

Radiocarbon in coal: is uranium the answer?

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Radiocarbon (^{14}C) found in coal by the RATE project is problematic for those who believe in the hundreds of millions of years ascribed by uniformitarian geologists to the Phanerozoic geological column. Given the sensitivity of the measuring instruments and the assumptions used in translating these measurements into a radiocarbon 'age', anything older than about 90,000 years would have an undetectable level of ^{14}C . Various hypotheses have been put forward to try to explain such ^{14}C within the 'long-age' paradigm. One is that the ^{14}C results from the presence of uranium in the coal or an adjacent ore body. Detailed analysis shows, however, that this hypothesis completely fails. Moreover, readily available data shows that the detected amount of ^{14}C is consistent with the biblical timescale when we allow for differences between ^{14}C -to- ^{12}C ratios in the atmosphere today and the pre-Flood era.

Baumgardner, in one study¹ of the RATE² project, sent coal samples he obtained from the US Department of Energy to "one of the foremost Accelerator Mass Spectrometer (AMS) laboratories in the world"³ for ^{14}C dating. These tests showed substantial amounts of ^{14}C present. These coal samples were from several disparate locations in the US, and from three separate layers in the geological column conventionally 'dated' to 37–56 Ma, 71–145 Ma, and 304–318 Ma, respectively. The sensitivity of the AMS machines, the half-life of ^{14}C , and the assumption about the ^{14}C -to- ^{12}C ratio in the sample at the time it stopped living together imply that after about 90,000 years there will be insufficient ^{14}C in any sample to be detected.

The level of ^{14}C detected was well above the minimum design sensitivity of the machines (c. 0.002 pMC⁴), being in the range 0.10 ± 0.03 to 0.46 ± 0.03 pMC. These values resulted from four separate runs on each sample, the uncertainty-weighted average of which was then 'corrected' by subtracting a 'standard background' of 0.077 ± 0.005 (table 1). This 'standard background' was measured from the ^{14}C to ^{12}C ratio in a natural gas sample assumed to be so old it would contain no detectable ^{14}C , so any measured amounts 'must be' due to 'background'. Should this assumption be incorrect (i.e. the natural gas is not as old as assumed), then the measured 'background' would be 'real' ^{14}C , and the results reported for the coal should be increased by 0.077 in each case.⁵

The mean results for the coal were 0.247 pMC, the median, 0.235 pMC, and the mode of a binned histogram (figure 1), about 0.225 pMC. The median value, 0.235 pMC, will be used in the calculations below. This level of ^{14}C is problematic for the standard geological timescale. This is why uniformitarians try to explain the ^{14}C as resulting from the presence of uranium, either in the coal or adjacent deposits.

Rotta⁶ discusses various evolutionary explanations for this anomalous ^{14}C content. He discusses cluster decay of uranium

and its 'normal' decay progeny, ternary fission of uranium/thorium, neutron absorption by ^{14}N , and contamination by atmospheric ^{14}C .

In cluster decay and ternary fission, one of the products can be ^{14}C . However, Rotta shows that the probabilities of these decay modes compared to those of normal alpha particle decay and binary fission are so small that they produce too little ^{14}C to explain the measured values. Regarding contamination by atmospheric ^{14}C , Rotta notes that this should result in wide ranges of ^{14}C -to- ^{12}C ratios in different coal beds due to the different exposures of these coal beds to the atmosphere over their alleged history. However, the observed uniformity in the observed levels of ^{14}C rules this out.

The absorption of thermal neutrons by ^{14}N is the same mechanism examined here. Rotta approached it using a 'thin layer' approximation, whereas we approach it from the perspective of a uniformly distributed neutron source in a spherical volume of indeterminate extent, similar to what is encountered in a nuclear power reactor. For completeness, we also examine the potential for ^{14}C being produced by the 'normal' decay products of uranium, i.e. alpha and beta particles.

Forming ^{14}C from uranium

Normally, ^{14}C is produced in the atmosphere when cosmic rays collide with nuclei in the upper atmosphere causing spallation, a process which also produces neutrons. These neutrons are absorbed by the ^{14}N nuclei in the atmosphere which then emit a proton and transform into ^{14}C . Clearly, this process cannot proceed deep underground, hence the appeal to uranium.

Uranium most commonly transforms through 'normal' radioactive decay, in which uranium transforms into lead through several intermediary elements, emitting several alpha particles, beta particles and gamma rays in the process.

Table 1. Measured ¹⁴C levels in 10 coal samples (from Baumgardner¹)

Sample	Coal seam name	State	Country	Geological interval	14C/12C (pMC)	Experimental uncertainty (±) pMC
DECS-1	Bottom	Texas	Freestone	Eocene	0.30	0.03
DECS-11	Beulah	North Dakota	Mercer	Eocene	0.20	0.02
DECS-15	Lower Sunnyside	Utah	Carbon	Cretaceous	0.35	0.03
DECS-16	Blind Canyon	Utah	Emery	Cretaceous	0.10	0.03
DECS-18	Kentucky #9	Kentucky	Union	Pennsylvanian	0.46	0.03
DECS-21	Lykens Valley #2	Pennsylvania	Columbia	Pennsylvanian	0.13	0.02
DECS-23	Pittsburgh	Pennsylvania	Washington	Pennsylvanian	0.19	0.02
DECS-24	Illinois #6	Illinois	Macoupin	Pennsylvanian	0.29	0.03
DECS-25	Pust	Montana	Richland	Eocene	0.27	0.02
DECS-28	Green	Arizona	Navajo	Cretaceous	0.18	0.02

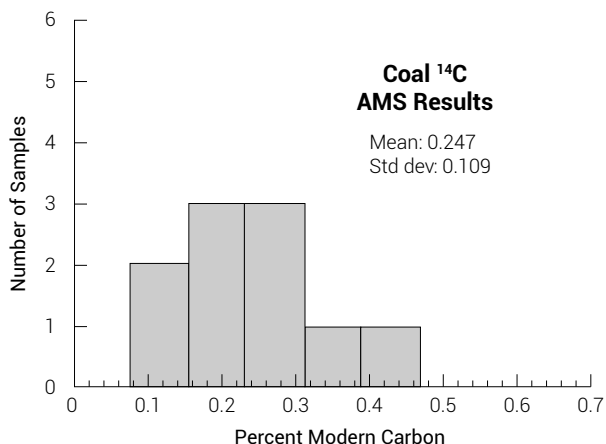


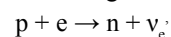
Figure 1. Histogram of number of samples as a function of observed ¹⁴C level measured as pMC (figure 4 from ref. 1)

However, neither alpha particles, beta particles, nor gamma rays can produce ¹⁴C in coal.

Producing ¹⁴C using alpha particles requires starting with ¹⁰Be. In the atmosphere, ¹⁰Be is produced at a very slow rate by cosmic ray spallation of oxygen. It is unstable and decays by beta decay with a half-life of about 1.39 Ma.⁷ While Be is listed⁸ as comprising 1–2 ppm of coal, this would necessarily have been buried with the initial vegetation that formed the coal. Therefore, given the alleged 37 Ma since the ‘youngest’ coal sample, any ¹⁰Be would have decayed to only about 10⁻⁸ of its original value. Consequently, it can be confidently concluded that any Be in the coal is the stable isotope ⁹Be, with the result that the alpha particles emitted

by the radioactive decay of uranium cannot be the source of the ¹⁴C in the coal.

Producing ¹⁴C with an electron (beta particle) would involve a proton in a nucleus absorbing an electron and transforming into a neutron:



where p is a proton, e is an electron, n is a neutron, and ν_e is an electron neutrino. This is an electron capture reaction. In such a reaction, the nucleus absorbs either a K-shell or L-shell electron from the electrons surrounding the nucleus as part of the constituent atom. The nucleus does not capture a free electron, such as would

be produced in beta decay. Moreover, to form ¹⁴C, such a reaction would need to start with ¹⁴N, which is a stable isotope that does not undergo electron capture—or indeed ‘decay’ of any sort.

Gamma rays, since they contain neither a proton nor a neutron, cannot change the isotope and so could only serve to move an already existing ¹⁴C nucleus to a higher energy level. Consequently, gamma rays cannot produce ¹⁴C in coal.

The only mechanisms that would be able to produce ¹⁴C are all thermal neutron capture reactions involving ¹⁴N, ¹³C, and ¹⁷O as the starting point.⁹ Given the relative abundances of these isotopes and their cross-sections for the associated reactions, only the one starting with ¹⁴N might contribute significantly. This is the same reaction that produces ¹⁴C in the atmosphere.

The only source of neutrons would be from spontaneous fission of uranium, either ²³⁸U or ²³⁵U. Since ²³⁸U comprises 99.274% uranium⁷ while ²³⁵U comprises only 0.720%⁷ and ²³⁸U fissions spontaneously at a rate at least 42 times that of ²³⁵U,¹⁰ ²³⁸U produces far more neutrons per second per g of material than does ²³⁵U. Consequently, we can limit our consideration to just ²³⁸U.

The neutrons resulting from ²³⁸U fission have an energy of about 2 MeV (known as ‘slow’ neutrons), whereas the most effective neutrons for capture by ¹⁴N to produce ¹⁴C are ‘thermal’ neutrons with an energy of 0.025 MeV. Thus, the neutrons produced by the fission need to have their energy reduced, which would be accomplished by collisions with the surrounding carbon (and other) nuclei. In fact, carbon

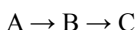
and/or hydrogen (either as water or paraffin) are often used as ‘moderators’ in nuclear power reactors to do exactly this.

So, the overall process would be:

- a ^{238}U nucleus undergoes spontaneous fission, producing two (actually 2.07) ‘slow’ neutrons
- these neutrons collide with surrounding nuclei and have their energy reduced to thermal energies
- these thermal neutrons are absorbed by a proton in ^{14}N nuclei to become, in effect, ^{15}N , which then emits a proton to become ^{14}C , i.e. $n + {}^{14}_7\text{N}_7 \rightarrow ({}^{15}_7\text{N}_8) \rightarrow {}^{14}_6\text{C}_8 + p$
- the ^{14}C decays to ^{14}N by emitting a beta particle.

Quantitative considerations

The simplest way to think about this process is as a two-step ‘decay’ chain. That is, radioactive element A ‘decays’ to produce radioactive element B, which, in turn, ‘decays’ to stable element C:



In this case, A is ^{238}U , B is ^{14}C , and C is ^{14}N . Normally, B is directly produced from A by simply removing the ‘decay radiation’ (alpha particle, beta particle, or gamma ray) from the nucleus of A. However, in this case, B (^{14}C) is indirectly produced from A (^{238}U) through fission, a process which produces neutrons, and the subsequent absorption of these neutrons by an intermediate (^{14}N) then transforms (‘decays’) to B (^{14}C). The steps from ^{238}U to ^{14}C via ^{14}N , however, can be considered as a single-step pseudo-transformation of ^{238}U to ^{14}C , where the transformation ‘rate’ is suitably adjusted to reflect the delayed outcome of the ‘decay’ of a single atom of ^{238}U to form a single atom of ^{14}C .

Since what is measured is the amount of ^{14}C in the coal (or, more precisely, the ratio of ^{14}C to ^{12}C), what must be determined is the number of ^{14}C atoms present at any particular time, t. This can be ascertained from the differential equation for the cascade ‘decay’ chain, namely

$$\frac{dN_B}{dt} = \lambda_A N_A - \lambda_B N_B \tag{1}$$

where N_B = the number of atoms of element B present at time t (^{14}C in this case), N_A = the number of atoms of element A present at time t (^{238}U in this case), λ_A = the ‘decay’ rate of element A, and λ_B = the ‘decay’ rate of element B. $\frac{dN_B}{dt}$ is the rate of change of the number of atoms of element B at time t, $\lambda_A N_A$ is the rate at which atoms of element B are appearing as a result of the transformation of atoms of element A to element B at time t, and $\lambda_B N_B$ is the rate at which the atoms of element B are disappearing as the result of the transformation of element B to element C at time t.

In general, one would solve this equation to find an expression for N_B . However, because of the relationship of the ‘decay’ rates, a simplification is possible. ‘Decay’ rate

is related to the half-life, which is the time required for one half the amount of a radioactive substance present at any given time, t, to transform into its ‘decay’ product. This relationship is given by

$$\lambda = \frac{\ln(2)}{T_{1/2}} \tag{2}$$

The half-life of ^{14}C is $5,700 \pm 30$ years.^{7,11} The half-life for the spontaneous fission of ^{238}U is around 8.27×10^{15} years.¹²

In situations like this, where the half-life of element A (^{238}U) is much longer than that of element B (^{14}C), the cascading process reaches an equilibrium, known as the secular equilibrium, where enough of element B has accumulated that the rate of atoms transforming to element C equals the rate at which atoms of element A are transforming into element B. This usually takes only a few half-lives of element B. At this point, the rate of change of the number of atoms of element B becomes zero:

$$\frac{dN_B}{dt} = \lambda_A N_A - \lambda_B N_B = 0 \tag{3}$$

From this equation, N_B can be determined:

$$N_B = \frac{\lambda_A N_A}{\lambda_B} \tag{4}$$

Another consideration is rate of change of N_A , especially the amount of change during the half-life of B. This is given by

$$\frac{N_A}{N_A(0)} = e^{-\lambda_A t} = e^{\left(\frac{-0.693 T_{1/2,C14}}{T_{1/2,U238}}\right)} = 0.9999999999995 \tag{5}$$

Thus, it is reasonable to treat the number of ^{238}U atoms as constant over a few half-lives of ^{14}C . Even over the alleged age of the oldest sample of coal, the number of ^{238}U atoms would reduce by a factor of only 0.99999997.¹³

However, equation (5) assumes that every atom of A directly results in an atom of B, which is not the case for the ^{238}U -to- ^{14}C transformation. Instead, the fission process produces (on average) 2.07 neutrons¹⁰ that are slowed to thermal energies and then absorbed by the ^{14}N nuclei.

However, a thermal neutron will not necessarily be absorbed by the next nitrogen nucleus it encounters. It could simply be scattered or ‘bounce off’ in another direction. This is also true for the nuclei of any other elements in the coal, such as carbon and uranium. The net effect is that the thermal neutron ‘bounces around’ in the coal for some time before being absorbed. This essentially decreases the effective ‘decay’ rate (or increases the effective half-life) of the ^{238}U -to- ^{14}C transformation.

The probability of either scattering or absorption happening depends on the cross-sections of the ^{14}N nucleus for these respective processes. These cross-sections are the

effective areas that the nucleus presents for scattering or absorptive collisions. The number of absorptions per second per cm³ is thus given by

$$\Phi\sigma_a N_N \tag{6}$$

where Φ is the neutron flux in neutrons per cm² per second, σ_a is the neutron absorption cross-section of ¹⁴N in cm², and N_N is the number of ¹⁴N atoms per cm³ exposed to the neutron flux.

Effect of uranium content of the coal

Now consider the case of the ¹⁴C being generated from ²³⁸U in the coal itself. In addition to carbon and nitrogen, coal contains a significant amount of hydrogen as well as trace amounts of other elements. Hydrogen nuclei (protons) have a considerable interaction with neutrons, especially non-absorptive scattering, because of the nearly identical masses of the proton and neutron. Consequently, it is necessary to include the hydrogen content of the coal in these considerations.

The relative amounts of the three major elements vary depending on the type of coal but are typically in the following ranges: C: 75–90%, H: 4.5–5.5%, N: ~1.5%.¹⁴ For the purposes of this analysis the following percentages will be used: C: 93%, H: 5.5%, N: 1.5%, (sum = 100%) except when it comes to calculating a ratio of nitrogen to carbon, in which case 1.5:75 = 0.02 will be used as this provides the maximum concentration of nitrogen to convert to ¹⁴C.

Assume that the uranium, hydrogen, and nitrogen are uniformly distributed throughout the coal and let N_{U238} be the number of ²³⁸U atoms, N_{C14} be the number of ¹⁴C atoms, N_H be the number of hydrogen atoms, and N_{N14} be the number of ¹⁴N atoms per cm³, respectively. The uranium atoms will be undergoing spontaneous fission and generating neutrons at a rate of λ_f fissions per second and 2.07 neutrons per fission.

Consider now a sphere of radius R. The neutron flux within this sphere is given by¹⁵

$$\Phi(r) = \frac{S}{\Sigma_t} \left[1 - \frac{R+d}{r} \frac{\sinh\left(\frac{r}{L}\right)}{\sinh\left(\frac{R+d}{L}\right)} \right] \tag{7}$$

where S is the number of neutrons per sec/cm³ being generated by the uniformly distributed uranium atoms, Σ_t is the macroscopic scattering cross-section in cm⁻¹, R is the radius of the sphere, in cm, d is the extrapolated length in cm, and L is the diffusion length in cm.

The macroscopic scattering cross-section $\sigma_t = \sum_{i=1}^n \sigma_i N_i$ where \sum represents the sum over the various elements in the material, σ_i is the microscopic scattering cross-section for

element i, and N_i is the number of atoms per cm³ of element i.^{16,17}

The extrapolated length, d, is the distance beyond the sphere at which the neutron flux is assumed to go to zero by extrapolating its rate of change with distance at R (a boundary condition used to solve the diffusion equation); $d \sim 0.71 \lambda_{tr}$ where λ_{tr} is the mean free transport length. The mean free transport length is the average distance the neutrons will have moved in their initial direction after an infinite number of collisions with other nuclei.¹⁸

The diffusion length, $L = \sqrt{\frac{D}{\Sigma_a}}$, where $D = \frac{1}{3(\Sigma_a + \Sigma_s)}$ is the diffusion coefficient, and Σ_a and Σ_s are the macroscopic cross-sections for absorption and transport, respectively.¹⁹

Values for these parameters for the elements under consideration herein are given in table 2.

In calculating the macroscopic cross-sections and related parameters, we must determine the number of carbon, hydrogen, and nitrogen atoms per cm³ of coal. To do this, a hypothetical coal ‘molecule’ was defined as consisting of 0.93 atoms of carbon, 0.055 atoms of hydrogen, and 0.025 atoms of nitrogen, which would then have a molecular weight of 11.425 g/mole. Using a density of 1.35 g/cm³ for coal,²⁰ we can then calculate the number of moles of this coal molecule per cm³ (0.1182), and from this the number of atoms of carbon, hydrogen, and nitrogen per cm³, respectively.

Note that for the aggregate coal, the transport mean free path, the extrapolated path, and the diffusion length are all in the order of a few cm. This means that the neutron flux at any point is determined only by the coal near a few tens of cm (at most) of the point under consideration, and the actual size of the overall coal bed is not significant.

Multiplying the denominator of the second term inside the bracket in (7) by L/L gives

$$\Phi(r) = \frac{S}{\Sigma_t} \left[1 - \frac{R+d}{\left(\frac{L}{L}\right)r} \frac{\sinh\left(\frac{r}{L}\right)}{\sinh\left(\frac{R+d}{L}\right)} \right] \tag{8}$$

which can be rearranged to give

$$\Phi(r) = \frac{S}{\Sigma_t} \left[1 - \frac{R+D}{L\left(\frac{r}{L}\right)} \frac{\sinh\left(\frac{r}{L}\right)}{\sinh\left(\frac{R+d}{L}\right)} \right] \tag{9}$$

and further rearranged to give

$$\Phi(r) = \frac{S}{\Sigma_t} \left[1 - \frac{\left(\frac{R+d}{L}\right)}{\sinh\left(\frac{R+d}{L}\right)} \frac{\sinh\left(\frac{r}{L}\right)}{\left(\frac{r}{L}\right)} \right] \tag{10}$$

Table 2. Values for various parameters relating to determining the neutron flux in coal resulting from spontaneous fission of uranium

Material	Microscopic cross-sections (barns = 10 ⁻²⁴ cm ²)		Macroscopic scattering cross-section (cm ⁻³)	Macroscopic transport cross-section (cm ⁻¹)	Transport mean free path (cm)	Extrapolated length d (cm)	# Atoms per cm ³	Macroscopic absorption cross-section (cm ⁻¹)	Diffusion coefficient	Diffusion length L (cm)
	Scattering	Absorption								
Carbon	5,559	0.00353	0.3679	0.3474	2.88	2.04	6.62E+22	0.0002	0.9588	64.06
Hydrogen	82.03	0.3326	0.3210	0.1070	9.34	6.64	3.91E+21	0.0013	3.0775	48.62
Nitrogen	11.53	1.91	0.0123	0.0117	85.32	60.61	1.07E+21	0.0020	24.2261	109.01
Coal	n/a	n/a	0.7012	0.4662	2.15	1.52	7.12E+22	0.0036	0.7096	14.09

Figure 2 plots equation (10) for the values of d and L in table 1, and a sphere of radius R = 100 m. Note the logarithmic scales on both axes. Figure 3 expands the region near the edge of the sphere with a linear scale for both axes. These show that the flux remains essentially constant at its value at r = 0 until r is within a few multiples of the diffusion length of the surface of the sphere, when it begins to drop off, eventually decreasing to zero at the extrapolated length beyond the edge of the sphere. Since the spatial impact of any given fission is limited by the mean free transport length and the diffusion length for the emitted neutrons, both of which are quite small for coal, the interior flux is uniform. The reduction in flux near the edge of the sphere only happens when the source of the neutrons is a few diffusion lengths from the edge, when some of the neutrons start to leak out of the sphere. As the source of the neutrons gets closer to the edge, the higher the probability of leakage.

Thus, for the coal, except near the very edge of the formation, the flux, in neutrons per sec/cm², is

$$\Phi = \frac{S}{\Sigma_t} \tag{11}$$

Substituting this in (6) results in the number of neutron absorptions per second per cm³ being given by

$$\frac{S}{\Sigma_t} \sigma_a N_N \tag{12}$$

where S is the rate of neutron production per cm³, σ_a is the neutron absorption cross-section of ¹⁴N in cm², N_N is the number of ¹⁴N atoms per cm³ exposed to the neutron flux, and Σ_t is the macroscopic scattering cross-section for coal.

The rate of neutron production per cm³ is

$$S = 2.07\lambda_f N_{U238} \tag{13}$$

so the steady-state rate of formation of ¹⁴C from the spontaneous fission of ²³⁸U is

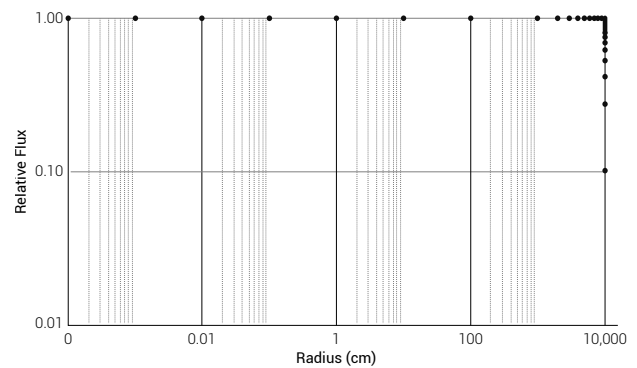


Figure 2. Relative neutron flux as a function of radius for a sphere of coal with radius 100 m and other parameters as per table 1

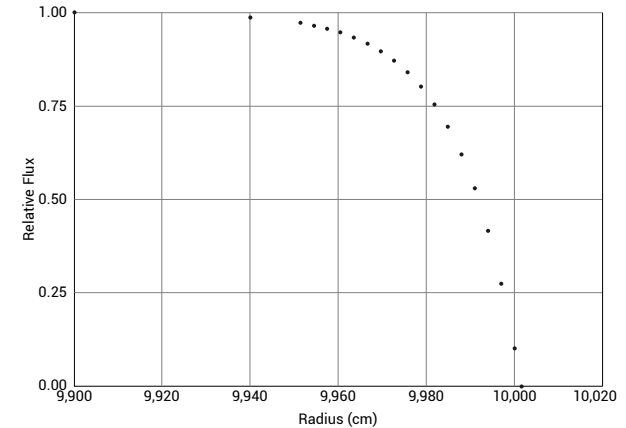


Figure 3. Plot of relative neutron flux vs radius near the edge of a sphere of coal of radius 100 m

$$\begin{aligned} \lambda_A N_A &= \frac{2.07\lambda_f N_{U238} \sigma_a N_{N14}}{\Sigma_t} \\ &= \frac{2.07\lambda_f \sigma_a N_{N14}}{\Sigma_t} N_{U238} \\ &= \lambda_U N_{U238} \end{aligned} \tag{14}$$

where λ_U is the effective ‘decay’ rate of ^{238}U to ^{14}C . Substituting this in (4) with $N_B = N_{C14}$, and rearranging gives

$$N_{U238} = \frac{\Sigma_t \lambda_\beta N_{C14}}{2.07 \lambda_f \sigma_a N_{N14}} \quad (15)$$

where N_{U238} , N_{C14} and N_{N14} are, respectively, the number of ^{238}U , ^{14}C , and ^{14}N atoms per cm^3 , λ_f is the ‘decay’ rate for the beta decay of ^{14}C to ^{14}N , λ_β is the ‘decay’ rate for the spontaneous fission of ^{238}U , σ_a is the thermal neutron absorption cross-section for ^{14}N , and Σ_t is the macroscopic scattering cross-section of the coal. Dividing the numerator and denominator on the righthand side by N_{C12} , the number of ^{12}C atoms per cm^3 , gives

$$N_{U238} = \frac{\Sigma_t \lambda_\beta \left(\frac{N_{C14}}{N_{C12}} \right)}{2.07 \lambda_f \sigma_a \left(\frac{N_{N14}}{N_{C12}} \right)} \quad (16)$$

$\frac{N_{N14}}{N_{C12}}$ is the ratio of ^{14}C to ^{12}C in the coal, which is the actual AMS measurement in pMC, and $\frac{N_{N14}}{N_{C12}}$ is, effectively, the ratio of the amount of nitrogen in the coal to the amount of carbon in the coal. Thus,

$$N_{U238} = \frac{\Sigma_t \lambda_\beta \left(\frac{\text{pMC}}{100} \text{MC} \right)}{2.07 \lambda_f \sigma_a \left(\frac{N_{N14}}{N_{C12}} \right)} \quad (17)$$

As noted earlier, the composition of coal varies as C: 75–90%, H: 4.5–5.5%, N:1–1.5%, so the maximum value for N_N/N_{C12} (i.e. the ratio that would provide the largest amount of ^{14}N , and therefore the highest rate of ^{14}C production) would be $1.5/75 = 0.02$.

Thus, for the situation under discussion, $\text{pMC} = 0.235\%$ = 0.00235, $\text{MC} = 1.2 \times 10^{-12}$ atoms of ^{14}C to atoms of ^{12}C ,^{21,22} $\lambda_\beta = \ln(2)/(5,700 \times 365 \times 24 \times 3,600) = 3.856 \times 10^{-12}$ per second, $\lambda_f = \ln(2)/(8.27 \times 10^{15} \times 365 \times 24 \times 3,600) = 2.66 \times 10^{-24}$ per second, $\sigma_a = 1.91 \times 10^{-24} \text{ cm}^2$,²³ $\frac{N_{N14}}{N_{C12}} = 0.02$, and $\Sigma_t = 0.7012$ (table 1). Solving for N_{U238} gives $N_{U238} = 3.6 \times 10^{22}$ atoms per cm^3 .

Since a mole of ^{238}U consists of 6.022×10^{23} atoms, this corresponds to approximately 0.06 moles of ^{238}U per cm^3 . A mole of ^{238}U weighs very nearly 238 g. Therefore, 0.06 moles of ^{238}U would weigh 14.3 g, which would mean that the density of the ‘coal’ would be at least 14.3 g/cm^3 . However, the bulk density of coal is about 1.35 g/cm^3 . This means that the coal does not contain the amount of ^{238}U required to produce the observed number of ^{14}C atoms.

Moreover, uranium generally occurs in the form of uraninite, a.k.a. pitchblende, which is mainly UO_2 . Thus 0.06 moles of uranium implies 0.06 moles of uraninite. Since the molecular weight of oxygen is essentially 16 g, the

molecular weight of uraninite is 270 g. Thus a 1 cm^3 volume containing 0.06 moles of uraninite would have a density 16.2 g/cm^3 . However, the density of pure uraninite is only about 10.8 g/cm^3 . So, material containing sufficient uranium atoms to sustain the amount of ^{14}C observed in the coal would need to be more than 100% pure uraninite.

Alternately, given the measured density of coal, 1 cm^3 of coal, if pure carbon, would contain 0.11 moles of carbon. Putting this amount of carbon with the required amount of ^{238}U would mean that the ‘coal’ would be about 35% ^{238}U ($0.06/(0.06 + 0.11)$). The richest uranium deposits in the world (at Cigar Lake and McArthur River, both in the Athabaskan Basin in Canada) have ore grades (uranium concentrations) of 18% and 17% respectively. Thus, if the levels of ^{14}C measured in the coal were the result of the presence of uranium, the ‘coal’ would more correctly be called ‘top-rate uranium ore’ and mined for its uranium content rather than its coal content.

Finally, one can take the observed concentration of uranium in coal and use this to calculate the number of ^{14}C atoms that would be present once secular equilibrium had been achieved and compare this to the observed concentration of ^{14}C in the coal. Coal contains about 1–2 ppm uranium.²⁴ Thus, per cm^3 of coal, there will be about

$$N_{U238} = N_{C12} 10^{-6} \text{ atoms of uranium} \quad (18)$$

These will be producing $2.07 \lambda_f N_{C12} 10^{-6}$ neutrons per second from spontaneous fission, resulting in a neutron flux

$$\Phi = \frac{2.07 \lambda_f N_{C12} 10^{-6}}{\Sigma_t} \text{ neutrons per second per cm}^2.$$

This means that the number of ^{14}C atoms being produced per second per cm^3 would be

$$N_{C14} = \frac{2.07 \lambda_f N_{C12} 10^{-6} \sigma_a \left(\frac{N_{N14}}{N_{C12}} \right)}{\Sigma_t} \quad (19)$$

Setting this equal to the rate of decay of ^{14}C (i.e. assuming secular equilibrium) gives

$$\lambda_\beta N_{C14} = \frac{2.07 \lambda_f N_{C12} 10^{-6} \sigma_a \left(\frac{N_{N14}}{N_{C12}} \right)}{\Sigma_t} \quad (20)$$

Rearranging gives

$$\lambda_\beta N_{C14} = \frac{2.07 \lambda_f 10^{-6} \sigma_a \left(\frac{N_{N14}}{N_{C12}} \right)}{\lambda_\beta \Sigma_t} \quad (21)$$

Using the preceding values for the various parameters gives the expected ratio of ^{14}C atoms to ^{12}C atoms as

$$\frac{N_{C14}}{N_{C12}} = 7.9 * 10^{-44} \quad (22)$$

which is about 6.6×10^{-30} pMC as compared to the measured 0.235 pMC.

From any of these perspectives, the claim that the ^{238}U content of coal would produce the observed levels of ^{14}C fails.

Effect from a uranium deposit adjacent to the coal

For the case of the ^{14}C being generated by an adjacent uranium ore body, a similar analysis can be done but with the uranium uniformly distributed within some different material than coal that is outside, but adjacent to, the coal seam.

Typically, uranium is found as uraninite (UO_2) distributed in some other rock. The richest uranium ore bodies are in the Athabaskan Basin which is largely sandstone. Sandstone is generally composed of feldspar, of which there are several variants. Assuming orthoclase feldspar ($\text{NaAlSi}_3\text{O}_8$), the macroscopic scattering cross-section is 0.19 cm^{-1} vs 0.70 cm^{-1} for coal, the transport mean free path is 2.15 cm vs 5.46 cm for coal, the diffusion length is 4 cm vs 14 cm for coal, and the extrapolated path length is 3.9 cm vs 1.5 cm for coal.

Thus, as with coal, the neutron flux in the feldspar matrix is determined by a relatively small volume and the neutrons do not travel overly far from their source. This means that only those from a relatively small portion of the uranium deposit immediately adjacent to the coal would penetrate the coal. Because the transport mean free path and diffusion length in the coal is also quite small, only the nitrogen in a relatively thin layer of the coal immediately adjacent to the uranium deposit would be exposed to this uranium flux. Furthermore, the neutron flux entering the coal would only be a portion of that generated in the uranium ore, since at least half the neutrons would be heading away from the coal. Since the concentration of uranium required to sustain the observed levels of ^{14}C when the uranium is uniformly mixed throughout the coal is already well above that of the richest uranium ore, clearly this explanation also fails.

Empirical neutron density measurements

Additionally, this issue can be analyzed using the empirically measured neutron density at depth. As reported in the RATE paper, Kuhn *et al.*²⁵ measured thermal neutron densities of 1.1–33 neutrons per cm^3 per year (3.49×10^{-8} – 1.05×10^{-6} neutrons per cm^3 per sec) in mines deeper than 800 m. More recently, Šrámek *et al.*²⁶ have used a more theoretical approach to calculate subterranean neutron

densities in the range of 10^{-3} to 10^{-6} neutrons per kilogram of rock per second. Using 2.7 gm/cm^3 as the density of the continental crust results in a neutron density of 2.7×10^{-9} to 2.7×10^{-6} neutrons per cm^3 per second. Using the geometric mean of these values gives an ‘empirical’ neutron density of approximately 1.26×10^{-7} neutrons per cm^3 per second regardless of source.

Using this for S in equation 14 and setting this equal to the rate of decay of ^{14}C (assuming secular equilibrium), rearranging and dividing both sides by N_{C12} gives

$$\frac{N_{C14}}{N_{C12}} = \frac{S\sigma_a}{\sum_f \lambda_f} = \frac{N_{N14}}{N_{C12}}$$

Substituting previously defined values gives

$$\frac{N_{C14}}{N_{C12}} = 1.48 * 10^{-9} = 0.000000148 \text{ pMC}$$

Thus, using empirically determined subterranean neutron densities, regardless of the source of these neutrons, generates a level of ^{14}C to ^{12}C that is orders of magnitude less than the measured levels.

Explanation within a biblical historical timeframe

Since the measured ^{14}C in coal cannot be effectively explained within an old-earth paradigm, it is reasonable to ask how the results compare with the expectation based on the history derived from a plain reading of the Bible. Rotta discusses this from the perspective that the atmospheric ^{14}C -to- ^{12}C ratio has not yet reached an equilibrium level and that, therefore, the fundamental assumption used in calculating radiocarbon ‘ages’ is incorrect. However, he does not try to reconcile the calculated ages with the biblically derived age. Therefore, what factors would affect the ^{14}C -to- ^{12}C ratio during the pre-Flood period, and how would these reconcile these disparate ages?

Granting the usual explanation that coal formed from buried vegetation, from a biblical perspective, this burial would have happened during the global Flood. This means that all the vegetation that was buried would have been growing during some, or all, of the c. 1,650-year-long pre-Flood era. As such, the vegetation would all have about the same ^{14}C -to- ^{12}C ratio, regardless of the geological layer in which it was buried. This precisely reflects the data.

Figure 4 shows the range of ^{14}C -to- ^{12}C values for each sample at $\pm 2\sigma$, with the geological layers ‘colour’ coded. There is no distinction between any of the three samples, which represent widely separated layers (in depth and, supposedly, time). Qualitatively, the results match the expectations of the biblical framework.

Quantitatively, the transformation of the measured pMC to age requires the atmospheric ^{14}C -to- ^{12}C ratio when the vegetation was growing. Normally this is assumed to be the same as today. However, this is arguably not the case. Since ^{14}C is not required to support life, it seems reasonable to assume God would not have created any. Thus, ^{14}C would have to build up in the atmosphere from cosmic ray collisions with nuclei in the upper atmosphere. Therefore, the more cosmic rays there are, the more ^{14}C is produced. In turn, the stronger the magnetic field, the smaller the cosmic ray flux. The earth's magnetic field has been measured to be decreasing by about 5% per century.²⁷ Projecting this back 45 and 60 centuries results in the earth's magnetic field being approximately 10 times stronger and 22 times stronger than it is today during the Flood and at creation, respectively. This implies a dramatically reduced cosmic ray flux with a correspondingly dramatic reduction in the ^{14}C production rate. Thus, it is reasonable to expect that the average level of ^{14}C in the atmosphere during the pre-Flood period would have been, perhaps, only $\frac{1}{20}$ to $\frac{1}{10}$ of what it is today.

Now consider the amount of ^{12}C in the atmosphere during that period. Again, if the coal has formed from vegetation that grew pre-Flood, the vast extent of coal fields around the planet would clearly indicate very extensive and luxuriant vegetation. This would require increased amounts of CO_2 in the atmosphere. For example, we know that an increase of 100% in the CO_2 concentration results in a 42% increase in (C3) plant growth.²⁸

In the Cambrian ('dated' c. 500 Ma) atmospheric CO_2 levels were 20–25 times greater than today, decreasing to 4–5 times during the Jurassic period, followed by a steady decline to today's levels.^{29,30} Moreover, the CO_2 levels in the Precambrian were similar to, or even higher than, those in the Phanerozoic rocks.³¹ The 'ages', of course, reflect the

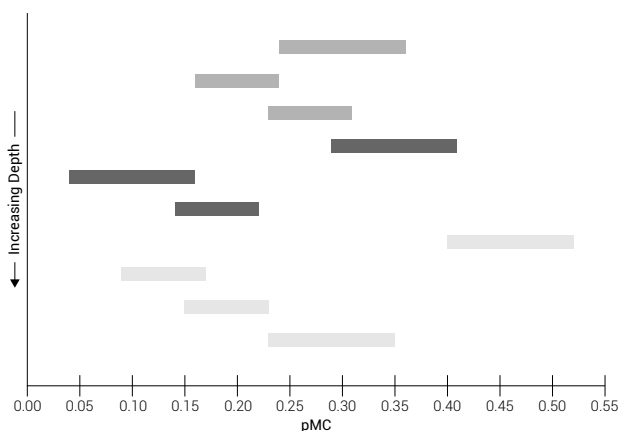


Figure 4. Range of pMC values for the ten coal samples at the $\pm 2\sigma$ level with the three associated geological layers 'colour' coded

uniformitarian interpretation. 500 Ma roughly corresponds to the Precambrian-Cambrian (PC-C) boundary; the Jurassic is supposedly the height of the 'age of the dinosaurs', and 49 Ma would correspond to about the middle of the Eocene layer.

Some creationists consider the PC-C boundary to correspond to the pre-Flood boundary, while others consider it to be lower. Similarly, some consider the post-Flood boundary to correspond to the Cretaceous-Paleogene (K-Pg) boundary, while others consider it to be higher. Whichever view we take, the general picture is still the same. First, the pre-Flood atmospheric CO_2 level was likely at least 20 times today's level.^{31,32} This would have reduced dramatically during the Flood, arriving at today's level some time shortly after the Flood.

Assuming, as above, that no ^{14}C was initially created and was building up only slowly in the atmosphere, the carbon in pre-Flood CO_2 would have been essentially all ^{12}C . Thus, the ratio of ^{14}C to ^{12}C prior to the Flood could have been as little as $\frac{1}{400}$ to $\frac{1}{200}$ of what it is today. This, of course, would mean that the calculated radiocarbon ages would all be dramatically reduced. If the ratio was $\frac{1}{247}$ of today's value, then the calculated ages for the coal would be about 4,500 years, which is the timing of the global Flood.

Summary

In summary:

- The assertion that the levels of ^{14}C observed in coal samples could have been produced *in situ* by uranium, whether as a 'contaminant' in the coal or as an adjacent ore body, is not sustained:
 - the density of the resultant material required would be 50% denser than pure uraninite
 - the level of uranium that would be required would make the 'ore' the highest grade pitchblende in the world (31% vs 18% actual), and
 - the measured level of uranium in coal (1–3 ppm) is insufficient by many orders of magnitude to produce the observed concentration of ^{14}C in situ.
- The observed uniformity in ^{14}C level, regardless of geological layer of origin, is consistent with the biblical perspective that the vegetation in all layers had been growing at the same time in the pre-Flood world, and was all buried during the year-long global Flood.
- The measured radiometric ages are also consistent with the Bible when the ratio of ^{14}C to ^{12}C in the atmosphere at the time the vegetation was growing is adjusted to account for the effect of the earlier strength of the earth's magnetic field and the apparent higher amounts of atmospheric CO_2 in the pre-Flood period.

References

- Baumgardner, J., ¹⁴C Evidence for a recent global flood and a young earth; in: Vardiman, L., Snelling, A. A., and Chaffin, E.F. (Eds.), *Radioisotopes and the Age of the Earth, vol. II*, Institute of Creation Research and Creation Research Society, El Cajon, CA, and St. Joseph, MO, p. 587–630, 2005; www.icr.org/i/pdf/technical/Carbon-14-Evidence-for-a-Recent-Global-Flood-and-a-Young-Earth.pdf.
- Radioisotopes and the Age of The Earth. For an overview of this project see RATE group reveals exciting breakthroughs! creation.com/rate.
- Baumgardner, ref. 1, p. 604.
- Baumgardner, ref. 1, p. 598. ‘pMC’ stands for ‘percent Modern Carbon’, where ‘Modern Carbon’ is, effectively, the ¹⁴C-to-¹²C ratio in the atmosphere today.
- Whereas the present discussion pertains to some particular coal samples, it should be noted that, as part of the project, the RATE paper listed 90 instances of non-zero AMS measurements of pMC in materials that were considered to be older than 100,000 years and, therefore, ¹⁴C ‘dead’. These were taken from papers published in the primary radiocarbon journals *Radiocarbon and Nuclear Instruments and Methods in Physics Research B* [Baumgardner, ref. 1, p. 592]. The reported values ranged from 0.014 to 0.71 pMC. Although these did not have a ‘background’ subtracted (since, because of their alleged age, they themselves, were intended to be used as ‘blanks’ to measure the ‘background’), fully 65 of them were greater than the 0.077 pMC used as the ‘background’ in the RATE coal measurements and 61 of the measurements were greater, even, than 0.077+0.005 pMC, which would be a reasonable upper limit for the so-called ‘background’ if the experimental uncertainty in the ‘background’ is included.
- Rotta, R.B., Evolutionary explanations for anomalous radiocarbon in coal? *CRSQ* 41(2):104–112, 2004.
- Chart of Nuclides, www.nndc.bnl.gov/chart, accessed 18 March 2017.
- Trent, V.A., Medlin, J.H., Coleman, S.L., and Stanton R.W., *Chemical analysis and physical properties of 12 coal samples from Pocahontas Field, Tazewell County, Virginia and McDowell County, West Virginia*, Geological Survey Bulletin 1528, US Department of the Interior, table 5 p. 19, 1982; pubs.usgs.gov/bul/1528/report.pdf.
- Yim, M.S. and Caron, F., Life cycle and management of carbon-14 from nuclear power generation, *Progress in Nuclear Energy* 48:2–36, 2006 | doi:10.1016/j.pnucene.2005.04.002; p. 5.
- Shultis, J.K. and Faw, R.E., *Fundamentals of Nuclear Science and Engineering*, 3rd edn, CRC Press, Boca Raton, FL, p. 151, table 6.2, 2017. However, Chart of Nuclides, ref. 7, gives the probability of spontaneous fission of ²³⁵U as 7×10^{-9} % ($= 7 \times 10^{-11}$) versus a probability of 2×10^{-9} in the table in Wikipedia. Using 7×10^{-11} instead of 2×10^{-9} would make the factor 1,190 instead of 42, which would make the spontaneous fission of ²³⁵U even more irrelevant.
- Bé, M.M. and Chechev, V.P., ¹⁴C-Comments on evaluation of decay data, www.nucleide.org/DDEP_WG/Nuclides/C-14_com.pdf, January 2012.
- Chart of Nuclides, ref. 7. The chart lists the overall decay rate for ²³⁸U as 4.468×10^9 years and the spontaneous fission probability as 5.5×10^{-7} , from which the spontaneous fission half-life can be calculated to be 8.12×10^{15} .
- This is the *reductio* resulting from spontaneous fission. The ²³⁸U is also decreasing by normal radioactive decay with a half-life of 4.54×10^9 years. This represents a decrease by a factor of 0.9999991 during one half-life of ¹⁴C, so the assumption of negligible change in the number of atoms of ²³⁸U during a few half-lives of ¹⁴C is still valid.
- Coal, chemistryexplained.com/Ce-Co/Coal.html, 2017.
- Lamarsh, J.R., *Introduction to Nuclear Engineering*, as cited in New flux in a sphere of moderator of radius R, physicsforums.com/threads/new-flux-in-a-sphere-of-moderator-of-radius-r.113397, accessed 19 March 2017.
- Macroscopic cross-section, nuclear-power.net, accessed 19 March 2017.
- Ragheb, M., One group reactor theory, mragheb.com, 4 December 2015.
- Vacuum boundary condition—extrapolated length, nuclear-power.net, accessed 19 March 2017.
- Diffusion length of neutron, nuclear-power.net, accessed 19 March 2017.
- Coal, Bituminous solid density, aqua-calc.com, accessed 19 March 2017.
- ESS 312 Geochemistry: Geochemistry practice problems, faculty.washington.edu, accessed 19 March 2017.
- en.wikipedia.org/wiki/Carbon-14, accessed 19 March 2017.
- Neutron scattering lengths and cross-sections, nqn.nist.gov, accessed 19 March 2017.
- Trent *et al.*, ref. 8, tables 5, 6, and 7.
- Kuhn, M.W., Davis, S.N., and Bentley, H.W., Measurements of neutrons in the subsurface, *Geophysical Research Letters* 11(6):607–610, 1984.
- Šrámek, O., Stevens, L., McDonough, W.F., Mukhopadhyay, S., and Peterson, R.J., Subterranean production of neutrons, ³⁹Ar and ²¹Ne: Rates and uncertainties, *Geochimica et Cosmochimica Acta* 196:370–387, 2017.
- Merrill, R.T. *et al.*, *The Magnetic Field of the Earth: Paleomagnetism, the Core, and the Deep Mantle*, Academic Press, San Diego, CA, p. 55, 1998.
- Poorter, H., Interspecific variation in the growth response to an elevated and ambient CO₂ concentration, *Vegetatio* 104/105:77–97.
- Berner, R.A. and Kothavala, A., GEOCARB III: A revised model of atmospheric CO₂ over Phanerozoic time, *American J. Science* 301:182–204, 2001.
- Carbon Dioxide through Geologic Time, earthguide.ucsd.edu, 2002.
- Sheldon, N.D., Precambrian paleosols and atmospheric CO₂ levels, *Precambrian Research* 147(1–2):148–155, 2006.
- Berner and Kothavala, ref. 29, figure 13, p. 201.

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