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ON THE ENERGY DISSIPATION OF MOVING IONS IN TISSUE

W. S. Snyder
J. Neufeld

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by

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TABLE OF CONTENTS

	Page
ON THE ENERGY DISSIPATION OF MOVING IONS IN TISSUE	1-9
Nuclear Collisions	1-2
Electronic Collisions	2-8
Conclusions	9

ON THE ENERGY DISSIPATION OF MOVING IONS IN TISSUE

J. NEUFELD and W. S. SNYDER

FAST-NEUTRON irradiation of tissue produces recoil ions, and it is generally assumed that the biological damage is primarily due to the dissipation of the energy of these ions in the tissue. The energy loss per centimeter of path of a moving ion of nuclear charge Z_1 is given by

$$\left(-\frac{dE}{dx}\right)_{Z_1} = \sum_{Z_2} N_{Z_2} \sigma_{Z_1 Z_2}$$

where N_{Z_2} is the number of atoms of atomic number Z_2 per cubic centimeter of tissue and $\sigma_{Z_1 Z_2}$ is the sum of two terms,

$$\sigma_{Z_1 Z_2} = \overset{e}{\sigma}_{Z_1 Z_2} + \overset{n}{\sigma}_{Z_1 Z_2}$$

The symbol $\overset{e}{\sigma}_{Z_1 Z_2}$ represents the energy losses due to the interaction of the ion with the electrons of the tissue atoms, and $\overset{n}{\sigma}_{Z_1 Z_2}$ represents the energy losses due to the interaction of the ion with the nuclei.

The interaction with the nucleus is termed an elastic collision, the moving ion giving a fraction of its kinetic energy to the target nucleus. The term $\overset{e}{\sigma}_{Z_1 Z_2}$ represents the effect of the moving electric field of the ion on the electrons of the atoms, and these atoms may either be ionized or excited. Most of the energy lost through this type of interaction is given to the ejected electrons.

There are thus at least two mechanisms of damage, the nuclear collisions which directly displace the struck atom, and thereby disrupt the molecular structure, and the electronic collisions which produce ionization and only indirectly produce chemical changes. At high energies, all but a few per cent of the energy is dissipated through electronic collisions, but at low energies, the energy losses due to nuclear collisions become more important. The energy at which nuclear collisions become more important than the electronic collisions varies with the ion under consideration, since it is found to depend primarily on the velocity of the ion.

In this report, we discuss the relative importance of these two interactions solely on the basis of the relative amounts of energy absorbed through each. This really amounts to a comparison of

$$\sum_{Z_2} N_{Z_2} \overset{e}{\sigma}_{Z_1 Z_2} \quad \text{and} \quad \sum_{Z_2} N_{Z_2} \overset{n}{\sigma}_{Z_1 Z_2}$$

as functions of velocity of the ions.

NUCLEAR COLLISIONS

The energy loss due to nuclear collisions has been calculated by Bohr:[1]

$$\overset{n}{\sigma}_{Z_1 Z_2} = \frac{4\pi e^4 Z_1^2 Z_2^2}{M_1 M_2 V^2} \ln \left(\frac{M_1 M_2}{M_1 + M_2} \cdot \frac{V^2 a_{12}^{scr}}{Z_1 Z_2 e^2} \right) \quad (1)$$

[1] N. Bohr, *Physical Review*, **59**, p. 271 (1941).

where $(M_1\ Z_1)$ gives the mass and charge of the moving ion and $(M_2,\ Z_2)$ the mass and charge of the target. The velocity of the ions is denoted by V, e is the electronic charge, m the electronic rest mass, and

$$a_{12}^{scr} = \frac{h^2}{4\pi^2 me^2 \left(Z_1^{2/3} + Z_2^{2/3}\right)^{3/2}}$$

represents the effect of screening.

ELECTRONIC COLLISIONS

The energy losses due to electronic collisions were calculated from the formula:

$$\sigma^{e}_{Z_1 Z_2} = (i^2)_{Av}\, \sigma'_{Z_1 Z_2}$$

where $(i^2)_{Av}$ is the mean square charge of the ion and $\sigma'_{Z_1 Z_2}$ is the specific electronic stopping cross-section; i.e., the cross-section which corresponds to a moving ion having unit charge in the absence of capture or loss of orbital electrons. The assumption that the energy losses are proportional to the mean square charge of the ion should be valid for $V > \frac{e^2}{\hbar}$ but may be expected to fail for lower velocities.[2]

The specific electronic cross-section has been calculated from the formula of Neufeld:[3]

$$\sigma'_{Z_1 Z_2} = \frac{4\pi e^4}{MV^2} \sum_{r=1}^{Z_2} \frac{U_r}{V} K_o\left(\frac{U_r}{V}\right) K_1\left(\frac{U_r}{V}\right) + \frac{2\pi e^4}{MV^2} \sum_{r=1}^{Z_2} \overline{\left| O,\ ln \frac{2mV^2}{I_r \times 1.602 \times 10^{-12}} \right|} \qquad (3)$$

The first term represents the energy loss due to resonance effects, and the second term the losses due to "close" collisions. K_o and K_1 are modified Bessel functions of the first and second kinds, U_r is the orbital velocity of the rth electron and I_r is the energy in electron volts necessary to remove the electron from the atom.

The symbol $\overline{|a,\ b|}$ denotes the larger of a, and b.

The mean square charge of the ion has been determined by the procedure of Knipp and Teller (*loc. cit.*) for $Z_1 = 2, 6, 7, 8$. For $Z_1 = 1$ the experimental data of Hall[4] were used.

The graphs of

$$\sum_{Z_2} N_{Z_2} \sigma^{e}_{Z_1 Z_2} \quad \text{and} \quad \sum_{Z_2} N_{Z_2} \sigma^{n}_{Z_1 Z_2}$$

as functions of V are shown in Figures 1 through 5 for ions $Z_1 = 1, 2, 6, 7, 8$ moving in tissue.

The accuracy of this method of calculating electronic stopping powers has been checked by computing the stopping power of protons in aluminum. Figure 6 shows these results, together with the experimental curve given by Warshaw.[5] The calculated results in general agree with the experimental curve to within 7 per cent.

---

[2] J. Knipp and E. Teller, *Physical Review*, **59**, p. 661 (1941).

[3] J. Neufeld, ORNL-884 (1950).

[4] Theodore Hall, *Physical Review*, **79**, p. 504-512 (1950).

[5] S. D. Warshaw, *Physical Review*, **76**, p. 1761 (1949).

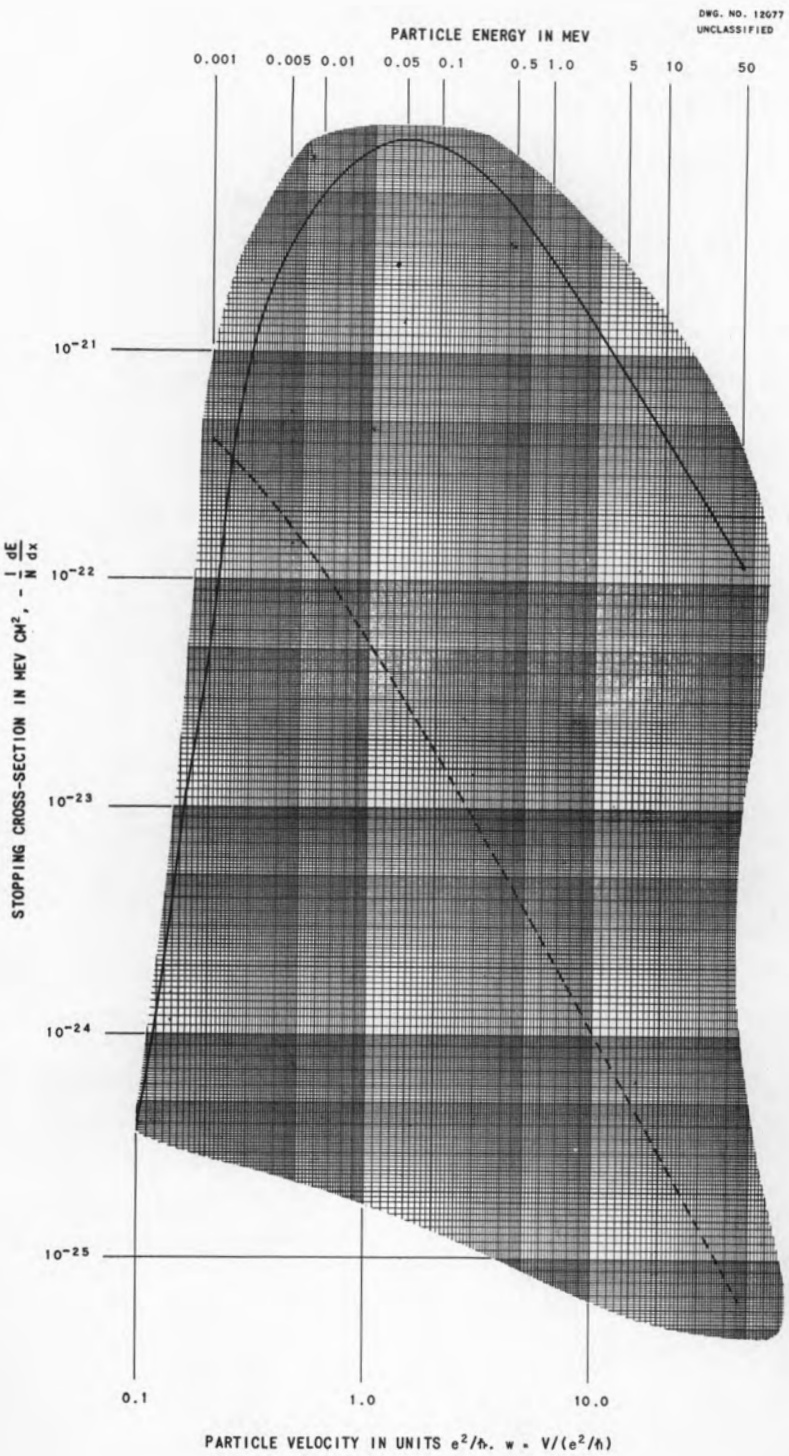

FIG. 1 – PROTONS IN TISSUE

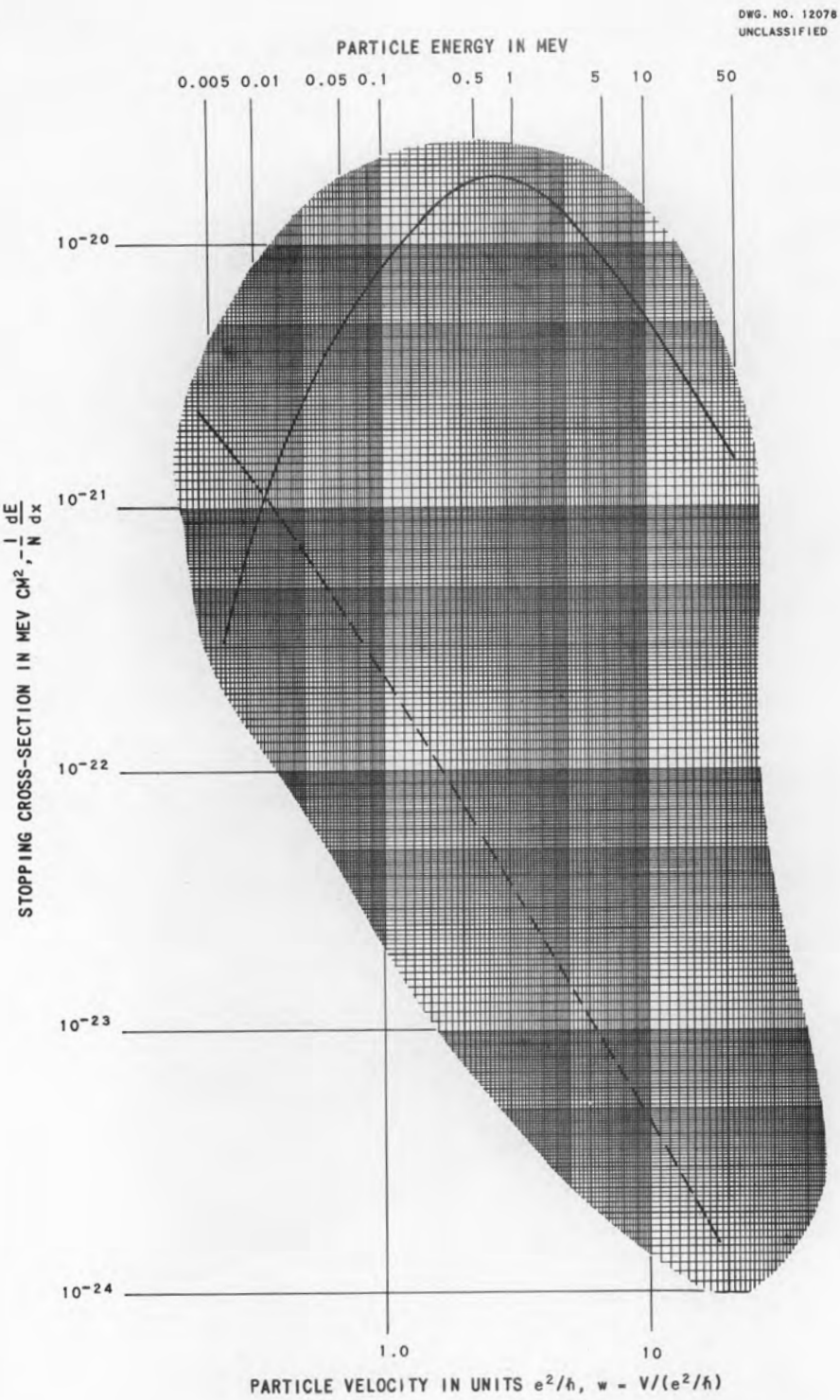

FIG. 2 – ALPHA PARTICLES IN TISSUE

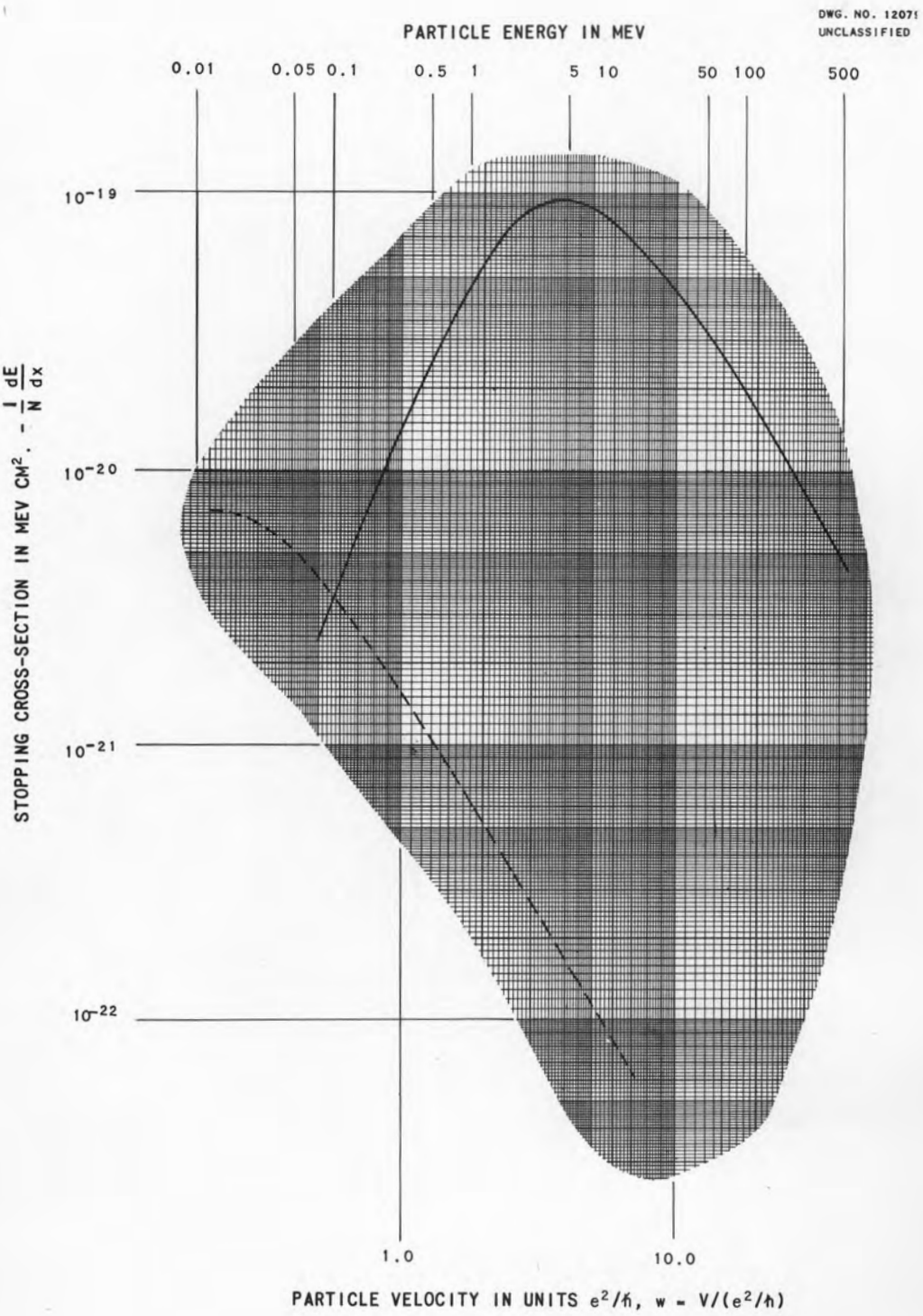

FIG. 3 – CARBON IONS IN TISSUE

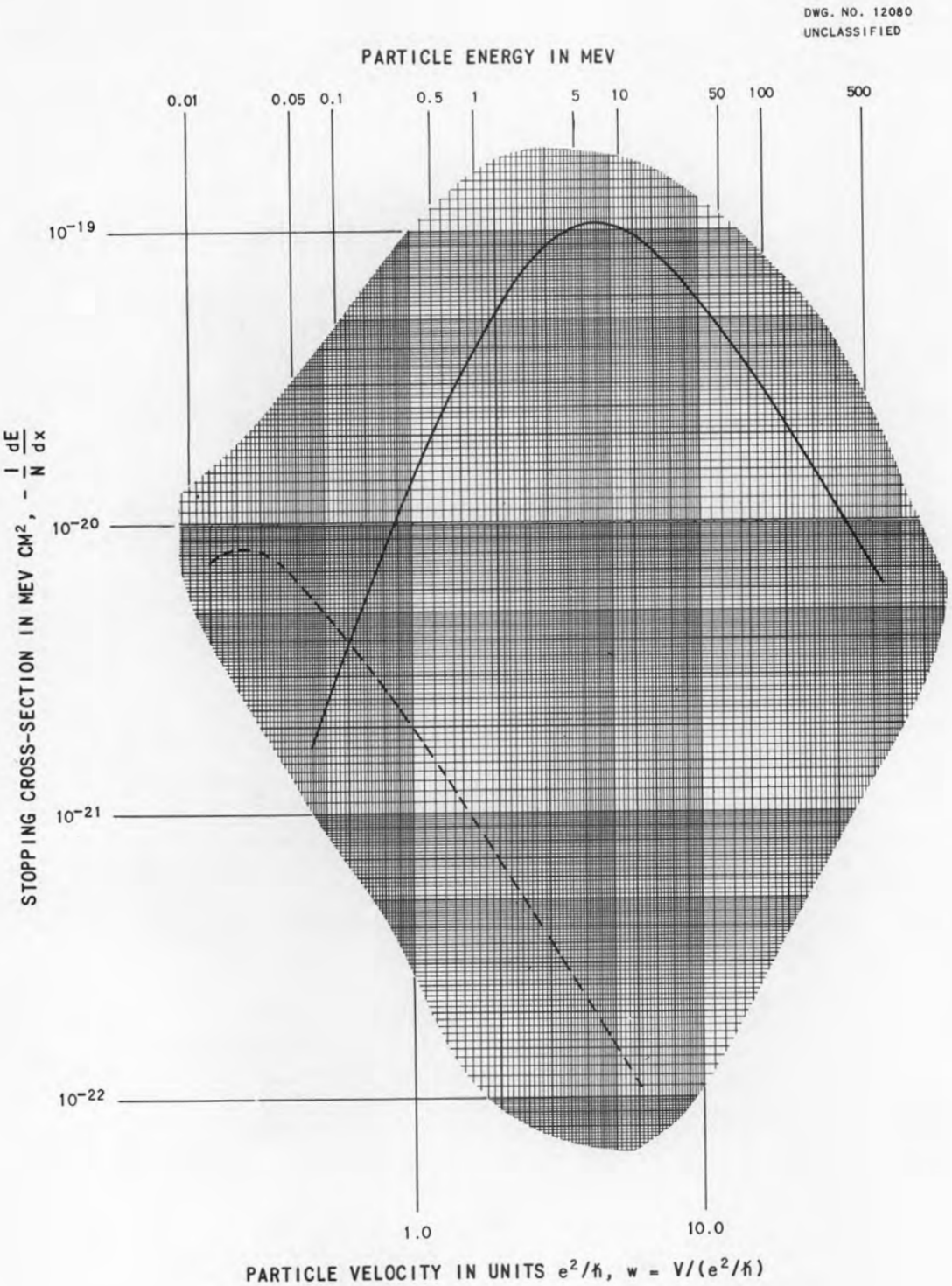

FIG. 4 – NITROGEN IONS IN TISSUE

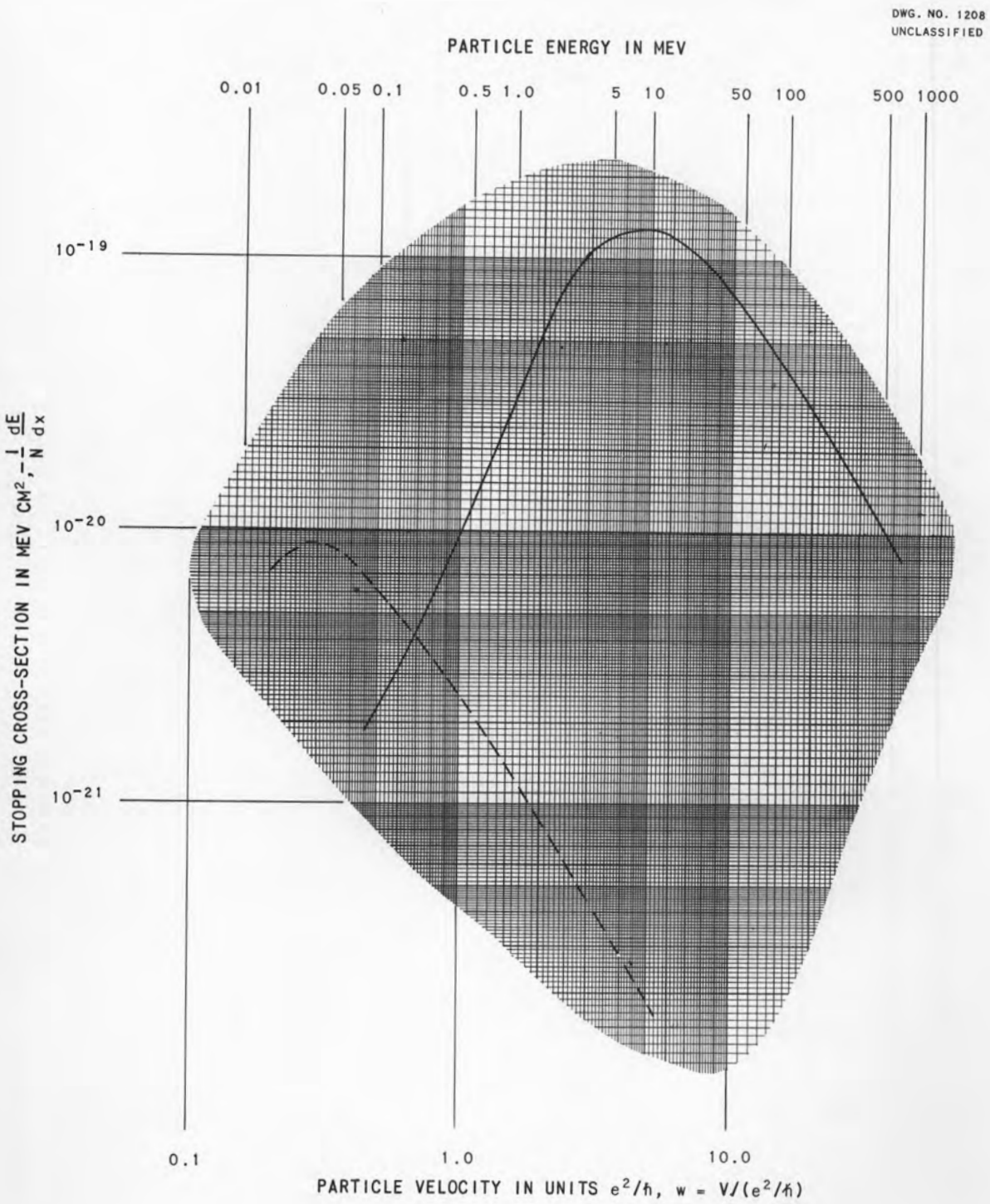

FIG. 5 – OXYGEN IONS IN TISSUE

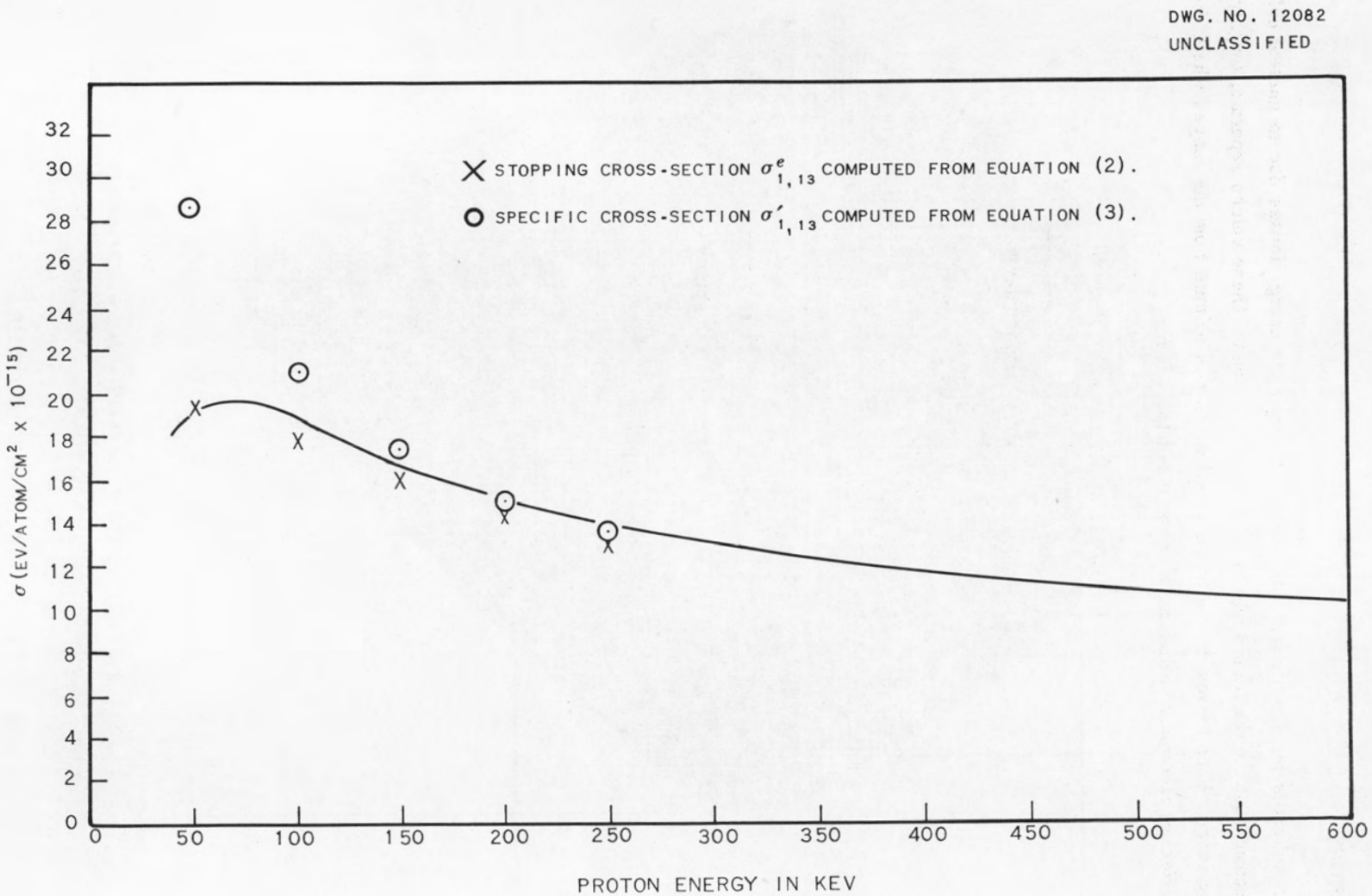

FIG. 6 – STOPPING POWER (VOLTS–CM^2) FOR PROTONS IN ALUMINUM

CONCLUSIONS

Table 1 indicates for various ions the energy at which the energy losses due to nuclear collisions become equal to the losses due to electronic collisions. These values separate, roughly, the energy range where losses due to nuclear collisions predominate from the ranges where the stopping effect of electronic collisions are most important.

Table 1

Z_1	Critical Energy Region (Mev)*
1	0.0015
2	0.013
6	0.094
7	0.13
8	0.18

*The critical energy region indicates, approximately, the energy for which

$$\sum_{Z_2} N_{Z_2} \sigma^{e}_{Z_1 Z_2} = \sum_{Z_2} N_{Z_2} \sigma^{\mu}_{Z_1 Z_2}$$

. . . . .