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Electron Penetration Ranges as a Function of Effective Number of Valence Electrons

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Range Overview

The range is the maximum distance an electron, of incident energy *E*, can penetrate through a material before all kinetic energy is lost and the electron comes to rest. Determining the range is a common way to parameterize electron interactions with materials. One of the most common effects of this electron interaction is material charging. This charging can have devastating effects on the materials and equipment, especially when in the harsh environment of space. Therefore, it is important to develop models to predict the approximate range for a broad span of electron energies commonly encountered (~10 eV to ~10 MeV.), that are realistic, accurate, and efficient.

The composite range formula (see Fig. 1 below) has three parts for low, medium and high incident energies *E*. The inelastic mean free path λ_{min} is the range at the energy for a single inelastic collision E_{min}. m_ec^2 is the electron rest mass energy. b_R and n_R are functions of N_v.

$$R(E_b;N_V)=\begin{cases}\left[\frac{E_b}{\bar{E}}\right]\left[\lambda_{IMFP}(\bar{E})\frac{\left(1-e^{-\bar{E}/\bar{E}}\right)}{\left(1-e^{-E_b/\bar{E}}\right)^2}\right] & ;E_b<\bar{E} \quad \text{Low Energy}\\ \left[\frac{E_b}{\bar{E}}\right]\frac{\lambda_{IMFP}(E_b)}{\left(1-e^{-E_b/\bar{E}}\right)^{-1}} & ;\bar{E}\le E_b\le E_{HI} \quad \text{Medium Energy}\\ b\,E_b^{\,n}\left[1-\left[1+\left(\frac{E_b/N_V}{m_ec^2}\right)\right]^{-2}\right] & ;E_b>E_{HI} \quad \text{High Energy}\end{cases}$$

Fig. 1. Range formula: Low energy, Medium energy, High energy.

Fig. 2. Front (Left) and side (Right) views of a Lichtenberg discharge tree. The white line (Right) indicates the narrow distribution of deposited charge from a ~1 MeV electron beam at R≈3 mm in a PMMA sample.

Applications

One application of the range is for spacecraft charging calculations. Figure 8 compares the flux of electrons in the L2 radiation region above the Earth with the energy of the electrons present in that region. Range is used to predict the charge distribution of deposited electrons in materials, to model secondary and backscattered electron emission and to predict radiation induced conductivity. Range is also used to predict the distribution of energy deposited by incident electrons as they travel through a material.

This range formulation has uses in any environment with high fluxes of energetic electrons. Beta (electron) radiation is a common example used in medical imaging and cancer treatment, as well as from many other radioactive sources commonly found in nature or used in industry.

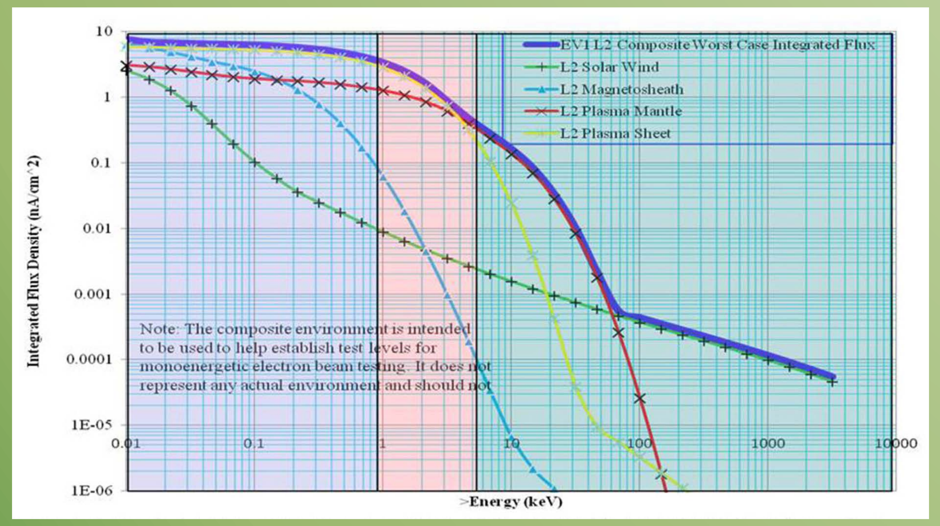

Fig. 8. Typical electron flux densities in the L2 region of space in near Earth orbit.

Abstract

The Continuous-Slow-Down Approximation (CSDA) is used to create a simple composite analytical formula to estimate the range or maximum penetration depth of incident electrons into diverse materials including conductors, semiconductors, and insulators. This formula generates an approximation to the range using a single fitting parameter, N_v, described as the effective number of valence electrons. This range of the formulation extends to electrons with energies from <10 eV to >10MeV, with 20% accuracy. A list comprised of 222 materials has been collected that greatly extends the applicability of this model. Several key material constants were compiled for each material, including the atomic number, atomic weight, density, and band gap. To determine the single fitting parameter, N_v, the model was then fit to existing data for these materials from the ESTAR and IMFP databases compiled by NIST. Comparison of N_v with the materials constants from this large database of materials is made, which could possibly lead to the prediction of N_v for materials which have no supporting data. These calculations are of great value for studies of high electron bombardment, such as electron spectroscopy or spacecraft charging.

Method

The number of valence electrons, N_v, for a given material is determined by fitting a simple composite analytic expression, developed to approximate the electron range as tabulated in two standard National Institute of Standards and Technology (NIST) databases. The ESTAR database was used for the high energy (10 KeV to 10 MeV) range and the IMFP database was used for the low energy (10 eV to 2 KeV) range. Figures 4-6 show various aspects of the fitting process.

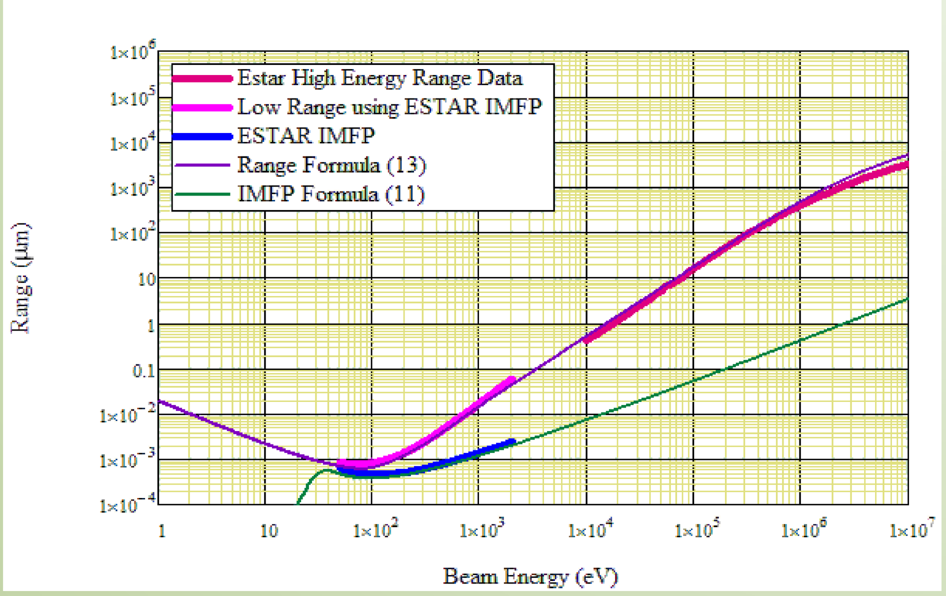

Fig. 4. Comparison of the range formula results to NIST database values for Au with N_v=12.0.

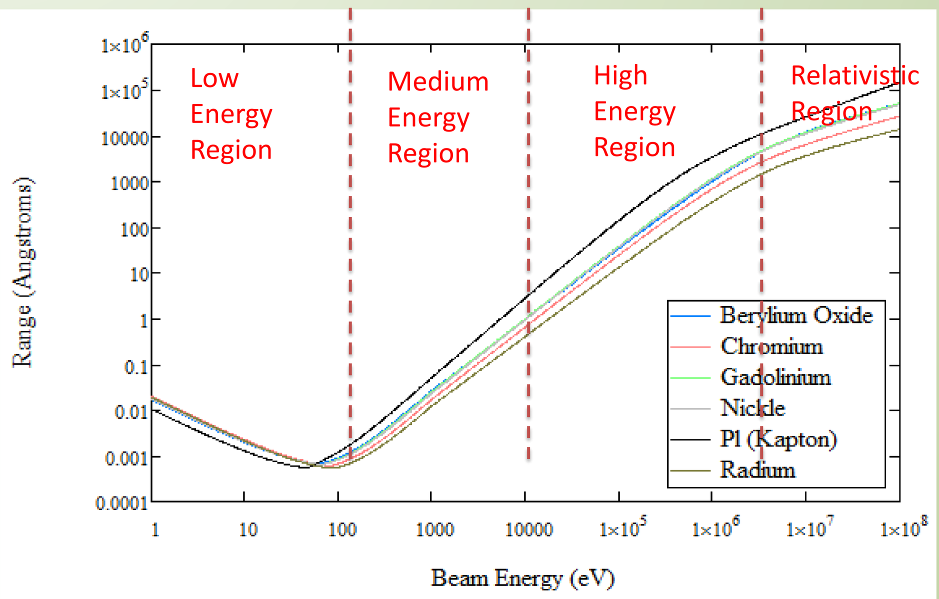

Fig. 5. Comparison of ranges for different materials. Regions corresponding to the different parts of the range formula.

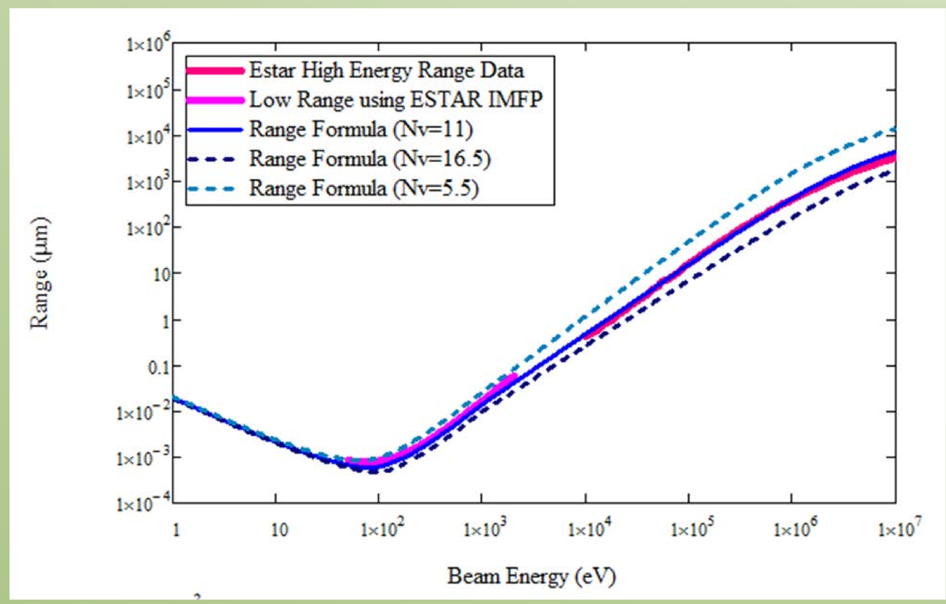

Fig. 6. Effects different N_v on results of range formula for Ag.

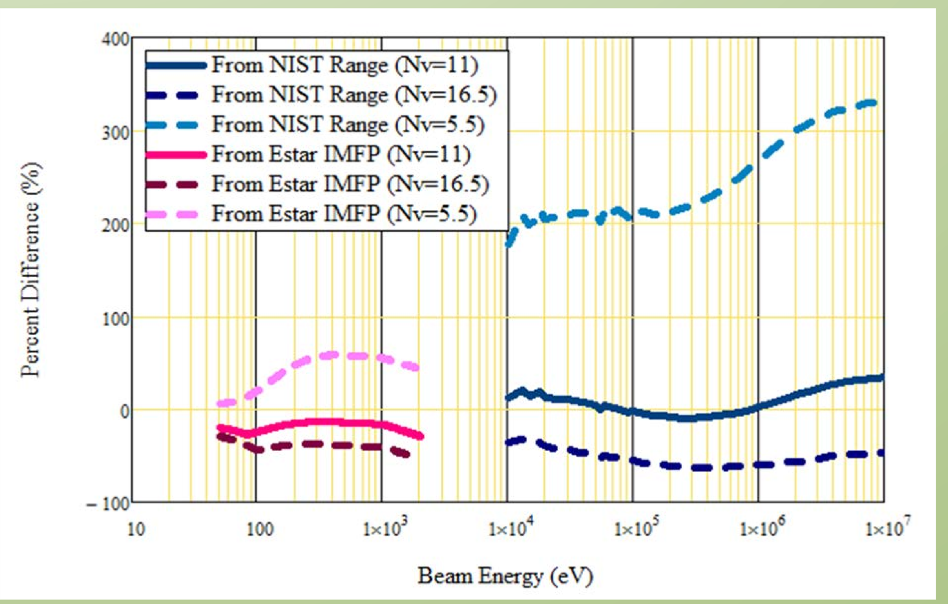

Fig 7. Comparison of single parameter fit with database values the percent difference for Ag.

References

Wilson, G., & Dennison, J.R. (2010). *Approximation of range in materials as a function of incident electron energy.*

Electronically Scanned Thinned Array Radiometer (ESTAR) and the electron Inelastic Mean Free Path (IMFP)

Extension of Materials Database

To further validate and the range formulations, comparisons needed to be performed between experimentally derived measurement and the results produced by the range equation (see Fig. 1). Two databases of experimentally acquired range data for common materials were combined with information on each of the material's physical properties. The wide variety of materials illuminates the range formula applicability across all currently tested material types including conductors, insulators, polymers, metals, and other material types. The resulting database is composed of 222 materials. Table 1 offers a small selection of the materials compiled, along with some of the materials applicable physical properties. Values of N_v for such a large number of materials also allows comparison of specific material characteristics verses N_v (see Fig. 3).

Table 1. Representative materials and specific material properties.

Material	N_v	Density (gm/cm³)	Mean Excitation Energy (eV)	Z* (Effective Atomic Number)	V_n (Effective Atomic Weight)
Chromium	3	7.18	257	4.8989	51.996
Gadolinium	12	7.9	591	8	157.25
PI (Kapton)	3.6	1.42	79.6	2.132	9.768
Berylium Oxide	4	3.01	93.2	2.414	12.505
Nickle	7	8.9	311	5.29	58.69
Radium	15	5	826	9.38	226.025

Generalization to Other Materials

To generalize the results of the study for use with materials not included in the NIST databases, a formula to estimate N_v, in terms of common materials parameters is desirable. Figure 3 compares N_v determined for database materials to several intrinsic and extrinsic properties: density, mean excitation energy, effective atomic weight, and effective atomic number. Taken together this suggests: $N_v \propto \rho_m E_m Z_{eff} A_{eff}$

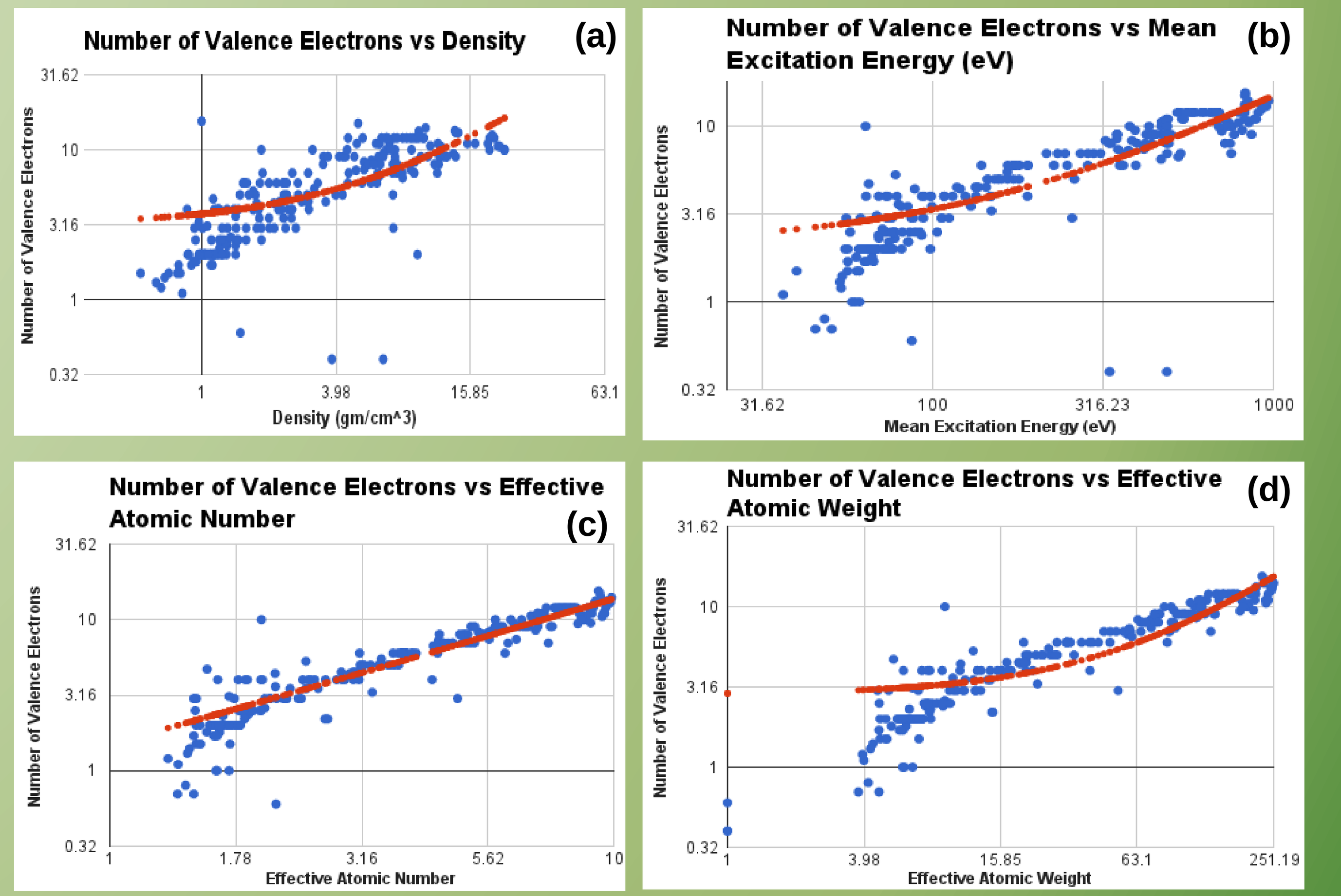

Fig. 3. N_v compared to different material properties: a) Density b) Mean Excitation Energy c) Effective Atomic Number d) Effective Atomic Weight

Future Work

Future work by the USU Materials Physics Group will:

- Develop a user friendly application to calculate the range verses incident energy for all materials in the database and for other arbitrary materials.
- Develop a general formula to predict values for N_v and the range for arbitrary materials, based on readily available materials properties.