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Paper Session I-A - Non-Ohmic Discharge Characteristics of the JSC MARS-1 Martian Regolith Simulant

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Charge Decay Characteristics of the JSC Mars-1 Martian Regolith Simulant

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Abstract: Studies of the voltage (charge) decay behavior of the JSC Mars-1 Martian Regolith simulant are presented for both moist and dry conditions in a simulated Earth/Mars environment. The results indicate that moisture content is the main driving force behind the form of the decay curve as well as temperature while atmospheric content and pressure play a little role. Dry simulant conditions act as well-behaved ohmic insulators with an expected exponential decay, while moist simulant possesses non-ohmic behavior decaying as 1/time. The decay relationships are derived from the experimental measurements of the current-voltage relationships. Some possible explanations of this behavior are discussed.

Introduction

Shortly before the launch of the Mars Pathfinder in 1997, scientists at the NASA Glenn Research Center decided to perform an experiment to measure the magnitude of the charge developed on the rover wheels by rubbing against the soil while roaming on the Martian surface. To their surprise, the voltage created by this rubbing or tribocharging measured 100-300 volts, a value that is higher than the Paschen discharge at Mars atmospheric pressure. To prevent an electrostatic catastrophe, the Jet Propulsion Laboratory added several discharge antennas to the rover to limit the potentials to acceptable levels. As a result, there were no voltage overloads and the Mars Pathfinder became the most successful Mars mission to date [1].

The Electromagnetic Physics Laboratory at the Kennedy Space Center has been testing and evaluating materials for NASA for over thirty years and the recent focus of the group has been testing and understanding the electrostatic properties of the Martian Regolith Simulant for future robotic missions to Mars [2]. Due to the dry Martian conditions and highly insulating properties of the Martian regolith, the success of any future manned/unmanned missions to Mars will depend on a full understanding of the electrostatic properties of the Martian soil. In particular, charge decay characteristics of the soil have never been measured. It has been proposed that even though lightning may not occur on Mars, corona fields may develop in its atmosphere, which will deposit hundreds of volts to its surface [3].

This paper is the first attempt at a complete study of the charge decay properties of the Martian Regolith Simulant. Here we show charge decay properties of the simulant under simulated Earth/Mars environmental conditions such as atmospheric content, pressure and temperature. It is shown that under certain conditions the soil behaves as an ohmic conductor while at other times it follows a quite different electronic behavior. This paper shows charge decay features under several conditions and attempts to provide insight into this behavior by looking at the current-voltage relationships.

Experiments

We used the JSC Mars-1, a Martian regolith simulant specifically developed for scientific research that is comprised of volcanic ash from Pu'u Nene, a cinder cone on the Island of Hawaii [4]. The simulant was chosen based on its spectral similarity to Martian material and its characterization match with actual Martian soil. The soil simulant is comprised of approximately 43% SiO₂, 23.3% Al₂O₃, 15.6% Fe₂O₃, 6.2% CaO, and trace amounts of TiO₂, MgO, and Na₂O. It has a density of 1.91 ± 0.02 g/cm³ and about 75% of the soil is larger than 149 μ m [4].

Preparation: Martian soil is extremely dry. In order to replicate the conditions on Mars, the soil must first be baked out to remove excess moisture. This is crucial for electrostatic measurements since water content increases conductivity. Therefore, the soil was kept above 160°C continuously to keep moisture from entering it. To prevent air/moisture from attracting to the regolith, most experiments were performed in a chamber at to 10⁻¹ torr and then backfilled with a 100% CO₂ gas atmosphere. This kept the relative humidity at or below 1%. There were, however, other measurements taken *without* completely removing the moisture in order to see the differences in the results.

Charge Decay Measurements: Charge decay measurements were performed with a JCI 155v4 Charge Decay Test Meter (Figure 1) [5]. This instrument is capable of depositing a large amount on charge to nearly any surface via a corona discharge. Applying a voltage in excess of 10,000 volts to small discharge points creates this corona. The corona ionizes the air and the ions find their way to the surface. Within a few milliseconds after charging occurs, the discharge points are removed exposing a field meter that measures the electric field present on the surface.

The JCI 155v4 is placed about 3mm away from the regolith, as shown in Figure 1. The apparatus is placed inside a large vacuum chamber and evacuated to remove excess moisture. The soil is placed inside a nine-inch metal dish with a thickness of about 2.5 cm which rests on a liquid nitrogen cold plate (not shown). The JCI is exposed to an area of 4.5 cm \times 5.5 cm and records the surface voltage immediately after the corona is applied.

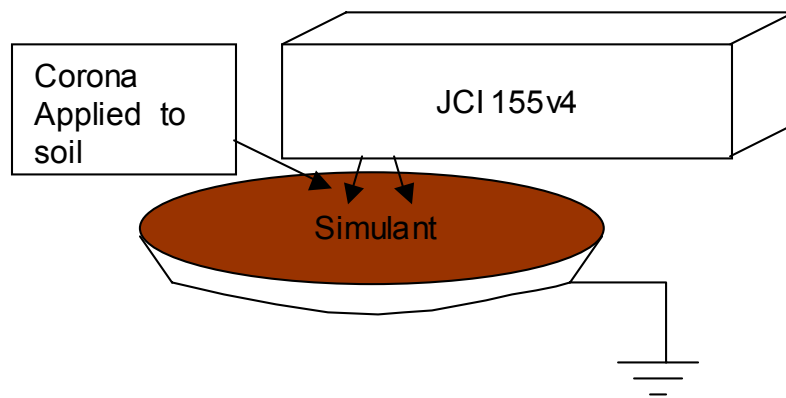


Figure 1. The setup for a corona voltage applied to the simulant. The JCI 155v4 applies up to 10,000 volts to the simulant and immediately records the resulting voltage remaining with a field electrometer.

Results and Discussion

Figure 2 shows the averages of several voltage decay curves at an atmospheric pressure of 7 torr CO₂. The JCI 155v4 provides up to 10,000 V from its corona but the soil surface only receives up to about 65 volts. This value depends on the number of ions present and on the mobility of these ions. At these low pressures, the surface voltage is lower due to the fewer number of ions present.

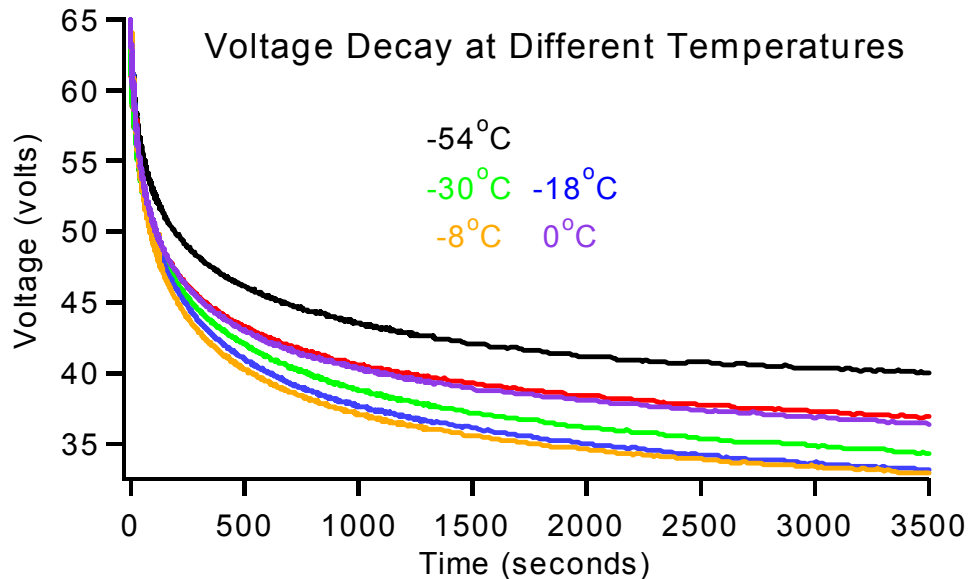


Figure 2. Average of many voltage decay curves at low temperatures under simulated Martian conditions.

After the initial corona voltage is applied, the system decays exponentially during the first 1000 seconds. Afterwards, the voltage appears to decrease linearly with time. However, there is dependence with temperature. Apparently at lower temperatures, the charge deposited onto the soil has a much more difficult time escaping the soil. At Martian temperatures (-54° C) and lower, the charge deposited on the soil remains for longer periods of time, suggesting that cold, dry conditions are worse for electrostatic hazards.

A common way to classify decay rates is the time τ required for the peak voltage to reach $1/e$ of its initial value, where τ is known as the decay constant. Average values of this decay time are shown in Table 1 for the various temperatures.

Table 1. Decay times τ for the voltage to reach $1/e$ of its initial peak voltage at different temperatures.

| Temperature | τ (sec) |
|-------------|--------------|
| -54°C | 62934.33 |
| -43°C | 51179.67 |
| -30°C | 38975.00 |
| -18°C | 34280.00 |
| -8°C | 29280.50 |
| 0°C | 30655.67 |

We notice that, in general, the decay times to reach $1/e$ increase with decreasing temperature. Again this behavior indicates that charge leakage through the soil becomes more difficult at lower temperatures and

that any charge deposited on the surface of Mars will stay for long periods of time, especially if the environment remains cold.

The next step is to understand how the decay curves derive their shape. For completeness, two data sets were taken at room temperature and room pressure as shown in Figure 3.

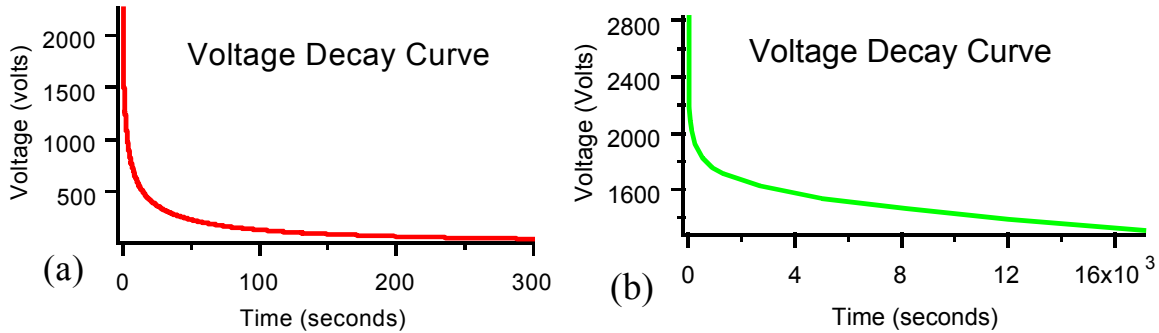


Figure 3. Decay curves for simulant prepared in different ways. (a) (red) represents soil not baked out beforehand while (b) (green) represents soil that was baked out beforehand.

Although the data was taken under similar conditions, the soil was prepared in very different ways. First the soil for curve (a) was taken from the container and placed inside the chamber. The chamber was then pumped down (to below 1 torr) and then backfilled with CO₂. The soil from decay curve (b) was baked out at temperatures over 200° C for several days and then placed in the chamber, pumped down, and then backfilled. The simulant that was baked out has a much larger decay time constant (~ 35,000 seconds) while the soil that was not baked out decayed very rapidly within the first 300 seconds. The voltage reading in soil 2 barely dropped below 1400 volts even after 16,000 seconds! This is due to the moisture content of the simulant. With added moisture, the simulant becomes more conductive, making it easier for the charge to reach ground while the simulant without moisture is highly resistive and large amounts of charge deposited onto the surface may even require several days to reach a value of ~100 volts.

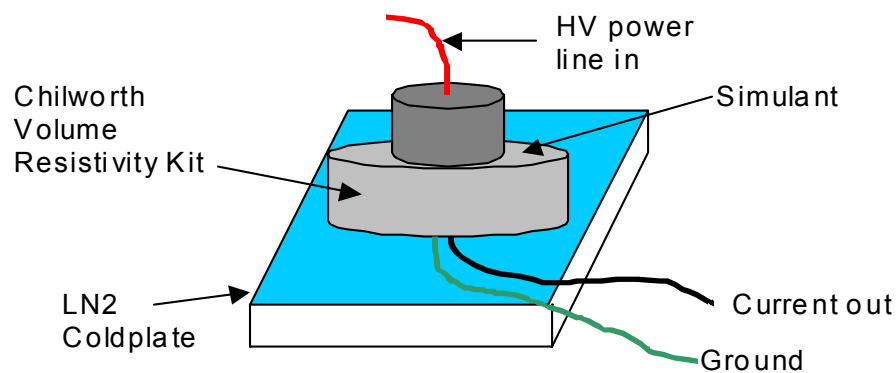


Figure 4. The Chilworth Volume Resistivity Kit. A high voltage (HV) line is fed through the top and any current that passes through the soil is read through a picoammeter (not shown).

Current-Voltage Measurements: To further understand the charge decay behavior one normally starts with a measure of the current-voltage characteristics of the material in question. Typical systems behave as ohmic conductors in which $I=V/R$. Replacing I with $-dQ/dt$ and V

with Q/C gives a standard charge (Q) decay relationship of $Q = Q_o \exp[-t/\tau]$, where $\tau = RC$ is the time constant and Q_o is the initial charge. To measure the I-V characteristics of the Martian simulant, a Chilworth Volume Resistivity Kit was used (Figure 4) [6]. A voltage is supplied to the simulant and the resulting current passing through the soil is measured by a picoammeter. The simulant acts as a capacitor while voltage is placed between the high voltage (HV) probe and the current plate that is insulated from ground. This system makes it not only possible to measure I-V relationships but also capacitance values for the simulant as well. The capacitance measurements were made simply by replacing the HV line with an RLC meter. The value for the capacitance with the soil was 7.5 pF while an empty container read 3.8 pF, giving a soil capacitance of 3.7 pF. The dielectric constant κ of the simulant is the ratio of the two measurements. We obtained a value of $\kappa \approx 2.0$, which is consistent with the literature [7].

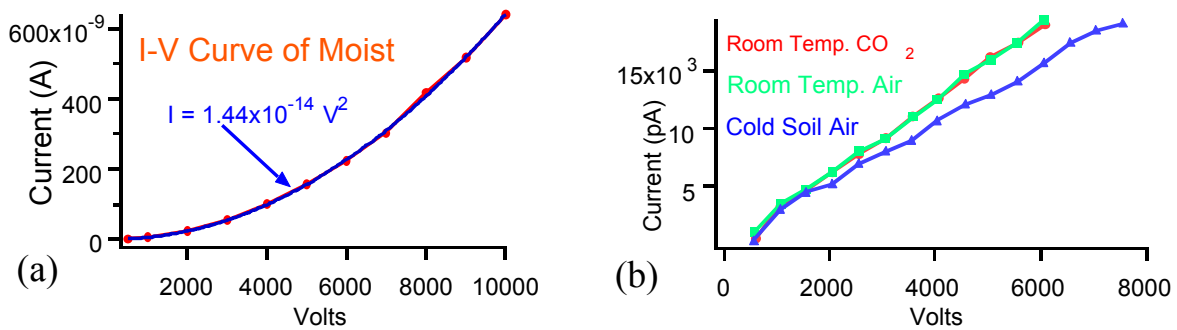


Figure 5. (a) The I-V curve for moist simulant (red) along with a best fit curve shown in blue. (b) I-V curves of dry simulant for three cases all at room pressure: room temperature simulant with CO₂ (red), room temperature simulant with dry air (green), cold simulant (-90° C) with dry air (blue).

Figure 5 shows the results of the current-voltage relationships for several cases. The first case (Figure 5a) is the I-V curve for moist soil at room pressure, temperature, and air (in red). The second graph (Figure 5b) shows the simulant under three cases all at room pressure: room temperature and CO₂ backfill (red), room temperature and dry air backfill (green), and cold simulant (-90° C) and dry air backfill (blue). The most notable difference is the magnitude of current for the separate cases. Relatively large currents are present in the moist soil of the order of hundreds of nanoamps while relatively small currents are present when the soil is dry (by baking for several hours) with currents of the magnitude of just a few nanoamps (or thousands of picoamps).

The next notable difference is the shape of the curves. The moist soil does not follow the typical linear behavior as the dry soil. Instead it follows a quadratic non-ohmic behavior (shown in blue). This behavior is common in electronic components such as diodes and inductors but is not generally seen in soils.

The dry soils in Figure 5b do indeed possess the linear behavior. The slope of best fit lines (not shown) gives the inverse resistivity. For the red, green, and blue cases respectively the volume resistivities are $1.2127 \times 10^{11} \Omega \cdot m$, $1.2224 \times 10^{11} \Omega \cdot m$ and $1.5065 \times 10^{11} \Omega \cdot m$, indicating the high resistance of the simulant. Notice that at lower temperatures the resistance increases as expected.

Knowing that an ohmic relationship is obeyed if the soil is dried out sufficiently, we can go back to Figure 3b and try to fit an exponential curve to it. Indeed, a fit to the decay curve of dry soil is exponential initially but turns to a linear decay with a slope of -0.023 V/s around 2000 seconds as in Figure 6b.

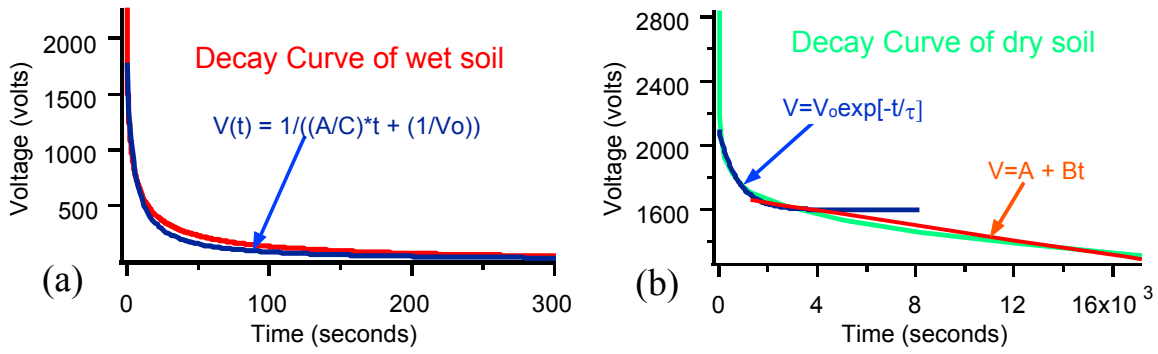


Figure 6. Decay curves from Figure 3 of both (a) wet (red) and (b) dry (green) simulant along with best fit curves. The colors match the curves with their equations.

It is not surprising that the decay time constant $\tau = 565$ seconds from the fit does not match the experimentally measured result $\tau = RC = (\rho/A)C = (1.2127 \times 10^{11} \Omega \cdot \text{m}/0.4 \text{ m}) \cdot (3.7 \times 10^{-12} \text{ F}) = 1.12$ seconds. It is very common in real systems that experimentally determined values of τ do not match the ones from the decay curve fit. However, it is enough to know that the decay *is* exponential in order to classify it as an ohmic conductor.

The wet soil on the other hand, does not follow an exponential behavior at all. Instead it seems to follow a $1/t$ behavior. This form of the decay can be derived by looking at the shape of the I-V curve in Figure 5a. The fit of the data in Figure 5a, shown as the blue curve in Figure 6a, has the form $I = AV^2$ with $A = 1.44 \times 10^{-14} (\Omega \text{V})^{-1}$. (Other terms in a polynomial fit are very small compared to the quadratic one). Using this form of the I-V relationship, the voltage decay with time curve can be found. Again, replacing I with $-dQ/dt$ and $Q = VC$, the voltage decay (not charge decay) now has the form

$$V(t) = \left(\frac{A}{C}t + \frac{1}{V_o} \right)^{-1} \quad (1)$$

where C is the capacitance of the soil and V_o is the initial voltage placed on the soil. Knowing the value of capacitance, A from the I-V fit, and the initial applied voltage, the voltage decay curve can be determined and compared with experiments, as in Figure 6a.

The fit to the decay curve gives a value of $A/C = 0.00011901$ and an error of 5.45×10^{-7} (not shown). This value correlates nicely with A measured from the I-V curve fit of $1.44 \times 10^{-14} (\Omega \text{V})^{-1}$ divided by the measured soil capacitance of $3.7 \times 10^{-12} \text{ F}$ which gives $3.7 \times 10^{-3} (\text{Vs})^{-1}$. The value of $1/V_o = 0.0005583 \pm 1.15 \times 10^{-6} \text{ V}^{-1}$ gives an initial surface voltage of 1791 volts compared with 2281 volts measured by the JCI 155v4. The fit is not exact but performs well above an exponential or power law fit. An exact fit would be extremely cumbersome considering the many complex factors such as temperature and pressure variations, soil packing, size and grain shape, actual moisture content, mineralogy composition, etc. We believe, however, that using the form of equation (1) and measuring A and the capacitance, a good fit to the voltage decay of wet simulant can be found.

The $1/t$ behavior is seen in polymers in which $I(t) \propto N(E) dE/dt$ where $N(E)$ is the density of trapped electron states with energy $E = k_B T \ln \nu t$ and $dE/dt = \nu k_B T / \nu t$ with ν being the escape frequency [8]. Using this formalism $I(t) \propto N(E)/t$ shows that a steady current decays with the inverse of time and the slope of this line can give the density of occupied electron states. What these states would actually represent in the soil has not been investigated and is beyond the present scope of this study.

It is interesting to note that these methods may be applied to future missions to test for possible moisture content on Mars. Even though there does not seem to be large amounts of water on the surface, small traces of water might be detected by simply measuring the soil's discharge and/or I-V characteristics. The simulant here on Earth can be prepared in such a way that moisture content can be directly correlated to I-V characteristics and thus measurements done on Mars can be compared with these characteristics.

Conclusions

It has been shown that the form of the voltage decay curves can be predicted by measurements of their I-V relationships. Whereas dry simulant possesses ohmic behavior in both the shape of the I-V curve as well as its decay curve, moist simulant does not behave as an ohmic system and has a decay curve that follows a $1/t$ form that can be derived from its current voltage curve.

In general, the soil on Mars should be very insulating under Martian conditions of low temperatures and very low humidities. Any charge deposited on the soil by natural phenomena such as corona discharge from the atmosphere, triboelectric dust charging by the Martian wind, or photoelectric charging by incident radiation, will remain on the surface for quite a long time. Therefore, knowledge of the decay times is crucial to the success of future missions.

It may also be possible to correlate I-V curves performed on Earth with future missions on Mars in order to estimate the amount of water content (if any) on Mars.

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