Preliminary Design Review

EASE

Electrodynamic Dust Shielding **A**ctivated **S**urface **E**mitter

AIAA Caltech Student Branch – 11/18/20
Advisor: Dr. Soon-Jo Chung

INTRODUCTION

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INTRODUCTION

COMPETITION OVERVIEW

Artemis Missions – Feet on the moon by 2024 & sustainable missions by 2028. NASA BIG Idea Challenge Finalists implemented 2026

- University teams of 5 – 25 students
- Teams submit proposals (Dec 13th 2020) for funding to develop concepts for technical paper and BIG Idea Forum (Nov 15th 2021)
- Awards from \$50,000 - \$180,00

Landing Dust Prevention & Mitigation - to preclude or protect from plume/surface interactions which may result in damaged landers and nearby surface assets

Spacesuit Dust Tolerance & Mitigation – to limit dust adherence to spacesuits and other damaging effects to its subsystems

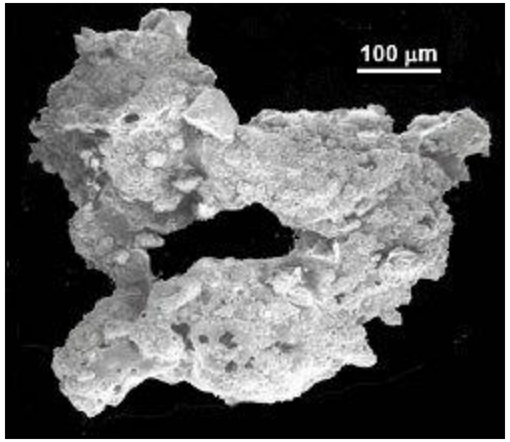
Exterior Dust Prevention, Tolerance, & Mitigation – to protect lunar surface systems or preclude dust from entering habitats and landers

Cabin Dust Tolerance & Mitigation - to clean habitable volumes and their interior surfaces, which helps prevent dust from making it back to Gateway and Orion when the lander returns to lunar orbit from the surface

Constraints

- Able to manage or mitigate lunar dust (~0.5-100 μm)
- Minimal barrier to NASA adoption
  - Cost, power, mass, size …
- Minimum Technological Readiness Level 4 (->5)
- Lifespan of 15 - 30 years
- Removes dust "in minutes"
- Lunar environmental conditions
  - South pole temperatures between -232C and -49C
  - Permanently shadowed craters as low as -243C

Gene Cernan covered in lunar dust



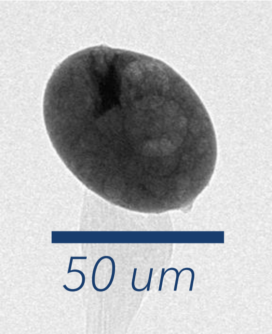
Lunar Dust Particle

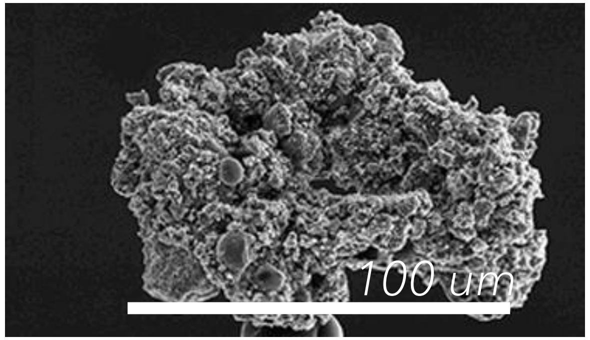
Considerations

- Aiming for 2026 deployment in lunar missions
- Simplicity of operation and maintenance
- Deployment method from NASA or commercial surface lander
- Effective packaging for launch and Moon landing
- Credible fabrication and material selection

INTRODUCTION
LUNAR DUST

Dust Properties



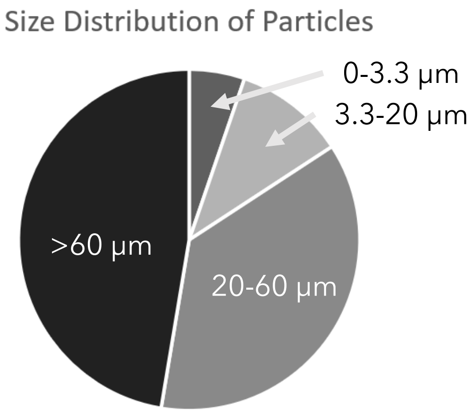


PROPERTY	VALUE	UNITS
Size range	4 to 500	[nm] – [μm]
Volume fraction	< 0.2	%
Relative permittivity	3 - 4	
Relative permeability	~ 1	
Specific gravity	~ 3	[g * cm^-3]
Charge	10^-11 to 10^-13	[C / kg]

Issues Posed

- Vision obscuration
- False instrument readings
- Dust coating and contamination
- Seal failures
- Abrasion of materials
- Inhalation and irritation risks
- **Loss of foot traction**

- Charged through solar emissions
- Trace magnetic elements
- 90% Silicate/Aluminosilicate minerals by volume
- Highly irregular and **sharp**
- Charge density increases with particle size



INTRODUCTION

PROBLEM STATEMENT

- Problems Caused By Spacesuit Dust Ingress Into Habitable Volumes
  - Increased loads on in-cabin dust mitigation technologies
  - Incorrect readings during in-cabin experiments
  - Performance reduction and possible failure of in-cabin equipment
  - Astronaut health risks
  - Dust brought to Gateway and Orion when lander returns to lunar orbit
- Existing Solutions

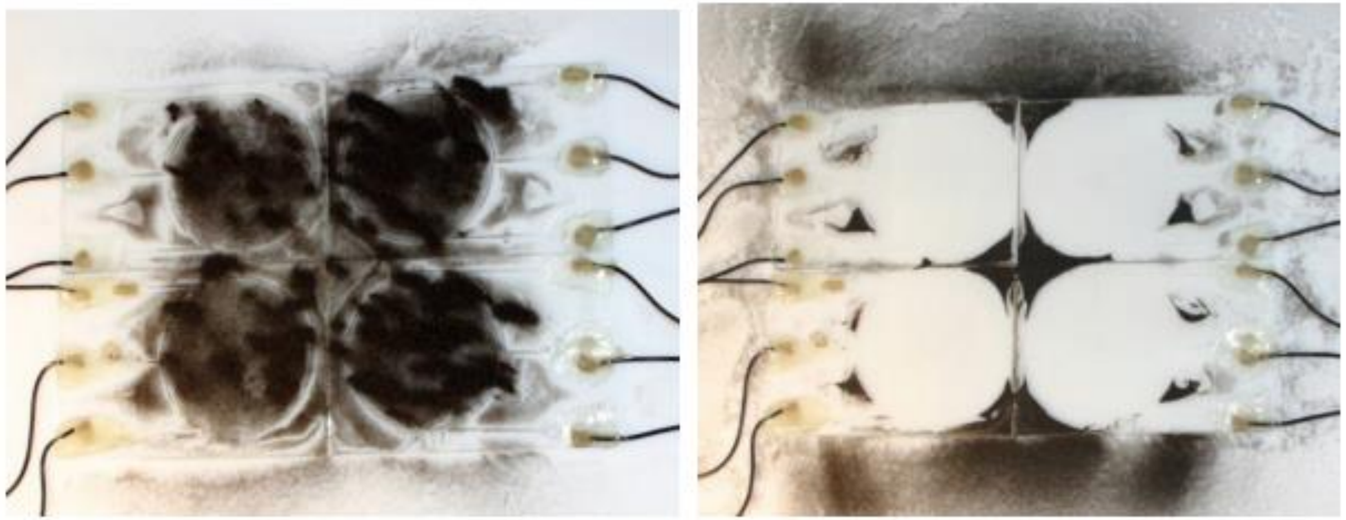


FIGURE 3–1. SIMULANT DUST REMOVAL WITH NASA KENNEDY SPACE CENTER'S EDS AT 10-6 KPA (CALLE ET AL. ACTA ASTRONAUT. 69, 2011: 1082-1088).

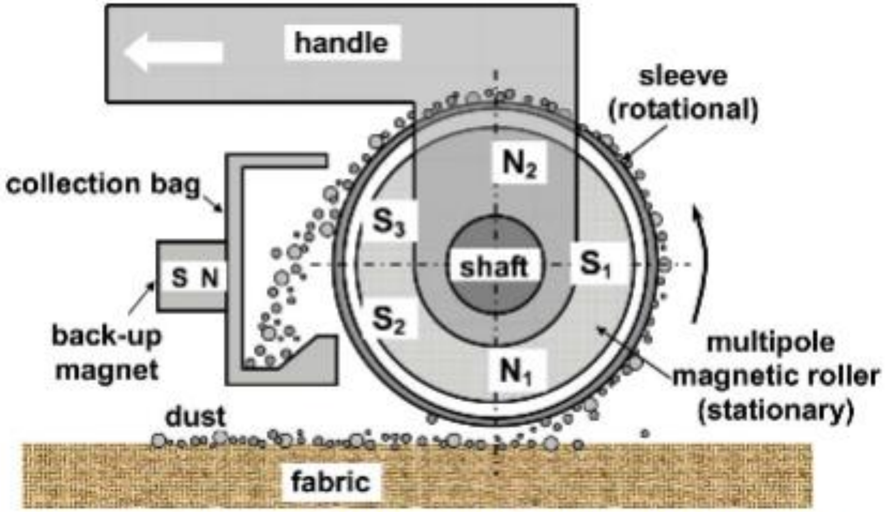


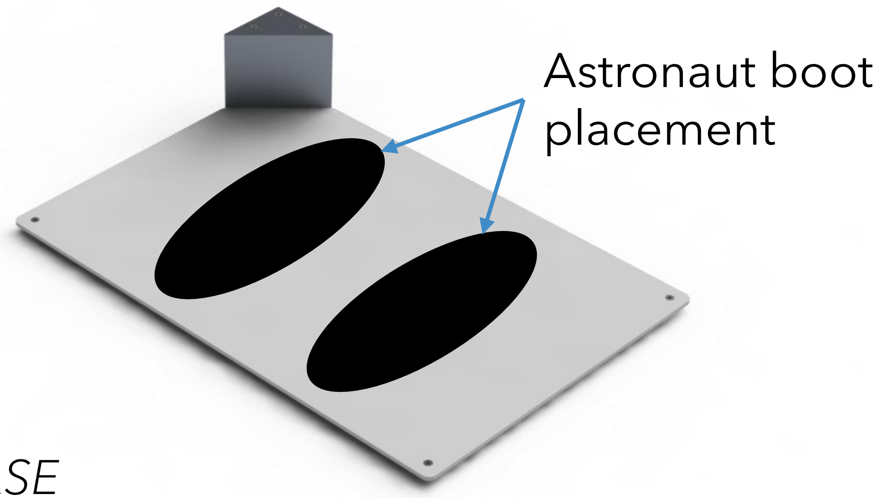
FIGURE 3–4. WASEDA UNIVERSITY'S MAGNETIC CLEANING DEVICE (KAWAMOTO, H. AND H. INOUE, J. AEROSP. ENG. 2012, 25: 139–142).

CONCEPT OVERVIEW
QUAD CHART

AIAA Caltech Student Branch – 11/18/20
EASE Preliminary Design Review

Objective:

- Minimize dust ingress into lunar habitat module on astronaut boots
- Increases traction of astronaut boots
- EASE is portable, durable, low SWaPs device
- Clears lunar dust from astronaut boots in < 30 sec and self cleaning
- Increases the state-of-the-art:
  - Largest, most compact, and durable implementation of electrodynamic shielding technology
- Develop and validate to **TRL 5**



Render of EASE

Approach:

Leverages 50-year-old dust mitigation technology currently being tested on ISS

- 3-Phase traveling square wave pushes dust particles off astronaut boots and EASE
- Touch-free operation using strain gauges in the mat
- Extensive validation and verification program though

Mass Estimate: < 4 kg   Power Estimate: 50 W max

Key Milestones:

Description	TRL	Deadline
Preliminary Design Review	2	11/18/20
Proposal	2	12/13/20
Functional Prototype	3	4/1/21
Midpoint Report	4	5/20/21
Technical Paper & Verification Demonstration	5	10/27/21

CONCEPT OVERVIEW

CONCEPT OF OPERATIONS

1 Astronaut should ensure the surface is relatively flat and cleared ***DA 1.0***

2 Astronaut lays out E.A.S.E in front of the lunar habitat and connects it to power source ***DA 2.0***

3 After moonwalk and sample collection, astronaut returns to stand on E.A.S.E, which senses the weight and begins attracting dust off the astronauts' boots and moving it to the center and the left and right edges ***DA 5.0, FR 1.0***

4 Astronaut leaves. E.A.S.E waits for another astronaut for two minutes, after which it self-cleans for several minutes, removing the dust from its surface by pushing it off its right edge, before entering standby mode until the pressure sensor is activated again.

FR 2.0, 4.0, 5.0

REQUIREMENTS

Functional Requirements	Description
FR 1.0	Remove at least 50% of dust from astronaut boots within 30 seconds
FR 2.0	Self-cleaning after astronaut departure
FR 3.0	Minimum 15-year lifetime on lunar surface
FR 4.0	Capable of enduring forces involved in launch and landing
FR 5.0	Capable of withstanding 400N load applied to surface
FR 6.0	Capable of enduring repeated impacts without loss in performance

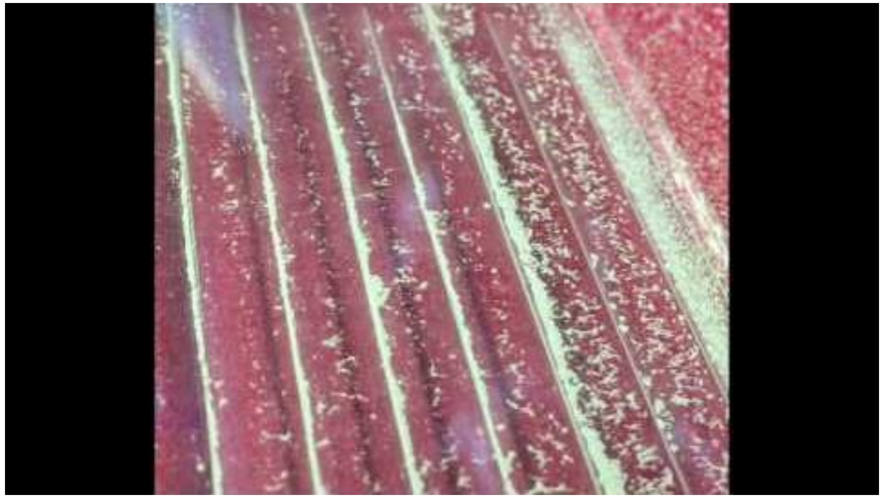
CONCEPT OVERVIEW

DESIGN ASSUMPTIONS

Design Assumption	Description
DA 1.0	EASE placed on 1 m x 1 m cleared and leveled area
DA 2.0	28 V DC power supplied by lunar habitats and landers
DA 3.0	Lunar regolith compresses under load of mat and astronaut
DA 4.0	Disregard off nominal solar activity
DA 5.0	No more than one astronaut at a time maximum load

Electrodynamic **D**ust **S**hielding

- Parent technology developed in **1970s**
- Lifts and transports charged and uncharged particles using **electrostatic** and **dielectrophoretic** forces
- Works best for particle size regimes of **5-300 μm** (encompasses size regime for lunar dust particles)
- Technology currently being used in:
  - Solar panel maintenance (dust removal efficiency of **90%**)
  - Tested in mock lunar environments
  - In-Situ Experiments on ISS on thermal radiators and solar panels
    - Ongoing; showed that **EDS works in vacuum**
    - Solar panel effectiveness **22.5%→98.4%** after EDS implementation with lunar simulant



Demonstration of EDS on a glass plate; particle size < 20 μm; time to clear ~30s (Guo, 2018)

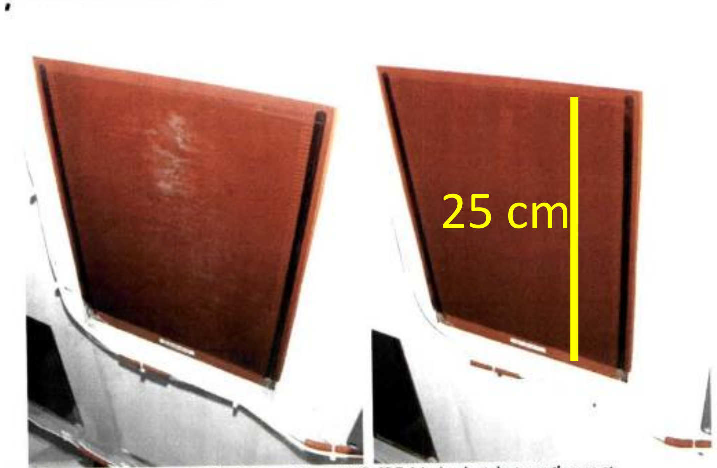


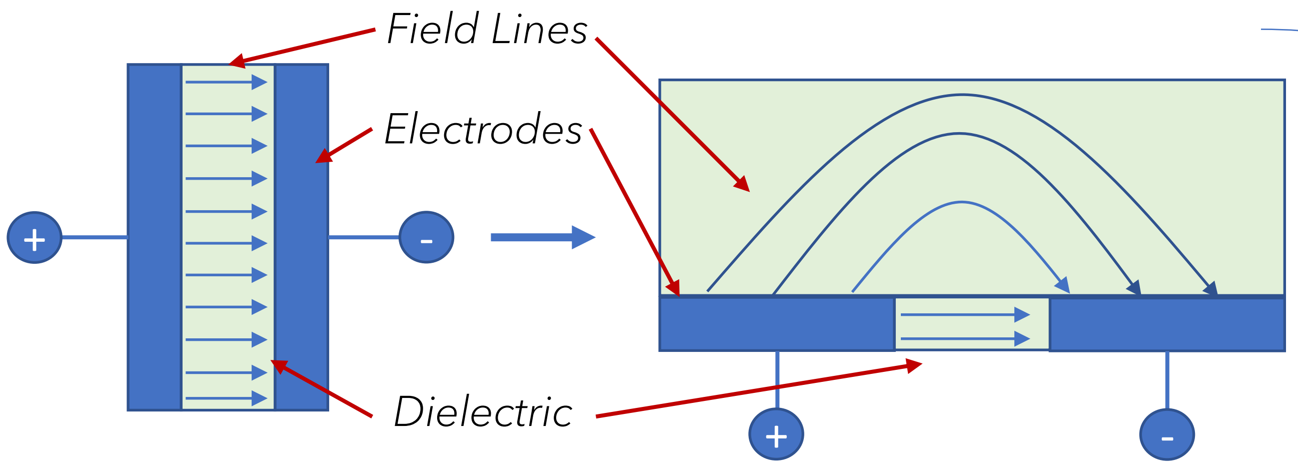
Fig. 7. Post installation tests of the 20 cm × 25 cm EDS. JSC-1A simulant dust was thrown at

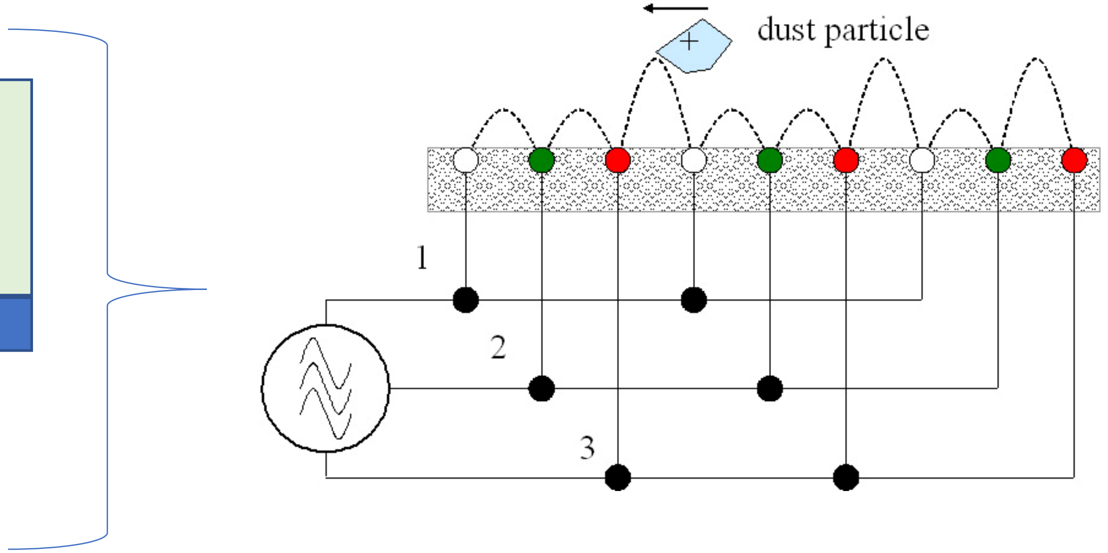
EDS System mounted on sim. Lunar habitat

FR 1.0

EDS OVERVIEW

HOW IT WORKS



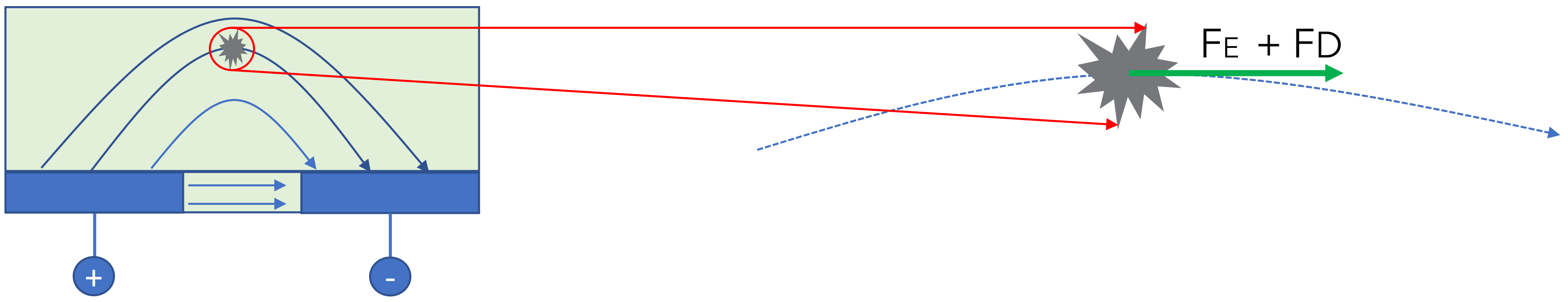


- Fringing electric field exerts force on charged dust particles
- 3 phased EDS Systems transport dust particles

(Calle, 2010)

MECHATRONICS

FORCES INVOLVED



Variables:
E = electric field strength
q = particle charge
ε_m = dielectric permittivity of medium
ε_o = dielectric permittivity of vacuum
R = particle diameter
γ = surface energy of adhering surface

Forces exerted by EDS:

FE : Electrostatic force

$$F_E = qE$$

FD : Dielectrophoretic force

$$F_D = 2\pi\varepsilon_o \frac{\varepsilon_m - 1}{\varepsilon_m + 2} R^3 \nabla E^2$$

>

Forces adhering particles to astronaut:

V : Van der Waals force

$$V = 4\pi R\gamma$$

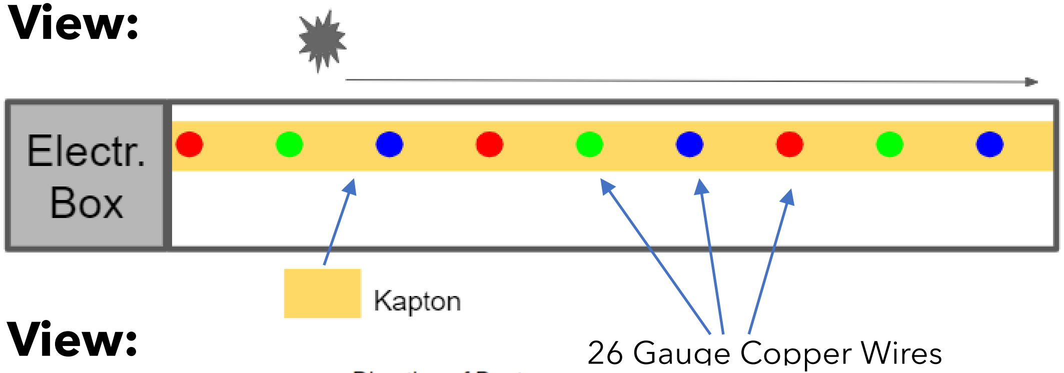
S : Image-charge static force

$$S = \frac{q}{4\varepsilon_o (2R)^2}$$

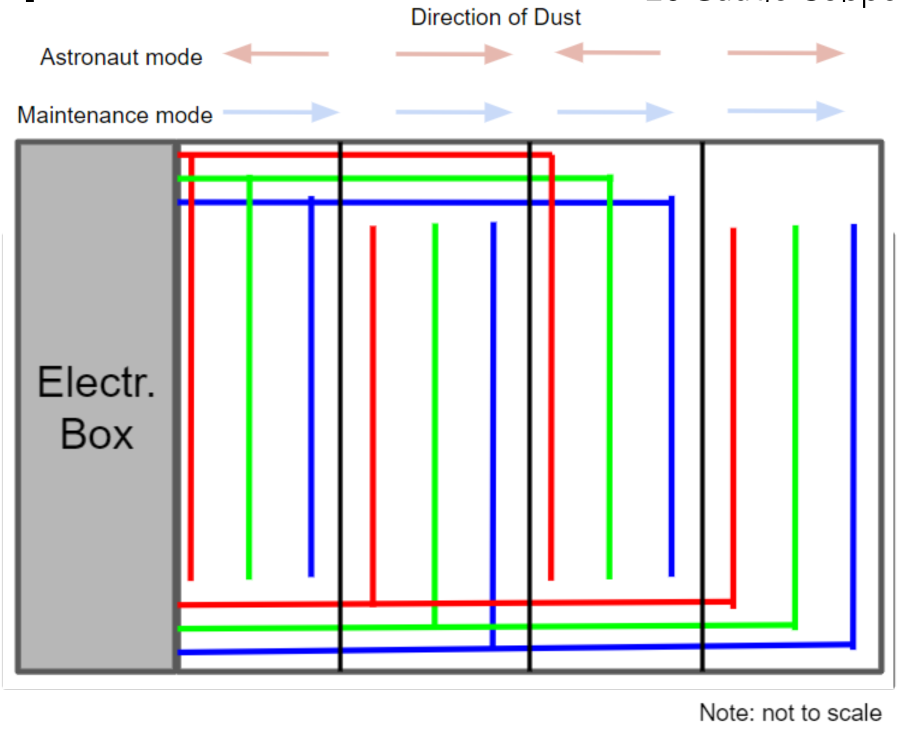
Feasible by analysis and prior implementations

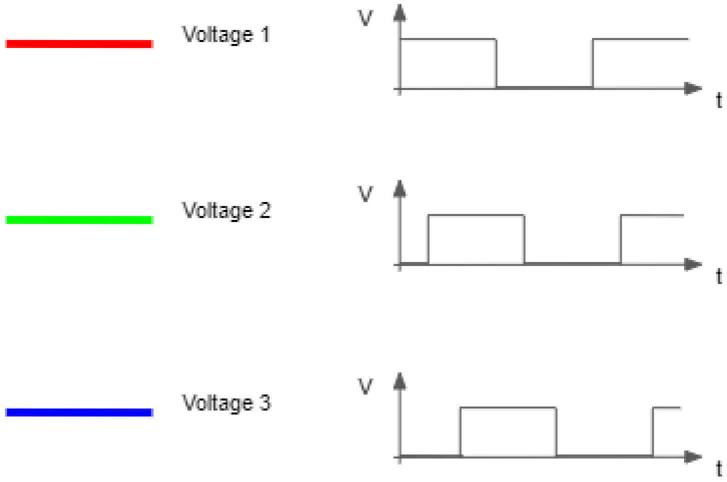
MECHATRONICS
LAYOUT & PHASING

Side View:



Top View:



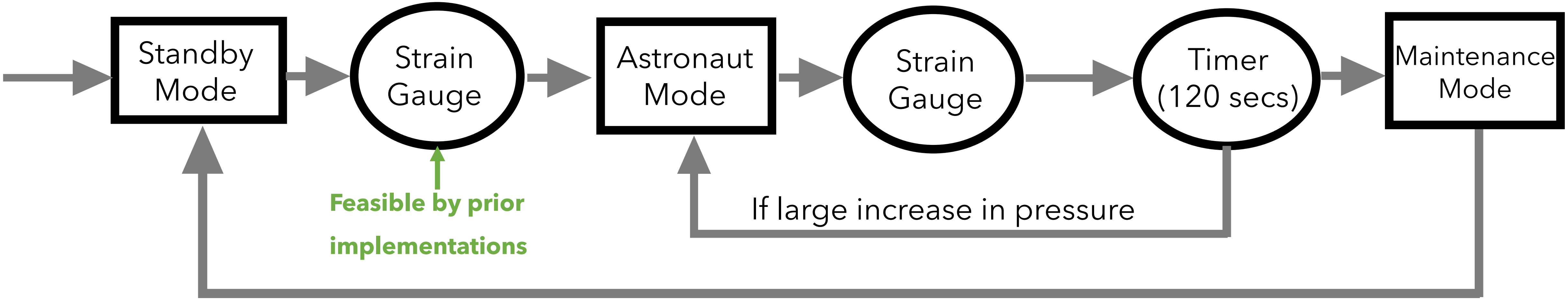


- Electronics box made of aluminum and Multi-Layer Insulation (MLI) to **protect against thermal and radiative environment**
- Kapton dielectric rated for **-268°C to 399°C**

DA 4.0

MECHATRONICS

CONTROLS & MODES

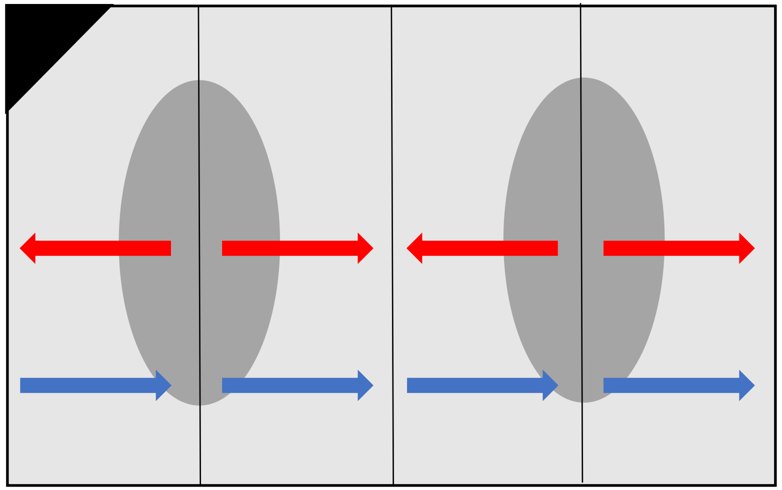


<u>Operational Modes</u>

Standby Mode: awaiting use, sensors are active

Astronaut Mode: capacitors are charged, suit is cleaned

Maintenance Mode: dust is removed from mat itself



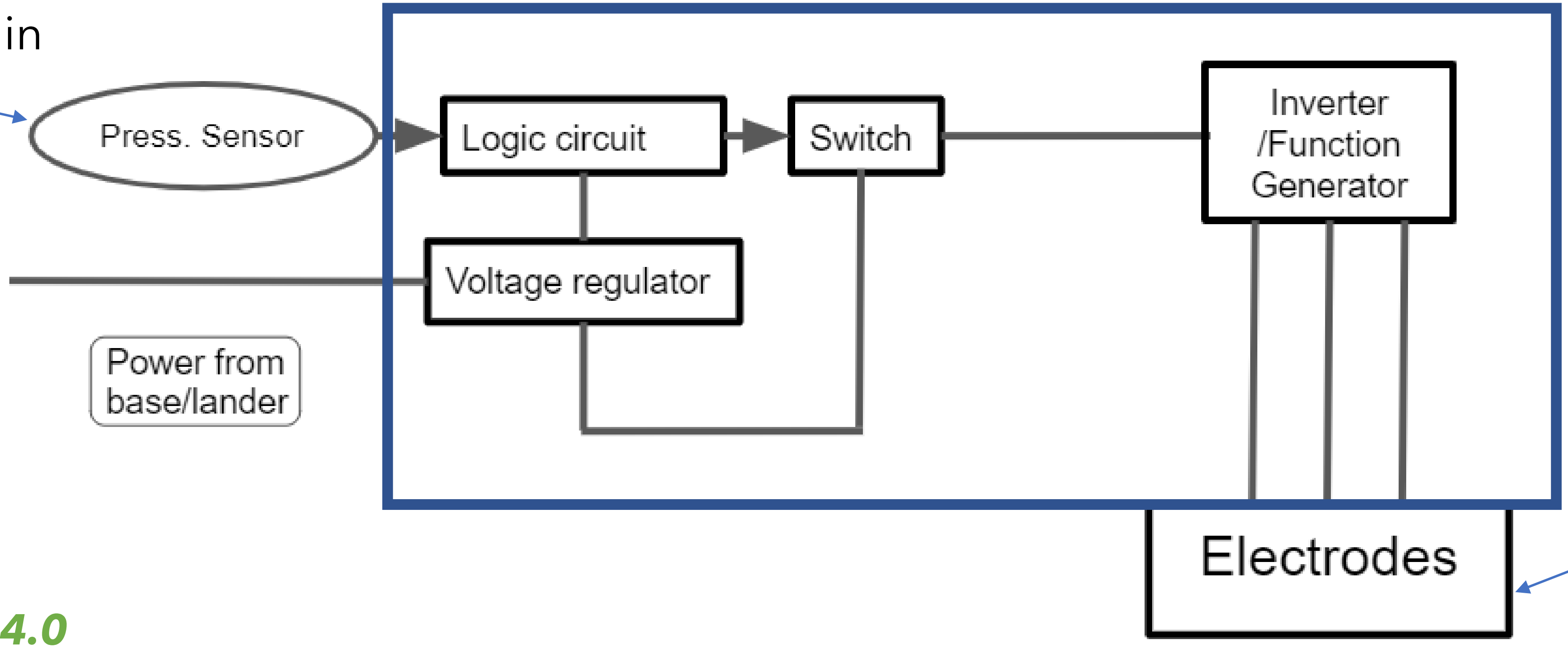
Note: not to scale

FR 2.0

CIRCUIT DIAGRAM

Embedded in mat

Components contained in electronics box



Embedded in mat

DA 2.0, 4.0

Sensors and components to be selected/designed from existing NASA satellite and spacecraft payloads.

Estimates based on finite difference electrostatic simulation

- Obtained mesh grid of electric field strength given electrode lay-out and voltage supply
- Determined electromagnetic field strength necessary to overcome adhesive and coulombic forces for particle sized 50 μm

Operational Mode	Time Estimate	Input Voltage (DC)	Power Requirements (W)
ASTRONAUT	<30 s / astronaut*	28 V	50 W
MAINTENANCE	120 s	28 V	25 W
STANDBY	VARIABLE	28 V	<100 mW

Electric Field Performance	Height
Maximum Effective range	0.5 m
"Deep Clean" Coverage	< 3 cm

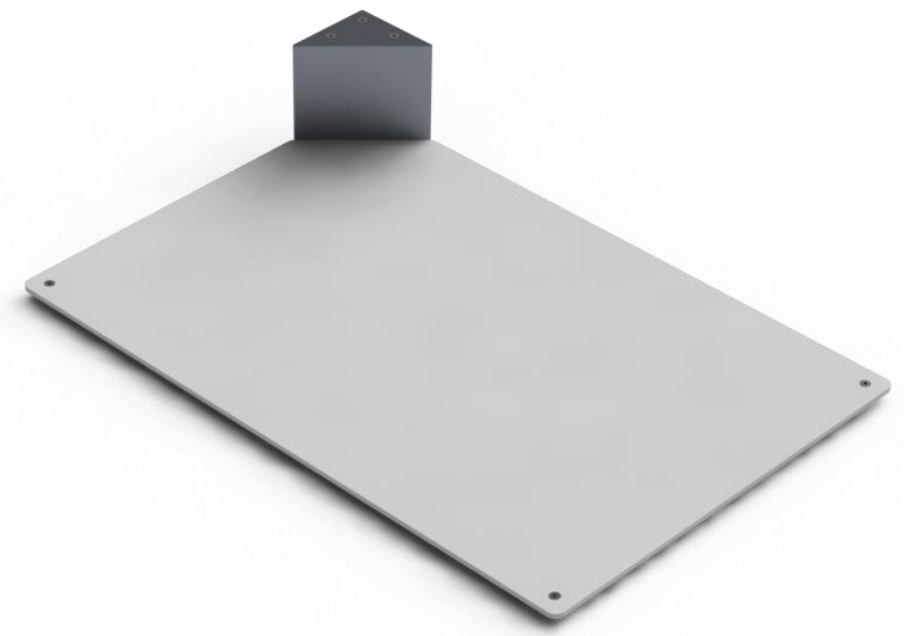
FR 1.0, 2.0

Feasible by analysis and prior implementations

- Current estimates predict EASE will have **low power requirements**

* Time estimate based on time efficacy of current EDS systems, will be verified during prototyping.

MECHANICAL
DESIGN OVERVIEW



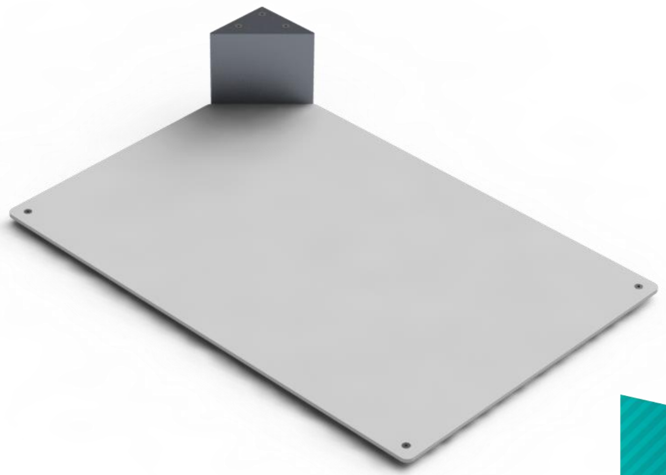
FR 3.0 - 5.0

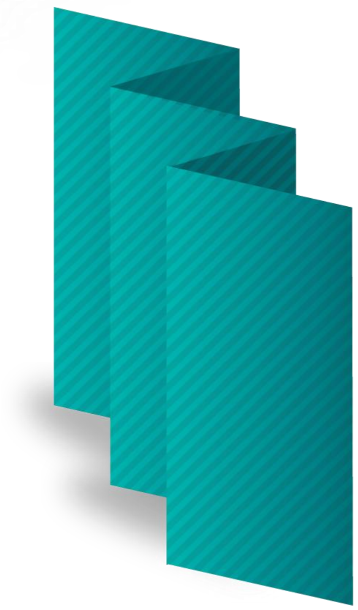
Objectives:

- Strong enough to sustain weight
- Easy to transport and use
- Large enough size to comfortably use
- Optimized for weight and volume
- Electronics are secured and protected
- Cost-effective solution
- Protected from the harsh lunar environment
- Use for 15-30 years.

MECHANICAL

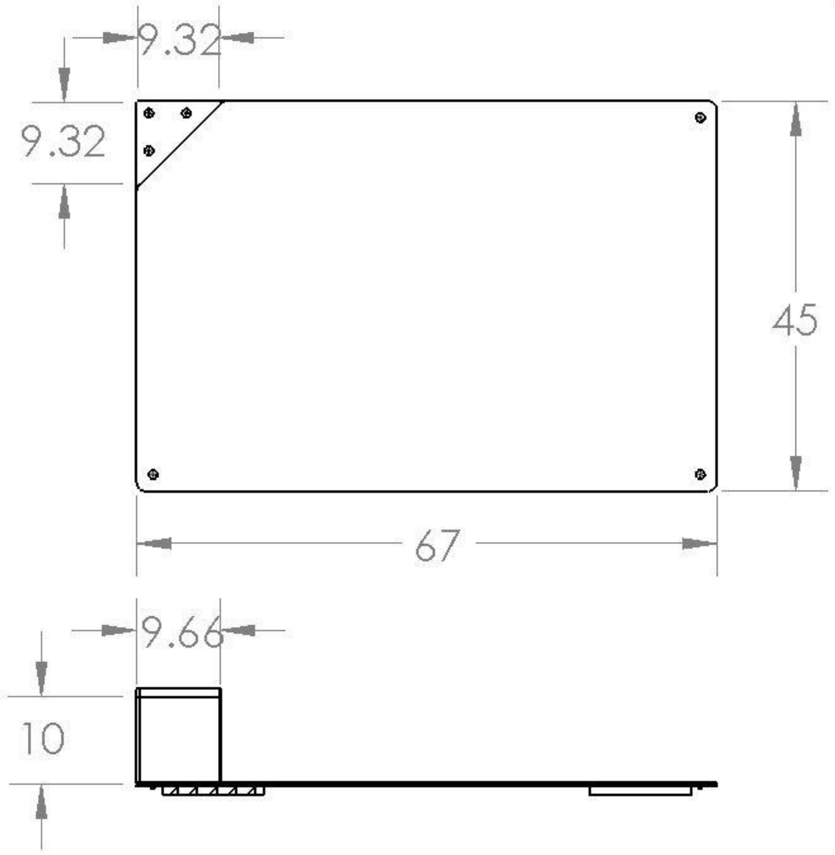
TRADE STUDY





Metric	Weight	Single Panel	Single Fold Accordion
Use with EDS	10	9	5
Robustness	30	25	20
Weight and Volume	20	20	12
Storage, transportation, deployment	20	20	12
Life Cycle	20	20	16
Total	100	94	65

MECHANICAL
DIMENSIONS

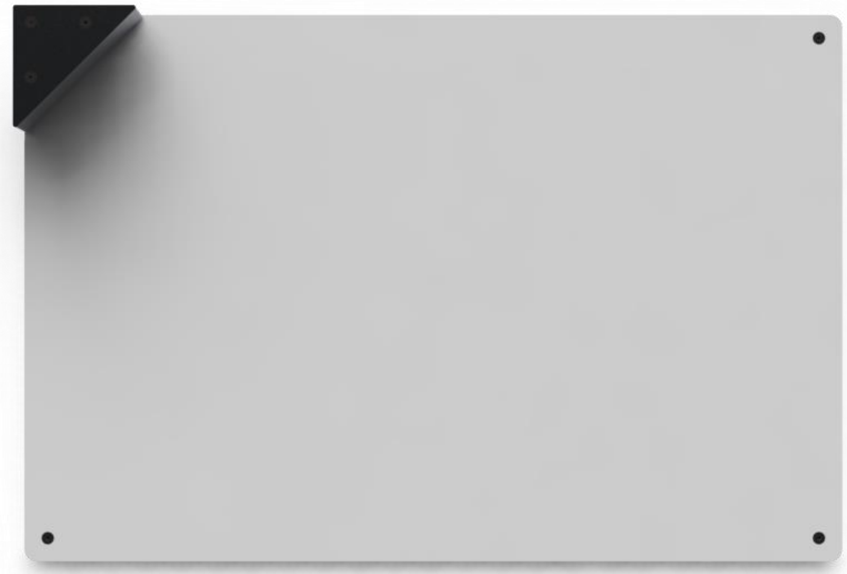


Note: Dimensions in centimeters

MECHANICAL

DIMENSIONS

45 cm

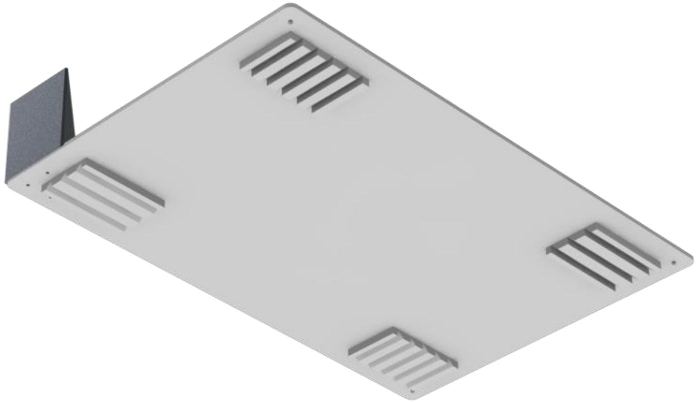


67 cm

46 cm

76 cm

MECHANICAL
FEATURES

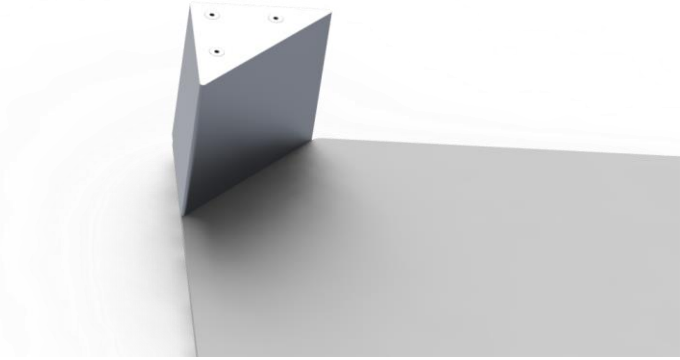


Spikes for security

DA 3.0

EDS System

MECHANICAL
ELECTRONICS BOX



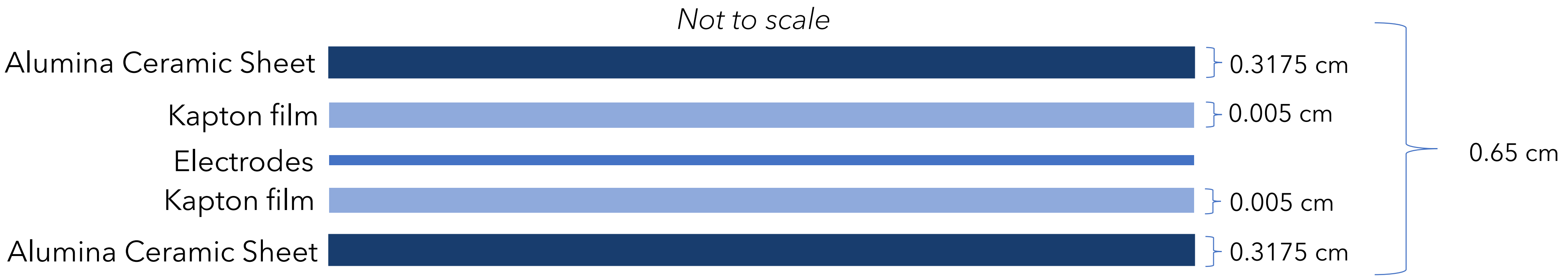
Electronics Box:

- Aluminum 2219 for housing
- Multilayered insulation

These materials are commonly used in space applications.

Properties	Aluminum 2219
Density	2.84 g/cm^3
Tensile Strength	290 MPa
Temperature Range	-250 to 315 (°C)
Coefficient of Thermal Expansion	22.3 to 24.1 (10^{-6}/°C)

MECHANICAL
PANEL COMPOSITION



Total mass estimate: 4 kg

MECHANICAL

MATERIAL SELECTION

	Alumina Ceramic (structure)	316 Stainless Steel (Bolt)	Kapton (dielectric)
Density	3.9 (g/cm^3)	8.0 (g/cm^3)	1.41 (g/cm^3)
Tensile Strength	260 (MPa)	482 (MPa)	230 (MPa)
Flexural Strength	379 (MPa)	290 (MPa)	120 (MPa)
Compressive Strength	2,600 (MPa)	170 (MPa)	172 (MPa)
Coefficient of Thermal Expansion	8.6 (10^{-6}/°C)	10.3 (10^{-6}/°C)	8.1 (10^{-5}/°C)
Dielectric Constant	9.1 (at 1 MHz)	-	5.42 (at MHz)
Dielectric Strength	16.7 (kV/mm)	-	217 (kV/mm)
Temperature Range	-273.15°C to 1,750°C	-252°C to 871°C	-267°C to 398°C

Note: we will use Cicoil wires

MECHANICAL
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DA 5.0
FR 3.0 - 5.0

MECHANICAL
MATERIAL JUSTIFICATION

Alumina	Kapton
Electrical insulator	Stability across wide temperature range
Low dielectric constant	Durability
Low thermal conductivity	Good dielectric qualities
Hardness	Used in spacecraft applications (Apollo launcher, Curiosity rover)
Strength	
Sufficient temperature range	
Abrasion resistant	
Used in many spacecraft applications	

FR 3.0 - 5.0

Top Plate:
- 3-axis CNC milling

Bottom Plate:
- 3-axis CNC milling

Electronics Box:
- 3-axis CNC milling

- Design considerations: 0.5 mm tolerance, large external and internal fillets

MISSION INTEGRATION
RISK ASSESSMENT

RISK MITIGATION STRATEGIES:

- Impact of radiation and cold temp on electronics:
  - The likelihood of single particle upsets is very low
  - MLI (multi-layered insulation) should protect the electronics from cold temperatures
- EDS field not strong enough to clean all the way up the boots
  - EDS geometry and electronics are easily altered to increase the field strength
- Abrasion of surface, materials or electrodes due to long-term use
  - Ceramic has high abrasion resistance

	Negligible	Minor	Moderate	Significant	Severe
Very Likely					
Likely			-Abrasion of surface, materials, or electrodes due to long-term use -Wear on bottom of EASE		
Possible		-Dust penetration between layers *-Materials expand at different rates due to difference in thermal expansion constants*		*-EDS field not strong enough to clean all the way up the boots*	-Concentrated force application onto E.A.S. E by rocks, etc on surface of moon
Unlikely		-Impact of radiation and cold temperatures on panel materials *-Difficulty in manufacturing ceramics*	-Moves out of correct positon - Impact of EDS system on suit electronics *-Kapton does not withstand full range of lunar temperatures*	-Impact of radiation and cold temperatures on electronics	
Very Unlikely					

RISK MITIGATION STRATEGIES CONT'D:

- Dust penetration between layers
  - Kapton is being compressed between two ceramic panels and acts as a gasket
- Concentrated force application onto EASE by rocks on the surface of the moon
  - Not a problem if astronauts clear the area
- Wear on bottom of EASE, as well as moving out of position:
  - The spikes on the bottom of EASE secure it to the surface, limiting slipping and abrasion by loose particles underneath it

	Negligible	Minor	Moderate	Significant	Severe
Very Likely					
Likely			-Abrasion of surface, materials, or electrodes due to long-term use -Wear on bottom of EASE		
Possible		-Dust penetration between layers *-Materials expand at different rates due to difference in thermal expansion constants*		*-EDS field not strong enough to clean all the way up the boots*	-Concentrated force application onto E.A.S.E by rocks, etc on surface of moon
Unlikely		-Impact of radiation and cold temperatures on panel materials *-Difficulty in manufacturing ceramics*	-Moves out of correct positon -Impact of EDS system on suit electronics *-Kapton does not withstand full range of lunar temperatures*	-Impact of radiation and cold temperatures on electronics	
Very Unlikely					

VERIFICATION

TEST PROGRAM

Goal: Validate to TRL4

- Implement safety factor of 1.2 – 1.5

Key:
^ Under vacuum conditions
* Under thermal conditions
! Destructive test
† Full prototype needed

Miscellaneous:
- Vibration Test for Deployment †
- EMI Test for EDS System^*†
- Electronic Life Test for 45 years^*

Abrasion Test*!

Simulated Abrasion Test* → Operational Test^*†

Dust Exposure Test → Operational Test^*†

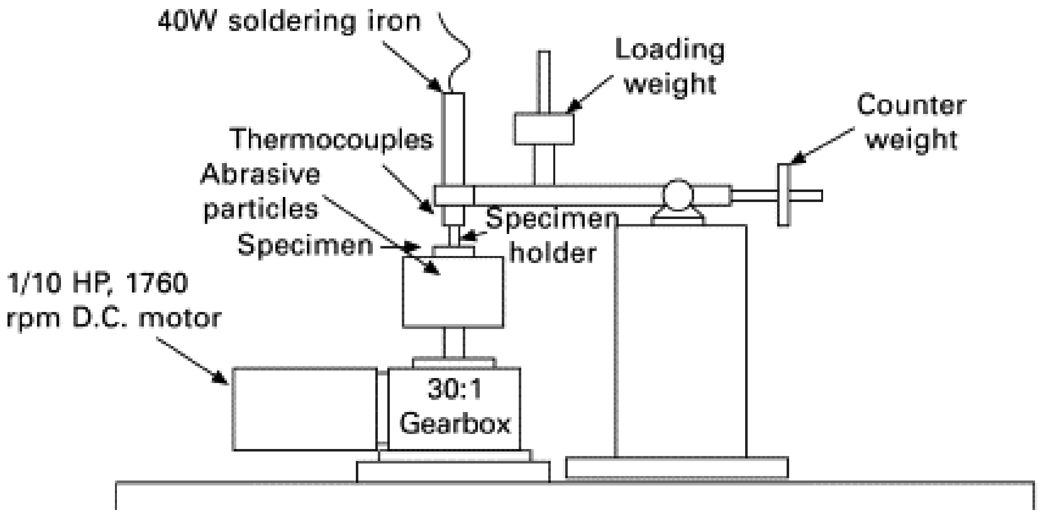
Mechanical Load Tests → Maximum Load Test*!

Mechanical Load Tests → 600 N Pulsating Fatigue Test*!

Mechanical Load Tests → Sharp Impact Test Simulating Micrometeorites*!

DA 5.0

Equipment and Testing Conditions



Three-Body Abrasive Wear Test Rig

- We will use NTS for thermal vacuum chamber testing
- Lunar Simulant JSC-1A will be used for EDS-related testing
- Lunar Simulants OB-1 and Chenobi are the most recommended simulants for abrasion and dust exposure testing
- We will test from -260°C to 140°C to simulate lunar thermal conditions

(Roy, 2008)

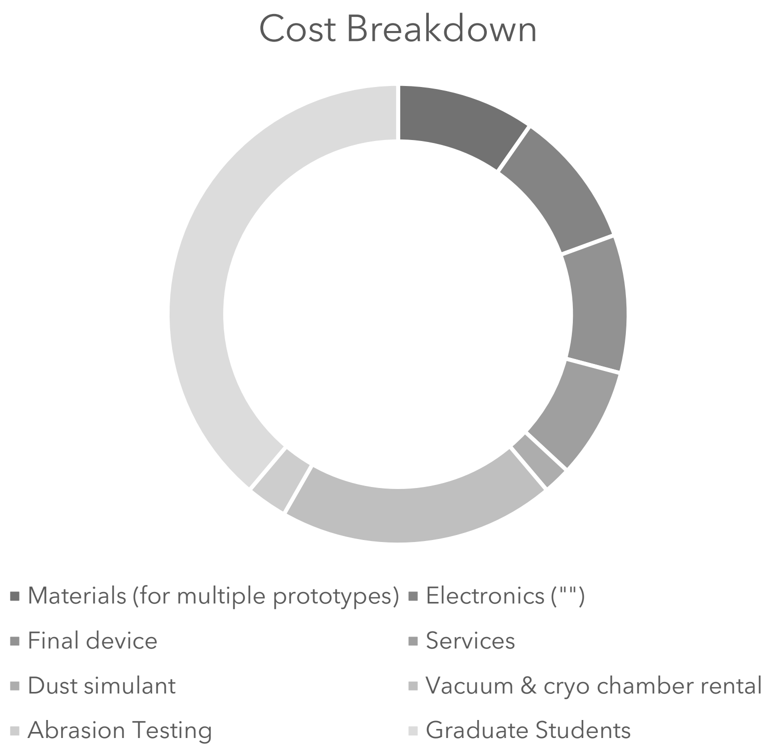
LOGISTICS

SCHEDULE

Phase	Details	December	January	February	March	April	May	June	July	August	September	October	November
Proposal	Writing	TRL 2											
Preparation	Supplier and facility acquisition												
	Subsystem prototypes												
	Full functional prototype												
	Testing prototypes												
Prototyping	Final prototype												
Mid-Project Report	Writing						TRL 3						
	Mechanical load tests												
	Operational Tests								TRL 4				
Verification	Lifetime Test											TRL 5	
Technical Paper	Writing												

LOGISTICS
BUDGETING

Category	Constituents	Subtotal
Prototyping	Materials (for multiple prototypes)	$5,000.00
	Electronics ("")	$5,000.00
	Final device	$5,000.00
Manufacturing	Services	$4,000.00
Testing	Dust simulant	$1,000.00
	Vacuum & cryo chamber rental	$10,000.00
	Abrasion Testing	$1,500.00
Labour	Graduate Students	$20,000.00
Total		$51,500.00



Raw Material Costs Est.

- 4 prototypes without EDS System
- 1 complete prototype
  - Costs will increase if a need for iteration arises

CONCLUSION

FEASIBILITY REVIEW

Function / Characteristic	Solution	Feasible?
Transport dust	EDS	YES
Touch-free operation	Strain Gauge	YES
Rugged housing	Ceramic	YES

CONCLUSION
THANK YOU

Thank you for listening!

We appreciate any feedback through:

- Email
- Feedback form
- Q & A

Points of Contact:

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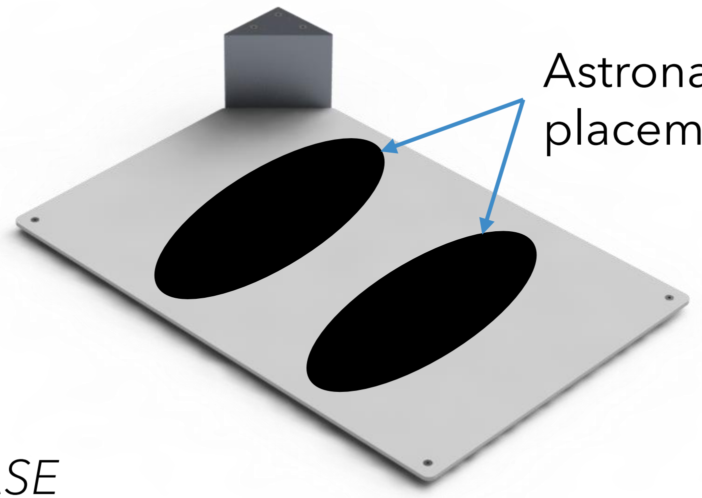
CONCEPT OVERVIEW

QUAD CHART

Objective:

- Minimize dust ingress into lunar habitat module on astronaut boots
- Increases traction of astronaut boots
- EASE is portable, durable, low SWaPs device
- Clears lunar dust from astronaut boots in < 30 sec and self cleaning
- Increases the state-of-the-art:
  - Largest, most compact, and durable implementation of electrodynamic shielding technology
- Develop and validate to **TRL 5**



Render of EASE

Approach:

Leverages 50-year-old dust mitigation technology currently being tested on ISS

- 3-Phase traveling square wave pushes dust particles off astronaut boots and EASE
- Touch-free operation using strain gauges in mat
- Extensive validation and verification program though

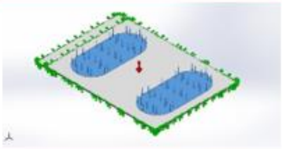
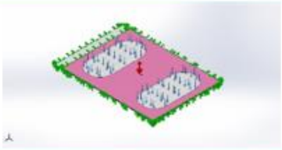
Mass Estimate: < 4 kg   Power Estimate: 50 W max

Key Milestones:

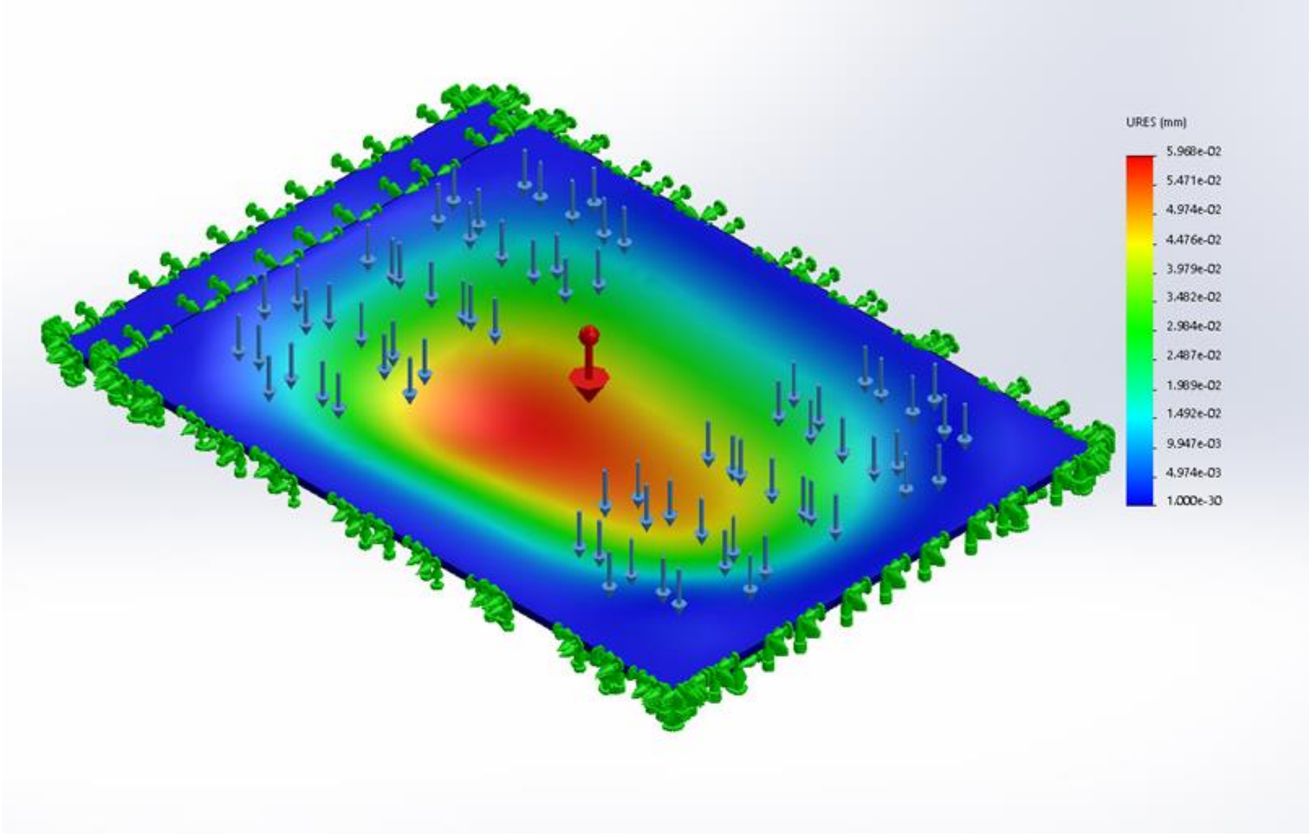
Description	TRL	Deadline
Preliminary Design Review	2	11/18/20
Proposal	3	12/13/20
Functional Prototype	3	4/1/21
Midpoint Report	4	5/20/21
Technical Paper & Verification Demonstration	5	10/27/21

LOAD VALIDATION
FEA ANALYSIS

Name: Alumina
Model type: Linear Elastic Isotropic
Default failure criterion: Mohr-Coulomb Stress
Tensile strength: 2.17185e+07 N/m^2
Compressive strength: 2.99922e+07 N/m^2
Elastic modulus: 3e+11 N/m^2
Poisson's ratio: 0.22
Mass density: 2,075.99 kg/m^3
Thermal expansion coefficient: 7.02e-06 /Kelvin

Load name	Load Image	Load Details
Force-1		**Entities:** 2 face(s) **Type:** Apply normal force **Value:** 400 N
Gravity-1		**Reference:** Face< 1 > **Values:** 0 0 -9.81 **Units:** m/s^2

Displacement Plot



Maximum Displacement: 0.0597 mm

LOAD VALIDATION
FEA ANALYSIS

Name: Alumina
Model type: Linear Elastic Isotropic
Default failure criterion: Mohr-Coulomb Stress
Tensile strength: 2.17185e+07 N/m^2
Compressive strength: 2.99922e+07 N/m^2
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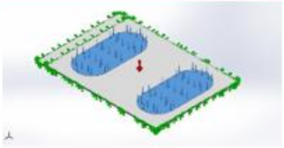
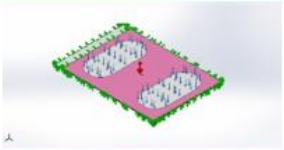
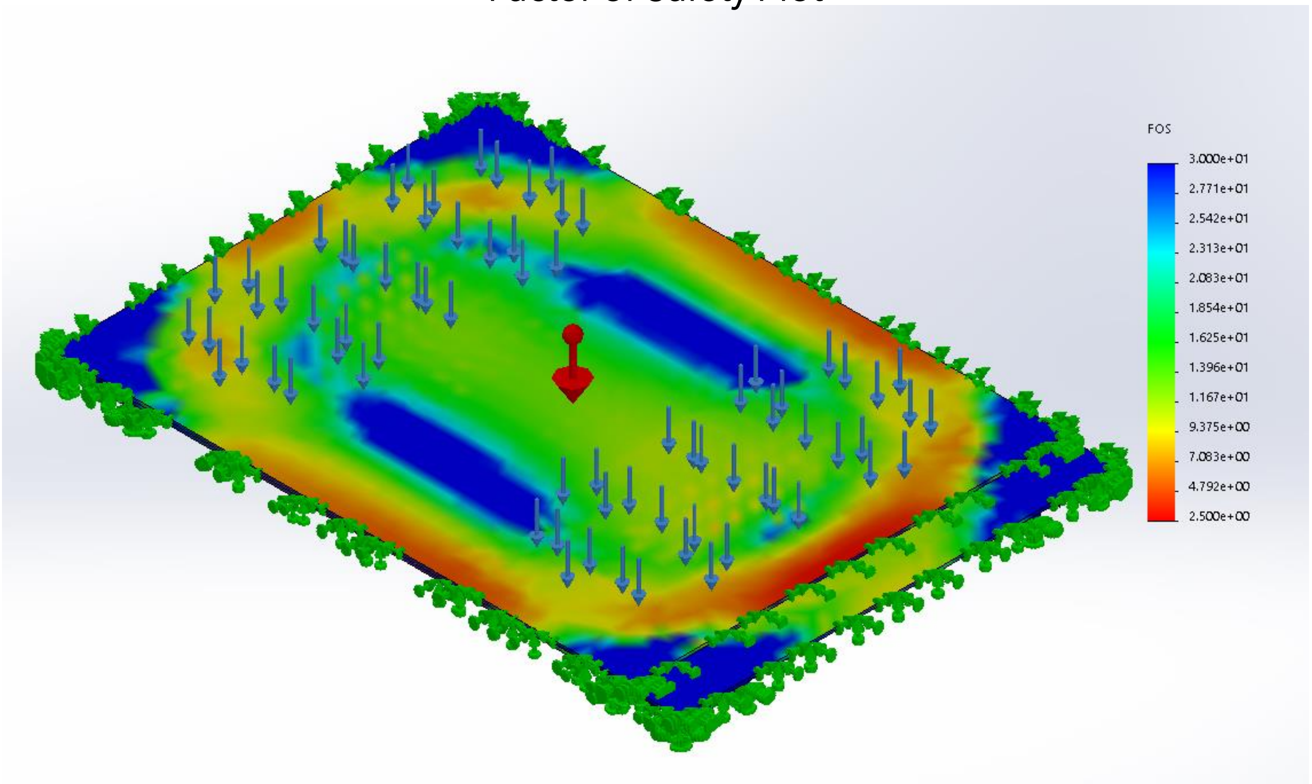
Force-1		**Entities:** 2 face(s) **Type:** Apply normal force **Value:** 400 N
Gravity-1		**Reference:** Face< 1 > **Values:** 0 0 -9.81 **Units:** m/s^2

Factor of Safety Plot



Minimum FOS: 2.67
(Load includes a 1.5 FOS already, so there is room for mass reduction)