OPTIMIZATION OF THE PHOTOVOLTAIC POWERED SYSTEMS WITH DUST MITIGATION TECHNOLOGY FOR FUTURE LUNAR AND MARTIAN MISSIONS

N. Sorloaica-Hickman 1, J. McFall 2, S. Nason 1, K. Davis 1, E. Arens 3

1 Florida Solar Energy Center- University of Central Florida, Orlando Fl

2 ASRC Aerospace Corporation- Titusville

3 Kennedy Space Center, Kennedy Space Center

Abstract -- **The dust mitigation technologies are critical for deployment of photovoltaic (PV) arrays in remote, dusty atmospheres such as the surface of the Moon, Mars and even Earth. As dust collects on the photovoltaic modules, the amount of light hitting the surface is decreased, thus decreasing the overall power output. In general, it is not practicable to use moving parts in high-dust areas due to the damaging effects dust has on joints and electronics. We developed a hybrid experimental system that incorporates a transparent Electrodynamic Screen (EDS) with a PV array allowing us to study the total efficiency of different technologies (GaAs, Mono Si and Multi Si). In order to give a qualitative and quantitative analysis of performance measures of solar cells with the integrated EDS technologies, prototypes were developed and tested in the indoor and outdoor conditions. The effect of the UV aging on the EDS coatings were performed in a Q-Sun Xenon Test Chamber Model Xe-3-H. The Jasco V-670 Spectrophotometer was used to measure the UV/Vis transmission in the wavelength range from 190 nm to 750 nm before and after each UV aging increment of 99 hours.**

Index Terms —**Lunar Dust, El, ectrodynamic Screen, PV technologies**

I. INTRODUCTION

For humans to explore the Moon and Mars, most mission scenarios require that we shall make use of in-situ resources. This requires us to understand the physical properties of the space regoliths, to understand and predict the behavior of dust particles in lunar, Martian, and even earth environments, and to design technologies capable to control the various behaviors of these materials. It is well known that the entire lunar and Martian surfaces are covered with a layer of dust with sizes in the micrometer and submicrometer range [1]. Charged and uncharged dust on the surface of the Moon presents several challenges to manned and unmanned exploration missions currently being planned [2]. The dust adversely affects the operation of most mechanical systems required by these missions. It can easily levitate and penetrate into mechanical devices, space suites, and habitat compartments. If the dust particles are electrically charged they become very adhesive reducing drastically the efficiency of the solar panels [3,4]. In general special considerations must be made for solar cells and systems designed for space applications [5]. The efficiency needs to be as high as possible per mass of the solar panels due to the high cost of launch per pound of payload. Causes of degradation of the efficiency include ultraviolet (UV) light exposure, dust exposure, radiation, plasma sputtering, impact damage, high temperature gradients, and contamination [6]. The incorporation of dust mitigation technology can help mitigate efficiency degradation of the solar panels on the lunar and Martian surface; however, the additional materials and processes needed for inclusion of these technologies must not adversely affect the solar panel efficiency in such a way as to negate the benefits derived from these technologies.

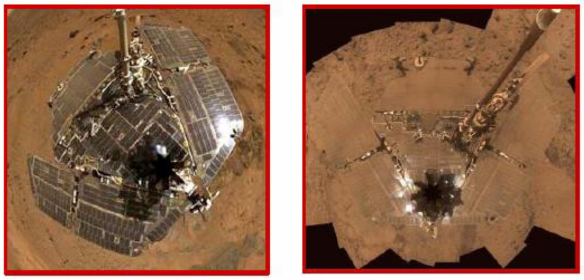

Fig 1. Comparison view of the clean solar panels and the rover almost blended into the dusty background on Mars [7]

II. EXPERIMENT

Prototype PV/EDS cells and testing methodologies needed to determine the performance effects of integrating the dust mitigation technology into solar cells/panels on the lunar surface have recently been developed by the Electrostatics and Surface Physics Lab (ESPL) at Kennedy Space Center (KSC) and Florida Solar Energy Center. The optical and electrical interference as well as the power draw of the dust mitigation technology have to be balanced with the overall improved power efficiency if accumulated dust can be sufficiently removed from the panel surfaces. The first step in the performance analysis was to determine if the dust mitigation technology can be integrated into a solar panel design and not significantly degrade the performance of the clean device operating under earth ambient conditions.

The Electrostatics and Surface Physics Laboratory at the Kennedy Space Center (ESPL) began development of the electrodynamic screen dust mitigation technology in 2003 as a solution for solar panels intended for robotic Mars operations [8].

For this research the screens were processed using soda-lime float glass coated with ITO [9]. Typical composition

of this glass is 73% SiO_2, 0.15% Al_2O_3, 9% CaO, 4% MgO, 0.03% K_2O, 0.02%TiO_2, 0.1% Fe_2O_3 and 14% Na_2O. ITO is applied to the substrate with no SiO_2 passivation layer. The sputtered ITO has a surface resistivity of 10-15 ohms per square with thickness ranging from 1200 to 1600 Å and has a refractive index of approximately 1.45. The pattern chosen for this project was a two electrode pattern with "feathering" along the electrodes designed to provide maximum coverage of the solar panel for dust removal. "Feathering" appears to aid in the removal of regolith that falls between the electrodes. (Figure 2) For the chemical etching process, the screen designs are printed on to the wax paper and used as a mask for a chemical etching process. A heat press was used to transfer the design from the wax paper to the glass coated ITO. The end result was a transparent glass slide capable of moving dust under air and vacuum conditions. The ITO electrodes have different transmission and reflection characteristics than the glass alone and are noticeable under the right lighting conditions.

Tests of the dust mitigation technology on glass substrates performed under vacuum show that voltage levels on the order of a few kilovolts were needed to perform dust removal. Than good insulators were needed to ensure no electrical breakdown occurred over the substrate surface. Coating choices were based on experience with insulating coatings used for dust mitigation technology demonstrations as well as manufacturer recommendations. The MgF_2, SiO_2, and Al_2O_3 stack coating was used by the ESPL on a reduced gravity flight; the other coatings were suggestions of the manufacture for broadband transmittance as well as high dielectric constant.

In order to test the integrated PV/EDS dust mitigation systems, a custom mounting device was designed and built. (Figure 2) The structure of the solar cell module is characterized by a structure in which the PV cells are incorporated into a frame such as an aluminum frame to maintain structural strengths. The front surface of a photovoltaic element is sealed by glass with ITO and the bottom surface is sealed with plastic material to secure sufficient electric insulation properties and weathering resistance. The PV cell plate was designed so that multiple contacts could be maintained. The adaptation of the four corner insulated fasteners was included so that a variable size glass electrostatic screen could be held evenly in place. Two of the four contacts were assigned to be permanently soldered to the positive and negative sides of the solar cell. These same contacts were then soldered to more durable wires that acted as leads to the portable I-V curve tracer. In creating this design, the overall durability and flexibility of the probe plate significantly improved experimental consistency without affecting the sensitive measurements. The PV device used for this research consisted of two identical cells of Mono-Si, Poly-Si and multijunction GaAs connected to I-V curve tracer. First, the bare test cells were disconnected from one another and thermocouples were attached to the rear surface of each using adhesive tape. A reference cell was first set up parallel to the plane of the system and the pyranometer stand was adjusted to the same orientation with the cells. An I-V curve was then taken for this reference module. The pyranometer was then readjusted to the angle of the bare PV cells and 5 or 6 I-V curves were taken. These I-V curve measurements, together with their associated temperatures and irradiance measurements, constituted the "first run" of the bare PV cells. Identical measurements were performed on the PV cells with the glass, glass/EDS layer, and JSC-1A dust/glass/EDS layers.

The extraterrestrial solar spectrum has a larger content of radiation in the UV wavelengths than the terrestrial spectrum so that space based solar systems must be more robust to withstand UV degradation. The encapsulate material used to laminate the cover glass material to the solar cells can degraded or discolored by UV exposure. Cerium (Ce) doped glass is normally used to block the transmission of UV (<400 nm) to the solar cell. In this

978-1-4673-0066-7/12/$26.00 ©2011 IEEE

work the UV radiations were applied to what would be the exterior sun facing side of the cover glass material so any Ce doping would not protect the dust mitigation electrodes or coatings.

The test chamber maintained the UV irradiance level for each of the three lamps at 0.68 W/m2 using a 340 nm UV sensor. The 340 nm sensor measures a narrow band of wavelengths that are centered at 340 nm with a bandwidth of 10 nm.

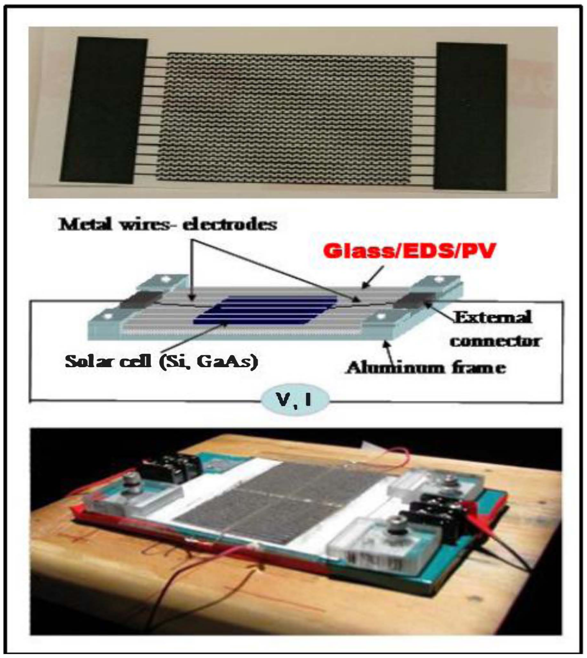

Fig 2. Solar Panel Screen Design with "Feathering" and PV/EDS cells setup - illustration and real picture with the JSC-1A lunar stimulant

An extended UV-Q/B filter was used to filter the light from the Xenon source to simulate a spectral power distribution, which provides faster degradation as it allows transmission of wavelengths shorter than natural sunlight. Temperature, humidity, and irradiance values are listed in Table 3 for each increment of 99 hours that the samples were run. The slides underwent four UV aging cycles of 99 hours each.

Parameter	Set	Actual @99 h	Actual @198h	Actual @ 396h
Irradiance (W/m^2)	0.68	0.68	0.68	0.68
Black Panel T (°C)	50	50	50	50
Chamber Air T (°C)	38	40	40	40
Relative Humidity (%)	10	20	16	20

Table 1. UV aging parameters

III. RESULTS AND DISCUSSION

Initially, three sets of cover glass, with four slides in each set, were tested outdoor and the results were compared to the efficiency values for the bare PV and the plain glass covered PV. The three sets included ITO patterned but not coated slides (FSP71, FSP72, FSP73, FSP74) as well as the ITO patterned slides with the two different insulating coatings (FSP 66, FSP 67, FSP 68, FSP 69, FSP1, FSP2, FSP3, FSP4). The efficiency of the illuminated Mono, Poly Si and GaAs PV cells with different ITO patterned and insulating coatings are shown in Figure 3. The variations in efficiency between bare PV cells, plain glass covered cells, and glass covered cells with the screen technology and coating applied for the Mono Si PV technology indicate that the ITO pattern and coatings are not reducing the performance of the cell. Combinations of PV and cover glass were also tested indoors under more stable irradiance conditions and showed even less variation from the measured plain glass efficiency. Broadband coated screens actually show a slight increase in efficiency over the plain glass slides, probably due to the slightly increased transmission that the coating provides.

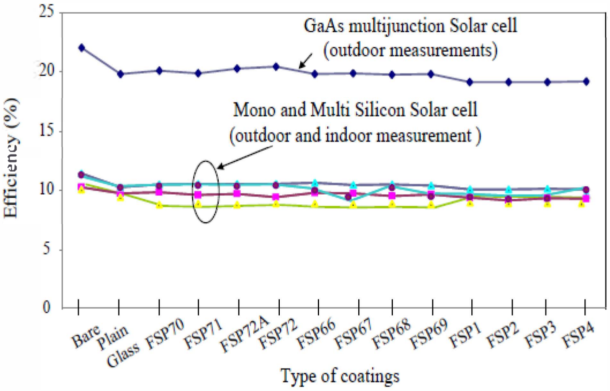

Fig 3. Efficiency of the bare/glass/coated PV cells

Figure 4 shows a reduction in the I-V measurements after UV aging. Comparing this data to the UV/VIS spectroscopy data, points to the reduction in efficiency possibly to be due to a UV aging effect on the glass substrate and not necessarily on the coatings chosen.

I-V measurements of the PV/EDS systems with a very thin layer of dust were performed and compared with the results after the removal using the EDS. The results shown in figure 5 indicate an improvement in the panel performance.

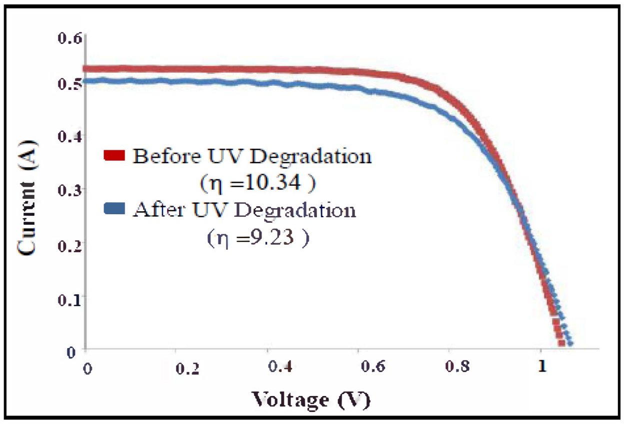

Fig 4. IV curves for pre and post UV exposure of Al_2O_3-SiO_2 coated screens (FSP66) tested outdoors with Mono Si PV cells

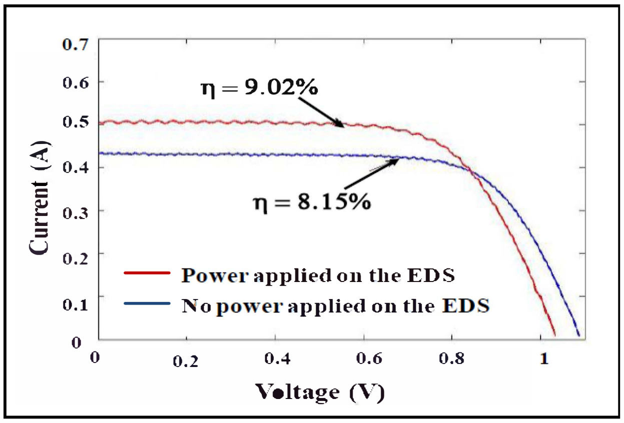

Fig 5. Dust removal effect on the performance of the Polycrystalline-Si PV cells (FSP66)

IV. CONCLUSION

The possibility of using the electrodynamic screen as a method to clear regolith from structures such as solar panels on the lunar and Martian surface was demonstrated. The electrodynamic screens were incorporated onto a photovoltaic device to determine the effect on PV cell performance. Screens with ITO and three different coating layers were used in this study. The solar panel performance tests were conducted under Earth ambient conditions, on single monocrystalline silicon, polycrystalline silicon, and gallium arsenide multijunction solar cells in an indoor and outdoor test facility. All results indicate that the screen assemblies do not degrade the performance of any of the tested solar cells as compared to a plain glass cover glass. UV radiation was an important parameter needed to be assessed for EDS coating materials so UV aging for 396 hours and UV/Vis Spectroscopy measurements were performed on all the screens between each of the four 99 hour cycles. There are variations in the UV and near-UV portion of spectrum that seemed to be due to the aging of the glass substrate under UV light exposure but not major change was observed in the efficiency measurements.

This systematic study shows that this technology is a viable candidate to mitigate dust on solar panels for the lunar and Martian and even Earth surface. However, further research needs to be performed

REFERENCES

[1]. Greenberg, Paul (2005). Nanoparticulates on the Moon and Mars. *2nd International Symposium on Nanotechnology and Occupational Health*; Minneapolis, MN, 2005.

[2]. Greenberg, Paul (2005). Sensor Development for the Detection and Characterization of Lunar Dust. Report of the Space Resources Roundtable VII: *LEAG Conference on Lunar Exploration*, League City, TX, 2005, p. 57

[3]. Jones L, Jacques S, Rask JC, Tranfield E, Taylor L, Kerschmann R, Loftus DL. Lunar dust biological effects. *NLSI Lunar Science Conference.* 2008

[4]. Vaniman D, Reedy R, Heiken G, Olhoeft G, Mendell W. The Lunar environment. In: Heikin GH, Vaniman DT, French BM editors. *Lunar sourcebook: a user's guide to the moon.* New York: Cambridge University Press; 1991. P. 27-60.

[5]. Hickman JM, Curtis HB, Landis GA. Design considerations for Lunar base photovoltaic power systems. *Record of the Twenty First IEEE Photovoltaic Specialists Conference*; 1990 May 21-25; p. 1256-1262 vol. 2

[6]. Kerslake TW, Gustafson ED. On-orbit performance degradation of the international space station P6 photovoltaic arrays. *First International Energy Conversion Engineering Conference*; 2003 Aug 17-21; Portsmouth, Virginia. National Aeronautics and Space Administration NASA/TM 2003-212513.

[7].(http://marsrovers.jpl.nasa.gov/gallery/press/spirt/20071210a.html)

[8]. C.I. Calle, J.L. McFall, C.R. Buhler, S.J. Snyder, E.E. Arens, A. Chen, M.L. Ritz, J.S. Clements,C.R. Fortier1, and S. Trigwell (2008) Dust Particle Removal by Electrostatic and Dielectrophoretic Forces with Applications to NASA Exploration Missions Comets for Beginners, *Proc. ESA Annual Meeting on Electrostatics* 2008, Paper O1

[9]. Calle CI, Arens EE, McFall JM, Buhler CR, Snyder SJ, Geiger JK, Hafley RA, Taminger KM. Reduced gravity flight demonstration of the dust shield technology for optical systems. *IEEE Aerospace Conference*; 2009 March 7-14; p. 1-10.