Basics of Radiation Dosimetry for the Physicist

http://en.wikipedia.org/wiki/Ionizing_radiation

I. Ionizing radiation consists of subatomic particles or electromagnetic waves that ionize electrons along their path in traversing materials. Examples of ionizing particles are energetic alpha particles, beta particles, protons, and neutrons.

The ability of a photons to ionize depends on the wavelength. Radiation on the short wavelength end of the electromagnetic spectrum - ultraviolet, x-rays, and gamma rays - are ionizing radiation. Longer waves, near-UV, infrared are damaging but not considered ionizing radiation.

The energy loss of a particle $-(dE/dx)$ is related to energy absorbed by the medium, "linear energy transfer", *LET*. The *LET* plays an important role in the absorbed dose given to a material or body when exposed to ionizing radiation.

$$LET \simeq -(dE/dx)$$

II. Absorbed Dose and Dose rate

The unit of absorbed dose *D* for ionizing radiation is the Gray. It is defined as the energy deposited in Joules per kilogram of material. The cgs unit of absorbed dose is the **rad**, and is slowly being phased out.

1 Gy= 1 J/kG
1Gy=100 rad

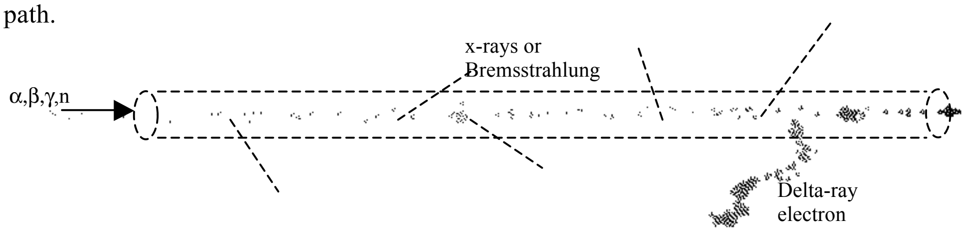
$$D = \frac{1}{m_V}\oint_V \frac{dE}{dx}\,dx \approx \frac{<E(J)>}{m(kg)} \qquad \text{dose}$$

$$A_D = \frac{dD}{dt} = \frac{<dE/dt>}{m}\left[\frac{J/s}{kg}\right] \qquad \text{dose rate}$$

III. Restricted LET

The *LET* in a target represents the degradation of energy of the incident beam particle along its quasi-linear path. But this may not strictly be equivalent to the energy absorbed in the target! This is due to the fact that the $-(dE/dx)$ may not be localized, as energy may be deposited well away from the particles line of flight.

In the trace below a particle is losing energy along it's path and then abruptly produces a delta-ray or hard knock-on electron producing significant ionization away from the flight path. The dose to the cells along the path will be dependent on the hypothetical cylinder radius, related to the energy of ionized electrons on the path.



To address the problem, we define a restricted $LET_\Delta = -(dE/dx)_\Delta$ where *Δ* represents the maximum energy transferred to an ionized electron along the quasi-path. Smaller *Δ* would indicate energy deposited closer to the quasi-path. These values are calculated and supplied in tabular form, Tables 7.1, 7.2.

Other types of radiation may escape the target area cylinder in terms of x-rays and bremsstrahlung. In radiation physics a term KERMA (*K*) is used “Kinetic Energy Released in Material” to describe radiation dose due to uncharged particles, eg. photons and neutrons,

$$K = Kcol + Krad$$

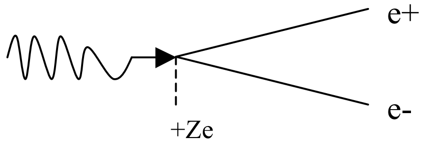
Kcol is related to LET for charged particles. (col = ionizing collisions)

Krad = x-rays + bremsstrahlung + pair production.

1) X-rays are produced when core electrons are ejected from an atoms either by charged or neutral radiation. and these levels are back-filled.

2) Bremsstrahlung is produced by accelerated charges, with electrons being highly susceptible due to their low mass.

3) Pair production is the production of an electron-positron pair by a photon in the field of a nucleus when the photon’s energy is greater than 2 electron masses, $E\gamma > 2m_e$.



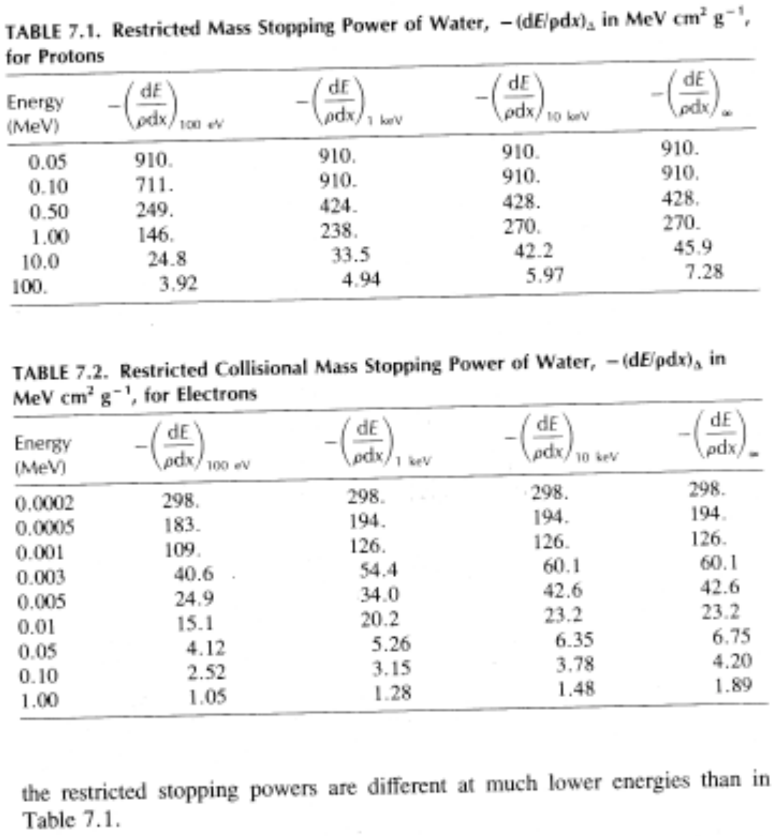


TABLE 7.1. Restricted Mass Stopping Power of Water, $-(dE/\rho dx)_\Delta$ in MeV cm^2 g^{-1}, for Protons

Energy (MeV)	$-\left(\frac{dE}{\rho dx}\right)_{100\ eV}$	$-\left(\frac{dE}{\rho dx}\right)_{1\ keV}$	$-\left(\frac{dE}{\rho dx}\right)_{10\ keV}$	$-\left(\frac{dE}{\rho dx}\right)_{\infty}$
0.05	910.	910.	910.	910.
0.10	711.	910.	910.	910.
0.50	249.	424.	428.	428.
1.00	146.	238.	270.	270.
10.0	24.8	33.5	42.2	45.9
100.	3.92	4.94	5.97	7.28

TABLE 7.2. Restricted Collisional Mass Stopping Power of Water, $-(dE/\rho dx)_\Delta$ in MeV cm^2 g^{-1}, for Electrons

Energy (MeV)	$-\left(\frac{dE}{\rho dx}\right)_{100\ eV}$	$-\left(\frac{dE}{\rho dx}\right)_{1\ keV}$	$-\left(\frac{dE}{\rho dx}\right)_{10\ keV}$	$-\left(\frac{dE}{\rho dx}\right)_{\infty}$
0.0002	298.	298.	298.	298.
0.0005	183.	194.	194.	194.
0.001	109.	126.	126.	126.
0.003	40.6	54.4	60.1	60.1
0.005	24.9	34.0	42.6	42.6
0.01	15.1	20.2	23.2	23.2
0.05	4.12	5.26	6.35	6.75
0.10	2.52	3.15	3.78	4.20
1.00	1.05	1.28	1.48	1.89

the restricted stopping powers are different at much lower energies than in Table 7.1.

From the table one sees that as the incident electron or proton energy increases the more energetic secondary ionizating electrons are produced.

Examples:

1) What is the LET_{1KeV} and LET_{5KeV} for kinetic energy 1MeV protons in water (density = 1g.cc)?

$$LET_{1KeV} = 238\ MeV/cm$$

$$LET_{5KeV} = 238 + (270 - 238) * \left(\frac{5 - 1}{10 - 1}\right)\ MeV/cm = 252\ MeV/cm \qquad \text{linear interpolation}$$

2) What is LET_{∞} for a 5.0 MeV alpha particle in water using table 7.1?

For a proton in water $LET_{\infty} = 270 - (270 - 46)\frac{5 - 1}{10 - 1} = 171\ MeV/cm$

For an alpha z=2 and $LET \sim z^2$ -> $LET_{\infty} \approx 4 \times 171\ MeV/cm = 684\ MeV/cm$

IV. Biological Dose

http://www.hps.org/publicinformation/ate/q647.html

It has long been known that radiation is harmful to man and biological samples, Acute doses of radiation sometimes referred to as "Radiation Sickness" or Acute Radiation Syndrome will occur with 24hrs.

~ 0.3 Gy	onset of radiation sickness
> 0.7 Gy	is considered a large dose, with destruction of bone marrow, nausea, vomiting, fever.
>1.2 Gy	internal bleeding and infections may be deadly
2.5-5.0 Gy	50% mortality withing 60 days
6.0-10.0 Gy	Loss of cells lining the gastrointestinal tract, severe diarrhea
10Gy	~100% mortality withing 14 days
20-50Gy	cardiovascular and nervous system damage, collpase, 3days
50Gy	

RBE

Radiation damage effects to biological samples are better calculated with a biological damage factor call an RBE (Relative Biological Effectivness) multiplying the dose. The units of biological dose are

1 sievert = D(Gy) x RBE
1 rem = D(rad) x RBE

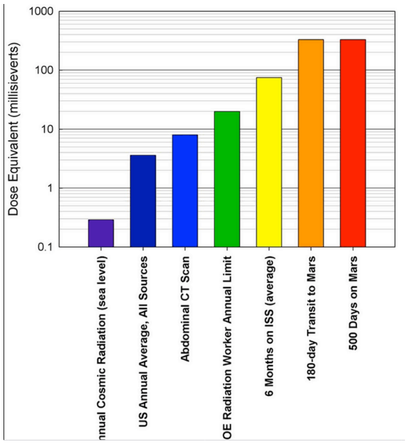
RBE factor

To determine RBE a standard dose D_X is used to induce damage in a biological sample. A similar biological damage induced by dose D_{TEST} of an emitter under test. The ratio defines the RBE factor:

$RBE = D_X / D_{TEST}$ = Dose from reference radiation / Dose from test radiation

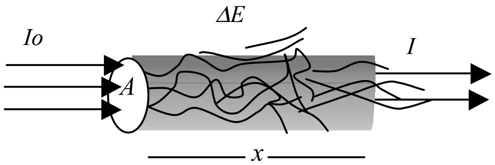
If it took 200 mGy of x rays to produce the same biological effect as 20mGy of neutrons, the RBE would be 200/20 = 10 using x rays as the reference radiation.

D_{TEST} Type	RBE
X-rays and Gamma rays	1.0
Betas	1.0-1.7
Alphas	10-20
Slow Neutrons	4-5
Fast neutrons and protons	10
Heavy ions	20


Dose Equivalent (millisieverts)
1000
100
10
1
0.1
nnual Cosmic Radiation (sea level)
US Annual Average, All Sources
Abdominal CT Scan
OE Radiation Worker Annual Limit
6 Months on ISS (average)
180-day Transit to Mars
500 Days on Mars

V. **Dose due to Sources and Particle Beams**

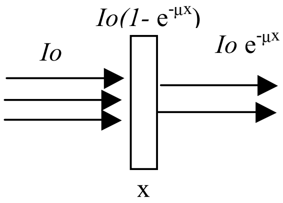
Radioactive sources and particle beams are generally specified in terms of activity (dps), beam intensity $I(\#/s) = N/s$, particle flux $F(\#/area - s) = N/A - s$, or current $I(C/s) = N \cdot e/s$. The dose delivered to a volume of area *A* of thickness *x* $(m_V=\rho V)$, by a source or beam with energy loss *ΔE* will be determined by the LET = *–dE/dx* stopping power laws or photon attenuation law $I = I_0 e^{-\mu x}$.



$$D = \frac{I_{beam}(A)}{e} \cdot \Delta t \cdot \frac{\overline{\Delta E}}{m_V}$$

1) Dose due to Photon Beams

Photon beams are penetrating and we can estimate the dose by finding the fraction of the beam absorbed in the target and assuming the gamma energy E_γ is deposited . If $I_o e^{-\mu x}$ of the beam is transmitted, then $I_o(1 - e^{-\mu x})$ is absorbed. The dose is given by



$$D = I_{beam} \cdot \Delta t \cdot \frac{1}{m_V} \cdot \overbrace{\left(1 - e^{-\mu x}\right)}^{fraction\,absorbed} \cdot E_\gamma$$

Example: A 1 MHz beam of 662 KeV photons impinges on your hand (2 cm H_2O) for 30s. What is the radiation dose? Assume the energy is deposited in 1 cm^3 flesh ~ 1g.

$\mu = 0.09\ cm^{-1}$ $\qquad \rho_{H20} = 1\ g/cm^3$

$\Delta E = (10^6 s^{-1})(30s)(1 - e^{-(0.09cm^{-1})(2cm)})(662KeV) = 3.3\text{x}10^{12}\text{eV} = (3.3\text{x}10^{12}\text{eV})(1.6\text{x}10^{-19})\text{J} = 5.3\text{x}10^{-7}\text{J}$

$D = \dfrac{5.3\text{x}10^{-7}\text{J}}{10^{-3}kg} = 5.3\times10^{-4}\text{Gy} \qquad \text{RBE=1} \qquad \boxed{D_{bio} = 0.53mSv}$

2) Dose due to Stopped Electrons

Electrons loose energy in matter by both ionization and brehmstrahlung radiation. An electron range table can be used to estimate the energy loss. If we assume that *dE/dx* is about constant.

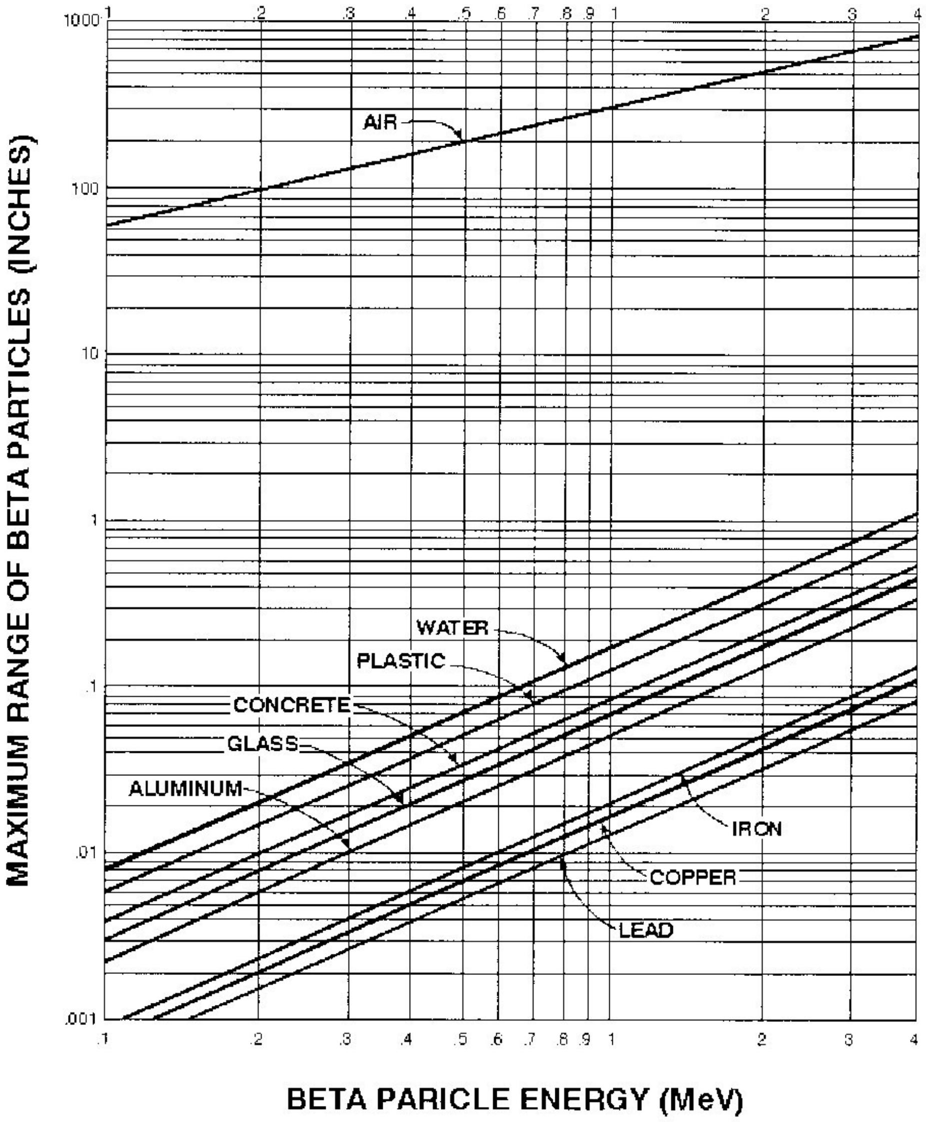
$$\Delta E = \int_0^{R_{\max}} (dE/dx)\ dx \sim \overline{dE/dx}\ \ R_{\max}$$

Example: Find the dose to a your palm (x=1cm) by holding a 1MeV β^- source (1 μCi) in your palm for a minute. Assume the energy is deposited in 1 cc of flesh =1g. (1 Ci= 3.7e10 dps). Let $\text{RBE}_{\text{electrons}}$ = 1.5.

From the range table 1 MeV corresponds to a range of 0.2 inches = 0.51cm. At 1MeV *dE/dx* = 1.89 MeV/cm from Table 7.1 . Then *ΔE*/decay = (1.9 MeV/cm)(0.51cm) =0.97 MeV/decay = $1.55\text{x}10^{-12}$J
D = [($1.55\text{x}10^{-12}$J x $3.7\text{x}10^{4}$ dps) / 0.001kg)](60s) x ½ = 0.0017 Gy
D_{bio}= 1.7mSv x RBE_e = 2.55 mSv

MAXIMUM RANGE OF BETA PARTICLES

as a Function of Energy in Various Materials



3) Heavy Charged particles

Heavy charged particles loose energy primarily by atomic ionization processes.

$$-\frac{dE}{dx} = \frac{2\pi z_1^2 e^4 NZ}{M_o^2}\ln\left(\frac{2M_o^2 Q_{\max} - 2\beta^2}{I^2(1-\beta^2)}\right) \qquad Bethe - Bloch\ \ Formula$$

We can determine *dE/dx* from a table or use the Bethe-Bloch Formula. For cases where the absorber is thin or *-dE/dx* is about constant we can use equation , $D = \frac{\overline{\Delta E}}{m}$.

Table: dE/dx for Alphas in Air		
MeV	MeV cm2/g	MeV/cm
1.0	1924	2.48
1.5	1626	2.09
2.0	1383	1.78
2.5	1206	1.55
3.0	1072	1.38
3.5	969	1.25
4.0	887	1.14
4.5	818	1.06
5.0	761	0.98
5.5	712	0.91

Example: Determine the energy loss for 5 MeV alpha particles in 1 cm of air from the values in your table. What is the alpha range *R(cm)*? (ρ_{AIR} = 1.205 x 10^{-3} g/cc @NTP)

a) *-dE/dx* = 0.98 MeV/cm from the table.

b) The alphas will travel on average $R = \frac{E_\alpha}{dE/dx}$ = 5 MeV/0.98 MeV/cm ~ 5 cm-air

Example: A current of 2 µA is observed in a gaseous ionization chamber (W=36eV/ip) from a 1g lung sample contaminated with the alpha emitter Th-230. What is the sample activity and observed dose rate from the 1 g tissue? The alpha energy is E_α= 2.68 MeV

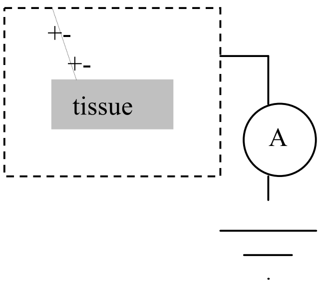
$$I = 2\times10^{-6} A = \frac{2\times10^{-6} C/s}{1.62\times10^{-19} C/e} = 1.24\times10^{12}\ e/s\ detected\ current$$

$$\frac{E_\alpha}{W} = \frac{2.68\times10^6 eV}{36eV/ip} = 7.44\times10^4 ip/decay\ \ in\ the\ chamber$$

$$A = \frac{1.24\times10^{12}\ e/s}{7.44\times10^4\ ip/decay} = 1.67\times10^7 dps\ \ \ Activity$$

$$\dot{D} = A\cdot\frac{\Delta E}{m} = 1.67\times10^7 dps\frac{(2.68\times10^6)(1.6\times10^{-19})J/eV}{0.001kg}$$

$$= 7.2\times10^{-3} Gy/s\ \ \ observed\ dose\ rate$$

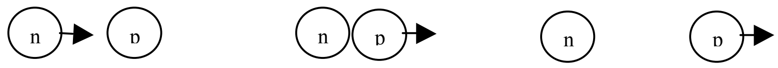


4) Neutrons

(a) Fast neutrons (>2-3 MeV) deposit energy by scattering from protons in matter.

$$n + X_Z^A \rightarrow X^{*A}_{Z-1} + p \rightarrow X^A_{Z-1} + \gamma + p$$

The neutron slows and with energy transferred to the proton. The charged proton then looses energy by ionizing *-dE/dx*. The neutron may then collide again and again to achieve s*low* or *thermal* energy.



Light elements like boron and proton rich polyethylene can be used as effective neutron shields for fast neutrons. *The neutron will loose about 1/2 of it's original energy in the collision.*

Example - Fast neutron energy transfer:
Calculate the first collision dose rate (D/s) to tissue per unit fluence 1/(cm^2-s) of 5 MeV neutrons. First collision refers to full neutron energy transfer.

dD/dt = (1/s) (½) (5.0MeV) /1g = 2.5 MeV/s = 4.0e-13 Gy/s

(b) Slow and thermal neutrons (<<1MeV) are captured by nuclei, leaving the nucleus in an excited state. The nucleus may then de-excite by gamma emission. Gamma shielding may need to accompany neutron shielding! The neutron capture reaction $n + N^{14} \rightarrow p + C^{14}$ releases *Q* = 626KeV of kinetic energy to be shared between proton and C^{14}.

$$N^{14}(n,p)C^{14} \qquad Q = 626 \text{ KeV}$$

A neutron source with activity *A* =*dN/dt* would deliver a dose *D* = *A Δt Q*

Example - Slow neutron capture:
Calculate the *Q* value for the neutron capture reaction $n + N^{14} \rightarrow p + C^{14}$. What is the biological dose rate from a neutron emitter with activity *A* = 1Mbq in to a 1kg sample of tissue.

Q = [m(n)+m(N-14) – m(p) –m(C-14)]c^2= 626KeV
dD/dt =(A Q / m) x RBE = (10^6/s (626KeV) /1kg) x RBE = 5 (6.26 x 10^{11}) (1.6x10-19 J/eV) = 5 e-7 Sv

Exercise I -Proton Radiation Therapy and the Bragg Peak

In this exercise we will look at how protons slow down in body tissue. The table on the left gives the proton energy loss from the Bethe-Block formula for water (~body tissue). We divide the persons depth into 20 1cm divisions and look at the energy and loss in each section.

Imagine at 0cm we shoot a Eo= 100MeV beam into the body. The energy loss from the table is ~7.3 MeV/cm. So in the next step the beam energy has degraded to E1=(100 – 7.3)MeV = 92.7 MeV. I have completed the first 3 steps. Finish the table until the proton beam has reached zero energy. You should interpolate to reasonable accuracy.

At what depth does the energy loss (Column 3) maximize? D_{MAX} = ___________________

This abrupt rise in the energy loss at D_{MAX} is called the Bragg peak. You have determined the approximate range of a 100 MeV the proton in tissue (water). In cancer therapy with proton beams the proton energy and thus position of the Bragg peak is calculated to coincide with the tumor position. Radiation dose to other organs can be better avoided Remember Xrays and gamma rays have an exponential attenuation $I = I_o \exp(-\mu x)$ and would spread the radiation throughout in the depth profile. Thus an advantage with protons.

E **MeV**	**dE/dx** **MeV/cm**
0.0100	500.00
0.0400	860.00
0.0500	910.00
0.0800	920.00
0.1000	910.00
0.5000	428.00
1.0000	270.00
2.0000	162.00
4.0000	95.400
6.0000	69.300
8.0000	55.000
10.000	45.900
12.000	39.500
14.000	34.900
16.000	31.300
18.000	28.500
20.000	26.100
25.000	21.800
30.000	18.700
35.000	16.500
40.000	14.900
45.000	13.500
50.000	12.400
60.000	10.800
70.000	9.5500
80.000	8.6200
90.000	7.8800
100.00	7.2800
150.00	5.4400
200.00	4.4900
300.00	3.5200
400.00	3.0200
500.00	2.7400
600.00	2.5500
700.00	2.4200
800.00	2.3300
900.00	2.2600
1000.0	2.2100
2000.0	2.0500
4000.0	2.0900

Depth	Proton Energy	-dE/dx
0cm	100 .0 MeV	7.3 MeV/cm
1cm	92.7 MeV	7.7 MeV/cm
2cm	85.0 MeV	8.2 MeV/cm
3cm		
4cm		
5cm		
6cm		
7cm		
8cm		
9cm		
10cm		
11cm		
12cm		
13cm		
14cm		
15cm		
16cm		
17cm		
18cm		
19cm		
20cm		

Exercise II - Energy-Range Relationship

The range of a charged particle in matter can be determined from the dE/dx table or Bethe-Bloch formula (2) .

$$R = \int_E^0 \frac{1}{dE/dx} dE \qquad (2)$$

(1) Calculate the range of a 200 MeV proton by converting the integral to a sum

$$R = \sum_{i=200MeV}^{0MeV} \left(\frac{1}{dE/dx}\right)_i \Delta E_i \; = \; (1/\,4.49)\;50 + (1/5.44)50 + \;(1/7.28)10 + \ldots\ldots \; = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \text{ cm}$$