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TABLE II. ENERGY AND CHARGE DEPTHS AS A FUNCTION OF DENSITY

| Density (g/cm^3) | > 90% Energy Depth (um) | Charge Dep. Peak Depth (um) |
|---|---|---|
| 1 | 105 | 90 |
| 1.5 | 70 | 60 |
| 2 | 55 | 45 |
| 3 | 34 | 30 |
| 5 | 21 | 18 |
| 7.5 | 13.5 | 11.5 |
| 10 | 10.5 | 9 |

Finally we wanted to isolate the effect of density on the energy and charge depth profiles. We took a single element, carbon, varied its mass density in the simulation, and plotted the results for a single incident electron energy (100 keV).

There was a clear inverse relationship between the depth profiles and the density as can be seen from Table II and Fig. 8. This is an expected result as increasing the density will proportionately increase the number of interactions thereby creating shallower energy and depth profiles.

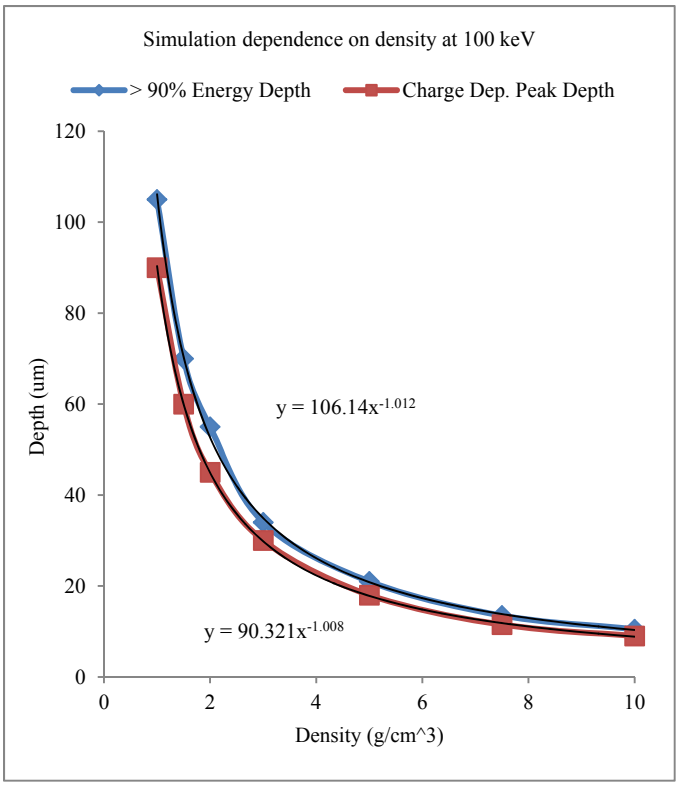


Figure 8: Density dependence of 100 keV electrons incident on a carbon target. Depth profiles fall off as one over the density.

## III. NEW ALGORITHM FOR MODELING CHARGING

### A. *An interpolative approach*

For the purposes of modeling charging, it is extremely helpful to have an algorithm that quickly determines the electron and energy depositions as a function of depth. Useful charge modeling requires the exploration of numerous materials of varying thicknesses bombarded simultaneously by a wide range of electron energies. Set up of one Monte Carlo simulation is difficult; running a Monte Carlo simulation is time consuming. If every exploration of a new material or a different electron flux energy spectrum required new Monte Carlo simulations, then the usefulness of charge modeling would be severely diminished. Also, either the charging model would have to run somehow in conjunction with a Monte Carlo code, or the modeling would have to be done in an awkward two-step sequence which would necessitate operating two different programs and transferring the data between them.

Although previous algorithms have been found by fitting multiple functions with multiple fitting parameters [11, 14, 18, 25], we have begun to explore a different approach that could have significant advantages. Modern computational software programs such as *Mathematica*® and MATLAB® have many useful tools, including the ability to interpolate within complicated data sets. At least one of the newer NUMIT models [5, 6, 26] is written in MATLAB, so it was appropriate to investigate the possibility of using these interpolation tools.

MATLAB has several potentially relevant functions. As of this writing, we have tried three, focusing our efforts on *scatteredInterpolant*. This function performs an interpolation on a scattered data set that has three independent variables and one dependent variable. For a set of points defined in three dimensions, a corresponding set of values is input. Queries for values that are not in the original inputs are made by choosing different three-dimensional points. Then, *scatteredInterpolant* will return the interpolated value.

In our case, the three dimensions defining a point were depth in the dielectric ($x$), incident electron energy ($T_0$), and the atomic number of the dielectric (Z). The *scatteredInterpolant* function was used separately for the two different types of Monte Carlo data described earlier: the energy deposition

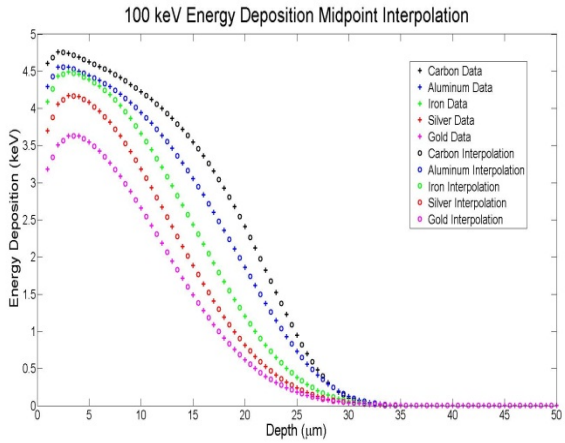


Fig. 9: Interpolation of Monte Carlo data for energy deposition based on depth.

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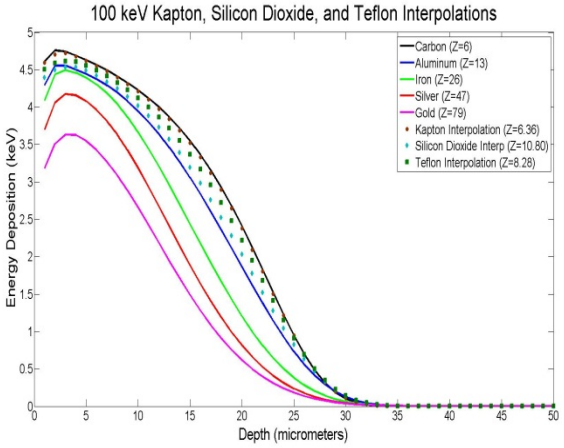


Fig. 10: Interpolation of energy deposition materials based on effective Z.

profiles and the charge deposition profiles.

### B. *Results of Energy Deposition Interpolation*

The first interpolation done changed only the depth inputs. The values were queried at depths midway between the Monte Carlo points. The results for such a simple interpolation were just as expected (see Fig. 9).

Next, an interpolation of the atomic number was attempted. Composite materials of interest to spacecraft charging were chosen: Kapton® with $Z_{eff}$ = 6.36, silicon dioxide with $Z_{eff}$ = 10.80, and Teflon® (polytetrafluoroethylene) with $Z_{eff}$ = 8.28. The effective atomic numbers were found using the method identified by Tabata [11]. The results are shown in Fig. 10. Because all of the materials attempted have effective atomic numbers that fall between that of carbon and aluminum, we expect the interpolated results to be there also—exactly as they appear in the graph.

Deep-dielectric charging models will also require deposition profiles for incident electron energies that do not happen to be precisely those used in the Monte Carlo simulation. The ability of *scatteredInterpolant* to interpolate between incident electron energies on carbon was tested using two values between the data at 100 keV and 500 keV. The results are shown in Fig. 11. Overall, the interpolation looks somewhat reasonable, although the small glitch in the interpolations at shallow depths indicates that more exploration in using the interpolative method is needed in this case.

Based on these plots, early indications are that the MATLAB function *scatteredInterpolant* does a decent job interpolating over $x$ and $Z$ for the energy deposition profiles. However, interpolating between different incident energies ($T_0$) does not appear to work as well. Further investigation needs to be done to ensure confidence in the validity of this approach over wider ranges and to determine if the approach can be effective interpolating between different values of $T_0$.

### C. *Results of Charge Deposition Interpolation*

A valid profile of the electron deposition is the second important input to charging models such as NUMIT. Again *scatteredInterpolant* was used, but this time to interpolate the charge deposition profiles for the same dielectrics: Kapton, silicon dioxide, and Teflon. Fig. 12 shows some very reasonable results for these materials.

Unfortunately, the *scatteredInterpolant* did not work effectively when it was asked to interpolate between different incident energies in the same materials. Charge deposition profiles typically have a peak at some depth. As would be expected, that peak moves towards the surface at low incident energy and moves deeper at higher incident energies. The *scatteredInterpolant* function apparently distributes the charge deposition between the two peaks when it is interpolating between two incident energies. The result is an unphysical double-peak in the deposition profile. This situation is illustrated in Fig. 13 with Monte Carlo data for 100 keV and 500 keV incident electron energies on carbon and three interpolated incident energies in between. Such a result casts further doubt on a strictly interpolative approach to an algorithm for finding deposition profiles between different incident energies.

### D. *Possible Path forward for Interpolative Approach*

Using the built-in interpolative functions in software tools such as MATLAB has important potential advantages over finding functional fits with a host of fitting parameters. The task should be simpler, and probably more importantly, the realism of such an approximation should be easily improved as

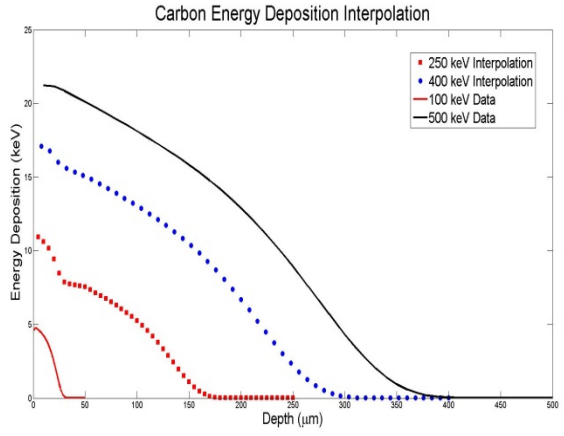


Fig. 11: Interpolation of energy deposition based on incident electron energy.

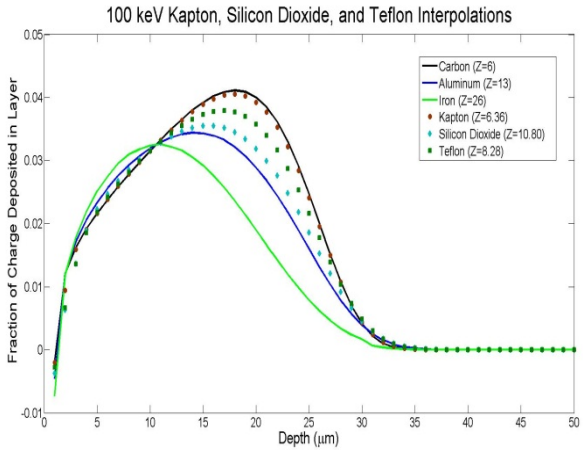


Fig. 12: Interpolation of charge deposition based on effective Z.

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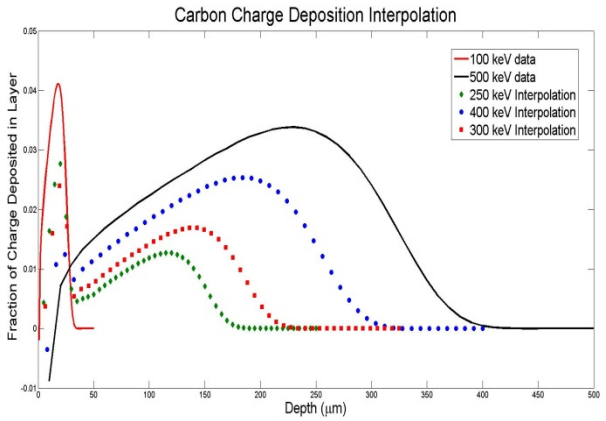


Fig. 13: Interpolation of charge deposition based on incident energy.

more Monte Carlo data is obtained. Therefore, we do not want to give up on this possible approach too hastily.

The serious issue with an interpolative approach occurred when there when trying to interpolate between different incident energies. This situation occurs most obviously when determining charge deposition profiles. Previous investigators have noticed that the shape of the energy deposition profile for beams does not really change with changing incident energy—rather, it just scales [11, 25]. Although those observations were only for energy deposition of beams, and the issue here is both energy and charge deposition from isotropic incidence, the shapes of the profiles are somewhat similar. It could easily turn out that these isotropic deposition profiles also scale. If that were the case, then an algorithm could be written that scales Monte Carlo data for different incident energies on the same material, and then incorporates an interpolative approach to determine the profiles for different materials at those energies.

It is also true that there are several interpolative functions in MATLAB that have yet to be studied for use in this approach. Some of these functions allow for more inputs than *scatteredInterpolant*, which is limited to three independent inputs for each dependent value. Not only might the interpolation work better, but the realism should increase. For example, including mass density in the inputs would bring the number of independent inputs to four ($x$, $T_0$, $Z$, and $\rho_m$), requiring the development of a surface in five-dimensional hyperspace. MATLAB claims it can do this with a function called *griddatan*, but we have not yet had an opportunity to carefully examine this possibility.

## IV. CONCLUSION

A radically new approach has been utilized to find both energy and charge deposition profiles caused by isotropically incident electrons on various materials. Monte Carlo simulations were devised and carried out using isotropic incidence which automatically accounts for secondary electron emission and backscatter of the incident electrons at all possible angles. This comprehensive approach to determining deposition profiles should prove very useful for spacecraft charging models, as previous attempts found in the literature seem to only consider one incident angle at a time.

Simulation results were obtained for a wide energy range of nearly two orders of magnitude and for five different elements spanning $Z$ numbers from 6 to 79. The results from the simulations showed a quadratic dependence of the depth profiles on incident energy at low energies with a linear dependence at higher energies. The dependence of the depth profiles on density was also determined and shown for carbon to be a simple inverse relationship. The depth profiles' dependence on $Z$ at low energies was proportional to the natural logarithm of the inverse of Z, but at higher energies deviated from this relationship. Running simulations for more atomic numbers and energies hopefully will determine this relationship more accurately.

In addition, a new method for utilizing these Monte Carlo results in charging models has been explored. Although there is some promise in the idea of using interpolative tools, rather than fitting functions to quickly find approximate deposition profiles, it has become clear that such an approach is not as simple as it might first appear. However, it may be that a combination of both scaling and interpolation will provide a workable solution.

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