Radiocarbon from Nuclear Tests

During the past 4 years man has been producing carbon-14 about 15 times faster than nature.

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As a result of the generation of neutrons in nuclear tests and their subsequent reaction with nitrogen in the atmosphere, considerable "man-made" C^{14} has been added to the earth's dynamic carbon reservoir. On the basis of the measured neutron yield per unit energy release and on the assumption that about two-thirds of the C^{14} produced falls back as calcium carbonate, Libby (*1*) has estimated that 10×10^{27} atoms of C^{14} have been introduced into the atmosphere as CO_2. Rafter and Fergusson (*2*) have shown that the C^{14} concentration in Southern Hemisphere tropospheric CO_2 has been increasing 2.1 percent per year since 1955. For the Northern Hemisphere, de Vries (*3*) has suggested an increase of 4.3 percent between 1953 and 1957. The results of Munnich and Vogel (*4*) point to an increase of about 3.2 percent per year for central Europe and 2 percent per year in South Africa over the period from 1954 to 1957. Considerable interest has been aroused in the possible genetic effects of this increase in the C^{14} concentration, the potential hazards having been reviewed by Leipunsky (*5*), Pauling (*6*), Sakharov (*7*), and Totter *et al.* (*8*). Recent data related to this increase are presented in this article together with a brief discussion of the probable distribution of bomb C^{14} within the dynamic carbon reservoir.

Results

The general rise in the concentration of C^{14} in atmospheric CO_2 has been monitored by direct measurement of the C^{14}/C^{12} ratio in samples of atmospheric CO_2 as well as by measurement of plant material which has recently fixed atmospheric CO_2. In order to make these measurements directly comparable, all the results are normalized to a common C^{13}/C^{12} ratio. This eliminates any differences created by isotopic fractionation during the photosynthetic process, during the collection of atmospheric CO_2, or during the chemical processing of samples in the laboratory.

The results are summarized in Table 1; δC^{14} represents the age-corrected permillage difference in the radioactivity of the sample CO_2 gas from that of a standard.

$$\delta C^{14} = \frac{A^{*}_{\text{sample}} - 0.950 A^{0}_{\text{oxalic standard}}}{0.950 A^{0}_{\text{oxalic standard}}} \times 1000 \qquad (1)$$

where A^{*}_{sample} is the measured C^{14} activity of the sample corrected for radioactive decay during the period between sample formation and measurement, and $A^{0}_{\text{oxalic standard}}$ is the C^{14} activity of the National Bureau of Standards C^{14} standard, corrected for radioactive decay between 1 January 1958 and the measurement date. The factor 0.950 is introduced so that the age-corrected values of wood grown during the 19th century fall close to zero on the scale. Activity measurements were made by the technique described by Broecker *et al.* (*9*); errors are based on the reproducibility of the counting measurements rather than on radioactivity statistics alone.

Following Craig (*10*), the δC^{13} results are expressed as per-millage difference from the Belemnite standard. The isotope ratio measurements were made with a Consolidated 401 double-collecting mass-spectrometer on the CO_2 gas used for the radioactivity measurement (*11*). The uncertainty in the δC^{13} results is about 1 per mill.

Normalization to a common C^{13}/C^{12} ratio is carried out as follows:

$$\Delta C^{14} = \delta C^{14} - 2\delta C^{13} \left[1 + (\delta C^{14}/1000)\right] - 50.0 \qquad (2)$$

Again, the constant term (− 50.0) is introduced so that ΔC^{14} for age-corrected 19th-century wood falls close to zero on the scale (*12*).

The results from the Northern Hemisphere are plotted against time in Fig. 1 and suggest a general increase of about 50 per mill (5 percent) per year in the C^{14} concentration of atmospheric CO_2 over the past 3 years. This is somewhat higher than the estimates given by de Vries (*3*) and Munnich and Vogel (*4*). The spread of the points in Fig. 1 must be related at least in part to local release of large quantities of industrial CO_2 (*13*). Consequently, the curve has been drawn through points obtained on samples collected in areas removed from intense industrial activity (the Great Basin, the North Atlantic Ocean, and the Mediterranean Sea). The horizontal portion of this curve has been fixed by using Fergusson's value of − 20 per mill for the average Suess effect (*13*). It is interesting to note that data obtained by Munnich and Vogel (*4*) on plant material from Germany show, in general, a smaller increase than the data that define the curve in Fig. 1. If plotted in Fig. 1, these data would agree well with the data from Kearney, Palisades, and Rome.

The difference between the C^{14} concentration in leaf samples grown at Lamont Geological Observatory and that in average Northern Hemisphere tropospheric CO_2 appears to be increasing with time. Such an increase would not be expected if the difference were a result of a higher local Suess effect. The suggestion of Munnich and Vogel (*4*) that plants grown in areas of dense vegetation may take up an appreciable quantity of CO_2 given off by adjacent soils provides a possible explanation for such a divergence. For, since much of the CO_2 given off by soils probably results from the decay of organic materials formed prior to bomb testing, the contrast between the C^{14} concentration in soil CO_2 and that in atmospheric CO_2 is increasing rapidly with time. In this connection it is of interest to note that the points defining the curve in Fig. 1 are all from areas of sparse

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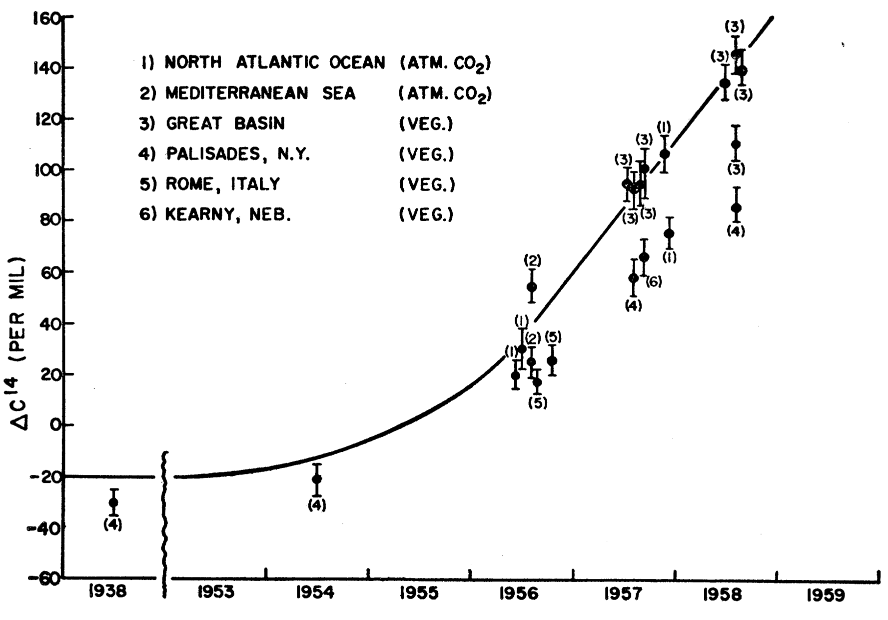

Fig. 1. Carbon-14 concentration of atmospheric CO_2 in the Northern Hemisphere plotted against time.

vegetation and thus are free from influence of soil CO_2 as well as from that of local industrial CO_2.

Figure 2 compares the data for the Northern Hemisphere (Fig. 1) with those published by Rafter and Fergusson (*2*) for the Southern Hemisphere. In drawing the curve for the Southern Hemisphere it was assumed that the Lamont and New Zealand 1890 wood standards have identical activities. Recent measurement of the New Zealand wood standard at Lamont supports this assumption (the New Zealand laboratory pre-1900 wood average is within 10 per mill of the value for the Lamont 1890 wood standard). The two added points represent Lamont data from the Southern Hemisphere. In the following paragraphs it is shown that the proximity of the two curves lends support to Fergusson's (*13*) conclusion (based on the distribution of industrial CO_2) that the mixing rate between the two hemispheres must be quite rapid (less than 2 years).

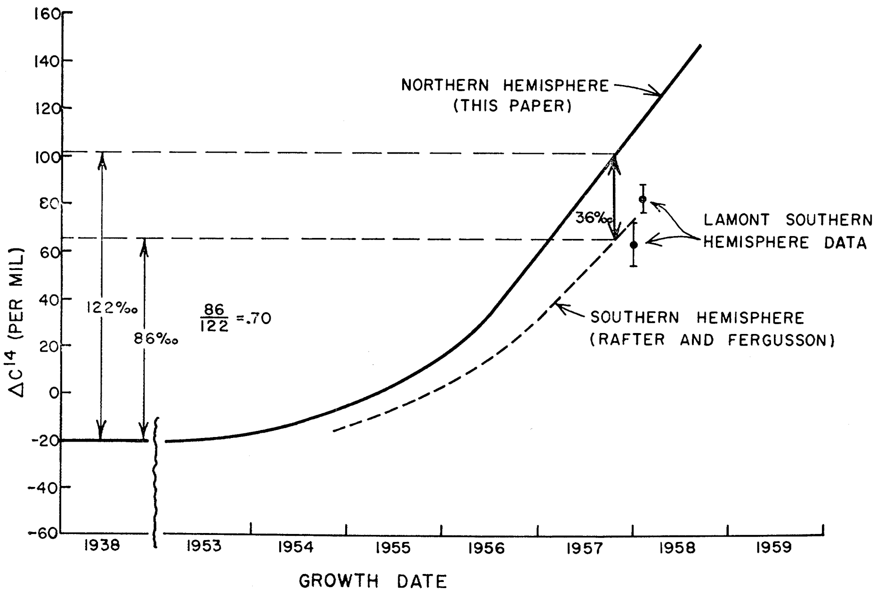

Fig. 2. Comparison of atmospheric C^{14} data for the Northern Hemisphere with data published by Rafter and Fergusson (*2*) for the Southern Hemisphere.

Interhemispheric Mixing

Since most of the bomb-produced C^{14} (bomb C^{14}) is added to the stratosphere of the Northern Hemisphere, there are two possible modes of mixing between the hemispheres: mixing above the tropopause and below the tropopause. Two extreme cases may then be considered: (i) transfer of bomb C^{14} from the Northern Hemisphere to the Southern Hemisphere dominantly in the stratosphere, and (ii) transfer dominantly in the troposphere. In the absence of a more precise model for atmospheric mixing, the simple model of four internally mixed reservoirs (Northern and Southern Hemisphere tropospheres and stratospheres) separated by semipermeable membranes is used.

In the first case, the rate of change in the number of bomb-produced C^{14} atoms in the Southern Hemisphere troposphere (N_{S_T}) at any time t is given by:

$$\frac{dN_{S_T}}{dt} = \lambda_1 N_{S_S} \quad (3)$$

where λ_1 is the mixing coefficient between the stratosphere and troposphere and N_{S_S} is the number of bomb-produced C^{14} atoms in the Southern Hemisphere stratosphere. In words, this equation simply says that the rate at which the amount of tropospheric bomb C^{14} increases is directly proportional to the amount of bomb C^{14} in the stratospheric source. The troposphere is so much more massive than the stratosphere that the return flux of C^{14} to the stratosphere is neglected in Eq. 3. In the case of intrastratospheric transfer, however, both directions are important, so the equation defining the rate of increase in the Southern Hemisphere stratosphere is as follows:

$$\frac{dN_{S_S}}{dt} = N_{N_S}\lambda_2 - N_{S_S}\lambda_2 \quad (4)$$

where λ_2 is the stratosphere mixing coefficient between the Northern and Southern Hemispheres and N_{N_S} is the number of bomb-produced C^{14} atoms at any given time in the Northern Hemisphere stratosphere. An equation similar to Eq. 3 can be written for the stratosphere-to-troposphere transfer in the Northern Hemisphere:

$$\frac{dN_{N_T}}{dt} = \lambda_1 N_{N_S} \quad (5)$$

Since the rate of increase, dN_{N_T}/dt, is proportional to the slope of the curve in Fig. 2, and since this slope is approximately constant after early 1955, dN_{N_T}/dt is set equal to a constant, B. Again, the return flux, as well as any loss of bomb C^{14} to the ocean or biosphere, is neglected (see below).

Simultaneous solution of the above equations yields

$$N_{S_T} = Bt - \frac{B}{\lambda_2}(1 - e^{-\lambda_2 t}) \tag{6}$$

It is assumed that at time zero (March 1955) all the N terms are zero. Since $N_{N_T} = Bt$, it follows that

$$\frac{N_{S_T}}{N_{N_T}} = 1 - \frac{1}{\lambda_2 t}(1 - e^{-\lambda_2 t}) \tag{7}$$

From Fig. 2 it may be seen that the tropospheric bomb C^{14} concentration in the Southern Hemisphere was 0.70 times that in the Northern Hemisphere in September 1957—that is, at $t = 2.5$ years, $N_{S_T}/N_{N_T} = 0.70$. Substitution of these values in Eq. 7 shows λ_2 to be about 1.3. Since the reciprocal of λ_2 is mean residence time, it follows that the average bomb-produced C^{14} atom spends about 1 year in the Northern Hemisphere stratosphere before it enters the Southern Hemisphere stratosphere.

In the second extreme case, bomb C^{14} travels to the Southern Hemisphere solely through the troposphere. The equation defining the rate of increase of Southern Hemisphere tropospheric bomb C^{14} has the form of Eq. 4, as follows:

$$\frac{dN_{S_T}}{dt} = N_{N_T}\lambda_3 - N_{S_T}\lambda_3 \tag{8}$$

When combined with the previously used relationship, $N_{N_T} = Bt$, and integrated, Eq. 8 becomes identical to Eq. 6, except that λ_3 replaces λ_2. Similarly, Eq. 7 will represent case 2 if λ_3 replaces λ_2. This means that the reciprocal of λ_3, the mean residence time of a bomb-produced C^{14} atom in the Northern Hemisphere troposphere, is also about 1 year. Although somewhat lower, this value is consistent with that of 1.5 years based on a similar calculation by Munnich and Vogel (*4*).

The model on which these results are based is admittedly greatly oversimplified, for, among other things, no attempt was made to take into account direct addition of bomb C^{14} to the Southern Hemisphere atmosphere during tests carried out near the equator or in the Southern Hemisphere itself. Consequently, it can only be said that mixing between the hemispheres is rapid enough so that either the entire stratosphere or the entire troposphere mixes horizontally with a mean mixing time of less than 2 years. From the bomb C^{14} data alone it is impossible to determine whether the rapid mixing occurs above, below, or possibly both above and below the tropopause.

Quantity and Distribution of Bomb-Produced Carbon-14

Two major questions next arise: (i) What is the total quantity of bomb C^{14} added to the dynamic carbon cycle up to March 1958? and (ii) If no more bomb C^{14} were added after March 1958, how would the bomb C^{14} concentration in the atmosphere change with time?

The answer to the first question requires not only a knowledge of the

Table 1. Data showing the rise in the C^{14} concentration of atmospheric CO_2 as a result of nuclear testing.

Growth date	Location	Material	δC^{14}	δC^{13}	ΔC^{14}	Lamont No.
1875	Pacific Northwest (U.S.)	Spruce wood	0 ± 6	– 21.4	– 7 ± 6	L-353D
1890	Palisades, N.Y.	Oak wood	1 ± 5	– 24.0	0 + 5	L-314
1938	Palisades, N.Y.	Oak wood	– 29 ± 5	– 24.1	– 32 ± 5	L-313
1954	Palisades, N.Y.	Oak leaves	– 17 ± 6	– 23.2	– 21 ± 6	L-316B
Pre-1955	Lake Winnemucca, Nev.	Sage wood	4 ± 7	– 11.2	– 23 ± 7	L-288M
June 1956	North Atlantic (34°N, 64°W)	Atmospheric CO_2	62 ± 8	– 9.0	31 ± 8	L-367A
June 1956	North Atlantic (32°N, 59°W)	Atmospheric CO_2	54 ± 6	(– 8 ± 4)	(21 ± 7)	L-367B
July 1956	Mediterranean Sea (41°N, 13°E)	Atmospheric CO_2	88 ± 8	– 7.4	54 ± 8	L-367C
July 1956	Mediterranean Sea (36°N, 23°E)	Atmospheric CO_2	64 ± 6	– 5.3	25 ± 6	L-367D
Nov. 1956	Rome, Italy	Poplar twigs	17 ± 5	– 25.0	18 ± 5	L-371B
Nov. 1956	Rome, Italy	Grain	23 ± 6	– 25.1	24 ± 6	L-371A
Oct. 1957	Palisades, N.Y.	Leaves	53 ± 7	– 25.6	57 ± 7	L-445
Aug. 1957	Kearney, Neb.	Leaves	48 ± 7	– 31.8	65 ± 7	L-415B
Aug. 1957	Evanston, Wyo.	Leaves	83 ± 7	– 28.2	94 ± 7	L-415G
Aug. 1957	Oquirrh Mtn., Utah	Leaves	89 ± 7	– 26.0	96 ± 7	L-415EEE
Aug. 1957	Wadsworth, Nev.	Leaves	85 ± 7	– 27.8	95 ± 7	L-415HH
Aug. 1957	Truckee, Calif.	Leaves	91 ± 7	– 27.2	100 ± 7	L-415QQ
Nov. 1957	North Atlantic (25°N, 56°W)	Atmospheric CO_2	131 ± 7	– 10.8	105 ± 7	L-464C
Dec. 1957	North Atlantic (11°N, 35°W)	Atmospheric CO_2	109 ± 6	– 7.2	75 ± 6	L-466B
Jan. 1958	South Atlantic (33°S, 50°W)	Atmospheric CO_2	94 ± 9	– 8.8	63 ± 9	L-466C
Feb. 1958	South Atlantic (54°S, 64°W)	Atmospheric CO_2	103 ± 6	– 13.1	82 ± 6	L-466D
Oct. 1958	Palisades, N.Y.	Leaves	77 ± 5	– 27.0	85 ± 5	L-487S
Sept. 1958	Evanston, Wyo.	Leaves	142 ± 7	– 23.7	146 ± 7	L-487B
Sept. 1958	Oquirrh Mtn., Utah	Leaves	111 ± 7	– 22.6	111 ± 7	L-487C
Aug. 1958	Wadsworth, Nev.	Leaves	131 ± 9	– 26.1	140 ± 9	L-487D
Aug. 1958	Truckee, Calif.	Leaves	126 ± 7	– 26.1	135 ± 7	L-487E

Table 2. Summary of C^{14} measurements on dissolved bicarbonate from the North Atlantic and equatorial Atlantic surface waters.

Collection date	No. of samples	Average ΔC^{14} (0/00)	Standard deviation from mean (0/00)	Standard error of mean (0/00)
		North Atlantic		
Nov. 1955	8	−49	± 8	±3
June 1956	4	−48	± 9	±5
June 1957	1	−44 ± 7		
Oct. 1957	1	−23 ± 7		
Nov. 1957	4	−33	±12	±6
		Equatorial Atlantic		
Feb. 1956	2	−61	± 7	±5
Jan. 1957	2	−62	±13	±9
May 1957	1	−68 ± 7		
Dec. 1957	1	−48 ± 9		

amount of bomb C^{14} in the troposphere but also of the amounts which have entered the ocean and the terrestrial biosphere as well as of the amount still stored in the stratosphere.

If complete mixing within each hemisphere is assumed, the amount of bomb C^{14} in the troposphere can be estimated directly from Fig. 2 and a knowledge of the pre-bomb tropospheric C^{14} inventory (25×10^{27} atoms). Up to March 1958 the amounts are 1.5×10^{27} atoms of bomb C^{14} in the Southern Hemisphere troposphere and 2.1×10^{27} atoms for the Northern Hemisphere.

The amount of bomb C^{14} which has entered the terrestrial biosphere can be estimated in the following manner. The rate of change of bomb C^{14} in the biosphere may be written as

$$\frac{dN^*_B}{dt} = \frac{R_P N^*_T}{N_T} - N^*_B \lambda_{B-T} \qquad (9)$$

where N^*_T and N^*_B are the number of bomb-produced C^{14} atoms in the troposphere and biosphere at any given time t; N_T is the number of stable carbon atoms in the troposphere; R_P is the rate of photosynthesis by terrestrial plants (that is, atoms of carbon fixed per unit time); and λ_{B-T} is the average rate of decay of terrestrial plant material back to CO_2 (that is, atoms of carbon decaying per unit time per atom of biospheric carbon). When N^*_T is expressed as $B't$, where B' is the observed constant rate of increase in the number of atoms of bomb C^{14} in the total troposphere (Northern plus Southern Hemispheres), the following relationship results from integration of Eq. 9:

$$N^*_B = \frac{R_P B'}{N_T \lambda_{B-T}} \left[t - \frac{1}{\lambda_{B-T}} \left(1 - e^{-t\lambda_{B-T}} \right) \right] \qquad (10)$$

As before, the rate of increase, B', is computed on the assumption that the bomb C^{14} concentration in the troposphere has increased at a linear rate since March 1955—an approximation close enough to the actual situation so that no significant error is introduced. From data in Fig. 2, $B' = 1.2 \times 10^{27}$ atom/yr. From Goldschmidt (*14*), R_P is estimated to be about 20×10^{15} grams of carbon per year, and $1/\lambda_{B-T}$, the mean life of carbon in the biosphere, to be about 15 years. When these values are substituted in Eq. 10, the value of N^*_B turns out to be 0.2×10^{27} atoms. Since this is small compared with the bomb carbon entering other reservoirs, the relatively large uncertainties associated with R_P and λ_{B-T} are not critical to the over-all inventory.

The amount of bomb C^{14} which has entered the ocean can be estimated from Craig's (*15*) value of mean residence time of CO_2 in the atmosphere with respect to entry into the ocean. If the rate, A, for addition of bomb C^{14} to the troposphere, is considered to be constant (this was essentially the case over the 3-year period from March 1955 to March 1958), and if loss of bomb C^{14} to the biosphere is neglected, then the number of bomb-produced C^{14} atoms which have entered the ocean, N^*_O, up to time t is simply the difference between the total amount added to the troposphere, At, and the amount, N^*_T, in the troposphere at time t; that is

$$N^*_O = At - N^*_T \qquad (11)$$

When differentiated with respect to t, Eq. 11 becomes

$$dN^*_O/dt = A - (dN^*_T/dt) \qquad (12)$$

The rate at which bomb C^{14} enters the ocean is assumed to be directly proportional to the amount of bomb C^{14} present in the troposphere, and the return flux from ocean to atmosphere is considered negligible; therefore

$$dN^*_O/dt = \lambda_{T-O} N^*_T \qquad (13)$$

where λ_{T-O} is the mixing coefficient for transfer of CO_2 from troposphere to ocean. Combining Eqs. 12 and 13 to eliminate N^*_O and integrating the result gives

$$N^*_T = \frac{A}{\lambda_{T-O}} \left(1 - e^{-\lambda_{T-O} t} \right) \qquad (14)$$

Substituting this result into Eq. 11 gives

$$N^*_O = A \left[t - \frac{1}{\lambda_{T-O}} \left(1 - e^{-\lambda_{T-O} t} \right) \right] \qquad (15)$$

By using the limits of 0.25 and 0.10 yr^{-1} given by Craig (*15*) for λ_{T-O} and a value of A based on B' and an iterative correction for loss to the ocean, upper and lower limits of 1.5×10^{27} and 0.6×10^{27} atoms of C^{14} are obtained for N^*_O, with a most probable value of 1.0×10^{27} atoms. This indicates that only about one-fourth of the bomb C^{14} added to the troposphere has entered the ocean.

If the bomb C^{14} that has entered the ocean were concentrated entirely in the upper 100 meters, the C^{14}/C^{12} ratio in average surface ocean bicarbonate should be from 12 to 32 per mill higher than in 1955. Table 2 summarizes actual measurements on samples from the surface of the north and equatorial Atlantic over the two-year period from 1955 to 1957. Although the results suggest a small increase (∼ 15 per mill), the uncertainties are large enough so that no precise estimate of the magnitude of the

Table 3. Inventory of bomb-produced C^{14} as of March 1958 (10^{27} C^{14} atoms).

	Troposphere N^*_T	Terrestrial biosphere N^*_B	Ocean N^*_O	Stratosphere N^*_S	Total $N^*_T + N^*_B + N^*_O + N^*_S$
Minimum	3.6	0.2	0.6	0.7	5.1
Most probable	3.6	0.2	1.0	7.0	11.8
Maximum	3.6	0.2	1.5	22.5	27.8

increase can be given. It appears, however, to be less than 30 per mill and is thus consistent with the calculated estimate. It should be noted that these calculations involve only the bomb C^{14} which is converted into CO_2 and not that which falls into the ocean as $CaCO_3$. The fate of the latter is not known.

From these data the fraction of bomb C^{14} which has entered the ocean appears to be somewhat lower than that given by Munnich and Vogel (*4*), who based their estimate on the atmospheric CO_2 residence time given by Rafter and Fergusson (*2*) (1.4 years) rather than on the value of Craig (*13*) (7 years) used in this study. The Rafter and Fergusson value is based on the 18 per mill increase in C^{14} concentration of the dissolved bicarbonate in surface ocean water from Markara Bay, off New Zealand, over the period from November 1954 to May 1957. Both the later measurements by Rafter and Fergusson (*2*), which indicate no further rise over the period from May 1957 to March 1958, and the data on the Atlantic Ocean presented in this article suggest that the 1.4-year value is not a reliable estimate.

The critical factor in the over-all inventory is the amount of bomb C^{14} stored in the stratosphere. As pointed out by Libby (*1*), most H-bomb clouds rise well into the stratosphere, and so it is reasonable to assume that most of the newly produced bomb C^{14} is added to the stratosphere. In this case a minimum estimate of the amount stored in the stratosphere would certainly be obtained if the fractional increase in stratospheric C^{14} were assumed to be the same as that measured for the troposphere. Since the stratosphere contains only about 20 percent of the amount of CO_2 in the troposphere, the minimum is thus 0.7×10^{27} atoms of C^{14}.

A maximum estimate can be made by taking the highest estimates of stratospheric residence time calculated for fission-product debris and by assuming that all bomb C^{14} added to the lower atmosphere comes down from the stratosphere. In this case

$$N^*_S = A/\lambda_{S-T} \qquad (16)$$

where N^*_S is the number of bomb C^{14} atoms in the stratosphere, A is the rate of addition of C^{14} to the troposphere from the stratosphere, and λ_{S-T} is the transfer coefficient from stratosphere to troposphere. Again, return flow can be neglected since the maximum residence time estimate is appreciably longer than the period of large-scale bomb testing. If the value of A (1.5×10^{27} atom/yr) computed in connection with Eq. 15 is used and 15 years is taken as an upper limit for the mean stratospheric storage time (*16*), a value of 22.5×10^{27} atoms is obtained as an upper limit on N^*_S. If this is actually the case, the amount of bomb C^{14} in the average mole of stratospheric CO_2 must be about 30 times greater than that in each mole of tropospheric CO_2. If the value of 5 years given by Machta (*16*) is taken as the best estimate, a value of 7×10^{27} atoms is obtained.

When the upper and lower limits for each reservoir are summed, limits can be set on the total amount of bomb C^{14} that had been added to the dynamic carbon reservoir through March 1958. The results, as summarized in Table 3, suggest an upper limit of 28×10^{27} and a lower limit of 5×10^{27} atoms (best estimate, 12×10^{27} atoms). These values may be compared with the estimate of 10×10^{27} atoms given by Libby (*1*) for the same period. The latter estimate is based on the neutron flux per megaton and the number of megatons exploded, rather than on direct measurements of C^{14} concentration. Since there are at present about 2000×10^{27} cosmic-ray-produced C^{14} atoms in the dynamic reservoir, the bomb C^{14} represents a total increase of from 0.25 to 1.4 percent (best estimate, 0.6 percent). Thus, complete mixing will result in a 50-fold reduction in the atmospheric bomb C^{14} concentration if the lower estimate is used and a 20-fold reduction if the upper value is used (provided there is no further production of C^{14} by bombs).

An important question is: How long will the mixing process require? Since great uncertainties exist concerning (i) the rate of exchange between the stratosphere and troposphere, (ii) the size and turnover rate of the biosphere, and (iii) the patterns and rates of mixing in the deep ocean, precise estimates must await further work. A contribution to (iii) is the extensive program currently being carried out at Lamont to determine mixing rates in the Atlantic Ocean (*17*).

Conclusions

The following conclusions can be drawn from the present study (*18*): (i) The C^{14} concentration in the tropospheric CO_2 of the Northern Hemisphere has increased by about 5 percent per year between March 1955 and March 1958. (ii) The distribution of bomb C^{14} between the hemispheres suggests that horizontal mixing must be so rapid that either the stratosphere or the troposphere becomes mixed in less than two years. (iii) Only about 10 percent of the bomb C^{14} produced up to March 1958 has entered the oceans. (iv) Differences within one hemisphere appear to be related to local dilution with C^{14}-deficient CO_2. (v) The total bomb C^{14} added to the dynamic carbon reservoir through March 1958 is between 5×10^{27} atoms and 28×10^{27} atoms. The range results largely from uncertainty about the amount stored in the stratosphere. (vi) When the bomb C^{14} produced through March 1958 is distributed uniformly throughout the dynamic reservoir, the concentration of C^{14} in the atmosphere will be 0.25 to 1.41 percent higher than in the pre-bomb era. This increment will then decay away, with a half-life of 5600 years. (vii) Critical factors still to be determined are the residence time of gas molecules in the stratosphere and the rate of mixing between surface waters and the deep ocean (*19*).

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17. The program is a cooperative project carried out under the direction of M. Ewing, R. Gerard, and B. Heezen of the geophysics group and W. Broecker, E. Olson, and J. L. Kulp of the geochemistry group. The results reported in Table 2 as well as the air samples reported in Table 1 were collected from aboard the Columbia University research vessel *Vema* as part of this program. Preliminary results have been reported at the Endicott Nuclear Geophysics Conference [W. S. Broecker, M. Ewing, R. Gerard, B. C. Heezen, J. L. Kulp, *Natl. Acad. Sci.–Natl. Research Council Publ. No. 572* (1958), p. 118].
18. This research was carried out at the Lamont Geological Observatory of Columbia University. Financial support for the oceanic sampling and analyses program was provided by the Atomic Energy Commission [grant AT (30-1) 1808] and by the International Geophysical Year Organization (grant Y/9.11/134). The terrestrial samples were measured in connection with a program supported by the National Science Foundation (grant N.S.F. G 4191). We appreciate the help and encouragement provided by J. L. Kulp and the extremely valuable review and criticism of the manuscript by E. A. Olson.
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Emotion in Prejudice

Physiological tests support the thesis that prejudicial attitudes are attended by relatively strong emotion.

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Attitudes are viewed psychologically as learned sets, preparations for action toward particular stimulus objects. Although some attitudes are referred to as prejudicial, the specific characteristics which social psychologists agree upon as essential criteria for judging whether or not an attitude is prejudical are not fully understood.

One of the characteristics most investigators agree upon as an essential criterion for designating an attitude as prejudicial is level of emotionality. In fact some psychologists (*1*) have gone so far as to define prejudice as ". . . an emotional attitude." Gordon Allport (*2*) has stated this thesis operationally in the following way: "We tend to become emotional when a prejudice is threatened with contradiction."

Grounds for the thesis that prejudicial attitudes are supported by emotion are not especially convincing when viewed empirically. It may be that the thesis is acceptable to many psychologists partly because there seems to be no contradictory evidence. What supporting evidence there is has come principally from two sources. First, when a person verbally expresses a strong negative or positive attitude toward some human group, or defends such an attitude in the face of contradiction, he commonly displays behavior which is interpreted by others as emotional. Second, emotionally charged words and phrases used in attitude scales are often selected by subjects as descriptive of their attitudes toward certain human groups (*3*). "Attitude scale" refers to any paper-and-pencil device to which subjects individually respond either by placing a given stimulus group (for example, ethnic or national) at some position on a preference continuum, or by checking a statement which is descriptive of the individual subject's feeling toward a given stimulus group.

If it is true that prejudicial attitudes are supported by emotion, it should be possible to detect the presence of emotion by physiological means as well as by attitude scale content analysis and overt behavior observation. Attitude scale "content analysis" is a procedure whereby statements which are descriptive of many possible feelings toward stimulus groups are categorized according to psychological meaning, that is, such meaning categories as emotional strength, type of emotion, cognitive state, and so forth. By "overt behavior observation" is meant observing humans react, and recording their reactions in accordance with certain categories; for example, emotional and nonemotional responses are tabulated. To our knowledge, physiological measurement has not been used to test the thesis that prejudicial attitudes which are subjected to verbal contradiction are supported by relatively high levels of emotionality (*4*).

It is known that emotion involves widespread physiological changes which have the effect of mobilizing the body to meet emergency. The galvanic skin response is regarded as a reasonably valid index of such physiological changes. When this response indicates a decrease in skin resistance, the inference is drawn that physiological mobilization has increased. Upon the basis of such an increase in physiological mobilization, the further inference is drawn that the level of emotion has increased. For a given subject, galvanic skin responses will provide an ordinal index of emotional level. That is, one measurement may be said to be greatest, another next greatest, and so on to that which is least. However, the response affords no information with respect to the cognitive direction an emotion may take. That is to say, the skin response does not distinguish scorn from fear, rage from joy.

This article (*5*) describes three exploratory studies, each designed to test the validity of the thesis that prejudicial attitudes are supported by relatively high levels of emotionality.

Responses to Verbal Contradiction of Positive and Negative Attitudes

In the first study (*6*) college students were asked to rate and rank 20 alphabetically listed ethnic and national groups in terms of preference. Subjects rated each group independently by checking one of six graded preference categories: "like intensely" to "dislike intensely." They ranked the groups by designating the group liked best, next best, and so on, to the group liked least. The groups were: Argentines, Austrians, Canadians, Chinese, English, French, Germans, Greeks, Indians (India), Irish, Italians, Japanese, Jews, Mexicans, Negroes, Filipinos, Poles, Russians, Swedes, Turks. Interest did not reside in the particular named groups, but rather in each subject's negative and positive attitude-indicating responses to groups as groups.

Of 126 subjects, 26 confirmed the validity of their highest and lowest rankings

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