Dust Abrasion Damage on Martian Solar Arrays:

Experimental Investigation and Opportunity Rover Performance Analysis

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Abstract

Here we investigate the effects of erosion and weathering that occur on epitaxial lift off triple-junction cover-glass interconnected cells (CICs) after exposure to Mars dust storm conditions. The durability of these materials in a Martian environment is not well characterized so we perform analogous experimentation. To replicate the dust impingement, test coupons were placed in an enclosure and sandblasted with Mars dust simulant. We show the J-V response dependency on both incident angle and exposure times. We employ data-driven modeling to quantify the soiling contribution and power degradation of the photovoltaic cells on Mars through analysis of 4.95 Martian years of report-out power conditions from the Opportunity rover. We find that atmospheric dust suspended due to a weather event does not result in instantaneous settled dust on the PV cells. We calculate via autocorrelation function that the dust settling rate is approximately 21 Sols from atmospheric dust suspension. The findings presented here deliver a realistic approximation for the insolation values and subsequent PV power expected over time on the Martian surface thus informing future dust abatement systems.

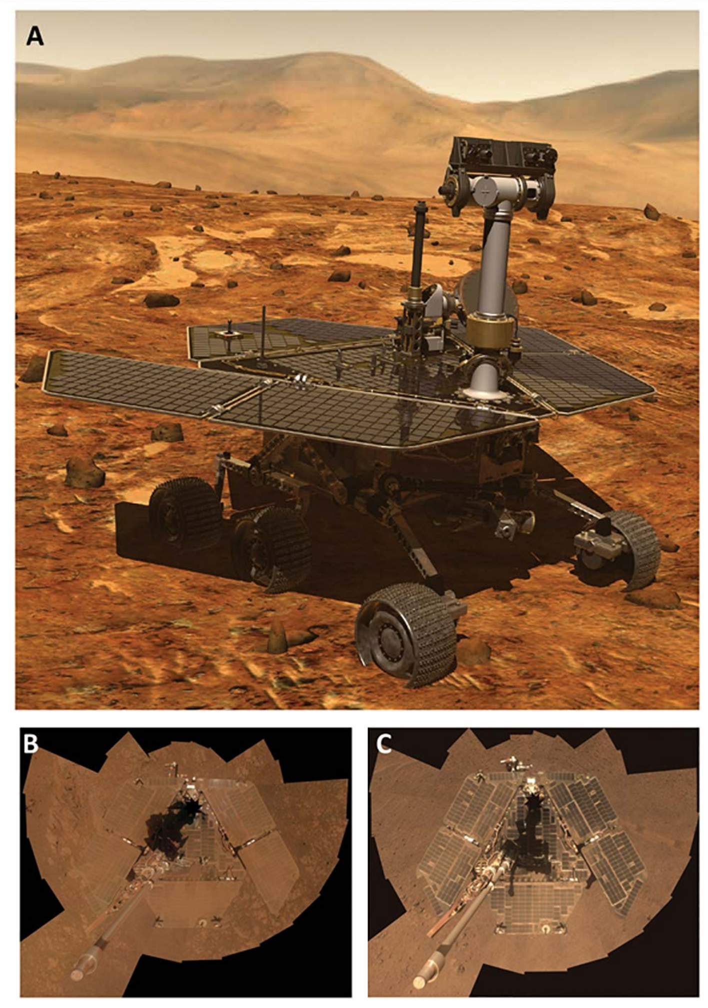

Figure 1. A) Artist rendering of Opportunity[1], a robot geologist rover. **B)** Opportunity selfie taken January 3-6, 2014 with significant dust cover.[2] **C)** Selfie taken March 22-24 2014 after a series of wind events that cleaned accumulated dust off the rover's solar panels.[3]

Computational Data Analysis

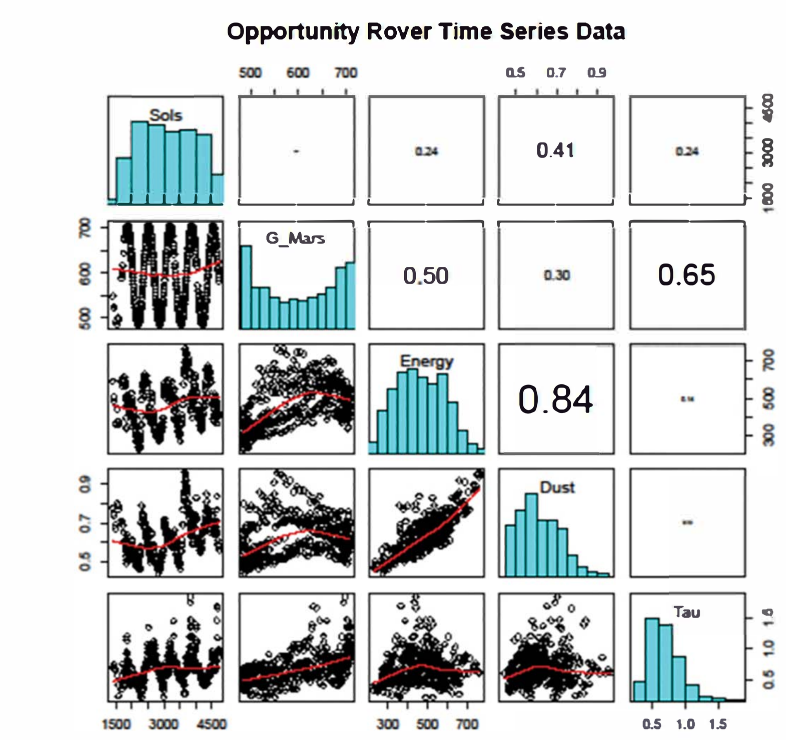

Figure 2. Pairwise scatter plot and correlation matrix for the four variables extracted from the published dataset for the Mars Opportunity Rover.

419 complete rover field data points spanning 4.95 Martian years are shown in Fig 2. The correlation between energy generated and the dust factor is very strong at 0.84 indicating that the data are largely governed by the settled dust on the panels. However, the energy variable is not highly correlated with Tau, the optical atmospheric density. Slewing the Tau data vector compared to the energy and dust vectors (Fig 3a) suggests the atmospheric dust settling time is approximately 21 days for 70% of weather events. A year-on-year approach was employed to remove seasonality and yields 95% confidence the degradation rate is below 23% per Martian year (Fig 3b).

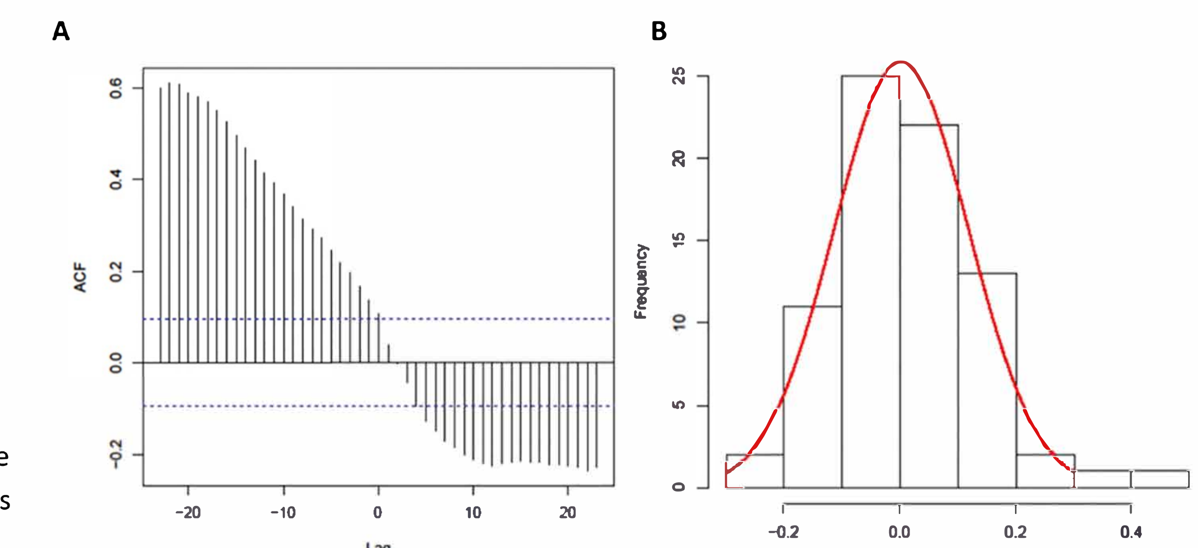

Figure 3. A) A plot of the autocorrelation function between the dust factor and Tau as a function of daily slewing. Note the highest correlation value is 0.6 at T-21 Sols. **B)** A plot of the distribution of slopes from daily energies at similar orbital positions.

Experimental Design

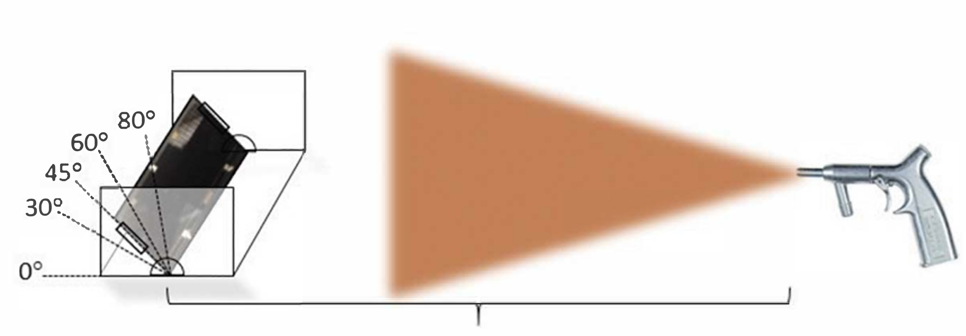

Figure 4. Dust Abrasion experimental setup

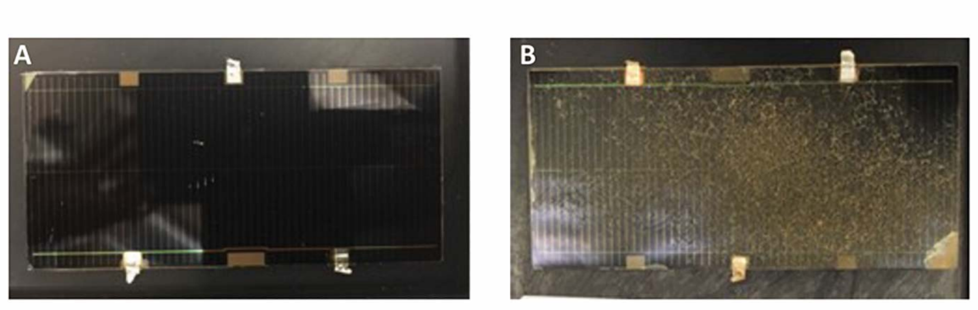

Figure 5. MicroLink Devices IMM 3J CIC **A)** pristine and **B)** post abrasion for 5 minutes at 80 degrees angle of incidence.

Experimental Data Analysis

In the instance of a constant 45° angle with varying exposure time we see increased reflectance from 450-650nm (Fig 6a) and consequently a reduced normalized J_{SC} (mA/cm^2) in those devices (Fig 6b). In all cases, after dust removal the cells optical performance (dashed lines) returns to initial behavior, confirming the optical losses are solely due to the presence of dust adhered to the cell surface. We probe the case of a 5 minute exposure time at varying angles (Fig 6c) CICs closer to normal to the dust nozzle (80°, 85°) display the greatest increase in reflectance and after dust removal they maintain a significant amount of dust, potentially embedded in their surface. JV characteristics suggest that 45° and 60° are the most dust resilient orientations for arrays (Fig 6d)

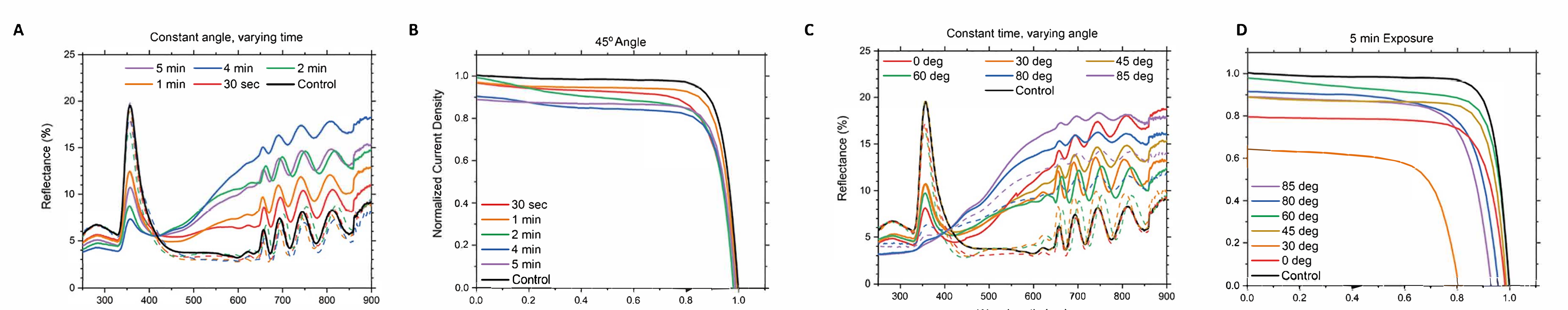

Figure 6. A) Reflectance spectra after dust exposure (solid) and post-dust removal (dashed) and **B)** J-V characteristics of CICs after exposure to dust abrasion at 45° angle of incidence for varying times. **C)** Reflectance spectra after exposure (solid) and post-dust removal (dashed) and **D)** J-V characteristics of CICs after exposure to abrasion for varying angles at 5 minute exposure time with inset of cell orientation to dust flow.

Investigating Permanent Damage

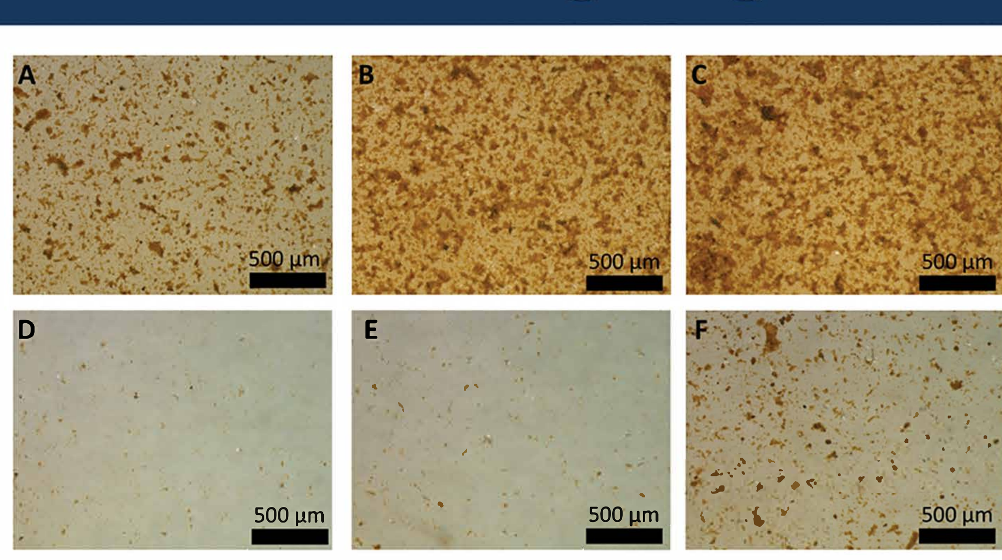

Figure 7. Optical microscopy of glass slides exposed at 45° angle to 4 PSI dust abrasion (A-C) for **A)** 1 min **B)** 3 min and **C)** 5 min dust exposure times and each respective sample post wipe clean (D-F).

The change in maximum power output for each CIC (pristine vs post sonication) is found to be 15.9± 6.4 percent, yielding a maximum degradation of 22.3% which is in agreement with the year-over-year limit of 23%.

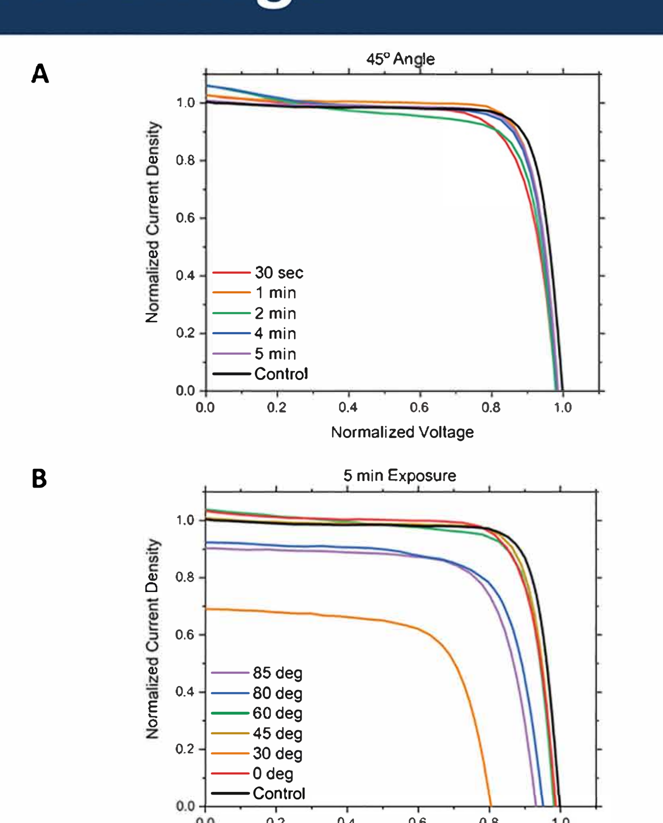

Figure 8. Normalized J-V characteristics of CICs after sonication cleaning in the case of cells exposed to dust at **A)** 45° angle of incidence for varying time and **B)** varying angles at 5 minute exposure time.

Conclusions

- First experimental study of ELO 3J CICs performance in Martian Dust Storm Environments
- Operational cells on Mars experience a 21 Sol lag for dust settling post severe weather event.
- The presence of dust on cell surface results in increased reflection in visible wavelengths 450-650nm
- Optical losses due to presence of Mars dust are reversible if the cells incident angle is <80° .
- Cells with exposure angles ≥ 80° will require the development of a more rigorous dust protocol to recover optical performance, as the dust becomes imbedded in the cell and cannot be removed.
- Opportunity data analysis suggests maximum power output degradation rate of cells on Mars is below 23% per Martian year. This value is verified by dust exposure experiments power degradation not exceeding 22.3%
- We recommend solar array's for Mars be designed from 45-60° angle of incidence as these storms are most dust resilient in simulated dust storm conditions.

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