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Space Radiation Cover Glass Experiment Part II: Experiment

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As commercial satellite launches become more common and the number of trajectories available for achieving a given orbit increases, the need will also increase for a way to model the radiation exposure for such missions. By using the concepts of ionizing energy loss and ionization damage dose, we modeled the radiation exposure of five different electric orbit raising trajectories for satellites whose ultimate mission is 15-years in geosynchronous orbit. We report here the results of an initial experiment designed as a proof-of-concept.

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SPACE RADIATION COVER GLASS EXPERIMENT
PART II: EXPERIMENT

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Introduction. Despite more than half a century of solar cell cover glass (CG) engineering, exposure to space radiation still causes CGs to darken.[1-3] Darkening reduces the amount of light that reaches the underlying solar cells and hence decreases their power output. In an effort to better understand radiation-induced cover glass degradation, Maxar engaged the U.S. Naval Research Laboratory (NRL) to perform modeling, simulations, and ground-based radiation tests using Qioptiq CMG cover glass materials (100 µm and 125 µm thicknesses, with and without anti-reflective (AR) coatings) intended to protect solar power cells during low-thrust electric orbit raising (EOR) transfer orbits from low earth orbit (LEO) to geostationary orbit (GEO), and for a 15-year mission in GEO. In this report, the experimental ground-test procedure is discussed and preliminary results are presented. The purpose is to explore the connection between measured amounts of CG darkening and calculated amounts of ionization damage. It is important to demonstrate a proof-of-concept because ionization damage and the ionization damage dose (IDD) have been used previously to discuss CG darkening, but no experimental correlation has been demonstrated.[3]

Proton fluences for ground tests. In Part I of this series, data pertaining to Earth's space radiation environment and the related ionization damage dose were tailored to 7 scenarios.[4] Five were EOR trajectories: Ariane 190-Day, Ariane Ground to Orbit (GTO), Ariane Single Stage to Orbit (SSTO), Falcon 9, and Maxar Worst Case (WC). The other two were complete missions: 15 years in geosynchronous orbit (GEO) under typical space radiation conditions, and 15 years in GEO under Maxar's worst-case conditions. The task then was to choose how to replicate space radiation exposure on the ground as closely as possible without undue effort.

The primary requirement of the experiment was that the ionization damage dose be the same on the ground as in space. The secondary requirement was that the damage-depth profile within the CGs be reproduced as closely as reasonable. The results for the EOR trajectories are shown in Table 1. A graphical depiction of the same data is shown in Fig. 1 for the Maxar WC EOR trajectory.

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Trajectory	Φ(3.6 MeV p^+)	Φ(1.0 MeV p^+)	Φ(0.5 MeV p^+)	IDD_{calc}	IDD_{exp}
Ariane 190	1.00×10^{14}	3.50×10^{14}	5.20×10^{14}	1.59×10^{18}	1.58×10^{18}
Ariane GTO	4.00×10^{13}	1.34×10^{14}	3.00×10^{14}	6.96×10^{17}	6.97×10^{17}
Ariane SSTO	2.00×10^{13}	8.00×10^{12}	1.00×10^{14}	3.29×10^{17}	3.28×10^{17}
Falcon 9	3.50×10^{13}	1.35×10^{14}	2.20×10^{14}	6.03×10^{17}	6.03×10^{17}
Maxar WC	1.40×10^{13}	6.00×10^{13}	1.16×10^{14}	2.74×10^{17}	2.74×10^{17}

Table 1. Ground test fluences (Φ) for five EOR trajectories. The 3.6 MeV protons are incident from the back of the CGs. The rest are incident from the front. Also shown are the calculated (space-based) and experimental (ground-based) total ionization damage doses (IDD) for each trajectory, which ideally would be the same. Units of IDD are MeV/g. Units of fluence are p^+/cm^2.

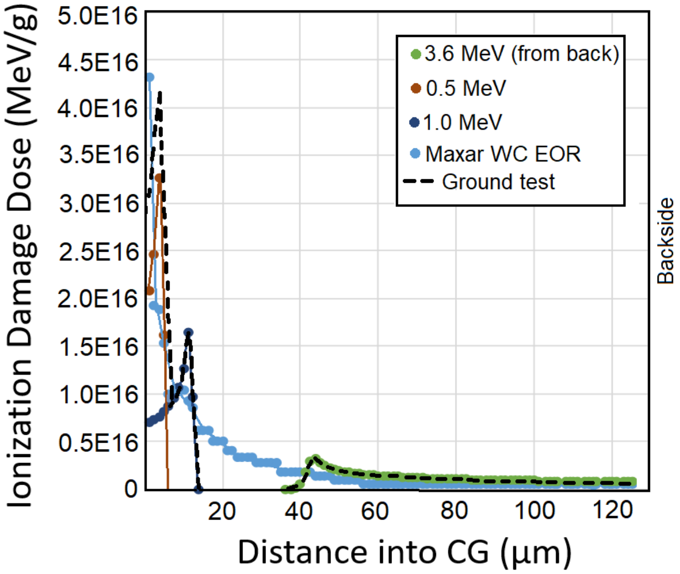

Fig. 1. Calculated ionization damage dose vs depth into a CG in space (solid line), and the sum of the three ground-based damage profiles (broken dashed black line). The main goal of ground-based testing is to produce the same amount of damage as would occur in space (i.e., to have equal areas under the dashed black and solid blue curves).

For the GEO missions, (standard and Maxar WC), eight proton energies and fluences were used. The calculated numbers are given in Table 2. The damage-depth profile for the 15-year Maxar WC GEO mission is shown in Fig. 2. It is clear from the figure that increasing the number of proton energies from 3 to 8 allows the space-based damage-depth profile to be reproduced much more accurately. (Note that in Fig. 2 "Maxar WC" does not include the Maxar WC EOR component).

Proton Energy (MeV)	Φ(GEO Only)	Φ(Maxar WC)
3.6 (rear)	2.20x10^{14}	3.70x10^{14}
2.25 (front)	1.00 x10^{14}	4.10x10^{14}
2.00 (front)	1.20 x10^{14}	1.00x10^{14}
1.75 (front)	1.50 x10^{14}	1.00x10^{14}
1.00 (front)	1.50 x10^{14}	1.50x10^{14}
0.75 (front)	3.00 x10^{15}	3.00x10^{15}
0.60 (front)	3.00 x10^{15}	2.50x10^{15}
0.50 (front)	1.26 x10^{15}	1.40x10^{15}
IDD_{calc} (MeV/g)	4.98x10^{18}	6.25x10^{18}
IDD_{exp} (MeV/g)	4.99x10^{18}	6.26x10^{18}

Table 2. Proton fluences (Φ) and energies for 15 typical years in GEO (GEO Only), and for 15 "worst case" years in GEO. Also shown are the calculated (space-based) and experimental (ground-based) total ionization damage doses (IDD) for each mission. Units of IDD are MeV/g. Units of fluence are p^+/cm^2.

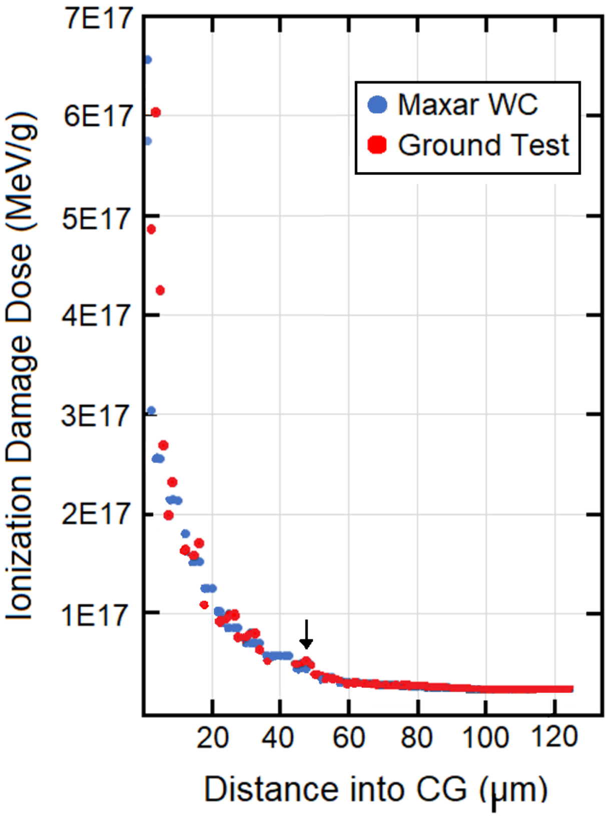

Fig. 2. Ionization damage dose vs distance into CG for the calculated space radiation environment (blue) and the ground test (red) for 15 years in the Maxar WC GEO orbit. The overlap is excellent, although remnants of Bragg peaks can still be seen (arrow). Such peaks are the result of replacing the continuous spectrum of proton energies in space with a discrete profile of energies on the ground

Mounting and Irradiation. Four CGs were mounted on a copper plate as shown in Fig. 3. The CGs were held to the mounting plate by thin strips of double-sided Kapton tape that were protected by stainless steel strips. The copper plate was mounted onto the end plate of the accelerator.

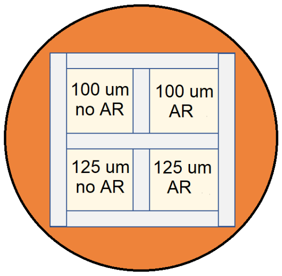

Fig. 3. Irradiation configuration. Samples are held in place on a copper plate by Kapton tape that is covered by stainless steel strips.

Mounted samples were irradiated in-situ at Auburn University's tandem van de Graaf accelerator. Beam currents were kept below 100 µA to avoid excessive sample heating. Seven plates similar to that of Fig. 3 were prepared for five EOR trajectories, and for the GEO Only and Maxar WC missions. The beam current was measured using a retractable Faraday cup. The beam itself was rastered in two directions in order to eliminate the effect of spatial variations within the beam, then collimated at the entrance of the irradiation chamber.

Spectroscopy. Two different spectrometers were used for measuring the transmittance of the CGs. The first was a Coherent Monaco 1035 femtosecond laser that was used to measure transmission at a single wavelength of 550 nm. Full transmittance spectra were measured using a PerkinElmer Lambda 750 spectrometer equipped with PMT and PbS detectors, and deuterium and tungsten lamps. An iris positioned before the sample was used to ensure that the light spot on each cover glass was not obstructed by the holder used to mount it.

For the 100 µm no AR, 100 µm with AR, 100 µm no AR, 100 µm with AR CGs, respectively, the pre-irradiation transmission percentages were 91.80, 90.11, 94.53, and 92.38. Antireflective coatings increase transmission by about 2%. Normalized post-irradiation transmission data taken at 550 nm are shown in Fig. 4 for each EOR trajectory. Values of IDD for the trajectories were taken from Table 1. For the current purpose we focus only on the qualitative trends of the radiation response because we are looking only to demonstrate that a correlation exists between CG darkening and IDD. Such a correlation can indeed be seen in Fig. 4, where the normalized transmission through the CGs decreases with increasing IDD, and also where the decrease appears to saturate at larger values of IDD.

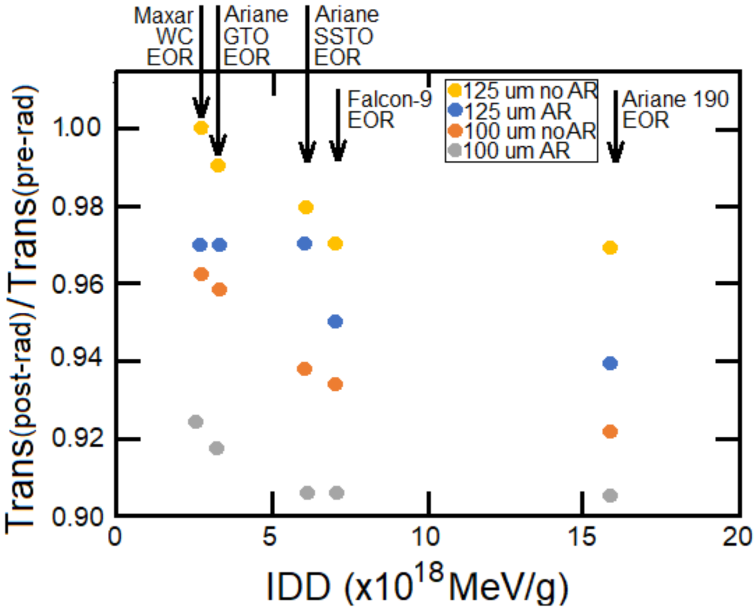

Fig. 4. Normalized transmission T_{norm} = T(post-rad)/T(pre-rad) versus ionization damage dose for five different EOR trajectories, measured at 550 nm. Two general trends are identified here. First, that T_{norm} decreases with increasing IDD, and second that the decrease appears to saturate at higher damage dose levels.

Summary. A ground-based experiment was designed and performed to study the effect of space radiation on Qioptiq CMG cover glass materials (100- and 125 µm thickness, with and without antireflective coatings) for five electric orbit raising trajectories and two 15-year missions in geosynchronous orbit. The primary goal was to provide a proof-of concept for characterizing CG darkening in terms of the ionization damage dose. It was found that such a correlation does exist, that increasing IDD causes increased CG darkening, and (perhaps) that the darkening could be saturating at higher damage doses.

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