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. To replicate the dust impingement, test coupons were 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 determine a performance degradation rate that is consistent with zero within uncertainty. We quantify the soiling contribution and power degradation of the cells on Mars through analysis of 4.95 Martian years of report-out power conditions from the Opportunity rover. We calculate via autocorrelation function that the settling rate of atmospheric dust suspended due to a weather event is approximately 21 Sols from 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.**

***Index Terms* — photovoltaic cells, III-V semiconductor materials, dust mitigation, Mars, solar cell durability**

I. INTRODUCTION

The atmosphere of Mars contains suspended dust, the amount of which varies, increasing when global or local dust storms raise dust into the atmosphere and decreasing in mild conditions.[1] The levels of dust suspended in the atmosphere rarely reach zero. These conditions pose concerns for the operation of solar cells, the selected power source for existing and future missions for Mars exploration. [2-4] The first concern raised is effects of erosion and weathering on cover-glass interconnected cells (CICs) that are exposed to a dust storm, the second concern is cell power output under reduced flux due to dust accumulating on the cell surface and reduced insolation due to atmospheric dust. This investigation addresses both concerns through data-driven modeling and analogous experimentation.

Extended observation of the Martian rover's field data were conducted in attempt to extract figures of merit based upon weather related insolation event forecasting and modeling of possible cell degradation rates. Efforts to quantify the soiling contribution and possible power degradation of PV cells on Mars through analysis of the report out of power conditions from Opportunity revealed the need for an experimental simulation of weather events to uncover latent factors impacting cell performance. We simulated the effect of Mars dust storm conditions at a CIC level to develop better predictions of Martian-weather-related PV performance.

II. METHODS

We utilized a dual thrust effort employing both computational and experimental investigations to explore the effects of Mars dust on CICs performance.

A. Computational Data Collection

All of the Mars rover field data were mined from publicly available sources using a custom web-scraping script written in 'R'. Up to date data were obtained from MER-JPL website and sister pages. Here the data include the total daily energy, measured in watt-hours, atmospheric opacity (Tau,) which is a quantification of the amount of the atmospheric dust present, as well as a "dust factor" or measure of the settled dust on the rover's PV cells. Data were post-processed to seek the string literals, "watt-hours", "Sols", "Tau", and "Dust Factor", to mine the variables nearly daily. Ultimately, after data cleaning we found 419 data points representing a daily solar energy, day in Sols, dust factor, and Tau and spanning 4.95 Martian years. The vectors were then assembled into a matrix, also known as a data frame, so that each index value is associated with its date, in Sols.

A year-over-year approach was applied to the data as an alternative method to reduce the inherent seasonality impacts. This method was developed by reliability researchers at SunPower for terrestrial power plants and involves plotting the daily energy in watt-hours for every specific day over the entire multi-year dataset, fitting the data with a line and building a distribution of the linear slopes.[5] Thus, the data for every January 1 are plotted and fitted (requiring at least 3 years of data, preferably much more) then every January 2, and so on for every day of the year, leading to 365 slopes for a terrestrial distribution analysis. In our case, the Martian year is 669 Sols, so the dataset covers 4.95 Martian years. A modified algorithm plot and fit the energy the energy data for every 669 Sols and captures the slope for that distribution. The data can be sparse and in the case that two Sols that exist in the same orbital position cannot be found then the data cannot be fit by a line and is ignored. Ultimately the algorithm found 76 slopes out of the possible 669 from our data array of 419 dates.

B. Experimental

Mid-range performing epitaxial lift off (ELO) triple-junction solar cell CICs were purchased from MicroLink Devices. This investigation aimed to understand changes in performance due to dust impact so cell selection was based largely on cost, and not on optimal pre-exposure performance. All samples optical and electrical performance were measured prior to and immediately following exposure to Martian dust storm conditions. Reflection spectra were measured using a Perkin Elmer Lambda 950 UV-Vis Spectrometer. The current-voltage characteristics of the devices were measured under AM0 conditions with an X25 triple source solar simulator. To obtain results most representational of in-situ CIC performance we did not remove any dust that adhered to the CIC, only loose dust resting on the CIC is removed by inverting the CIC before reflection spectra and J-V characteristics are measured.

Landis et al. estimated weather conditions on Mars including wing dust strength, and informed selections on expected technologies to be used in future missions [6]. A benchtop sandblasting cabinet was used with Martian Simulant JSC1a as the blasting media to replicate dust impingement.[1] Cells were mounted using a sample holder laser cut from acrylic to fix the samples position at the desired angle and a constant working distance (18 cm) with respect to the sand-blaster nozzle during testing as shown in Fig 1. Exposure time, angle, and flow pressure were varied.

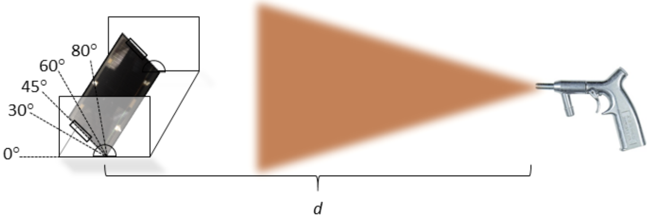

Fig. 1. Dust abrasion experimental setup.

There are two categories of losses in solar cells, optical and electrical. Optical losses result in a reduced short circuit current (J_{SC}) and are caused by reflection, shadowing by top contacts, and incident radiation not being absorbed. Electrical losses are more complex and can result in a reduced open circuit voltage (V_{OC}) due to carrier recombination, or fill factor (FF) from series Ohmic losses. Presently, the solutions to mitigate the optical losses due to reflection include anti-reflective coatings (ARC), and surface texturing. The cells used in this study have ARC, however it is anticipated that the exposure to Martian dust abrasion will damage or fully remove these coatings. By analyzing the resulting J-V characteristics of the devices post abrasion, we will be able to pinpoint which specific losses, if any, occur. We can therefore apply this knowledge towards implementing methods to suppress losses and better maintain power conversion efficiency during device operation in Martian environment.[1]

$$\eta_P = \frac{P_{max}}{P_{in}} = \frac{J_{SC}\times V_{OC}\times FF}{P_{in}} \qquad (1)$$

III. RESULTS AND DISCUSSION

A. Computational Data Analysis

The cleaned data are shown in Fig. 2 as a pairwise scatter and correlation matrix. This figure is described in detail in the caption.

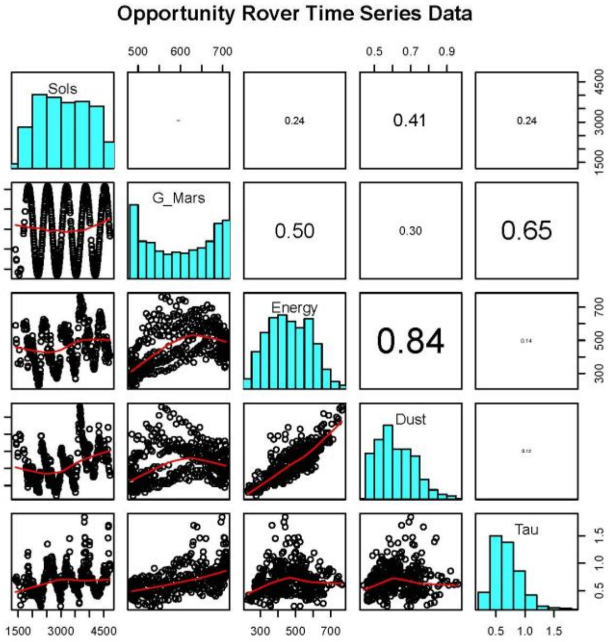

Fig. 2. A pairwise scatter plot and correlation matrix for the four variables extracted from the published dataset for the Mars Opportunity Rover. The variables and their histograms are shown along the diagonal of the matrix, with the scatter plots for each variable-variable relationship shown below the diagonal, and linear correlation coefficients corresponding to those scatter plots above the diagonal. The scatter plots are plotted such that the x-axis is the corresponding variable in the column of the plot, and the y-axis is the variable in the same row as the plot. The font size of the correlation matrix is linked to the value of the correlation coefficient itself.

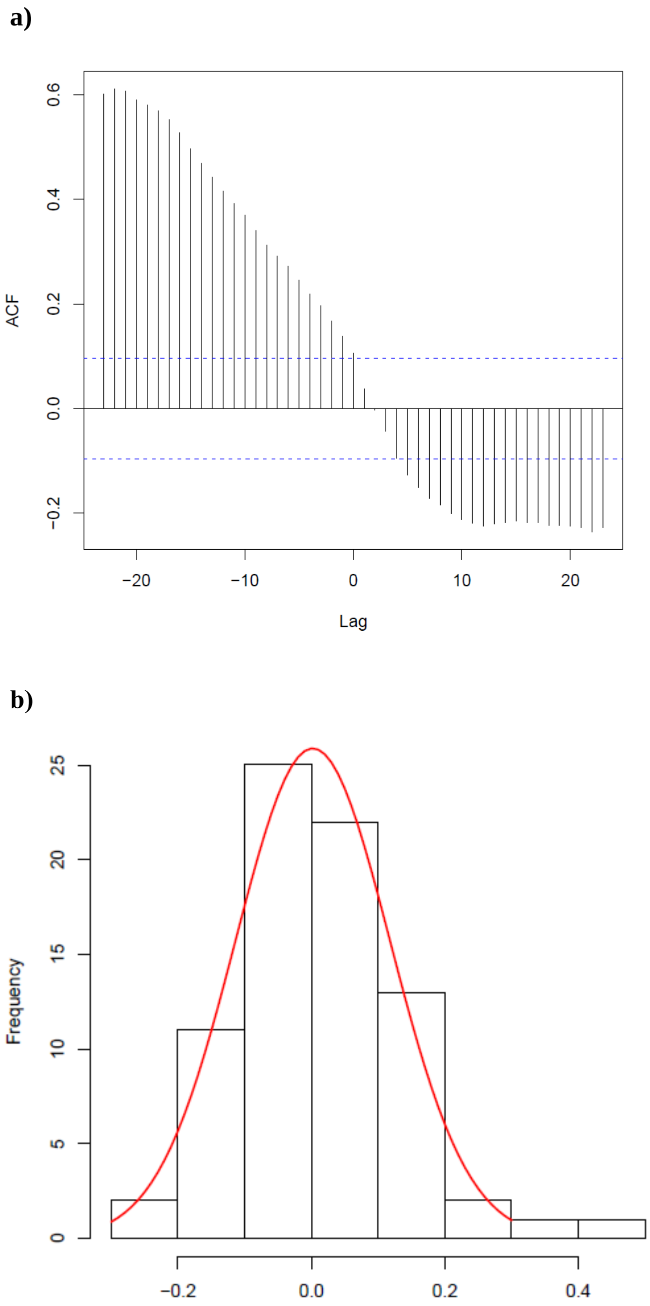

Fig. 3. a) A plot of the autocorrelation function between the dust factor and Tau as a function of daily slewing. Note the highest correlation value is 0.6 at T-21 Sols. b) A plot of the distribution of slopes from daily energies at similar orbital positions.

The data show clear seasonal trends and we include a variable, G_{Mars} as the calculated insolation in the matrix to determine its effects on energy output. The dependence on seasonality is clear, but soft, with a correlation coefficient of only 0.50, as observed in the third column, second row. The correlation coefficient for Tau is stronger at 0.65 indicating that there is a clear seasonal trend to the atmospheric dust, yet the contribution on suspended atmospheric dust on energy is insignificant.

To find the contribution from seasonality and calculate G_{Mars}, we follow the process outlined by Applebaum and Flood [7] and estimate the solar incident radiation at the top of the atmosphere. A function was written to determine the elliptical orbit of Mars with the Sun at one focus, and using simple geometry calculate the distance to the sun at any position in the orbit. To estimate the incident solar radiation at any point, we multiply the mean insolation at 1AU, 1367 W/m^2, and divide by the relative distance squared.

The available data span 4.95 Martian years. The eccentricity of the orbit of Mars is 0.0934, and its semi-major axis is 1.524 A.U. Hence the mean irradiance upon Mars at the top of the atmosphere is 588.6 W/m^2. The Opportunity rover is near latitude zero and longitude zero. Thus, we assume there is no major variation in daylight hours across the year, and we assume the orbital speed is approximately constant.

Fig. 2 reveals that 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 shading them, as is naively expected. However, the energy variable was not highly correlated with Tau, the optical atmospheric density, which was naively surprising. The scattered light within the atmosphere has little effect on the overall energy integrated over a day. The dust occlusion of the arrays dominates most of the power production, but slewing the Tau data vector compared to the Energy and Dust vectors to maximize the autocorrelation function (ACF) among these data indicated a peak correlation after a slew of 21 sols. This slewing, shown in Fig. 3a, indicates that approximately 60% of the variance in the data is explained by a 21 sol dust settling time.

This 21 sol dust settling time value is notable when compared to a study by Landis and Jenkins [8] on the dust settling rate using the Materials Adherence Experiment on Mars Pathfinder. They found a strongly linear rate of increase of 0.28% coverage per day for 24 days. The period of measurement is similar to our ACF peak time and suggests that the measured dust settling rate is due to a single weather event. Of course the weather even may be long in duration and we note that dust settling and subsequent removal are highly dynamic processes. The year-over-year approach yielded a histogram of the slopes and the probability density appear to have a Gaussian shape as shown in Fig. 3b. This distribution centered at 0 indicating there is no significant degradation of the arrays. To be more precise a Gaussian was fitted to the data and found excellent goodness of fit and a central value of 0.002±0.116 percent per Martian year which is consistent with zero degradation within uncertainty over the 4.95 Martian years in operation. Yet, this methodology yielded large uncertainty as determined by the width of the Gaussian fit, justified by invoking the central limit theorem. The Gaussian width may be an underestimate of uncertainty since the bins contain a measured value (a slope) that is fitted and itself contains an uncertainty, which is not modeled. A brief monte-carlo analysis indicated that the Gaussian width was a good first order estimate of uncertainty in this scenario. Thus it becomes more illuminating to quote a degradation rate in terms of the confidence bands of the Gaussian, ignoring the positive rates, and thus yielding a 95% confidence that the degradation rate is below 23% per Martian year. For comparison to laboratory work (below) this value is unsatisfying yet underscores the concept that data analytics may be used for a comparison of power losses in the field to laboratory observations.

B. Experimental Results and Analysis

From the computational analysis we found that the settling of atmospheric dust to has greater impact on cell performance than the presence of dust in the atmosphere. Given the year-over-year findings of zero seasonally independent degradation, our design of experiment aims to determine the optimal cell angle position for array operation and to probe if weather event duration had an observable impact on CIC performance. In Fig. 4 we compare a pristine CIC to one that has been abraded for 5 minutes at 80 degrees angle of incidence.

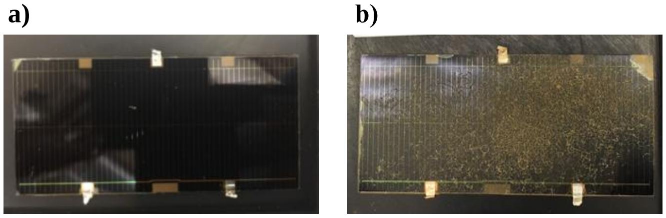

Fig. 4. MicroLink Devices IMM 3J cell a) pristine and b) post abrasion for 5 minutes at 80 degrees angle of incidence.

To systematically investigate the effects of severe weather on CIC performance we observe the CIC response dependency on both incident angle and exposure time. In all experimental cases the nozzle pressure was kept to 4 PSI resulting in a particle velocity of approximately 40 m/s, global Mars dust storms carry particles of dust at speeds ranging from 15-29 m/s [9] as observed by the Viking spacecraft, so here we simulate extreme weather conditions. Most of the JSC 1A simulant (75 wt%) is greater than 149 µm, while only 1 wt% is smaller than 5 µm [10]. CICs were abraded at constant 45 degree angle for varying time frames. An angle of 45° was selected as it is a popular/standard angle considered for array design. Since the devices used in this study are equipped with an anti-reflective thin coating (ARC) on the cover glass, abrasion to this coating would result in an increased reflection. In Fig. 5a we observe a heightened reflectance in the window from 450-650nm as the CIC's abrasion time increases. This increased reflection translates to a reduction of light reaching the active layers of the device, a source of a reduction in device current.

All J-V characteristics reported here have been normalized to the J_{SC} (mA/cm2) and V_{OC} (V) of a control device plotted in solid black line. Fig. 5b shows J-V characteristics of the same CIC's whose reflectance is shown Fig 5a. Overall there is no reduction in V_{OC}, confirming no structural damage is present in the devices crystalline structure post abrasion. We do observe a reduction in J_{SC} indicating optical losses. There are two potential sources of optical loss. The first being the remaining residue of dust that becomes affixed to the cell surface, the second is a result of damage to the CIC surface.

Any residual dust on the surface of the cell results in a reduction of light reaching the active layers of the device, thereby resulting in a smaller current. Mars dust has a reflectance profile similar to that which we observe on the devices in Fig.5a monotonically increased from 400-600nm with a dip in the amber (605nm) region leveling off to featureless reflectance at wavelengths higher than 700 nm.[11] To determine if the increased reflectance observed was due to either damage to the ARC or simply the presence of Mars dust, the CICs were sonicated for 5 min in water and then dried by a stream of N_2. Sonication was used as a method to rapidly clean the sample in lieu of long duration air flowing over the CICs. The dashed spectra in Fig. 5a show the reflectance of the CICs after the dust was removed, and in all instances the cells optical profile returned back to the control once the dust was removed, revealing that the observed modifications of the spectrum arriving onto the photoactive regions of the cell were due solely to the presence of Martian dust and not to ARC damage. Therefore our J_{SC} reductions are artifacts of performance losses due to the presence of dust adhered to the cell surface. To preserve the integrity of replicating a CIC operating on Mars, only J-V curves with resulting dust cover are within the scope of this investigation as, to date, CICs will perform in-situ without intervention.

We also probe the instance of constant exposure time (5 min) and constant pressure (4 PSI) at varying angles. In Fig. 5c we show that CICs positioned nearest to normal to the dust nozzle (80°, 85°) display the greatest increase in the reflectance spectrum. The direct and harsh exposure notably results in remarkable dust adhesion. Similarly, detrimental reflectance are observed in the case of low angles (0°) as large quantities of dust pile up on the CIC surface. After sonication to facilitate dust removal, the CICs at 80° and 85° maintained a significant amount of dust, potentially embedded, on their surface. Therefore the dashed (post-sonication) reflectance spectra for the 80° and 85° angles maintain increased reflection compared to the control device due to the persistent presence of Mars dust. Evaluating the J-V characteristics of the cells in Fig. 5d the cell positioned at 60° had the smallest PCE reduction (10%) followed by the 45° CIC which suffered from just a 13.54% PCE reduction. We acknowledge that the cell at 30° experiences a drastic performance drop off, this cell experienced some delamination and the cell stack was fractured.

C. Discussion

The experimental data here provide insights into the degradation modes and subsequent mechanisms of these triple junction CICs undergoing Martian dust ablation. The laboratory methods here allow for a controlled understanding of the degradation processes and feedback with the data-driven modeling of performance allow for calibration of the earth-based experimental tools and the understanding of the impact of Martian weather events. Modeling found a degradation rate consistent with zero during these ~5 Martian years, yet the uncertainty is large due to the methodology used [12] and the limited granularity in the energy data reported. Higher granularity and better models will indicate the amount of power drop due to non-reproducible processes, i.e. degradation, and

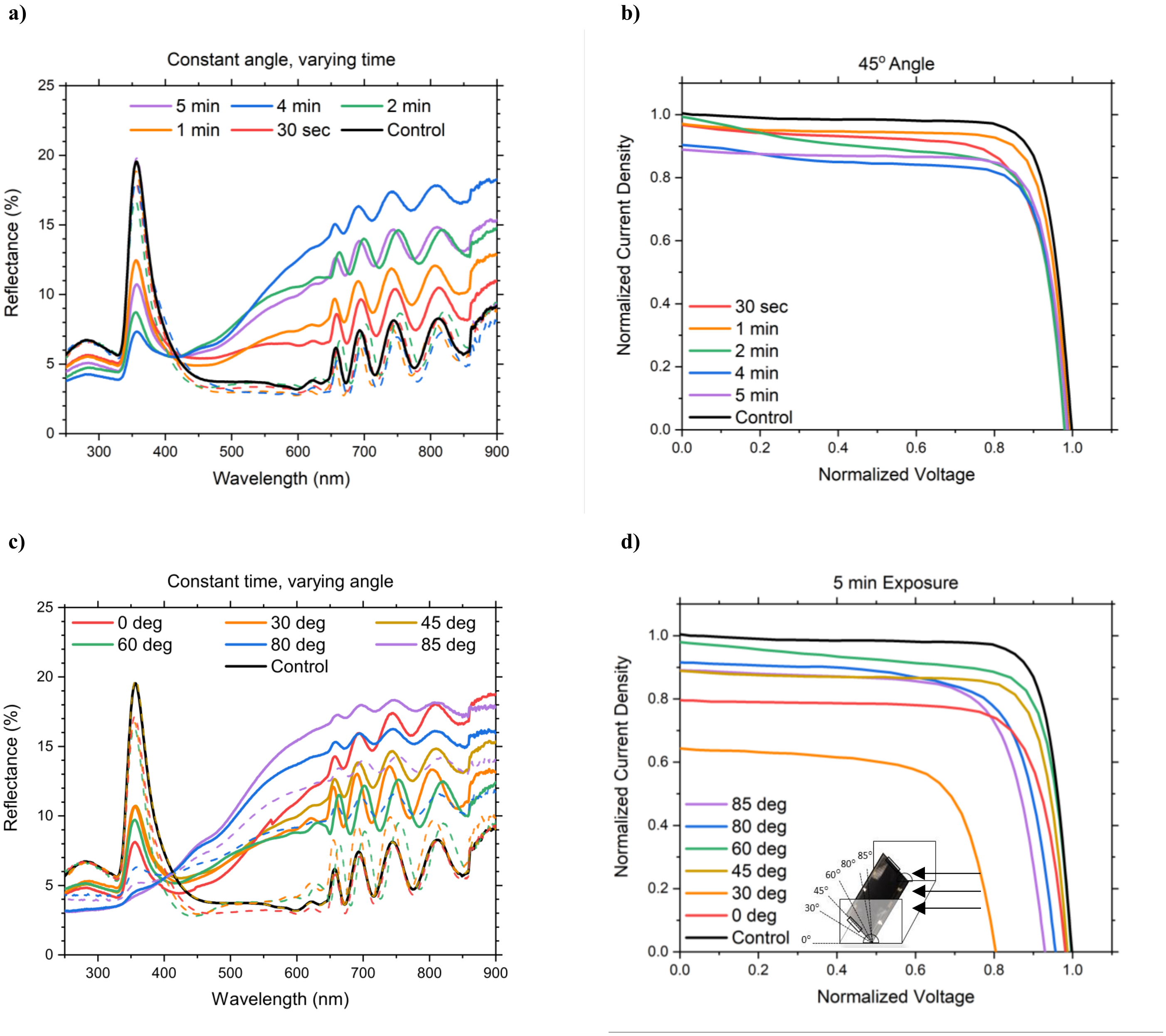

Fig. 5. **a)** Reflectance spectra after dust exposure (solid) and post-dust removal (dashed) and **b)** J-V characteristics of CICs after exposure to dust abrasion at 45° angle of incidence for varying times. **c)** Reflectance spectra after exposure (solid) and post-dust removal (dashed) and **d)** 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.

the laboratory-based effort is an attempt to mimic the degradation such that loss of power from weather events can be predicted. Our experiments here verify that the PCE degradation of CICs undergoing Martian weather events is non-zero. After just 5 minutes under dust storm conditions CICs at all orientations had reduction in PCE and we verify that the accumulation of dust in CIC surface reflects incident light away from the photoactive layers within the critical wavelengths of 400-650 nm.

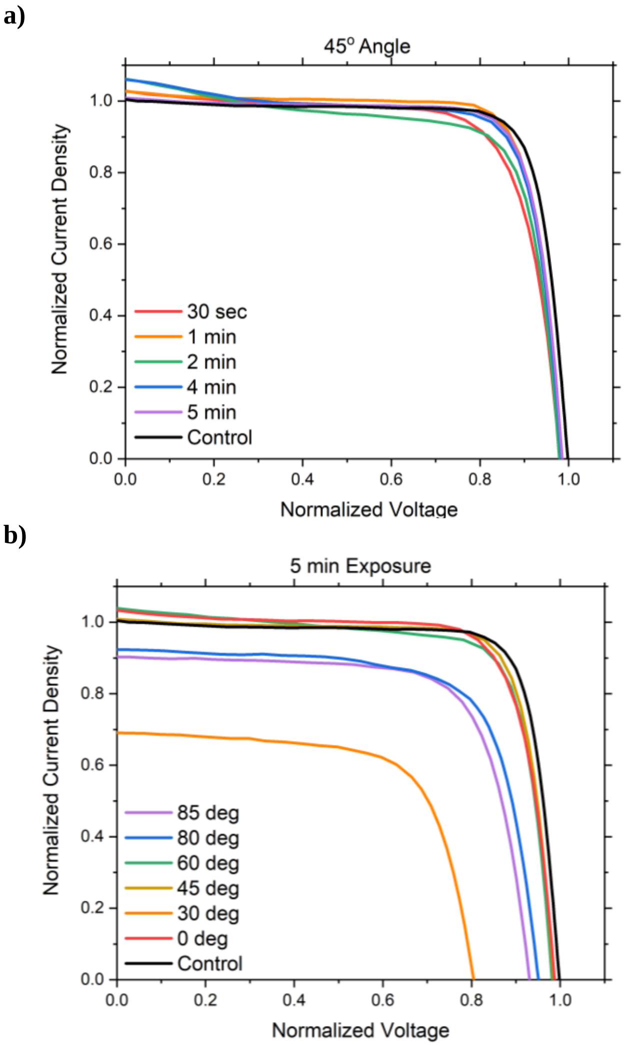

Fig. 6. J-V characteristics of CICs after sonication clean in the case of **a)** 45° angle of incidence for varying time and **b)** varying angles at 5 minute exposure time.

The nature of the irreversible damage of CICs exposed to extreme Martian dust storms was probed further by measuring the J-V characteristics of the CICs post sonication. In Fig. 6 we show the recovery of many CICs to near control performance (black line). The change in maximum power output for each CIC in pristine and post-sonication conditions is found to be 15.9±6.4 percent when all cells are considered. When the cells that could not be cleaned (85° and 80°) and the broken cell (30°) are excluded from calculations the irreversible max power degradation observed drops to 9.7±6.5 percent. Each method yields a respective maximum observed degradation of 22.3% and 16.2% both of which are in agreement with the computational year-over-year analysis. We acknowledge that this is a crude comparison, yet is promising and provides an opportunity for further investigation.

IV. CONCLUSION

The presence of dust on the cells results in an increased reflection in the visible wavelengths 450-650 nm. The gathering of dust on the CIC surface results in a primarily optical performance loss determined by the reduction in J_{SC} and generally unaffected values of V_{OC}. The optical performance of the device can be retrieved by dust removal and in cases where the exposure angle is less than 80° no CIC damage is observed. In the cases of exposure angles greater than or equal to 80° a more rigorous dust removal protocol will be necessary to retrieve optimal cell performance. Here we motivate the case for dust mitigation systems since the CICs are not irreversibly damaged, in the standard case, but performance reduction will be observed if left untreated. The irreversible damage observed experimentally is in agreement with the year-over-year calculation which suggests the degradation rate will not exceed 23% per Martian year when the dust cover is taken into account. The determined value of degradation rate was 0.0±0.2 percent per Martian year, and more data would be needed to shrink this uncertainty, because the largest effect on power loss was intermittent dust cover, which is an environmental factor and not included as an inherent degradation mechanism. Both the Mars Opportunity rover data and the experimental study demonstrate the overwhelming relationship governing energy is settled dust on the surface of the cells. In situ, this dust settling has a seasonal component with a 21 Sol lag for dust settling, post severe weather event. We ultimately recommend the ideal angles for CIC assembly are 45-60° as these orientations are most resilient in simulated dust storm conditions.

V. ACKNOWLEDGEMENTS

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