# MAANA ELECTRIC

# The Utility Company of the Solar System

## R2D2 Plug and Socket Final Review – November 2022

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# Agenda

- ✓ User case scenario presentation
- ✓ Literature review and trade-offs
- ✓ Proof of Concept
- ✓ Breadboard design
- ✓ Breadboard testing
- ✓ Conclusions and next steps

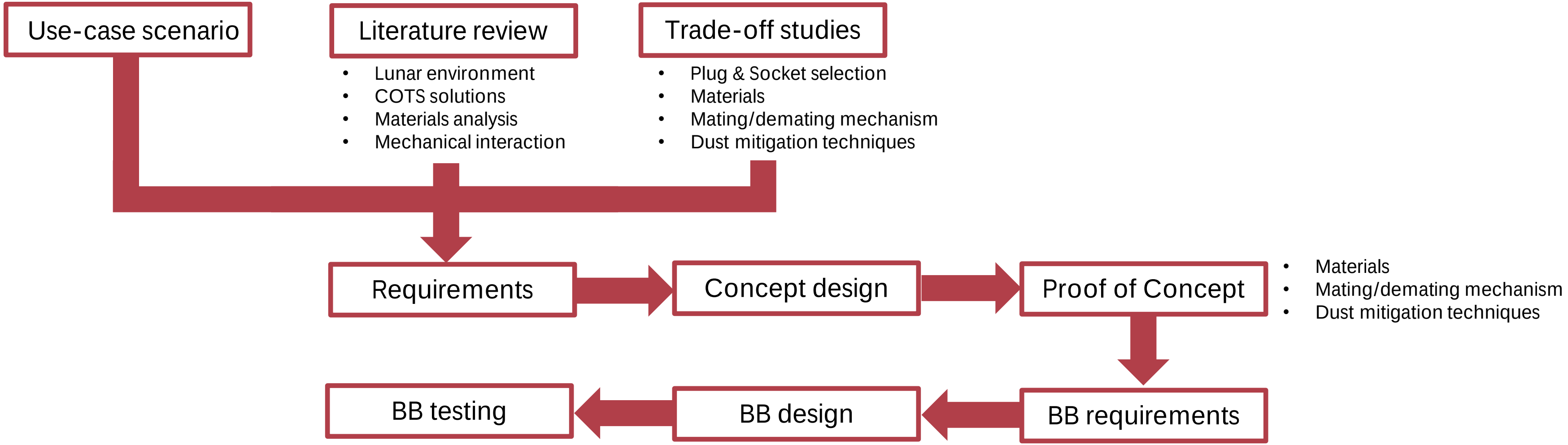
# R2D2 Plug and Socket

R: Reliable
R: Robust
D: Dust
D: Deflecting

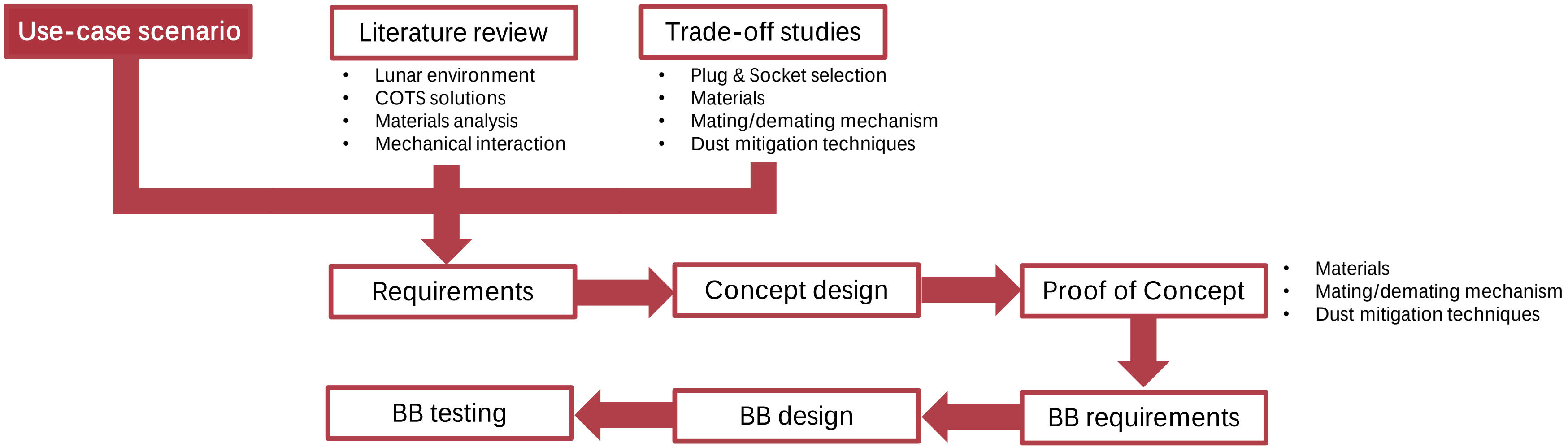
## Objective of the activity is:

- ✓ To define a dust resistant DC/DC plug and system concept to be operated in dusty environment.
- ✓ To develop a design of breadboard that includes features for dust tolerance and operations for both astronauts wearing gloves and robotic arms.
- ✓ To test the breadboard in conditions such the concept can be qualified for TRL 3/4.

# Applied project workflow

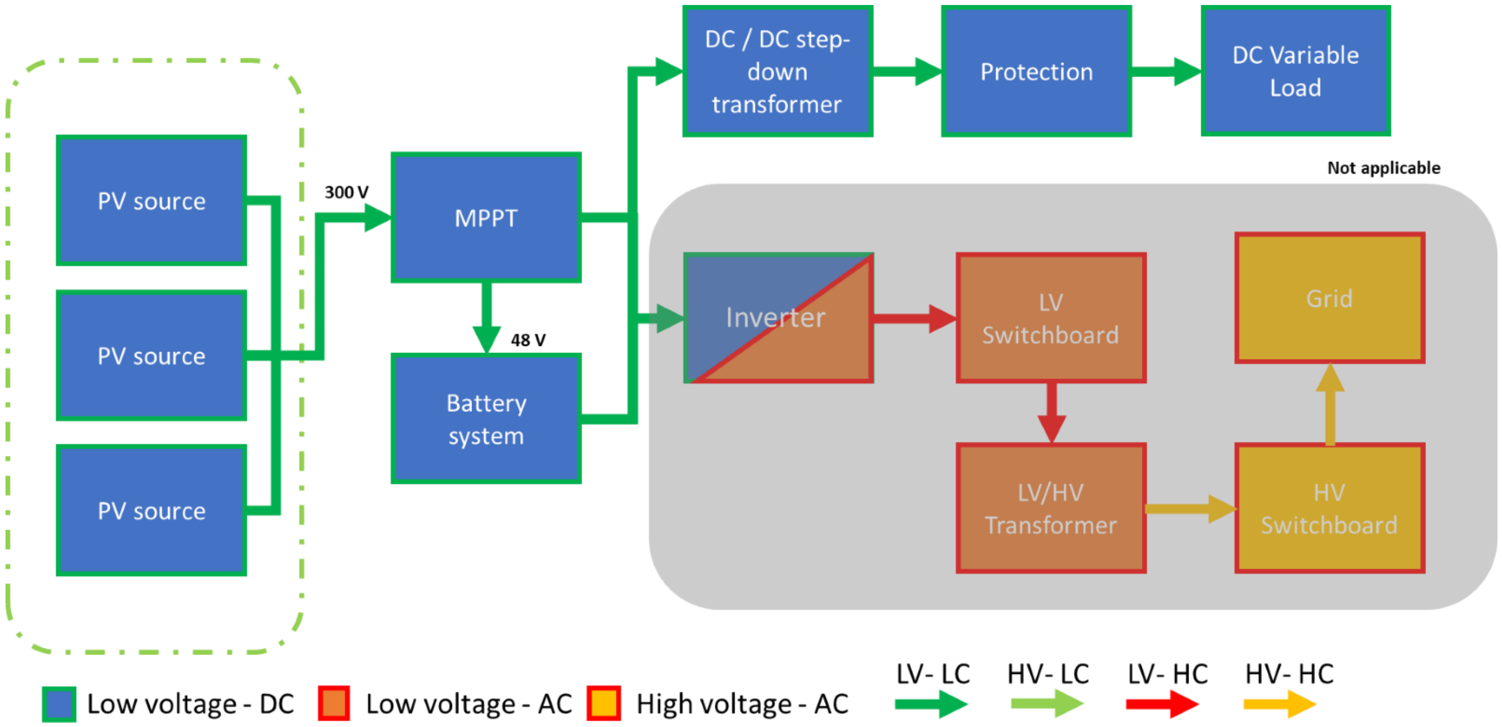


# Applied project workflow

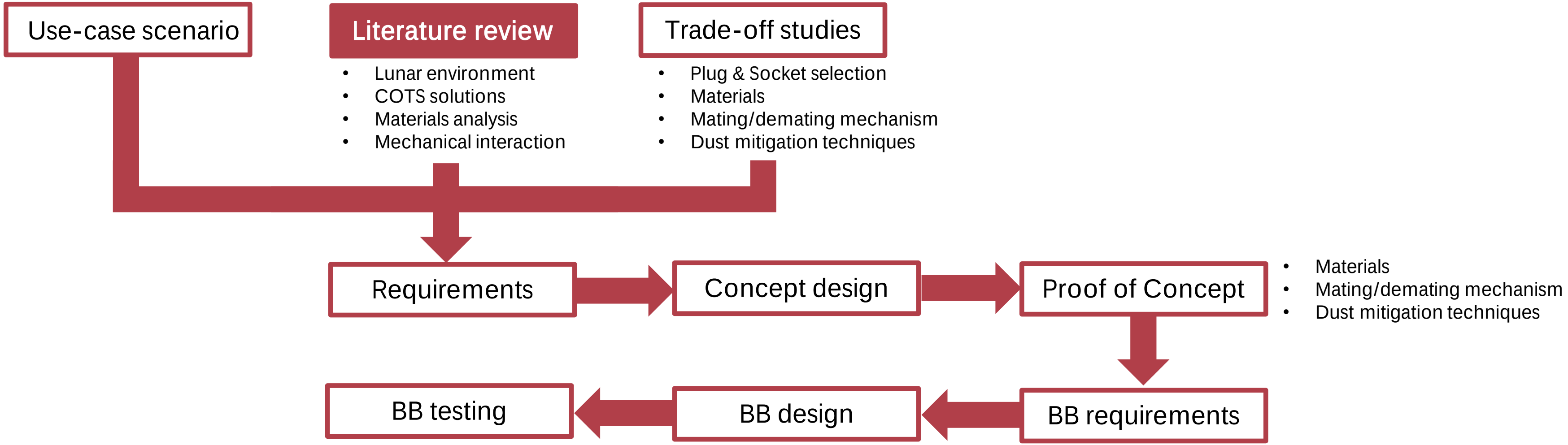


# Use case scenario definition

Vmax = 300 V Imax = 100 A

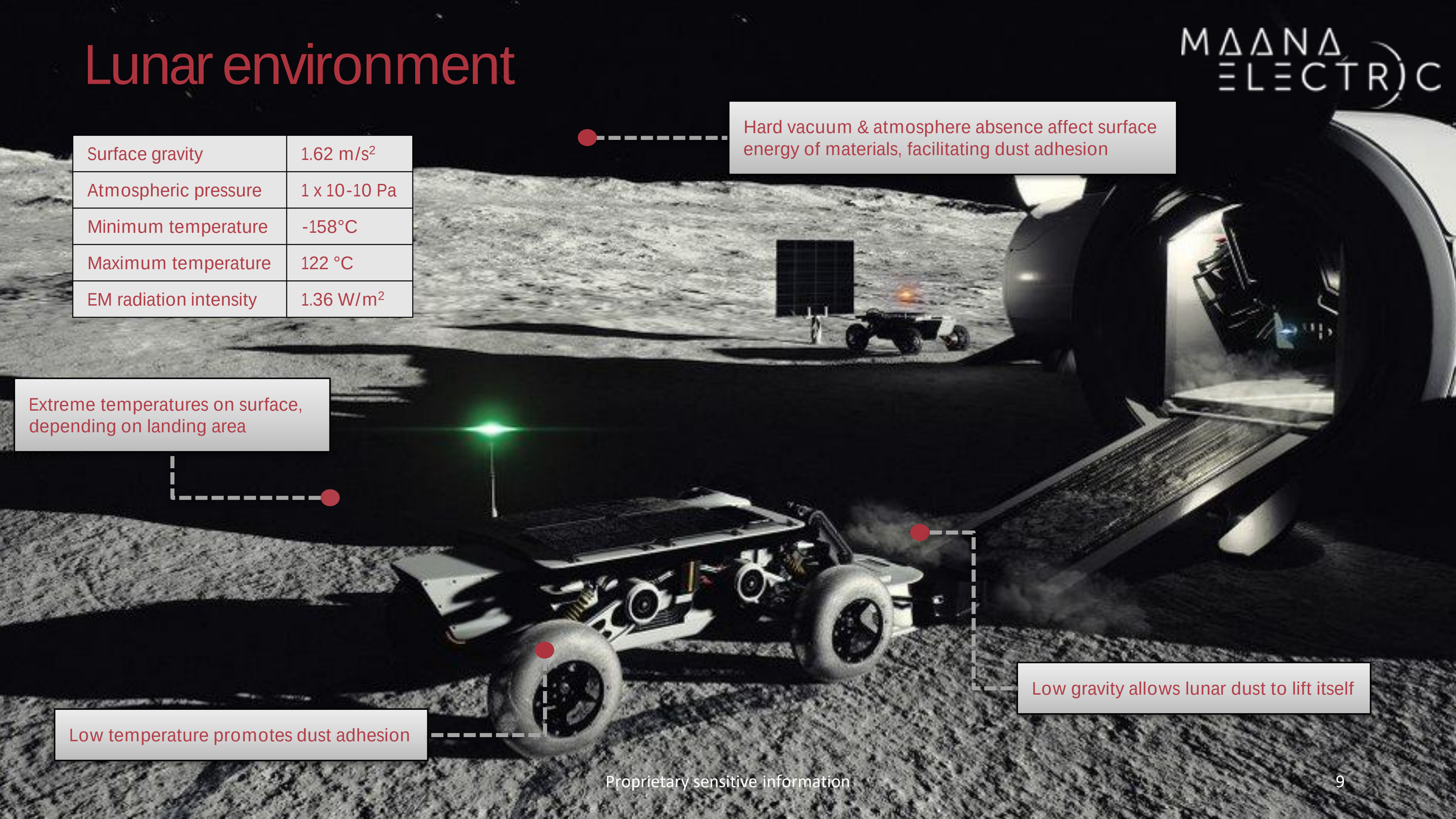


# Applied project workflow



# Lunar environment

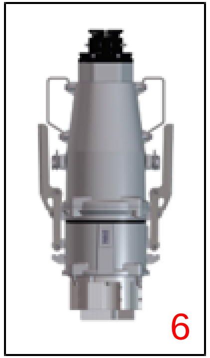
| | |
|---|---|
| Surface gravity | 1.62 $m/s^2$ |
| Atmospheric pressure | 1 x 10-10 Pa |
| Minimum temperature | -158°C |
| Maximum temperature | 122 °C |
| EM radiation intensity | 1.36 $W/m^2$ |



# COTS solutions analysis

1. Honeybee robotics dust tolerant connector
2. Smiths Interconnect HBB Series
3. Ametek ELITE Wet Mate Electric /WME) Series
4. Phase 3 powersafe
5. Bluelogic inductive couplice connector
6. Rausche and Stoecklin A/B-Line
7. TE Connectivity MIL-STL-38999 Series
8. NASA QD housing
9. Dust Tolerant Umbilical (DTAU)

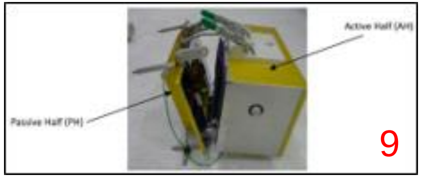













**No clear solution already exists in literature!**

# Materials analysis

Materials for contacts

- ✓ Copper, aluminum and silver are most used materials
- ✓ Copper-beryllium is often used as material for electrical conductors for connectors in satellites.
- ✓ Combined use of two different conductor materials to form a heterogeneous contact, reduces the risk of cold welding in vacuum.

Materials for insulation

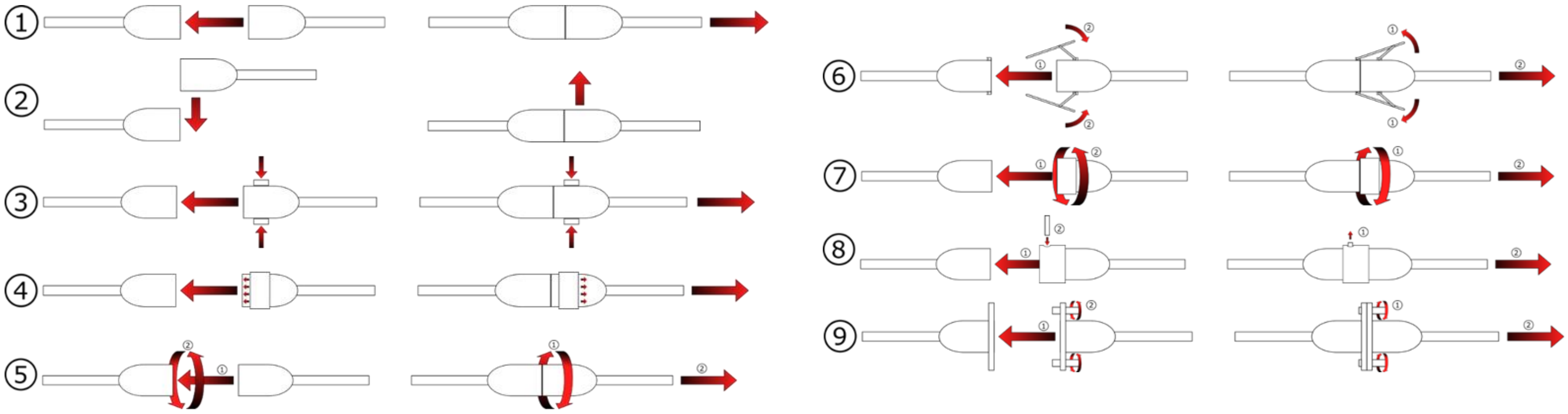
- ✓ Polymers such as Teflon, Tefzel, Kapton, Viton, Corona resistant PTFE.
- ✓ Ceramics and glasses.

Materials for shell or housing

- ✓ Polymers such as PI, PEEK, PEI, Teflon.
- ✓ Metals, such as aluminum, steel, titanium

# Mechanical interaction: mating/demating

The case considered was mating/demating by an astronaut wearing pressurized EVA suit. From this scenario 9 different mating/demating mechanisms have been identified:

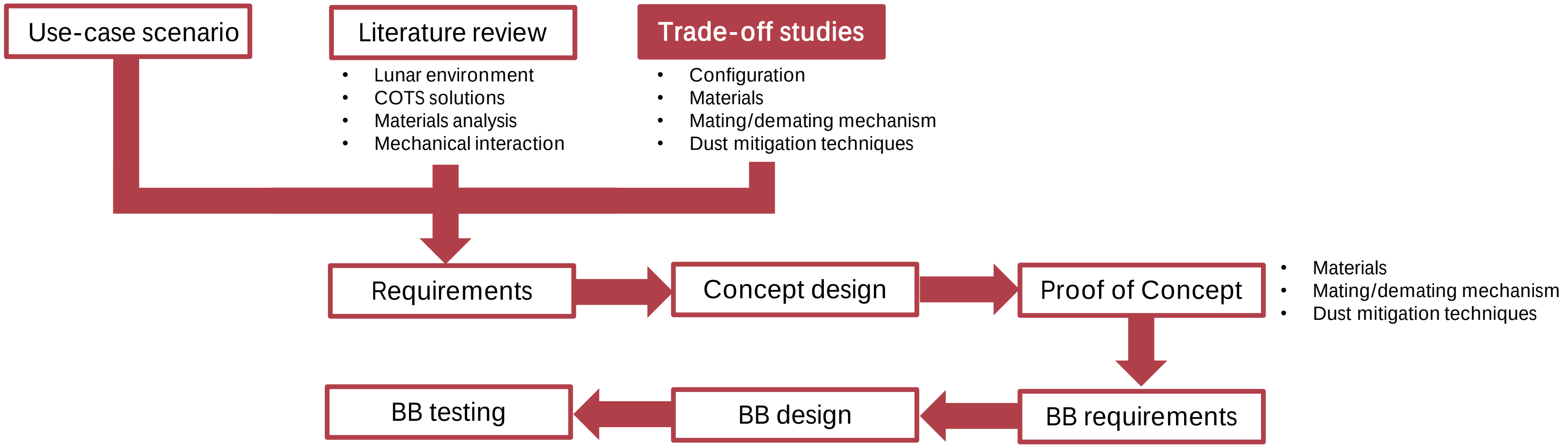


# Mechanical interaction: dust mitigation

Interaction with dust is the major issue when operating in lunar environment. The potential mitigation strategies are:

- ✓ Prevent dust from entering the Plug or the Socket (i.e. mechanical sealing or permeable membranes).
- ✓ Design contacts such that the presence of dust does not affect their functioning (i.e. brush or mesh contracts).
- ✓ Prevent dust from sticking to contacts (i.e. coatings).
- ✓ Remove dust from contacting surfaces once it has entered the Plug or the Socket (i.e. using physical attraction/repulsion forces, washing fluids, wiping) .

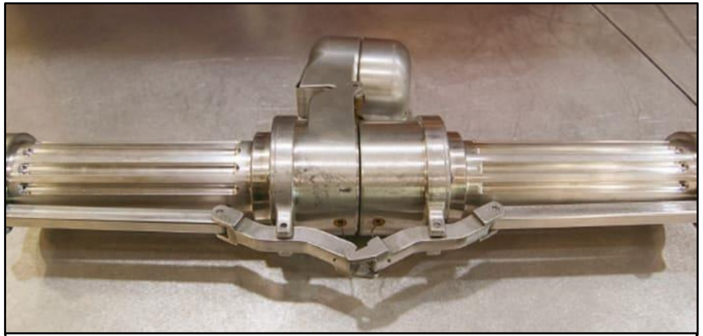
# Applied project workflow



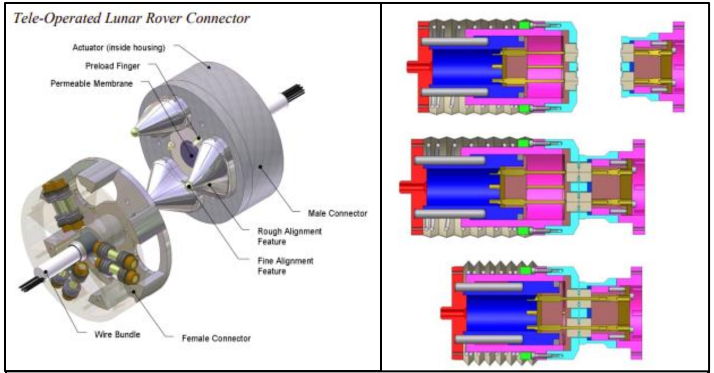
# COTS solutions analysis

The best solutions from the trade-off analysis are:

- Honeybee Robotics' dust tolerant connector.
- Smiths Interconnect's HBB Series (**Hypertac).**
- NASA's quick disconnect housing.



NASA quick disconnect housing in mated configuration. (Kennedy Space Center, 2016)




*Honeybee Robotics dust tolerant connector for automated use (left) and manual use (right). (Herman, Sadick, Maksymuk, & Chu, 2009)*

*Hypertac connector design (left) and Smiths Interconnect's HBB series connector. (Smiths Interconnect)*

# Materials analysis

## Materials for contacts: copper (male) and copper beryllium (female)

| Material | Density | Thermal conductivity | Volume resistivity | Young modulus | Poisson ratio | Tensile strength, yield | Low T limit | Melting point | Elongation at break |
|---|---|---|---|---|---|---|---|---|---|
| Cu | 8.93 $g/cm^3$ | 147 - 370 W/m°C | 1.82 – 4.9 x $10^{-7}$ Ωcm | 130/145 GPa | 0.34 | 137.9 MPa | -273°C | 1084°C | 60% |
| CuBe | 8.25 $g/cm^3$ | 105 – 130 W/m°C | 6.0 – 7.8 x $10^{-7}$ Ωcm | 125-130 GPa | 0.3 | 965-1205 MPa | -195°C | 866°C | 15-30% |

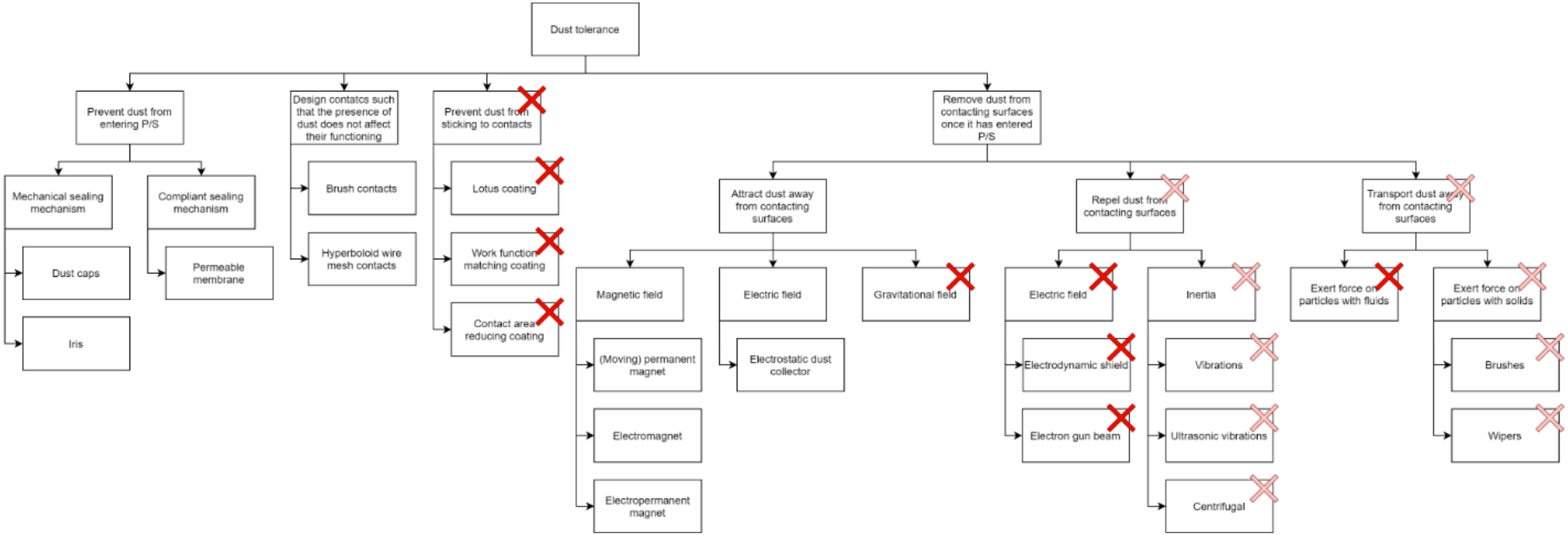
## Materials for insulation: PTFE

| Material | Density | Dielectric constant @1kHz | Volume resistivity | Corona resistance | Low temperature limit | Melting point | Ultraviolet radiation resistance | Nuclear radiation resistance | Elongation at break |
|---|---|---|---|---|---|---|---|---|---|
| PTFE | 2.15 $g/cm^3$ | 2.1 | 2.51 x $10^{14}$ Ωcm | Fair | -273°C | 327°C | Excellent | Good | 400% |

## Materials for shell or housing: aluminum

| Material | Density | Thermal conductivity | Volume resistivity | Young modulus | Poisson ratio | Tensile strength, yield | Low T limit | Melting point | Elongation at break |
|---|---|---|---|---|---|---|---|---|---|
| Al | 2.67 -2.73 $g/cm^3$ | 205 - 213 W/m°C | 3.1 x $10^{-8}$ Ωcm | 98.9 GPa | 0.32-0.36 | 90 MPa | -273°C | 660.3°C | 17% |

# Mechanical interaction: dust mitigation



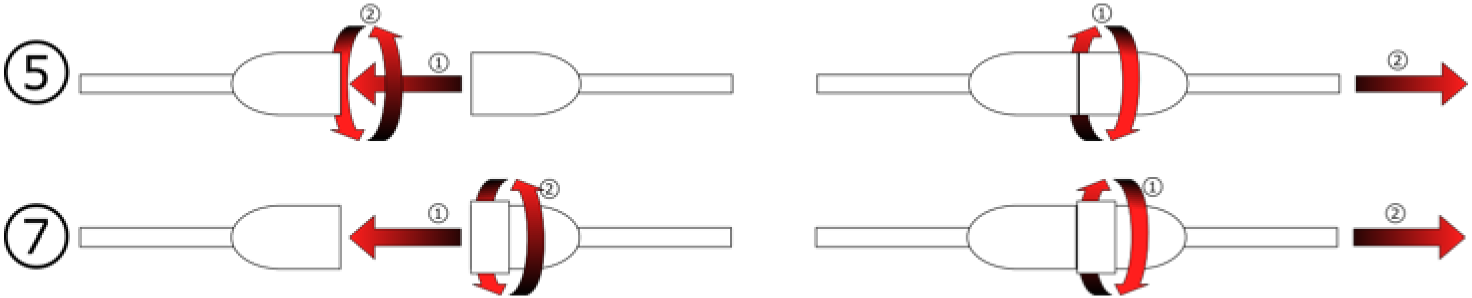

Prevent dust from entering the Plug or the Socket ---> High tolerance rubber seal

Design contacts such that the presence of dust does not affect their functioning ---> Spring contact

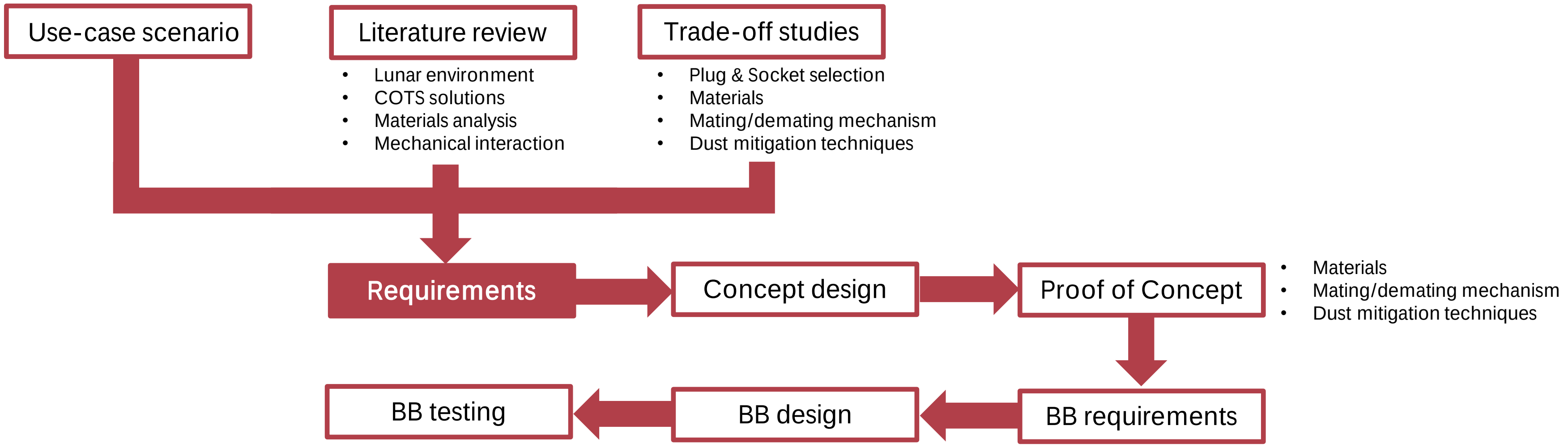
# Mechanical interaction: mating/demating

From the discussion with former astronaut Jean-Jacques Favier, the following observations have been outlined:

- Insertion guides required for manual and robotic operations.
- Designs that favor wrist over finger force application, are preferred.



# Applied project workflow



# Requirements: selected list

| ID | Requirement | Importance | Rationale |
|---|---|---|---|
| 1 | The P/S shall serve as a standard means of interconnecting lunar electrical equipment. | S | *One of the secondary goals of the P/S project is to provide a standard for electrical connections for any future lunar missions.* |
| 2 | The P/S shall be matable on the lunar surface. | M | *Given its intended use case, it is important that the P/S can be mated on the lunar surface and with the constraints that this implies (reduced mobility/dexterity of user, dusty environment, etc.).* |
| 3 | The P/S shall have a lifetime of 10 [years] or 500 (TBC) mating cycles, whichever comes first. | M | *To serve as a useful connection system, the P/S needs to reliably last for a given duration and a known number of mating cycles.* |
| 4 | The P/S shall be able to operate at a nominal voltage of 150 [V] with respect to ground when under maximal current load (DC). | M | *Following an analysis of current and predicted electricity needs in space, 150 V was deemed as being the desired nominal voltage of the power grid the P/S will be used in.* |
| 5 | The P/S shall be able to carry a maximal current of 50 [A] at the maximum voltage (DC). | M | *Following an analysis of current and predicted electricity needs in space, 50 A was deemed as being the maximum load expected to flow through the lines of the power grid the P/S will be used in.* |

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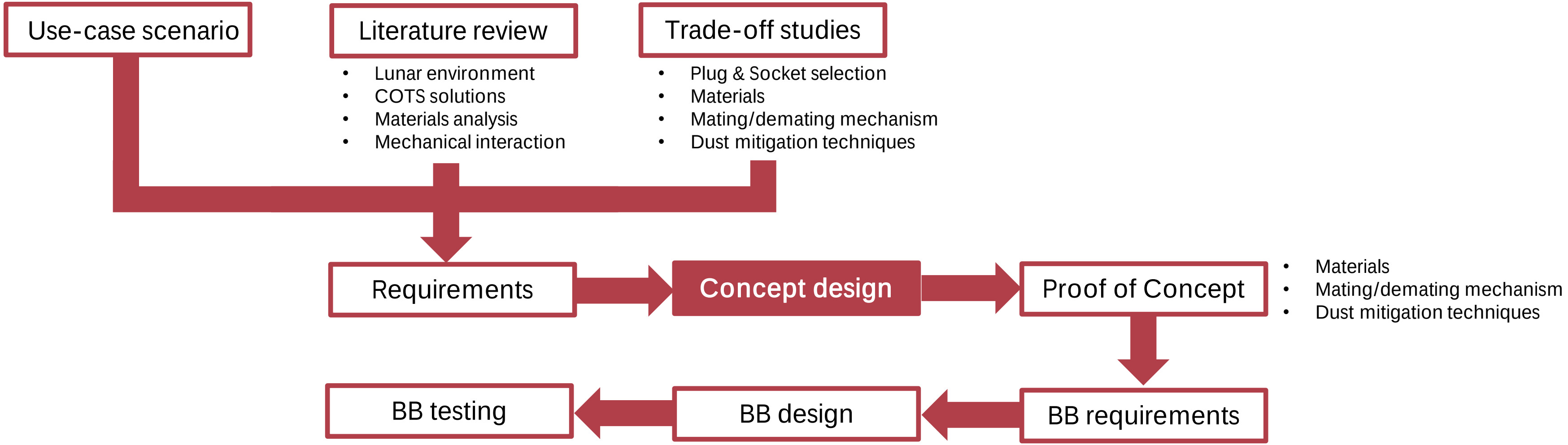
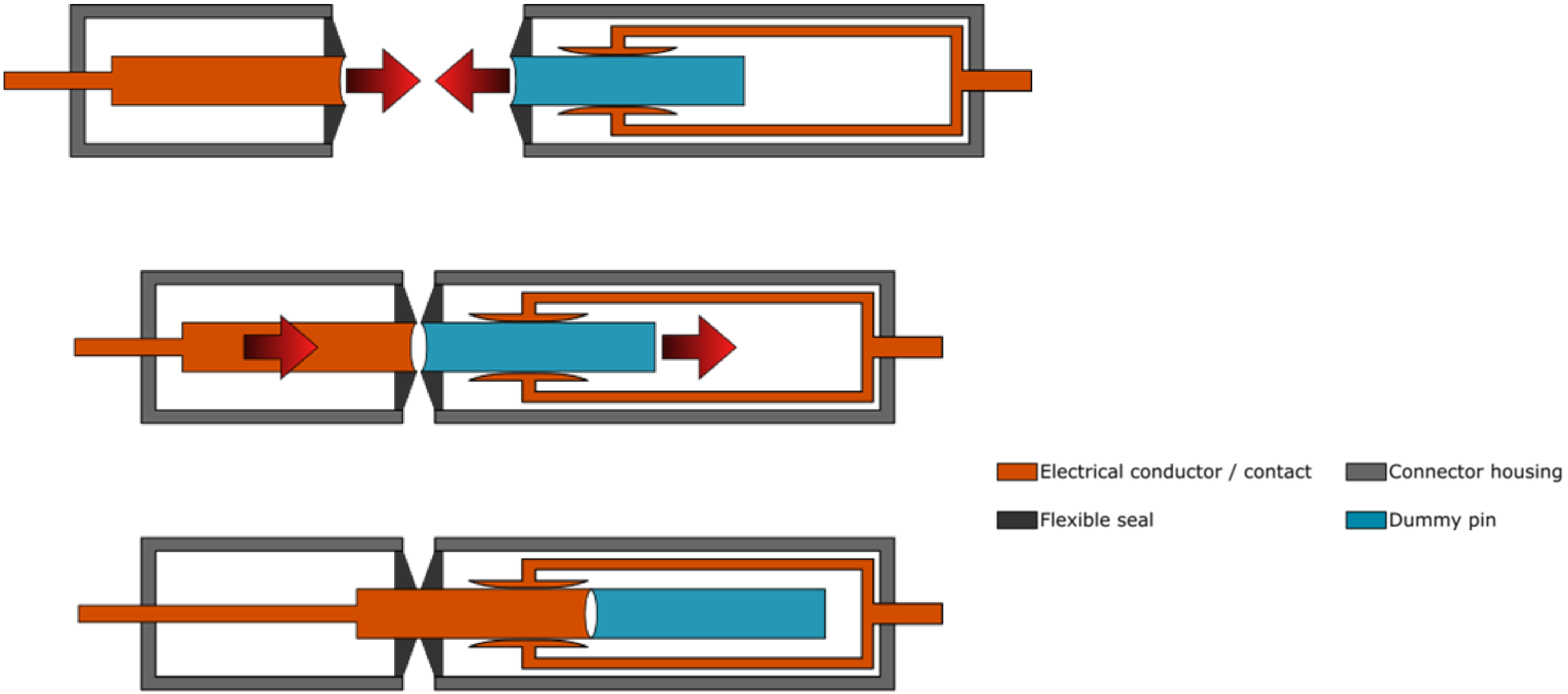
# Requirements: selected list

| ID | Requirement | Importance | Rationale |
|---|---|---|---|
| 6 | The P/S shall be able to operate at temperatures ranging from -158 to +122 [°C]. | M | *When excluding permanently shadowed polar craters, the temperatures on the lunar surface range from* -158 to +122 [°C]. |
| 7 | The P/S shall be operated in presence of lunar regolith with mineralogic characteristics compatible with a potential location in the lunar south pole | M | *Lunar regolith has different chemical compositions depending on the location. The most probable location for first human settlement will be lunar south pole, therefore the design should account characteristics of the dust that can be found there.* |
| 8 | The P/S shall be able to operate at pressures of $10^{-10}$ [Pa]. | M | *The absence of atmosphere on the Moon means that the P/S needs to be able to operate in high vacuum environments.* |
| 9 | The P/S shall allow astronauts wearing a pressurized EVA suit to establish the mechanical connection during the mating process. | M | *Astronauts need to be able to perform the mechanical joining of the two P/S halves, as they will be the primary users of the P/S.* |
| 10 | The P/S's terminals shall be made out of: copper; alloys with at least 58% copper content | M | Following IEC 60309, 11.2. |

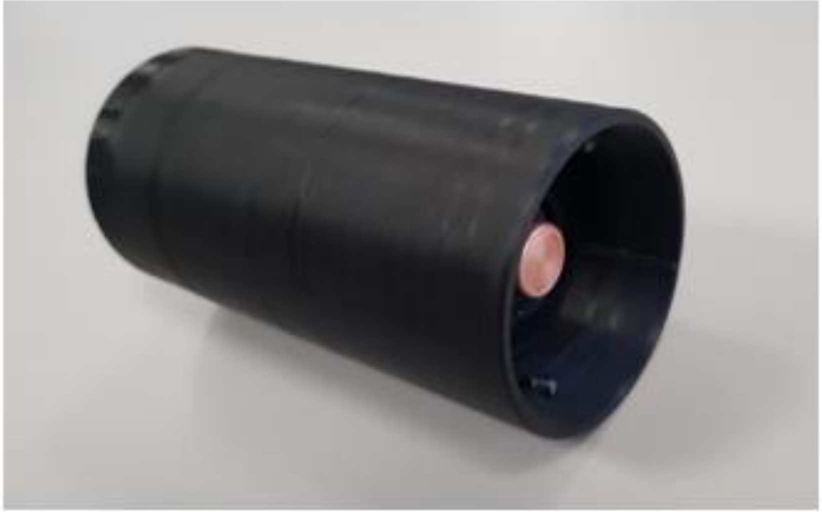
# Applied project workflow



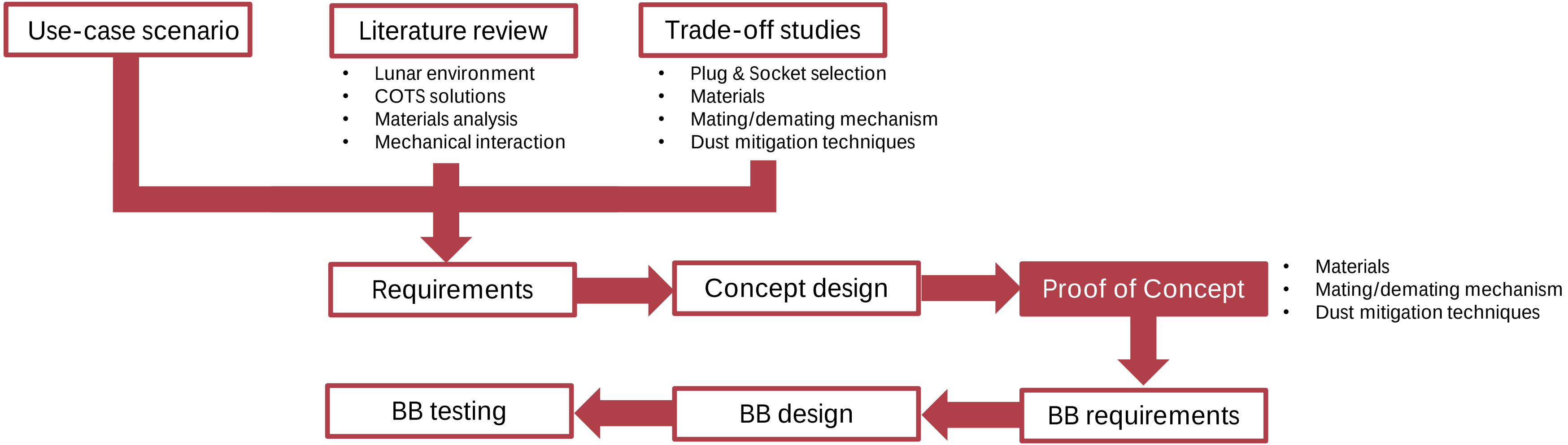
# Concept design



# Concept design



# Applied project workflow

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# Proof of Concept

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## Testing conditions

- Testing in ambient conditions in isolated chamber.
- Manual mating using stiff gloves limiting hands dexterity.
- Application of variable levels of current and voltage.
- Simulating regolith contamination using EAC-1 and Exolith LHS-1 simulants

☑ Materials: validation of the design and the sizing of the conductive terminals (male pin in copper and female spring in copper beryllium). Copper beryllium resulted to be more resilient to wear than simple copper with no real impact on resistivity.

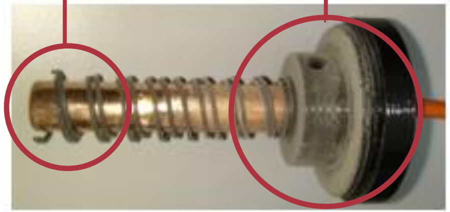
☑ Mating/demating mechanism: validation of the selected mating mechanism (candidate n.5) when using gloves limiting hands dexterity. However, the mechanism may not be easy to implement for robotic mating.

# Proof of Concept

☑ Dust mitigation techniques: validation of the rubber seal solution to minimize regolith contamination

Male pin wiping

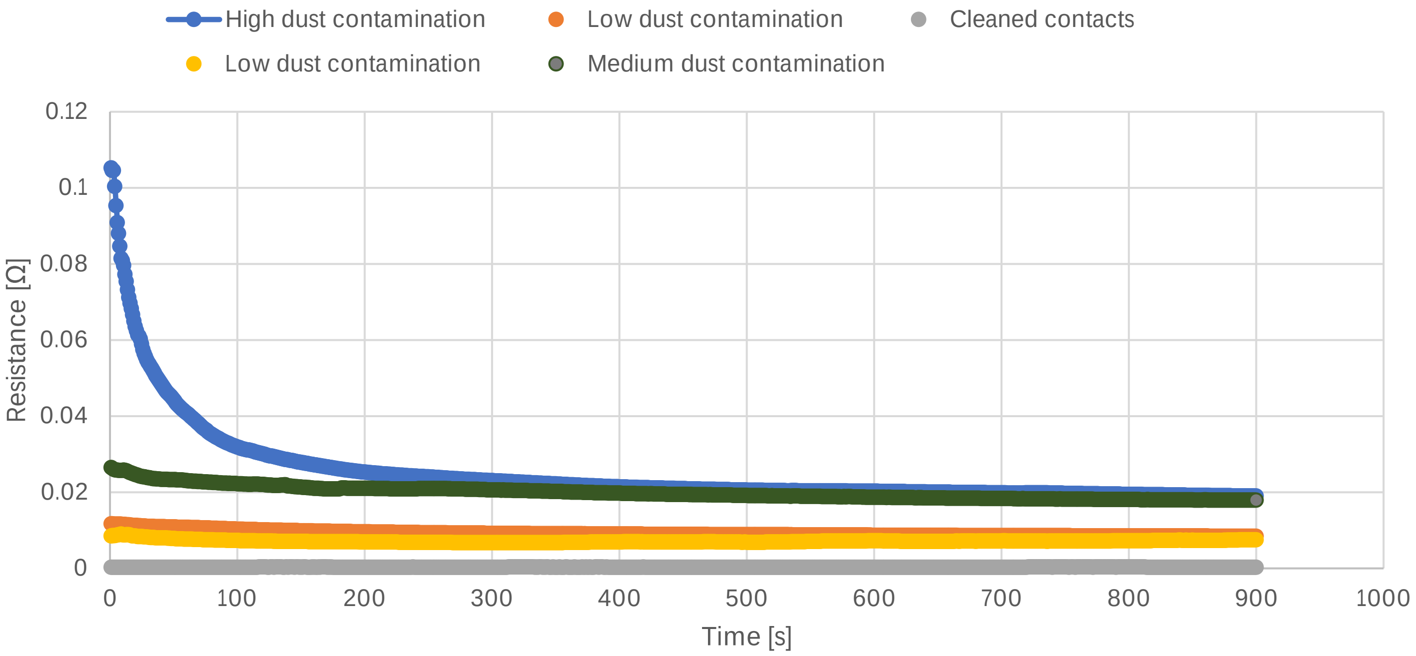
Male pin contamination



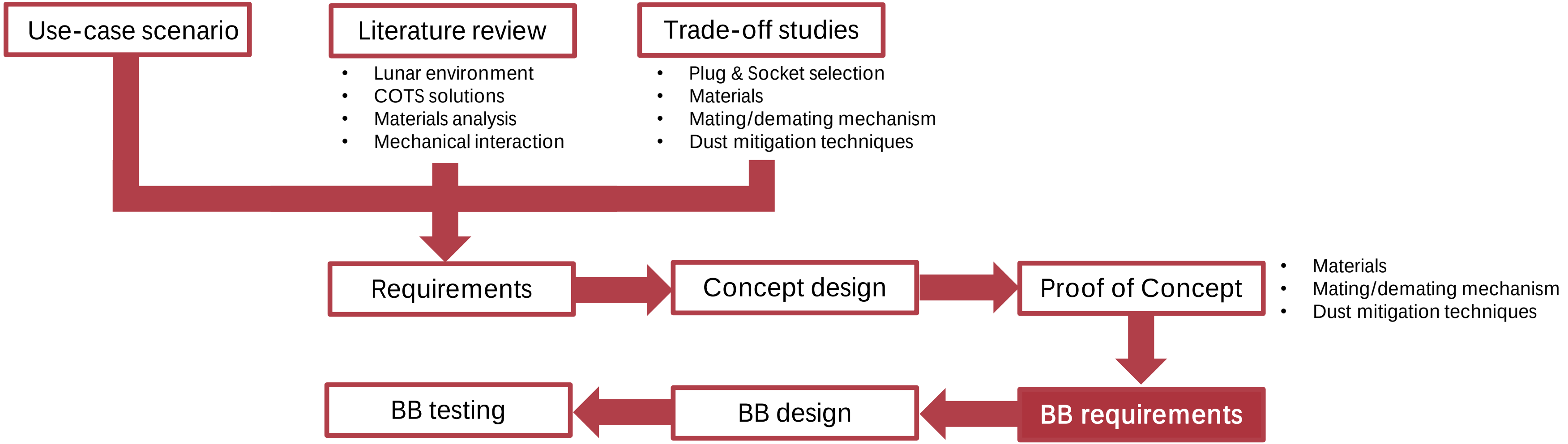
No signs of contamination or wear on the socket conductive elements

# Proof of Concept

- ☑ Dust mitigation techniques: validation of spring contact configuration to minimize the effect of regolith contamination



# Applied project workflow



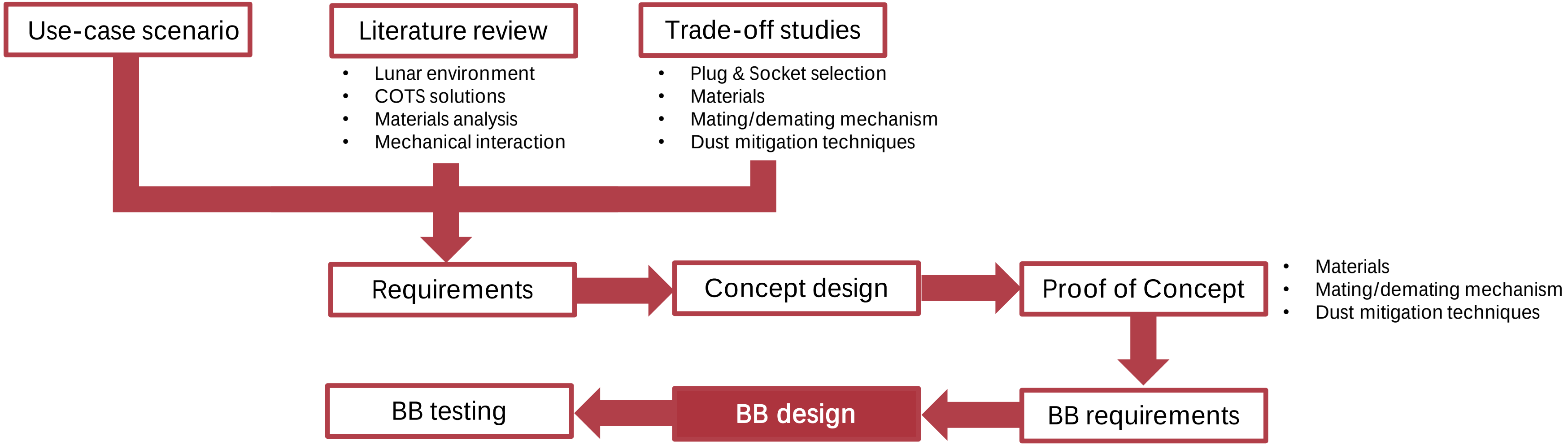
# Breadboard requirements: selected list

| ID | Requirement | Importance | Rationale |
|---|---|---|---|
| 1 | The P/S breadboard shall be capable of allowing electrical connectivity in dusty environment. | M | *The primary goal of the P/S design is to develop a connection system for that can survive during operations in presence of dust contaminants as in lunar environment.* |
| 2 | The P/S breadboard shall be designed following the outcomes of the configuration trade-offs and Proof of Concept testing. | M | *The assumptions resulting from engineering trade-offs and experimental campaign carried out for their validation shall be used for driving the design of the breadboard.* |
| 3 | The P/S breadboard shall limit the access of regolith to the housing. | M | *A major result of the Proof of Concept (please refer to [AD1]) is the degradation of the electrical performance due to wear on the electrical terminals. In order to ensure the required lifetime and constant performance, technical solutions must be adopted to limit the wear.* |
| 4 | The P/S breadboard shall be tested for 500 cycles of mating/demating. | M | *This requirement sets the minimum number of cycles to consider the testing of the breadboard sufficiently representative.* |
| 5 | The P/S breadboard shall be tested to withstand contamination from regolith simulant representative of lunar south pole chemistry. | M | *This requirement is in fulfilment of environmental requirement PS-E-013 and poses worst conditions to operational conditions as chemical composition of Highland simulants is more abrasive than Mare simulants.* |

# Breadboard requirements: selected list

| ID | Requirement | Importance | Rationale |
|---|---|---|---|
| 6 | The P/S shall be able to operate at a nominal voltage of 150V with respect to ground when under maximal current load (DC). | M | *Following an analysis of current and predicted electricity needs in space, 100 A was deemed as being the maximum load expected to flow through the lines of the power grid the P/S will be used in.* |
| 7 | The P/S breadboard shall transmit at least 50A current without damaging or overheating. | M | *Following an analysis of current and predicted electricity needs in space, 100 A was deemed as being the maximum load expected to flow through the lines of the power grid the P/S will be used in. The reference performance for the breadboard has been set to 50A DC in order to be sufficiently representative.* |
| 8 | The P/S breadboard shall ensure no current leakage below 1mA at 2kV DC. | M | *The maximum current leakage has been set to ensure correct functionality of the insulative components of the breadboard.* |
| 9 | The P/S breadboard shall experience no temperature increase over 30°C versus environmental conditions during nominal operations. | M | The maximum temperature increase has been set to ensure survivability of components of the breadboard under reasonable thermomechanical loads. |
| 10 | The P/S breadboard shall be designed to allow easy mating/demating by astronauts wearing pressurized gloves. | M | The design should take into account the early implementation of some solutions that could allow astronauts to interface with the system. |

# Applied project workflow



# Breadboard design

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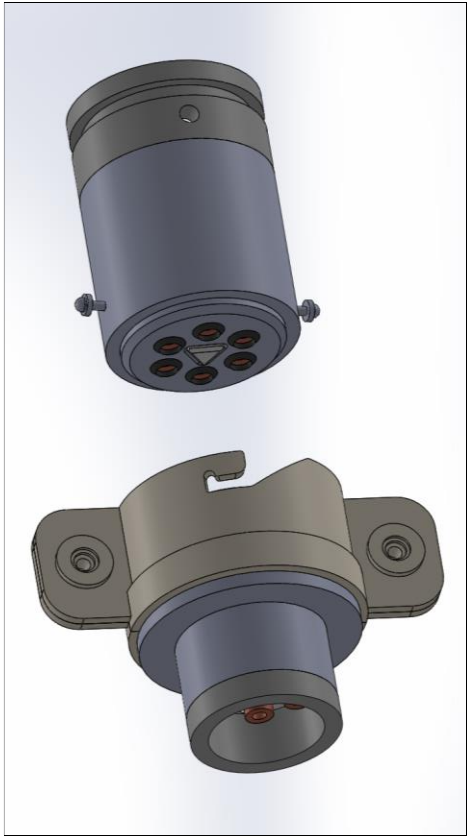
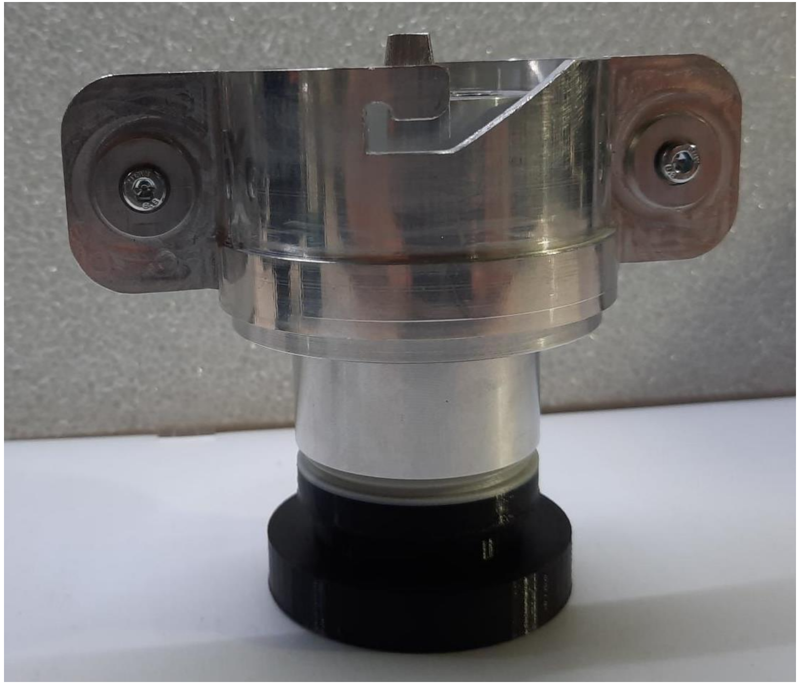
## Main features:

- ✓ 6 pins plug and socket, with 2 redundant elements.
- ✓ Conductive elements in copper and copper beryllium.
- ✓ Rated for nominal voltage 150 V at 50A.
- ✓ Rubber seals.
- ✓ PTFE insulation.
- ✓ Aluminum housing.
- ✓ Retractile pins based on spring mechanism.
- ✓ Mating/demating mechanism based on concept "7" to facilitate robotic mating
- ✓ Front triangular pin for mating guidance.



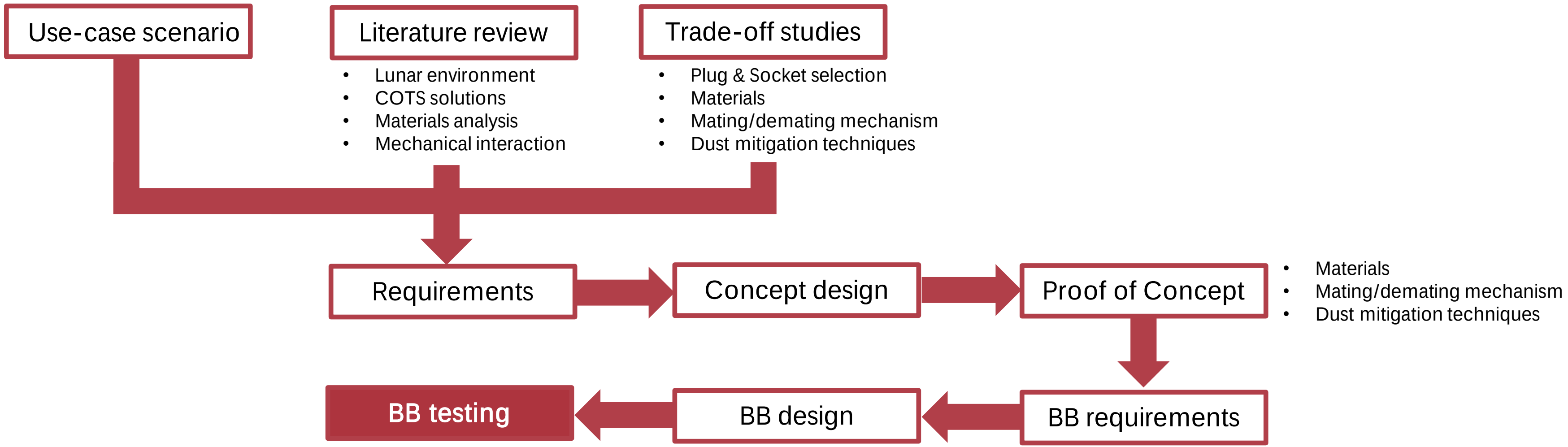
# Breadboard design

Plug element



Socket element

# Applied project workflow



# Testing conditions

## Testing equipment

- ✓ Multimeter.
- ✓ DC power supply, 150 VDC@50A output, 7.5kW.
- ✓ DC power supply, 30 kVDC@1mA output, 3kW.
- ✓ Scale.
- ✓ MPPT Charge controller, 150 VDC@50A maximum input.
- ✓ Chargeable solar battery, 12 VDC.
- ✓ Pyrometer.
- ✓ EVA robotic arm.
- ✓ Regolith dispenser.

## Regolith simulants

- ✓ Exolith LHS-1 (mean particle size: 60 µm, particle size range: <0.04 – 400 µm)
- ✓ Exolith LMS-1 (mean particle size: 50 µm, particle size range: <0.04 – 300 µm)

# Breadboard testing

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## 4 tests have been carried out on the breadboard

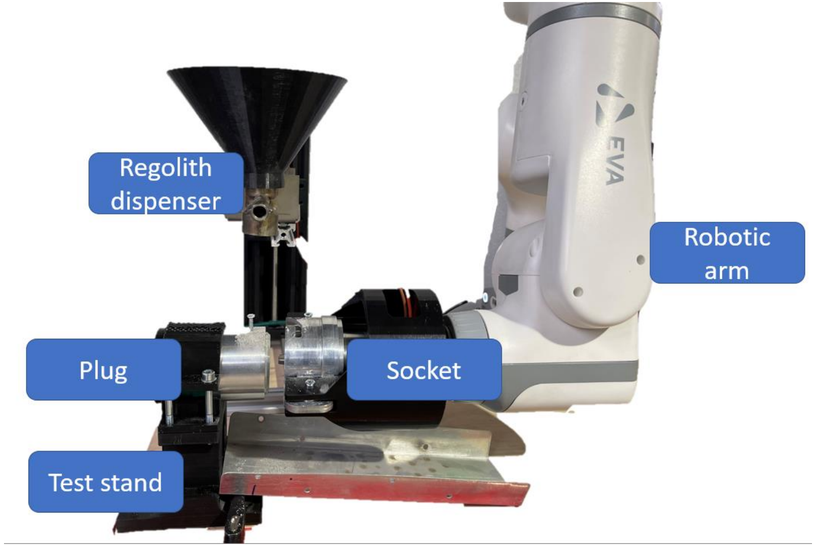
- ☑ **Sealing test:** To verify efficiency of dust mitigation strategy on current design.
- ☑ **Contact resistance test (with contaminating agent):** To measure the contact resistance between the mated connectors
- ☑ **Dielectric Withstanding Voltage test:** To verify that the connector system can operate at its rated voltage/can withstand momentary over-potentials due to switching and surges.
- ☑ **Current rating test:** To determine the continuous current rating of the PS system and measure expected temperature gradient.

# Sealing test

**Test objectives:**

- To assess the effectiveness of the pins' sealing system in preventing dust particles from entering the socket's housing.
- To characterize the system's performance in a high-contamination environment.

**Success criteria**: leaked dust particles' mass < 10 g after 500 mating cycles.




**Results**:

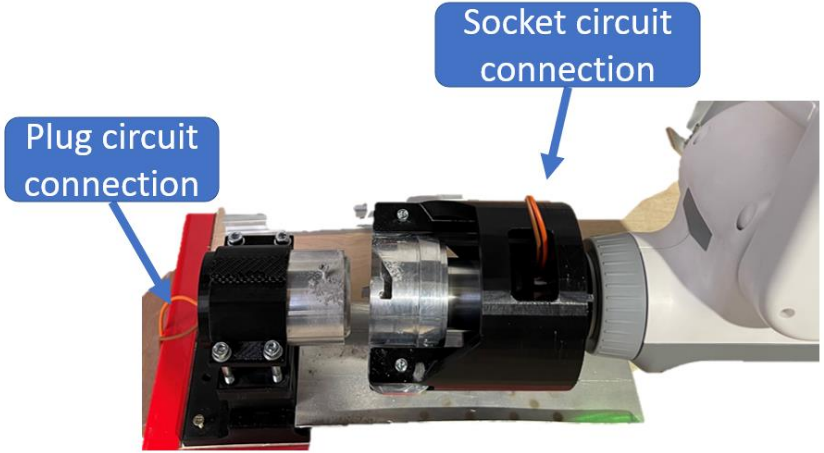
✓ 0.7g of simulant leaked after 500 mating cycles.

✓ No relevant effect of regolith contamination on components wear and tolerances.

# Contact resistance test

**Test objectives:**

- To measure the contact resistance between the mated connectors contact attached to the wire.
- To identify problems with loose connections, eroded contact surfaces, and contaminated or corroded contacts.




**Success criteria**: Target resistance within the range of 500 - 520 mΩ after 500 mating cycles.

**Results**:

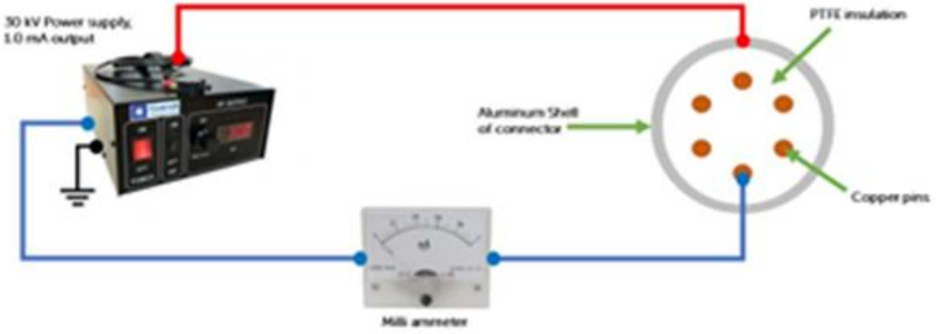
✓ Deviation from nominal resistance measured of 3 mΩ after 500 mating cycles.

✓ No substantial effect of regolith contamination on the electrical performance.

# Dielectric withstanding voltage test

<u>**Test objectives:**</u>

- To verify that the connector system can operate at its rated voltage.
- To verify that the connector system can withstand momentary over-potentials due to switching and surges.




<u>**Success criteria**</u>: Maximum leakage current is ≤1 milliamperes. No evidence of breakdown or flashover on the contacts at target voltage of ≥2kV.

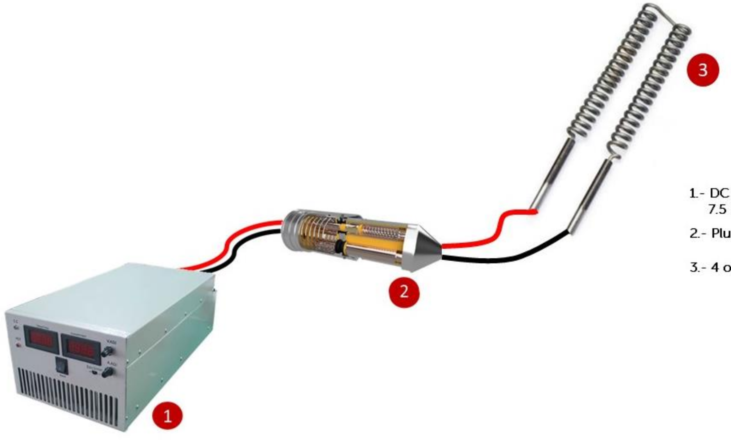
<u>**Results**</u>:

✓ Max leakage current of 0.02 mA with the application of 2kV DC.

# Current rating test

**Test objectives:**

- To verify that the connector system can operate at its rated voltage.
- To verify that the connector system can withstand momentary over-potentials due to switching and surges.




**Success criteria**: $\Delta T_{max}$ = 30°C on the housing while operating at maximum rated current. Minimum 50 A load, ±10% at a 30°C temperature rise for inner contacts energized.

**Results**:

✓ Maximum $\Delta$T of breadboard with maximum operational parameters (150V @ 50A) <30 °C.

# Conclusions

- ✓ The breadboard testing allowed to validate the assumptions of the Proof of Concept testing.
- ✓ The breadboard performed as expected in presence of limited contamination of regolith simulant after multiple matin/demating cycles.
- ✓ The breadboard has been validated for mating either by astronauts wearing gloves or robotic arms.
- ✓ The TRL of the concept is increased to 4.

# Next steps

- ✓ Design optimization of regolith mitigation solutions.
- ✓ Design optimization of mating mechanism and implementation of improved ergonomic solutions for astronaut handling.
- ✓ General optimization of masses and volumes of the lunar P/S.
- ✓ Identification of smart features to incorporate into the design to improve interaction with users.
- ✓ Testing of materials in simulated operational environment (vacuum, thermal cycles, radiation, etc.).
- ✓ Definition of a family of products derived from the baseline design to serve a range of operational conditions.