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DESIGN OF A DEVICE TO REMOVE LUNAR DUST FROM SPACE SUITS FOR THE PROPOSED LUNAR BASE

Submitted to:

Mr. James Aliberti

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MECHANICAL ENGINEERING DESIGN PROJECTS PROGRAM
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April 9, 1990

Mr. James Aliberti
Mail Stop PT-PMO
Kennedy Space Center
Florida 32899

Dear Mr. Aliberti:

Enclosed is our final report for the project entitled "Design of a Device to Remove Lunar Dust from Space Suits for the Proposed Lunar Base." This report contains a discussion of lunar dust properties, a detailed description of the dust removal device, and recommendations for further development and investigation.

The team is looking forward to seeing you at the final design presentation. The presentation is scheduled for Tuesday, April 24, 1990 at 9:00 a.m. in Engineering Teaching Center II, room 4.110, on campus at The University of Texas at Austin. A catered luncheon will be provided at noon.

Sincerely,

David Harrington

David Harrington, Team Leader

Jack Havens

Jack Havens

Daniel Hester

Daniel Hester

ACKNOWLEDGEMENTS

The team would like to thank the National Aeronautics and Space Administration (NASA), the Universities Space Research Association (USRA), and Mr. James Aliberti from Kennedy Space Center for sponsoring this project.

Special thanks to Dr. Kris Wood, our faculty advisor, and Mr. Richard Connell, teaching assistant, for their eagerness to help with both technical and nontechnical problems.

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The team would like to express their appreciation to Dr. Steven P. Nichols for coordinating the ME 366K Senior Design Projects Program and the lectures throughout the semester.

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The team would also like to thank Mr. Bert Herigstad, Design Projects Administrative Assistant, for his assistance throughout the project.

ABSTRACT

DESIGN OF A DEVICE TO REMOVE LUNAR DUST FROM SPACE SUITS FOR THE PROPOSED LUNAR BASE

The National Aeronautics and Space Administration (NASA) plans to begin construction of a lunar base soon after the turn of the century. During the Apollo missions, lunar dust proved to be a problem because the dust adhered to all exposed material surfaces. Since lunar dust will be a problem during the establishment and operation of this base, the need exists for a device to remove the dust from space suits before the astronauts enter clean environments.

The physical properties of lunar dust were characterized and energy methods for removing the dust were identified. Eight alternate designs were developed to remove the dust.

The final design uses a brush and gas jet to remove the dust. The brush bristles are made from Kevlar™ fibers and the gas jet uses pressurized carbon dioxide from a portable tank. A throttling valve allows variable gas flow. Also, the tank is insulated with Kapton™ and electrically heated to prevent condensation of the carbon dioxide when the tank is exposed to the cold (-240 degrees Fahrenheit) lunar night.

Key Words: Dust Removal, Lunar Soil, Clean Room

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INTRODUCTION

The United States National Aeronautics and Space Administration (NASA), established in 1957, is the government agency which operates the United States space program. NASA also conducts general aerospace research. In 1969, the Universities Space Research Association (USRA) was established by the National Academy of Sciences. The USRA, based at the Johnson Space Center in Houston, Texas, coordinates interaction between NASA and universities across the nation. One program administered by the USRA is the University Advanced Design Program. This program allows engineering students to work on projects of interest to NASA and develop innovative solutions to real-world problems.

A project submitted to The University of Texas at Austin Mechanical Engineering Design Projects Program is the design of a system for the removal of lunar dust from material surfaces.

This report describes the properties of lunar dust, eight alternate design concepts, the design solution, and gives recommendations for an improved design. Suggested avenues for further investigation are also given in the recommendations section.

Background

NASA has been interested in lunar dust since the beginning of the Apollo program. Some scientists believed that the moon was covered with a layer of dust which was many kilometers deep. This led to concern that lunar excursion modules (LEM) would sink into the dust, endangering the safety of the astronauts. Although the modules did not sink, the astronauts found that lunar dust was still a problem. It adhered to space suits, camera lenses, and all other exposed surfaces. In addition, the abrasive characteristics of the dust made it difficult to remove without damaging a material's finish.

When the astronauts reentered their LEM, they brought some of the dust with them on their space suits and equipment. This dust became a problem in the zero-gravity of space. The clouds formed by the loose dust obscured vision and caused breathing problems.

Recently, there has been a renewed interest in establishing a lunar base. Lunar dust will be a problem during the establishment and operation of the base. Since the dust is composed of hard oxides, it causes pitting and scoring of moving parts and mating surfaces. Also, surfaces on camera lenses or mirrors are easily scratched by the dust.

The purpose of this project was to design a device which can safely remove lunar dust from a material's surface. The following are the project requirements and design criteria.

Project Requirements

1. Characterize the physical properties of lunar dust based on available data. This includes the mechanical, chemical, and electrical properties of the lunar dust.

2. Design a system or set of devices which will remove the dust from various surfaces without damaging the finish.

3. If time allows, construct a working model to demonstrate the operating principle.

Design Criteria

1. The device should consume a minimum amount of power.

2. The device should use available resources; it should not require large amounts of precious materials, such as oxygen or water.

3. The device should be rugged, easy to use, and easy to maintain.

4. The device should be effective in removing the dust from material surfaces.

5. The device should be lightweight and portable.

6. The device should be versatile. It should be usable for the various geometries and materials of objects commonly encountered in space and lunar applications.

Solution Methodology

The team approached the lunar dust project using the previously stated requirements and criteria as guidelines. The solution was obtained using the following outline:

1. General research,
2. Creation of alternatives,
3. Selection of alternatives,
4. Development of alternatives, and
5. Investigation of prototype(s).

General research included patent searches, and examination of available information in books and periodicals. The research was directed towards characterization of the dust, investigation of energy domains capable of removing the dust, and classification of objects targeted for dust removal. The energy domains included, mechanical, electrostatic, and chemical energy.

The creation of alternatives involved formulating different methods of removing the dust from various surface types. The devices generated, removed the dust using the different energy domains.

Using a decision matrix, the team selected the alternative which optimized the balance between effectiveness and versatility. This alternative was developed into the final design solution. The design solution allows dust removal from many of the materials and geometries commonly encountered in space and lunar applications.

During the design process, the team consulted with Dr. Kristin Wood, faculty advisor, and Mr. Richard Connell, design project teaching assistant, both from The University of Texas at Austin Mechanical Engineering Department, for help and suggestions in the development of the design solution.

ALTERNATE DESIGNS

The project requirements, design criteria, and solution methodology for the removal of lunar dust from a material's surface were discussed in the previous chapter. In this chapter, alternate designs for removing the dust are presented. First, important physical properties of lunar dust such as particle size, density, chemical composition, abrasiveness, adhesiveness, and cohesiveness are presented. Next, the design approach used to generate the design alternatives is outlined. Finally, eight alternate designs, including each design's advantages and disadvantages, are discussed.

Lunar Dust Characteristics

Before designing a dust removal system, the physical properties of lunar dust must be understood. Several of the most important physical properties of the dust are discussed below. These properties are: size distribution, density, chemical composition, abrasiveness, adhesion, and cohesion. Several other properties are discussed in Appendix A.

Size Distribution. Much research has been done on samples of dust collected during the Apollo missions. One typical set of data showed that the particle size distribution for lunar dust ranged from less than 0.2 microns to over 400 microns in diameter [4]*.

Density. The density of lunar dust ranges from approximately 1.0 to 2.0 grams per cubic centimeter (g/cm^3) [7]. The team assumed an average density of 1.5 g/cm^3.

Chemical Composition. The dust particles are composed of various oxides with silicon oxide, aluminum oxide, calcium oxide, iron oxide, and magnesium oxide accounting for more than ninety percent of the composition of the dust [8].

Abrasion. Hardness and the shape of the particles are the most important factors influencing abrasiveness. Since the oxides in lunar dust are very hard and the particles have many sharp edges, the dust is very abrasive.

Adhesion. The adhesion of lunar dust to a surface is mainly due to electrostatic forces. For large dust grains, these forces are due to an electrostatic dipole moment. The dipole moment creates an induced mirror charge on the surface to which the dust is adhered. For smaller grains, adherence is due to Van der Waals forces [5].

Surveyor III, an unmanned exploratory lunar probe, was on the moon for 2.6 years. While on the moon, Surveyor III was covered with a layer of dust. When parts of Surveyor III were

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* All references are listed in alphabetical order on page 48.

returned to Earth on Apollo 12, examination of these parts showed that the dust adhered to painted surfaces, Teflon™, metal surfaces, and glass surfaces in decreasing order of preference [9].

Cohesion. Cohesion of dust particles is also the result of electrostatic forces. Cohesion on the order of 1000 Newtons per square meter (N/m^2) was indicated from data collected on the Apollo 15 mission [7].

Design Approach

The team approached the removal of lunar dust by thinking of the designed system as a black box. The inputs to the black box were the materials and energy that the system uses and the object from which the dust needs to be removed. The outputs of the black box were the cleaned object, the removed dust, and any by-products created. A representation of the black box is shown in Figure 1.

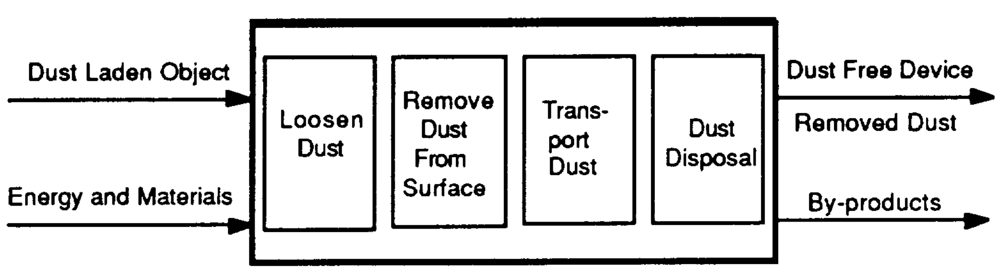

Figure 1: BLACK BOX SCHEMATIC FOR DUST REMOVAL SYSTEM

Figure 1 also shows the four main functions of the dust removal system. These functions are:

1. Loosen the dust by breaking the electrostatic and mechanical bonds holding the dust to a surface.

2. Remove the dust from the surface.

3. Transport the dust from the material's surface.

4. Dispose of the dust.

When developing a specific component to perform each function, every energy domain was considered. Design concepts from each domain were generated and promising concepts were retained for further development. The next section describes each function and the promising concepts generated to perform these functions. The concepts are grouped by energy domain.

Dust Loosening Function

Loosening of dust is accomplished by breaking the bonds holding dust on a surface. The energy domains which yielded promising component concepts are the mechanical, electrostatic, and chemical energy domains. These energy domains and the components generated to loosen the dust are detailed next.

Mechanical. One way of loosening the dust with mechanical energy is by using a brush. Brushes are effective in removing terrestrial dust from lenses, mirrors, and photographic films.

The dust particles adhered to a surface can be loosened by vibrating the surface at a specific frequency and amplitude. This process (fluidization) breaks the adhesive bonds between the particles and the material's surface. Fluidization also breaks the cohesive bonds between dust particles [3].

Electrostatics. Electrostatic forces are the main forces causing dust to adhere to a surface. Neutralizing the electrostatic charge between the dust and the surface will break these adhesive bonds. Grounding the surface to a large body, such as the lunar base or bedrock, will dissipate the electrostatic charge thereby breaking the adhesive bonds. However, only electrically conductive materials can be grounded.

Chemical. Acetate is used to loosen the dust by wetting the dust particles, thereby breaking the adhesive bonds between the dust particles and surface. This method was used to remove the lunar dust covering one of Surveyor III's mirrors [1]. Acetate can only be used in a pressurized environment.

Similar to acetate, soap can be used to loosen the dust in the same way it removes dirt from surfaces on Earth. Loosening is accomplished by wetting the surface of the dust particle, thus breaking the particles' adhesive bonds to the surface. Again, this method can only be used in a pressurized environment.

Dust Removal Function

Removing the dust is accomplished by pulling the dust off of a surface. This function is similar to the dust loosening function, however the dust removal function actually breaks physical contact between the dust and surface. The energy domains which yielded promising component concepts are the mechanical and electrostatic energy domains. These energy domains and the components generated to remove the dust are detailed next.

Mechanical. The dust can be blown off of a surface using a compressed gas jet. The gas is released through a nozzle, impacting the dust and dislodging it from the surface.

Suction can be used to remove dust from a surface with a vacuum cleaner like device. Suction is only possible in a pressurized environment.

Electrostatics. Active electrostatics removes the dust from a surface by creating a large attractive force between the dust and the dust removal device. This force is stronger than the remaining bonds between the dust and the material surface. Methods of creating the force include charged plates or a Van de Graaff generator.

Dust Transportation Function

After the dust has been removed from the surface, the dust is no longer in physical contact with the material surface. However, it is still near the surface and could come back into contact with the surface. The dust needs to be transported far away from the surface and disposed of. The energy domains which yielded promising component concepts are the mechanical, electrostatic, and chemical energy domains. These energy domains and the components generated to transport the dust are detailed next.

Mechanical. A blower can transport the dust away from a surface by using a gas jet. The jet will blow the dust off of the surface in much the same way that high pressure air is used in a machine shop to clean shavings off of a part. Note that this method implies that the dust is disposed of by allowing the dust to fall to the ground.

Suction can be used to transport dust away from the surface. Again, suction is limited to applications inside a pressurized environment.

Electrostatics. Active electrostatics can transport the dust from a material surface by using either charged plates or a Van de Graaff generator to set up an electric field. The field applies a force to the polar oxides, which make up most of the dust, thus pulling the dust particles away from the material surface and onto the charged surface of the dust removal device.

Chemical. If either acetate or soap were used in the previous functions, then the dust is currently in a dust-fluid mixture. Allowing this mixture to run off of the material surface and drain into a container for later disposal is one way to transport the dust from the material surface.

Dust Disposal Function

Disposal of the dust will be slightly different depending on whether the device is used inside or outside. If the device is used outside, disposal of the dust will be accomplished by allowing the dust to fall to the lunar surface. However, if the device is used inside, a method of dust disposal is required.

This section assumes that the dust removal device is operating inside. The energy domains which yielded promising component concepts for disposing of the dust are the mechanical and electrostatic energy domains. These energy domains and the components generated to dispose of the dust are detailed next.

Mechanical. Multi-stage filters can be used to remove dust from a fluid-dust mixture. A multi-stage system is required since there is a wide variation in dust particle size. The first filter stage will trap the largest particles and subsequent filter stages will trap progressively smaller particles. When the filters becomes dirty, they can be removed and cleaned.

Electrostatics. Attractor rods are electrostatically charged rods. The electrostatic force induced between the rods and the dust will pull the dust out of the fluid-dust mixture. Once the dust has been pulled out of the mixture, the dust can be scraped off of the rods and into a box. The box can be emptied outside to finally dispose of the dust.

Alternate Devices

After considering the many possible combinations of components for loosening, removing, transporting and disposing of the dust, the team chose eight design concepts for further consideration. A description of each device and a list of its advantages and disadvantages follow.

Vibrator-Suction Device. This device uses vibration to loosen the dust and suction to remove it from the material surface. When the vibrator is placed in contact with the surface, the vibrations will break the adhesive bonds between the surface and the dust. The needed vibration can be created by a rotating eccentric weight or by use of a pulsating piezoelectric crystal. The vibrator will be attached near the mouth of the suction hose to maximize effectiveness, ease of use, and compactness.

One way of creating the necessary suction is to use an electric powered blower. The blower will be connected via a hose to a filtration system which will collect the dust for disposal.

The filter system must be placed between the blower and the mouth of the suction hose to prevent wear of the blower due to abrasion by the dust. Both mechanical filters and attractor rods can be used in this design. The filtered dust will be collected after the device is used and disposed of outside the base. A conceptual sketch of this device is shown in Figure 2.

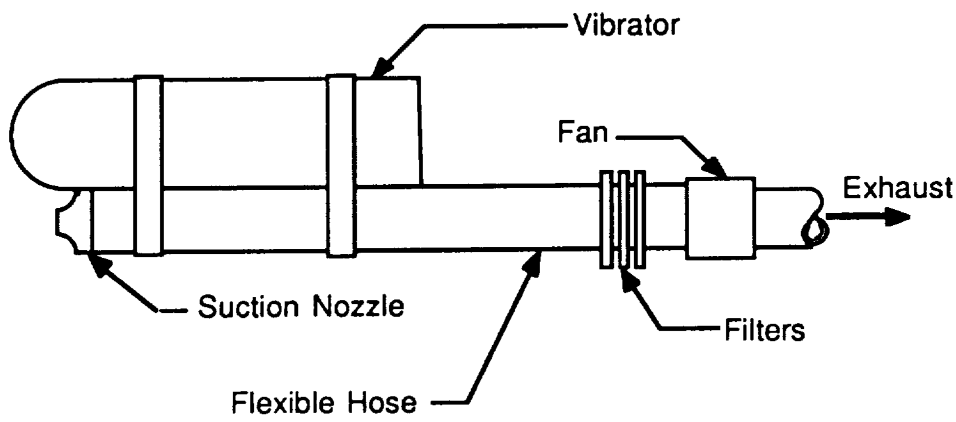

Figure 2: VIBRATOR-SUCTION DEVICE

The following are advantages and disadvantages of the vibrator-suction device.

Advantages

1. Frequent and/or extended periods of operation are practical.

2. All materials, such as air and filters, are recyclable.

3. No undesirable byproducts are created.

4. The device is easy to modify since each component operates independently.

Disadvantages

1. The device can only be used in a pressurized area.

2. The vibrator tip may scratch the surface.

Vibrator-Blower Device. This design also uses vibration to loosen the dust, however, it uses a gas jet to blow the dust off of the material surface. As in the first design, vibrational energy can be provided by either rotating an eccentric weight or by the use of a pulsating piezoelectric crystal.

The gas jet is provided by flow of a compressed gas through a nozzle. The nozzle increases the velocity of the gas, giving it enough kinetic energy to dislodge the dust from the surface. The gas will be supplied to the nozzle from a portable reservoir. Again, the vibrator will be attached near the gas jet's nozzle to maximize effectiveness, ease of use, and compactness.

Since the design will be used outside of the base, dust disposal will be accomplished by allowing the dust to fall to the lunar surface. A conceptual sketch of this device is shown in Figure 3.

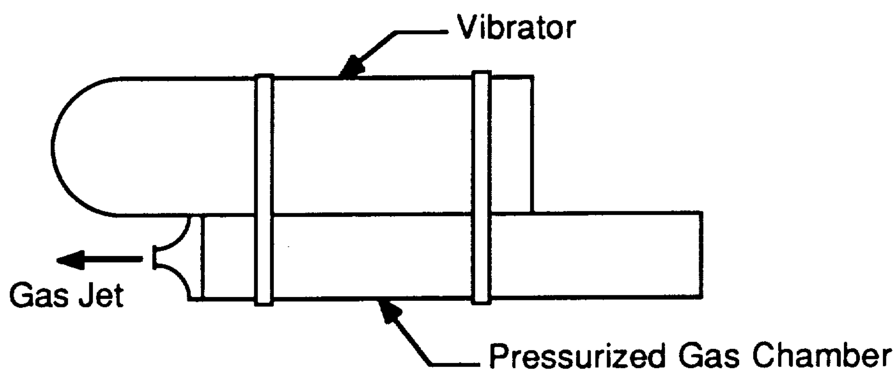

Figure 3: VIBRATOR-BLOWER DEVICE

The following are advantages and disadvantages of the vibrator-blower device.

Advantages

1. The device can be operated in a vacuum; therefore, an object does not have to be brought into a pressurized environment to be cleaned.

2. The device is portable.

3. The device is easy to modify since each component operates independently.

Disadvantages

1. The surface of the material can be abraded by the dislodged dust particles.
2. Operation period is limited by the gas supply.
3. The expelled gas is lost.
4. The effectiveness of the device will be a function of the distance of the nozzle from the material surface.

Passive Electrostatics-Suction Device. The third device uses passive electrostatics and suction. Loosening of the dust is accomplished by grounding the object, thus negating the electrostatic attraction between the material surface and the dust. Grounding is accomplished by connecting the surface to a large, electrostatically neutral body such as the lunar base or bedrock.

Removal of the dust is then accomplished by suction, thus limiting the system to operation in pressurized areas. The air-dust mixture will be transported away for disposal by flowing through the suction device's hose. Filtering the dust out of the mixture can be accomplished using either a filter or attractor rod system. A conceptual sketch of this device is shown in Figure 4.

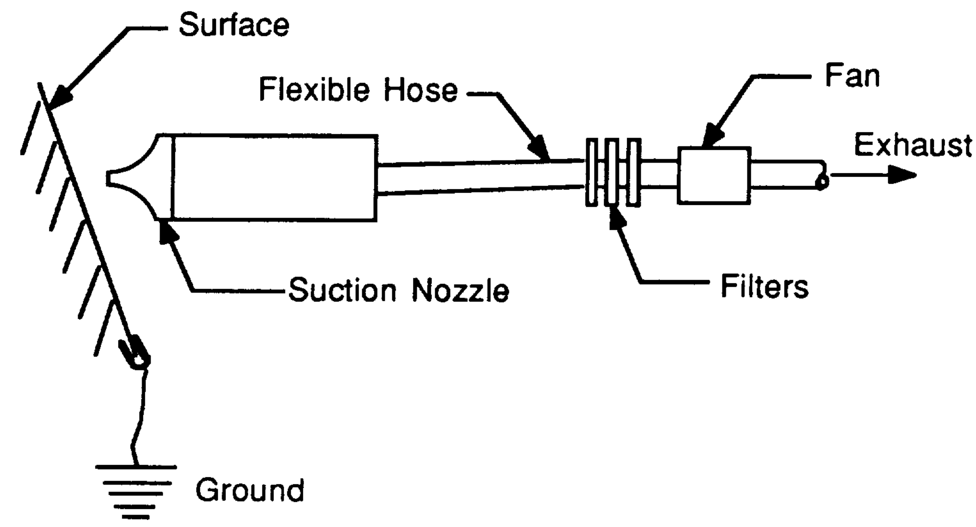

Figure 4: PASSIVE ELECTROSTATICS-SUCTION DEVICE

The following are advantages and disadvantages of the passive electrostatics-suction device.

Advantages

1. Frequent and/or extended periods of operation are practical.

2. No undesirable byproducts are created.

3. The device is easy to modify since each component operates independently.

Disadvantages

1. The device can only be used in a pressurized area.

2. Only conductive materials can be grounded.

Passive Electrostatics-Brush Device. This device loosens the dust by grounding the object. Grounding the object will break the electrostatic bonds between the dust and the material surface. Removal of the dust will then be accomplished using a brush. One possible configuration for the brush has a set of soft bristles and a set of hard bristles. The softer set of bristles will be used at first since they are less likely to scratch the surface. If the dust still adheres to the surface, the harder set of bristles will be used.

Disposal of the dust will be slightly different depending on whether the device is used inside or outside. If the device is used outside, the dust will simply fall to the lunar surface. However, if the device is used inside, a box will be used to collect the dust and then emptied outside to dispose of the dust. A conceptual sketch of this device is shown in Figure 5.

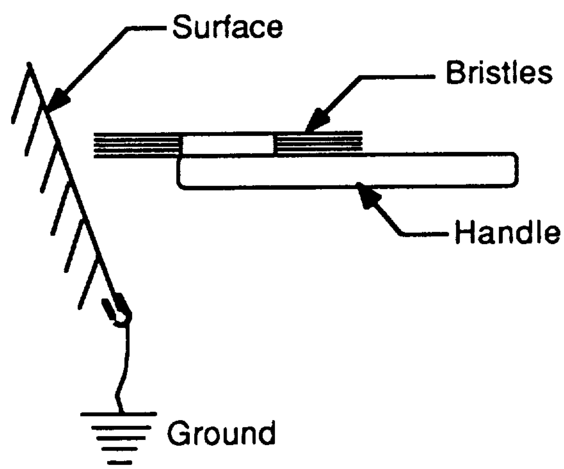

Figure 5: PASSIVE ELECTROSTATICS-BRUSH DEVICE

The following are advantages and disadvantages of the passive electrostatics-brush device.

<u>Advantages</u>

1. The device can be used outside of pressurized areas.
2. This device consumes the least power of the eight alternatives.
3. The device is portable.
4. Frequent and/or extended periods of operation are practical.
5. No undesirable byproducts are created.

Disadvantages

1. The brush can abrade the surface that is being cleaned.

2. Only conductive materials can be grounded.

Brush-Suction Device. This device uses a brush to loosen the dust. As mentioned before, various bristles types could be used. The dust is then removed using suction. A conceptual sketch of this device is show in Figure 6.

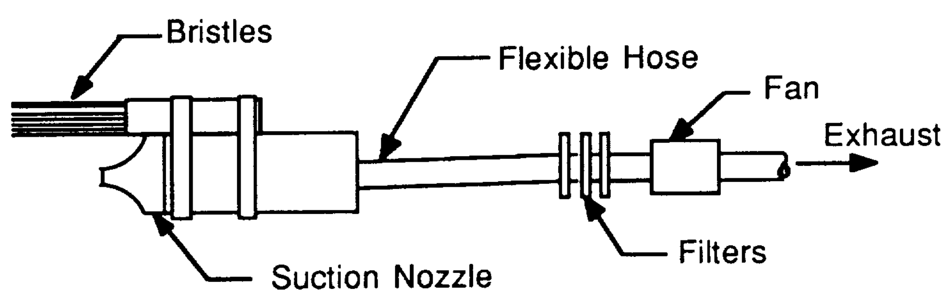

Figure 6: BRUSH-SUCTION DEVICE

The following are advantages and disadvantages of the brush-suction device.

Advantages

1. Frequent and/or extended periods of operation are practical.

2. All materials, such as air or filters, are recyclable.

3. No undesirable byproducts are created.

4. The device is easy to modify since each component operates independently.

Disadvantages

1. The device requires a pressurized environment.

2. The brush may abrade the surface.

Active Electrostatics-Brush Device. This device uses active electrostatics to loosen the dust. This is done by applying a large electrostatic force to the dust, overcoming the electrostatic bond between the dust and the material's surface. Either a Van de Graaff generator or a set of charged plates can be used to generate the required electrostatic force. A brush is used to remove the dust. As mentioned before, different bristle stiffnesses can be used for different applications. If used inside, the dust can be collected in a box and the box emptied outside to dispose of the dust. If the device is used outside, the dust will fall to the lunar surface. A conceptual sketch of this device is shown in Figure 7.

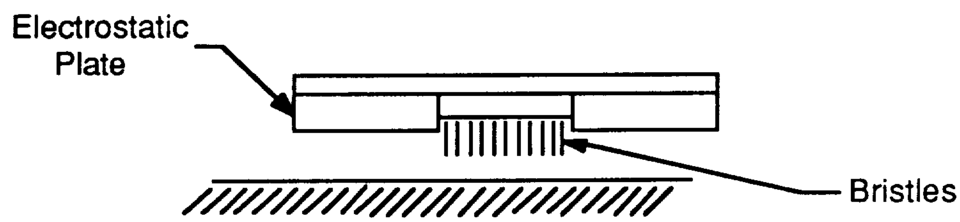

Figure 7: ACTIVE ELECTROSTATICS-BRUSH DEVICE

The following are advantages and disadvantages of the active electrostatic-brush device.

<u>Advantages</u>

1. The device does not require a pressurized environment.

2. Frequent and/or extended periods of operation are practical.

3. No undesirable byproducts are created.

<u>Disadvantages</u>

1. There is a shock hazard due to electrically charged surfaces.

Chemical-Suction Device. This design uses either acetate or soap to loosen the dust. The dust and acetate (or soap) mixture are then removed from the material surface using suction.

First, the acetate (or soap) is applied to the surface using a spray bottle. After the surface is coated with fluid, suction is used to remove the mixture. The suction device is as previously described. However, a filtering system for removing fumes from the air is required. A conceptual sketch is shown in Figure 8. The figure illustrates the two step process for removing the dust.

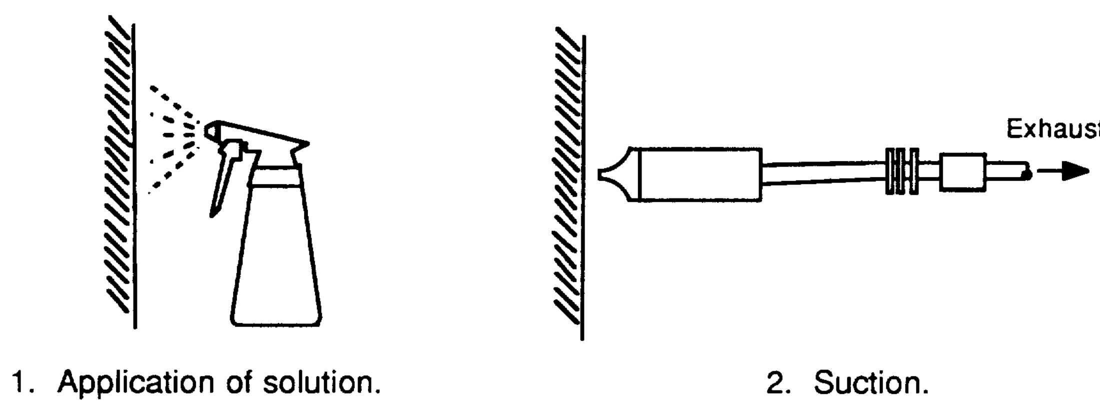

Figure 8: CHEMICAL-SUCTION DEVICE

The following are advantages and disadvantages of the chemical-suction device.

Advantages

1. A very clean surface can be achieved for certain surfaces.

2. No abrasive contact is made with the material's surface.

Disadvantages

1. Acetate will produce chemical fumes which must be filtered out of the air.

2. The device can only be used in a pressurized environment.

3. The fluid may leave a residue on the material's surface.

Brush-Blower Device. This device uses a brush to loosen the dust. As mentioned before, different bristle stiffnesses can be used for different applications. A gas jet is then used to remove the dust and transport it away from the material surface. The jet is provided by flow of a compressed gas through a supersonic nozzle. The nozzle increases the velocity of the gas, giving it enough kinetic energy to dislodge the dust from the surface. The gas will be supplied to the nozzle from a portable reservoir. A conceptual sketch of the brush-blower device is shown in Figure 9.

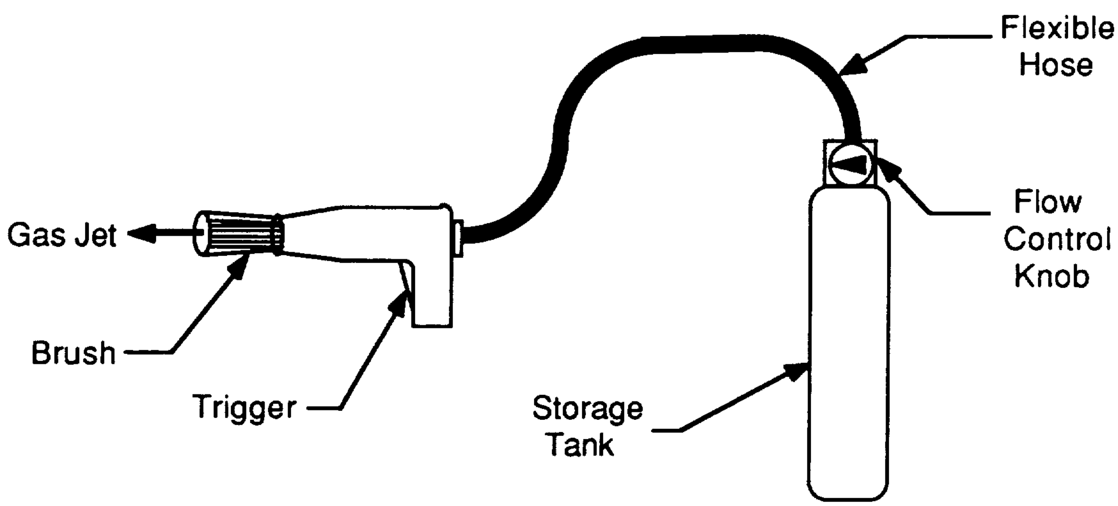

Figure 9: BRUSH-BLOWER DEVICE

The following are advantages and disadvantages of the brush-blower device.

Advantages

1. The device does not require a pressurized environment.

2. The device is portable.

Disadvantages

1. The surface of the material can be abraded by dislodged dust particles.

2. The expelled gas is lost.

3. The effectiveness of the device will be a function of the distance of the nozzle from the material surface.

Summary

In this chapter, the physical properties of lunar dust and their importance were presented. Also, eight alternate designs were presented and the design approach used to generate the alternatives was explained. In the next chapter the decision matrix will be discussed and the design solution presented. Criteria for selection will include considerations of the ease of use, versatility, weight, and the consumption of material resources and power by the device.

DESIGN SOLUTION

In the previous chapter, important physical properties of lunar dust were described, the design methodology was outlined, and alternate designs were presented.

This chapter presents the design solution. First, an overview of the design solution is given. Second, a discussion of the decision matrix is presented. Third, assumptions made during the design process are listed. Fourth, the method of operation for the design solution is explained. Then a description of each design component is detailed. Finally, brief comments about producibility are given.

Solution Description

This section gives a brief overview of the design solution. A detailed discussion of the design solution is presented later in this chapter. The alternate design chosen was the Brush Blower Device (BBD). As shown in Figure 10, the final design of the BBD is composed of a portable gas storage tank and a dusting attachment. This device is mainly constructed from titanium, aluminum, Kapton™ and Kevlar™.

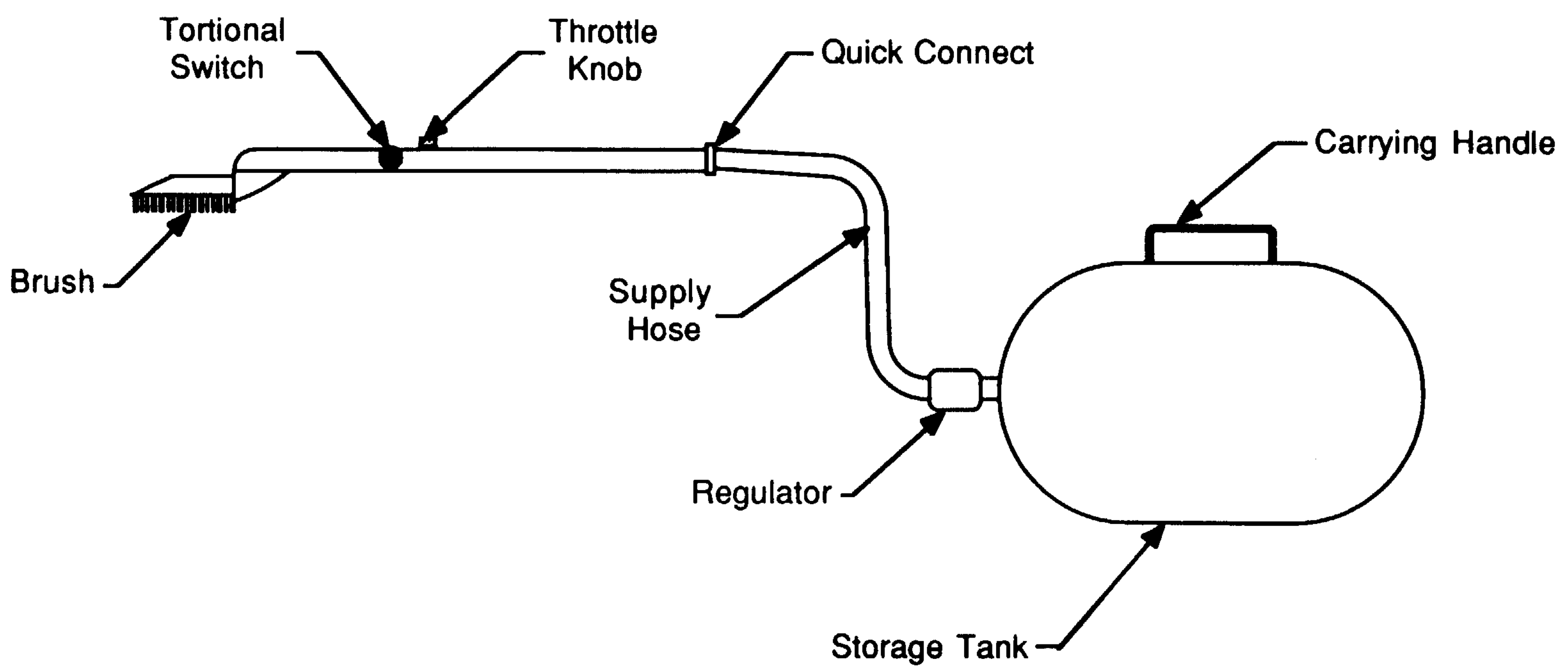

Figure 10: DRAWING OF BRUSH-BLOWER DESIGN

The device has a total mass of 12.6 kilograms when the storage tank is full. The dusting attachment, which is the only section held when the device is in use, masses 0.37 kilograms. (See Appendix B.)

The portable gas storage tank is insulated and electrically heated. The tank is pressurized to 20 atmospheres with carbon dioxide from a main storage tank and stores enough gas for 10 minutes of operation. (See Appendix C.) The heater is required to prevent condensation of the stored carbon dioxide gas when the tank is exposed to the cold of the lunar night. Also, during operation carbon dioxide will be bled out of the tank, causing the gas to expand and cool.

The body of the dusting attachment is constructed from aluminum and consists of a throttling valve, torsional switch, brush, and two nozzles. Overall length of the attachment is 56 centimeters. It is designed to be held in two hands, giving good control of the device. The throttling valve and torsional switch will control the mass flow of carbon dioxide to the nozzles and turn the gas flow on/off, respectively.

The dust loosening process is performed by the brush. Nozzles direct the flow of carbon dioxide onto the material surface being cleaned; removing the dust and transporting it away. During normal operation, the gas jet will contact the surface at an angle of 20 degrees to the horizontal.

Decision Matrix

After the eight alternate designs were generated, a decision matrix was used to select the best design. Each alternate was graded on its ability to meet nine design criteria. These criteria, listed in order of importance, are: versatility, mass and portability, effectiveness, surface damage, safety, waste products, surface variety, ease of use, and energy used. The definitions of these criteria, each criteria's weighing factor, and the decision matrix are shown in Appendix D.

Assumptions

Some significant assumptions were made during the design process. A post-design discussion of the repercussions of these assumptions and some suggested avenues for continued research are given in the recommendations section of this report. The assumptions and the team's reasoning when making each assumption are listed below.

1. Carbon dioxide (CO_2) will be used for the dust removal system. Since an average person produces about one kilogram of carbon dioxide each day, there will be a plentiful supply at the lunar base. This carbon dioxide can be removed from the air by current CO_2 extraction schemes and stored for future use.

2. The team assumed the geometry of the gas jet exiting to a

vacuum is conical, with a half angle of approximately 30 degrees. See Appendix E for a discussion of gas jet considerations in a vacuum.

3. Adhesive strength of lunar dust is no more than one kPa. This was the highest value reported by the Surveyor III experiments described in the dust characteristics section of this report. (See page 7.)

4. The team will target space suits as the object for dust removal. Space suits were chosen because they are made from many materials commonly encountered on lunar equipment. The space suits used on the Apollo missions to the moon were made from several materials. The torso, arms, and legs were covered with layers of Teflon™ coated Beta fibers™. The helmet was protected by a layer of Lexan™. The outer layer of the gloves was made from Chromel-R™. The boots and fingertips of the gloves were made of silicon rubber [5]. Space suits used in future lunar missions will probably be made of similar materials.

5. The demand for carbon dioxide by the dust removal device will rarely match the amount of CO_2 which is extracted from the atmosphere of the base. Therefore a main storage tank will be needed to store excess CO_2; supplying a reserve of gas for high demand situations.

6. A compressed gas storage tank implies a gas compressor. The team assumes that there is a gas compression system which is capable of compressing the CO_2 to twenty atmospheres.

Method of Operation

The process of dust removal requires two astronauts. The astronauts take turns "dusting" each other. During operation, the storage tank will sit on the ground next to the astronauts. A general storage tank will sit on the ground next to the astronauts. A general list of the steps to follow during the dust removal process follows.

1. Before leaving the lunar base, the portable supply tank is filled from a large storage tank.

2. The throttle (located on top of the dusting attachment) is adjusted to select the desired flow rate for the surface to be cleaned. A lower flow rate should be used for easily scratched (or precision) surfaces, such as the Lexan™ visor on the space suit. A higher flow rate should be used for surfaces that are less susceptible to wear, such as the fabric of the space suit.

3. The brush is held over the material surface to be cleaned and the torsional switch (located on the left side of the dusting attachment) is turned.

4. While turning the torsional switch, the brushing attachment is lowered onto the surface of the space suit and moved back and forth in order to clean the surface. The space suit should be dusted from the top down to prevent the dust from reattaching to a previously cleaned surface.

Design Description

There are two main components in the Brush-Blower Design. These are the gas storage tank and the dusting attachment. The gas storage tank is composed of a portable supply tank, a heater, and a flexible hose to connect the gas supply to the dusting attachment. The dusting attachment includes a throttle, trigger, two nozzles, and a brush. The gas storage tank and the dusting attachment are described in detail in the next paragraphs.

Gas Storage Tank. The gas storage tank includes a portable supply tank, a heater, and a flexible hose which carries the gas from the tank to the dusting attachment.

The tank supplies the carbon dioxide needed for the dust removal process. This tank is filled to 2020 kPa (at 300 Kelvin) by connecting it to a main storage tank and allowing carbon dioxide to flow from the main tank to the portable tank until the desired pressure in the portable tank is reached. A pressure gage is connected to the main supply tank outlet for this purpose.

The portable tank is constructed of ASTM B265 Titanium alloy and will store up to 471 grams of carbon dioxide at 2020 kPa. The cylindrical tank is 46 centimeters long, 25 centimeters in diameter and has a 3 millimeter wall thickness. (See Appendix F.) A bracket is mounted to the side of the tank to hold the dusting attachment when the device is not in use. A regulator is attached to the outlet of the tanks so that a constant pressure of 500 kPa is delivered to the dusting attachment, which further throttles the flow.

The temperature on the lunar surface during nighttime averages 120 Kelvin (-240 degrees Fahrenheit). Since this is well below the condensation temperature of CO_2, the portable storage tank must be heated. The tank will be wrapped with electric heating coils much like an electric blanket. The coils will then be covered with a 1 cm. thick layer of Kapton™ insulation as shown in Figure 11.

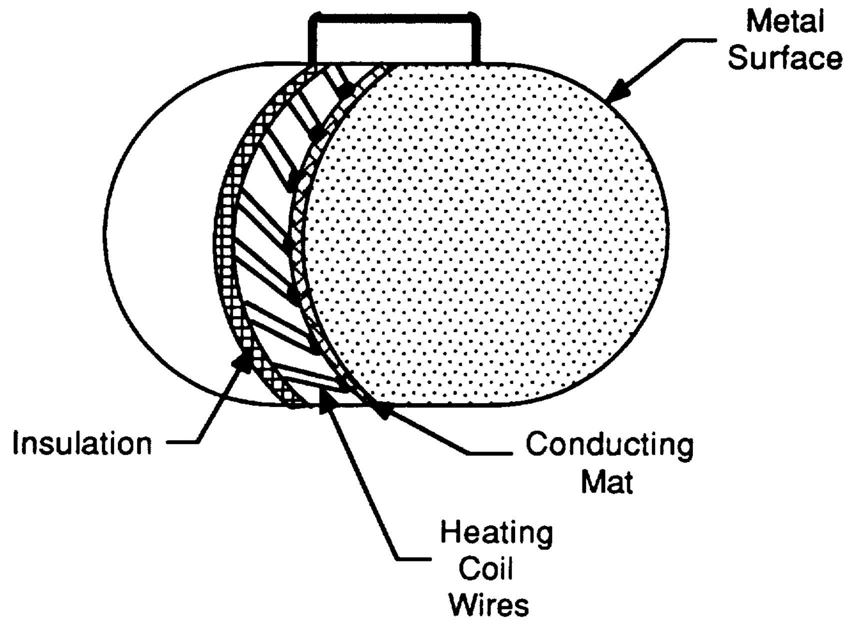

Figure 11: CUT-AWAY OF TANK INSULATION

The coils will be powered from a rechargeable battery and will hold the gas temperature at approximately 367 Kelvin (200 degrees Fahrenheit). This temperature is slightly below the temperature of the lunar surface during the day. By holding the gas temperature relatively constant for day and night use, the device will give more consistent results. During daytime, the heater will not be used. The heater is estimated to consume a maximum of 250 Watts during operation. (See Appendix G.)

A flexible hose connects the portable supply tank to the dusting attachment. The hose is two meters long and is made from

Kevlar™. Quick lock connections at both ends of the hose are made out of 6061-T6, an aluminum alloy.

Dusting Attachment. The dusting attachment includes a throttle, a trigger, a nozzle, and a brush. The gas is supplied to the dusting attachment through a hose connected to the portable supply tank. There are two controls for this gas supply. The first is a torsional switch which acts as an on/off switch. The second, a throttle control knob, is designed to regulate the mass flow of the carbon dioxide gas. The carbon dioxide flows out through two nozzles located near the brush. The brush and gas jet are used to loosen the dust particles. Then the gas jet removes the dust from the material surface and transports the dust away from the surface.

As shown in Figure 12, all of these parts are built into one piece. The main structure is cast from aluminum, and the springs are made from stainless steel.

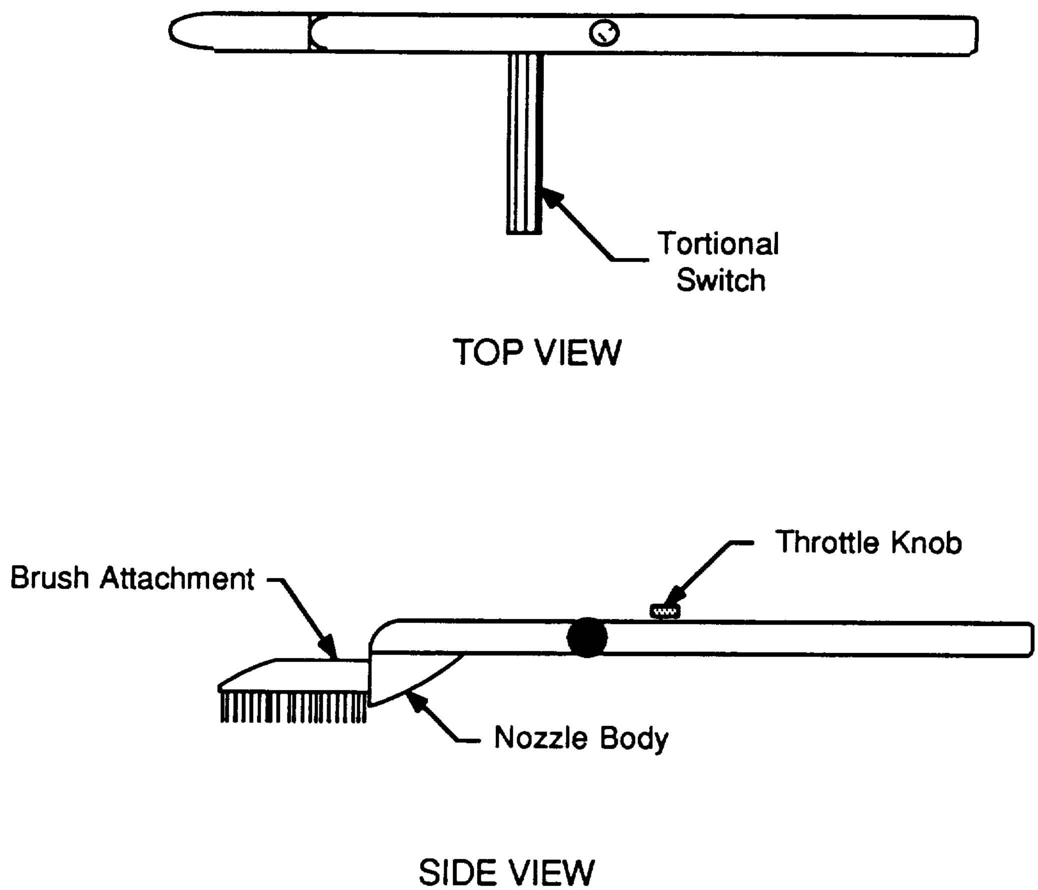

Figure 12: TOP AND SIDE VIEW OF THE DUSTING ATTACHMENT

The throttle is designed to control the mass flow that reaches the nozzle and is adjusted by turning a control knob located on the top of the handle. By controlling the flow at the throttle, the need for variable flow control using hand pressure on the torsional switch is eliminated. A low flow rate is used for the visor or other abradable surfaces and a high flow rate is used for wear resistant surfaces such as the fabric of the space suit. The maximum flow rate of the carbon dioxide is .80 grams/second. (See Appendix H.) Gas enters the throttle at about 500 kPa and leave the throttle at anywhere from 10 to 200 kPa, depending on the position of the throttle control knob. Figure 13 shows a cross sectional view of the throttle.

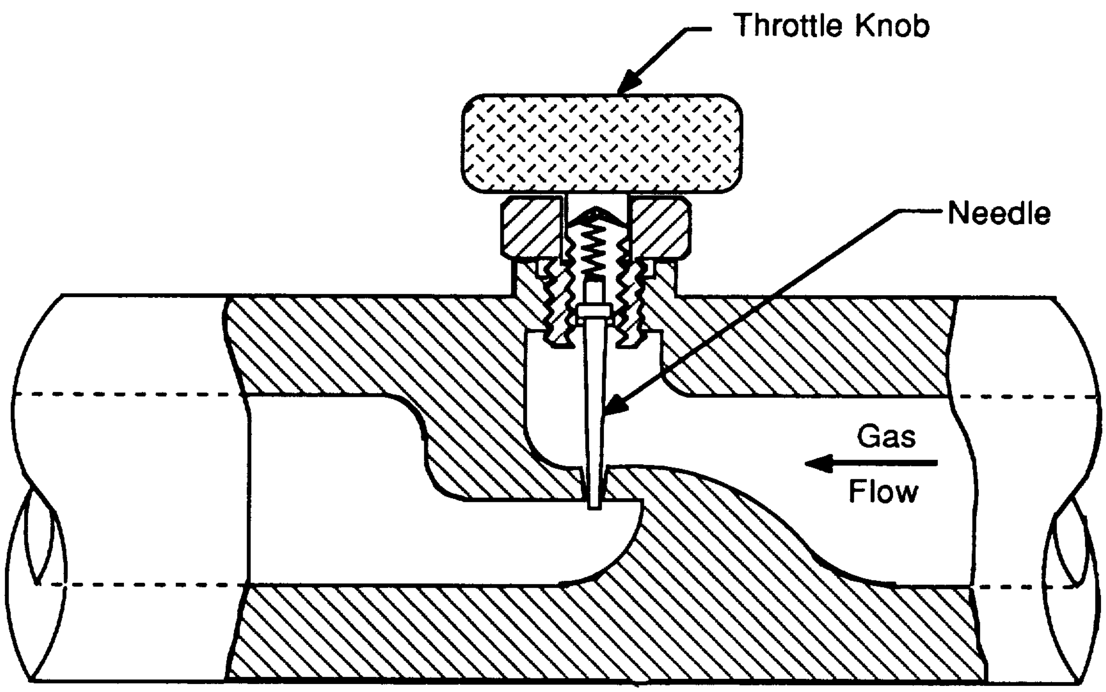

Figure 13: CROSS-SECTION OF THROTTLE

The torsional switch is designed to be an on/off switch. Turning the switch 20 degrees will fully engage a butterfly valve, allowing the gas to flow. Turning the switch beyond 20 degrees only tightens the spring, no harm is done. A recoil spring automatically closes the valve if the hand grip is released. This prevents excessive gas loss in case the device is dropped. A cross sectional view of the torsional switch is shown in Figure 14.

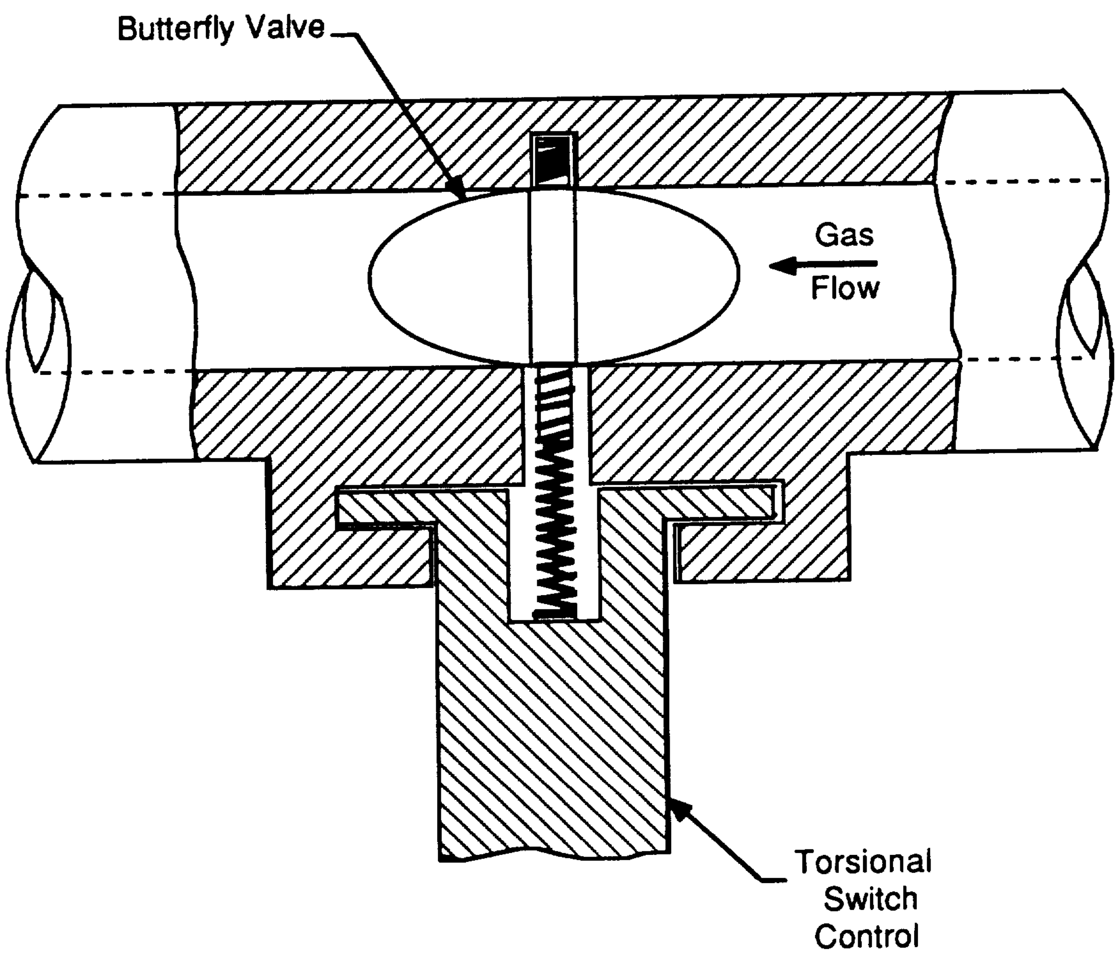

Figure 14: CROSS-SECTION OF TORSIONAL SWITCH

The nozzle body is a small triangular shaped prism with a cavity for gas flow inside it. (See Figure 15.) The gas will flow through the cavity and exit through two supersonic nozzles. The nozzles are designed as a separate piece and can be unscrewed for cleaning or replacement. They are angled so that during normal operation, the gas contacts the material surface at a 20 degree angle. This angle will put most of the flow parallel to the surface. Thus, most of the momentum of the gas is used to remove the dust, not to grind the dust into the surface. Only a conceptual design of the nozzle was performed.

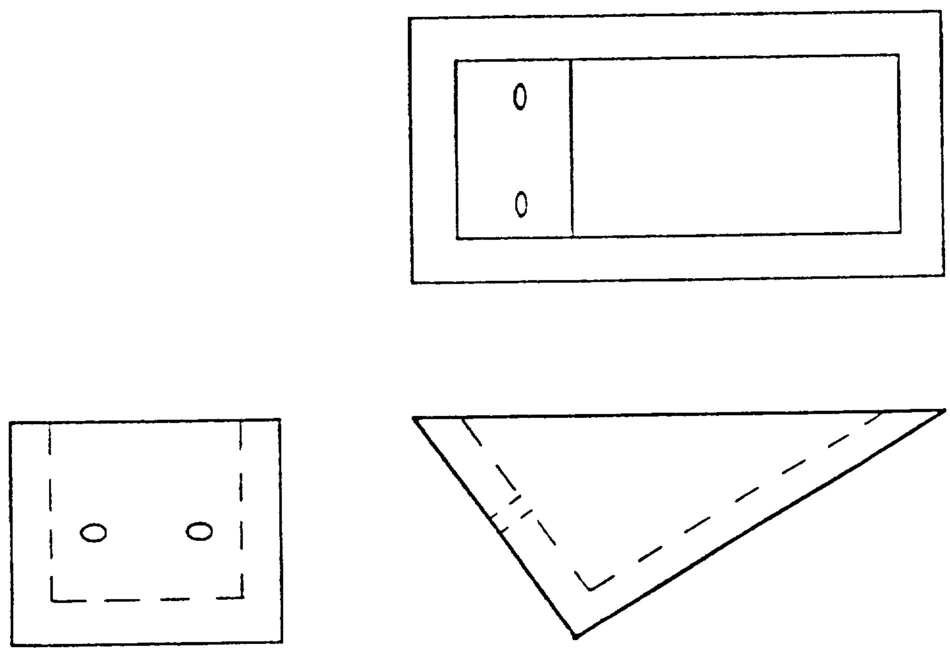

Figure 15: ORTHOGONAL VIEW OF NOZZLE BODY

The brush performs the dust loosening function by dislodging the dust from the surface of the space suit. This is done by exerting a mechanical force on the dust particles to break the adhesive bond between the particles and the surface of the space suit. The designed brush is 10 centimeters long, 5 millimeters wide, and is positioned between the two nozzles. The bristles are 2 centimeters in length, 0.5 millimeters in diameter and are made of Kevlar™. There are 765 bristles in the brush. Bristles of this length and diameter deflect 1.7 millimeters, when loosening the dust particles. A total force of about 0.2 Newtons must be applied by the brush to loosen the dust. (See Appendix I.)

Producibility

The components of the device are custom designed. Although the valves, quick lock connections, and hose could possibly be found commercially, all other parts will have to be custom made. The complex shape of the dusting attachment will probably require casting and milling. The portable tank can be produced using rolling and upsetting processes. The handle will have to be welded to the tank.

CONCLUSIONS AND RECOMMENDATIONS

In the previous section, the Brush-Blower Device was chosen as the design that best met the design criteria. Some significant assumptions were presented, the method of operation of the BBD was explained, and the main components of the design were described. In this section conclusions and recommendations are presented.

Conclusions

The requirements for this project were to 1) characterize the properties of lunar dust, and 2) design a device to remove lunar dust from a material surface. An optional goal of the project was to develop a working model of the dust removal device. Both of the project requirements were met, however the working model was not developed.

The BBD met all of the design criteria satisfactorily. Most importantly, the BBD removes dust from all of the materials of a space suit. Also, the BBD uses the available supply of carbon dioxide at the lunar base. It does not consume much power compared to the other design alternatives. The device is rugged since the BBD is composed of materials that can withstand the extreme temperatures of the moon and exposure to solar radiation without degrading. The operating procedures are easy to follow and do not require much physical exertion. The BBD is lightweight and portable, massing only 12.6 kilograms when the storage tank is full. However, the dusting attachment, masses only 0.37 kilograms.

In general, the assumptions made during analysis and design were valid, although some iteration was necessary. However, some assumptions could not be checked. These include the geometry of a gas jet exiting into a vacuum, and the maximum adhesive strength of the dust.

Recommendations

In this section, some comments concerning the assumptions are made. Then some avenues for further investigation are listed. Some of these avenues are not directly related to dust removal, but are still worth mentioning.

Assumptions. The team assumed a gas jet geometry based on available research. Further study of the behavior of a gas jet exiting to a vacuum is needed. The geometry of the nozzles of the BBD must be developed based on further research and empirical data detailing gas jets under vacuum conditions.

The team choose to make the bristles of the brush out of Kevlar™. However, tests should be run on other materials able to withstand the lunar environment to check for other bristle alternatives.

Research should be done to determine whether the gas jet will cause dangerous thermal transients on any of the materials of the space suit when the device is used during daylight periods. As the gas jet expands, it also cools rapidly. The teams estimates that the gas temperature will be in the range of 150 Kelvin as it contacts the surface. Thus there is a temperature difference of about 280 Kelvin between the surface and the gas jet. One possible solution is an electrically heated nozzle. Heating the nozzles will warm the gas and may prevent any problems with condensation or freezing of the CO_2.

Further Investigation. First, the dust removal process could be done on a raised platform. This would raise the astronauts above the layer of dust which levitates up to 30 centimeters above the surface of the moon [2]. Also, the platform could be given a static charge during the dust removal process. This charge would attract the dust particles as they are removed from the space suit, helping transport the dust away from the astronaut so that the dust does not land on the space suit.

Electrostatics play a major roll in the adhesion of lunar dust to material surfaces. The inclusion of antistatic chemicals when producing the Teflon™ (or other nonconducting materials) should reduce the adhesion forces significantly. (See Dust Characteristics; adhesion.)

Two possibilities for a main storage tank inside the lunar base were briefly considered by the team. These concepts were not developed since the design of this tank was beyond the scope of the project. The first storage tank design considered was a custom built tank made from titanium. The tank stores carbon dioxide at a pressure of 1500 kilopascals (kPa) at 300 Kelvin. The tank is made of ASTM B265 Titanium alloy and has a one cubic meter capacity. The tank is cylindrical and is one meter long and 0.9 meters in diameter. The wall thickness of the tank is about five millimeters. The second storage tank considered would use a discarded pressure vessel. Since many pressurized fluids must be shipped to the moon anyway, why not use one of the pressure vessels which have already been transported to the moon? This concept is superior in that the cost of transporting the tank to the moon has already been paid. The disadvantage is that a suitable tank may not exist. The tank must be reanalyzed to consider the pressure, temperature, fatigue and corrosion factors involved with this application.

Although also beyond the scope of the project, a method the team considered for compressing the carbon dioxide takes advantage of the cryogenic temperatures on the moon. The CO_2 would be allowed to cool until it condensed, and then the liquid CO_2 would be stored until needed. When filling the portable tank from the main storage tank, the CO_2 would be made to boil so that no liquid enters the portable tank.

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APPENDICES

APPENDIX A

LUNAR DUST CHARACTERISTICS

TABLE A.1: AVERAGE COMPOSITION OF SOIL SAMPLES (<MM FRACTION).

	Apollo 11 (%)	Apollo 12 (%)	Apollo 14 (%)	Apollo 15 (%)	Luna 16 (%)	Luna 20 (%)	Apollo 16 (%)
SiO_2	42.04	46.40	47.93	46.61	41.70	45.40	44.94
TiO_2	7.48	2.66	1.74	1.36	3.38	0.47	0.58
Al_2O_3	13.92	13.50	17.60	17.18	15.33	23.44	26.71
FeO	15.74	15.50	10.37	11.62	16.64	7.37	5.49
MgO	7.90	9.73	9.24	10.46	8.78	9.19	5.96
CaO	12.01	10.50	11.19	11.64	12.50	13.38	15.57
Na_2O	0.44	0.59	0.68	0.46	0.34	0.29	0.48
K_2O	0.14	0.32	0.55	0.20	0.10	0.07	0.13
P_2O_5	0.12	0.40	0.53	0.19	—	0.06	0.12
MnO	0.21	0.21	0.14	0.16	0.21	0.10	0.07
Cr_2O_3	0.30	0.40	0.25	0.25	0.28	0.14	0.12
Total	100.30	100.21	100.22	100.13	99.26	99.91	100.17

[1]

TABLE A.2: COMPARISON OF AVERAGE COMPOSITION OF LUNAR SOILS RETURNED BY THE APOLLO MISSIONS (OXIDES IN WT. %, ELEMENTS IN PPM).

						Apollo 17		
Constituent	Apollo 11	Apollo 12	Apollo 14	Apollo 15	Apollo 16	low-TiO_2 group	high-TiO_2 group	Sample 76501
SiO_2	42.04	46.40	47.93	46.61	44.94	45.08	41.46	43.71
Al_2O_3	13.92	13.50	17.60	17.18	26.71	20.60	12.97	18.83
Fe_2O_3	0.00	0.000	0.00	0.00	0.00	0.00	0.00	0.00
FeO	15.74	15.50	10.37	11.62	5.49	8.59	15.78	10.35
MgO	7.90	9.73	9.24	10.46	5.96	10.29	9.76	10.71
CaO	12.01	10.50	11.19	11.64	15.57	12.86	11.15	12.06
Na_2O	0.44	0.59	0.68	0.46	0.48	0.41	0.38	0.38
K_2O	0.14	0.32	0.55	0.20	0.13	0.16	0.10	0.11
TiO_2	7.48	2.66	1.74	1.36	0.58	1.62	7.76	3.20
P_2O_5	0.12	0.40	0.53	0.19	0.12	0.14	0.08	0.08
MnO	0.21	0.21	0.14	0.16	0.07	0.11	0.21	0.13
Cr_2O_3	0.30	0.40	0.25	0.25	0.12	0.26	0.44	0.26
Total	100.30	100.21	100.22	100.13	100.17	100.12	100.10	100.25
ΔRC*	+4.1	+1.3	+2.8	+2.1	+2.1	−1.64	+1.97	+0.81
Pb	<2	<2	10	2.8	3.8	<2	<2	<2
Zn	19	6.7	25	18	27	18	23	12
Cu	10	11	18	9.3	8.8	15	25	14
Ga	3.8	4.9	5.5	3.3	3.7	3.3	4.0	3.2
Li	11	18	23	9.2	7.3	9.3	9.4	7.5
Rb	2.7	8.2	13	5.3	2.8	2.6	1.5	2.3
Co	24	58	35	43	24	39	42	38
Ni	185	195	370	332	344	320	235	262
Ba	210	563	1030	320	121	176	136	114
Sr	130	131	189	159	149	142	149	130
V	50	107	56	87	23	35	75	50
Be	1.6	5.2	6.6	3.1	1.2	1.9	1.4	<1
Nb	18	38	55	16	10	12	20	10
Sc	56	40	27	22	10	19	60	30
La	16	54	74	32	<10	14	<10	<10
Y	81	164	276	80	38	59	73	44
Yb	—	—	—	8.8	3.1	5.4	7.2	3.4
Zr	273	548	813	299	151	232	262	133

[2]

TABLE A.3: ESTIMATES OF LUNAR SOIL COHESION AND FRICTION ANGLE BASED ON PRE-APOLLO DATA.

Basis	Cohesion c (kN/m^2)	Friction angle ϕ (deg)	Reference
(1) Boulder track analysis—Orbiter data	0.35	33	Nordmeyer (1967)
(2) Surveyor I strain gage and TV data	0.15–15	55	Jaffe (1967)
(3) Surveyor I	0.13–0.4	30–40	Christensen *et al.* (1967)
(4) Surveyor III, soil mechanics surface samples		> 35	Scott and Roberson (1968)
(5) Surveyor III, landing data	0 for 10 for	45–60 0	Christensen *et al.* (1968c)
(6) Surveyor VI, vernier engine firing	> 0.07 for	35	Christensen *et al.* (1968a)
(7) Surveyor VI, attitude control jets	0.5–1.7		
(8) Surveyor III and VII, soil mechanics surface samples	0.35–0.70	35–37	Scott and Roberson (1969)
(9) Lunar Orbiter boulder track records	0.1	10–30	Moore (1970)
(10) Lunar Orbiter boulder track records	0.5*	21–55 39+	Hovland and Mitchell (1971)

[3]

TABLE A.4: ESTIMATES OF LUNAR SOIL COHESION AND FRICTION ANGLE BASED ON APOLLO 11, APOLLO 12, AND APOLLO 14 DATA.

Mission	Basis	Cohesion c (kN/m^2)	Friction angle ϕ (deg)	Reference
Apollo 11	Astronaut footprints, LM landing data, crater slope stability	Consistent with lunar soil model from Surveyor data		Costes *et al.* (1969)
Apollo 11	Penetrometer tests in LRL on bulk soil sample	0.3–1.4	35–45	Costes *et al.* (1970)
Apollo 11	Penetration of core tubes, flagpole, SWC shaft	0.8–2.1	37–45	Costes *et al.* (1971)
Apollo 12	Astronaut footprints, LM landing data, crater slope stability	Consistent with lunar soil model from Surveyor data		Scott *et al.* (1970)
Apollo 12	Penetration of core tubes, flagpole, SWC shaft	0.6–0.8	38–44	Costes *et al.* (1971)
Apollo 14	Soil mechanics trench	< 0.03–0.3	35–45	Mitchell *et al.* (1971b)
Apollo 14	Apollo simple penetrometer	Soil shear strength equal to or greater than that of soil model from Surveyor data		Mitchell *et al.* (1971b)
Apollo 14	MET tracks		37–47	Mitchell *et al.* (1971b)

[3]

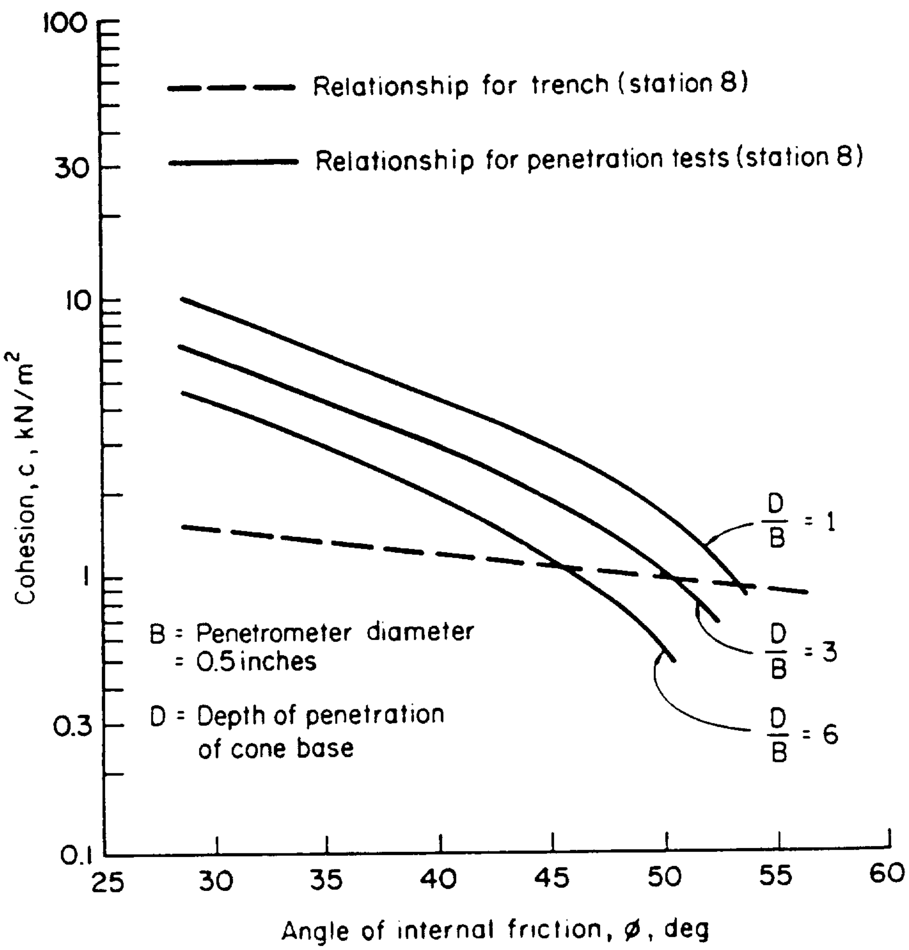


FIGURE A.1: VALUES OF COHESION AND FRICTION ANGLE AT INCIPIENT FAILURE OF THE SOIL MECHANIC TRENCH WALL AND FOR A 25-POUND FORCE APPLIED TO THE SELF-RECORDING PENETROMETER AT DIFFERENT PENETRATION DEPTHS, APOLLO 15 ALSEP SITE. [3]

TABLE A.5: THERMAL CONDUCTIVITY OF LUNAR SAMPLE 10084-68 (SAMPLE OF LUNAR FINES FROM APOLLO 11).

Temperature (°K)	Conductivity (w/m- K)	Pressure (Torr)
203	0·00150	10^{-2}
203	0·00142	10^{-3}
203	0·00141	10^{-3}
203	0·00142	10^{-3}
293	0·00227	10^{-7}
293	0·00207	10^{-6}
294	0·00158	10^{-6}
294	0·00156	10^{-6}
295	0·00246	10^{-6}
299	0·00194	10^{-3}
375	0·00259	10^{-5}
388	0·00246	10^{-5}
398	0·00230	10^{-4}
402	0·00246	10^{-4}
404	0·00245	10^{-4}
405	0·00255	10^{-4}

[4]

TABLE A.6: ROOM TEMPERATURE MAGNETIC PROPERTIES OF LUNAR SOILS.

	J_s (emu/gm)	χ_p (emu/gm Oe)	χ_0 (emu/gm Oe)	J_{rs}/J_s	H_{rc} (Oe)	H_c (Oe)	J_s/χ_0 (KOe)	Equiv. % Fe°	Equiv. % Fe⁺⁺	Chem. % Fe⁺⁺
		$\times 10^6$	$\times 10^4$							
10084,90	0.87		11.4	0.094		36	0.76	0.40		
12070,104	1.49	36.4	22.1	0.096	450	24	0.67	0.69	16.7	12.8[a]
14163,68	1.04	22.9	24.4	0.044	500	22	0.43	0.48	10.5	8.0[b]
14163,131	1.30	24.0	23.5	0.077	480	25	0.51	0.60	11.5	
15301,38	1.07	30.4	27.2	0.047	400	20	0.39	0.48	13.9	10.9[c]
15301,130*	0.60	23.6	18.0	0.055	340	20	0.33	0.28	10.8	
15471,72*	0.50	28.2	9.7	0.040	345	22	0.52	0.23	12.9	12.6[c]
15601,79	1.05	40.2	23.0	0.073	450	38	0.46	0.48	18.5	15.4[c]
15601,117*	0.44	35.4	9.8	0.052	320	24	0.45	0.20	16.2	
60501,29	1.31	9.8	24.8	0.032	500	21	0.53	0.60	4.5	4.24[d]
60600,2	1.1	14.0						0.5	6.0	
61241,25	0.89	7.2	11.9	0.030	550	20	0.75	0.41	3.3	4.15[e], 4.20[f]
64801,29	1.06	10.5	19.1	0.035	490	21	0.55	0.49	4.8	4.44[e]

[5]

TABLE A.7: MAGNETIC PARAMETERS OF THE LUNAR MATERIALS AT ROOM TEMPERATURE.

Magnetic parameter	Crystalline rock (10024-22)	Microbreccia (10085)	(10021-32)	Fines (10084-89)
Initial magnetic susceptibility X_0	$2{\cdot}6 \times 10^{-4}$	$4{\cdot}3 \times 10^{-3}$	$8{\cdot}6 \times 10^{-3}$	$8{\cdot}8 \times 10^{-3}$ e.m.u./g
Paramagnetic susceptibility X_a	$3{\cdot}4 \times 10^{-5}$	$4{\cdot}4 \times 10^{-5}$	$2{\cdot}7 \times 10^{-4}$	$3{\cdot}5 \times 10^{-5}$ e.m.u./g
Saturation magnetization I_s	0·155	0·44	0·74	1·17 e.m.u./g
Saturation remanent magnetization I_r	$1{\cdot}5 \times 10^{-3}$	$6{\cdot}7 \times 10^{-2}$	$5{\cdot}0 \times 10^{-2}$	$8{\cdot}4 \times 10^{-2}$ e.m.u./g
Coercive force H_c	—	125	19	36 oe
Remanence coercive force H_{rc}	—	670	—	460 oe
Natural remanent magnetization I_n	$7{\cdot}5 \times 10^{-6}$	$1{\cdot}53 \times 10^{-4}$	$1{\cdot}5 \times 10^{-5}$	— e.m.u./g
a.c.-demagnetization field to reduce to a half value (H_0)	20	>500	27	— oe

[6]

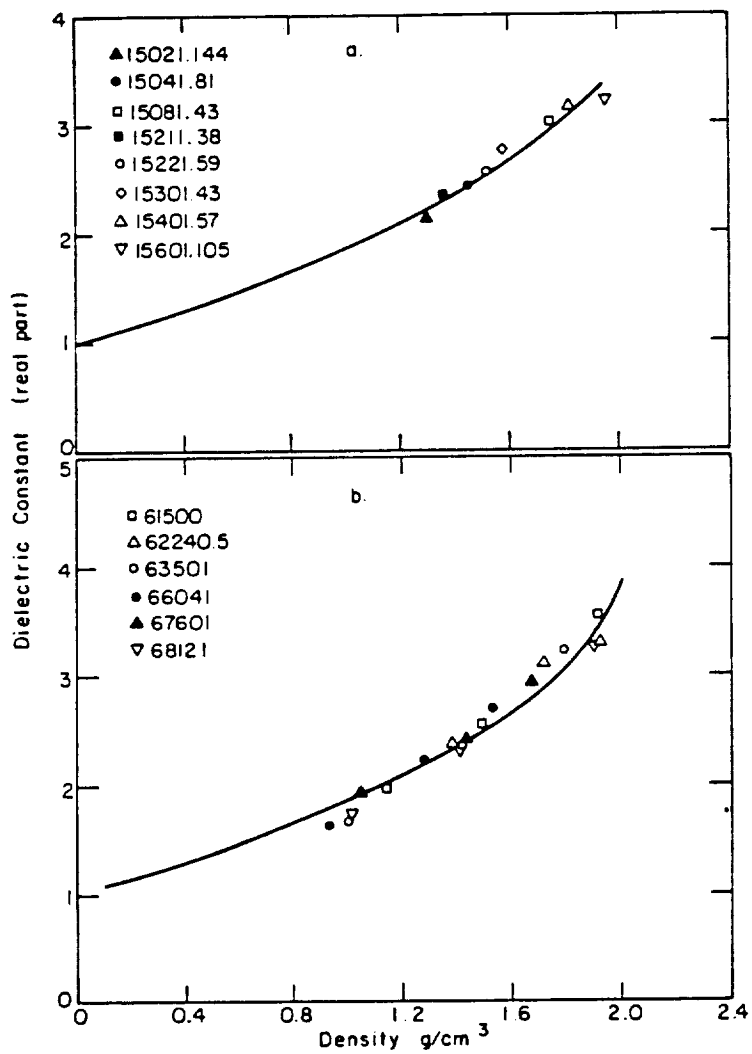


FIGURE A.2: (A) AVERAGE RAYLEIGH CURVE FOR APOLLO 15 POWDER SAMPLES WITH THE EXPERIMENTAL DATA POINTS (B) AVERAGE RAYLEIGH CURVE FOR APOLLO 16 POWDER SAMPLES WITH THE EXPERIMENTAL DATA POINTS.

[7]

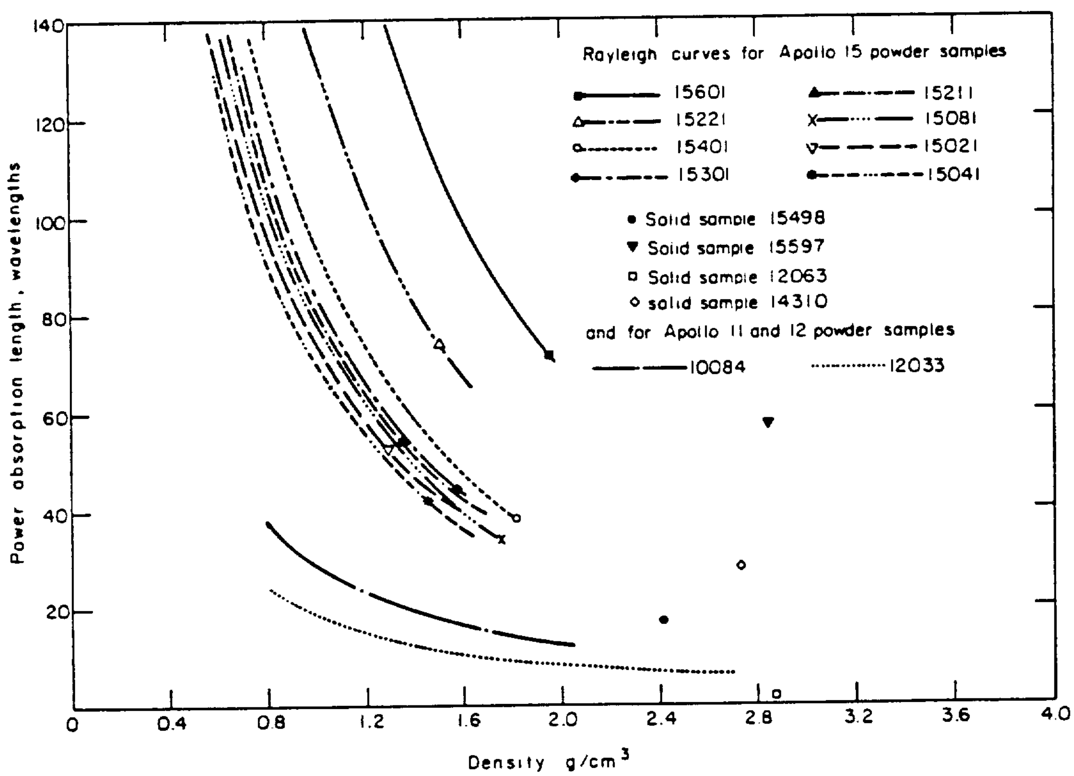


FIGURE A.3: THE VARIATION WITH DENSITY OF THE ABSORPTION LENGTH IN APOLLO 15 POWDER SAMPLES, IN THE APOLLO 11 BULK BOX POWDER SAMPLES AND IN THE APOLLO 12 POWDER SAMPLE, 12033. ABSORPTION LENGTH VS. DENSITY POINTS FOR AN APOLLO 15, 14, AND 12 SOLID SAMPLES ARE ALSO SHOWN.

[7]

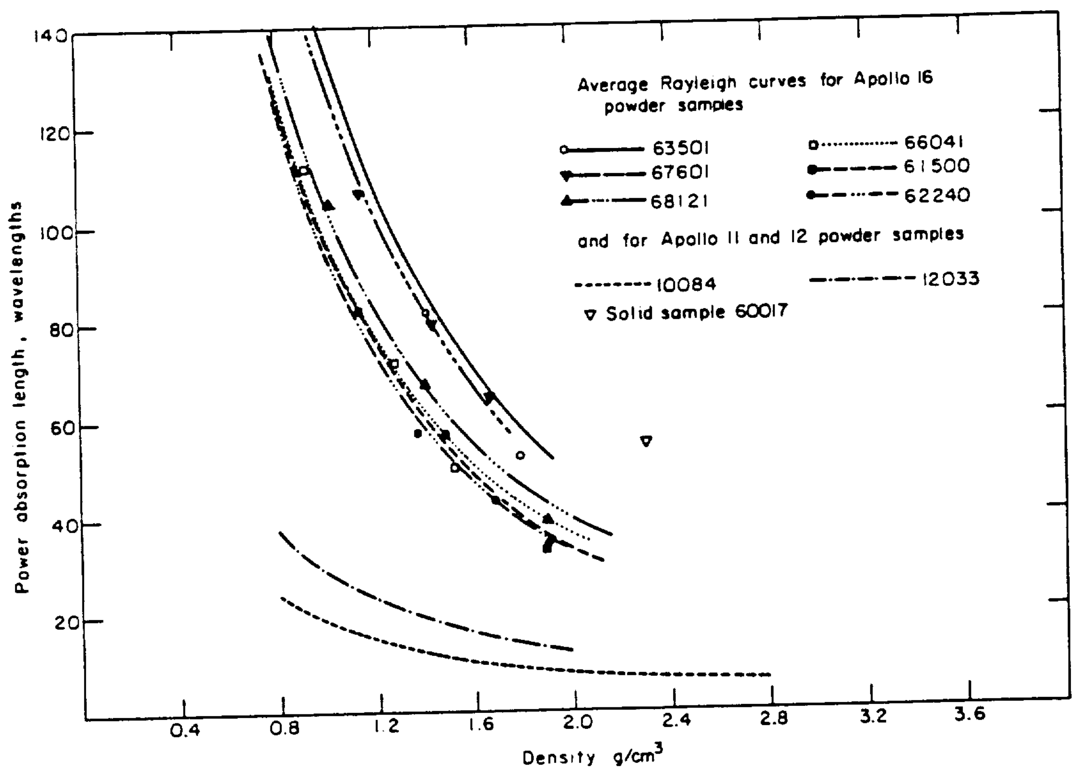


FIGURE A.4: THE VARIATION WITH DENSITY OF THE ABSORPTION LENGTH IN APOLLO 12 POWDER SAMPLE, 12033. AN ABSORPTION LENGTH VS. DENSITY POINT FOR AN APOLLO 16 SOLID SAMPLE IS ALSO SHOWN.

[7]

TABLE A.8: SUMMARY OF DIELECTRIC PROPERTIES OF APOLLO 11 AND APOLLO 12 SAMPLES.

Electrical parameter	Frequency	10017.30† Type A	10065.22 Type C	10084.83 Type D	12070.107 Type D	12002.84 Type B	12002.85 Type B
K'; real relative permittivity (dielectric constant)	10^3 Hz	9.1	8.8	3.8	3.1	8.8	9.4
	3 × 10^3	8.7	8.4	3.8	3.1	9.0	8.5
	10^4	9.0	8.0	3.8	3.1	9.0	9.0
	3 × 10^4	8.1	8.0	3.8	3.1	8.6	8.5
	10^5	8.5	7.3	3.8	3.1	8.8	8.3
	3 × 10^5	8.3	7.3	3.8	3.1	8.3	8.5
	10^6	8.8	7.3	3.8	3.0	8.3	7.8
	3 × 10^6	8.5	7.3	3.8	2.9	8.3	7.9
	10^7	9.3(?)	7.3	3.8	3.0	8.3	8.8
tan δ; loss tangent	10^3 Hz	0.090	0.14	0.108	0.128	0.049	0.038
	3 × 10^3	0.080	1.11	0.051	0.061	0.040	0.039
	10^4	0.085	0.087	0.036	0.038	0.040	0.039
	3 × 10^4	0.085	0.078	0.030	0.027	0.044	0.044
	10^5	0.080	0.067	0.025	0.025	0.047	0.051
	3 × 10^5	0.079	0.053	0.021	0.027	0.049	0.056
	10^6	0.075	0.053	0.0175	0.025	0.051	0.056
	3 × 10^6	0.047	0.040	0.0143	0.0145	0.040	0.034
	10^7	0.021	0.019	0.0089	0.0053	0.0158	0.0114
σ′; dielectric conductivity in mhos/m	10^3 Hz	4.2 × 10^{-8}	6.7 × 10^{-8}	2.2 × 10^{-8}	2.2 × 10^{-8}	2.4 × 10^{-8}	1.89 × 10^{-8}
	3 × 10^3	1.15 × 10^{-7}	1.4 × 10^{-7}	3.2 × 10^{-8}	3.6 × 10^{-8}	6.6 × 10^{-8}	5.7 × 10^{-8}
	10^4	3.9 × 10^{-7}	3.9 × 10^{-7}	7.7 × 10^{-8}	6.1 × 10^{-8}	2.1 × 10^{-7}	1.97 × 10^{-7}
	3 × 10^4	1.20 × 10^{-6}	1.0 × 10^{-6}	1.90 × 10^{-7}	1.40 × 10^{-7}	6.7 × 10^{-7}	6.8 × 10^{-7}
	10^5	3.8 × 10^{-6}	2.8 × 10^{-6}	5.2 × 10^{-7}	4.6 × 10^{-7}	2.3 × 10^{-6}	2.4 × 10^{-6}
	3 × 10^5	1.11 × 10^{-5}	6.7 × 10^{-6}	1.31 × 10^{-6}	1.41 × 10^{-6}	6.6 × 10^{-6}	7.1 × 10^{-6}
	10^6	3.5 × 10^{-5}	1.9 × 10^{-5}	3.7 × 10^{-6}	4.3 × 10^{-6}	2.1 × 10^{-5}	2.2 × 10^{-5}
	3 × 10^6	6.7 × 10^{-5}	4.2 × 10^{-5}	9.1 × 10^{-6}	7.1 × 10^{-6}	5.5 × 10^{-5}	4.4 × 10^{-5}
*	10^7	9.7 × 10^{-5}	7.1 × 10^{-5}	1.88 × 10^{-5}	8.7 × 10^{-6}	1.0 × 10^{-4}	—

* Samples measured at room temperature and in a dry atmosphere.

† Measurement precision (±15% for real relative permittivity, K') for this sample is lower than that of the others, due to its irregular shape.

[8]

APPENDIX A: REFERENCES

1. Taylor, S.R., Lunar Science: A Post-Apollo View, Pergamon Press Inc., p. 62, 1975.

2. Rose, H.J., Jr., et al., "Chemical Composition of Rocks and Soil at Taurus-Littrow", Proceedings of the Fifth Lunar Conference, Vol. 2, Pergamon Press Inc.,, pp. 1119-1133, 1974.

3. Mitchell, J.K., et al., "Mechanical Properties of Lunar Soil: Density, Porosity, Cohesion, and Angle of Internal Friction", Proceedings of the Third Lunar Science Conference, Vol. 3, The M.I.T. Press, pp. 3235-3253, 1972.

4. Cremers, C.J., et al., "Thermal Conductivity of Fines From Apollo 11", Proceedings of the Apollo 11 Lunar Science Conference, Vol. 3, Pergamon Press Inc., pp. 2045-2050, 1970.

5. Pearce, G.W., et al., "Magnetic Studies on Apollo 15 and 16 Lunar Samples", Proceedings of the Fourth Lunar Science Conference, Vol. 3, Pergamon Press Inc., pp. 3045-3076, 1973.

6. Nagata, T., et al., "Magnetic Properties and Natural Remanent Magnetization of Lunar Materials", Proceedings of the Apollo 11 Lunar Science Conference, Vol. 3, Pergamon Press Inc., pp. 2325-2340, 1970.

7. Gold, T., et al, "Grain Size Analysis and High Frequency Electrical Properties of Apollo 15 and 16 Samples", Proceedings of the Fourth Lunar Science Conference, Vol. 3, Pergamon Press Inc., pp. 3093-3100, 1973.

8. Katsube, T.J., and Collett, L.S., "Electrical Properties of Apollo 11 and Apollo 12 Lunar Samples", Proceedings of the Second Lunar Science Conference, Vol. 3, The M.I.T. Press, pp. 2367-2379, 1971.

APPENDIX B

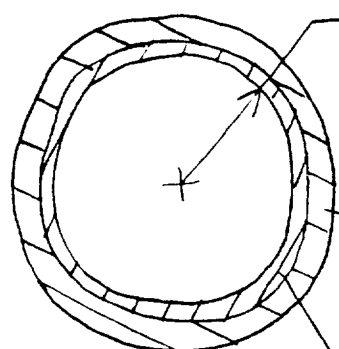
DEVICE MASS CALCULATIONS

APPENDIX B

DEVICE MASS CALCULATIONS

I. MASS OF PORTABLE TANK

ASSUME:
1. UNIFORM WALL
2. AREA CHANGE WITH INCREASING RADIUS IS NEGLIGIBLE



$m_t = \Sigma \rho V$ = TOTAL MASS

APPROXIMATE MASS BY

$$m_t = A_t \Sigma t \rho$$

A_t = SURFACE AREA OF THE TANK INTERIOR

$$A_t = 4\pi r^2 + 2\pi r h \qquad h = 0.149\ m$$

$$A_t = 4\pi (0.125m)^2 + 2\pi (0.125m)(0.149m)$$

$$A_t = 0.313\ m^2$$

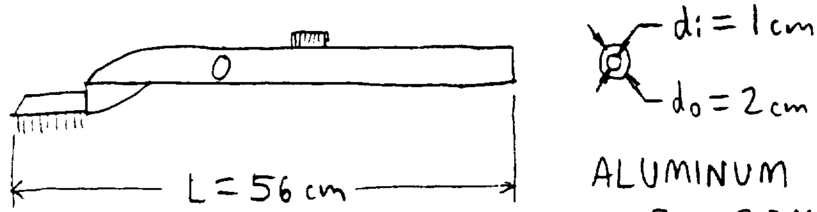
$$m_t = A_t(t_{ins}\rho_{ins} + t_{Ti}\rho_{Ti})$$

$$m_t = (0.313\ m^2)\big((0.010\ m)(1450\ kg/m^3) + (0.003\ m)(4500\ kg/m^3)\big)$$

$$\boxed{m_t \approx 8.76\ kg}$$

II. MASS OF THE DUSTING ATTACHMENT

ASSUME: 1. UNIFORM CROSS-SECTION ALONG THE LENGTH FOR APPROXIMATION – TREAT AS 56 cm LONG TUBE WITH INSIDE DIAMETER OF 1 cm AND OUTSIDE DIAMETER OF 2 cm.



ALUMINUM
$\rho_{Al} = 2800\ kg/m^3$

$$m_{da} \approx \left(L\,\frac{\pi}{4}(d_o^2 - d_i^2)\right)\rho_{Al}$$

$$m_{da} \approx (0.56\ m)\left(\frac{\pi}{4}\right)\big((0.02\ m)^2 - (0.01\ m)^2\big)(2800\ kg/m^3)$$

$$\boxed{m_{da} \approx 0.37\ kg}$$

III. MASS OF REGULATOR, HEATING EQUIPMENT, AND HOSE

ESTIMATE MASS OF REGULATOR AND GAS HEATING EQUIPMENT TO BE $m_{r,he} = 1\ kg$.

ESTIMATE MASS OF HOSE TO BE

$$\boxed{m_h = 2\ kg.}$$

IV. MASS OF CARBON DIOXIDE

$m_{CO_2} = \forall_t / v_s$ $\forall_t = 0.0155\ m^3$

$v_s = 0.0329\ m^3/kg$

(APPENDIX C.2)

$$m_{CO_2} = \frac{(0.0155 m^3)}{(0.0329 m^3/kg)}$$

$$\boxed{m_{CO_2} = 0.471\ kg}$$

V. APPROXIMATE TOTAL MASS

$$m_T = m_t + m_{da} + m_{r,he} + m_h + m_{CO_2}$$

$$m_T = 8.76\ kg + 0.37\ kg + 1\ kg + 2\ kg + 0.471\ kg$$

$$\boxed{m_T \approx 12.6\ kg}$$

APPENDIX C

GAS USAGE CALCULATIONS

APPENDIX C

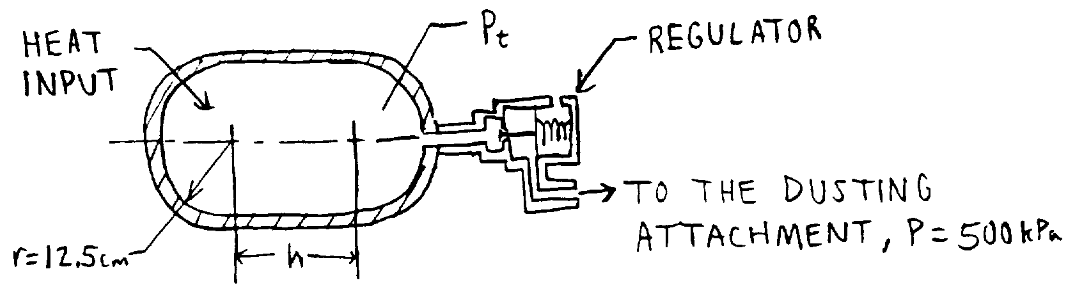
GAS USAGE CALCULATIONS

I. MASS STORAGE REQUIREMENTS

ASSUME:

1. 10 MINUTE GAS SUPPLY AT INTERMEDIATE PRESSURE STAGE SETTING OF $P_i = 150$ kPa
2. HEATING WILL MAINTAIN GAS TEMPERATURE AT $T = 367$ K DESPITE GAS EXPANSION
3. REGULATOR MAINTAINS STEADY 500 kPa OUTPUT FROM THE PORTABLE TANK, THUS OPERATION ENDS WHEN THE PORTABLE TANK PRESSURE DROPS TO 500 kPa
4. MAXIMUM TANK PRESSURE OF 2000 kPa

PORTABLE TANK



USABLE MASS CALCULATION

$m_v = \dot{m}\, t \qquad t = 10\,\text{min}$

$\dot{m} = (3.98\times10^{-9}\ \text{kg}\cdot\text{m}^2/\text{N}\cdot\text{s})\,P_i$ (APPENDIX H.2)

$P_i = 150\ \text{kPa}$

$\dot{m} = (3.98\times10^{-9}\ \text{kg}\ \text{m}^2/\text{N}\cdot\text{s})(150\ \text{kPa})$

$\dot{m} = 0.597\ \text{g/s}$

$m_t = (0.597\times10^{-3}\ \text{kg/s})(10\,\text{minutes})\left(\frac{60\,\text{seconds}}{1\,\text{minute}}\right)$

$m_t = 0.358\ \text{kg}$

STARTING AND FINISH SPECIFIC VOLUME CALCULATIONS

START: $T = 367\ \text{K}$
$P = 2000\ \text{kPa}$

FINISH: $T = 367\ \text{K}$
$P = 500\ \text{kPa}$

CO_2: $P_{CR} = 7.38\ \text{MPa}$
$T_{CR} = 304.2\ \text{K}$

$Z = \frac{Pv}{RT}$ Z = COMPRESSIBILITY FACTOR

$v = \frac{ZRT}{P}$

START $P_r = P/P_{CR}$ $T_r = T/T_{CR}$

$P_r = \frac{2000 \text{ kPa}}{7.38 \text{ MPa}} = 0.271$

$T_r = \frac{367 \text{ K}}{304.2 \text{ K}} = 1.21$

$\Rightarrow Z = 0.950$ (REFERENCE 1)

$v = \frac{(0.950)(189 \text{ J/kg K})(367 \text{K})}{(2000 \text{ kPa})}$

$v_s = 0.0329 \text{ m}^3/\text{kg}$

FINISH

$P_r = \frac{500 \text{ kPa}}{7.38 \text{ MPa}} = 0.0678$

$T_r = 1.21$

$\Rightarrow Z = 0.990$ (REFERENCE 1)

$v = \frac{(0.990)(189 \text{ J/kg-K})(367 \text{K})}{(500 \text{ kPa})}$

$v_f = 0.1373 \text{ m}^3/\text{kg}$

II. CALCULATION OF TOTAL VOLUME OF PORTABLE TANK TO CONTAIN THE MASS NEEDED AND MAINTAIN THE REQUIRED MINIMUM PRESSURE, P = 500 kPa

$\forall_t$ = TOTAL VOLUME OF TANK

$$m_t = \forall_t / v_s - \forall_t / v_f = \forall_t \left(\frac{1}{v_s} - \frac{1}{v_f} \right)$$

$$\forall_t = m_t / \left(\frac{1}{v_s} - \frac{1}{v_f} \right)$$

$$\forall_t = (0.358\ kg) / \left(\frac{1}{0.0329\ m^3/kg} - \frac{1}{0.1373\ m^3/kg} \right)$$

$$\boxed{\forall_t = 0.0155\ m^3}$$

TANK INSIDE DIMENSIONS

$$\boxed{r = 0.125\ m}$$

$$\forall_t = \frac{4}{3}\pi r^3 + \pi r^2 h$$

$$h = \frac{\forall_t - \frac{4}{3}\pi r^3}{\pi r^2}$$

$$h = \frac{0.0155\ m^3 - \frac{4}{3}\pi (0.125\ m)^3}{\pi (0.125\ m)^2}$$

$$\boxed{h = 0.149\ m}$$

INTERNAL LENGTH

$$L = h + 2r = (0.149\ m) + 2(0.125\ m)$$

$$\boxed{L = 0.399\ m}$$

REFERENCE:

1. BUCKIUS, R. O., AND HOWELL, J. R., <u>FUNDAMENTALS OF ENGINEERING THERMODYNAMICS</u>, <u>SI VERSION</u>, MCGRAW-HILL BOOK COMPANY, 1987, P. 555

APPENDIX D

DECISION MATRIX

DECISION MATRIX METHODOLOGY

Nine criteria were used for the decision matrix. The criteria were first defined and then compared for relative importance. They were rated against each other using the method of pairs. Then each criterion was normalized to a fraction of one by taking the ratio of its total tally to the total number of tally points for all the criteria.

Scales from zero to one hundred were then created for the rating of each device for each criterion. Each device was rated according to the results of preliminary analysis and engineering intuition.

Finally, the decision matrix was drawn by multiplying the rating for each design by its weighting factor. The result was divided by one hundred to normalize to one and the sum of these ratings was the device's overall rating. The Brush-Blower Device had the highest rating and was chosen for development.

CRITERIA DEFINITIONS AND RATING SCALES

Safety- The potential for physical injury to the user of the dust removal device. (e.g. electric shock, inhalation of harmful fumes, breach of the space suit)

100- No potential for injury.
90- No potential for serious injury.
75- No potential for a serious injury but a significant minor injury is possible.
50- Slight potential for serious injury.
25- Serious injury is probable.
0- Chance of death.

Energy- This is a measure of the amount of energy needed to clean a unit area of a surface to a specified level of cleanliness.

100- Human powered only.
90- Negligible energy consumption. (less than 100 watts)
75- About 500 watts.
50- Energy consumption is excessive for any application larger than a space suit. (about 1000 watts)
25- About 1500 watts.
0- Unacceptable energy consumption for any application.

Waste- The amount of material that is either lost and unrecoverable, pollutes the lunar environment, or must be detoxified after the cleaning of a unit area.

100- No waste products.
90- Relatively small amounts of non-toxic recyclable wastes.
75- Relatively small amounts of toxic or nonrecyclable wastes.
50- Relatively large amounts of non-toxic or recyclable wastes.
25- Device use depletes accessible resources.
0- Large amounts of toxic, nonrecyclable wastes, or a severe depletion of resources.

Effectiveness- For analytical purposes, this was regarded as the time needed for the device to clean a unit area to perfection. This assumes that perfection is attainable if the device is used on that area for a long enough period of time.

100- >144 in^2/s
90- 100-144 in^2/s
75- 50-100 in^2/s
50- 20-50 in^2/s
25- 10-20 in^2/s
0- <10 in^2/s

Versatility- The ability to use the dust removal device only, ranked here in increasing order of desirability, within a pressurized environment only, in a vacuum only, or either.

100- The device works well in either a pressurized environment or a vacuum.
90- The device can work in either environment but needs modification to go from one to the other.
75- The device works in a vacuum only.
50- The devices works well in a pressurized environment but poorly in a vacuum.
25- The device works in a pressurized environment only.
0- The device works poorly in both a pressurized environment and a vacuum.

Surface Variety- The range of different surface materials and geometries that the device can be used on.

100- The device works well on all surface materials and geometries.
90- The device suffers some limitations on uncommon surface materials or geometries.
75- The device suffers some limitations on uncommon surface materials and geometries.
50- The device suffers some limitations on common surface materials or geometries.
25- The device suffers some limitations on common surface materials and geometries.

0- The device works on very few surface materials or geometries.

Surface Damage- The amount of permanent harm such as scratching and scuffing, that the device will do to material surfaces over time.

100- Use of the device will not harm any surface.
90- Use of the device results in acceptable wear for 50 cleanings of precision glass (16 micro-inch finish).
75- Use of the device results in acceptable wear for 10 cleanings of precision glass (16 micro-inch finish)
50- Use of the device results in acceptable wear for 10 cleanings of precision steel (16 micro-inch finish)
25- Use of the device results in acceptable wear for 10 cleanings of non-precision surfaces.
0- Use of the device results in unacceptable wear for all surfaces.

Portability- The capability of the device to be carried around and not be tied down to one location because of weight, bulkiness, or some other factor.

100- The mass of the device is less than 10 lbm and the volume is less than 1 ft^3.
90- The mass of the device is between 10 and 20 lbm and the volume is under 1.5 ft^3.
75- The mass of the device is between 20 and 30 lbm and the volume is under 2 ft^3.
50- The mass of the device is between 30 and 50 lbm and the volume is under 3 ft^3.
25- The mass of the device is between 50 and 100 lbm and the volume is under 6 ft^3.
0- The mass of the device is greater than 100 lbm and the volume is greater than 10 ft^3.

Ease of Use- The ability of an astronaut to use the device with a minimum of physical and mental effort. Three subcriteria were created for comparing the devices:

1. Maximum Force- The force that the user must exert to clean a surface should be minimized.
2. Complexity- The device should be kept simple so the user does not have to expend mental energy to clean a surface.
3. Device Modification for Different Surfaces- The device should require a minimum of changes to clean different surface types and geometries.

100- The device has no problems with any of the criteria.
90- The device has minor problems with one of the criteria.
75- The device has significant problems with two of the criteria.
50- The device has significant problems with all of the criteria.
25- The device has serious problems with one of the criteria.
0- The device has serious problems with more than one of the criteria.

TABLE D.1: CRITERIA RATINGS AND WEIGHTING FACTORS

CRITERIA	Tally	Weighting Factor
Safety	4	0.1111
Energy	2	0.0556
Waste	4	0.1111
Effectiveness	5	0.1389
Versatility	5	0.1389
Surface Variety	3	0.0833
Surface Damage	6	0.1667
Portability	5	0.1389
Ease of Use	2	0.0556
Total	36	1.0000

Table D.2: DECISION MATRIX

Design Considerations → / Weighting Factor / Alternates ↓	Safety	Energy	Waste	Effectiveness	Versatility	Variety	Damage	Portability	Ease of Use	Sum of Products
Weighting Factor	.111	.056	.111	.139	.167	.083	.139	.139	.056	1.000
Vibration-Suction	100 / .111	90 / .05	100 / .111	75 / .104	25 / .042	75 / .063	90 / .125	75 / .104	90 / .05	.760
Vibration-Blower	75 / .083	90 / .05	75 / .083	75 / .104	75 / .125	75 / .063	75 / .104	90 / .125	90 / .05	.787
Passive Electrostatics-Suction	75 / .083	90 / .05	100 / .111	75 / .104	25 / .042	50 / .042	100 / .139	25 / .035	90 / .05	.656
Passive Electrostatics-Brush	75 / .083	100 / .056	100 / .111	75 / .104	90 / .15	50 / .042	75 / .104	25 / .035	90 / .05	.735
Brush-Suction	100 / .111	90 / .05	100 / .111	75 / .104	25 / .042	90 / .075	90 / .125	75 / .104	90 / .05	.772
Active Electrostatics-Brush	50 / .056	75 / .042	100 / .111	50 / .069	100 / .167	75 / .063	75 / .104	90 / .125	75 / .042	.779
Chemical-Suction	75 / .083	75 / .042	50 / .057	75 / .104	50 / .083	50 / .042	100 / .139	25 / .035	75 / .042	.627
Brush-Blower	75 / .083	90 / .05	75 / .083	75 / .104	90 / .15	75 / .063	75 / .104	90 / .125	90 / .05	.812

APPENDIX E

GAS FORCES ON DUST PARTICLES

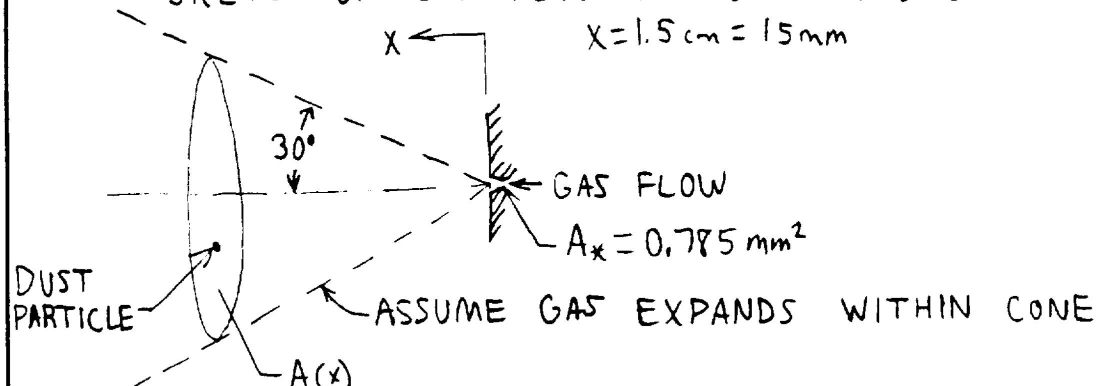
APPENDIX E

GAS FORCES ON DUST PARTICLES

I. FORCES ON 4 μm AND 400 μm DIAMETER DUST PARTICLES AT A DISTANCE OF 1.5 cm FROM THE NOZZLE

ASSUME:
1. USE CARBON DIOXIDE
2. IDEAL GAS: $\gamma = 1.3$, $R = 189$ J/kg K
3. ISENTROPIC EXPANSION
4. GAS DISPERSES IN A CONE WITH A HALF ANGLE OF 30°.
5. DRAG PROPORTIONAL TO VELOCITY SQUARED; $C_D = 1$ FOR DUST
6. NEGLIGIBLE WAVE DRAG FOR INDIVIDUAL PARTICLES

SKETCH OF GAS FLOW OUT OF A NOZZLE



$$A(x) = (X \sin 30°)^2 \pi = \left(\frac{\pi}{4}\right) X^2$$

At $X = 15\text{mm}$, $A(x) = \left(\frac{\pi}{4}\right)(15\text{mm})^2 = 177\ \text{mm}^2$

$$\frac{A(x)}{A_*} = \frac{177\ \text{mm}^2}{0.785\ \text{mm}^2} = 225$$

$$\frac{A}{A_*} = \frac{1}{M}\left[\frac{1 + \frac{1}{2}(\gamma - 1)M^2}{\frac{1}{2}(\gamma + 1)}\right]^{(1/2)(\gamma+1)/(\gamma-1)}$$

SOLVE ON CALCULATOR, $\gamma = 1.3$, $A/A_* = 225$

$\Rightarrow M = 6.71$

$V = M \cdot a \qquad a = \sqrt{\gamma R T}$

$T = T_0 / \left(1 + \frac{\gamma - 1}{2} M^2\right)$

$T = 367\text{K} / \left(1 + \frac{(1.3-1)}{2}(6.71)^2\right)$

$T = 47\ \text{K}$

$a = \sqrt{(1.3)(189\ \text{J/kg K})(47\text{K})}$

$a = 108\ \text{m/s}$

$V = (6.71)(108\ \text{m/s})$

$V = 725\ \text{m/s}$ ⇐ APPROXIMATE VELOCITY OF GAS 15mm FROM NOZZLE

$\rho_g = \rho_i / \left(\frac{T_i}{T}\right)^{1/(\gamma-1)}$

$\rho_0 = \frac{P_i}{RT_i} = \frac{200\ \text{kPa}}{(189\ \text{J/kg}\cdot\text{K})(367\ \text{K})}$

$\rho_i = 2.88\ \text{kg/m}^3$

$\rho_g = (2.88\ \text{kg/m}^3) / \left(\frac{367\text{K}}{47\text{K}}\right)^{1/(1.3-1)} = 0.00305\ \text{kg/m}^3$

DRAG ON 4 μm DIAMETER DUST PARTICLE AT REST IN THE GAS FLOW

F_D = DRAG FORCE

C_D = DRAG COEFFICIENT

A_p = CROSS SECTIONAL AREA OF PARTICLE

ρ_p = PARTICLE MASS DENSITY $\simeq 1500\ kg/m^3$

ρ_g = GAS DENSITY

V = GAS VELOCITY RELATIVE TO PARTICLE STATIONARY IN FLOW

$\forall_p$ = VOLUME OF PARTICLE

m_p = PARTICLE MASS

$$F_D = \frac{1}{2} C_D \rho_g V^2 A_p$$

$$A_p = \frac{\pi}{4} d^2 \quad \text{(ASSUMING SPHERICAL PARTICLE)}$$

$$\forall_p = \frac{\pi}{6} d^3$$

$$d = 4\ \mu m$$

$$A_p = \frac{\pi}{4}(4\times10^{-6} m)^2 = 1.26\times10^{-11} m^2$$

$$\forall_p = \frac{\pi}{6}(4\times10^{-6} m)^3 = 3.35\times10^{-17} m^3$$

$$m_p = \forall_p \rho_p$$

$$m_p = (3.35\times10^{-17} m^3)(1500\ kg/m^3) = 5.03\times10^{-14} kg$$

$$F_D = \frac{1}{2}(1)(0.00305\ kg/m^3)(725 m/s)^2(1.26\times10^{-11} m^2)$$

$$\boxed{F_D = 1.01\times10^{-8} N}$$

$$a_p = F_D/m_p$$

$$a_p = (1.01\times10^{-8} N)/(5.03\times10^{-14} kg)$$

$a_p = 201\times10^{3} m/s^2 \Rightarrow$ PARTICLE ACCELERATES QUICKLY TO FLOW VELOCITY

DRAG ON 400 μm DIAMETER DUST PARTICLE AT REST IN THE GAS FLOW

$d = 400\ \mu m$

$A_p = \frac{\pi}{4}(400 \times 10^{-6}\ m)^2 = 1.26 \times 10^{-7}\ m^2$

$V_p = \frac{\pi}{6}(400 \times 10^{-6}\ m)^3 = 3.35 \times 10^{-11}\ m^3$

$m_p = (3.35 \times 10^{-11}\ m^3)(1500\ kg/m^3) = 5.03 \times 10^{-8}\ kg$

$F_D = \frac{1}{2}(1)(0.00305\ kg/m^3)(725\ m/s)^2(1.26 \times 10^{-7}\ m^2)$

$\boxed{F_D = 1.01 \times 10^{-4}\ N}$

$a_p = (1.01 \times 10^{-4}\ N)/(5.03 \times 10^{-8}\ kg)$

$a_p = 2\,010\ m/s^2 \Rightarrow$ PARTICLE ACCELERATES QUICKLY TO FLOW VELOCITY

COMPARISON OF DRAG FORCE TO ADHESIVE FORCE FOR 400 μm DIAMETER DUST PARTICLE

ASSUME:
1. PARTICLE ON SURFACE HAS SAME DRAG AS A PARTICLE IMMERSED IN THE FLOW
2. ADHESIVE STRENGTH TO SURFACE OF 1 kPa
3. ADHESIVE STRENGTH ACTS OVER AN AREA OF THE PARTICLE EQUIVALENT TO ITS CROSS SECTION

F_A = ADHESIVE FORCE TO AN INDIVIDUAL DUST PARTICLE

S_A = ADHESIVE STRENGTH = 1 kPa = 1×10^3 N/m^2

$F_A = S_A A_h$ A_h = HEMISPHERICAL AREA = $\frac{\pi d^2}{2}$

$F_A = (1 \times 10^3 \, N/m^2)\left(\frac{\pi (400 \times 10^{-6} m)^2}{2}\right)$

$\boxed{F_A = 2.51 \times 10^{-4} \, N}$

COMPARE TO $F_D = 1.01 \times 10^{-4}$ N

⇒ GAS MAY LOOSEN DUST WITH MAXIMUM ADHESIVE STRENGTH AT DISTANCES FROM THE NOZZLE SOMEWHAT LESS THAN 15mm

II. FORCES ON 4 μm AND 400 μm DIAMETER DUST PARTICLES AT A DISTANCE OF 10 cm FROM THE NOZZLE

SAME ASSUMPTIONS AS IN SECTION I.

$x = 10 \, cm = 100 \, mm$

$A(x) = \left(\frac{\pi}{4}\right)(100 mm)^2 = 7850 \, m^2$

$\frac{A(x)}{A_*} = \frac{7850 \, mm^2}{0.785 \, mm^2} = 10000$

$$\frac{A}{A_*} = \frac{1}{M}\left[\frac{1+\frac{1}{2}(\gamma-1)M^2}{\frac{1}{2}(\gamma+1)}\right]^{(1/2)(\gamma+1)/(\gamma-1)}$$

SOLVE ON CALCULATOR, $\gamma = 1.3$, $A/A_* = 10000$

$\Rightarrow M = 12.5$

$V = M \cdot a \qquad a = \sqrt{\gamma R T}$

$T = T_0 / \left(1 + \frac{\gamma-1}{2} M^2\right)$

$T = 367K / \left(1 + \frac{(1.3-1)}{2}(12.5)^2\right)$

$T = 15K$

$a = \sqrt{(1.3)(189\ J/kg\,K)(15K)}$

$a = 60.7\ m/s$

$V = (12.5)(60.7\,m/s) = 759\ m/s \Leftarrow$ APPROXIMATE GAS VELOCITY 100 mm FROM THE NOZZLE

$\rho_g = \rho_i / \left(\frac{T_i}{T}\right)^{1/(\gamma-1)}$

$\rho_i = 2.88\ kg/m^3$

$\rho_g = (2.88\ kg/m^3) / \left(\frac{367K}{15K}\right)^{1/(1.3-1)} = 67.7 \times 10^{-6}\ kg/m^3$

DRAG ON 4 μm DIAMETER DUST PARTICLE AT REST IN THE GAS FLOW

$d = 4\,\mu m$

$A_p = 1.26 \times 10^{-11}\ m^2$

$m_p = 5.03 \times 10^{-14}\ kg$

$$F_D = \frac{1}{2}(1)(67.7\times10^{-6}\ kg/m^3)(759\ m/s)^2(1.26\times10^{-11}\ m^2)$$

$$\boxed{F_D = 2.46\times10^{-10}\ N}$$

$$a_p = F_D/m_p$$

$$a_p = (2.46\times10^{-10}\ N)/(5.03\times10^{-14}\ kg)$$

$a_p = 4890\ m/s^2 \Rightarrow$ PARTICLE ACCELERATES QUICKLY TO FLOW VELOCITY

DRAG ON 400 μm DIAMETER DUST PARTICLE AT REST IN THE GAS FLOW

$$d = 400\ \mu m$$

$$A_p = 1.26\times10^{-7}\ m^2$$

$$m_p = 5.03\times10^{-8}\ kg$$

$$F_D = \frac{1}{2}(1)(67.7\times10^{-6}\ kg/m^3)(759\ m/s)^2(1.26\times10^{-7}\ m^2)$$

$$\boxed{F_D = 2.46\times10^{-6}\ N}$$

$$a_p = F_D/m_p$$

$$a_p = (2.46\times10^{-6}\ N)/(5.03\times10^{-8}\ kg)$$

$a_p = 48.9\ m/s^2 \Rightarrow$ PARTICLE ACCELERATION SUFFICIENT TO REMOVE DUST FROM SURFACE

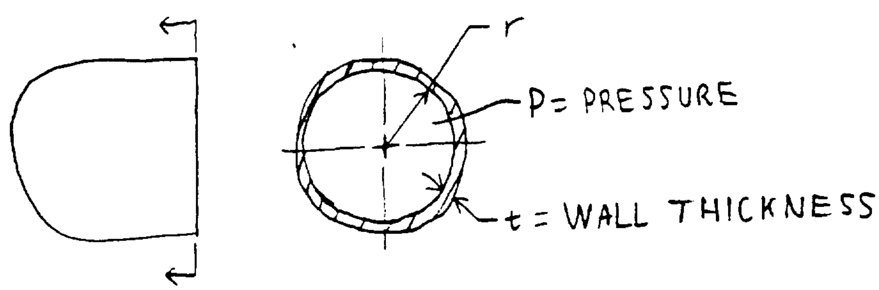
APPENDIX F

STRESS CALCULATIONS FOR THE PORTABLE TANK

APPENDIX F

STRESS CALCULATIONS FOR THE PORTABLE TANK

THE THICKNESS OF THE PORTABLE TANK'S WALL IS DEPENDANT ON THE PRESSURE INSIDE, THE MATERIAL USED, AND THE SAFETY FACTOR. SINCE HOOP STRESSES AROUND THE CENTRAL, CYLINDRICAL PORTION OF THE TANK ARE TWICE THE STRESSES IN THE HEMISPHERICAL ENDS, ONLY HOOP STRESSES WILL BE CONSIDERED.



ASSUME:
1. ONLY CONSIDER HOOP STRESS
2. SAFETY FACTOR, $n = 3$
3. TANK MADE FROM TITANIUM ALLOY, Ti 6-Al 4-V, $\sigma_y = 1000$ MPa
4. MAXIMUM PRESSURE OF $P = 2000$ kPa

F2

$$\sigma_y = \frac{nPr}{t}$$

$$t = \frac{nPr}{\sigma_y}$$

$$t = \frac{(3)(2000\,kPa)(0.125\,m)}{(1000\,MPa)}$$

$$\boxed{t = 0.75\ mm}$$

THIS IS A MINIMUM THICKNESS REQUIRED TO WITHSTAND THE STRESSES OF CONTAINING A GAS. TO WITHSTAND THE STRESSES OF ACCIDENTAL IMPACTS, A THICKNESS OF $\underline{t = 3mm}$ WILL BE USED.

APPENDIX G
HEATING REQUIREMENT CALCULATIONS FOR THE PORTABLE TANK

APPENDIX G

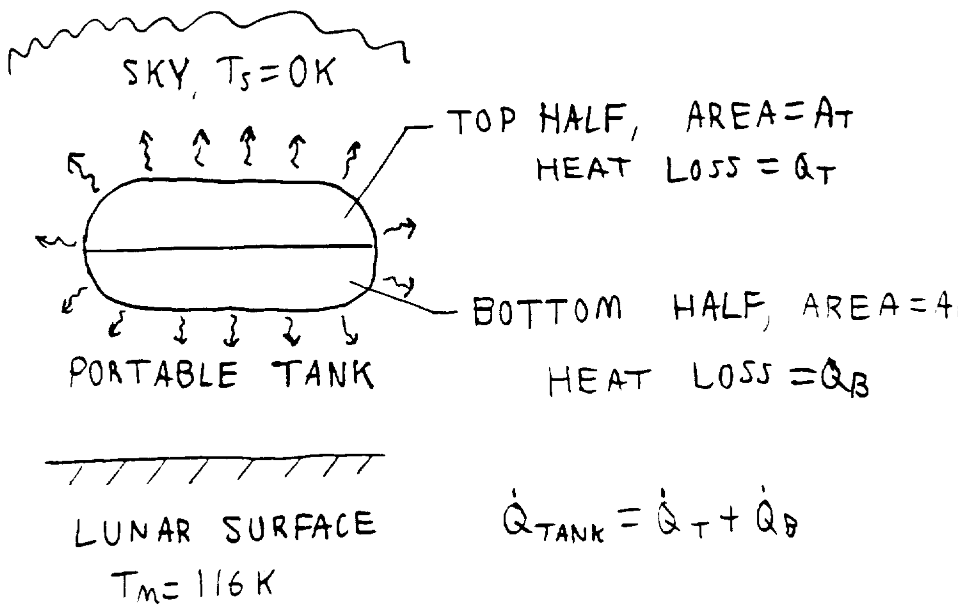
HEATING REQUIREMENT CALCULATIONS FOR THE PORTABLE TANK

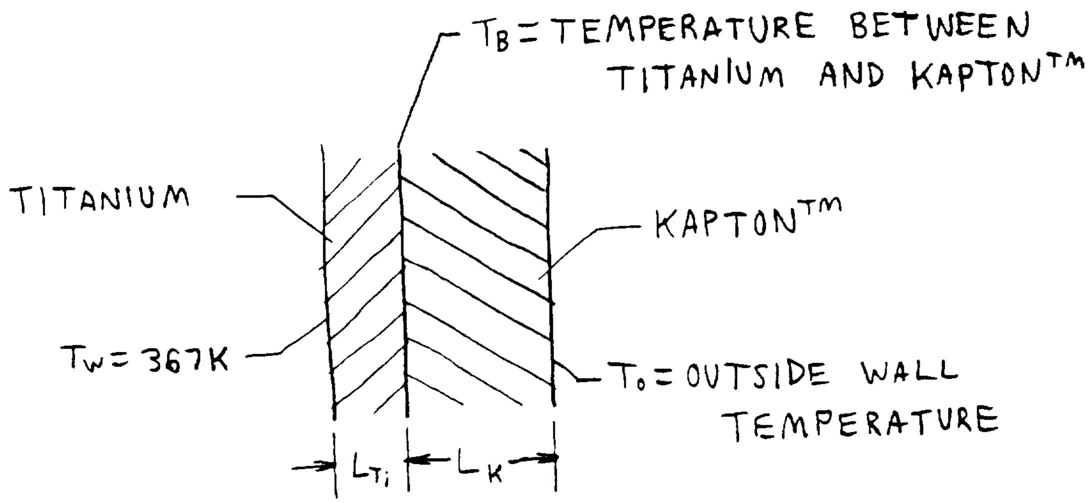
I. HEAT LOSS FROM PORTABLE TANK DURING THE LUNAR NIGHT

ASSUME:

1. SKY TEMPERATURE, $T_S = 0$ K
2. LUNAR SURFACE TEMPERATURE, $T_M = 116$ K
3. DIVIDE TANK INTO TWO HALVES, ONE HALF EXPOSED TO THE SKY, THE OTHER HALF EXPOSED TO THE LUNAR SURFACE
4. ALL SURFACE BEHAVE AS BLACKBODIES
5. NEGLECT CONVECTION INSIDE THE TANK
6. TEMPERATURE OF THE TANK INSIDE WALL, $T_W = 367$ K

G2





CROSS-SECTION OF TANK WALL

COEFFICENTS OF THERMAL CONDUCTIVITY

TITANIUM $k_{Ti} = 30.5$ W/mK AT 100K (REFERENCE 1)

KAPTON™ $k_K = 0.155$ W/mK AT 298K (REFERENCE 2)

$L_{Ti} = 0.003$ m $L_K = 0.010$ m

TOP HALF

$$A_T = A_B = \frac{1}{2}A = \frac{1}{2}(4\pi r^2 + 2\pi r h)$$

$$A_T = A_B = \frac{1}{2}(4\pi(0.125m)^2 + 2\pi(0.125m)(0.149m))$$

$$A_T = A_B = 0.157\,m^2$$

$$\dot{Q}_T = \frac{k_{Ti} A_T}{L_{Ti}}(T_W - T_B) = \frac{k_K A_T}{L_K}(T_B - T_0) = \sigma A_T (T_0^4 - T_s^4)$$

$$\sigma = 5.67 \times 10^{-8}\, W/m^2K^4$$

$$(30.5\,W/mK)(0.157m^2)((367K) - T_B)/(0.003m)$$

$$= (0.155\,W/mK)(0.157m^2)(T_B - T_0)/(0.010m)$$

$$= (5.67\times 10^{-8}\,W/m^2K^4)(0.157m^2)(T_0^4 - (0K)^4)$$

$$586000 - 1600\,T_B = 2.43(T_B - T_0)$$

$$T_B = \frac{586000 + 2.43\,T_0}{1602}$$

$$2.43\left(\left(\frac{586000 + 2.43T_0}{1602}\right) - T_0\right) = 8.90\times 10^{-9}\,T_0^4$$

SOLVE FOR T_0 ON CALCULATOR

$$\Rightarrow T_0 = 325K$$

$$\dot{Q}_T = (5.67\times 10^{-8}\,W/m^2K)(0.157\,m^2)(325K)^4$$

$$\dot{Q}_T = 99.2W$$

BOTTOM HALF

BY SIMILARITY WITH TOP HALF ANALYSIS:

ONLY DIFFERENCE IS $T_M = 116$ K

INSTEAD OF $T_S = 0$ K

$$2.43\left(\left(\frac{586000 + 2.43T_0}{1602}\right) - T_0\right) = 8.9\times10^{-7}\left(T_0^4 - (116)^4\right)$$

SOLVE FOR T_0 ON CALCULATOR

$$\Rightarrow T_0 = 325\,K$$

$$\dot{Q}_B = (5.67\times10^{-8}\ W/m^2K)(0.157\,m^2)((325\,K)^4 - (116\,K)^4)$$

$$\dot{Q}_B = 97.7\ W$$

$$\dot{Q}_{TANK} = 99.2\ W + 97.7\ W$$

$$\boxed{\dot{Q}_{TANK} = 197\ W}$$

II. HEAT REQUIRED TO MAINTAIN 367K INSIDE THE PORTABLE TANK DESPITE EXPANSION

ASSUME: 1. IDEAL GAS

2. CONSTANT TEMPERATURE $T = 367$ K

Q_e = HEAT TRANSFER TO COMPENSATE FOR EXPANSION

$$Q_e = \int \forall\, dP \qquad P = \frac{mRT}{\forall}$$

$\forall$ = VOLUME ⇒ CONSTANT

$$dP = \frac{RT}{\forall}\, dm$$

$$Q_e = \int RT\, dm$$

$$\dot{Q}_e = RT\,\dot{m}$$

$\dot{m}_{max}$ = 0.796 g/s (APPENDIX H.2)

CARBON DIOXIDE : R = 189 J/kg K

$$\dot{Q}_e = (189\ \text{J/kg K})(367\ \text{K})(796 \times 10^{-6}\ \text{kg/s})$$

$$\boxed{\dot{Q}_e = 55.2\ \text{W}}$$

III. MAXIMUM HEATING CAPABILITY THAT WILL BE NEEDED TO KEEP THE GAS AT 367 K WHILE OUTSIDE DURING THE LUNAR NIGHT

$$\dot{Q}_{max} = \dot{Q}_e + \dot{Q}_{TANK} = 55.2\ \text{W} + 197\ \text{W}$$

$$\boxed{\dot{Q}_{max} = 252\ \text{W}}$$

REFERENCES:

1. DEWITT, D.P., AND INCROPERA, F.P., FUNDAMENTALS OF HEAT AND MASS TRANSER, SECOND EDITION, JOHN WILEY AND SONS, INC., 1985, P. 758

2. DATA BOOKS: HEAT TRANSFER AND FLUID FLOW, GENIUM PUBLISHING CORPORATION, HEAT TRANSFER DIVISION, JULY 1974, SECTION 515.23, P. 3

APPENDIX H

GAS MASS FLOW AND CONTROL CALCULATIONS

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GAS MASS FLOW AND CONTROL CALCULATIONS

I. GAS MASS FLOW; CALCULATE MAXIMUM GAS FLOW

ASSUME: 1. USE CARBON DIOXIDE

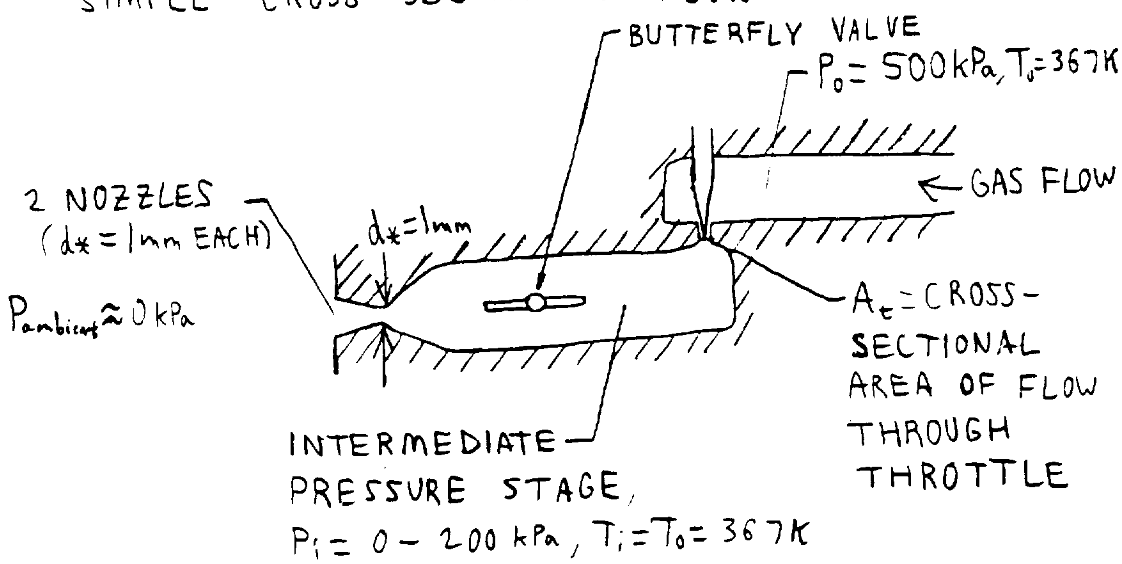
2. IDEAL GAS: $\gamma = 1.3$, $R = 189$ J/kgK

3. CONSTANT PRESSURE SOURCE AT $P_o = 500$ kPa, $T_o = 367$ K

4. ISENTROPIC FLOW

5. FULL ENTHALPY RECOVERY AFTER THROTTLE ($T_i = T_o$)

SIMPLE CROSS-SECTION OF FLOW:



EQUATION FOR MASS FLOW THROUGH NOZZLE AS A FUNCTION OF P_i:

$$\dot{m} = 2\left[\gamma^{1/2}\left(\frac{2}{\gamma+1}\right)^{(1/2)(\gamma+1)/(\gamma-1)} A_* P_i/(RT_i)^{1/2}\right]$$

$$A_* = \left(\frac{\pi}{4}\right) d_*^2 = \left(\frac{\pi}{4}\right)(1\,mm)^2 = 0.785 \times 10^{-6}\,m^2$$

FOR GAS OF $\gamma = 1.3$ $\quad (\gamma^{1/2})\left(\frac{2}{\gamma+1}\right)^{(1/2)(\gamma+1)/(\gamma-1)} \simeq 0.6673$

$$\dot{m} = 2\left[(0.6673)(0.785\times10^{-6}\,m^2)\,P_i/((189\,J/kg\,K)(367\,K))^{1/2}\right]$$

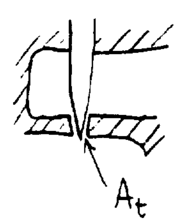
$$\dot{m} = (3.98\times10^{-9}\,kg\,m^2/N{\cdot}s)P_i$$ ⇐ GENERAL EQUATION

$$\dot{m}_{max} = \dot{m}(P_i = 200\,kPa) = (3.98\times10^{-9}\,kg\,m^2/N{\cdot}s)(200\,kPa)$$

$$\boxed{\dot{m}_{max} = 0.796\,g/s}$$

II. CONTROL OF MASS FLOW THROUGH CONTROL THROTTLE BY VARIATION OF FLOW CROSS-SECTIONAL AREA WITH A NEEDLE VALVE

THROTTLE



SAME ASSUMPTIONS AS BEFORE

$$\dot{m} = 2\left[(0.6673)\,P_0 A_t/(RT_0)^{1/2}\right]$$

$$\dot{m} = 2\left[(0.6673)(500\,kPa)A_t/((189\,kJ/kg)(367\,K))^{1/2}\right.$$

$$\dot{m} = (2534 \ kg/m^2 s) A_t$$

$$A_t = \frac{\dot{m}}{(2534 \ kg/m^2 s)}$$

FOR MAXIMUM MASS FLOW OF $\dot{m} = 0.796 g/s$

$$\boxed{A_t = 314 \times 10^{-9} \ m^2}$$

FOR CONTROL OF GAS MASS FLOW, THROTTLE FLOW AREA SHOULD BE VARIABLY CONTROLLED FROM 0 TO $0.314 \ mm^2$.

APPENDIX I

BRUSH FORCE CALCULATIONS

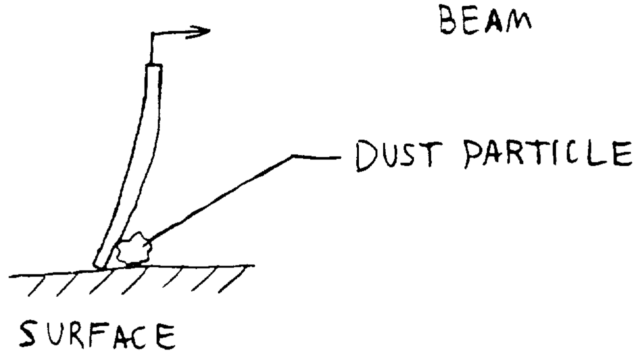
APPENDIX I

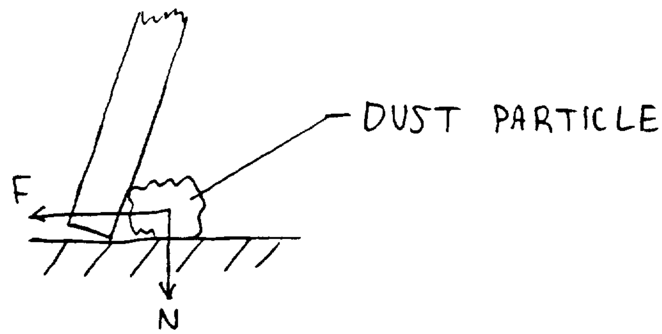
BRUSH FORCE CALCULATIONS

I. DEFLECTION OF ONE BRISTLE DUE TO THE LARGEST DUST PARTICLE WITH MAXIMUM ADHESIVE STRENGTH

ASSUME:

1. LARGEST PARTICLES HAVE DIAMETER, $d = 400\,mm$
2. MAXIMUM ADHESIVE STRENGTH IS $S_A = 1000\,Pa$
3. FRICTION COEFFICIENT OF $\mu = 0.9$
4. BRISTLE LENGTH OF $L = 2\,cm$ AND DIAMETER OF $d_b = 0.05\,cm$
5. BRISTLES MADE OF KEVLAR™, $E_\sigma = 117\,MPa$
6. ANALYZE AS CANTILEVER BEAM





$N = S_A A_h$ $\quad A_h$ = HEMISPHERICAL AREA ASSUMING EACH PARTICLE IS A SPHERE

F IS THE FORCE REQUIRED TO BREAK THE ADHESIVE BOND

$$A_h = \frac{\pi d^2}{2} = \frac{\pi(400 \times 10^{-6}\,m)^2}{2} = 251 \times 10^{-9}\,m^2$$

$$N = (1000\,Pa)(251 \times 10^{-9}\,m^2)$$

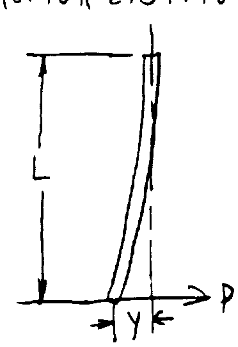
$$N = 2.51 \times 10^{-4}\,N$$

$$F = \mu N$$

P = FORCE THE BRISTLE PUTS UPON THE DUST PARTICLE

$$P = F = \mu N$$

$$P = (0.90)(2.51 \times 10^{-4}\,N) = 2.26 \times 10^{-4}\,N$$



$y = \frac{PL^3}{3EI}$ $\quad$ $I = \frac{\pi d_b^4}{64}$ FOR A ROUND BRISTLE

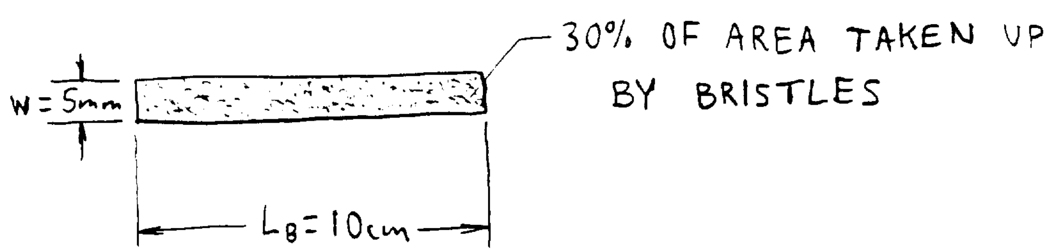
$$I = \frac{\pi (0.0005\,m)^4}{64} = 3.07 \times 10^{-15}\ m^4$$

$$y = \frac{(2.26 \times 10^{-4}\,N)(0.02\,m)^3}{(3)(117\ MPa)(3.07 \times 10^{-15}\,m^4)}$$

$$\boxed{y = 1.7\ mm}$$

II. CALCULATION OF MAXIMUM LATERAL FORCE THAT MUST BE EXERTED ON THE BRUSH

ASSUME:
1. BRISTLE SURFACE AREA COVERAGE OF $C_A = 30\%$
2. EACH BRISTLE IS BREAKING THE BOND OF ONE DUST PARTICLE AT ANY INSTANT



BOTTOM OF BRUSH

A_B = AREA OF THE UNDERSIDE OF THE BRUSH

A_b = CROSS-SECTIONAL AREA OF A BRISTLE

n = NUMBER OF BRISTLES

$$n = \frac{A_B C_A}{A_b}$$

$$A_B = W L_B = (0.005 m)(0.10 m) = 0.0005 m^2$$

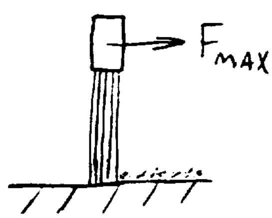
$$A_b = \frac{\pi}{4} d_b^2 = \frac{\pi}{4}(0.0005 m)^2 = 196 \times 10^{-9} m^2$$

$$C_A = 0.30$$

$$n = \frac{(0.0005 m^2)(0.30)}{(196 \times 10^{-9} m^2)}$$

$n = 765$ BRISTLES

F_{MAX} = MAXIMUM LATERAL FORCE THE USER MUST EXERT TO CLEAN A SURFACE COVERED WITH DUST OF THE STRONGEST ADHESIVE STRENGTH



$$F_{MAX} = nP = (765)(2.26 \times 10^{-4} N)$$

$$\boxed{F_{MAX} = 0.173 N}$$