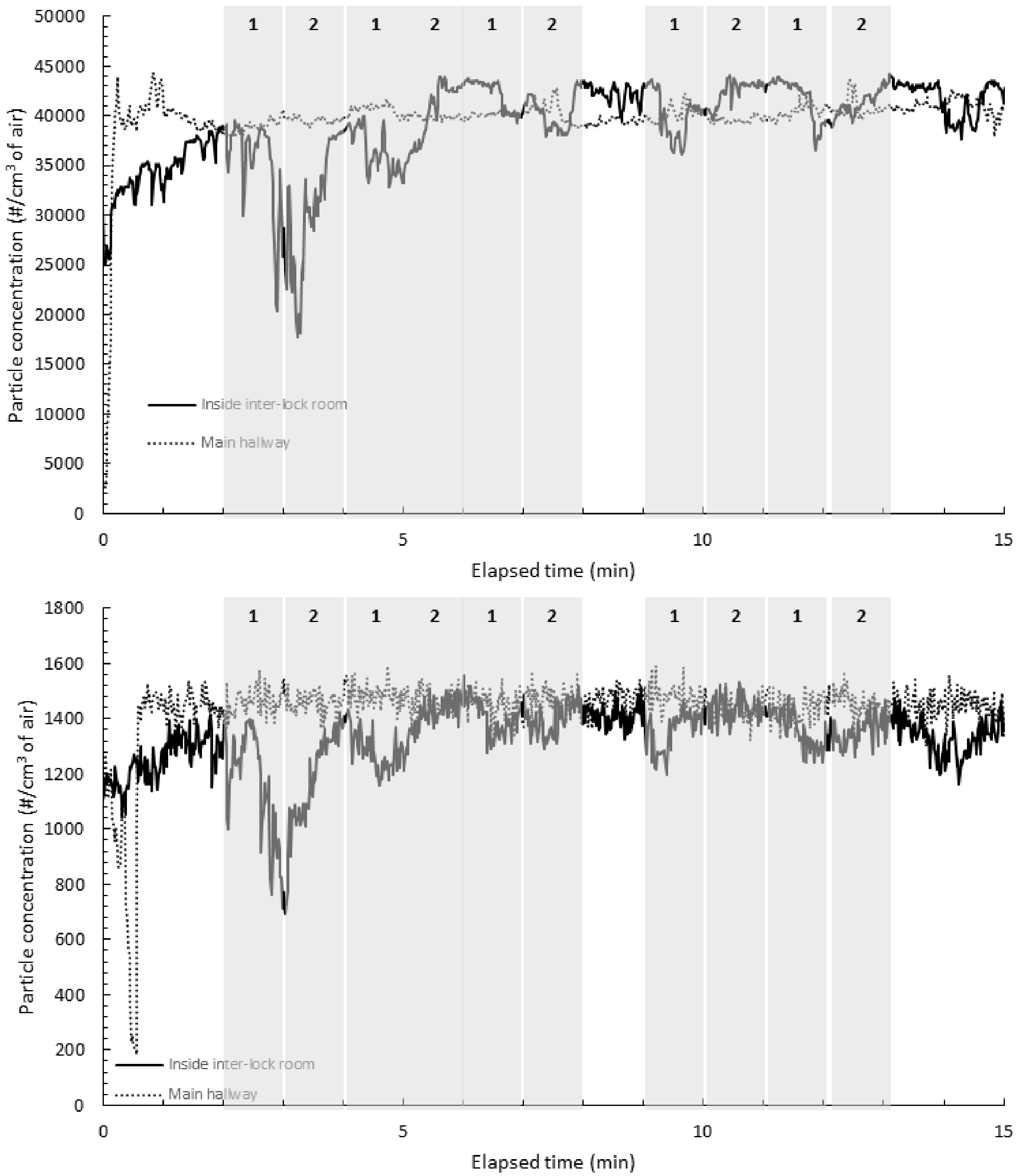


Figure B42. Particle concentrations measured simultaneously in the main hallway and inside the inter-lock room.

Time	Event	Description
2	1	Opened main hallway-side inter-lock door
3	2	Closed main hallway-side inter-lock door
4	1	Opened main hallway-side inter-lock door
5	2	Closed main hallway-side inter-lock door
6	1	Opened main hallway-side inter-lock door
7	2	Closed main hallway-side inter-lock door
9	1	Opened main hallway-side inter-lock door
10	2	Closed main hallway-side inter-lock door
11	1	Opened main hallway-side inter-lock door
12	2	Closed main hallway-side inter-lock door

Figure B42 (continued). Particle concentrations measured simultaneously in the main hallway and inside the inter-lock room. The main hallway-side inter-lock door was opened and closed five times on 15 May 2023 (afternoon): P-TRAK data (top panel), OPS data (bottom panel). Each time the inter-lock door to the main hallway was opened, the particle concentration was the same in the inter-lock room and main hallway.

Based upon the results of the real-time instrument monitoring we recommend the following:

- For version 1 machine sieving (task 2), increase staff awareness that if an error message is displayed on a sieve station or if two or more stations are operating simultaneously, those performing these tasks should, as per existing company policy, wear PAPRs to minimize opportunity for inhalation exposure.
- For version 1 sieve uncoupling flow bins (task 8), increase staff awareness that bin uncoupling can impact room particle concentrations so those performing these tasks should wear PAPRs to minimize opportunity for inhalation exposure.
- For version 1 powder vacuuming (task 5) and opening v1 access doors (task 15), increase staff awareness that use of an external dry vacuum can impact room particle concentrations so those performing these tasks should wear PAPRs to minimize opportunity for inhalation exposure.
- For the depowdering station de-inerting (task 6), opening depowder station door (task 13), and depowdering process (task 20), 1) replace the seal for the glove box in accordance with the manufacturers' specifications and visually inspecting it periodically for signs of ageing, cracking, crimping or other compromises that could affect integrity; 2) periodically monitor the seal around the glove ports to ensure its integrity remains intact; and 3) allow several chamber air exchanges to occur before opening the door to reduce the amount of dust released into the PBF room air (the best number of air exchanges could be determined by monitoring the particle concentration inside the chamber after depowering to calculate a decay rate using the approach by Bau et al. [2020]).
- Version 2 wet vacuum cleaning (task 7), cleaning of residual powder within build chamber (task 11), Opening v2 access doors (task 15), and version 2 powder cleaning (task 17), allow several

chamber air exchanges to occur before opening the door to reduce the amount of dust released into the PBF room (the best number of air exchanges could be determined by monitoring the particle concentration inside the chamber after dry vacuuming to calculate a decay rate using the approach described by Bau et al. [2020]).

- For manual powder scooping, the high density of stainless-steel powder might have contributed to the low observed particle counts during this task though the same outcome might not be true for lower density powders such as AlSi10Mg or Ti64 so this task should be performed in a ventilated hood or cabinet to minimize opportunity for inhalation exposure to metals.
- All tasks increased particle concentrations in the PBF room to some degree, as such all staff present in the room should wear a PAPR because the NF and FF measurements do not show clear consistent differences that unambiguously support a policy to not wear respiratory protection if not performing a task or directly handling powder.

Inhalation exposure

Two types of time-integrated samples were collected in the PBF room, MCE filters for nine elements and PVC filters for hexavalent chromium [Cr(VI)], a type of chromium. Tables C10 and C11 summarize these results for general area and employee personal breathing zone samples, respectively.

As shown in Table C10, one general area air sample was collected for Cr(VI), but it was below the analytical limit of detection (<0.002 $\mu g/m^3$ of air). Four general area MCE filter samples were collected; levels of Al, Co, and Mn were below their respective analytical limits of detection on all samples. Only total Cr was quantified on all samples (range: 0.43 to 2.06 $\mu g/m^3$ of air). Several metals were measurable on three of four MCE filter samples: Mo (range: 0.10 to 0.37 $\mu g/m^3$ of air), Ni (range: 0.54 to 4.87 $\mu g/m^3$ of air), and Ti (range: 0.03 to 0.71 $\mu g/m^3$ of air).

As shown in Table C11, a total of seven PBZ samples were collected from employees in the PBF room (6 MCE, 1 PVC). Potential adverse effects from breathing in these metals are:

- Aluminum metal dust – respiratory irritation [NIOSH 2019a].
- Chromium metal dust – lung fibrosis [NIOSH 2019b].
- Chromium (hexavalent) – nasal septum perforation, respiratory irritation, liver damage, kidney damage, leukopenia (reduced blood white blood cells), leukocytosis (increased white blood cells), and eosinophilia (increased eosinophils, a type of white blood cell) [NIOSH 2019h]. NIOSH considers all hexavalent chromium compounds to be potential occupational carcinogens [NIOSH 2018a].
- Cobalt metal dust – respiratory symptoms (cough, breathing difficulty, wheezing, decreased pulmonary function), asthma, respiratory hypersensitivity, pulmonary fibrosis, and weight loss [NIOSH 2019c]. Cobalt is also identified as probably carcinogenic to humans [IARC, 2023].
- Copper metal dust – nose, and throat (pharynx) irritation and nasal septum perforation and metallic taste [NIOSH 2019d].

- Manganese metal dust – manganism, a neurological condition which has symptoms like those of Parkinson's disease (such as trembling, stiffness, slow motor movement, potentially severe depression, anxiety, and hostility) [NIOSH 2019i]. Manganese can also cause insomnia, mental confusion, and metal fume fever (dry throat, cough, chest tightness, breathing difficulty, rales, and flu-like fever). Other effects include low-back pain, vomiting, malaise (vague feeling of discomfort), weakness/exhaustion, and kidney damage [NIOSH 2019j].
- Molybdenum metal dust – nose and throat irritation, anorexia, diarrhea, weight loss, and listlessness as well as liver and kidney damage in animals [NIOSH 2019k].
- Nickel metal dust – allergic asthma and pneumonitis (inflammation of the lung tissue) [NIOSH 2019e]. NIOSH considers nickel metal dust to be a potential occupational carcinogen [NIOSH 2018b, 2019e].
- Tin metal dust respiratory irritant [NIOSH 2019f].
- Titanium metal dust – there is no exposure limit for titanium in the form of metal dust. Titanium in the form of titanium dioxide causes lung fibrosis, and NIOSH considers titanium dioxide to be a potential occupational carcinogen [NIOSH 2019l].

The PVC filter for Cr(VI) is below the analytical limit of detection (<0.01 µg/m^3 of air). Table C11 also includes applicable occupational exposure limits and measured values for all metals. Concentrations of metals are well below their respective exposure limits.

Based upon the results of the PBZ air sampling in the PBF room, and if you wish to further control emissions and exposures to hazardous substances, the following recommendations are offered to you:

- Continue to monitor exposures to metals among staff by air sampling when performing routine tasks (e.g., vacuuming) as well as non-routine tasks (e.g., maintenance) to understand levels. Note that another option might be biological monitoring for metals in urine, which would give an indication of total exposure from both the breathing in metals in air as well as getting them on skin. Currently, there are biological exposure limits for chromium, cobalt, and nickel [ACGIH, 2024].
- Consider implementing portable local exhaust ventilation with HEPA filtration to capture the airborne particles near the source and minimize exposures during routine and non-routine tasks where powder may be released into the air.

DED Room

At the time of this site visit, the DED printers were not operating, and no air sampling was performed in this room.

Post-Processing Room

Printed parts that needed to be removed from a build plate were moved by an employee using a cart to the post-processing room. In this room, an EDM was used to cut printed parts from their build plate, and grinders were used to resurface the build plates to dimensional tolerances for re-use. Employees did not wear respirators in this work area. Air monitoring was performed on three separate days in the post-processing room. On the first two days, particle concentration was measured using a P-TRAK. On all three days, a PID was used to monitor TVOC concentration. Figure B43 illustrates the NF and FF basket placement in this room on two of the days (on the other day, the NF basket was positioned next to the grey table by the HAAS grinder, and the FF basket remained in the same location as in the Figure).

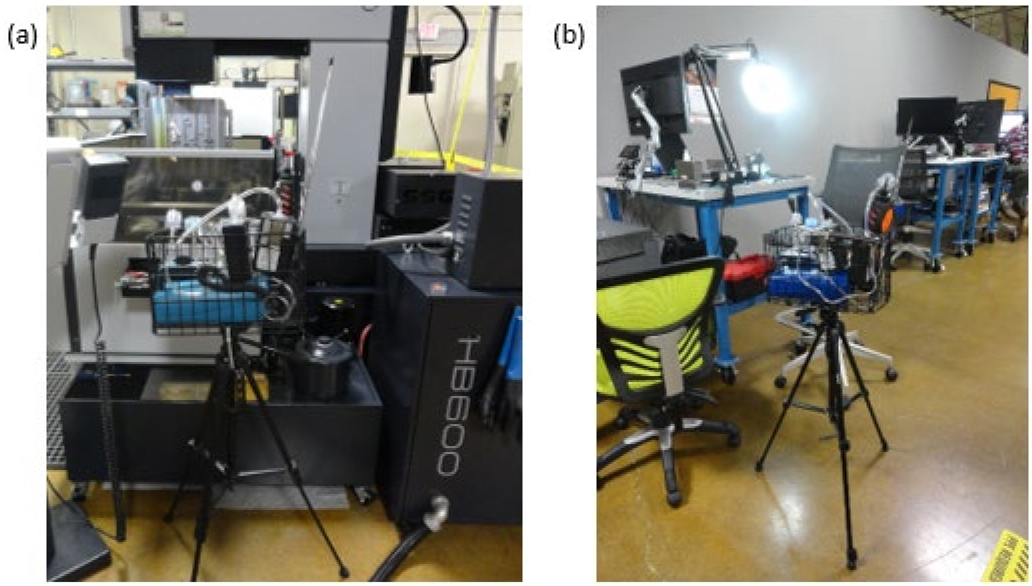
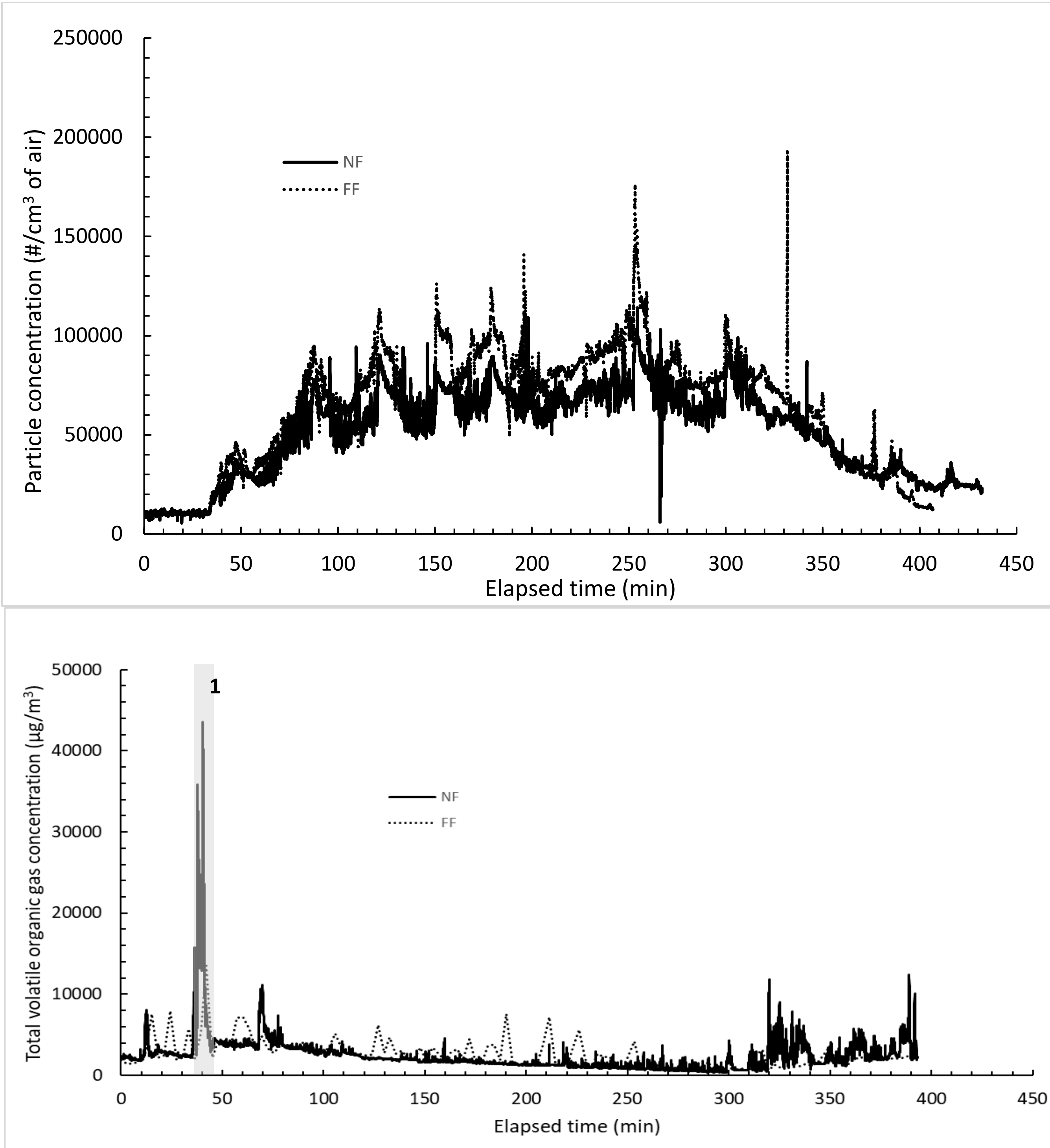


Figure B43. Sampler placement in the post-processing room on 16 May 2023: (a) Near field basket with monitors positioned near the electrical discharge machine control panel, (b) Far field basket with monitors positioned near work desks.

Figure B44 shows the real-time monitoring results for the post-processing room on the first day of monitoring. Note that particle concentrations reach 200,000/cm^3 of air, which was much higher than seen in the PBF room where powders are handled routinely. TVOC levels were approximately 2,000 $\mu g/m^3$ with a notable spike at minute 36 when cleaning with isopropyl alcohol. Additional transient spikes in TVOC levels were seen throughout the workday, though contextual information was not systematically collected in the post-processing room (because the focus of the survey was on the PBF room) to explain this variability. Similar particle and TVOC concentrations were seen on the other two days (results not shown).



Time	Event	Description
36	1	Build plates cleaned using isopropyl alcohol

Figure B44. Real-time monitor in the post-processing room on 15 May 2023 (all day): P-TRAK data (top panel), PID data (bottom panel). Particle concentrations were notable higher compared with the PBF room.

Table C12 summarizes results from general area air samples collected using MCE and PVC filters. In general work room air, total Cr (range: 0.44 to 2.08 µg/m^3 of air), Cr(VI) (range: 0.01 to 0.05 µg/m^3 of air), molybdenum (range: 0.35 to 1.18 µg/m^3 of air), and nickel (range: 1.35 to 6.44 µg/m^3 of air) were quantifiable on all seven samples. Cobalt was not detected on any sample. The remaining elements were present at levels above their detection limit on two to six of the seven samples.

Table C13 summarizes results of PBZ zone samples from employees in the post-processing room. Among the three PBZ samples, chromium (range: 1.75 to 1.93 µg/m^3 of air), molybdenum (range: 0.52 to 0.79 µg/m^3 of air), nickel (range: 2.68 to 5.6 µg/m^3 of air), and titanium (range: 0.08 to 1.14 µg/m^3 of air) were quantified on all samples. Unexpectedly, the concentrations of these elements fell within the range of PBZ exposures in the PBF room where bulk powder was handled (see Table C11). None of these PBZ concentrations of elements exceeded their respective occupational exposure limit.

Levels of triethanolamine were below the analytical limit of detection for all samples (<82.10 µg/m^3 of air) collected in the post-processing room.

A total of six DNPH samples were collected for aldehydes, four in general area air and two in the PBZ of employees. Each sample was analyzed for 11 different aldehydes. Table C14 summarizes the results of the general air samples. Levels of all but two aldehydes (2,5-dimethylbenzaldehyde; o,m,p-tolulaldehyde) were above their respective limits of detection on all samples. Among the detected aldehydes, levels were higher for acetaldehyde, formaldehyde, hexanal, and isovaleraldehyde compared with benzaldehyde, butyraldehyde, pentanal, and propionaldehyde. For the two PBZ samples, the air sampling pump for one personal sample stopped after 26 minutes, leaving only one valid sample. Levels of aldehydes on the valid sample were thousands of times below the occupational exposure limits (results not shown), which indicates a low risk for adverse health effects from exposure to these substances and no respiratory protection is needed for these gases.

Based upon the results of the PBZ air sampling, and if you wish to further control emissions and exposures to hazardous substances in the post-processing room, the following recommendations are offered to you:

- Evaluate the necessity and feasibility of installing local exhaust ventilation on the wire EDM machine to capture particles, metals, and aldehyde near their sources and lower their concentrations in the post-processing room and potentially throughout the entire production-side of the facility.
- Consider implementing portable local exhaust ventilation for the grinding process to capture the airborne particles near the source and minimize exposures.
- Consider enhancing the air change rate of the general ventilation in the post-processing room to minimize the migration of particles, metals, and aldehyde to other spaces of the facility.

Main Hall and Administrative Areas

Time integrated general area air samples were collected in various non-production areas, including the *in-situ* bay, main hallway, and general office space. Sampling included MCE filters for elements, PVC filters for Cr(VI), and DNPH sorbent tubes for aldehydes.

Table C15 summarizes the results of the general area air MCE and PVC filter samples. Short-term (approximately 15 to 45 minute) samples collected in the *in-situ* bay have levels of most elements that were below their respective analytical limits of detection. The one exception being chromium which was detected on all samples, though levels were less than approximately 2 $\mu g/m^3$. Two area air samples were collected at the black bench across from the inter-lock room. Total Cr, Mo, and Ni were detected on both samples, albeit at levels less than approximately 1.3 $\mu g/m^3$. As expected, levels of elements in the general administrative space were near or below their respective detection limit.

Table C16 summarizes the results of two short-term DNPH samples collected in the *in-situ* bay. Levels of acetaldehyde, benzaldehyde, butyraldehyde, formaldehyde, and isovaleraldehyde were within the ranges of these compounds measured in the post-processing room (see Table C14). Since the post-processing room was the only known source of aldehydes in the facility, it is likely that the levels of aldehydes in the *in-situ* bay reflect migration from the post-processing room (e.g., via open doors) and could be controlled using ventilation recommendations as noted in the previous section of this report.

Discussion

Bulk feedstock powders

SEM-EDX analysis of four virgin (before printing) feedstock powders used for printing at this facility showed particles with shape and composition consistent with their respective SDSs (see Figures B1 and B2). Hajnys et al. [2020] and Sousa et al. [2023] evaluated virgin 316L stainless steel feedstock powders and reported similar morphology, i.e., mostly spherical shape with some satellite particles attached to surfaces and a few irregular-shaped particles. Hajnys et al. [2020] reports that used 316L stainless steel powder has slightly larger size compared with virgin though Sousa et al. [2023] notes no discernable differences. van Ree et al. [2023] evaluated a virgin Inconel 718 feedstock powder and the same powder after DED printing. They reported that both the virgin and used powder had spherical shape with some satellite particles attached to surfaces, and they had similar chemical composition. du Preez et al. [2018] inspected Ti64 feedstock powders used for PBF printing and observed spherical particles with satellite attachments. These authors noted no significant differences in particle size between the virgin and once used powders. Azzougagh et al. [2021] characterized virgin AlSi10Mg feedstock powder for PBF printing and noted spherical particles with smaller satellite particles attached to surfaces. It is common practice in metal powder additive manufacturing to recycle used powder by sieving. Azzougagh et al. [2021] further characterized AlSi10Mg powder after one print and sieve cycle and again after a second print cycle (but not sieved). SEM images show that the particle size decreased, and the number of visible agglomerate particles increased from virgin to twice printed powder.

Objective 1: Does migration of feedstock powders occur from the PBF and DED rooms to other rooms in the facility?

SEM-EDX analysis of samples collected throughout the facility provides qualitative evidence that feedstock powders migrate from powder handling areas (PBF and DED rooms) to non-powder handling areas. Specifically, particles consistent with shape and composition consistent with feedstock powders were present in the clean-side PPE change out room (Figure B4), main hallway floors (Figures

B5 and B12), the parts testing laboratory area (Figure B14), throughout the post-processing room (Figures B8 and B9), employee lounge (Figure B10), and on desks and computer peripherals in offices and the engineering suite (Figures B14 and B15). The identification of individual feedstock powder particles on surfaces indicates material migration but does not quantify the levels of metals on surfaces.

Objective 2: Are there potential or actual skin and inhalation exposures to metals in this workplace?

Measurable levels of metals on wipe samples of surfaces in powder handling areas (PBF and DED rooms), non-powder handling areas (post-processing and adjacent rooms, main hallway, final parts testing area, *in situ* bay, administrative and engineering suite, breakrooms), and from employee clothing and protective equipment documents potential for exposure (material was available and could get on skin). Importantly, levels of metals on surfaces tended to be highest in the PBF, DED, and post-processing rooms. Levels of most metals were at or near analytical detection limits in the employee lounge, front breakroom, individual offices, administrative suite, engineering suite. This observation supports the efficacy of existing housekeeping efforts to minimize powder migration, though several recommendations are given earlier in Section B on ways to further reduce surface contamination throughout the facility.

Tables C6 through C8 show levels of metals on external surfaces of clothing, Tyvek® suits, and gloves indicating potential for skin exposure. A survey of the literature identified one study that purported to measure potential skin exposure among PBF workers at a facility using alloys containing high levels of cobalt, chromium, and nickel [Dugheri et al. 2022]. They collected samples by attaching filters to operators' arms, chest, and front side of the shoulders. Numerical results were not reported, only that the filters had measurable levels of Cr, Co, and Ni, and these metals were especially prevalent on workers' arms.

Table C9 summarizes levels of metals on wrists of employees in the PBF room demonstrating that skin exposures occurred. We identified one study that reported levels of metals on skin of workers that operate PBF machines [Ljunggren et al. 2019]. In that study, the PBF machines used Hastelloy® feedstock powder (47% Ni, 22% Cr, 18% Fe, 9% Mo, 1.5% Co, and unspecified metals at <1%). Levels of metals on skin of the index finger on the dominant hand of the workers were Co = 0.11 μg/cm², Ni = 0.63 μg/cm², and Cr = 0.37 μg/cm². If we assume the total area of skin wiped on both wrists in the NIOSH survey was 100 cm² per sample (area of a 10 cm x 10 cm template), values in Table C9 translate to: Co = 0.002 to 0.67 μg/cm², Ni = 0.002 to 1.6 μg/cm², and Cr = 0.001 to 0.16 μg/cm², which are consistent with Ljunggren et al. [2019].

Table C10 summarizes results of five area air samples for metals in the PBF room during various tasks involving Ti64, 316L stainless steel, and Inconel 718 powders. These samples were collected from different locations in the room so levels cannot be assigned to any individual employee, though they are indicative of potential for inhalation exposure. Several studies in the literature report area air sampling results for metals in PBF additive manufacturing facilities [Assenhoj et al. 2023; Azzougagh et al. 2021; Beisser et al. 2017; Dugheri et al. 2022; Graff et al. 2017; Jensen et al. 2020; Karlsson et al. 2023; Kolb et al. 2017; Ljunggren et al. 2019; Noskov et al. 2020; Oddone et al. 2022; Walter et al. 2018]. Among these studies, there are differences in types of air samplers (e.g., some sample for "total" dust, others for "respirable" dust, and others for "inhalable" dust), analytical method sensitivities, durations of samples (e.g., task-based, full-shift), and types of feedstock powders. Additionally, task descriptions in these studies are sometimes vague or include different activities (e.g., some studies include powder sieving as powder production, whereas others consider it part of post-processing). We used closed-face filter cassette samplers to measure levels of airborne metals in the PBF room, and only one study in the literature used the same type of sampler, so it was chosen for comparison to our results. Graff et al. [2017] monitored air levels on two occasions near a PBF printer and sieve station using Inconel 939 feedstock powder. A comparison of levels of airborne metals is as follows (our study vs. Graff et al.): Al (<2.74 μg/m^3 vs. <20 μg/m^3), Cr (0.43 to 2.06 μg/m^3 vs. 21 to 50 μg/m^3), Co (<0.37 μg/m^3 vs. 13 to 42 μg/m^3), Cu (<0.05 to 0.28 μg/m^3 vs. <2 μg/m^3), Mn (<0.37 μg/m^3 vs. 0.16 to 0.22 μg/m^3), Mo (<0.46 to 0.37 μg/m^3 vs. <2.0 μg/m^3), and Ni (2.6 to 20.90 μg/m^3 vs. 48 to 110 μg/m^3). In general, levels reported by Graff et al. [2017] exceed those measured in the PBF room air.

Table C11 summarizes results of seven PBZ air samples for metals in the PBF room during various tasks involving Ti64, tool steel, 316L stainless steel, and Inconel 718 powders. Of the studies identified in the prior paragraph, just two used closed-face sampling cassettes to monitor PBZ exposures. We measured PBZ exposures to Al of <1.76 to 3.80 μg/m^3. Graff et al. [2017] reported a PBZ exposure of <20 μg/m^3 for a PBF printer operator using Inconel 939 feedstock powder. Azzougagh et al. [2021] reported a PBZ exposure to Al of 27.2 mg/m^3 for a PBF process worker using AlSi10Mg feedstock powder. One milligram contains 1000 micrograms, so the level of Al given by Azzougagh et al. was over 7,000 times higher than any value in the PBF room. This higher level could be due to differences in work practices and/or type of feedstock powder. A comparison of levels of other airborne metals is as follows (our study vs. Graff et al.): Cr (1.51 to 8.36 μg/m^3 vs. 44 μg/m^3), Co (<0.04 to 0.33 μg/m^3 vs. 38 μg/m^3), Cu (<0.05 to 0.53 μg/m^3 vs. <2 μg/m^3), Mn (<0.07 to 0.53 μg/m^3 vs. 0.17 μg/m^3), Mo (<0.18 to 1.22 μg/m^3 vs. <2.0 to 3.2 μg/m^3), and Ni (<0.55 to 4.87 μg/m^3 vs. 99 μg/m^3). Among these metals, levels of Mn were similar otherwise they were higher in the Graff et al. [2017] study.

Objective 3: Is there a difference in particle levels in proximity to, and a distance from, production activities?

P-TRAK and/or OPS results indicate that all tasks increased particle concentrations measured in the PBF room to some degree. As such, all staff present in the room, as per existing company policy, should wear PAPRs because the NF and FF measurements for both instruments did not show clear consistent differences that unambiguously support a policy to only wear respiratory protection when directly handling or agitating powder.

Several investigators report particle monitoring data for PBF processes [Assenhoj et al. 2023; Azzougagh et al. 2021; Ding and Ng 2021; Dugheri et al. 2022; Graff et al. 2017; Jensen et al. 2020; Karlsson et al. 2023; Ljunggren et al. 2019; Oddone et al. 2022; Pernetti et al. 2022; Sousa et al. 2023]. Comparison of particle monitoring results in this facility to data in the literature is difficult because there are differences in types of particle monitors (size range and measurement principle), types of feedstock powders, and activities included in task definitions.

For **task 2, sieving**, at this facility particle levels were monitored while handling 316L stainless steel and Inconel 718. During normal operation, particle concentrations were generally stable but increased notably when a sieve station encounters and error or when two stations were running simultaneously. There was not clear consistent differences in particle concentrations between the NF and FF sampling locations. Assenhoj et al. [2023] used an OPS to monitor particle levels in the NF during a sieving task described as emptying vacuum cleaners and overflow chambers, during recirculation and sieving of Fe-, Ni-, Ti-, and Co-based powders. They reported high average and peak particle concentrations from open pouring of powders, removing of sieving cloth and using compressed air. Azzougagh et al. [2021] used an OPS to monitor particle levels in the NF during a "pre-manufacturing" task consisting of sieving and loading AlSi10Mg powder into a PBF printer. They reported results as mass concentration rather than number concentration and indicated that levels did not exceed 80 $\mu g/m^3$ during this task. Ding and Ng [2021] monitored particle levels in the NF using an OPS during a pre-processing task with 316L stainless steel powder consisting of sieving and loading powder into a PBF printer. These authors observed a noticeable increase in particle concentration during powder sieving and loading. Dugheri et al. [2022] monitored a "sifting" task with Co, Cr, and Ni alloys using an instrument with different size range and measurement principle as the P-TRAK and OPS. They reported a single transient peak for particles with size 10 μm that was three times higher than background though they did not describe what was happening at the time of the peak. Graff et al. [2017] monitored particles in the NF using an OPS during "straining" of Inconel 939 powder. Unfortunately, the authors reported the combined particle concentration for five tasks, so it is unknown what contribution sifting has to the data. Sousa et al. [2023] monitored particles in the NF using a P-TRAK during sieving 316L stainless steel powder for reuse and cleaning the powder container. Particle concentrations were increased by approximately a factor of two during this task relative to background levels.

For **task 8, uncoupling flow bins in the sieve v1 sieve stations**, at this facility particle levels were monitored using a P-TRAK and OPS while processing 316L stainless steel and Inconel 718 powders. An increase in particle concentration was seen for uncoupling bins during processing 316L stainless steel powder but not for Inconel 718 powder. Particle concentrations in the NF and FF sampling locations were inconsistent between sieve stations. Particle levels were similar between locations for the M27 (316L stainless steel) sieve station but higher for the P-TRAK in the NF compared with the FF and similar for the OPS between locations for the M26 (Inconel 718) sieve station. Only one study in the literature reported particle monitoring data for a similar task. Karlsson et al. [2023] monitored particles in the NF using an OPS during a task described as sieving Hastelloy® powder, including opening and fastening/removal of sieving containers. Like our results for 316L stainless steel, these authors reported transient increases in particle concentrations during this task.

Task 1 was opening a version 1 printer door, and **task 5 was dry vacuuming using an external vacuum to remove excess powder from a built part**. These tasks were monitored at the M26 printer with Inconel 718 powder using P-TRAK and OPS instruments and shown to increase particle concentrations in the PBF room. There was no clear consistent pattern in particle concentrations between the NF and FF sampling locations for either instrument. Comparison of results at this facility with studies in the literature was difficult because even if a task description was similar to tasks 1 and 5, most studies are ambiguous about the type of vacuum (wet or dry, internal or external). Azzougagh et al. [2021] monitored particles in the NF using an OPS during a vacuum-assisted "powder unpacking" task with AlSi10Mg powder. Results are reported as mass concentration, not number concentration, though they noted that levels increased during this task. Ding and Ng [2021] monitored particle levels in the NF using an OPS during a post-print door opening task with 316L stainless steel. In contrast to our findings, they reported an "insignificant" increase in particle concentration for this task. The absence of an increase in concentration during door opening in their study was attributed to the internal exhaust ventilation of the printer which removed particles in the build chamber prior to opening the door. A similar internal exhaust ventilation system could be effective for machines in use at this facility. Dugheri et al. [2022] monitored particle levels in the NF using an instrument with different size range and measurement principle as the P-TRAK and OPS. They described the task as removing and cleaning final product and recovery of unused powder with an external vacuum for parts made from Co, Cr, and Ni alloys. These authors reported multiple transient peaks for particles with size 10 μm that were more than a factor of two times higher than background though they did not label the peaks, so it is unknown which activities they represent. Graff et al. [2017] monitored particles in the NF using an OPS during a task they described as opening a printer door and vacuuming a build plate with Inconel 939 powder. They reported the combined particle concentration for five tasks, so it is unknown what contribution opening the printer door and vacuuming the build plate have to the data. Jensen et al. [2020] is the only study to also report NF and FF monitoring results using P-TRAK and OPS instruments. They monitored particle levels during a task described as cleaning a printer build chamber and printed part made of Ti64 with an external vacuum. Their P-TRAK monitoring data shows a transient increase in particle concentration in the NF but not the FF sampling locations, whereas the OPS instrument was stable and similar in both locations for this task. Kolb et al. [2017] monitored particle levels in the NF using an optical particle counter with size range of 0.3 to 20 μm, which exceeds the range of an OPS (0.3 to 10 μm) during removal of excess (unknown type) powder from a build platform (the text does not specify if removal is by vacuuming, brushing, or other means). Their results show transient peaks during this task which is consistent with our findings using an OPS instrument. Pernetti et al. [2022] monitored particle levels in the NF using an instrument with narrower size range (10 to 300 nm) compared with our P-TRAK (20 to 1000 nm) for a task they describe as cleaning by removal of the substrate, removal of the built object, cleaning of object with compresses air, cleaning build volume with brushes and vacuum, emptying of the overflow container and cleaning of the filters. This task was monitored for three different feedstocks, 316L stainless steel, Al-based alloy, and pure copper powders. The authors reported that particle concentrations increased above background for this task with all feedstock powders though the specific contribution of vacuuming among all activities to the rise in concentration is unknown. Finally, Sousa et al. [2023] monitored particle levels using a P-TRAK during removal of a part made from 316L stainless steel from a printer and cleaning it with a brush though it is not mentioned if opening the printer door was part of this task. They reported particle concentrations two times higher compared with background during this task.

For **task 6, de-inerting the depowdering station, task 13, opening the depowdering station door, and task 20, depowdering** at this facility, particle levels were monitored during handling parts made of Inconel 718 and Ti64 powders. The depowdering station glove box seal was not fully intact and outward leakage occured when starting depowdering, scraping walls, de-inerting, and opening the door. Particle concentrations in the NF were consistently similar or higher compared with the FF sampling location. Assenhoj et al. [2023] monitored particle levels in the NF using an OPS during several variations of depowdering, described as including manually handling in a fume hood, using depowdering stations, using automated systems that required that an open job-box was moved from a printer to a depowdering station by the operator, and automated systems with an enclosed job-box that was moved by forklift to a depowdering station. These variations of depowdering were monitored for Fe-, Ni-, Ti-, and Co-based powders and results, given as mass concentration not number concentration, showed opening a depowdering station as a task that caused the high average and peak particle concentrations. Dugheri et al. [2022] monitored particle levels in the NF using an instrument with different size range and measurement principle as the P-TRAK and OPS. They described the task as depowdering with compressed air (did not specify if it was done in an open environment of glove box) for parts made from Co, Cr, and Ni alloys. These authors reported that the concentration of particles with size 10 μm increased by seven times that of background, reached a plateau, and decreased when the task was completed, but they did not label the events, so it is unknown which activities they represent. Jensen et al. [2020] monitored particle levels in the NF and FF with both a P-TRAK and OPS during depowdering parts made of Ti64, but the operator used a glove box with vacuum not compressed gas, so their results are not reasonably comparable. Ljunggren. [2019] and Karlsson et al. [2023] monitored particle levels in the NF using an OPS during depowdering parts made of Hastelloy at the same facility. They described the depowdering station as enclosed (no other details given) and reported a small transient peak in particle levels during this task, which is consistent with our results.

Multiple tasks were monitored for version 2 printers at this facility: **task 7, using an external wet vacuum; task 11, cleaning residual powder in a build chamber; task 15, opening printer doors; and task 17, cleaning powder from printer surfaces**. These tasks were monitored at the M306 printer that uses Ti64 feedstock powder. The door seals were highly effective during dry vacuuming though opening printer doors resulted in rapid burst of particle released into the PBF room. As noted above, an internal exhaust ventilation system could be an effective solution to mitigate this burst of particles during machine door opening. Using a wet external vacuum and cleaning powder from surfaces did not affect particle concentrations in room air. For two of three monitoring sessions, particle concentrations were similar in the NF and FF sampling locations for both the P-TRAK and OPS instruments. For one session, particle concentration levels tended to be higher in the NF compared with the FF sampling location for both instruments. Comparison of results at this facility with studies in the literature is difficult because studies are ambiguous about the type of vacuum (wet or dry, internal or external). As such, much of the same studies reviewed for tasks 1 and 5 with version 1 printers [Azzougagh et al. 2021; Ding and Ng 2021; Dugheri et al. 2022; Graff et al. 2017; Jensen et al. 2020; Kolb et al. 2017; Oddone et al. 2022; Pernetti et al. 2022] could also apply to the version 2 printers.

Objective 4: Is the ventilation system effective and is there potential for improvements?

A review of the ventilation system in the facility notes that it was designed with the primary consideration of 1) providing sufficient outdoor air per ASHRAE Standard 62.1; and 2) providing negative pressure in PBF room and removing particles released to the air in the PBF room by HEPA filter in the exhaust air of the PBF room, to minimize particle concentration in the PBF room and particle migration into other spaces of the facility. The ventilation system can benefit from the following improvements:

- Close the access doors in the main hall to minimize air exchange and contaminant migration between the PBF room and the post-processing room.
- Increase the clearance in front of the exhaust vents in the PBF room to allow 1) improved airflow into the vents; and 2) convenient access to the vents for maintenance (see Figure B45 for examples of equipment near vents that could obstruct airflow). The service clearances for the exhaust vents are specified in the engineering drawings of the ventilation system in the PBF room. However, the working clearance for the exhaust vents in the PBF room were not seen in the engineering drawings. Consider consulting the ventilation designer/engineer to determine the minimum working clearance around the exhaust vents to provide optimal airflow.
- Consider installing the existing air filter manometers in a manner so that they measure the pressure drop across the HEPA filters that serve the exhaust vents in the PBF room. The configuration of the existing manometers only provides a pressure reading across the pre-filters. According to the facility, the pre-filters are changed in monthly intervals regardless of the static pressure readings measured on the manometers. Changing the manometer installation to read across the HEPA filter will also provide a quantitative method to determine when the more costly HEPA filter has reached it end of life i.e., maximum operating static pressure.
- Ensure airflow direction from supply air vents in the ceiling is not blowing particle-laden air into employees' breathing zones during tasks, e.g., setting up desirable positions for the workers and/or providing trainings to workers to always position themselves upstream of the process in terms of airflow.
- Implement local exhaust ventilation, e.g., capturing hood or negative pressure enclosure with HEPA filtration, for the tasks in the post-processing room that may release powder/particles to the air as noted in the previous section of the report. NIOSH can provide additional guidance on designing proper local exhaust ventilation.

Figure B45. Photos showing examples of equipment near exhaust vents in the powder bed fusion room: (a) cabinets, (b) printers.

Limitations

An important limitation of this survey is that current technology for real-time particle counters was non-specific meaning it is unknown if particles measured using the P-TRAK and OPS were composed of metals from feedstock powder. Our recommendation that all staff present in the PBF room wear PAPRs because the NF and FF measurements did not show clear consistent differences is based on non-specific particle counts. To verify this assumption, all staff in the PBF room should wear PBZ samplers to compare levels of metals between those actively working with powders to those who are not and determine if meaningful differences exist.

Section C: Tables

Table C1. Categories of surfaces that were sampled using Ghost Wipes, PVC filters, and SEM stubs.	
Category	Description
Boots	Sole of work boots worn throughout the facility
Build plate	Surface upon which a part is built by additive manufacturing
Cart	Assistive device to move or lift things (usually the handle) but includes Artie the robot
Clothing	Textiles used to cover the body and includes accessories such as backpacks but not PPE such as Tyvek suits
Containers	Vessels for storing materials such as virgin or waste powders
Door handle	Handle of a door used for access/egress between rooms
Floor	Walking surface in non-administrative areas
Furniture	Chairs, tables, and appliances such as refrigerators in administrative but not work areas
Gloves (exterior)	Outer surface of disposable gloves such as those made of nitrile
Gloves (interior)	Inside surface of re-usable gloves such as cloth gloves or glovebox gloves
Interface	Machine touchscreens, keyboards, keypads, or buttons
Laboratory coat	Cloth coat worn over clothing
Machine handle	Latch or handle for opening a door or hatch on a printer or other device in a non-administrative area
Office equipment	Computer keyboards, peripherals (e.g., mouse) and desktops in administrative areas
PAPR	Interior or exterior surface of a Powered Air Purifying Respirator
Powder prep equipment	External surfaces of powder prep machines in DED and PBF rooms
Printer	Surface on a machine designed to print parts by additive manufacturing
Shelving	Horizontal surface intended for storing items
Shop pack	Plastic sleeve for papers in work areas
Skin	Bare skin of employee (forearms)
Structural surfaces	Surfaces of building components such as HEPA boxes and vertical walls
Tool	Device for work such as a sander or broom
Vacuum	Device for removing loose materials by suction and includes nozzles and cart handles
Work surface	Horizontal bench or tabletop in non-administrative areas
Note: PVC: polyvinyl chloride; SEM: scanning electron microscopy; DED: directed energy deposition; PBF: powder bed fusion; HEPA: high-efficiency particulate air filter.	

Table C2. Levels of metals on surfaces in the powder bed fusion printer room (March 14 and 15, 2023)

	Nanograms per square centimeter (ng/cm^2)										
Surface	Al	Cr	Cr(VI)	Co	Cu	Fe	Mo	Ni	Tin	Ti	V
M306 v2 titanium printer											
Loading door handle	115.4	42.3	n/a	6.0	<9.6	*346.2*	7.9	71.2	<9.6	4.4	<0.4
Powder station right glove port cover/knob	39.0	7.5	n/a	1.4	<5.0	<100.0	1.6	16.0	<5.0	1.7	*0.2*
Black shop pack hanging on printer	58.0	27.0	n/a	3.0	<5.0	<100.0	5.4	38.0	<5.0	2.1	<0.2
M307 v2 aluminum printer											
Glove door handle	3076.9	12.1	n/a	5.8	<9.6	<192.3	4.6	25.0	<9.6	1.7	*0.5*
Powder station right glove port cover/knob	210.0	42.0	n/a	9.5	<5.0	*220.0*	10.0	89.0	<5.0	2.3	<0.2
Touch panel screen	13.0	<0.2	n/a	<0.1	<5.0	<100.0	<0.4	<0.3	<5.0	<0.2	<0.2
M319 v2 Ti-64/17-4 PH stainless steel printer											
Laptop cover on cart near powder station	17.0	3.4	n/a	1.8	<5.0	<100.0	1.6	20.0	<5.0	<0.2	<0.2
Powder station right glove port cover/knob	200.0	51.0	n/a	11.0	29.0	*230.0*	12.0	110.0	*7.7*	5.5	*0.4*
New v2 customer machine installation											
Glove door handle	*17.8*	1.8	n/a	2.1	<5.6	<111.1	1.7	2.6	<5.6	0.6	<0.2
Touch panel screen	14.0	0.6	n/a	1.7	<5.0	<100.0	1.5	*0.7*	<5.0	*0.2*	<0.2
Edge under glove box door			0.3								
Inside build chamber by loading door	64.0	19.0	n/a	3.0	<5.0	*110.0*	3.8	23.0	*5.3*	11.0	<0.2
M26 v1 Inconel 718 printer											
Glove door handle latch	45.6	44.4	n/a	24.4	<5.6	*322.2*	18.9	133.3	<5.6	1.8	<0.2
Touch panel screen	*12.0*	58.0	n/a	3.6	<5.0	<100.0	9.7	140.0	<5.0	2.5	<0.2
Edge under glove box door			0.3								
M26 v1 Inconel 718 Powder Sieve Station											
Loading door handle			1.0								
Touch panel screen	37.0	57.0	n/a	5.1	<5.0	*180.0*	9.8	95.0	<5.0	2.0	<0.2
Right exterior wall	24.0	3.5	n/a	2.6	<5.0	<100.0	2.4	5.8	<5.0	0.7	<0.2
M27 v1 316L Stainless steel printer											
Glove door handle latch	200.0	455.6	n/a	7.1	<5.6	1777.8	57.8	355.6	<5.6	1.1	<0.2
Touch panel screen	35.0	150.0	n/a	5.8	<5.0	600.0	21.0	120.0	<5.0	0.6	<0.2
Edge under glove box door			0.6								
M27 v1 316L Stainless steel Sieve Station											
Loading door handle			1.2								
Touch panel screen	28.0	10.0	n/a	3.1	<5.0	<100.0	3.2	15.0	<5.0	<0.2	<0.2
Right exterior wall	390.0	9.6	n/a	26.0	*10.0*	*230.0*	15.0	73.0	<5.0	8.0	*0.3*
Vacuums											
M306/M307 hose nozzle attachment	120.0	210.0	n/a	32.0	<5.0	950.0	43.0	270.0	<5.0	3.8	<0.2
M26/M15 hose nozzle (Inconel 718/17-4 PH)			0.2								
M27/M14 hose nozzle (316L SS/Maraging)			0.3								

Table C2. Levels of metals on surfaces in the powder bed fusion printer room (March 14 and 15, 2023)

	Nanograms per square centimeter (ng/cm^2)										
Surface	Al	Cr	Cr(VI)	Co	Cu	Fe	Mo	Ni	Tin	Ti	V
Depowdering station											
Right side of cover handle	32.1	3456.8	n/a	16.0	*21.0*[a]	13580	444.4	2345.7	<6.2	3.0	3.3
Left side of cover handle			0.2								
Inner surface of right glove	36.2	2.0	n/a	0.4	<1.6	<32.9	*0.4*	4.3	<1.6	0.2	<0.07
Inner surface of left glove			0.04								
Corner of build plate – after vacuuming	310.3	4482.8	n/a	103.5	65.5	8275.9	793.1	12069	<17.2	482.8	9.3
Corner of build plate – after depowdering	217.2	689.7	n/a	15.5	<17.2	1758.6	86.2	1620.7	<17.4	25.5	<0.7
Transport carts/lifts/storage											
Both handles of Location A12 lift	62.0	30.3	n/a	16.9	*8.5*	323.9	13.4	59.2	<3.5	1.2	*0.3*
Handle of M27 PBF → post-processing cart	35.8	25.9	n/a	5.4	<6.2	*135.8*	6.4	27.2	<6.2	*0.4*	<0.2
Second shelf in cabinet behind M27 printer	240.0	280.0	n/a	18.0	<5.0	1200.0	45.0	490.0	<5.0	18.0	*0.6*
Room walls											
Above HEPA screen near M27 printer	*13.0*	35.0	n/a	4.0	<5.0	<100.0	6.9	81.0	<5.0	1.5	<0.2
Above HEPA screen near flammable cabinets	21.0	7.3	n/a	2.7	<5.0	<100.0	2.8	9.6	<5.0	*0.4*	<0.2
Above HEPA screen near M306 printer	*16.0*	*0.3*	n/a	1.7	<5.0	<100.0	*1.2*	*1.1*	<5.0	<0.2	<0.2
PPE change out room											
Floor in dirty side	52.0	78.0	n/a	4.7	<5.0	*240.0*	12.0	120.0	<5.0	2.2	<0.2
Floor in dirty side			0.2								
Handle of door from dirty to clean side	220.2	28.0	n/a	2.3	31.0	5119.0	4.7	71.4	<3.0	2.9	0.6
Floor in clean side after exiting dirty side	640.0	240.0	n/a	67.0	25.0	2000.0	66.0	380.0	<5.0	15.0	*0.5*
Floor in clean side after exiting dirty side			0.4								
Handle on clean side door going to PBF room	19.6	4.3	n/a	10.1	14.9	*113.1*	6.0	31.0	<3.0	*0.2*	<0.1

[a] Italic font denotes a semi-quantitative value, i.e., between the limit of detection and limit of quantification.
Note: Al: aluminum; Cr: total chromium; Cr(VI): hexavalent chromium; Co: cobalt; Cu: copper; Fe: iron; Mo: molybdenum; Ni: nickel; Sn: tin; Ti: titanium; V: vanadium.

Table C3. Levels of metals on surfaces in the directed energy deposition printer room (March 13 – 15, 2023)

	Nanograms per square centimeter (ng/cm^2)										
Surface	Al	Cr	Cr(VI)	Co	Cu	Fe	Mo	Ni	Tin	Ti	V
Modulo 400 printer											
Keypad on left	19.0	8.8	n/a	1.6	<5.0	<100.0	1.5	14.0	<5.0	0.8	<0.2
" " – after cleaning	*11.0*[a]	4.3	n/a	0.9	<5.0	<100.0	*0.5*	5.5	<5.0	<0.2	<0.2
Touch screen on GTV 30044 powder loader	120.0	80.0	n/a	21.0	<5.0	*280.0*	10.0	69.0	<5.0	1.6	*0.3*
Top of left tube on GTV 30044	61.0	230.0	n/a	14.0	71.0	930.0	26.0	180.0	<5.0	5.1	1.1
Right side of keyboard near GTV 30044	39.0	3.5	n/a	3.0	<5.0	<100.0	1.6	8.8	<5.0	0.8	<0.2
Modulo 800 printer											
Computer keyboard	55.0	110.0	n/a	42.0	20.0	520.0	19.0	130.0	<5.0	3.1	*0.6*
Touch screen on GTV 30028 powder loader			0.4								
Top of left tube on GTV 30028			0.3								
Work surfaces											
Black bench near door to main hall	41.0	20.0	n/a	3.2	<5.0	*300.0*	3.7	29.0	<5.0	1.0	<0.2
Powder containers											
Top of tool steel waste bucket			*0.05*								
Handles of four steel waste buckets	35.6	83.3	n/a	136.4	<3.8	1439.4	83.3	409.1	<3.8	5.4	*0.2*
Handles on three bottles of 316L powder	164.5	539.5	n/a	32.9	34.9	2368.4	92.1	421.1	<3.3	6.6	2.2
Handle on middle bottle of 316L powder			0.2								
Floors and doors											
Floor near doors to hall and PP room	71.0	32.0	n/a	7.1	<5.0	*170.0*	5.4	28.0	<5.0	*0.4*	<0.2
Floor near doors to hall and PP room			1.0								
Bar handle on door to PP room	<5.0	*0.4*	n/a	<0.1	<5.0	<100.0	<0.4	*0.7*	<5.0	<0.2	<0.2
Handle on door to hall	*10.1*	1.4	n/a	*0.2*	*4.4*	<59.5	*0.7*	5.1	<3.0	<0.1	<0.1
Transport carts											
Left handle	290.0	110.0	n/a	470.0	*9.2*	730.0	29.0	500.0	<5.0	5.3	<0.2
Right handle			0.2								
Vacuums											
Handle of wet vacuum	80.6	66.0	n/a	38.8	*9.2*	475.7	15.5	80.6	<4.9	0.6	<0.2
Handle of wet vacuum			0.2								
Miscellaneous											
Seat of fabric office chair	73.0	150.0	n/a	4.9	<5.0	670.0	22.0	110.0	<5.0	3.9	<0.2
Employee backpack	46.0	1.6	n/a	0.8	<5.0	<100.0	<0.4	2.6	<5.0	*0.3*	<0.2

[a] Italic font denotes a semi-quantitative value, i.e., between the limit of detection and limit of quantification.
Note: Al: aluminum; Cr: total chromium; Cr(VI): hexavalent chromium; Co: cobalt; Cu: copper; Fe: iron; Mo: molybdenum; Ni: nickel; Sn: tin; Ti: titanium; V: vanadium.

Table C4. Levels of metals on surfaces in the post-processing and adjacent rooms (March 13 – 15, 2023)

	Nanograms per square centimeter (ng/cm²)										
Surface	Al	Cr	Cr(VI)	Co	Cu	Fe	Mo	Ni	Tin	Ti	V
EDM machine											
Computer keyboard cover	2700.0	520.0	n/a	230.0	*14.0*[a]	2500.0	260.0	890.0	<5.0	15.0	3.0
Corded control panel	190.0	16.0	n/a	2.4	<5.0	*170.0*	27.0	38.0	<5.0	2.9	<0.2
Black table	84.0	3.8	n/a	12.0	<5.0	*110.0*	6.7	13.0	<5.0	3.0	<0.2
Black table			0.1								
Transport carts											
Handle of cart 2013170	19.7	2.0	n/a	2.3	<6.2	148.0	4.6	4.7	<6.2	<0.2	<0.2
Handle of cart 201132	28.4	2.8	n/a	*0.4*	<6.2	123.3	4.8	3.7	<6.2	0.9	<0.2
Shelving											
Grey shelf for ground Ti build plates	490.0	130.0	n/a	5.9	*8.9*	1500.0	68.0	190.0	<5.0	19.0	1.0
Grey shelf for ground tool steel build plates			2.5								
Blue shop pack on 316L rework shelf	5900.0	280.0	n/a	9.5	*8.9*	2200.0	90.0	320.0	<5.0	12.0	1.3
Black shop pack on 316L rework shelf			1.3								
Black shop pack on Ti rework shelf	2600.0	240.0	n/a	8.5	<5.0	1400.0	73.0	270.0	<5.0	7.2	*0.7*
Manual finishing area											
Grey bench in manual finishing area	4100.0	440.0	n/a	4.0	<5.0	2100.0	79.0	460.0	<5.0	91.0	4.9
" " – after cleaning	120.0	10.0	n/a	1.5	<5.0	<100.0	4.0	11.0	<5.0	1.7	<0.2
Grey bench in manual finishing area			0.9								
" " – after cleaning			0.3								
Handle of pneumatic tool with green hose	3725.9	127.6	n/a	1.9	*20.7*	620.7	24.1	275.9	<8.6	9.3	*0.4*
Handle of pneumatic belt sander			0.7								
Inner lining of reusable cloth over glove	4600.0	450.0	n/a	7.3	*11.0*	2700.0	68.0	370.0	<5.0	16.0	1.2
Floors and doors											
Floor in front of door to PP room	380.0	86.0	n/a	49.0	<5.0	390.0	18.0	75.0	<5.0	4.0	<0.2
Floor in front of door to PP room			1.4								
Computer equipment											
Keyboard on desk	730.0	62.0	n/a	4.5	<5.0	420.0	32.0	100.0	<5.0	4.1	*0.4*
Maintenance cage											
Work bench top in front of whiteboard	220.0	280.0	n/a	18.0	34.0	1500.0	34.0	380.0	<5.0	8.2	1.2
Work bench top in front of whiteboard			0.5								
Employee lounge											
Back of chair	31.0	1.6	n/a	<0.1	<5.0	<100.0	*0.9*	3.1	<5.0	*0.4*	<0.2
Left corner of table top	30.0	*0.5*	n/a	<0.1	<5.0	<100.0	<0.4	*0.9*	<5.0	<0.2	<0.2
Right corner of table top	32.0	5.4	n/a	<0.1	<5.0	<100.0	<0.4	2.9	<5.0	<0.2	<0.2
Refrigerator door handle	31.6	4.6	n/a	1.1	*6.0*	*135.5*	1.5	11.0	<3.2	0.6	<0.1
Quality control laboratory											
Inconel build plate on shelf by door	140.0	4900.0	n/a	24.0	34.0	19000	620.0	3300.0	<5.0	9.9	4.7

Table C4. Levels of metals on surfaces in the post-processing and adjacent rooms (March 13 – 15, 2023)											
	Nanograms per square centimeter (ng/cm^2)										
Surface	Al	Cr	Cr(VI)	Co	Cu	Fe	Mo	Ni	Tin	Ti	V
Marble table by 3-D scanner	74.0	4.3	n/a	<0.1	<5.0	<100.0	*0.6*	3.1	<5.0	16.0	*0.2*
Marble table by 3-D scanner			0.2								
Door handle for tensile testing machine	129.3	9.5	n/a	1.0	50.0	577.6	3.2	63.8	<4.3	1.8	<0.2
Desk with roughness testing instruments	150.0	24.0	n/a	*0.2*	<5.0	<100.0	4.3	22.0	<5.0	2.1	<0.2
Desk with roughness testing instruments			0.6								

[a] Italic font denotes a semi-quantitative value, i.e., between the limit of detection and limit of quantification.
Note: Al: aluminum; Cr: total chromium; Cr(VI): hexavalent chromium; Co: cobalt; Cu: copper; Fe: iron; Mo: molybdenum; Ni: nickel; Sn: tin; Ti: titanium; V: vanadium.

Table C5. Levels of metals on surfaces in the main hall and other non-powder handling rooms (March 13 and 14, 2023)

	Nanograms per square centimeter (ng/cm^2)										
Surface	Al	Cr	Cr(VI)	Co	Cu	Fe	Mo	Ni	Tin	Ti	V
In situ bay											
Artie robot wheel	560.0	60.0	n/a	32.0	*34.0*[a]	2400.0	28.0	104.0	<10.0	17.0	2.0
Left side HEPA filter box	630.0	75.0	n/a	17.0	19.0	6100.0	16.0	69.0	<5.0	16.0	1.4
Floor in front of admin office suite door	63.0	9.8	n/a	1.2	<5.0	*180.0*	2.3	11.0	<5.0	1.0	<0.2
Floor in front of admin office suite door			0.5								
Final part testing area											
Slide plate on black bench opposite airlock	570.0	29.0	n/a	4.3	*6.3*	*310.0*	8.3	51.0	<5.0	4.9	*0.4*
Center of black bench opposite airlock	110.0	6.8	n/a	1.9	<5.0	*140.0*	2.4	12.0	<5.0	4.2	<0.2
Control panel on Allied AD-5 polisher	19.0	0.9	n/a	*0.2*	<5.0	<100.0	<0.4	2.3	<5.0	0.8	<0.2
Main hall											
Control panel on PPE vending machine	27.0	3.0	n/a	*0.2*	<5.0	<100.0	*1.2*	5.0	<5.0	*0.4*	<0.2
Floor in front of door to PP/DED hall	110.0	340.0	n/a	33.0	<5.0	1300.0	9.7	94.0	<5.0	1.8	*0.7*
Floor in front of door to PP/DED hall			0.7								
Floor in front of garage door to DED room	120.0	13.0	n/a	3.7	<5.0	*130.0*	3.0	19.0	<5.0	*0.5*	<0.2
Floor in front of garage door to DED room			0.6								
Floor in front of clean side change out door	86.0	300.0	n/a	8.5	*5.5*	1200.0	36.0	190.0	<5.0	0.7	1.0
Floor in front of clean side change out door			0.6								
Floor in front of individual office	190.0	14.0	n/a	1.8	<5.0	*170.0*	3.5	20.0	<5.0	1.2	0.2
Floor in front of individual office			0.6								
Hall to PP/DED rooms											
Floor in front of DED room door	140.0	18.0	n/a	2.8	100.0	*170.0*	4.9	78.0	<5.0	0.9	*0.3*
Floor in front of DED room door			1.2								
Computer equipment											
Keyboard in individual office	100.0	5.5	n/a	*0.2*	*14.0*	<100.0	*1.0*	7.4	<5.0	*0.3*	0.2
Mouse in individual office	76.1	4.1	n/a	0.8	10.9	*59.8*	1.1	8.2	<2.7	0.5	<0.1
Desktop in individual office	130.0	2.9	n/a	*0.1*	*7.7*	<100.0	*0.8*	5.3	<5.0	*0.6*	<0.2
Keyboard cover in administrative suite	140.0	100.0	n/a	30.0	*10.0*	1100.0	28.0	160.0	<5.0	4.7	<0.2
Desktop in administrative suite	21.0	2.5	n/a	5.8	<5.0	<100.0	3.5	18.0	<5.0	1.0	<0.2
Keyboard in administrative suite	24.0	6.0	n/a	1.9	<5.0	<100.0	1.5	13.0	<5.0	*0.4*	<0.2
Desktop in administrative suite	*5.6*	<0.2	n/a	<0.1	<5.0	<100.0	<0.4	<0.3	<5.0	<0.2	<0.2
Keyboard cover in engineering suite	*15.0*	*0.6*	n/a	<0.1	<5.0	<100.0	<0.4	1.1	<5.0	*0.4*	<0.2
Desktop in engineering suite	*9.3*	*0.3*	n/a	<0.1	<5.0	<100.0	<0.4	*0.4*	<5.0	<0.2	<0.2
Front breakroom											
Countertop near microwave	*11.0*	*0.2*	n/a	<0.1	<5.0	<100.0	<0.4	<0.3	<5.0	*0.5*	<0.2
Refrigerator door handles	7.1	<0.3	n/a	<0.1	<6.7	<133.3	<0.5	*1.0*	<6.7	<0.3	<0.3

Table C5 (continued). Levels of metals on surfaces in the main hall and other non-powder handling rooms (March 13 and 14, 2023)

Nanograms per square centimeter (ng/cm²)

Narrow hall along back of PBF room											
Top of HEPA box near empty containers	2100.0	73.0	n/a	13.0	48.0	3000.0	9.3	54.0	<5.0	64.0	2.9
Top of HEPA box near empty containers			6.1								
Floor in front of door to PBF room	130.0	20.0	n/a	3.5	<5.0	*290.0*	5.9	31.0	<5.0	2.5	*0.4*
Floor in front of door to PBF room			0.4								
Handles of red and yellow brooms	31.5	1.9	n/a	*0.2*	<3.1	<61.7	*0.5*	2.7	<3.1	0.7	<0.1

[a] Italic font denotes a semi-quantitative value, i.e., between the limit of detection and limit of quantification.

Note: Al: aluminum; Cr: total chromium; Cr(VI): hexavalent chromium; Co: cobalt; Cu: copper; Fe: iron; Mo: molybdenum; Ni: nickel; Sn: tin; Ti: titanium; V: vanadium.

Table C6. Levels of metals on respirators, coverings, boots, and shirts (March 13 and 15, 2023)										
	Nanograms per square centimeter (ng/cm^2)									
Surface	Al	Cr	Co	Cu	Fe	Mo	Ni	Tin	Ti	V
a. Respirators, coverings, and boots										
PPE change out room										
PAPR helmet – clean side	76.0	33.0	5.4	<5.0	*130.0*[a]	7.6	60.0	<5.0	1.5	<0.2
PAPR battery – clean side	78.0	36.0	5.7	<5.0	*150.0*	8.4	59.0	<5.0	2.5	<0.2
Front of blue cloth lab coat – clean side	250.0	210.0	8.1	<5.0	740.0	31.0	270.0	<5.0	12.0	*0.4*
DED room										
PAPR head and neckband	36.2	15.5	4.1	<5.2	*113.8*	3.0	18.6	<5.2	0.9	<0.2
Left chest of Tyvek® suit	*13.0*	1.3	*0.3*	<5.0	<100.0	<0.4	1.7	<5.0	*0.4*	0.2
" " – after cleaning printer	22.0	44.0	100.0	<5.0	*250.0*	7.7	96.0	<5.0	*0.3*	<0.2
Sternum of Tyvek® suit	13.0	7.6	12.0	<5.0	<100.0	2.2	10.0	<5.0	*0.3*	<0.2
" " – after cleaning printer	54.0	1000.0	2100.0	*7.1*	1800.0	69.0	1800.0	<5.0	5.3	0.9
Facility-wide										
Bottom of left boot – NIOSH staff	1300.0	130.0	95.0	*13.0*	1900.0	62.0	270.0	*17.0*	15.0	0.8
Bottom of right boot – NIOSH staff	2800.0	660.0	180.0	33.0	5100.0	180.0	1100.0	34.0	32.0	2.7
Bottom of right boot – NIOSH staff	1300.0	170.0	44.0	*10.0*	1700.0	46.0	260.0	*5.9*	14.0	*0.6*
b. Shirts										
PBF room										
Vacuuming M26 sieve station	300.0	110.0	4.8	<5.0	360.0	17.0	180.0	<5.0	3.5	<0.2
" " – post task	63.0	88.0	3.9	<5.0	*280.0*	14.0	140.0	*5.1*	2.4	<0.2
Loading powder in M26 printer	260.0	450.0	14.0	<5.0	2200.0	65.0	580.0	<5.0	7.9	*0.5*
" " – post task	40.0	50.0	4.1	<5.0	*150.0*	8.8	89.0	<5.0	2.2	<0.2
Setting up new v2 printer	140.0	110.0	270.0	*8.9*	2800.0	150.0	640.0	<5.0	5.1	<0.2
" " – post task	320.0	120.0	130.0	*13.0*	1800.0	82.0	420.0	<5.0	12.0	<0.2
Setting up new v2 printer	55.0	9.9	2.5	*5.8*	1300.0	2.7	14.0	<5.0	1.0	<0.2
" " – post task	50.0	26.0	44.0	*5.5*	540.0	27.0	110.0	<5.0	1.5	<0.2
Setting up new v2 printer	52.0	8.7	2.6	<5.0	<100.0	1.9	17.0	*5.7*	<0.2	<0.2
" " – post task	27.0	5.3	3.5	<5.0	<100.0	2.8	8.2	<5.0	*0.4*	<0.2

[a] Italic font denotes a semi-quantitative value, i.e., between the limit of detection and limit of quantification.
Note: Al: aluminum; Cr: total chromium; Cr(VI): hexavalent chromium; Co: cobalt; Cu: copper; Fe: iron; Mo: molybdenum; Ni: nickel; Sn: tin; Ti: titanium; V: vanadium.

Table C7. Levels of elements on single gloved hand (March 13 and 15, 2023)										
	Micrograms per gloved hand palm (µg/palm)									
	Al	Cr	Co	Cu	Fe	Mo	Ni	Tin	Ti	V
DED room										
Left outer glove palm	3.5	7.6	1.0	*0.67*[a]	44.0	1.3	6.7	<0.5	0.07	<0.02
" " – after cleaning printer	17.0	50.0	100.0	5.0	360.0	12.0	110.0	<0.5	0.06	*0.04*
Left under glove palm – after cleaning printer	0.95	2.6	7.7	<0.5	<10.0	0.19	0.57	<0.5	<0.02	<0.02
Right outer glove palm	4.7	8.8	2.8	*0.68*	53.0	1.5	9.8	<0.5	0.13	*0.03*
" " – after cleaning printer	30.0	100.0	100.0	7.2	750.0	25.0	130.0	*1.7*	0.84	*0.05*
Right under glove palm – after cleaning printer	0.82	0.47	1.1	<0.5	<10.0	*0.09*	1.0	<0.5	<0.02	<0.02

[a] Italic font denotes a semi-quantitative value, i.e., between the limit of detection and limit of quantification.
Note: Al: aluminum; Cr: total chromium; Cr(VI): hexavalent chromium; Co: cobalt; Cu: copper; Fe: iron; Mo: molybdenum; Ni: nickel; Sn: tin; Ti: titanium; V: vanadium.

Table C8. Levels of elements on both gloved hands (March 13 and 15, 2023)										
	Micrograms per both gloved hand palms (µg/both palms)									
	Al	Cr	Co	Cu	Fe	Mo	Ni	Tin	Ti	V
PBF room										
Loading Al powder	520.0	3.2	0.85	<0.5	*18.0*[a]	0.90	6.5	<0.5	0.59	*0.05*
“ “ – post task	1200.0	11.0	1.4	<0.5	39.0	2.1	21.0	<0.5	0.85	*0.07*
DED room										
Outer glove palms	10.0	56.0	9.2	<0.5	240.0	7.8	45.0	<0.5	0.28	<0.02
“ “ – after cleaning printer	140.0	460.0	1400.0	17.0	2100.0	69.0	1300.0	2.5	10.0	1.6
Under glove palms – after cleaning printer	2.5	2.6	5.4	<0.5	<10.0	0.21	3.9	<0.5	*0.02*	<0.02

[a] Italic font denotes a semi-quantitative value, i.e., between the limit of detection and limit of quantification.
Note: Al: aluminum; Cr: total chromium; Cr(VI): hexavalent chromium; Co: cobalt; Cu: copper; Fe: iron; Mo: molybdenum; Ni: nickel; Sn: tin; Ti: titanium; V: vanadium.

Table C9. Levels of elements on employees' wrist skin in the PBF room (March 13 and 15, 2023)										
	Micrograms per both wrists (µg/wrists)									
	Al	Cr	Co	Cu	Fe	Mo	Ni	Tin	Ti	V
Vacuuming M26 sieve station	15.0	1.1	0.18	<0.5	<10.0	0.26	1.2	<0.5	0.05	<0.02
" " – post task	7.4	3.8	0.40	<0.5	*15.0*[a]	0.75	5.1	<0.5	0.11	<0.02
Setting up new v2 printer	9.4	1.1	0.26	*1.1*	710.0	0.37	2.1	<0.5	0.17	<0.02
" " – post task	4.5	3.2	1.9	*0.51*	27.0	1.30	7.3	*0.52*	0.14	<0.02
Setting up new v2 printer	1.5	0.64	0.22	<0.5	<10.0	0.25	1.0	<0.5	0.08	<0.02
" " – post task	*1.2*	0.11	0.23	<0.5	<10.0	0.17	0.18	<0.5	<0.02	<0.02
Setting up new v2 printer	13.0	16.0	67.0	*1.0*	630.0	37.0	160.0	*0.58*	0.49	<0.02
" " – post task	13.0	5.4	26.0	*1.0*	250.0	14.0	60.0	<0.5	0.69	<0.02

[a] Italic font denotes a semi-quantitative value, i.e., between the limit of detection and limit of quantification.
Note: Al: aluminum; Cr: total chromium; Cr(VI): hexavalent chromium; Co: cobalt; Cu: copper; Fe: iron; Mo: molybdenum; Ni: nickel; Sn: tin; Ti: titanium; V: vanadium.

Table C10. General area air concentrations (in micrograms per cubic meter of air, μg/m^3) of metals in the PBF printer room (May 15 – 17, 2023)[a]

Description	T (min)	Vol (m^3)	Al	Cr	Cr(VI)	Co	Cu	Mn	Mo	Ni	Tin	Ti
M306 titanium printer												
Far field (vacuuming)	36	0.11	<2.74	1.19	n/a	<0.37	<0.46	<0.37	<0.46	<0.55	<0.55	<0.09
Various tasks[b]												
Near field	355	1.07	<0.28	2.06	n/a	<0.04	<0.05	<0.04	0.37	4.87	*0.10*[c]	0.09
Far field	292	0.89	<0.34	0.72	n/a	<0.05	<0.06	<0.05	*0.10*	1.36	<0.07	*0.03*
M26 & M27 Sieve Stations												
Near field (sieving)	270	0.54			<0.002							
Inter-lock room												
Inside room	461	1.44	<0.21	0.43	n/a	<0.03	0.28	<0.03	*0.10*	0.54	<0.04	0.71

[a] T = air sample duration (minutes), Vol = air sample volume (m^3), n/a = not applicable (no sample collected), < = below analytical limit of detection expressed as a concentration based on air sample volume.
[b] Vacuuming Ti64 powder (version 2 M306 printer), depowdering Ti64 part, uncoupling Inconel 718 powder flow bins (M26 sieve station), simultaneous sieving of Inconel 718 powder (M26 sieve station) and 316L stainless steel powder (M27 sieve station).
[c] Italic font denotes a semi-quantitative value, i.e., between the limit of detection and limit of quantification.
Note: Al: aluminum; Cr: total chromium; Cr(VI): hexavalent chromium; Co: cobalt; Cu: copper; Fe: iron; Mo: molybdenum; Ni: nickel; Sn: tin; Ti: titanium.

Table C11. Personal breathing zone air concentrations (in micrograms per cubic meter of air, µg/m³) of metals among powder bed fusion printer room employees (May 15 – 17, 2023)[a]												
Description	T (min)	Vol (m³)	Al	Cr	Cr(VI)	Co	Cu	Mn	Mo	Ni	Tin	Ti
M306 Titanium Printer												
Vacuuming & depowdering	56	0.17	<1.76	5.04	n/a	<0.23	<0.29	<0.23	*0.70*[b]	10.54	<0.35	0.70
Vacuuming & depowdering	91	0.28	<1.08	1.51	n/a	<0.14	<0.18	<0.14	*0.24*	2.77	<0.22	0.57
M14 Tool Steel Sieve Station												
Decommissioning machine	183	0.55	<0.55	1.76	n/a	0.33	<0.09	<0.07	0.47	3.27	*0.16*	*0.07*
M26 Inconel 718 Printer												
Vacuuming & removing part	86	0.27	3.80	8.36	n/a	<0.15	*0.53*	<0.15	1.22	20.90	<0.23	0.49
Vacuuming & removing part	84	0.18			<0.01							
M26 Inconel 718 Sieve Stations												
Maintenance	330	1.01	<0.30	7.20	n/a	<0.04	<0.05	0.53	0.90	5.40	<0.06	0.17
M26 & M27 Sieve Stations												
Sieving & vacuuming	272	0.85	<0.36	1.80	n/a	<0.05	<0.06	*0.07*	0.29	2.64	*0.11*	*0.04*
Occupational exposure limits[c]												
OSHA PEL			15,000	1,000	5	100	1,000	5,000	15,000	1,000	2,000	15,000
NIOSH REL			10,000	500	0.2	50	1,000	1,000	--	15	2,000	--
ACGIH TLV®			1,000	500	0.2	20	1,000	100	10,000	1,500	2,000	10,000

[a] T = air sample duration (minutes), Vol = air sample volume (m³), n/a = not applicable (no sample collected), < = below analytical limit of detection expressed as a concentration based on air sample volume.
[b] Italic font denotes a semi-quantitative value, i.e., between the limit of detection and limit of quantification.
[c] OSHA = Occupational Safety and Health Administration; ACGIH = American Conference of Governmental Industrial Hygienists; NIOSH = National Institute for Occupational Safety and Health; PEL = permissible exposure limit; TLV® = Threshold Limit Value; REL = recommended exposure limit; -- = no exposure limit available
Note: Al: aluminum; Cr: total chromium; Cr(VI): hexavalent chromium; Co: cobalt; Cu: copper; Fe: iron; Mo: molybdenum; Ni: nickel; Sn: tin; Ti: titanium.

Table C12. General area air concentrations of metals (in micrograms per cubic meter of air, µg/m³) in the post-processing room (May 15–17, 2023)[a]

Description	T (min)	Vol (m³)	Al	Cr	Cr(VI)	Co	Cu	Mn	Mo	Ni	Tin	Ti
May 15, 2023												
Near field (grey table)	396	1.23	*0.55*[b]	0.50	n/a	<0.03	<0.04	<0.03	0.37	1.49	<0.05	1.24
Near field (grey table)	397	0.81			0.01							
Far field (desks)	391	1.20	*0.33*	0.44	n/a	<0.03	<0.04	<0.03	0.35	1.35	<0.05	1.01
Far field (desks)	391	0.80			0.01							
May 16, 2023												
Near field (EDM control)	474	1.43	0.84	1.96	n/a	<0.03	1.54	*0.08*	0.84	3.29	<0.04	2.03
Near field (EDM control)	474	0.98			0.02							
Far field (desks)	474	1.42	0.77	1.34	n/a	<0.03	1.27	*0.06*	0.56	2.39	<0.04	2.18
Far field (desks)	474	0.96			0.02							
May 17, 2023												
Near field (EDM control)	480	1.45	*0.24*	2.08	n/a	<0.03	<0.04	<0.03	1.18	6.44	<0.04	0.10
Near field (EDM control)	479	0.96			0.05							
Far field (desks)[c]	136	0.41	<0.74	1.08	n/a	<0.10	<0.12	<0.10	0.59	2.43	*0.29*	<0.02
Far field (desks)	479	1.44	<0.21	1.11	n/a	<0.03	<0.03	<0.03	0.64	3.33	<0.04	*0.03*
Far field (desks)	480	0.97			0.05							

[a] T = air sample duration (minutes), Vol = air sample volume (m³), n/a = not applicable (no sample collected), < = below analytical limit of detection expressed as a concentration based on air sample volume.
[b] Italic font denotes a semi-quantitative value, i.e., between the limit of detection and limit of quantification.
[c] Sampler placed on personal sampling vest at lunch time, but employee did not wear it during afternoon so treated as a replicate far field sample.
Note: Al: aluminum; Cr: total chromium; Cr(VI): hexavalent chromium; Co: cobalt; Cu: copper; Fe: iron; Mo: molybdenum; Ni: nickel; Sn: tin; Ti: titanium.

Table C13. Personal breathing zone concentrations (in micrograms per cubic meter of air, µg/m³) of metals among post-processing room employees (May 16 and 17, 2023)[a]												
Description	T (min)	Vol (m³)	Al	Cr	Cr(VI)	Co	Cu	Mn	Mo	Ni	Tin	Ti
May 16, 2023												
Grinding	183	0.57	*0.86*[b]	1.75	n/a	<0.07	1.79	<0.07	0.52	2.68	<0.11	1.14
Cutting	275	0.82	<0.36	1.82	n/a	<0.05	1.34	*0.11*	0.68	3.41	<0.07	0.74
May 17, 2023												
Cutting	243	0.72	<0.41	1.93	n/a	<0.06	<0.07	<0.06	0.79	5.66	*0.14*	0.08
Occupational exposure limits[c]												
OSHA PEL			15,000	1,000	5	100	1,000	5,000	15,000	1,000	2,000	15,000
NIOSH REL			10,000	500	0.2	50	1,000	1,000	--	15	2,000	--
ACGIH TLV®			1,000	500	0.2	20	1,000	100	10,000	1,500	2,000	10,000

[a] T = air sample duration (minutes), V = air sample volume (m³), n/a = not applicable (no sample collected), < = below analytical limit of detection expressed as a concentration based on air sample volume.
[b] Italic font denotes a semi-quantitative value, i.e., between the limit of detection and limit of quantification.
[c] OSHA = Occupational Safety and Health Administration; ACGIH = American Conference of Governmental Industrial Hygienists; NIOSH = National Institute for Occupational Safety and Health; PEL = permissible exposure limit; TLV® = threshold limit value; REL = recommended exposure limit; -- = no exposure limit available.
Note: Al: aluminum; Cr: total chromium; Cr(VI): hexavalent chromium; Co: cobalt; Cu: copper; Fe: iron; Mo: molybdenum; Ni: nickel; Sn: tin; Ti: titanium.

Table C14. General area air concentrations of aldehydes (in micrograms per cubic meter of air, µg/m³) in the post-processing room (May 15 and 16, 2023)[a]												
Description	T (min)	Vol (m³)	2,5-DMB	Acetald.	Benzald.	Butyrald.	Formald.	Hexald.	Isoval.	Pentanal	Propion.	O,m,p-tol.
May 15, 2023												
Near field (grey table)	397	0.58	<0.09	11.23	2.22	1.24	8.85	5.45	7.83	2.89	1.33	<0.09
Far field (desks)	391	0.68	<0.08	9.13	1.43	0.90	6.77	4.09	6.93	1.89	1.07	<0.08
May 16, 2023												
Near field (EDM control)	474	0.70	<0.07	13.21	1.99	1.26	10.09	7.39	7.25	3.41	1.31	<0.07
Far field (desks)	474	0.70	<0.07	11.73	1.86	1.20	10.01	7.58	4.72	3.72	1.12	<0.07

[a] T = air sample duration (minutes), Vol = air sample volume (m³), 2,5-DMB = 2,5-dimethylbenzaldehyde, Acetald. = acetaldehyde, Benzald. = benzaldehyde, Butyrald. = butyraldehyde, Formald. = formaldehyde, Hexald. = hexaldehyde, Isoval. = isovaleraldehyde, Propion. = propionaldedyde, o,m,p-tol. = o,m,p-tolulaldehyde, < = below analytical limit of detection expressed as a concentration based on air sample volume.

Table C15. General area air concentrations (in micrograms per cubic meter of air, (µg/m³) of metals in the main hall and other areas (May 15 – 17, 2023)[a]												
Description	T (min)	Vol (m³)	Al	Cr	Cr(VI)	Co	Cu	Mn	Mo	Ni	Tin	Ti
May 15, 2023												
In situ bay	46	0.14	<2.13	0.78	n/a	<0.28	<0.36	<0.28	<0.36	<0.43	<0.43	0.36
In situ bay	39	0.08			<0.01							
May 16, 2023												
In situ bay	21	0.06	<4.76	2.06	n/a	<0.63	<0.79	<0.63	<0.79	<0.95	<0.95	*0.40*[b]
In situ bay	21	0.04			<0.02							
Black bench across from inter-lock	463	1.45	*0.37*	0.41	n/a	<0.03	0.36	<0.03	*0.12*	0.51	<0.04	0.99
May 17, 2023												
In situ bay	21	0.06	<4.76	2.06	n/a	<0.63	<0.79	<0.63	<0.79	<0.95	<0.95	<0.16
In situ bay	17	0.03			<0.03							
Black bench across from inter-lock	515	1.61	<0.19	0.47	n/a	<0.03	<0.03	<0.03	0.27	1.33	<0.04	<0.01
Administrative office suite	241	0.72	<0.41	*0.09*	n/a	<0.06	<0.07	<0.06	<0.07	<0.08	*0.10*	<0.01

[a] T = air sample duration (minutes), Vol = air sample volume (m³), 2,5-DMB = 2,5-dimethylbenzaldehyde, Acetald. = acetaldehyde, Benzald. = benzaldehyde, Butyrald. = butyraldehyde, Formald. = formaldehyde, Hexald. = hexaldehyde, Isoval. = isovaleraldehyde, Propion. = propionaldedyde, o,m,p-tol. = o,m,p-tolulaldehyde, < = below analytical limit of detection expressed as a concentration based on air sample volume

[b] Italic font denotes a semi-quantitative value, i.e., between the limit of detection and limit of quantification

Note: Al: aluminum; Cr: total chromium; Cr(VI): hexavalent chromium; Co: cobalt; Cu: copper; Fe: iron; Mo: molybdenum; Ni: nickel; Sn: tin; Ti: titanium.

Table C16. General area air concentrations (in micrograms per cubic meter of air, µg/m³) of aldehydes in the main hall and other areas (May 15 and 16, 2023)[a]

Description	T (min)	Vol (m³)	2,5-DMB	Acetald.	Benzald.	Butyrald.	Formald.	Hexald.	Isoval.	Pentanal	Propion.	o,m,p-tol.
May 15, 2023												
In situ bay	44	0.06	<0.77	12.29	*1.26*[b]	*1.34*	8.60	*1.84*	3.69	*1.09*	<0.77	<0.77
May 16, 2023												
In situ bay	21	0.03	<1.59	22.54	*2.76*	*1.81*	9.21	<2.22	*2.06*	<1.90	*3.17*	<1.59

[a] T = air sample duration (minutes), Vol = air sample volume (m³), n/a = not applicable (no sample collected).
[b] Italic font denotes a semi-quantitative value, i.e., between the limit of detection and limit of quantification.

Section D: Occupational Exposure Limits

NIOSH investigators refer to mandatory (legally enforceable) and recommended occupational exposure limits (OELs) for chemical, physical, and biological agents when evaluating workplace hazards. OELs have been developed by federal agencies and safety and health organizations to prevent adverse health effects from workplace exposures. Generally, OELs suggest levels of exposure that most employees may be exposed to for up to 10 hours per day, 40 hours per week, for a working lifetime, without experiencing adverse health effects.

However, not all employees will be protected if their exposures are maintained below these levels. Some may have adverse health effects because of individual susceptibility, a preexisting medical condition, or a hypersensitivity (allergy). In addition, some hazardous substances act in combination with other exposures, with the general environment, or with medications or personal habits of the employee to produce adverse health effects. Most OELs address airborne exposures, but some substances can be absorbed directly through the skin and mucous membranes.

Most OELs are expressed as a time-weighted average (TWA) exposure. A TWA refers to the average exposure during a normal 8- to 10-hour workday. Some chemical substances and physical agents have recommended short-term exposure limits (STEL) or ceiling values. Unless otherwise noted, the STEL is a 15-minute TWA exposure. It should not be exceeded at any time during a workday. The ceiling limit should not be exceeded at any time.

In the United States, OELs have been established by federal agencies, professional organizations, state and local governments, and other entities. Some OELs are legally enforceable limits; others are recommendations [OSHA 2021].

- OSHA, an agency of the U.S. Department of Labor, publishes permissible exposure limits [29 CFR 1910 for general industry; 29 CFR 1926 for construction industry; and 29 CFR 1917 for maritime industry] called permissible exposure limits (PELs). These legal limits are enforceable in workplaces covered under the Occupational Safety and Health Act of 1970.
- NIOSH recommended exposure limits (RELs) are recommendations based on a critical review of the scientific and technical information and the adequacy of methods to identify and control the hazard. NIOSH RELs are published in the *NIOSH Pocket Guide to Chemical Hazards* [NIOSH 2020]. NIOSH also recommends risk management practices (e.g., engineering controls, safe work practices, employee education/training, PPE, and exposure and medical monitoring) to minimize the risk of exposure and adverse health effects.
- Another set of OELs commonly used and cited in the United States include the threshold limit values or TLV®s, which are recommended by the American Conference of Governmental Industrial Hygienists (ACGIH®). The ACGIH TLVs are developed by committee members of this professional organization from a review of the published, peer-reviewed literature. TLVs are not consensus standards. They are considered voluntary exposure guidelines for use by industrial hygienists and others trained in this discipline "to assist in the control of health hazards" [ACGIH 2024].

Outside the United States, OELs have been established by various agencies and organizations and include legal and recommended limits. The Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (Institute for Occupational Safety and Health of the German Social Accident Insurance) maintains a database of international OELs from European Union member states, Canada (Québec), Japan, Switzerland, and the United States. The database, available at https://www.dguv.de/ifa/gestis/gestis-stoffdatenbank/index-2.jsp, contains international limits for more than 2,000 hazardous substances and is updated periodically.

OSHA (Public Law 91-596) requires an employer to furnish employees a place of employment free from recognized hazards that cause or are likely to cause death or serious physical harm. This is true in the absence of a specific OEL. It also is important to keep in mind that OELs may not reflect current health-based information.

When multiple OELs exist for a substance or agent, NIOSH investigators generally encourage employers to use the lowest OEL when making risk assessment and risk management decisions.

Aluminum (Al)

	micrograms per cubic meter of air (µg/m³)
OSHA PEL	15,000
NIOSH REL	10,000
ACGIH TLV®	1,000

Chromium (Cr)

	micrograms per cubic meter of air (µg/m³)
OSHA PEL	1,000
NIOSH REL	500
ACGIH TLV®	500

Chromium (VI) [Cr(VI)]

	micrograms per cubic meter of air (µg/m³)
OSHA PEL	5
NIOSH REL	0.2
ACGIH TLV®	0.2

Cobalt (Co)

	micrograms per cubic meter of air(µg/m³)
OSHA PEL	100
NIOSH REL	50
ACGIH TLV®	20

Copper (Cu)

	micrograms per cubic meter of air($\mu g/m^3$)
OSHA PEL	1,000
NIOSH REL	1,000
ACGIH TLV®	1,000

Manganese (Mn)

	micrograms per cubic meter of air($\mu g/m^3$)
OSHA PEL	5,000
NIOSH REL	1,000
ACGIH TLV®	100

Molybdenum (Mo)

	micrograms per cubic meter of air ($\mu g/m^3$)
OSHA PEL	15,000
NIOSH REL	--
ACGIH TLV®	10,000

Nickel (Ni)

	micrograms per cubic meter of air ($\mu g/m^3$)
OSHA PEL	1,000
NIOSH REL	15
ACGIH TLV®	1,500

Tin (Sn)

	micrograms per cubic meter of air ($\mu g/m^3$)
OSHA PEL	2,000
NIOSH REL	2,000
ACGIH TLV®	2,000

Titanium (Ti)

	micrograms per cubic meter of air ($\mu g/m^3$)
OSHA PEL	15,000
NIOSH REL	--
ACGIH TLV®	10,000

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