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Electric discharge in the Martian atmosphere, Paschen curves and implications for future missions

H.L.K. Manning [a,*], I.L. ten Kate [b,c], S.J. Battel [d], P.R. Mahaffy [b]

[a] Concordia College, 901 8th Street South, Moorhead, MN 56562, USA
[b] NASA Goddard Space Flight Center, Code 699, 8800 Greenbelt Road, Greenbelt, MD 20771, USA
[c] Goddard Earth Science and Technology Center, UMBC, Baltimore, MD 21228, USA
[d] Battel Engineering, Inc., 10020 North 58th Street, Scottsdale, AZ 85253, USA

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Abstract

Electric discharge between two electrically charged surfaces occurs at a well-defined, gas-dependent combination of atmospheric pressure and the distance between those two surfaces, as described by Paschen's law. The understanding of when the discharge will occur in the conditions present on Mars is essential for designing space-flight hardware that will operate on the Martian surface as well as understanding electrical discharge processes occurring in the Martian atmosphere. Here, we present experimentally measured Paschen curves for a gas mixture representative of the Martian atmosphere and compare our results to breakdown voltages of carbon dioxide, nitrogen, and helium as measured with our system and from the literature. We will discuss possible implications for instrument development as well as implications for processes in the Martian atmosphere. The DC voltage at which electric discharge occurred between two stainless steel spheres was measured at pressures from 10^{-2} to 100 torr in all gases. We measured a minimum voltage for discharge in the Mars ambient atmosphere of 410 ± 10 V at 0.3 torr cm. As an application, the breakdown properties of space-qualified, electrical wires to be used in the Sample Analysis at Mars (SAM) instrument suite on the Mars Science Laboratory (MSL) were studied.

Keywords: Electrical discharge; Mars; Atmosphere; Paschen curve; Space flight instrumentation

1. Introduction

In the recent years numerous missions have been and will be launched to the surface of Mars, including the 1996 Mars Pathfinder lander with the Sojourner rover (Golombek, 1997), the 2003 Mars Exploration Rovers (Squyres et al., 2004a,b), the 2007 Phoenix Lander (Smith et al., 2008) and the 2011 Mars Science Laboratory (Vasavada et al., 2006). One of the risks to rovers, landers, and instrumentation at the Martian surface is electric discharge between charged components within the hardware. Electrification is a fundamental process in planetary atmospheres throughout the solar system. Lightning discharge is the most obvious effect of electrification, but electrification also plays a role in the physical behavior of aerosols, cloud droplets, and dust movements (see the book *Planetary Atmospheric Electricity* (Leblanc et al., 2008) for an overview). Dust is a big part of the Martian atmosphere. In terrestrial dust devils, dust particles generate and transfer electric charge through collisions with each other and with the surface (Ette, 1971; Eden and Vonnegut, 1973; Farrell et al., 2003). In this process smaller particles get charged negatively and are eddied up in dust storms, whereas larger grains become positively charged and stay close to the surface (Ette, 1971; Gierasch and Goody, 1973; Melnik and Parrot, 1998; Farrell et al., 2003; Krauss et al., 2003). This displacement in grain charge types creates a dust storm-sized electric dipole moment and results in the development of coherently varying electric fields that extend well outside

* Corresponding author. Tel.: +1 218 299 3393; fax: +1 218 299 4308.
E-mail address: manning@cord.edu (H.L.K. Manning).

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the dust storm. Field strengths varying from 500 V/m at a distance of many 10s of meters from the features to 120 kV/m within the dust devil have been measured (Freier, 1960; Crozier, 1964; Jackson and Farrell, 2006). Simple saltating grains were found to generate electric fields exceeding 160 kV/m (Schmidt et al., 1998). These coherent electric fields from dust devils are not impulsive "discharge fields" or lightning, but long-lasting electrostatic fields associated with the build-up of vertical, well-separated charge centers in the feature. Discharges occur when these electrostatic fields become anomalously large creating "breakdown" conditions leading to increased impulsive electron flow. Using Earth as an analogy, it is anticipated that Martian dust storms will also be electrical in nature, as long as (1) vertical winds exist to mass stratify grains and (2) the lifted grains possess a variation in size and composition (required for efficient grain–grain charge generation Desch and Cuzzi, 2000). Both required conditions exist with the easily lifted iron/basalt grain mix on Mars. Melnik and Parrot (1998) modeled these electrical processes in dust storms and found that the macroscopic electrostatic fields within a Martian dust cloud could reach breakdown levels of ~20 kV/m. Farrell et al.'s (2003) analytical model compared the development of a terrestrial and Martian dust storm of similar size and found that both would ultimately develop comparable electric field strengths (>20 kV/m). Electric discharge in a dust-free gas or gas mixture occurs when a high voltage ionizes the gas, which then becomes conductive. An understanding of when this electric discharge will occur in the conditions present on Mars is essential for designing space-flight hardware that will operate on the Martian surface (Hillard and Kolecki, 1993; Ferguson et al., 1999). Although dust plays an important role in Martian atmospheric electricity, we focus this paper on the electric discharge in dust-free atmospheres only to emphasize that even within a spacecraft, at places not exposed to dust, electric discharge can be an issue at the Martian atmospheric pressure range.

Paschen published a paper in 1889 that set forth what is known as Paschen's Law (Paschen, 1889). This law states that there is a non-linear relationship between the minimum voltage required for electric discharge to occur and the pressure multiplied by the spacing between electrodes. The mechanism responsible for the breakdown is called Townsend discharge, where a very small amount of free electrons are accelerated by an electric field and collide with other molecules creating more free electrons causing a cascading effect (Osmokrovic, 1993). Paschen's law is illustrated in what are known as Paschen curves, graphs of breakdown voltage versus pressure × gap distance.

A Paschen curve for carbon dioxide indicates that the minimum breakdown voltage occurs at Mars surface pressures for an electrode gap on the order of a centimeter (Hackam, 1969a). Kolecki et al. (1991) proposed that the Martian atmosphere may have a breakdown voltage as low as 100 V. In the work published by Leach (1991), it was shown that adding as little as 0.1% Ar to Ne radically changed the breakdown voltage compared to either pure neon or pure argon. Since the Martian atmosphere is not pure carbon dioxide but has a small amount of argon, this work illustrates the necessity to investigate breakdown voltages in a simulated Martian atmosphere. Current designs for electrical components on spacecraft that will operate on the surface of Mars are based on estimations by either using curves for carbon dioxide or argon, but neither of these is representative of the breakdown characteristics of Mars atmosphere. Preliminary laboratory results have been presented by Buhler et al. (2003) comparing Paschen curves for carbon dioxide to a gas mixture representative of the Martian atmosphere (95.3% CO_2, 2.7%, 1.6% Ar, 0.13% O_2, 0.07% CO, 0.03% water vapor, and trace gases). However, although using symmetric electrodes, they found a strong polarity dependence. In the case of symmetric electrodes, reversing the polarity should not alter the effect on the electrons. It only reverses the direction of the electric field and changes the electrode emitting the electrons, and thus, the direction the electrons move. Therefore, the polarity should not affect the discharge curves. The Paschen curves in Hackam (1969a) do show a difference in polarity, which as he describes is most likely due to the difference in the electric fields around each electrode of the coaxial cylinders. These cylinders do not represent symmetrical electrodes. For asymmetrical electrodes, one would expect to measure a difference in breakdown potentials when reversing polarity (Chang et al., 1991).

The results presented here were obtained using two identical, spherical electrodes while the majority of previously published Paschen curves have been made using parallel-plate electrodes. Spheres were chosen because of the difficulty ensuring that flat plates remain absolutely parallel. Paschen curves of select pure gases were made with our system for comparison with previously published data. Additionally, since much of the pre-launch testing of hardware destined for the surface of Mars is tested in thermal vacuum chambers filled with nitrogen, we believe it is important to compare the Paschen curve of nitrogen to a gas mixture representative of the Martian atmosphere. Therefore, we have experimentally determined the Paschen curve for a gas mixture representative of the Martian atmosphere as well as for pure carbon dioxide, nitrogen, and helium. To validate our results, the pure gases are presented so they may be compared to previously published data (Hackam, 1969a; Hartmann et al., 2000).

In order to better understand the occurrence of electrical breakdown occurring in spacecraft hardware on Mars, a study of the breakdown properties of wires typically used on flight instrumentation was also undertaken. In general, pre-launch qualification of space-flight hardware is conducted in a pure nitrogen environment, which has different breakdown properties than pure carbon dioxide (Hackam, 1969a). Therefore, it is expected that nitrogen would also have different breakdown properties than the Martian atmosphere. The breakdown properties of flight hardware in more Mars-like conditions need to be understood to

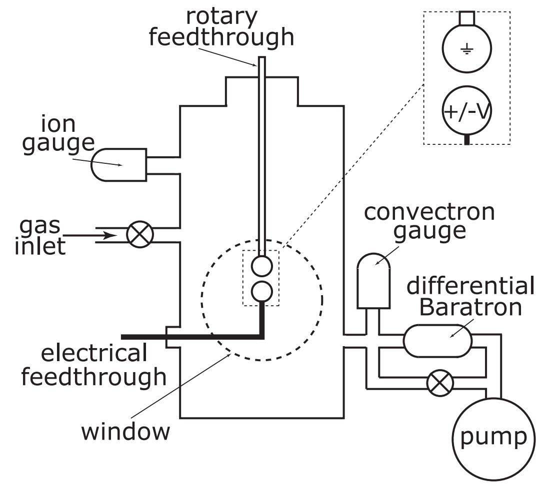

Fig. 1. Schematic of vacuum system used to measure electrical breakdown between two, 12.7 mm diameter 302 stainless steel spherical electrodes. The inset shows the polarity of the two spheres.

prevent hardware failure. The results of the study described here determine at what voltage wires of opposite polarity need to be in separate flight wire harnesses for both pre-launch testing and in operation on the surface of Mars.

2. Experimental setup

2.1. Experimental chamber

Paschen curves have been measured in a stainless steel chamber specifically designed for this purpose. A schematic of the vacuum system test facility that was assembled at NASA's Goddard Space Flight Center is shown in Fig. 1. The chamber was pumped by a drag pump, backed by a diaphragm pump (Adixen Drytel 1025). An ion gauge, a Convectron gauge, and a differential 100 torr Baratron gauge (range of 10^{-2}–100 torr) were used to determine the chamber pressure over many orders of magnitude with varying degrees of accuracy. Due to its gas dependency, the Convectron gauge could only be used reliably to measure air and pure nitrogen pressures. The residual pressure in the chamber was typically 8×10^{-6} torr. A 20.3 cm window was mounted onto the chamber to allow for visual monitoring of the breakdown.

2.2. Electrical system

A small electric circuit was developed to apply positive and negative voltages to the lower one of the two spheres, while the upper one was grounded (see Fig. 1). Fig. 2 shows a cartoon of the circuit, which consisted of variable voltage supply (positive polarity: Bertan PMT-50A/P (0–5 kV, 500 μA DC), negative polarity: Bertan PMT-20A/N (0 to −2 kV, 2 mA DC)), a couple resistors, a capacitor, and Ne bulb for overvoltage protection. An oscilloscope (Hewlett Packard 54601 A) and an analog ammeter were used to monitor when breakdown occurred as the applied voltage was increased. When breakdown occurred, the oscilloscope was triggered and showed a spike in voltage. At the same time the voltage was measured and recorded using a multimeter (Fluke 77 series). After a range of initial experiments it appeared the breakdown sometimes occurred before the scope was triggered, therefore an ammeter was added to the circuit. The ammeter responded on smaller changes in the current and therefore allowed for more accurate measurements of the breakdown voltage.

2.3. Spherical electrodes

Inside the chamber, two 12.7 mm spheres of 302 Stainless Steel were mounted. Sphere 1 was attached to a rotary feedthrough and was grounded (Fig. 1). Sphere 2 was attached to an electrical feedthrough to which a voltage was applied. Either a positive or a negative voltage could be applied to this sphere. Spherical electrodes were chosen because of the small test chamber and for simplicity in that they eliminate the co-planarity issues associated with parallel plates. The electric field varies with gap distance between spherical electrodes in a different way than between parallel-plate electrodes, which is shown in Fig. 3. Fig. 3A shows the shape of the electric field between two spheres at a

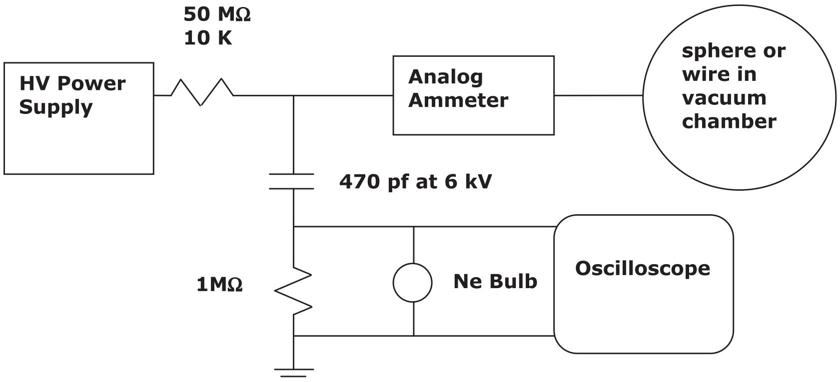

Fig. 2. Circuit diagram for monitoring the onset of electrical breakdown. Detection of electrical breakdown was monitored on both the oscilloscope and the ammeter.

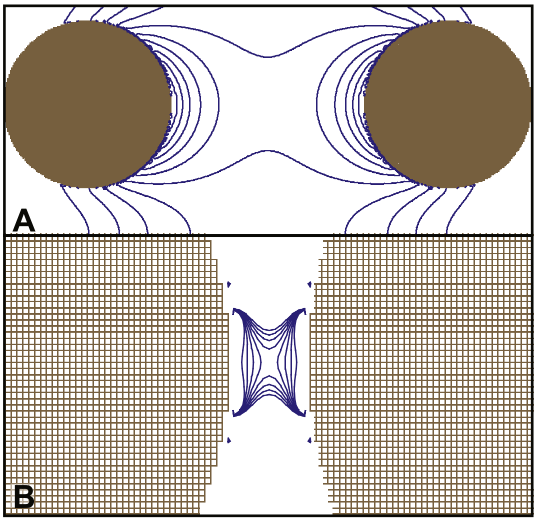

Fig. 3. Schematic model of the electric field between two spheres (A) at a large distance and (B) at distance small enough to resemble parallel plates.

distance of several cm, which is not at all constant. In Fig. 3B the same two spheres are shown, but at a much smaller distance, on the order of 1–2 mm. The electric field between the spheres at this distance is nearly constant and comparable to that between two parallel plates. To minimize the effects of the spheres and to simulate an electric field between parallel electrodes, the gap between the spheres was chosen to be 1.5 mm, because the electric field between the spheres at this distance does not vary from a constant value by more than 3% from the sphere surface to the center plane between the spheres. In addition, a 1.5 mm gap is a typical distance potentially found in a space-flight cable and provides a realistic test for that situation. This allows our data for pure gases to be usefully compared to previously published Paschen curves obtained with parallel-plate electrodes.

2.4. Space flight qualified wires

The integrity of the wires of type 22759/33, to be used in the Sample Analysis at Mars (SAM) instrument suite on the Mars Science Laboratory (MSL), was tested. These wires are AWG#26 silver coated high strength copper alloy conductors with single insulation cross-linked ethylene–tetrafluoroethylene. In order to simulate a flight harness, two bundles of wires were passed through a copper tube. One bundle of wires contained 18 wires (bundle #1) and the other contained 15 wires (bundle #2). The wires were randomly intertwined through the copper tube. Outside of the electrically grounded copper tube, the wires were separated and connected to two separate electrical feedthroughs.

3. Experimental procedure

The same experimental procedure was used for investigating breakdown for the spherical electrodes and the wires. Electrical breakdown was determined in pure carbon dioxide, nitrogen, helium and a gas mixture simulating the Martian atmosphere for both the spherical electrodes and the wires. The Mars atmosphere gas mixture, hereafter referred to as Mars gas, was created using a dedicated gas mixing system at NASA's Goddard Space Flight Center and consisted of 95.7% CO_2, 2.7% N_2 and 1.6% Ar of partial pressure by volume. The trace amounts of oxygen and CO that are present in the Martian atmosphere (and in the mixture used by Buhler et al., 2003) were not added to this mixture. Based on other work (e.g. Hackam, 1969a,b; Leach, 1991) it was anticipated that the trace amounts of Ar and N_2 in the predominantly CO_2 atmosphere of Mars would have the greatest effect on the voltage at which breakdown occurs and the trace amounts of CO and O_2 would have a minimal effect. Before the experiments, the chamber was evacuated. Gas was introduced through a valve while the pump was closed off. Experiments were conducted both at increasing pressures, starting at high vacuum, and decreasing pressures, starting with a chamber filled with the desired gas. To measure the breakdown voltage the chamber was first filled (or pumped) to a certain pressure and closed off; then the voltage on sphere 2 was slowly, manually increased until breakdown was indicated by an increase in current on the ammeter and a spike in the voltage displayed on the scope. This breakdown voltage was recorded, after which the voltage on the sphere was increased further to ensure that actual discharge was occurring. Then, the electrode voltage was reduced to 0 V, the pressure was increased (or decreased) and the procedure was repeated. Measurements were taken from 1×10^{-3} to 100 torr, which was sufficient to obtain a curve, to determine the lowest breakdown point, and to test the range of possible pressures that may occur on the surface of Mars.

4. Results

4.1. Spherical electrodes

Breakdown voltages for four different gases, He, N_2, CO_2, and Mars gas, were measured with the spherical electrodes 1.5 mm apart, at a range of pressures, and are shown in Fig. 4. CO_2 and Mars gas have comparable curves, suggesting that the addition of small amounts of N_2 and Ar does not considerably alter the discharge potential. Fig. 5 shows the effect of opposite polarity on the breakdown in the Mars gas. The similarity of the positive and negative data is expected and indicates the symmetry of the electrodes. The data show that for Mars gas the lowest discharge voltage occurs at a pressure between 0.1 and 10 torr. This means that at pressures of ~10 torr, a typical pressure on the surface of Mars, discharge could occur at a voltage difference of as low as ~400 V over distances around 1 mm. We measured a minimum voltage for electrical discharge in the Mars ambient atmosphere of 410 ± 10 V at 0.3 torr cm.

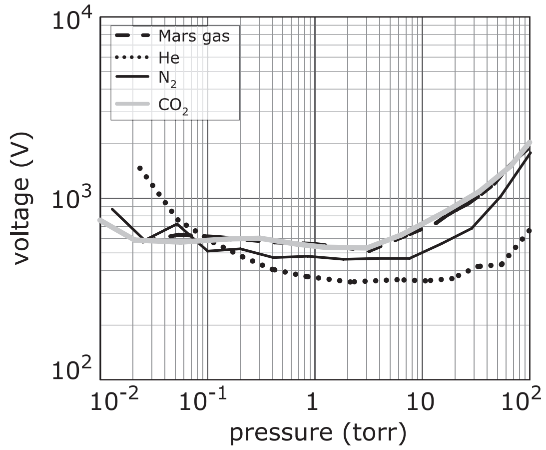

Fig. 4. Breakdown curves in pure CO_2 (thick grey line), pure N_2 (solid line), pure He (dotted line), and Mars gas (dashed line), for spherical electrodes.

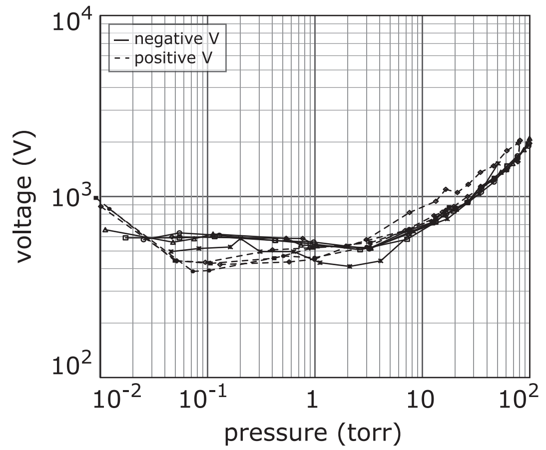

Fig. 5. Breakdown curves in Mars gas for spherical electrodes. The solid lines show breakdown for a positive voltage difference and the dashed lines for a negative voltage.

4.2. Space flight qualified wires

Two different experiments have been performed using the wires. In the first experiment bundle #1 was kept at ground and the voltage applied to bundle #2 was varied, both positively and negatively. To more closely simulate the conditions of the wire harness, both bundles were subjected to the same voltage but opposite polarity in the second experiment. The copper tube surrounding the wires was grounded in both experiments. Breakdown voltages in the first experiment, with the wires in bundle #1 grounded, were determined for both N_2 and Mars gas and are shown in Fig. 6. The data indicate that the breakdown voltage for the nitrogen is lower than for Mars gas and show the polarity comparison. The large difference in the nitrogen data between the positive and the negative polarity may be explained by the fact that the nitrogen data were obtained at the very end of the testing period after the wires had undergone substantial arcing. Aside from the offset in voltage, the plots of nitrogen data have the same general shape and the minimum occurs at roughly the same pressure. Fig. 7 shows the results of simultaneously applying a positive voltage to one bundle of wire and a negative voltage to the other. Data are shown for the breakdown properties for the Mars gas and CO_2 when a negative voltage was applied to bundle #1 and positive voltage to bundle #2. For the CO_2 environment, the opposite condition was created by applying a positive voltage to bundle #1 and negative voltage to bundle #2. This graph shows that (i) the different polarity configurations for CO_2 and (ii) the Mars gas and CO_2 data for the same polarity configuration are comparable. This implies that reversing polarity would have the same effect in Mars gas.

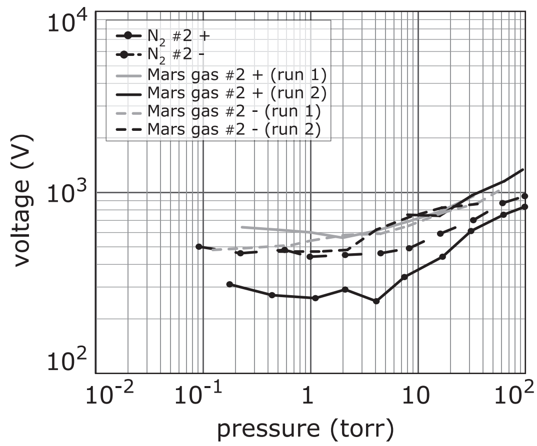

Fig. 6. Breakdown curves in N_2 (lines marks with dots) and Mars gas for space flight qualified wires. Potential differences are created by keeping bundle #1 at ground and bundle #2 at a positive (solid line) or negative (dashed line) voltage.

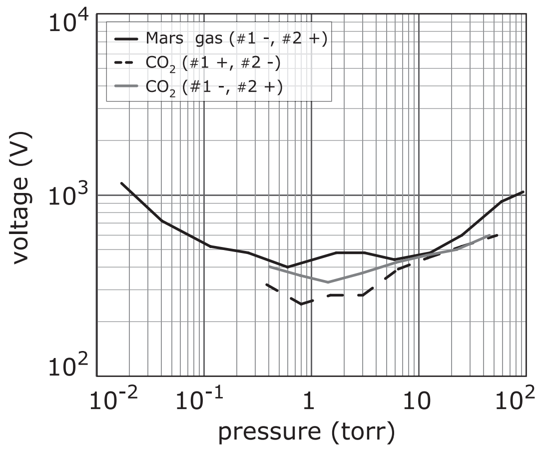

Fig. 7. Breakdown in Mars gas and CO_2 for space flight qualified wires. Potential differences are created by applying the same voltage, but with different polarity to bundles #1 and #2. The solid line shows breakdown in Mars gas with a negative voltage on bundle #1 and a positive voltage on bundle #2. The thick grey line shows the same voltage scenario but in CO_2. The dashed line shows breakdown in CO_2 with a positive voltage on bundle #1 and a negative voltage on bundle #2.

Following the testing of the wires in the vacuum chamber, they were removed and inspected. Dark spots seen in Fig. 8 were observed in many places along the wires. On

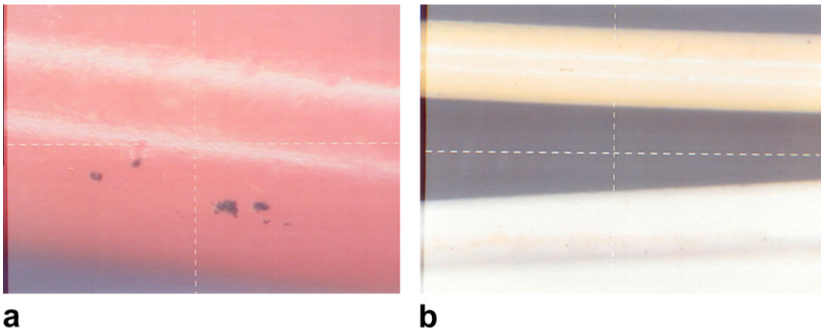

Fig. 8. Images of the wires obtained with a microscope after removal from the vacuum chamber. (A) A close up of the dark spots indicate places where discharge occurred. (B) The brown smear along the white wire. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

some of the lighter colored wires, lighter brown smears could be seen along the length of the wires in addition to the dark spots. Besides the visual observations of the wires, evidence of the damage done to the wires could be felt as one ran their fingers down the length of the wires. In the region where the copper tube surrounded the wires, they were a bit rougher and at the ends where the wire bundles were separated, the wires were smoother.

5. Discussion

The results of the tests using the spheres are comparable to existing data (Hackam, 1969a; Hartmann et al., 2000). The data described in this work show a less sharp increase in breakdown voltage when the pressure drops below 0.01 torr. The minimum breakdown voltage for CO_2 in our experiments was of the same order of magnitude and occurred at the same pressure as Hackam's (1969a) CO_2 data. The breakdown voltage for our Mars gas data followed very closely to that of our CO_2. The breakdown voltages for He and N_2 in our experiments were slightly higher, though of the same order of magnitude as the earlier data (Hackam, 1969a; Hartmann et al., 2000). The difference between our data and existing data is caused by a few factors, including different geometries (two spheres in our case versus two concentric tubes in Hackam's (1969a,b) work) and the continuous use of the spheres, without polishing in between experiments. The approach of reusing the same spheres without polishing after each measurement was chosen because "flight-like" scenarios were being investigated in this study.

To realistically simulate the use of wires in space hardware, only one set of wires (consisting of bundle #1 and bundle #2) was used. These wires were not cleaned or taken out of the setup during the tests. Therefore the same wires were subjected to all tested conditions. The more arcing they endured, the lower the minimum breakdown voltage needed as the dielectric insulation surrounding the wires became compromised. For the space-qualified wires, the breakdown voltages in nitrogen are much lower than the breakdown voltages in Mars gas. This correlates with the breakdown behavior observed with the spherical electrodes, but also can in part be due to the deterioration of the dielectric sleeve surrounding the wires. The nitrogen data were obtained after extensive testing was done in other gases.

The wires were tested just like the spheres by exposing them to a certain gas pressure and then increasing the voltage until breakdown occurred at that pressure. Measurements were made at a range of pressures with the wires subjected to one polarity. Then, the chamber was evacuated and the same protocol was followed for the other polarity. In a few cases, both polarity tests were conducted in immediate succession; while in other cases the system was left for a few days between the two tests. It was observed that the breakdown voltages for the wires would be much lower in the second polarity test when both tests were performed immediately after each other. However, when the system was left alone for several days between the two polarity tests, the voltage of breakdown in the second test was higher than in the first. Following an arc, charges were deposited onto the wires, but were slow to bleed off because of the high insulating property of the dielectric sleeves around the wires. The presence of these additional charges required a lower voltage to cause breakdown for the opposite polarity.

6. Conclusion

Using a dedicated simulation facility we measured a minimum breakdown voltage for electrical discharge in a Mars-like atmosphere of 410 ± 10 V at 0.3 torr cm, in the case of symmetrical spherical electrodes. These experiments furthermore illustrate that for symmetric electrodes, reversing polarity has minimal if any effect on the voltage when electrical breakdown occurs. Comparison of our He, N_2, and CO_2 results with previous work (Hackam, 1969a; Hartmann et al., 2000) suggests that the discharge voltage for Mars gas measured in the experiments described here is an upper limit and that in the case of a very clean system and well-polished electrodes the values may be even lower. Our results, however, may be more typical for materials used on a spacecraft. Future work should explore how this behavior changes in a dusty environment typical of the Martian surface.

To understand the limitations that electrical breakdown poses on space-flight hardware an experiment was performed in which space flight qualified wires were subjected multiple times to voltages of different polarities inducing breakdown. Testing of the flight wires 22759/33 indicate that for pressures of 5–12 torr, the conditions typical for possible MSL landing sites, the wires will not breakdown unless a potential difference of greater than 400 V occurs. Flight hardware may have components with potential differences greater than 400 V such as an RF power supply for a quadrupole mass spectrometer (up to 1200 V) or an electron multiplier (up to 3500 V), but these are always shielded to prevent electrical breakdown. The results of this experiment imply that flight electronics should be designed such that bundled wires do not exceed an absolute potential difference of more than 400 V when operating in the Martian environment. When the potential difference exceeds this value, the wire bundles of positive and negative polarity need to be separated in different harnesses.

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