Task 4. Request for Proposals:

2025

Life Support Systems: Dust Mitigation in Lunar Habitats

Sponsored by the New Mexico Space Grant Consortium

This is the full Task 4 Problem Statement. Major updates have been made since the Task 4 Overview was published. Updated 9/30/24 to increase flexibility in the bench-scale demo.

Task

Your crew has just landed on the moon and embarked on a 30-day mission. They're transporting a cargo container containing logistics and supplies to the newly commissioned lunar surface habitat. The area of the lunar habitat where crew will live and work is separated from the lunar surface by an airlock, an isolated volume that the crew uses to don/doff spacesuits, conduct repairs, store equipment, and transfer supplies between the lunar surface and the habitat. When the crew returns from a mission on the lunar surface, their suits and everything they need to bring back into the habitat is covered with dust. When the spacesuits, dusty containers, etc. enter the airlock, a dust-removal system (designed by your team) completely removes dust from its surface. The dust-removal system prevents dust from intruding into the habitat's volume, where it could pose a danger to crew and systems equipment. Successful designs may help the space industry identify new approaches that will help humanity return to the Moon and possibly prepare for eventual missions to Mars.

Background

When the next crew sets foot on the surface of the Moon during the Artemis Program, they will be performing extravehicular activities (EVAs) to conduct science and engineering studies. These studies will develop technologies in support of future exploration to help us better understand how humans can live beyond Earth [1, 2]. NASA's plans for a long-term sustainable presence on the Moon includes a progressive increase in habitation capability that will eventually support crews of four for 30 days or longer.

A primary challenge in lunar exploration is the potential for large amounts of lunar dust to cling to equipment and spacesuits during EVAs, then enter a vehicle or a habitat when the crew returns from exploring the lunar surface. Dust has been a matter of concern since the Apollo missions, as it compromises crew health and damages equipment. Because future lunar explorers will need solutions to this problem, NASA is testing dust-mitigation technology for lunar habitats and hopes to apply these technologies toward future missions to Mars.

Lunar Regolith

Regolith, whether on Earth, Moon, Mars, etc., is the layer of unconsolidated sediments that lie on top of solid bedrock. Lunar regolith varies in thickness from 5-10 m on the lunar surface; it is categorized by particle size, with soil and dust being the smallest particles. Lunar dust includes particles 0.5-50 µm in diameter. Roughly 10% to 20% of lunar soil is on the lower end of this range, being finer than 20 µm [3, 4].

Characteristics of Lunar Dust

Lunar dust consists of fine or ultrafine particulates and has a very sharp morphology since no weathering processes are active on the Moon to smooth the edges. The dust is highly variable in shape but tends to be elongated, causing the particles to pack together along the long axes. As particle size decreases, adhesive, cohesive, and excitatory forces become very strong, causing them to stick together and tightly adhere to spacesuits, tools, equipment, and lenses. An additional challenge is solar radiation that creates a positive electrical charge on the dust, causing it to cling even more tightly to surfaces [4, 5].

Damage Caused by Lunar Regolith Dust

As was discovered during the Apollo missions, lunar dust can be dangerous to a mission due to its sharp edges and small particle size. After three Apollo EVAs, the suit bearings became so highly contaminated with dust that the astronauts had difficulty moving, and a fourth EVA would not have been possible. In addition, the dust was found to have toxic properties. During their return to Earth in the Lunar Module, microgravity was reestablished, causing the dust on the suits to become airborne and float through the cabin. It damaged instruments and caused respiration hazards and cytotoxicity in the crew [3, 6, 7].

For humanity's return to the Moon, measures must be taken to ensure that lunar dust does not compromise crew health and performance, contaminate products used by the crew, or damage systems equipment. Fans, bearings, and other rotating equipment are particularly susceptible to dust damage [5, 7, 8]. Refer to Chapter 4 of Ewert, et al. [8] for an overview of the effects of dust exposure on NASA life-support systems.

Equivalent Mass: Evaluating Space Systems

Instead of the traditional techno-economic analysis, the space industry frequently evaluates the affordability of a project using the system's "equivalent mass." Equivalent System Mass (ESM) reduces all elements of a technology into a single parameter that is stated in units of mass. Mass is used as the standard for this evaluation method because it is a major factor in the cost of launching mass into space. ESM for space technologies typically includes mass, volume, power, cooling, and crew time. Teams will evaluate ESM for each of these factors. Refer to the "Advanced Life Support Equivalent System Mass Guidelines" [9] for more information about computing ESM.

Systems and Process Planning

NASA currently plans for the crew to enter and egress a habitat once every other day. Supplies will arrive on the lunar surface at the beginning of the mission and will be staged outside the habitat. The crew will load a portion of the supplies into the habitat every 7 days.

Since crew time is a scarce and costly resource, ideal solutions will minimize operational complexity to ensure that minimal crew time is spent on training, use, maintenance, or repair. This may drive teams to automation or ground-commanded control. Designs should also ensure crew safety (See NASA Technical Standards 6001 [10]) while minimizing energy requirements, material volume, and mass.

Note that there are multiple objectives for this challenge and many variables to consider. Designs need to be optimized to prevent the crew's and the habitat system's exposure to lunar dust. Optimizing these many variables is a challenge that the space industry has faced for decades. To address these issues, teams are encouraged to engage industrial engineers and human-factors engineers as a part of their team.

WERC Guidelines for Implementing Dust-Mitigation for Lunar Habitats

Current plans for lunar habitats will place an airlock between the exterior lunar surface and the interior habitation area. Dust removal will be performed within the airlock to prevent dust from entering the habitat. This is the primary line of defense for dust mitigation. A second line of defense, not addressed in this design challenge, would be removing any dust that does enter the habitat.

Spacesuits and CTB Prototypes

NASA has identified two primary items that will need to be cleaned in the airlock: space suits and cargo transfer bags (CTB). Teams will select and design one of these items for testing their dust-removal system.

NASA is engaging Axiom Space Inc. to design the next generation spacesuit; suit testing is currently underway [11]. Teams interested in removing dust from spacesuits may research current technologies and spacesuit materials, propose innovations, if warranted, and design an appropriate dust-mitigation approach.

The concept of a CTB is lesser known. CTB have been used to organize, stow, and carry supplies and equipment in space since the 1990s when they were designed for the Shuttle and Spacehab (See [12] for a history of the CTB). (*Note: You may find references in the literature for a "notional logistics container." This is a more general term for a cargo container that is still in the conceptual stages and is not specifically a CTB.)*

CTB were designed to hold a volume of 0.053 cubic meters, and this became a standard unit of measure called the Cargo Transfer Bag Equivalent (CTBE). The CTBE is still used today, and CTB have historically been made in sizes that are one-third, one-half, two times, three times, etc. that of CTBE. Each of these sizes is referred to, respectively, as ⅓CTBE, ½CTBE, 2CTBE, 3CTBE, etc.

Traditionally, CTB have been made of fabric, and have been designed to be multi-purpose (foldable, used as shelving when not carrying cargo, etc.). The current fabrics and construction tend to retain dust, therefore the space industry is exploring new designs for Artemis. Considerations in the design include: equip the CTB with handles and transparent panels to allow the contents to be viewed from outside the bag. (See [13], Section IX for CTB details.) Teams are encouraged to identify dust-resistant materials or materials that will facilitate dust removal in some other way. In the technical report, teams working on the CTB should draw up plans to demonstrate that their materials can meet the requirements described in this paragraph.

When preparing for the bench-scale demonstration, the selected item prototype (spacesuit or CTB) may be built as a simple box of appropriate volume (see Bench-scale Demonstration, pp. 5-7), and covered with the selected material(s), or it may be a partially- or fully-constructed prototype of the selected item. For example, a partial spacesuit prototype may be a segment of a sleeve. Whether covering a simple box or constructing a partial or full prototype for the bench-scale demonstration, teams should provide diagrams in the technical report that illustrate how their bench-scale prototype correlates to a full-scale item.

Dust-mitigation Strategies

A number of dust-mitigation strategies are being pioneered. These include electrostatic treatments that use electrical energy to disperse dust and physical removal systems that include a variety of agitation or cyclone technologies. Teams are encouraged to identify gaps in existing technology by thinking outside the box and finding creative new ways to prevent dust from entering the habitat.

You may consider an innovative tiered approach in which multiple new or existing technologies would be implemented in tandem or in series to yield optimal results. If in series, consider the optimal sequence from both an effective dust-removal perspective and a systems perspective. There are no constraints set on your approach, only that it will be operable within the WERC-provided "airlock" chamber and have an optimized ESM. For a review of some technologies currently being explored and laboratory techniques for working with dust, see reference [14], though you might find additional approaches in the published literature.

Although the moon's gravity is ⅙ of Earth's, teams are not required to simulate reduced gravity for their bench-scale demonstrations because such simulations would be difficult to achieve under WERC's contest conditions. In the technical report, teams should address the predicted outcome of their solution at ⅙ of Earth's gravity and present supporting analyses.

Problem Statement

Your challenge is to research, design, and demonstrate a method for preventing dust from entering a lunar habitat by effectively removing lunar dust simulant from an object while it is in an airlock and prior to it entering the habitat's volume.

The team-designed object, representing a spacesuit or a CTB, shall be covered in hardgoods or soft goods, or a combination of these, that are selected to enhance your process. The team-built bench-scale dust-removal system shall fit inside a simulated airlock provided by WERC, as described on pp. 6-7, unless other arrangements are made.

Success will be judged primarily by the percent of dust reduction due to the dust-mitigation system, and its ESM: ease of use, minimization of crew time, expected reliability, and conservation of power, volume, and mass. See Bench-scale Demonstration, below, for more bench-scale parameters.

Design Considerations

Your proposed design should provide specific details and outcomes as follows:

- Review available literature on the mechanical properties of lunar dust, Apollo lessons learned, and the fundamentals of dust mitigation borrowed from lunar and other applications. Generate concepts for your solution, narrow the focus to a small number of options, then fabricate one or more prototypes of dust mitigation processes; test and iterate.
- Design a dust-mitigation system that strikes an appropriate balance between minimizing crew time (simplicity in setup, training, operation, and maintenance), energy to operate, mass, volume, footprint, and cost.
- The system will operate in Earth's gravity. Address in the technical report: the design's applicability in ⅙ Earth's gravity at the lunar surface, and document your conclusions.
- Include a complete process flow diagram in your technical report showing all inputs, outputs, and processes, and documenting appropriate mass and energy balances.
- Follow the Bench-scale Demonstration criteria for building the bench-scale prototype item (CTB or space suit) from which dust will be removed.
    - Select exterior materials. These may include hard goods, fabric, soft goods, dust-resistant materials, etc.
    - The surface materials must be abrasion- and impact-resistant, durable, and suited for use in space. Provide supporting evidence for this in the technical report.
    - Include diagrams in the Technical Report that illustrate a full-scale design of your item prototype.
- Follow the Bench-scale Demonstration criteria for building the bench-scale dust-removal system. Your team's plans for transferring an item from the lunar surface to the airlock to the habitation area shall be included in the technical report, but is not expected in the bench-scale demonstration.
- Ensure that the dust-removal process does not damage the surface of the container either due to the mechanisms that remove the dust nor by dragging dust particles against the prototype.
- Conduct an engineering analysis on the ability to scale the process so that it can be integrated into an actual lunar habitat airlock and be able to clean multiple full-size objects (of size 1·CTBE) in a reasonable amount of time. These factors will be addressed in the technical report, but are not required of the bench-scale demonstration:
    - Time needed for the system to complete the cleaning of one item and for cleaning a set of 4 similar items. Cleaning of multiple items may be conducted in any way chosen by the team (in bulk or one at a time, etc.). Consider, as applicable to your design, the expected frequency and time requirements for recharging or resetting equipment between cleaning jobs, disposing of dust, cleaning the system itself, etc.)
    - Containment, disposal, and/or re-use of the dust collected during cleaning.
    - Expected power usage, volume, and mass;
    - Operational controls for item transfer from the lunar surface to the airlock and then to the habitat: Consider automation vs interaction by crew members or ground control. Provide supporting documentation.
    - Expected effect on crew members' workload (direct interaction, time, convenience, etc.);
    - Expected routine maintenance of the system;
    - Modularity of parts in the event of repairs, maintenance, etc.

- Consider safety concerns for the crew, including dust exposure, off-gassing, flammability, etc. [10].
- Evaluate the possibility of waste products or by-products being produced by your system (in addition to collecting dust). If there is a potential for these, address how they will be disposed or retained for another use.
- Present a Techno-Economic Analysis (TEA) to construct and operate a full-scale dust-mitigation system for a lunar habitat airlock; The TEA will include your estimate of capital costs (CAPEX) and operational costs (OPEX) for a full-scale solution, expected revenue (if applicable) and appropriate graphical representation of your cost data. Include:
  - Capital expenses: These typically include, but are not limited to, equipment, pipes, pumps, electronics, etc. needed to build the system as well as any surface materials required. Do not include costs of buildings in which the dust-removal system will be manufactured. Do not include the cost of the airlock, unless its design is a specific and integral part of the dust-mitigation design.
  - Operating expenses: These should be calculated as the cost for launch, based on total ESM. Equivalent mass considerations include crew time, consumables, repair parts, power, cooling, mass, volume, etc. (see [9]).
  - Crew time: Conduct human-in-the-loop testing in your lab.
  - Visualization tools: Sensitivity analyses, cash flow diagrams, etc.
- Address safety aspects of handling the dust or cleaning equipment. Safety issues for the full-scale design should be included in the technical report. Safety issues and PPE needed for the bench-scale demonstration should be addressed in both the written report and the Experimental Safety Plan (ESP).

Bench Scale Demonstration

Teams will demonstrate a bench-scale design that will clean lunar dust simulant from a team-provided CTB or spacesuit prototype.

To reduce the amount of bulky equipment your team needs to bring to the contest, WERC will provide three sealed chambers (see Figure 1) representing the lunar surface, the airlock, and the lunar habitation area. The test chambers will provide a controlled test environment designed to prevent dust from escaping into public spaces at the contest. If this configuration does not suit your team's needs, either 1) send us suggested modifications to the chambers or 2) bring your own sealed airlock chamber. In either case, notify WERC immediately of your request and/or plans, and address this in the ESP (werc@nmsu.edu).

At the bench-scale demonstration, WERC will arrange to transfer the team's prototype item from the "lunar surface" to the "airlock." WERC will contact your team to determine the best method of transfer, based on your design. After the dust is removed, WERC will transfer the prototype item into the "habitat". Teams are not expected to build mechanisms for transferring their prototype from chamber to chamber. Plans for this are expected only in the technical report.

Lunar Regolith Simulant

The lunar regolith dust to be used in the bench-scale demonstrations is simulant LHS-1 (from Space Resources Technologies/Exolith Labs) [15]. As of this writing, the simulant has a median particle size of 51 µm and costs $45/Kg. To test your bench-scale apparatus at your home institution, purchase new batches of the simulant directly from the manufacturer. Do not use older regolith (particularly that produced before 08/01/23) because LHS-1 has gone through at least 3 feedstock changes that could produce variable results during testing. Adhering to these standards will ensure consistency among teams. During the contest, WERC will provide newly purchased LHS-1 simulant for all teams.

Safe Handling of Lunar Regolith Simulant

Fine dust is a potential health hazard. Teams are advised to consult with their school's safety officer regarding safe handling at their home institution. At the contest, WERC will engage NMSU's EH&S Department and the WERC Safety Officer to conduct a careful review of your team's ESP. They will monitor the bench-scale demonstrations at the contest in April to ensure safe handling of the dust.

Teams will provide at the contest:

- A prototype item (spacesuit or CTB) designed by the team from which dust will be removed.
    - This item may be either a fully or partially designed spacesuit or CTB, or it may be a simple rectangular parallelopiped covered with team-selected material(s).
    - The prototype shall be comparable in size to ½ CTBE*.
    - All items shall be sized to easily pass through a 20" x 20" square opening*. The third dimension may be longer.
    - The exterior may include materials that are currently used in the space industry for your selected item or may include innovative materials that minimize dust accumulation and/or improve the performance of your dust-removal system. The materials may be made of either soft or hard goods. In either case, provide supporting evidence that the selected material is feasible for use in space expeditions and is feasible for your selected item.
- A functional bench-scale dust-mitigation system that is compatible with the WERC-provided test chambers* that can remove dust from the surface of the team's selected item.

** If your team wishes to use a larger prototype or requires larger testing chambers, we are happy to work with you. Contact WERC as soon as possible and also note this in the ESP. If this is a nearly universal request, WERC will increase the size of the CTB/spacesuit and/or the chambers—watch the FAQs for updates.*

WERC will provide at the contest*:

- As a guideline for bench-scale testing, WERC will consult NASA-STD-1008 [16].
- Testing chambers (Figure 1), with each plexiglass chamber currently planned to have exterior dimensions of 36"L x 36" W x 40" H. Thickness of the chamber walls will be approximately ¼".
- Devices for analytical testing, high-resolution digital cameras, and a means of loading dust onto each team's prototype item.
- LHS-1 simulant.
- Dust-removal supplies (sprays, cloths, etc.) for cleaning the chambers between demonstrations.
- A means of transferring your item from chamber to chamber. WERC will contact your team to determine the best means of conducting the transfers.
- Additional bulky items requested by your team, if needed. Although teams will provide the majority of items needed for the bench-scale demonstration, you may submit requests to WERC by February 26, 2025 for additional bulky items (large, but low-cost) needed to run the bench-scale demonstration at the contest. (*See Team Manual*). As an example, for water-based projects, these often include kiddie wading pools for secondary containment.

*** It is imperative that you contact WERC to let us know your testing-chamber requirements as soon as you have tentative plans. We cannot anticipate all of the variables that are possible in teams' innovative designs, and we would like to work with you to make sure you have what you need to demonstrate your technology.*

WERC-Provided Testing Chamber Details (See Figure 1, next page):

Chamber dimensions and features:

- Exterior dimensions: 36"W x 36"D x 40"H;
- Pass-through cutouts for cargo transfer between chambers that will allow an object that is 20” x 20” or smaller in cross-section to pass through. (*It is possible that the pass-through cutouts are not needed. WERC will make this decision after assessing every team’s dust-removal plans);*
- Sealed vertical-sliding access doors between chambers (*If pass-through cutouts are used*);
- Large access door on the back of the airlock chamber to allow for equipment load-in. Additional access doors may be added.

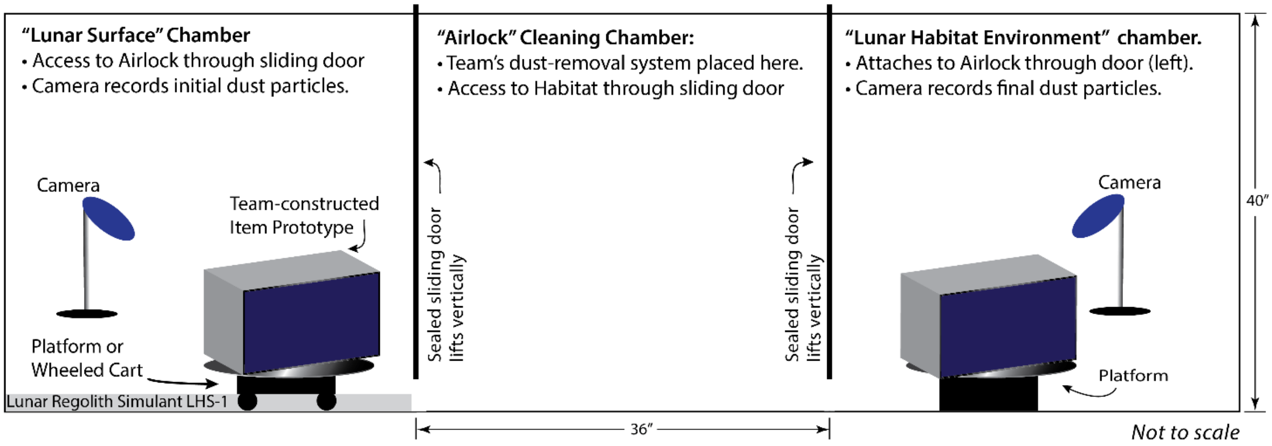

Figure 1. Schematic of Bench-scale demonstration chambers provided by WERC. (*Subject to change.)*

Chamber 1: “Lunar Surface.” Pre-loading of dust will be conducted here (method TBD, depending on all teams’ designs). The chamber will contain LHS-1 lunar regolith dust simulant, a platform (or wheeled cart) on which the prototype item will be placed, and a high-resolution digital camera to record initial dust amounts while the prototype item rests on the platform.

Chamber 2: “Airlock.” Prior to your bench-scale demonstration, your team will clean chambers 2 and 3, to remove excess dust, and then set up your dust-mitigation system within the airlock. To allow room for teams to set up their dust-cleaning system within the chamber, this space will not contain any WERC equipment.

Chamber 3: “Lunar Habitat Environment.” The lunar habitat environment will contain a high-resolution digital camera. The camera will record the final dust amounts remaining on the prototype item while the item rests on a platform (or the wheeled cart).

Chamber Transitions: Contact WERC as soon as you can to suggest the best way for item transfer from chamber to chamber. One possibility could include placing the prototype item on a cart while it is in Chamber 1, rolling the cart and the prototype item it is carrying into Chamber 2 for dust removal, and finally rolling the cart into Chamber 3 for dust analysis. The access doors would slide up/down to allow access between chambers and would be fitted with gaskets to prevent dust from escaping during the demonstration. However, the wheeled cart might obstruct the space needed for your dust-removal equipment.

This is an interesting challenge in experimental design, and we are flexible! Contact us to propose method(s) of transfer from chamber to chamber.

Contest Analytical Testing:

Equipment Prototype Requirements

The materials used to cover your prototype item should be technically and logistically feasible for its application, including being tear-, scratch- and impact-resistant. This will be evaluated based on evidence your team presents in the technical report, bench-scale demonstration photographs taken before and after cleaning, and the judges' assessments of the material's integrity.

Analytical Testing

To test your system's success at removing dust from your prototype, WERC will use high-resolution cameras to conduct dust-particle point counts before and after cleaning. If your system would benefit from a different dust-measurement method, email WERC and also suggest an alternative dust-measurement protocol in your ESP.

Evaluation Criteria

Each team is advised to read "Evaluation Criteria" and "Contest Scoring" in the 2025 Team Manual for a comprehensive understanding of the contest evaluation criteria. For a copy of the Team Manual, Public Involvement Plan, and other important resources, visit the WERC website: Guidelines | werc.nmsu.edu

In addition to evaluation criteria that applies to every task, judges will evaluate your team's response to the problem statement, with consideration of the Design Considerations listed above.

Experimental Safety Plan (ESP) and Required On-Demand Short Course.

All members of your team are required to attend the ESP Preparation short course. Due dates are listed below. See team manual for details.

Specific to this task, email WERC (werc@nmsu.edu) and include in the ESP any special requests for bench-scale testing (item size, chamber size, means of transporting your team's item between test chambers.

Dates, Deadlines, FAQs (*dates subject to change—watch website FAQs*)

- Today: Email us to let us know you are interested in this task. We will contact you with breaking news, including any changes to the bench-scale testing procedures. (werc@nmsu.edu)
- Any time: Keep us posted on your bench-scale demo needs: chamber size, cutouts, item transfer.
- October 15, 2024 - December 31, 2024 – Early Bird Registration (discount applies).
- December 1, 2024 - February 20, 2025: Mandatory On-demand Course: Preparing the Experimental Safety Plan. See website and Team Manual for information.
- February 17 - 26, 2025: Experimental Safety Plan (ESP) due. Include requests for volume of brine concentrate and ancillary equipment needed at the contest.
- March 7, 2025: Late-registration deadline. Final date to register a team.
- March 31, 2025: Technical Report due
- Weekly: Check FAQs weekly for updates:
  - Task-specific FAQs: 2025 Tasks/Task FAQs
  - General FAQs: 2025 General FAQs
- All dates or task requirements are subject to change. Check FAQs for updates online.

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