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Ranges of alpha particles in various media

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It is now well established that the TL or ESR signal induced by an alpha particle is very nearly proportional to its range (Aitken and Bowman, 1975; Lyons, 1988; Lyons and Brennan, 1989a, 1989b). Knowledge of the variation of alpha particle range with energy is thus important to the estimation of the alpha particle contribution to the environmental dose rate for samples used in ESR and TL dating. Zimmerman (1971) used data on ranges in aluminium from Marion and Young (1968) to infer ranges in ceramics, while interpolations between neon and sodium in the tabulations of Northcliffe and Schilling (1970) and Williamson et al. (1966) were used by Aitken and Bowman (1975) to estimate ranges in pottery. A later tabulation by Zeigler (1977) has been employed by Lyons and Brennan (1989a, 1989b) to estimate ranges in calcite, and by Valladas (1988) to tabulate stopping powers and ranges in silica.

A more recent volume by Zeigler et al. (1985) provides a data set which is a development of the work of Zeigler (1977) and companion volumes relating to heavy ions other than alpha particles. Because the 1985 volume employs a more complete and recent set of experimental data together with improvements in the calculation techniques employed, the results are more reliable than the 1977 volume and earlier tabulations referred to above. Zeigler and his co-workers make available computer software for the calculation of ranges and stopping powers and Monte-Carlo simulation of target penetration by heavy ions. The software is updated continuously and the most recent (1988) version is written in TURBO-BASIC for an IBM-PC or compatible computer.

In this paper we present the results of calculations employing the software provided by Zeigler and his co-workers. We used the implementation of the PRAL transport equation to calculate average projected ranges (that is, distance traveled in the original direction of motion) for alpha particles in the various media. While it might be argued that the total path length is the fundamental determinant of ionization damage and thus ESR or TL signal for an alpha particle, the difference between total and projected path length is less than 1% for energies of 1 Mev or greater; and in addition the projected path length is fundamental to estimation of dose due to sources external to a sample. In Zeigler's 1988 computer program, the stopping power of the target is calculated as the appropriately weighted sum of the stopping powers of the constituent elements, and bonding corrections can be made for some bonds involving light elements. Nuclear as well as electronic stopping effects are including. The stopping powers for carbon and oxygen in solids have been used. Base data for stopping powers is in units of eV/(1×10^{15} molecules cm^{-2}), but range data is presented here in mg cm^{-2} for ease of comparison.

The compositions used for the various materials are given in table 1. As Zeigler's software accepts no more than 6 elements, it was sometimes necessary to combine some of the lower concentration elements with others of similar atomic number e.g. aluminium and magnesium, potassium and calcium. Note that most materials which are commonly used in ESR or TL dating have similar effective atomic masses (A_{av}) and charges (Z_{av}) with the result that their ranges are very similar if measured in mg cm^{-2} (fig. 1). The most notable exception is bone, which has a much lower effective atomic mass and charge due to the high proportion of hydrogen and carbon, and hence shorter ranges. Silica and dry pottery represent the extremes for the remaining dating materials, with the majority lying closer to silica than to pottery.

While the difference between some materials may not be significant in a particular application, all the data sets are included in table 2 for completeness as they represent the most up-to-date information available; it is left to the user to assess the degree of accuracy required. For simplicity of presentation the corresponding stopping powers are not tabulated here; they may be derived from Zeigler's software or from the equations in table 3. Alternatively, we would be pleased to supply them and/or more details of range data on request.

From the values given in table 2 the ranges for other energies may be readily obtained by interpolation using, for example, a cubic spline. Alternatively, ranges for each compound may be generated using the cubic polynomials for range as a function of energy given in table 3. These polynomials were obtained by a least squares fit to 80 range data points which were approximately logarithmically distributed between 10 keV and 10 MeV, and are accurate to within 0.01 mg cm^{-2} for ranges up to 10 MeV. The differential with respect to energy (dR/dE) gives quadratics from which ranges and stopping powers (dE/dR) may be

Table 1. Ranges in mg cm^{-2} for alpha particles of different energies (MeV) for dating materials:

a) simple

Energy	$CaCO_3$	SiO_2	Albite	Orthoclase	Anorthite	Al
0.01	0.026	0.027	0.027	0.027	0.027	0.027
0.05	0.096	0.098	0.098	0.100	0.100	0.101
0.10	0.155	0.156	0.155	0.160	0.159	0.160
0.15	0.203	0.201	0.200	0.206	0.206	0.209
0.2	0.245	0.241	0.240	0.247	0.248	0.254
0.3	0.322	0.311	0.311	0.319	0.323	0.337
0.4	0.391	0.374	0.376	0.385	0.392	0.418
0.6	0.519	0.495	0.500	0.511	0.522	0.576
0.8	0.644	0.615	0.623	0.635	0.651	0.737
1	0.769	0.739	0.750	0.764	0.782	0.901
2	1.50	1.47	1.49	1.52	1.55	1.82
3	2.44	2.42	2.45	2.49	2.52	2.94
4	3.59	3.58	3.60	3.67	3.71	4.27
5	4.94	4.93	4.96	5.05	5.10	5.80
6	6.48	6.47	6.49	6.62	6.67	7.53
7	8.19	8.19	8.21	8.38	8.42	9.46
8	10.07	10.07	10.09	10.31	10.35	11.58
9	12.12	12.13	12.15	12.41	12.45	13.88
10	14.33	14.35	14.38	14.68	14.72	16.38

b) complex

Energy	Bone	Plagioclase	Pottery (sat)	Basalt	Pottery
0.01	0.021	0.027	0.027	0.027	0.027
0.05	0.074	0.099	0.099	0.101	0.101
0.1	0.118	0.157	0.156	0.161	0.161
0.15	0.154	0.203	0.202	0.208	0.208
0.2	0.186	0.244	0.242	0.251	0.250
0.3	0.242	0.317	0.313	0.326	0.324
0.4	0.293	0.384	0.378	0.395	0.391
0.6	0.387	0.511	0.501	0.525	0.520
0.8	0.479	0.637	0.624	0.653	0.648
1	0.575	0.766	0.751	0.785	0.782
2	1.15	1.52	1.5	1.56	1.56
3	1.92	2.48	2.47	2.55	2.57
4	2.87	3.66	3.64	3.75	3.78
5	4.00	5.03	5.01	5.15	5.2
6	5.28	6.58	6.57	6.75	6.8
7	6.72	8.32	8.31	8.53	8.6
8	8.3	10.22	10.23	10.48	10.57
9	10.04	12.3	12.31	12.61	12.72
10	11.92	14.55	14.57	14.91	15.05

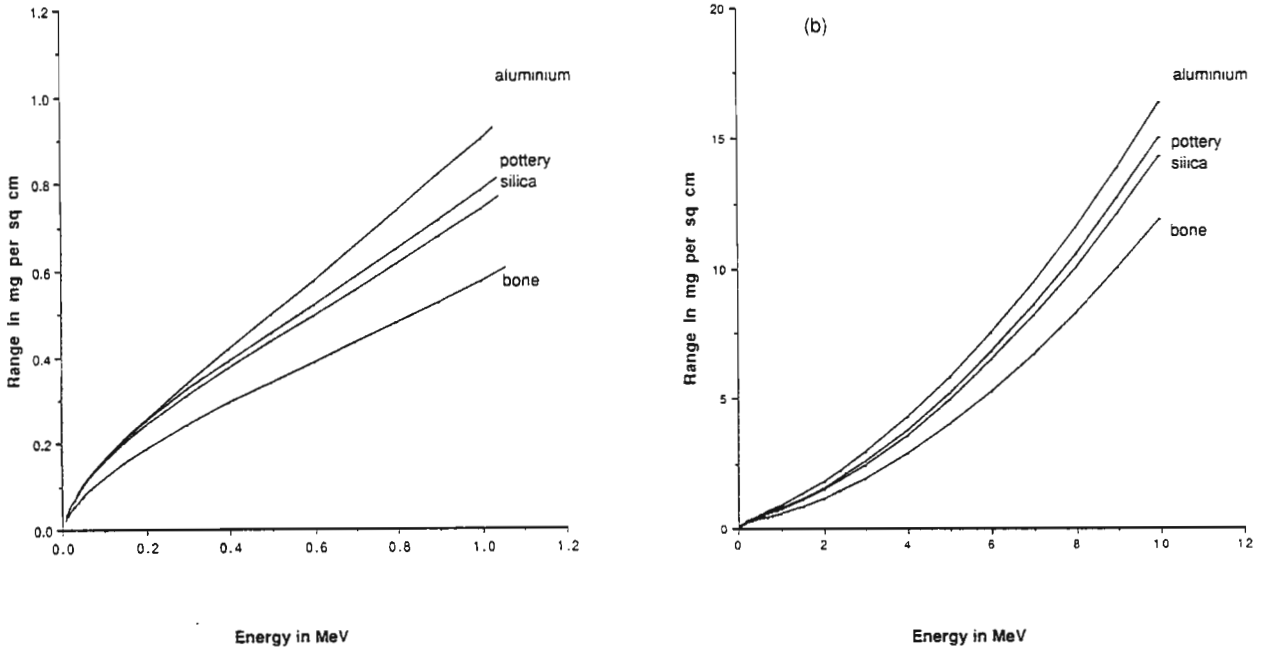

Figure 1.
Range as a function of energy for typical dating materials a) 0-1 MeV b) 0-10 MeV. Silica and dry pottery represent the extremes for most dating materials, except bone, with the majority lying closer to silica than pottery.

Table 2. Compositions, average atomic weights (A_{av}) and atomic numbers (Z_{av}) of dating materials used in calculating ranges. Note that, as the composition for pottery is highly variable, the values given for pottery are approximate only. Specific values, where required, must be derived from the actual composition of the sample. Compositions are in % by weight.

$$A_{av} = \left(\frac{\Sigma\, n_i\, A_i}{\Sigma\, n_i\, A_i^{0.5}} \right)^2 \qquad A_{av} = \left(\frac{\Sigma\, n_i\, Z_i}{\Sigma\, n_i\, Z_i^{0.5}} \right)^2$$

where n_i is the atomic abundance of the ith element.

Material	A_{av}	Z_{av}	Composition (% by weight)
Albite	20.1	10.2	$NaAlSi_3O_8$
Aluminium	27.0	13.0	Al
Anorthite	22.0	10.9	$CaAl_2Si_2O_8$
Basalt	22.8	11.3	SiO_2 (45), Al_2O_3 (14), FeO (10), Fe_2O_3 (3), MgO (11), CaO (10),Na_2O (3), TiO_2 (2), K_2O (1)
Bone	11.8	5.6	H (7), C (30), O (44), P (4), Ca (15)
Calcium carbonate	21.1	10.5	$CaCo_3$
Orthoclase	22.0	10.2	$KAlSi_3O_8$
Plagioclase	21.2	10.5	50% albite/50% anorthite
Pottery (dry)	23.1	11.3	SiO_2 (70), Al_2O_3 (15), Fe_2O_3 (5), K_2O (3), CaO (2), MgO (2), NaO (1), TiO_2 (1)
Pottery (sat.)	21.0	10.2	as above (93), H_2O(7) ie 15% porosity
Silica	20.4	10.2	SiO_2

Table 3. Coefficients for polynomial approximations for deriving ranges in mg.cm^{-2} for alpha particles of different energies (MeV),
$R = A_3E^3 + A_2E^2 + A_1E + A_0$
Note that the constant term is negligible in the low energy polynomials as R = 0 for E = 0. The corresponding equations for stopping powers may be calculated as the reciprocal of dR/dE.

Material	0 - 1 MeV			1 - 10 MeV			
	A_3	A_2	A_1	$A_3.10^3$	A_2	A_1	A_0
Albite	0.73	-1.28	1.29	-1.14	0.1107	0.422	0.22
Anorthite	0.72	-1.29	1.33	-1.26	0.1143	0.431	0.24
Basalt	0.75	-1.33	1.36	-1.37	0.1174	0.430	0.24
Bone	0.55	-1.00	1.01	-1.26	0.1012	0.286	0.19
Calc carb.	0.68	-1.26	1.33	-1.45	0.1160	0.391	0.26
Orthoclase	0.77	-1.36	1.34	-1.31	0.1158	0.416	0.23
Plagioclase	0.72	-1.29	1.31	-1.26	0.1135	0.423	0.23
Pottery	0.78	-1.37	1.35	-1.18	0.1152	0.448	0.22
Pottery (sat)	0.76	-1.33	1.31	-1.25	0.1140	0.420	0.22
Silica	0.76	-1.34	1.31	-1.36	0.1146	0.402	0.22

calculated. Valladas (1988) quotes linear expressions for dR/dE analogous to the expression 1+0.29E used by Zimmerman (1971). We note, however, that Zimmerman in fact assumed that dR/dE was proportional to (1 + 0.29E) , and, in the absence of the appropriate proportionality constants, the expressions quoted by Valladas do not provide useful estimates for dR/dE.

For silica, the ranges calculated using the 1988 implementation of Zeigler are 10 - 5 % percent smaller (for alpha energies from 3 - 10 MeV) than the ranges based on the data of Zeigler (1977), presented in Valladas (1988). In absolute terms the differences increase from 0.1 mg cm^{-2}, for 50 keV alphas through 0.31 mg cm^{-2} for 4 MeV alphas to 0.66 mg cm^{-2} for 10 MeV alphas. Differences are due largely to the updated data set and calculation method but the use of projected range instead of total range also makes a small contribution, reducing the ranges calculated by approximately 0.05 mg cm^{-2} (<1% for all alphas above 4 MeV).

Because the composition of pottery is highly variable, the difference between compositions used in range calculations may outweigh the effect of using different calculation methods. For example, the composition we used for dry pottery, which lay between the extremes we found in a brief literature search, gave us an A_{av} and Z_{av} of 23.1 and 11.3 (cf values of 21.4 and 10.6, respectively, in Bowman, 1982). Our higher values for A_{av} and Z_{av} were sufficient to offset the difference in calculation methods and coincidentally yielded very similar ranges to those cited in Aitken and Bowman (1985).

We have compared the different calculation methods, including one given in Benton and Henke (1969), by applying them to calcium carbonate (fig. 2). Note that the ranges derived by other methods are not simply proportional to the Zeigler (1988) ranges. The discrepancies are not large at the energies found in the natural environment, being generally less than 8%. At the energies below 1 MeV the differences are much more striking and may be important in estimating alpha doses due to external sources. It may reasonably be inferred that similar variations would also result from the application of the different methods to other materials.

Total ranges per parent disintegration for the uranium and thorium series, assuming equilibrium, in the various materials are given in table 4. Energies and branching ratios are taken from Nambi and Aitken (1986). The branching ratios in the Th-232 and U-235 chains have been applied to the ranges of the contributing alpha particles, not to the energies, as it is the average tracklength that is required, not the tracklength corresponding to the average energy. The difference in the two methods is small; averaging energies gives an underestimate of 1.5% for the branch in the Th-232 chain i.e. only 0.4% in the total Th-232 chain in equilibrium.

If dose rates are being calculated from range data, as in Aitken (1985), p287, the relevant data on total ranges from table 4 may be used to derive the average alpha ranges for lines 12 and 13 in Aitken's table G.4, for the specific material. The figures in lines 16-19 are then proportional to the appropriate alpha range.

The adjustments to natural dose rates implied by these revised estimates will generally be smaller than the uncertainty in the overall dating technique. Nevertheless, it is desirable to avoid systematic errors wherever possible by taking advantage of the most recent data and techniques.

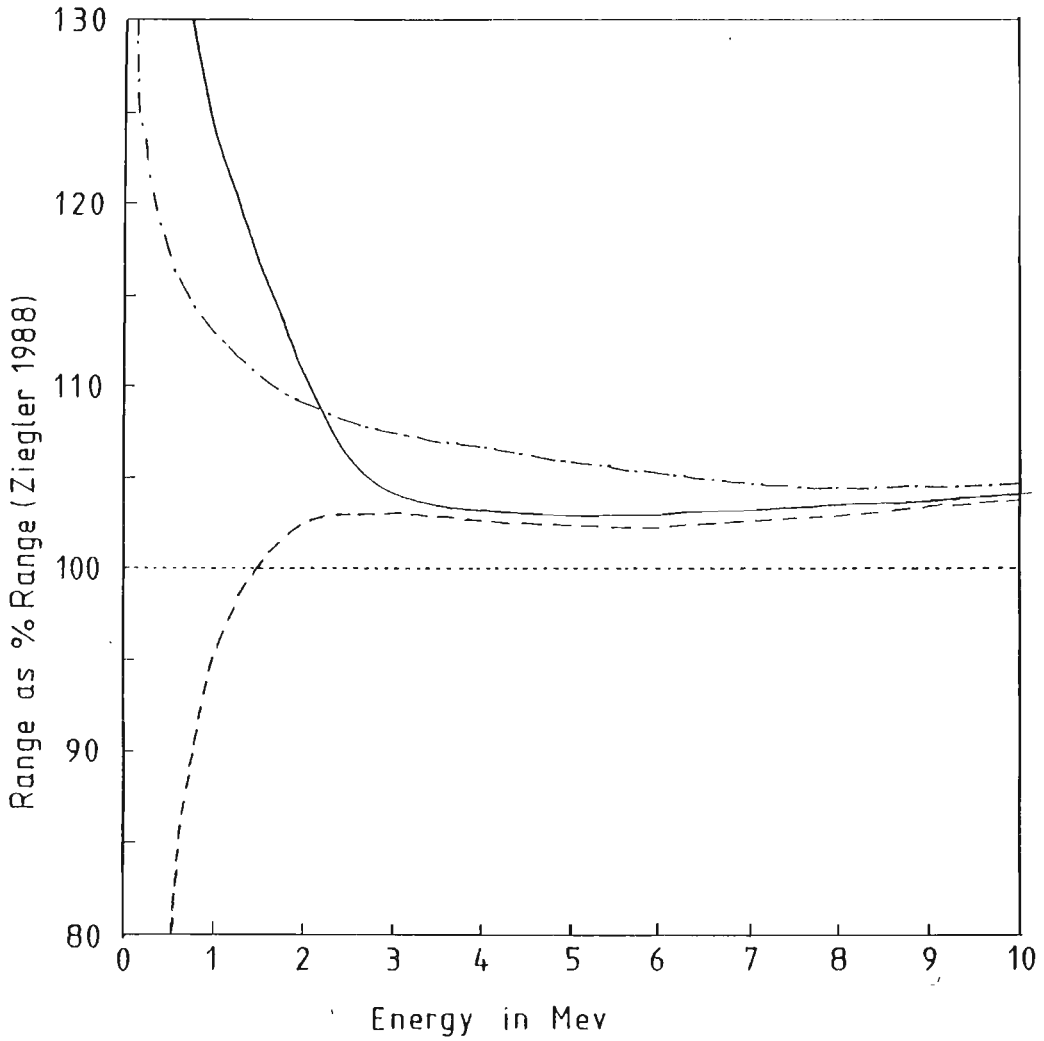

Figure 2.
Ranges for calcium carbonate calculated by various methods as a percentage of ranges calculated using Zeigler (1988), for alpha particle energies up to 10 MeV.

— . — . — *Zeigler 1977*
———— *Northcliffe and Schilling*
---------- *Benton and Henke*
..... *Zeigler 1988*

Table 4. Total ranges in mg cm^{-2} for the uranium and thorium series in equilibrium. Values are per parent disintegration. Energy and branching ratio data is from Nambi and Aitken (1986). For a concentration of 1ppm by weight of natural uranium and thorium, the corresponding flux in a^{-1} cm^{-2} may be calculated by multiplying the total ranges by 389.7, 18.2, and 128.0 for U-238, U-235 and Th-232, respectively.

	$CaCO_3$	SiO_2	Albite	Ortho-clase	Anor-thite	Al	Bone	Plagio-clase	Pot (sat)	Basalt	Pot
Full chain											
U-238	44.56	44.47	44.64	45.54	45.90	52.03	36.17	45.29	45.18	46.43	46.81
U-235	45.28	45.22	45.39	46.30	46.61	52.63	36.92	46.01	45.93	47.18	47.26
Th-232	39.67	39.64	39.76	40.56	40.83	46.07	32.38	40.31	40.25	41.34	41.31
Pre-radon											
U-238	17.55	17.49	18.11	17.93	18.11	20.68	18.44	17.86	17.77	18.30	18.44
U-235	21.22	21.17	21.86	21.67	21.86	23.59	22.29	21.57	21.51	22.11	22.29
Th-232	15.08	15.05	15.55	15.41	15.55	17.68	15.86	15.34	15.30	15.73	15.86

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PR Reviewer's comments (Martin Aitken)

It is good to see these definitive data on alpha ranges as well as on A_{av} and Z_{av} values; the latter will be useful in other contexts too. As the authors comment there is unlikely to be any significant shift in ages but it's reassuring to be on firmer ground.