Many contemporary spacecraft materials exhibit cathodoluminescence when exposed to electron flux from the space plasma environment. A quantitative, physics-based model has been developed to predict the intensity of the glow as a function of incident electron current density and energy, temperature, and intrinsic material properties. We present a comparative study of the absolute spectral radiance for several types of dielectric and composite materials based on this model which spans three orders of magnitude. Variations in intensity are contrasted for different electron environments, different sizes of samples and sample sets, different testing and analysis methods, and data acquired at different test facilities. Together, these results allow us to estimate the accuracy and precision to which laboratory studies may be able to determine the response of spacecraft materials in the actual space environment. It also provides guidance as to the distribution of emissions that may be expected for sets of similar flight hardware under similar environmental conditions.

The model developed for the observed electron-induced luminescence phenomenon is based on a band theory of highly disordered insulating materials [3, 10]. The observed luminescence occurs when an incident high energy, charged particle undergoes a series of inelastic collisions exciting valence band electrons into the conduction band. The excited electrons rapidly decay to localized (shallow trapped) states, with a mean binding energy \( E_b \) below the mobility edge. A final electron transition, from the shallow to the deep trap states of longer-lived deep trap states is the origin of the emitted photon.

The model predicts that the overall luminescence intensity:

\[
I_{\text{lum}}(E, E_b, T, \lambda) \propto \frac{f_{\text{emit}}(E)}{E_{\text{inc}}} \frac{E_{\text{inc}}}{E_{\text{c}}} \frac{1}{E_{\text{c}}} \left[1 - \exp(-E_{\text{c}}/kT)\right] \frac{1}{1 - \exp(-E_b/kT)}
\]

The dose rate \( D \) (absorbed power per unit mass) is given by:

\[
D_{\text{lum}}(E, E_b, T, \lambda) \propto \frac{f_{\text{emit}}(E)}{E_{\text{inc}}} \frac{E_{\text{inc}}}{E_{\text{c}}} \frac{1}{E_{\text{c}}} \left[1 - \exp(-E_{\text{c}}/kT)\right] \frac{1}{1 - \exp(-E_b/kT)}
\]

The energy dependence of the spectral radiance is more complicated, due to the dependant relative detector sensitivity.

Changes in cathodoluminescence spectra for highly disordered insulating materials. Shown are the c-cyanate ester/graphite fiber composite at ~100 K (red), 300 K (blue), and 250 K (green). These spectra are normalized at maximum intensities and are not corrected for the wavelength-dependent relative detector sensitivity.

The energy dependence of the spectral radiance is more complicated, due to the energy-dependent penetration depth or range, \( R(E_{\text{c}}) \), in Eq. (2).

For nonpenetrating radiation—where the energy-dependent penetration depth or range, \( R(E_{\text{c}}) \), is less than the film thickness \( L \)—all incident power \( P_{\text{inc}} \) is absorbed by the material. At low incident power, both \( D \) and \( I \) exhibit saturation effects for increasing energy and fixed current density. For penetrating radiation where \( R(E_{\text{c}}) > L \) the absorbed power is reduced by a factor \( (L/R(E_{\text{c}})) \) and is controlled by a similar dependence for \( I \). Eq. (1) shows the range and dose for select dissimilar materials as functions of incident energy.

An energy-dependent correction to the incident flux, \( f_{\text{emit}}(E) = f(E_{\text{c}}) \), is also included in Eq. (2) to account for excitonic backscattered electrons that do not deposit substantial energy; \( f(E_{\text{c}}) \) is the backscattered electron yield [11]. For the most part, this correction is small and weakly dependent on energy. For biased samples, or energy does not exceed the trap states, a surface voltage \( V \), results and \( E_{\text{c}} \) is replaced everywhere in Eq. (1) and (2) by the landing energy. \( E_{\text{c}} = qV \).

Variations with Energy and Penetration Depth

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Variations with Materials

Comparison of different methods to determine the absolute spectral radiance per incident electron power density as a function of incident electron energy for some samples. The color bar represents the dose rate and the size of the symbols are linearly proportional to the incident power density (\( P_{\text{inc}} \)).

(a) Comparison of different methods to determine the absolute spectral radiance per incident electron power density as a function of incident electron energy for some samples. The color bar represents the dose rate and the size of the symbols are linearly proportional to the incident power density (\( P_{\text{inc}} \)).

(b) Comparison of different methods to determine the absolute spectral radiance per incident electron power density as a function of incident electron energy for some samples. The color bar represents the dose rate and the size of the symbols are linearly proportional to the incident power density (\( P_{\text{inc}} \)).

Conclusion

Cathodoluminescence is an important space environment-induced phenomenon to understand, especially in applications where extremely sensitive space-based optical detection is necessary.

Measurements of the absolute spectral intensities per incident electron flux have been presented that confirm a quantitative, physics-based model to predict the intensity of the glow as a function of incident electron current density and energy, temperature, and sample thicknesses and thickness.

Comparisons for these materials show three orders of magnitude variation. For bulk nonpenetrating materials, spectral radiance increases with increasing incident electron power and flux. In thin films where electron penetration is possible, a linear relation is seen at all energies, but once penetration occurs intensity decreases with increasing energies.

Comparisons of materials, where both penetrating and nonpenetrating electron effects were present, required a combination of these two effects in the model. Saturation effects at higher doses were observed and accurately modeled, for both penetrating and nonpenetrating electrons.

Statistical analysis of the observed statistical fluctuations of cathodoluminescence for a large set of similar epoxy samples exposed simultaneously to similar space-like monoelectric electron flux conditions provides a more precise measure of both the instrumentation precision and the stochastic variations inherent to the material.

The statistical results of the analysis of the variations of the cathodoluminescence spectra of many similar samples led to higher precision and accuracy results that allow for quantification of additional more subtle effects. Together, the results allow us to estimate the accuracy and precision to which laboratory studies may be able to determine the response of spacecraft materials in the actual space environment. It also provides guidance as to the distribution of emissions that may be expected for sets of similar flight hardware under similar environmental conditions.