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Experimental Results of a Mission-Ready Triboelectric Device for Mars Robotic Missions

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Abstract

The highly insulating Martian regolith, subjected to low atmospheric pressures, low temperatures, and extremely dry conditions, is conducive to the build-up of electrostatic charge. NASA developed the Mars Environmental Compatibility Assessment (MECA) Electrometer, a mission-ready instrument to characterize the triboelectric properties of the Martian soil. This instrument consists of five electrometer sensors covered with different insulators designed to make contact with the Martian soil. The MECA electrometer has been thoroughly tested and calibrated in our laboratory under several environmental conditions, including ambient Martian atmospheric conditions. In this paper we discuss the configuration of the instrument, its intended use on the mission, and the results of the data collected in the laboratory. The JSC Mars-1 Simulant, a Martian regolith analog developed at NASA Johnson Space Center, was used in these experiments. The simulant can be placed in a triboelectric series relative to the five insulators on the instrument. We report on the ability for insulators to exceed the breakdown voltage of metals.

Introduction

Large portions of the Martian surface are covered by fine, weathered soil material, which has been homogenized by global dust storms into a single *geological unit* [Banin 1991]. Evidence for the existence of dust storms predates the exploration of Mars by spacecraft. Telescopes on earth showed color and albedo pattern changes which were attributed to the occurrence of large dust storms [Greeley 1991]. The existence of dust storms on Mars reaching global proportions and lasting for several months has now been extensively documented by spacecraft observations ranging from Mariner 9, Viking 1 and 2, Pathfinder, and Mars Global Surveyor [Martin 1974, Hardin 2001].

Surface soil and dust particles on Mars may become electrostatically charged due to incident UV radiation reaching the surface. Although the total integrated UV flux over 200-400 nm on Mars is comparable to Earth's, shorter wavelengths contribute a larger proportion of this flux [*Catling* and *Cockell*, 2000]. Contact charging may also occur due to collisions between wind-blown dust particles and stationary surface particulate matter. The high frequency of dust devil appearance and the presence of local and global dust storms produce a favorable environment for inter-particle contact charging in the Martian atmosphere.

Electrostatic charging of dust and sand particles on Mars is exacerbated by the low temperatures and low humidities of the atmosphere near the surface. The surface temperatures measured by Pathfinder ranged from a minimum of 197 K (–76 degrees Celsius), reached just before sunrise, to a maximum of 263 K (–10 degrees Celsius), reached every day at 2 p.m. local solar time. The atmosphere on Mars is primarily 95% carbon dioxide with a few percent each of nitrogen and argon and contains only traces of water vapor. Measurements made over a three and a half year period by the Viking Landers showed that the pressure reached minimum values of about 6.7 mbars and maximum values of about 10.4 mbars. This low atmospheric pressure does not provide enough pressure to prevent liquid water from boiling into vapor.

The robotic landing missions to Mars planned for this decade as well as the possible manned missions that might take place during the second decade of this century require a better understanding of the electrostatic response of the materials used in landing crafts and equipment when exposed to wind-blown dust or to surface dust and sand particles. No experiments to determine the magnitude of the charge exchange between contacting particles or between airborne moving particles and stationary surfaces have been conducted in any Mars exploration mission so far [Calle 2001].

The Mars Environmental Compatibility Assessment (MECA) Electrometer, a flight-ready multisensor, was developed by this laboratory in conjunction with the Jet Propulsion Laboratory[Buehler 2000]. In this paper, we report on the capabilities of this instrument and on the results of extensive calibration and testing experiments performed under simulated Martian atmospheric conditions.

The MECA Electrometer

The MECA Electrometer (Figure 1) was designed primarily to investigate the electrostatic interaction between the surfaces of insulating materials and the soil on the surface of Mars in preparation for human exploration. The insulating materials were selected for their use on previous space missions. The five insulators selected for the MECA Electrometer were: Fiberglass/Epoxy, Polycarbonate (known as Lexan^{TM}), Polytetraflouroethylene (Teflon^{TM}), Rulon J^{TM}, and Polymethylmethacrylate (Lucite^{TM} or PMMA).

Figure 1. The MECA Electrometer showing five insulators over the triboelectric sensors (lower part), a bare electrometer (top left) and an ion gauge (top right).

The five small circular patches shown in Figure 1 are the five types of insulators. The two openings shown above the five insulators in the electrometer photo are the local electric field sensor (ELF) on the left, and the ion gauge (IG) on the right. The temperature sensor is a dedicated integrated circuit chip that is mounted inside the case, and is not shown in the photo of the MECA Electrometer.

The five insulating materials of the tribroelectric sensor array are placed above metal electrodes that are connected to five independent electrometer circuits, one circuit for each type of insulator. The tribo sensors are housed inside a case made of titanium with a volume of ~50 cm^3, a total mass of ~50 g, and power consumption of <250 mW. The electrometer, which will be attached to the robot arm, as shown in Figure 2, is used to measure the triboelectrically-induced charge after the Triboelectric Sensor Array is rubbed through the Martian soil and pulled away from the surface. The electrometer will also measure the electric field strength above the Martian soil using the Electric-Field Sensor as well as atmospheric ion currents using the Ion Gauge.

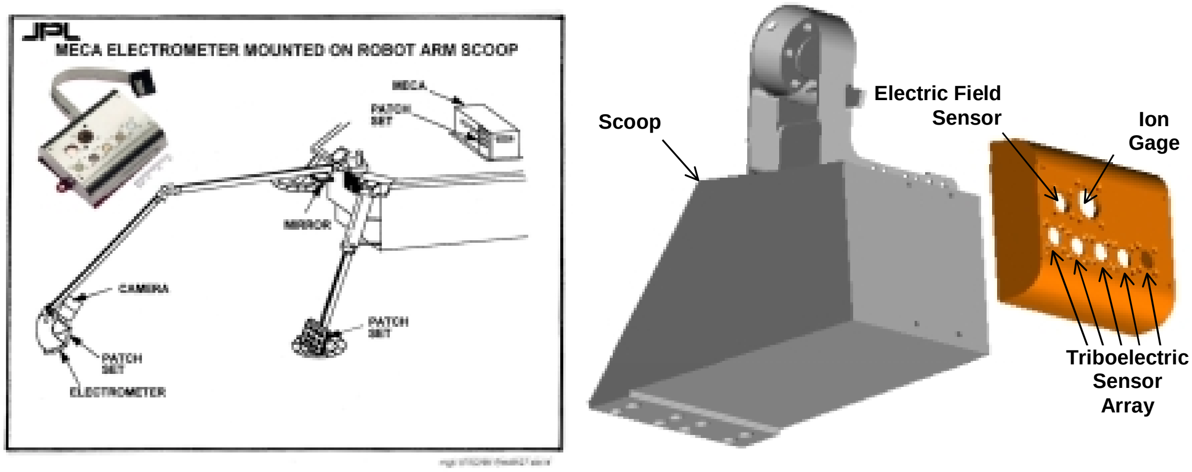


Figure 2. **(Left)** Schematic of the MECA Electrometer mounted on the robot arm scoop on the lander. (**Right)** Close up of the position of the electrometer on the scoop.

The electronics contained within the MECA Electrometer housing have been described elsewhere [Buehler 1999], and will only be discussed as needed in this paper. The tribo sensor circuit has an output voltage, V_{out}, that is proportional to the electric charge that develops on the surface of the insulator. The circuit is shown schematically in Figure 2. The overall gain of the tribo circuit (not shown) is 4×. Thus, $V_{out} = 4Q/C$, where the fixed capacitor C = 1 nF. So, the charge Q on the surface of the insulator must be given by $Q = V_{out} / (4\times10^9\ F^{-1})$. Hence, the tribo circuit's gain is 0.25 nC/V as measured at the output. If the A/D converter has a 2 mV per bit resolution, then the device can detect an amount of electric charge as small as 0.5 pC, which is numerically equivalent to 3.1×10^6 electrons or protons.

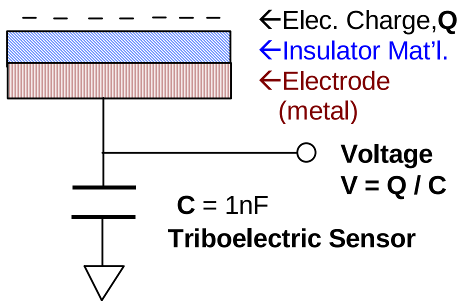
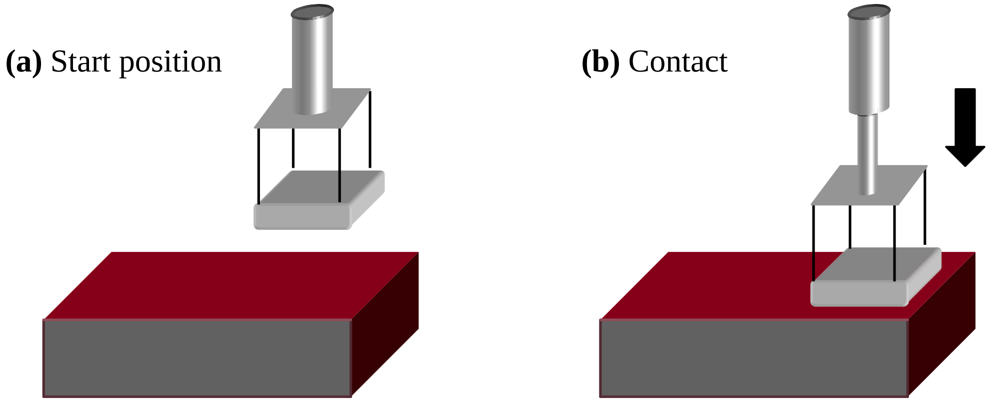


Figure 3. Simplified circuit diagram one of the induced-charge triboelectric sensors.

Experimental Procedure

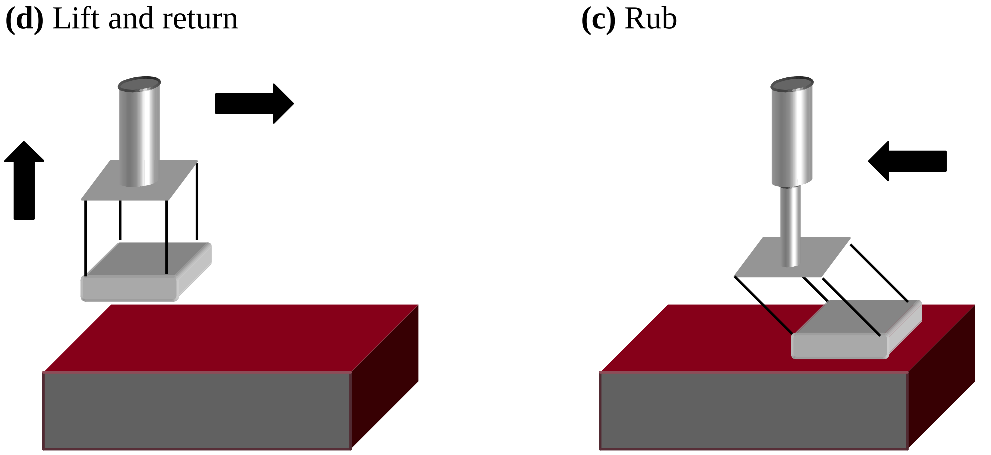
Testing the triboelectric sensor array involved measuring the degree to which the insulator surfaces became electrically charged when rubbed over Martian soil simulant (JSC Mars-1) at

CO_2 pressures and temperatures similar to those near the surface of Mars. The electrometer, which was kept electrically insulated, swings freely from a metal plate. This plate is connected to a pneumatic piston system that lifts and drops the assembly, as shown in Figure 4. After 5 seconds of contact with the soil (Figure 4 b), the electrometer is slid along the surface under its own weight for 4-5 seconds (Figure 4 c). This is done by attaching the assembly to a motorized pulley system. Once the electrometer reaches the end of its motion, it is lifted off the surface and returns to the starting position (Figure 4 d). All of these movements are controlled by a LabView program which stores the electrometer position along with the data. Data was taken using the Parallax Basic Stamp II^{TM} controlled by a PC laptop running LabView^{TM}.



(a) Start position

(b) Contact



(d) Lift and return

(c) Rub

Figure 4. The movement of the MECA Electrometer is shown above. The electrometer is placed above the soil in **(a)** and then positioned in contact with it in **(b)**. The electrometer is dragged across the soil under its own weight in **(c)**. Finally, the electrometer is lifted off the surface in **(d)** and returned to its initial position in **(a).**

Experiments were performed in a Martian pressure of 5-7 torr CO_2 environment in a LabView controlled vacuum chamber. The JSC Mars-1 Martian regolith simulant was baked out for several days beforehand to remove as much moisture as possible. After the soil was placed inside the vacuum chamber, the system was evacuated below 1 torr and then backfilled with the atmospheric gas. The soil was placed in a grounded metal container that contained liquid N_2 lines to cool the simulant (not shown in Figure 4). Thermocouples were then placed in contact with the soil to monitor its temperature.

Room Temperature Results

Figure 5 shows a typical experimental data run in which the soil was kept at room temperature but under Martian atmospheric conditions. There is a background signal of ~30 mV before rubbing takes place. While rubbing the polymers onto the simulant, a certain amount of charge is deposited onto the sensors depending on the polymer material. In response to being rubbed over the Martian simulant, Fiberglass and Lucite tend to charge positively, Teflon and Rulon J tend to charge negatively, while Lexan does not tend to charge very much. The peaks and dips in the figure correspond to repeated movements of the electrometer, as described in Figure 5.

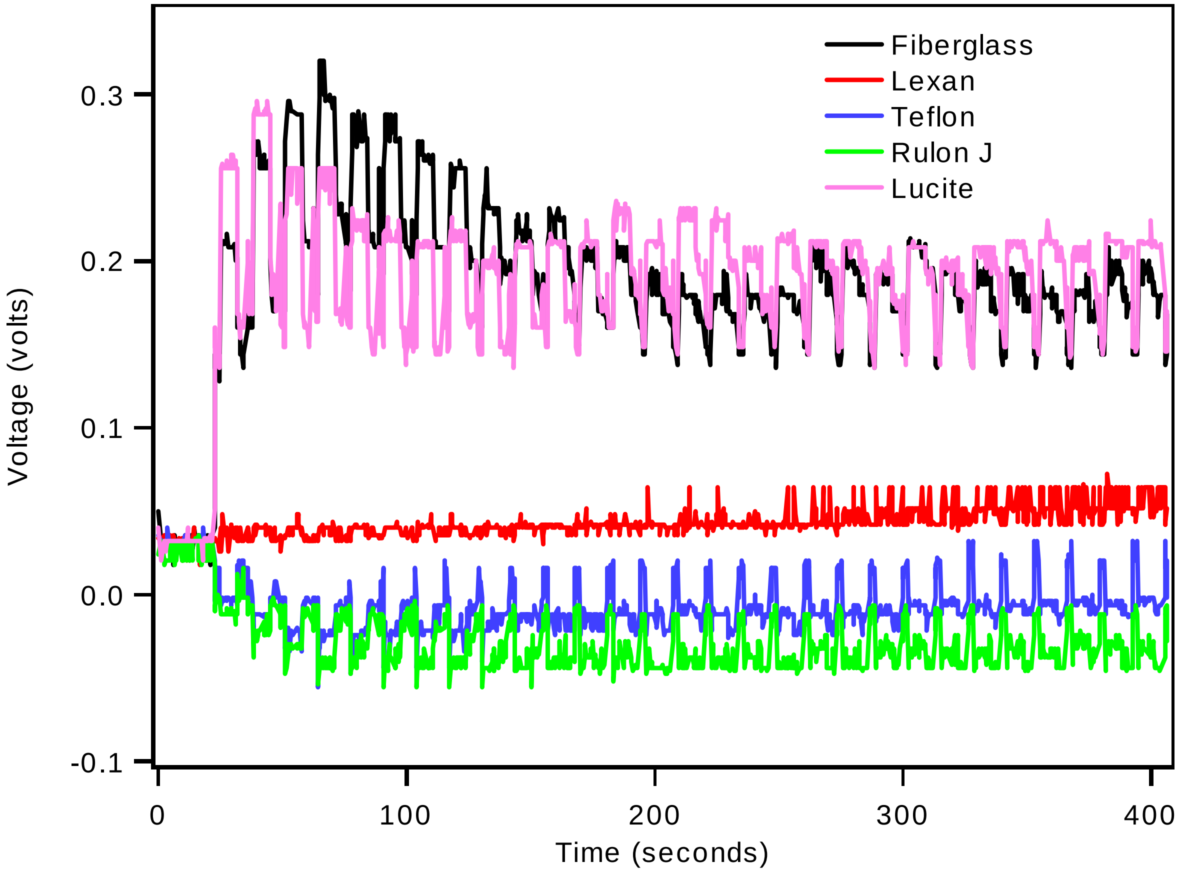


Figure 5. A typical experiment in which the MECA electrometer is rubbed repeatedly onto the JSC Mars-1 simulant at Martian atmospheric conditions at room temperature.

A closer examination of the charging process for Figure 5 is shown in Figure 6. Initially there is a background signal (~30 mV) before contact. At 18 seconds the electrometer is placed onto the soil simulant but no charge is detected due to simple contact. At 21 seconds the electrometer starts to be dragged over the simulant under its own weight for about 4 seconds. During this stage, charge, created by friction is exchanged between the polymer material and the soil. In many cases the particles adhere to the surface and the resulting charge layer is measured. Charge leakage into the bulk of the insulators may also be measured. However, the maximum amount of charge actually exchanged is not detected due to the charge double layer that is formed during contact.

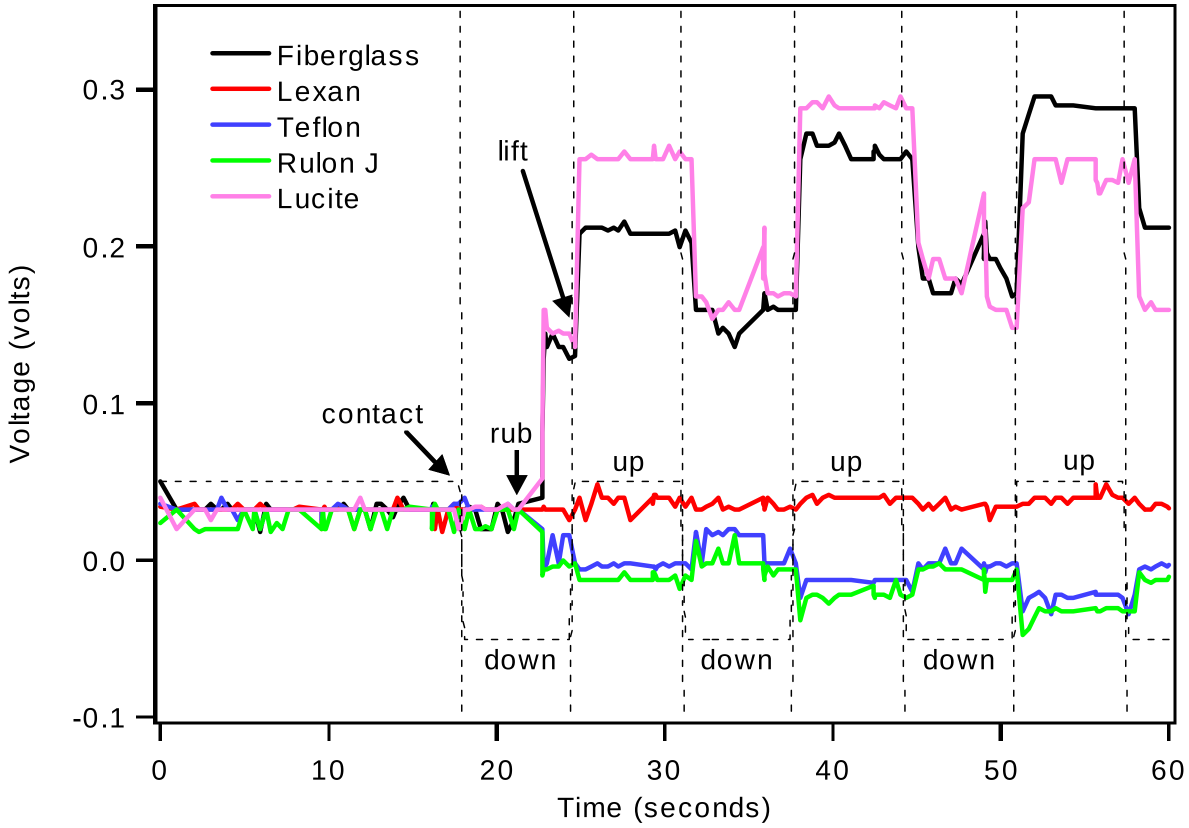


Figure 6. An explanation of the charging process for the MECA Electrometer. This is a blown up version of Figure 5. The dashed lines indicate electrometer contact (down) and non-contact (up) with the soil.

Once the electrometer is lifted from the soil, charge separation of the double layer takes place. Now the total amount of charge on the surface of the insulator is no longer masked by nearly equal amounts of charge on the surface. Again, once the electrometer is placed in contact with the soil at 31 seconds, the double layer is again formed and the combined electric field from the two layers cancels. The remaining charge detected has either made its way into the bulk, or is simply still attached to the particles adhering to the polymer's surface. The difference in voltage between contact and non-contact is referred to as the step voltage.

This process was repeated until the charge on the insulators remained unchanged. Note that only two contacts were needed to produce a significant change in the amount of charge on the surface. The background voltage, average voltage and its standard deviation, along with the step voltage are shown in Table 1 for the room temperature case of Figures 5 and 6.

Table 1. Electrometer rubbing results for simulant at room temperature under Martian atmospheric conditions.

Polymer	Background Voltage	Average Voltage	Standard Deviation	Step Voltage (+/- 0.05 Volts)
Fiberglass	0.0321	0.176	0.0186	0.06
Lexan	0.0316	0.0443	0.0077	0.02
Teflon	0.0318	-0.0075	0.0129	0.045
Rulon J	0.0266	-0.0310	0.0125	0.04
Lucite	0.0320	0.193	0.027	0.07

Generally speaking, a triboelectric series could be formed and the placement of the regolith simulant could be added. From positive to negative, the following arrangement is conceived: Lucite, Fiberglass, Lexan, Mars-1 Regolith Simulant, Teflon, and Rulon J.

Since the Electrometer will be unable to be cleaned and deionized once on Mars, another test was performed an hour later to allow the insulators time to discharge on their own without being cleaned. The results in Figure 7 show that even though there was significant charging, there may not have been enough time for complete discharge to occur.

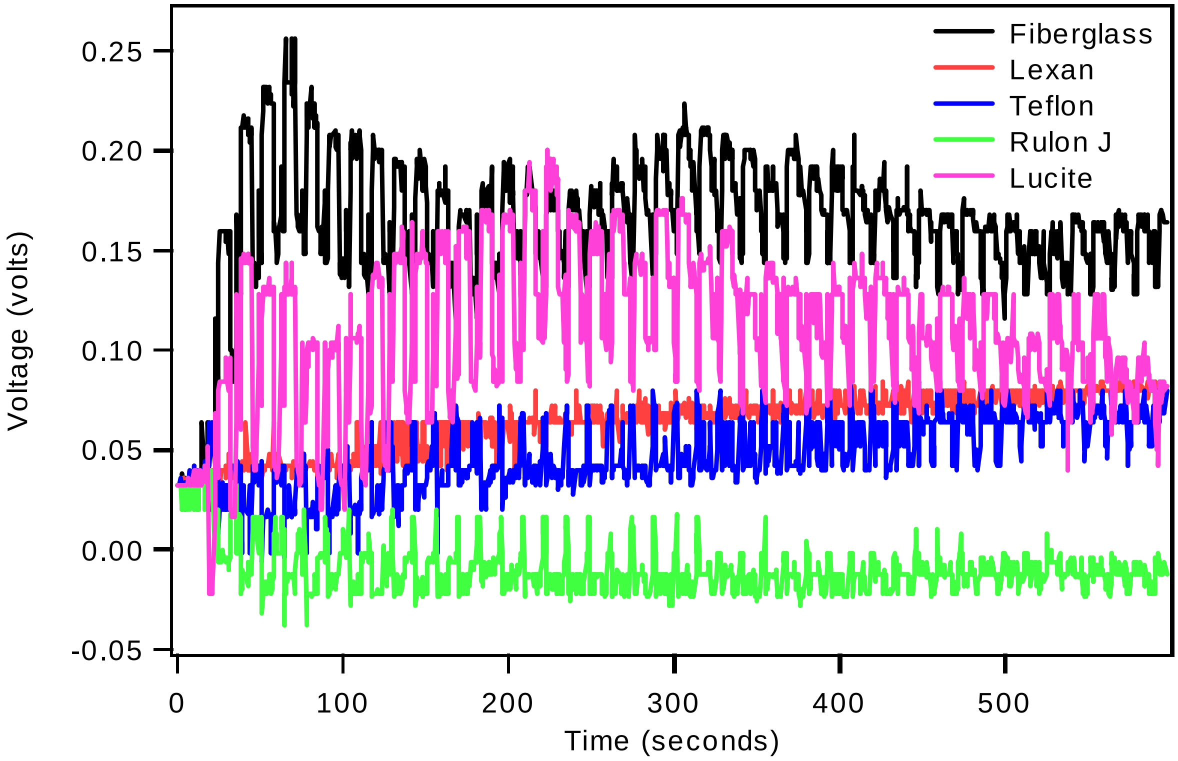


Figure 7. A second set of rubbing data one hour later than those shown in Figure 5. Here the electrometer was neither cleaned nor deionized.

This can be seen in the results of Table 2 that have the same general trend as in Figure 5 with a few small differences. It should be pointed out that in between sequential runs, the electrometer resets itself making all subsequent voltage measurements relative. Therefore, the slightly different magnitudes in Figure 7 (and Table 2) reflect the electrometer resetting itself without necessarily having the insulators totally discharged. In the future, longer time delays will be needed between experiments where cleaning and deionizing are not implemented.

Table 2. Voltage measurements taken approximately one hour after the initial results without cleaning or deionizing the sensors.

Polymer	Background Voltage	Average Voltage	Standard Deviation	Step Voltage (+/- 0.05 Volts)
Fiberglass	0.0319	0.167	0.025	0.05
Lexan	0.0318	0.064	0.0137	0.015
Teflon	0.0317	0.0496	0.0175	0.03
Rulon J	0.0251	-0.0104	0.0094	0.035
Lucite	0.031	0.1135	0.034	0.07

Notice that in the case above, Teflon has now charged slightly positive where before it charged slightly negative. This is perhaps due to not allowing enough time for the insulator to discharge itself before the second run. For example, Teflon finished the first run with an average voltage of –0.0075 V. This voltage remaining on the insulator for the next run became the background voltage +0.0317 V from Table 2. Therefore the change in voltage from +0.0317 V to +0.0496 V appears to be +0.0179 V. In reality the actual charge on the insulator should be calculated from the voltage –0.0075 V + 0.0179 V = +0.0104 V. This is still a significant *drop* in voltage when compared to the original background signal of +0.0318 V from Table 1. Thus Teflon is still charging negative.

It is important to note that the step voltages are fairly consistent, indicating that subsequent experiments may be reliable. This means that, as long as charge saturation is not reached, the magnitude of charge generated by rubbing is independent of the actual amount of charge remaining on the insulators from previous tests. Our experience indicates that it should be possible for repeatable order-of-magnitude average voltage levels to be seen in different sequential experiments provided that a fair amount of time is allowed between tests. Therefore reliable tests can be performed without cleaning or deionizing the insulators between subsequent rubs. This is crucial for flight criteria for our Martian instrument, which, due to power constraints during the mission, lacks cleaning mechanisms and high voltage corona sources to deionize the electrometer.

Low Temperature Results

Tests have also been performed at temperatures comparable to those lowest attainable on Mars. We have performed tests in which the soil was carefully dried as before, but placed in contact with a liquid N_2 cold plate. The temperatures quickly dropped below ~-100°C and the results are shown in Figure 8.

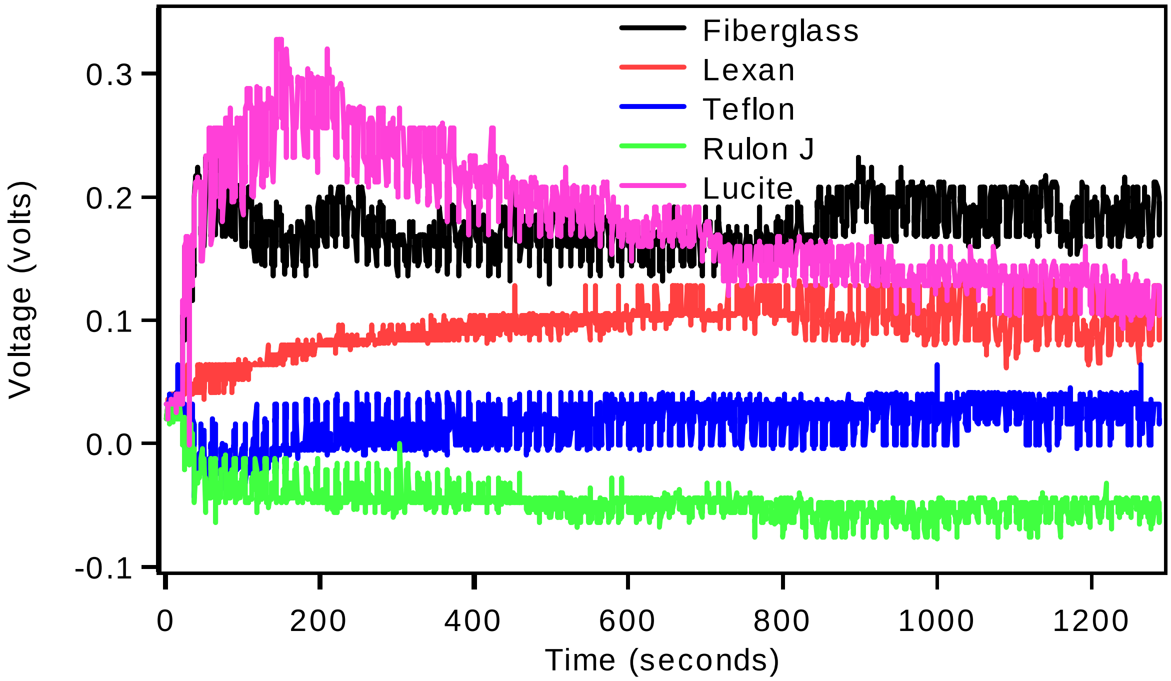


Figure 8. Electrometer rubbing test performed with cold soil at a temperature of about -100°C.

The results of Figure 8 are typical for low temperature data. Note that there is very little difference between the sign and the magnitude of charging for all of the insulators. The maximum amount of charge allowed by Paschen's Law for a metallic surface of area 0.28 cm^2 on the surface of Mars is calculated to be 5 pC (or 20 mV). However, the experiments above indicate that triboelectric charging is fully capable of producing charge in excess of about 75 pC (or 300 mV) on the *insulating* surfaces. The main reason why this occurs may be that some of the charge deposited onto the surface is no longer exposed to the atmosphere. If it were, the large electric field created by the charge would cause discharge to the atmosphere. In this case, charges deposited on the surface either propagate through the bulk material or become shielded by the electrostatically adhering dust particles. Therefore, in either case, the some of the charges are no longer exposed to the environment and are not subject to the Paschen limits.

There are limits to the amount of charging that can take place. Our observations show that charge deposited onto the insulators does not exceed 75 pC at Martian conditions. Therefore, Paschen's Law must govern the limit. Even though there is at present no theoretical relationship between of the amount of triboelectric charging of insulators and the Paschen curve, this work, as well as that of other experiments, clearly show that the maximum amount of charge deposited onto an insulating surface depends strongly on the Paschen limit [Matsuyama, 1995]. Once measurements are made on Mars, the maximum charging can be directly related to this limit experimentally. Thus, triboelectric charging provides an indirect measurement of the Paschen limit without the use of high voltage sources.

Conclusions

Several tests performed with the MECA electrometer have shown that it exhibits reliable, consistent behavior when triboelectrically charged against a Martian regolith simulant at a range of temperatures. The instrument should facilitate the characterization of the electrostatic properties of materials exposed to the soil on the surface of Mars. From the results obtained, a Triboelectric series with the simulant can be constructed. The repeated contact between the insulated-covered sensors and the soil will most likely induce the maximum charge per area allowed by the Paschen limit of the Martian atmosphere. The experimental evidence above shows that insulators can charge above the Paschen limit for metals under similar conditions. The charge deposited may reside inside potential wells and would require larger electric fields to be extracted.

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