"ARTIFICIAL PRODUCTION OF ^{14}C FROM NUCLEAR WEAPON TESTS AND ITS UPTAKE BY MAN"

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BY

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TO MY PARENTS

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ERRATA

p.8, ℓ.6: 'screen-wall Geiger counter' should read 'Geiger-Müller counter'.

p.23, Fig. 1.3: letter abbreviation for troposphere should be 'a', not 't'.

p.24, ℓ.5from bottom: equations should be:

$$k_{am} = \frac{\lambda(N/N_a - x_a)}{(x_a - x_m)} \text{ gives } k_{ma} = \frac{\lambda k_{am}/N_m(N - N_a x_a)}{(x_a - x_m)}$$

p.27, ℓ.3 from bottom: equation should be:

$$n_a = \frac{f}{k_{am}} .(1 - e^{-k_{am}t})$$

p.29, ℓ.9: should read $A = \frac{Bk_{ab}}{k_{ab} - b} = C$, the constant of integration.

p.30, Table 1.3: delete entry Nydal (1968) - - - - -

p.44, ℓ.1 and 2: should read 'Natural ^{14}C was first detected routinely using a screen-wall Geiger counter (Anderson et al. 1951)'.

p.59, ℓ.20: 'filtered' should be 'passed'.

p.89, ℓ.8 from bottom: formula should be:

$$f = \frac{pCO_2(\text{sample + inactive})}{pCO_2(\text{sample})}$$

p.91, ℓ.4: '$A_m.f.1000$' should be '$A_s.f.1000$'.

p.119, ℓ.2: 50% should be 55%.

p.124, ℓ.13: equation should be: $N_A^i \Delta_A^i = N_S^i \Delta_S^i$

p.125, ℓ.7 from bottom: 'Δ_S^{ni}' should be 'Δ_D^{ni}'.

p.152, ℓ.1: 'for the original' should read 'for half the origin

p.161, ℓ.4: 'comparison to' should read 'comparison with'.

p.191, ℓ.13: D_N = the annual dose rate attributable to natural

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SUMMARY

The equilibrium distribution of natural ^{14}C has been disturbed over the past two decades by the release to the atmosphere of ^{14}C produced in nuclear weapon tests. Observation of the rate at which the human body responds to the resultant pulse of ^{14}C activity in the atmosphere enables an assessment of the kinetics of tissue carbon transfer. In this way, the bulk of evidence, from comparison of experimentally measured ^{14}C activities of human tissues with theoretically predicted corresponding ^{14}C levels, indicates a mean residence time for soft tissue carbon of 6 ± 4 years. In many organs analysed, a turnover time >10 years is apparent and the significance of such a slow turnover rate is discussed. No correlation between age of individual and mean residence time of tissue carbon is observed. Application of bomb-produced ^{14}C as a biochemical tracer is demonstrated via ^{14}C activity measurement of arterial lipid extracts; the results of such a study imply a turnover of lipid >10 years. Concern over the potential radiation burden of man-made ^{14}C has been expressed; thus present and future dose levels to body tissues attributable to this radionuclide have been determined. On the basis of extensive data recently compiled on the somatic and genetic risks from ionising radiation, corresponding risk estimates for artificially produced ^{14}C have been prepared. The resultant estimates suggest that, owing to its dilution with inactive carbon derived from fossil fuel consumption, this source of radioactivity neither does nor will represent a severe threat to mankind. Overall, the net extent of severe damage over that from natural ^{14}C is assessed at 1100 offspring with genetic disorders, of which 20-40 occur in first generation offspring, while 20-40 persons will suffer from ^{14}C-induced leukaemia. In a world population of 2.5×10^9, and over a period of 3 generations, such an incidence of damage is so low as to occur undetected.

CHAPTER 1. INTRODUCTION.

1.1 General Considerations

Since the advent of the nuclear era almost three decades ago, nuclear weapon tests have released a wide variety of radionuclides to the environment and thereby increased levels of background radiation. Many of the more hazardous radionuclides e.g. ^{95}Nb, ^{145}Ba, ^{95}Zr, have short half-lives and have therefore decayed to negligible levels; a few longer-lived radioisotopes, however, have not been affected significantly by decay since their artificial production. In particular, an estimated 9×10^{28} ^{14}C atoms have been added to the total atmospheric inventory of 4×10^{28} ^{14}C atoms. Owing to the easy access of this nuclide to man, and to the fact that carbon is a basic constituent of organic material, the resultant increase in ^{14}C concentration in humans has caused wide speculation on the potential radiation health hazard presented by ^{14}C to both present and future generations. In contrast, the feature of interest to the geochemist/geophysicist from bomb-produced ^{14}C is its unforeseen application as tracer for studies of the world-wide distribution of ^{14}C in the carbon cycle (see 1.2). As the excess ^{14}C in the atmosphere tends towards an equilibrium distribution throughout the other exchangeable carbon reservoirs, the rate at which the ^{14}C concentration in each part of the carbon cycle responds should in theory allow some understanding of the transfer processes of carbon in nature. Extrapolation of present ^{14}C levels in humans, from a knowledge of the relationship between the ^{14}C content of the biosphere and other carbon reservoirs will, in turn, enable an assessment of future human burdens of this radioisotope and aid in the accurate determination of the potential radiation hazard. Thus, the tracer role of ^{14}C can be used to gain a

valuable insight into both its more hazardous aspects and also into the geophysical processes which control carbon distribution. Furthermore, the tracer technique can be applied not only to carbon transfer between the major reservoirs (atmosphere and ocean) in this way, but also, on a much smaller scale, to the turnover of carbon in specific human tissues. As long as the non-equilibrium state of ^{14}C exists in nature, the opportunity is available for measuring residence times of carbon in the human body. The information obtained from such a study might be expected to reflect biochemical processes in the tissue without conducting experiments which could alter these processes. In this way, a closer cooperation between the geochemist and medical research worker is possible.

1.2 Development of Basic Concepts

The present state of knowledge of the environmental distribution of ^{14}C would perhaps be more limited but for development of the radiocarbon dating technique by Libby and the resulting period of intense research and improvement in instrumentation. The establishment of dating laboratories and the subsequent appearance of discrepancies in the dating concept paved the way for further research into the factors which influence the ^{14}C distribution in the exchangeable reservoirs. By 1952, when nuclear weapon testing produced its first global effects on environmental ^{14}C levels, laboratories were well equipped to measure the perturbation.

Natural ^{14}C

The existence of natural ^{14}C was predicted by Libby in 1946 after being influenced by 2 items of research from the previous decade, viz.

1) the discovery of the neutron-induced transmutation of ^{14}N to ^{14}C.

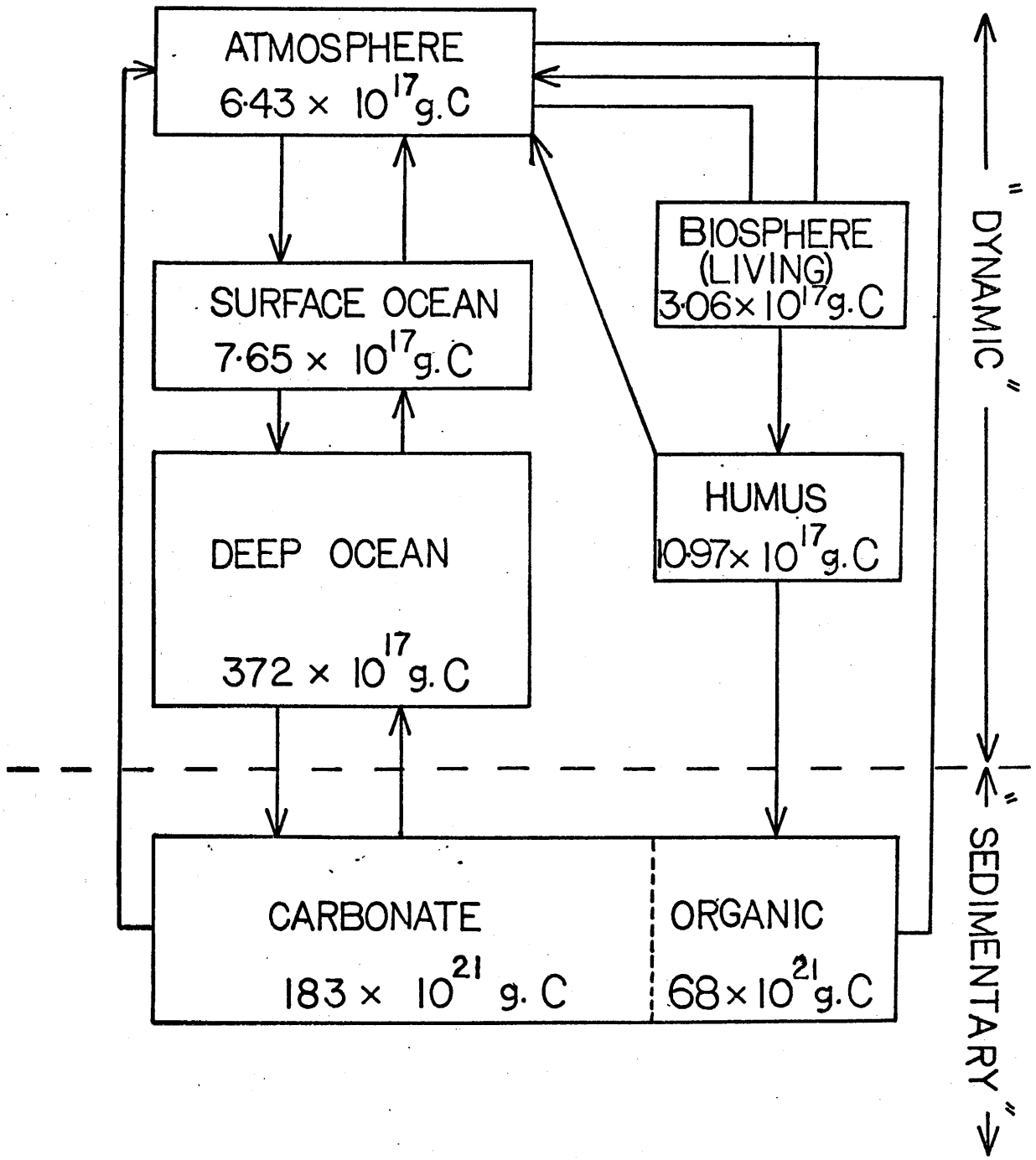
The ^{14}N (n,p) ^{14}C reaction using fast neutrons was first suggested by Kurie in 1934. Two years later, the slow neutron disintegration of nitrogen was attributed to the (n,p) process — the absorption of a neutron with the emission of a proton — by Bonner and Brubaker (1936) and Burcham and Goldhaber (1936). The latter workers also estimated the cross-section value of the transmutation to be 1 barn ($\equiv 10^{-24}$ cm^2). This value, a measure of the probability of occurrence of the ^{14}N (n,p) ^{14}C reaction, is relatively larger than for most materials.

2) the detection in the upper atmosphere of cosmic-ray produced neutrons by Korff and Danforth (1939). These neutrons were thought to originate from a series of interactions between cosmic-ray primaries, essentially high-energy protons, and naturally occurring atoms in the upper atmosphere.

With these observations in mind, Libby (1946) reasoned that ^{14}C would be produced virtually quantitatively with respect to the neutron production via ^{14}N (n,p) ^{14}C in the stratosphere. From data of Korff and Hammermesh (1946) he estimated a production rate of ~ 2 ^{14}C atoms/cm^2/sec. and that this ^{14}C, on rapid oxidation to $^{14}CO_2$ and incorporation into the carbon cycle (Fig. 1.1), would be diluted by the stable $^{12}CO_2$ and $^{13}CO_2$ present in the natural atmosphere at levels around 290 p.p.m. (Callender 1940).

The reservoirs within the carbon cycle may be subdivided into: (a) a dynamic system in which carbon is exchanged between reservoirs within the time scale represented by the decay of ^{14}C, and (b) a sedimentary system which includes rock weathering and precipitation/dissolution of carbonaceous sediments in the oceans. The latter cycle

FIG. 1.1 THE CARBON CYCLE



is estimated to turn over carbon once every 10^5 years (Brown 1957) during which time ^{14}C initially present decays to negligible levels. The oceans themselves do not represent a uniformly mixed reservoir and are more realistically described by a two-component system:

(a) a mixed surface layer extending to a depth of approximately 100 m. This water volume is well mixed by the action of wind and waves and contains the majority of marine life, whereas

(b) the deep ocean mixes very slowly via thermocline transport on a time scale in the order of several hundred years.

The terrestrial biosphere consists of the living materials of plants and animals and the dead component of humus deposits. The inventory of carbon stored in each reservoir is included in Fig.1.1; it is apparent that the deep ocean contains ~95% of the exchangeable carbon.

Distribution of ^{14}C

As ^{14}C is produced in the stratosphere, the isotopic distribution depends on several factors:

(i) rate of production of ^{14}C

(ii) rate of exchange of carbon between reservoirs

(iii) size of each carbon reservoir and its inventory of exchangeable carbon

(iv) isotopic fractionation (discussed in 2.8). For example, carbonate shells are enriched in $^{13}C/^{12}C$ ratio by ~2.5% relative to terrestrial plants; the corresponding $^{14}C/^{12}C$ ratio ought to be enriched by 2 x 2.5% (Craig 1954)

(v) radioactive decay, an additional mechanism over the stable isotopes ^{12}C and ^{13}C, for removal of ^{14}C from any reservoir.

The total ^{14}C inventory, given in Table 1.1 based on data by Craig (1957a) is only accurate to ± 5%, but errors of a factor of 2 are possible in defining the relative sizes of the biosphere and surface ocean carbon contents. On the assumption that the half-life ($t_{\frac{1}{2}}$) of ^{14}C is sufficiently large to allow several cycles of the isotope through the exchangeable reservoir system, Libby postulated that an equilibrium situation would arise in which

rate of disintegration of ^{14}C ≡ rate of production of ^{14}C.

Thus ^{14}C would be incorporated into all reservoirs of the dynamic cycle in a fixed isotopic ratio, dependent on the particular reservoir and its controlling factors. All living systems should therefore maintain an equilibrium specific activity (d.p.m./g.carbon). After death, however, the carbon within any organism can no longer be replenished and the ^{14}C content decays exponentially according to the equation:

$$A_t = A_o e^{-\lambda t} \qquad - - - - - - - - \quad (1.1)$$

where A_t = activity of ^{14}C in the sample t years after death,

A_o = equilibrium activity of ^{14}C during life,

and λ = radioactive decay constant ≡ $\dfrac{\ln_e 2}{t_{\frac{1}{2}}}$

Knowing A_o and λ, one can calculate the age, t, of a sample — the time during which decay of ^{14}C has taken place — from the measurement of its residual activity A_t. This simple relationship is the basis of the radiocarbon dating method. Libby (1955) in his initial exposition, predicted an approximate value of A_o (17.3 d.p.m./g.carbon) from an estimate of the total amount of diluting carbon in exchange equilibrium with atmospheric CO_2. His original estimates of the carbon content in

TABLE 1.1 NATURAL ^{14}C INVENTORY *

RESERVOIR	TOTAL ^{14}C/RESERVOIR ($\times 10^{27}$ ATOMS)
Atmosphere	39
Terrestrial biosphere	18
Humus	64.5
Surface ocean	47
Deep ocean	1928
TOTAL	2100

* Figures based on data of Craig (1957a) and on the natural ^{14}C concentration of 1890 wood: - 5.9×10^{10} ^{14}C atoms/g. carbon.

the exchangeable reservoir agree favourably with the more recent values shown in Fig. 1.1.

Radiocarbon dating

Anderson et al. (1947) verified that natural ^{14}C did, in fact, exist at picoCurie levels as predicted, by counting CH_4, isotopically enriched with respect to ^{14}C, in a screen-wall Geiger counter. With the development of this counting technique, activity measurements soon became possible without the need for isotopic enrichment. Measurement of the activities of environmental samples of different biological and geographical origin (Libby 1955) showed that, within the limits of the counting technique, there was a uniform specific activity (A_o) throughout the world, and that atmospheric mixing must therefore be rapid, as had been assumed for the radiocarbon dating concept. At this time, a more accurate estimate of the half-life of ^{14}C produced a value of 5568 $\pm$ 30 years (Libby 1955), which is slightly lower than the presently accepted mean figure of 5730 $\pm$ 40 years (Godwin 1962). It only remained to test the validity of the dating method by age-dating archaeological samples of well documented history (e.g. Egyptian Dynasty artifacts, Libby et al. 1949). Good agreement between early data not only established ^{14}C dating as a useful archaeological tool but also substantiated, to a first approximation at least, Libby's original assumptions of constant ^{14}C production and exchange. Refinement in experimental technique enabled the activity measurement of smaller amounts of carbon (10g. $\longrightarrow$5g.) and the reduction in the statistical uncertainty of sample count rates. The theoretical limitation of the dating method is fixed by the half-life of ^{14}C at ~50,000 years; any sample of this age has a residual activity (A_t) of 0.03 d.p.m./g.carbon

which is indistinguishable from background count rates in most counters. Sample integrity was considered to minimise the possibility of sample contamination by non-contemporaneous carbon (Olson and Broecker 1958). In this way, radiocarbon dating of ancient mortar, plaster and bone samples is particularly susceptible to errors (Baxter and Walton 1970a, Krueger 1965). The improvement in accuracy gained by the initial advances of the dating method and the more precise estimates of dates made a significant contribution to archaeological and geological sciences (Johnson 1965). As the method was further perfected and the accuracy of age assessments correspondingly improved to levels of $<1\%$ uncertainty, discrepancies between ^{14}C and archaeological dates became increasingly apparent, up to 600 years in some cases (Egyptian 3rd Dynasty, Libby 1952, Kusumgar 1963). Owing to the degree of uncertainty associated with some archaeological estimates, an alternative source of material suitable for radiocarbon dating and with an independent time-scale was sought and found in the annual growth rings of trees. Each ring participates in the carbon-oxygen cycle for one year only and thereafter remains essentially a closed system. Thus, after correction for slight changes of isotope ratio which take place during the biochemical reactions in a plant, the ^{14}C activity measured for any tree ring is representative of the ^{14}C activity in the atmosphere at time of growth. Non-statistical variations in ^{14}C activity, corrected for decay using equation (1.1), were first found by Suess (1953) in tree rings of 20th century wood and by de Vries (1958) in pre-20th century wood. The former variations were caused by known artificial disturbances of the dynamic carbon cycle (see 1.4) but the latter could be attributed only to natural effects. The implication of the latter findings was the

breakdown of Libby's fundamental postulate for radiocarbon dating that the atmospheric ^{14}C activity had remained constant with time.

1.3 Natural fluctuations of ^{14}C

Variations of about 2% over the course of several centuries were found by de Vries (1958) in the ^{14}C activity of tree rings and hence in atmospheric activity. A 2% change of initial activity yields an error in a radiocarbon age of 160 years. De Vries suggested that the observed fluctuations were caused by the effect of climatic change on the rate of mixing between the deep and mixed layers of the oceans. An increase in atmospheric/surface-water temperature causes a decrease in the rate of upwelling of deep water which, via exchange, dilutes atmospheric ^{14}C activities with its less active carbon. The resultant effect is an increase in atmospheric $^{14}CO_2$ concentration which was indeed found and attained a maximum at A.D. 1690. The hypothesis was supported by the available information on glacier advance and retreat during this period known as the Little Ice Age(A.D. 1500 - A.D. 1790); the glacial minimum corresponded in time to the maximum atmospheric ^{14}C activity.

Since the initial measurements and observations by de Vries, a large number of ^{14}C activity measurements on wood specimens of known age have been accumulated (Münnich 1957, Broecker et al. 1959, Willis et al. 1960, Ralph and Stuckenrath 1960, Suess 1961, Damon and Long 1962). In most cases, ages were assigned by dendrochronological examination of the tree rings. By this method, master chronologies are constructed from sequences of overlapping ring sections of different trees. By correlation of plotted tree-ring widths of an unknown sample with the master chronologies, it is possible to obtain an absolute age

of each ring to an accuracy of ± 1 year (Ferguson 1968). This technique is superior to simple counting of rings which can lead to errors caused by "missing" rings (lack of growth for one year) or "double" rings (two rings formed during one year's growth). In some cases, well documented historical samples have been used to check dendrochronological sequences, with good agreement (Damon et al. 1965). Subsequent systematic investigations by several workers have confirmed the maximum in atmospheric ^{14}C concentration at A.D. 1690 (Damon et al. 1965, Suess 1965) - the "de Vries effect" - and extended the chronology beyond the past 8,000 years (Damon et al. 1970, Ralph and Michael 1970, Suess 1970a). The main sources of dated wood are the bristlecone pine ('pinus aristata') and 'sequoia gigantea', both exceptionally long-lived trees and reliable indicators of the atmospheric ^{14}C concentrations prevalent during the growth of each ring. The advantage of this research for radiocarbon dating lies in the resultant calibration tables or curves constructed to allow conversion of ^{14}C-calculated dates to their appropriate calendar dates (Damon et al. 1972, Michael and Ralph 1972, Suess 1970a); of these, the Suess calibration curve is probably the most widely used. The geophysical value to be gleaned from the ^{14}C vs. tree-ring chronology lies in the analysis of possible reasons for the observed variations in ^{14}C with time. Two trends are apparent:

1) a long-term increase in ^{14}C concentration of ~10% from 2500 B.P. (before 1950) to 6000 B.P. with, superimposed upon this,

2) short-term fluctuations of 1-2% over a period of centuries.

Two of the most likely causes of these temporal variations are:

(a) change in the ^{14}C production rate caused by variation in the

cosmic-ray flux, and

(b) change in the size and/or exchange rate of one or more of the reservoirs of the dynamic carbon cycle.

It is now widely accepted that the long-term ^{14}C trend is due to modulation of the cosmic-ray flux by a variable terrestrial magnetic field, while the short-term fluctuations reflect a similar modification of the cosmic-ray flux by variable solar activity. A third factor of some relevance is the effect of climatic change on the parameters given in (b).

Geomagnetic modulation of the cosmic-ray flux

The effect of geomagnetism on the cosmic-ray flux is such that the total production rate of ^{14}C in the atmosphere is approximately inversely proportional to the square root of the geomagnetic dipole moment (Elsasser et al. 1956). Archaeomagnetic measurements imply that the earth's dipole field has fluctuated in an approximately sinusoidal manner with a period of about 8000 years (Smith 1967, Bucha and Neustupný 1967). The intensities at maximum and minimum are 1.5 x and 0.5 x the present geomagnetic field respectively. Model treatments of varying complexity have been performed to obtain estimates of the resultant atmospheric ^{14}C variations expected from these findings (Kigoshi and Hasegawa 1966, Damon 1970, Lal and Venkatavaradan 1970, Yang and Fairhall 1972). The resultant data suggest that a correlation between variations in atmospheric ^{14}C concentration and fluctuations in the terrestrial magnetic dipole moment is indeed possible, at least over the past 6000 years. However, the limited number and quality of the magnetic data recorded to date make it difficult to assess the significance of results (Bucha 1970).

Heliomagnetic modulation of the cosmic-rays

Forbush (1954) showed that an approximately inverse relationship exists between the mean level of solar flare (sunspot) activity and the level of the cosmic-ray flux which enters the earth's atmosphere. The increased flux of charged particles, mainly high-energy protons emanating from the sun during periods of high solar activity, deflects some of the incident cosmic rays so that variations in the production rate of ^{14}C are to be expected. Stuiver (1961) first attempted a prediction of an empirical relationship between sunspot activity and ^{14}C concentrations in the atmosphere. His early comparison of the tree-ring ^{14}C activity fluctuations found by Willis et al. (1960) with the sunspot curve of Schove (1955) suggested some, but slight, interdependence. Subsequently, in more detailed studies, a good inverse correlation was found between experimentally observed ^{14}C concentrations in pre-19th century A.D. tree rings and values calculated from solar cycle data (Stuiver 1965, Suess 1965, Grey and Damon 1970, Grey 1969). Suess (1970b) recognised repeated minima at about 400 year intervals, in atmospheric ^{14}C concentration after allowance for the effects of geomagnetic field modulation; this observation together with postulates of 400 year cycles of solar activity (Dewey 1960, Schove 1961, Link 1964) has given weight to the hypothesis that solar modification of the ^{14}C production rate is the prime cause of the small secular fluctuations in atmospheric ^{14}C activity.

Climatic changes

Several correlations of atmospheric ^{14}C levels with general patterns of climatic change have been noted (Lamb 1961), the most remarkable of these being the correlation of the de Vries effect with

the retreat of the glacier front. Despite these observations, Damon (1970) and Suess (1970b) conclude independently that climatic changes in the last 8 millenia are of minor importance with respect to the previous two causes, and in fact point out that certain climatic factors would compensate each other. Thus the former two effects remain the most favoured causes of secular variations in atmospheric ^{14}C concentration. The effects of the solar modulation of the cosmic-ray flux are superimposed on the larger effect of geomagnetic modulation.

Fluctuations over a much shorter time scale have been found, although the causes of such variations are still in question (Baxter and Walton 1971, Farmer and Baxter 1972, Damon et al. 1973). Annual instability of atmospheric ^{14}C levels was first detected by Dyck (1965) in a systematic study of annual growth rings of a fir tree. The data, although uncorrected for isotopic fractionation, suggested cyclic variations of up to 3% amplitude during A.D.822-831 and A.D.1616-1627. Subsequent research by Baxter and Walton (1971) into the ^{14}C levels in seeds, wines, whiskies, and sheeps' wool, samples which are representative of one year's growth, confirmed the existence of annual fluctuations and determined that cyclic variations of up to 3% in 10 years are possible; a dependence on latitude is also suggested. The possibility of dating errors of up to $\pm$ 120 years on samples with a lifetime in the order of 1 year was emphasised as a consequence of such fluctuations (Farmer and Baxter 1972), together with the geophysical implication of an uncertainty in the values of exchange rates of carbon for different reservoirs and, indeed, in the concept of a constant transfer rate.

The assumptions inherent in the radiocarbon dating technique

have been scrutinised thoroughly, with the aid of independent chronologies, and shown to be valid only to a first approximation. Examination of the causes of the fluctuations has led to a better, though still incomplete, understanding of the geophysical processes responsible. Two further influences during the last century, due to the activities of man, have upset the equilibrium balance of ^{14}C activity not only in the atmosphere but in all exchangeable carbon reservoirs, and have offered a further opportunity to study carbon transport parameters.

1.4 Artificial Fluctuations of ^{14}C

The two artificial disturbances of the natural ^{14}C distribution are :

(a) the 'Suess effect', a dilution of the natural $^{14}CO_2/^{12}CO_2$ ratio by the addition of inactive CO_2 from the combustion of fossil fuels, and

(b) the 'bomb effect', an increase in ambient ^{14}C levels by the addition of ^{14}C produced during the explosion of nuclear devices.

The latter effect is by far the major perturbation and has been manifested in the northern hemisphere as a rise in atmospheric ^{14}C activities to double 'natural' levels.

Suess effect

Callender (1940) first stated that, between A.D. 1890 and 1940, the average CO_2 concentration in the atmosphere increased by approximately 10%; his estimate was based on a survey of the direct CO_2 measurements reported during this period. The increase was believed to be the result of the accelerating input to the atmosphere of CO_2 produced in the industrial combustion of fossil fuels such as coal,

oil, and natural gas. Suess (1953) first pointed out that the effect of this CO_2, since it derives from sedimentary systems and is therefore inactive, would be to decrease the natural $^{14}CO_2/^{12}CO_2$ ratio. Furthermore, he suggested that measurement of the activity of atmospheric CO_2 would give some indication of the rate of exchange of CO_2 between atmosphere, biosphere, and surface ocean (see 1.5). Following an assessment of the industrial production of fossil fuel CO_2 during each decade from A.D. 1860-1950 (Revelle and Suess 1957), a more detailed estimate of the fossil fuel combustion effect was performed by Baxter and Walton (1970b). The latter workers then were able to evaluate theoretically the expected decrease in atmospheric ^{14}C concentration from A.D. 1860-1950. This theoretical approach yielded data which showed good agreement with experimental observation and yielded a 1950 value of 3.2 ± 0.45% for the decrease in the ^{14}C level in the atmosphere relative to 1890 wood. The reasonable agreement obtained here justifies a further theoretical assessment of the Suess effect since 1950, when direct measurement of the resultant decrease in atmospheric ^{14}C concentration is not possible due to the predominant effect of nuclear weapon testing. The significance of the Suess effect to the geochemist is the realisation of the necessary correction of present day activities before any subsequent treatment of results is possible. The Suess effect also reflects the general increase in atmospheric CO_2 concentration, estimated to reach 50% of the normal atmospheric CO_2 content (290 p.p.m. - Callender 1940) by A.D. 2025 (Baxter and Walton 1970b). According to calculations by Plass (1956), such an increase could raise global temperatures by about 2°C, although this value is considered to be too high since the calculation was based on a dry atmosphere. Manabe and Strickler (1964)

indicate that the temperature increment may be compensated by a change in humidity and cloud cover.

Bomb effect

Since 1952, large yields of artificial ^{14}C have been injected into the atmosphere during testing of nuclear weapons. Neutrons, generated in the fireball at the centre of the nuclear blast, react with surrounding nitrogen to form 'man-made' ^{14}C via the mechanism identical to that for natural production, viz. ^{14}N (n,p) ^{14}C. The first nuclear bombs operated by the fission of uranium or plutonium, but were succeeded by hydrogen bombs in which the main energy is released by fusion reactions (e.g. $^{2}H + {}^{2}H \longrightarrow {}^{3}He + n$). The total energy yield for a nuclear process is related to the neutron yield, and several estimates of the resultant ^{14}C produced per megaton (Mton) equivalent have been made (Libby 1956, ibid. 1958, Pauling 1958). This quantity depends on the type of device and on whether the explosion takes place near the earth's surface or in the atmosphere. The most recent average figures quoted for total weapon yield (fission + fusion) are 2×10^{26} neutrons/Mton for an air burst and 1×10^{26} neutrons/Mton for a surface burst, when 50% of the neutrons are absorbed by the elements of the earth's crust (Junge 1963). On this basis, a summary of the ^{14}C inventory from nuclear explosions since 1945 is given in Table 1.2. As most of the bomb cloud of nuclear explosions >1 Mton rises into the stratosphere (Libby 1957), the majority of the ^{14}C produced is released there, similar to the natural ^{14}C location source, although the geographical sites of the explosions are in no way related to the distribution of natural ^{14}C production.

TABLE 1.2 ARTIFICIAL ^{14}C INVENTORY. *

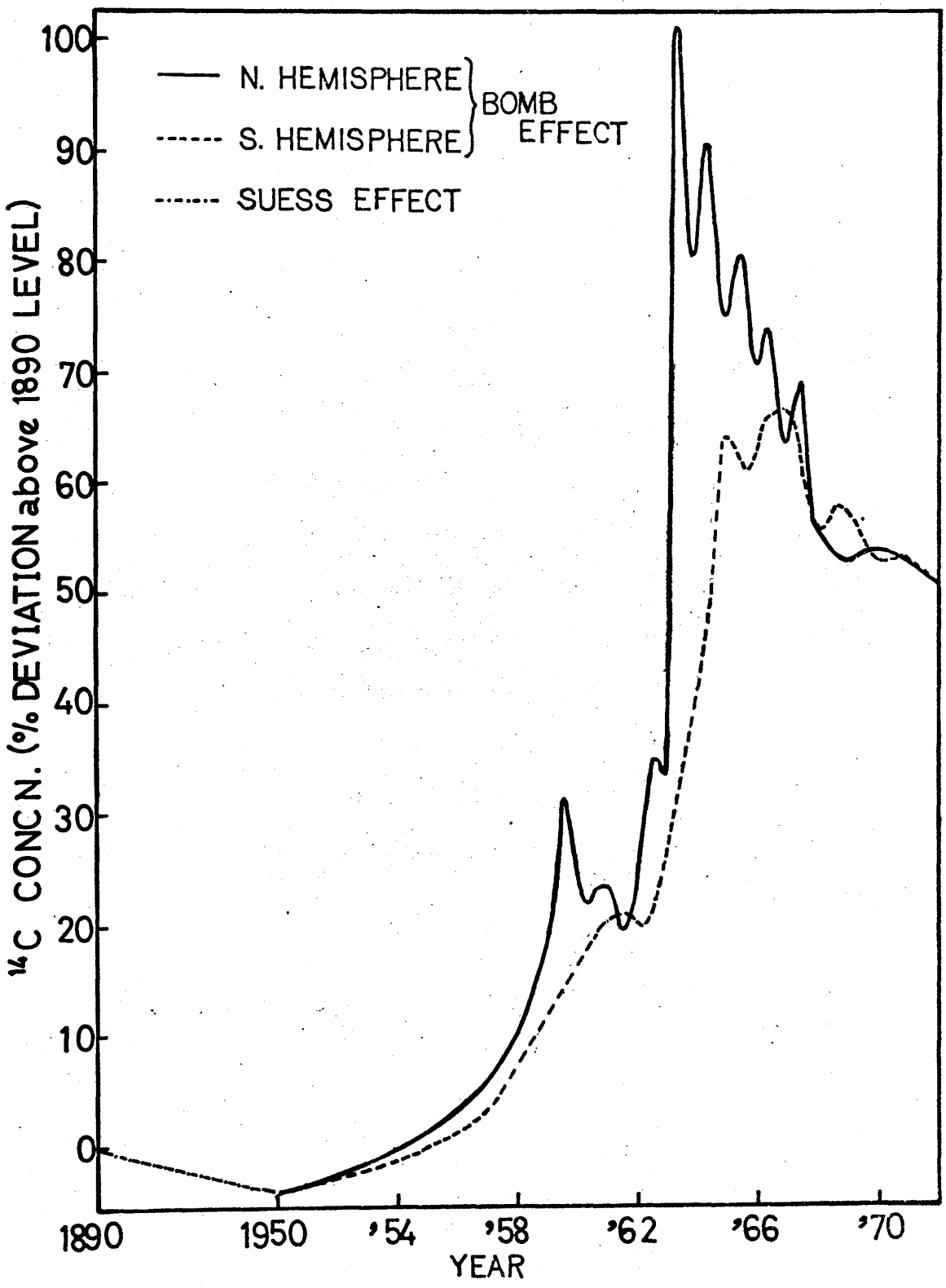
TIME PERIOD	TOTAL ^{14}C PRODUCTION (x 10^{27} ^{14}C atoms)
1945 - 1951	0.1
1952 - 1954	6.0
1955 - 1956	3.8
1957 - 1958	14.2
1959 - 1960	—
1961	24.0
1962	43.4
1963	—
1964 - 1970	4.0
1971 - 1973	2.3
TOTAL	98.0

* Data obtained from published energy yields;
1971 - 1973: information from Chatters (personal communication).

Increases in ^{14}C concentration in the atmosphere were first detected by direct measurement of the $^{14}CO_2/\ ^{12}CO_2$ ratio in samples of atmospheric CO_2 (Rafter 1955). The potential of ^{14}C as a tracer in the elucidation of the mechanism and rates of the numerous mixing processes of carbon in the dynamic reservoir was realised by Broecker and Walton (1959), who were among the first of many to utilise bomb ^{14}C and to calculate rates of transfer of ^{14}C. After the moratorium in 1958 and the resumed testing on a larger scale in 1961, a more systematic collection programme was initiated in many laboratories to follow the movement of ^{14}C through the carbon cycle.

The ^{14}C concentration variations in the northern hemisphere troposphere produced by both artificial effects is shown in Fig. 1.2. The decrease in ^{14}C concentration caused by the Suess effect is apparent up to 1954 but thereafter is masked by the bomb effect. Tropospheric ^{14}C activities in the northern troposphere rose to 100% above the prebomb level in late 1963, one year after the end of large-scale testing. Since then, this ^{14}C activity has followed a general decrease as carbon transfer takes place between reservoirs, interrupted only by seasonal injections of CO_2 of higher activity from the stratosphere, and by sporadic production of ^{14}C from French and Chinese nuclear tests. The majority of nuclear explosions were carried out at high northern latitudes; as a result, the appearance of bomb ^{14}C in the southern hemisphere was delayed due to the finite mixing times of CO_2 between both stratosphere and troposphere and north and south hemisphere tropospheres. The maximum ^{14}C concentration reached in the southern hemisphere corresponded to only $\sim$65% of the northern maximum 3 years earlier, as shown also in Fig. 1.2.

FIG. 1.2 ^{14}C CONCENTRATIONS IN THE TROPOSPHERE (1890-1970)



Before the realisation of the Suess effect, several laboratories used samples of 20th century organic material as reference standards to represent the steady-state atmospheric $^{14}C/^{12}C$ ratio maintained by all living materials, A_o (see, for example, de Vries 1958). This practice introduced errors of up to 120 years in resultant radiocarbon dates (Baxter and Walton 1971). The larger perturbation caused by the bomb effect further emphasised the need for a reference standard based on a time period outwith the artificial perturbations, and resulted in the distribution, to radiocarbon dating laboratories, of a new substance as standard - the National Bureau of Standards (NBS) Oxalic Acid Standard (see 2.6.2).

1.5 Calculation of Exchange Rates and Residence Times of Carbon in the Dynamic Reservoir

One of the most common treatments employed to calculate the rates at which transfer processes take place in the carbon cycle is the box-model approach. In this method, each reservoir of the type shown in Fig. 1.1, dynamic system, may be subdivided, combined with one or more others, or left unchanged to form a number of compartments, or 'boxes'. Within such boxes, a rapid and homogeneous mixing of ^{14}C is assumed. Thus, the atmospheric reservoir may be subdivided into the stratosphere, that part of the atmosphere above 30,000 - 50,000 ft. depending on latitude, and the troposphere, the turbulent air-mass below the stratosphere. Further subdivision into the northern and southern hemispheres may be necessary if a latitudinal dependance of the ^{14}C distribution is suspected. In the resultant box model, calculations are performed via the following assumptions:

1) each box is internally well-mixed so that the $^{14}C/^{12}C$ ratio

at any location within the box is representative of the total,

2) rate of flow of material between boxes is uniform with time and location,

3) internal mixing times are negligible relative to the exchange times between adjacent reservoirs,

4) flow of material between boxes and reservoirs conforms to first order kinetics i.e. flow rate $\propto$ concentration.

Fig. 1.3 illustrates two such box-models of diverse complexity, which may be compared with the dynamic carbon cycle shown in Fig.1.1. All flows of material into and out of a reservoir are computed. Thus in Fig. 1.3(a), the exchange of normal carbon (^{12}C, ^{13}C) between reservoirs is given by the following equation:

$$dN_a/dt = -k_{am}N_a + k_{ma}N_m$$

where, in the general case,

N_i = the amount of carbon in reservoir 'i',

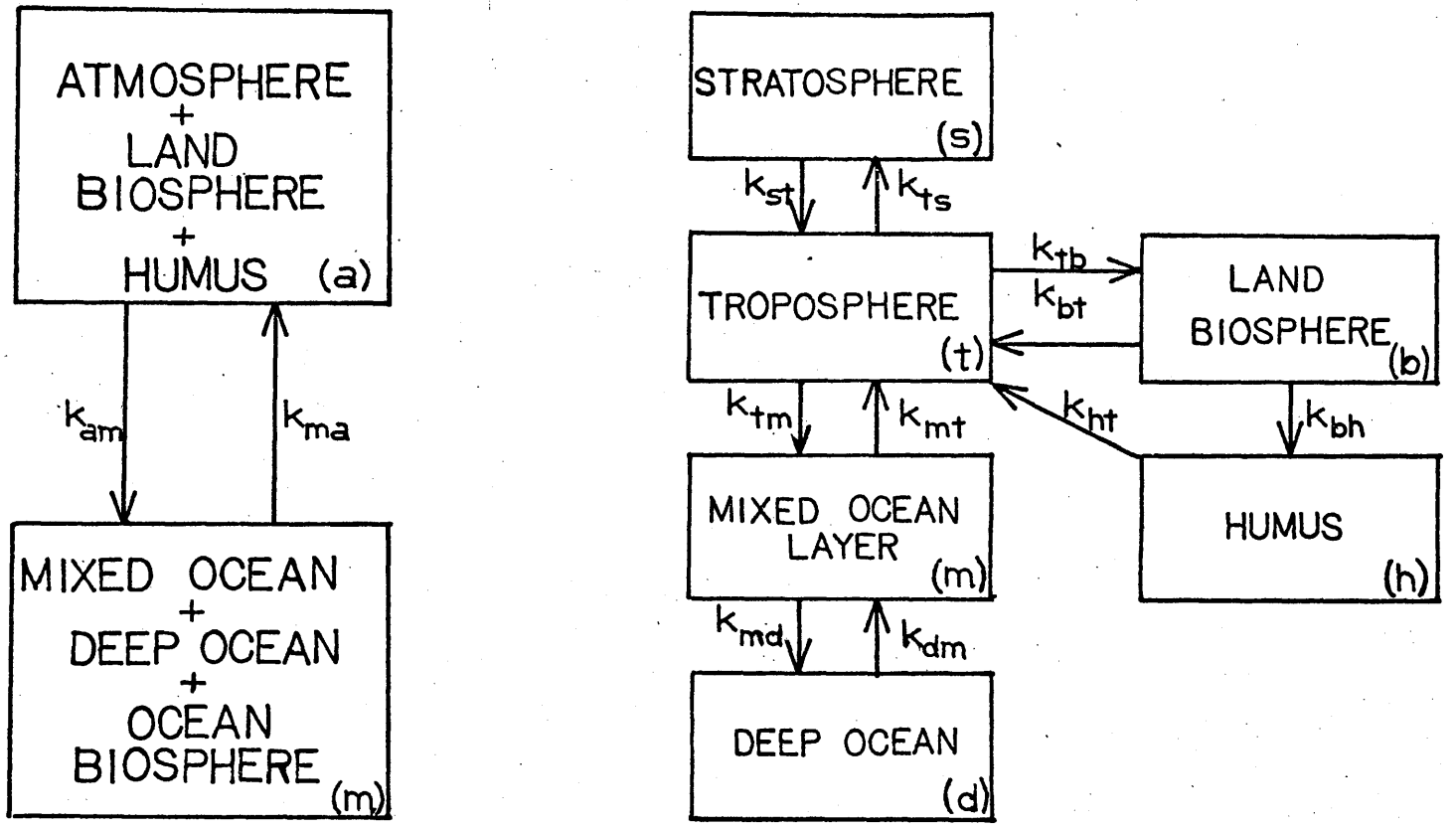
k_{ij} = the first order rate constant for transfer of carbon from reservoir 'i' to reservoir 'j',

dN_i/dt = the net flow of material, arbitrarily negative for outflows and positive for inflows, while subscripts 'i', 'j' correspond to the letters ascribed to reservoirs in Fig. 1.3.

Evaluation of rate constants is achieved with the application of steady-state conditions i.e. the carbon content of each reservoir remains constant:

$$dN_i/dt = 0$$

FIG. 1.3 TWO EXAMPLES OF BOX-MODEL SYSTEMS



(a) 2-COMPARTMENT

(b) 6-COMPARTMENT

With respect to Fig. 1.3 (a),

$$\left.\begin{aligned} dN_a/dt = 0 &= -k_{am}N_a + k_{ma}N_m \\ dN_m/dt = 0 &= -k_{ma}N_m + k_{am}N_a \end{aligned}\right\} \quad - - - - - \quad (2)$$

One of these equations is redundant, since either expression defines the ratio k_{am}/k_{ma} in terms of N_a and N_m. Similar equations can be written for the steady-state ^{14}C balance, with additional terms necessary to describe ^{14}C production in reservoir 'a' and ^{14}C decay:

$$N_a\, dx_a/dt = 0 = N\lambda - N_a x_a \lambda - k_{am}N_a x_a + k_{ma}N_m x_m \quad - - - \quad (3)$$

where in the general case,

x_i = ^{14}C activity/unit weight of carbon in reservoir 'i',

i.e. $N_i x_i$ = amount of ^{14}C in reservoir 'i',

λ = radioactive decay constant of ^{14}C, and

N = total amount of ^{14}C present = $\sum N_i x_i$, where,

for steady-state conditions,

^{14}C production = total ^{14}C decay

The rate constants for ^{14}C exchange are assumed to be the same as for ordinary carbon transfer; the assumption is valid provided activities, x_i, are corrected for isotopic fractionation. Simultaneous solution of equations (2) and (3) yield an expression for either rate constant from which the other may be calculated, e.g. :

$$k_{am} = \frac{\left(\frac{N}{N_a}\lambda - x_a\right)}{(x_a - x_m)} \qquad \text{gives} \qquad k_{ma} = \frac{k_{am}/N_m\,(N\lambda - N_a x_a)}{(x_a - x_m)}$$

Evaluation of k_{am}, k_{ma} is possible provided values of λ, N, N_a, N_m, x_a, and x_m are known and $x_a \neq x_m$. The reciprocal of k_{ij} in a two-box model is called the residence time (τ_{ij}), which is defined as

the average lifetime of an atom or molecule in reservoir 'i' before it transfers to 'j'. When a particular reservoir 'i' exchanges with n other reservoirs, the total residence time in that reservoir with respect to removal by all possible routes 'j' is given by the expression:

$$\frac{1}{\tau_i} = \sum_{j=i}^{j=n} \frac{1}{\tau_{ij}}$$

where τ_{ij} are the individual residence times of reservoir 'i' with each exchangeable reservoir 'j'.

Solution of models containing more than two boxes may be obtained in a similar manner; however, in any treatment, it is usually necessary to compromise between the complexity of calculation and accuracy obtained in its solution, both of which normally increase with the size of the box model. Three different approaches have been used to determine reservoir residence times of carbon and are based on:

1) Natural ^{14}C budget

The steady-state ^{14}C balance relative to cosmic-ray production, physical removal, and decay in the atmosphere is treated by Craig (1957a) to obtain τ_{am}, the residence time of a CO_2 molecule in the atmosphere before transfer to the ocean-mixed layer. From Fig. 1.3 (b), the ^{14}C steady-state condition in the atmosphere is given by:

$$\overline{Q} + k_{ma}N_m x_m + k_{ha}N_h x_h + k_{ba}N_b x_b = k_{am}N_a x_a + k_{ab}N_a x_a + N_a x_a \lambda \quad - - - \quad (4)$$

where $\bar{Q}$ is the mean production rate of ^{14}C from cosmic-ray flux (atoms/cm^2.sec), and similarly in the biosphere and humus by:

$$k_{ab}N_a x_a = k_{ha}N_h x_h + k_{ba}N_b x_b + (N_h x_h + N_b x_b)\lambda - - - \quad (5)$$

Using equation (5), equation (4) may be rewritten:

$$k_{am}N_a x_a - k_{ma}N_m x_m - \bar{Q} + (N_h x_h + N_b x_b + N_a x_a)\lambda = 0$$

From steady-state conditions, $N_a k_{am} = N_m k_{ma}$

and substituting for k_{ma} yields the expression:

$$k_{am}N_a x_a - k_{am}N_a x_m - \bar{Q} + (N_h x_h + N_b x_b + N_a x_a)\lambda = 0$$

from which τ_{am} may be obtained:

$$\tau_{am} = \frac{\frac{1}{\lambda}\left(1 - \frac{x_m}{x_a}\right)}{\frac{\bar{Q}}{N_a x_a \lambda} - \left\{\frac{N_b x_b}{N_a x_a} + \frac{N_h x_h}{N_a x_a} + 1\right\}}$$

In Craig's treatment, insertion of estimates of $\bar{Q}$, N_a, N_b, N_h, and λ with calculations of x_a, x_b, x_h, and x_m based on $^{13}C/^{12}C$ fractionation measurements yielded a value of $\tau_{am} = 7 \pm 3$ years; the error was largely based on the uncertainty of the true value of $\bar{Q}$.

2) Suess effect approach

The transient distribution of fossil CO_2 in the atmosphere and marine environment was computed and the exchange time of CO_2 between atmosphere and sea, τ_{am}, calculated by Revelle and Suess (1957) from the observed effect of industrial fuel

consumption on the specific ^{14}C activity of wood. In their treatment - a closed system of two reservoirs, atmosphere and oceans - any effect of industrial CO_2 on the rate constants k_{am}, k_{ma} was neglected. From consideration of the transfer of CO_2 between atmosphere and surface ocean,

$$dn_m/dt = k_{am}(ft - n_m) - k_{ma}n_m \quad - - - - - - - \quad (6)$$

where f = annual amount of industrial CO_2 added to the atmosphere,

t = time in years, and

n_m = amount of industrial CO_2 in the oceans,

N.B. subscript 'm' applies to the total ocean reservoir.

Integration of equation (6) yields the expression:

$$n_m = ft.\frac{k_{am}}{(k_{am} + k_{ma})} - f.\frac{k_{am}}{(k_{am} + k_{ma})^2}\left\{1 - e^{-(k_{am} + k_{ma})t}\right\} \quad - (7)$$

Since $k_{am}/k_{ma} = N_m/N_a$ (steady-state conditions)

and $N_m \gg N_a$, (here, N_m = total carbon in oceans)

k_{ma} is negligible compared to k_{am} and equation (7) becomes:

$$n_m = ft - f/k_{am}.(1 - e^{-k_{am}t})$$

or, if n_a is the amount of CO_2 derived from industrial fuel combustion in the atmosphere at time t, i.e. $n_a = ft - n_m$

$$n_a = f/k_{am}.(1 - k_{am}t)$$

n_a is also equal to the observed decrease in $^{14}CO_2/^{12}CO_2$ ratio, i.e. the Suess effect, which was measured for tree rings of

different time periods. From an estimate of f and an average value of n_a, Revelle and Suess obtained a value of 7 years for τ_{am}. Since rapid mixing of the oceans was assumed for the calculation, the resultant value was considered only as an estimate.

3) Bomb ^{14}C

In this case, the transfer of excess ^{14}C is considered for each reservoir. The rate constants for ^{14}C exchange are assumed to be equal to those for ordinary carbon transport, as excess ^{14}C activities are normally corrected for isotope fractionation. Under these non-equilibrium conditions, solution to the problem becomes more complex, and assumptions have to be made to solve the rate equations. Thus, for exchange between two reservoirs A and B, the equation for the rate of change of bomb ^{14}C in reservoir A is

$$N_a \, dx_a/dt = - k_{ab} N_a x_a + k_{ba} N_b x_b$$

where x_a, x_b are the excess concentrations of bomb ^{14}C in A and B respectively (in units of excess ^{14}C activity per unit weight of carbon) and dx_a/dt, N_a, N_b, k_{ab}, k_{ba} are defined as before.

Assuming steady-state conditions for ordinary carbon, (i.e. $N_a k_{ab} = N_b k_{ba}$), and substituting for k_{ba}, the following relationship is obtained:

$$dx_a / dt = k_{ab} (x_b - x_a) \quad - \quad - \quad - \quad - \quad - \quad (8)$$

Solution of this equation may be sought by two methods:

(i) if the rate of change of x_a is known, substitution of specific values of x_b and x_a at particular time t will enable calculation of k_{ab}, or

(ii) if an empirical expression of x_b in terms of t is known, integration of equation (8) is then possible. Thus, in a case where $x_b = Be^{-bt}$

integration of equation (8) gives the following equation:

$$x_a = Ae^{-bt} + Ce^{-k_{ab}t} \quad - - - - - \quad (9)$$

where $A = \frac{Bk_{ab}}{b - k_{ab}}$ and C = constant of integration

A figure for k_{ab} is found by seeking those values of B, b, and k_{ab} which produce the best fit between mathematical expression and direct observations. Both methods require data from the measurement of excess ^{14}C activity in the reservoirs concerned; as a result, estimates of such residence times will tend to improve with the accumulation of more data. A selection of values of residence times evaluated by these methods of approach is given in Table 1.3.

1.6 Bomb ^{14}C in the Biosphere

In some of the foregoing treatments adopted to obtain the residence times shown in Table 1.3, the biosphere and humus reservoirs were combined; in other methods, to distinguish the different turnover rates of carbon in each reservoir, one box was assigned per component, i.e. (a) the living biosphere which contains carbon estimated to have a residence time similar to that of CO_2 in the troposphere, and (b) the humus fraction in which the turnover of carbon is estimated to be

TABLE 1.3 MODEL PREDICTIONS OF RESIDENCE TIMES OF CARBON IN THE RESERVOIRS OF THE DYNAMIC CARBON CYCLE

REFERENCE/METHOD OF CALCULATION		RESIDENCE TIME (YEARS) *			
		γ_{s-t}	γ_{t-m}	γ_{m-d}	γ_{t-b}
Arnold and Anderson (1957)	N		10-20		
	S		20		
Craig (1957a)	N		7±3		
Revelle and Suess (1957)	S		10		
Bolin and Eriksson (1959)	S		5		
Plesset and Latter (1960)	N		5.5	18	5-6
Bien and Suess (1967)	B		25		
Munnich and Roether (1967)	B		5.4		
Nydal (1967)	B	2	5-10		
Nydal (1968)	B	2	5-10		
Young and Fairhall (1968)	B	1.5	2.5		
Rafter and O'Brien (1970)	B		12	4.5	
Walton et al. (1970)	B	4	9	11	8
Gulliksen and Nydal (1972)	B		8	3.8	
Rafter and O'Brien (1972)	B			0.6-2.1	

* γ_{i-j} terms are defined as in text; s = stratosphere, t = troposphere; m = mixed/surface ocean layer; d = deep ocean; b = biosphere.

Method of calculation: N = natural ^{14}C; B = bomb ^{14}C; S = Suess effect.

on a time scale $>$ 10 years ($\sim$ 15 years : Goldschmidt 1954). According to the particular conditions under which a model is constructed, either assignment may be a valid approximation. In other simplified treatments, the living biosphere and humus reservoirs may be included with the atmosphere, as in Fig. 1.3 (a), or the troposphere and living biosphere alone may be considered as a single reservoir (Nydal et al. 1971). The latter approximation is valid since the carbon content of the living biosphere is relatively small — $<$ 20% of the size of the atmospheric reservoir; in this situation, a minor difference between the residence time of carbon in the biosphere and atmosphere has a negligible effect on box-model calculations. More detailed examination of the biosphere, however, indicates that this reservoir is not truly homogeneous. This fact is borne out by the difference in concentration of bomb ^{14}C between its two main components viz. (a) plant life and (b) animal life. In general, the ^{14}C activity of plant material is a good indicator of the ambient atmospheric level (Baxter and Walton 1971) although under certain conditions this relationship is not valid as the first measurements of bomb ^{14}C in biospheric material indicated. An increase in the ^{14}C activity of plant material smaller than the corresponding increase in the atmospheric ^{14}C level was observed (Münnich and Vogel 1958). This finding was attributed to an enhanced humus-atmosphere-biosphere interaction in the presence of dense vegetation. In such cases, a relatively high proportion of the CO_2 in the surrounding atmosphere is thought to originate directly from the soil; owing to the longer residence time of carbon in this fraction of the humus reservoir, the soil-produced CO_2 will be less radioactive than the atmosphere. Subsequent data (Broecker and Walton 1959, Broecker and Olson 1960) were

in agreement with such an effect.

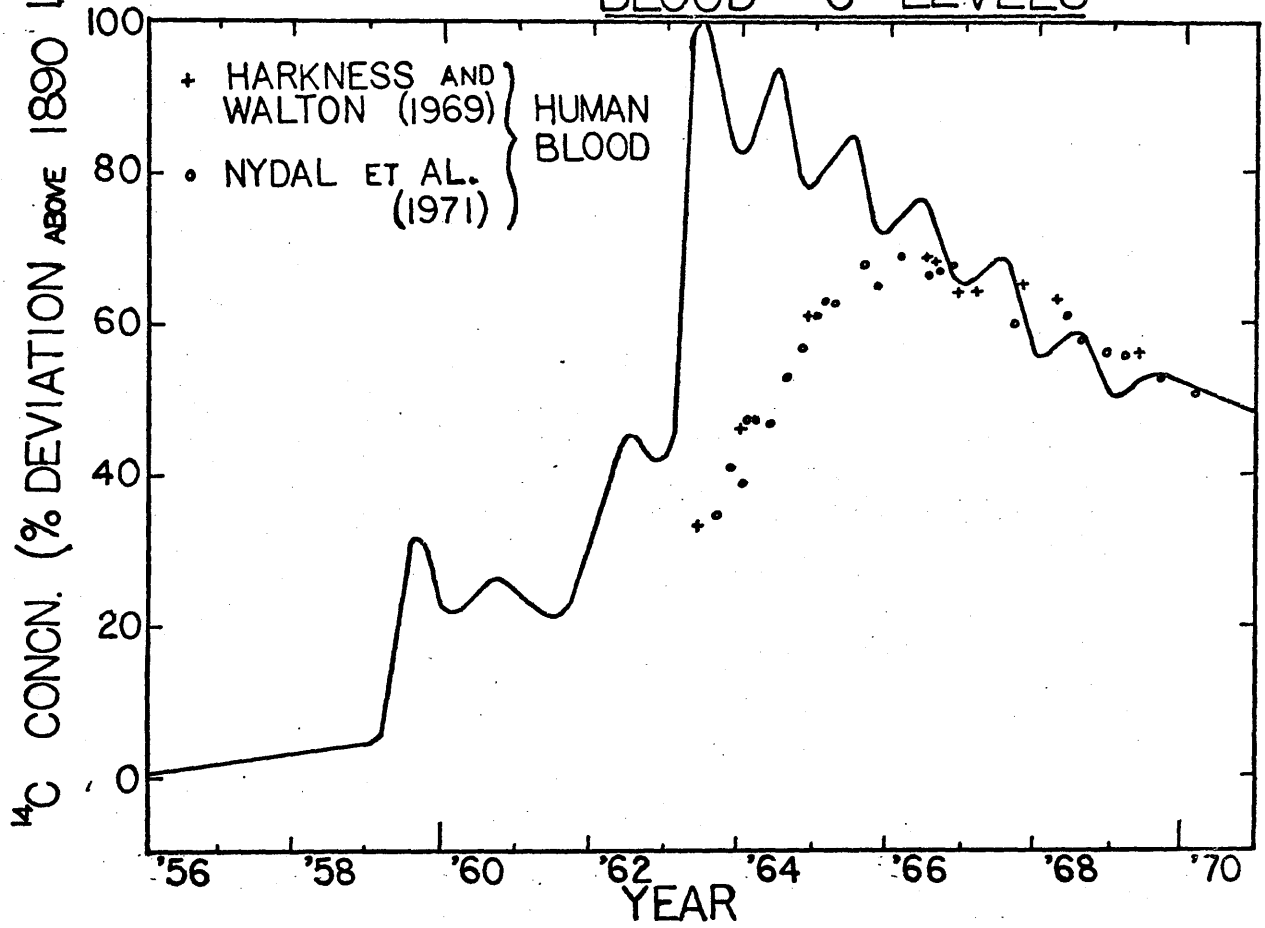
The calculation of residence times of carbon in various tissues of the human body, via measurements of bomb ^{14}C levels in man, was first suggested by Broecker et al. (1959) who measured the ^{14}C activity of a specimen of lung tissue in addition to that of blood and breath CO_2 samples from several individuals. From the resultant data and on the assumption that the carbon in tissue is derived from that in blood, Broecker et al. concluded that the mean residence time of carbon in blood is no greater than 6 months, while that of carbon in lung tissue is longer, although a fixed value could not be specified from such limited data. Libby et al. (1964) investigated bomb ^{14}C levels in tissue and brain samples from humans of a single age group (73-74 years old) and in blood samples from residents of both north and south hemispheres. In addition to a 'lag' time of 1.5 years between similar blood and atmospheric ^{14}C levels, results indicated that cartilage samples had incorporated negligible amounts of bomb ^{14}C in the 10 years since the first effects of bomb ^{14}C were observed in tropospheric ^{14}C activity. Cartilage carbon therefore apparently possesses a very slow turnover rate, a conclusion in agreement with the results of tritium tracer experiments performed on rats (Thompson and Ballou 1956). Incorporation of bomb ^{14}C was also found in brain protein and lipid fractions by Libby et al. who suggested that, in this case, the predominant method by which bomb ^{14}C reached the brain was not from exchange of ^{14}C with blood plasma, as is the probable procedure for other tissues. Instead, rapid fixation of atmospheric CO_2 with the resultant formation of aspartic and glutamic acids in the brain was thought to have occurred. Previous animal tracer experiments performed by Nicholas and Thomas (1959) and

Bloch et al. (1943) predicted the latter mechanism. Nydal and Lövseth (1965) measured the ^{14}C activity of different biospheric samples and compared the results with recent atmospheric ^{14}C levels. The ^{14}C concentration of cereal samples was observed to reflect closely the atmospheric ^{14}C content while the ^{14}C activity in milk reflected the corresponding level in the cow's diet which consisted essentially of grass. The decrease in ^{14}C activity detected in milk collected during winter months was attributed to the cow's diet of stored grass which, for the particular period studied, was low in ^{14}C activity. Early measurements of the ^{14}C concentration in blood suggested a 'lag' time behind the tropospheric ^{14}C level of 1.3 years (Nydal 1963). Subsequent more detailed analyses indicated a 'lag' time < 1 year. However, the concept of a true 'lag' time is misleading, since, by such a relationship, the maximum ^{14}C concentration in blood ought to attain the same value as the corresponding atmospheric maximum. More recent series of blood ^{14}C levels in humans have been measured and show that the 'lag' time concept is not strictly valid, the maximum in blood ^{14}C level being $\sim 35\%$ below the corresponding tropospheric maximum (see Fig. 1.4) (Harkness and Walton 1969, Nydal et al. 1971). Thus although human carbon is essentially derived from photosynthetic fixation of tropospheric CO_2, there is no direct relationship between both ^{14}C levels. Furthermore, results to date of ^{14}C concentrations in humans indicate that man himself is inhomogeneous with respect to ^{14}C levels in blood, tissues and skeleton.

1.7 Bomb ^{14}C — Health Hazard

The presence of artificially produced $^{14}CO_2$ in the atmosphere has caused concern over its potential radiation hazard to man. Most of the

FIG. 1.4 COMPARISON OF TROPOSPHERIC CO_2 ACTIVITIES WITH HUMAN BLOOD ^{14}C LEVELS



estimated total excess of 9×10^{28} ^{14}C atoms produced during nuclear explosions throughout the last three decades was injected initially into the stratosphere but, through exchange with the lower atmosphere, was sufficient to double the natural concentration of $^{14}CO_2$ in the troposphere in late 1963. The present atmospheric ^{14}C level is ~ 50% higher than the pre-bomb ^{14}C concentration and is slowly decreasing at the rate of ~2 % per year via exchange of $^{14}CO_2$ with the biosphere and ocean reservoirs. Rapid incorporation of ^{14}C into human tissues is facilitated by assimilation of $^{14}CO_2$ in plant material during photosynthesis and subsequent passage through the food chain to animals and man himself. Considerable attention has been focussed on the radiation hazard represented to man by the major fission nuclides, rather than ^{14}C; in particular, the incorporation of ^{90}Sr in bone, the build-up of ^{131}I in the thyroid and the ingestion of ^{137}Cs in humans have been investigated. Although ^{14}C is a weak radioactive emitter compared to these fission nuclides, there are certain significant features of the distribution, availability, and biological properties of this radioisotope which suggest that ^{14}C as a potential radiation hazard should not be neglected. For example, the fission nuclides are rapidly rained out or deposited from their atmospheric source while ^{14}C remains in the atmosphere for a relatively long period during which it is available for human uptake. The characteristic fallout pattern and incorporation in man of ^{14}C and other fission nuclides are summarised in Table 1.4. Owing to its long half-life, ^{14}C produced by nuclear explosions will persist for thousands of years. The radiation hazard of bomb ^{14}C should therefore be evaluated not only for the present generation but also for future generations.

TABLE 1.4 COMPARISON OF FALLOUT PATTERN OF ^{14}C WITH OTHER FISSION NUCLIDES

^{14}C	OTHER FISSION NUCLIDES
relatively slow transfer from stratosphere results in global distribution	most nuclides are 'rained-out' from atmosphere — rapid removal
mean life-time > 8000 years: available to man for many generations	many short-lived: exceptions notably ^{90}Sr and ^{137}Cs.
easy access to humans via the food chain	soil/plant deposition; ingestion/ inhalation
approximately even distribution throughout the body	very often uneven distribution e.g. ^{131}I in thyroid;
constituent atom of genetic material	in some cases discrimination factor e.g. $\frac{^{90}Sr/Ca_{plants}}{^{90}Sr/Ca_{milk}} > 1$

Biological damage from ^{14}C

The biological damage associated with any radioisotope is dependent on the ionisation produced by the radiation and is thought to arise from the chemical reactions which ionised atoms subsequently undergo. In turn, the amount of ionisation produced depends on the type and energy of the emitted radiation; in the case of ^{14}C decay, ionisation is confined to a relatively small radius - the maximum range of such a β-particle is < 0.3mm. in soft tissue. Most of the energy of the β-particle is transferred to water which comprises, on average, 70%-80% of the contents of a cell. Changes in the cell molecules (protein, lipid, nucleic acids and inorganic substances) caused by the β-particle alone would, under these circumstances, be created by interaction of these molecules with ionised water and subsequent energy transfer. However, besides the β-particle itself, the additional energy characteristics related to the decay process are 1) the recoil energy of the nitrogen nucleus, and 2) the residual electronic energy within the nitrogen atom, both occurring after β-emission. Both these processes are further, more direct methods which may effect breakdown of one or more of the cell constituents, the most important of these being the nucleic acids. While the protein, lipid, and enzyme constituents of cells are often present in excess, in which case biological damage to one of these components is less likely to be detrimental, deoxyribonucleic acid (DNA), one of the nucleic acids, is one of the rare species of molecule in the cell and plays the widest, most critical role in metabolism. DNA consists of sugar-nitrogenous base complexes linked by phosphate bonds in a double-helix structure. The bases are of 4 types and are linked in a specific arrangement which

determines the identity of any particular gene — the structure which controls inheritance and metabolism. Besides the radiochemical change in DNA which can be caused by the ^{14}C decay processes previously mentioned, an additional mechanism exists whereby the basic structure of the macromolecule may be altered, viz. the transmutation of ^{14}C to ^{14}N. Fracture of a DNA molecule is possible by this method although, under certain circumstances, the molecule can in a relatively short time restitute itself (Pizzarello and Witcofski 1967), but equally possible is a change in the specific sequence of bases which results in a mutated cell — one with different characteristics. Thus in such a case, if a ^{14}C atom that has been part of a DNA molecule decays, its replacement by the chemically different ^{14}N atom might be expected to have a profound effect (Purdom 1962). Although relatively little research has been devoted to this aspect of radiation biology as yet, Totter et al. (1958) suggest that, 'subject to large uncertainty', the transmutation effect of a ^{14}C atom contained in the genetic material of the human body could lead to about the same number of genetic mutations as those caused by the radiation effect of ^{14}C itself. In an experiment to determine the radiation effects resulting from the pre-natal administration of high levels of a ^{14}C-labelled precursor of DNA, Simpson and Bennett (1963) failed to detect any gross effects of the radiation on the somatic cells — cells of which the body is composed. However, in consideration of the ultimate damage that might be caused by the presence of ^{14}C in nucleic acids of an animal population, the authors pointed out that their experiments were limited to the study of only one generation of mice and were not designed to study more subtle genetic effects that might not be apparent for generations. It is these

long-range genetic effects, however, that have been the chief cause for concern over the release of ^{14}C into the atmosphere (Totter et al. 1958, Pauling 1958, Sakharov 1958, Leipunsky 1957). Furthermore, Uphoff and Stern (1949) conclude that there is no threshold below which radiation fails to induce mutation. Since mutations are, in most cases, detrimental to the individual in which they occur, and ionising radiation is known to increase the natural rate of mutation without the production of new types of mutation, the potential hazard of ^{14}C to man cannot be ignored. In order to appreciate the biological hazard to man from the ^{14}C produced from nuclear weapon tests, it is necessary to know the amount of ^{14}C available and the manner in which it becomes available for incorporation into humans, besides the degree to which it affects living tissue. At present, direct measurement of the ^{14}C activity in human tissues and skeleton remains the only accurate method of assay of human ^{14}C levels.

1.8 Aims of Research

Numerous data on the distribution of bomb ^{14}C in the atmosphere and oceans have enabled theoretical estimates of biospheric levels in the past, present, and future. The number of results on the measured ^{14}C activity in human tissues available for comparison with these theoretical estimates is, on the other hand, limited. Harkness and Walton (1969) compared theoretically calculated biospheric ^{14}C concentrations predicted from a two-box model, Fig. 1.3 (a), and a more complex six-box model, similar to Fig. 1.3 (b), with the atmosphere subdivided into stratosphere and troposphere. The results of the estimates of residence times indicated that there is a considerable error involved

during the decade after the major disturbance of equilibrium conditions. The principal discrepancy over this period arises from the uncertainty of the role of the biospheric reservoir in relation to the dynamic carbon cycle and the limitations inherent in each box-model treatment. The concept of uniform mass transfer between reservoir boundaries in location and time is not strictly correct for the atmosphere in which exchange and mixing patterns of CO_2 show strong seasonal dependence. Maximum stratosphere - troposphere exchange occurs at mid latitudes during the spring months, the time which coincides with the growth period of plants and results in an enhanced transfer of carbon to the biosphere. In addition, uncertainty in the mass of biospheric carbon and the diverse physical content of this reservoir greatly reduce the degree of confidence with which the $^{14}C/^{12}C$ ratio of any sample can be regarded as representative of the whole reservoir. The ^{14}C concentration in man is necessarily affected by his dietary intake which includes not only young terrestrial biospheric carbon but also a certain amount of carbon of marine origin. According to Nydal et al. (1971), the transfer of ^{14}C into the human body depends on 3 factors:

(a) the time between photosynthesis of vegetational food and its consumption,

(b) the human diet, and

(c) the residence time of carbon in human tissues.

Of the ^{14}C analyses performed on human tissue (e.g. Berger and Libby 1966) and blood samples (Nydal et al. 1971, Harkness and Walton 1969), no detailed measurement of ^{14}C levels in different tissues of the same individual as a function of age has been performed. The results of such a study might be expected to yield a more quantitative measure of

the metabolic activity of tissues. It is sometimes difficult to draw definite conclusions based on work in which ordinary tracer ^{14}C, labelled at only one or two positions, is incorporated in complicated molecules after a complex chain of chemical reactions. In this respect, terrestrial tissues - plant and animal - appear to have responded in a natural way to bomb ^{14}C; compounds involved in the usual processes of photosynthesis and feeding have a fraction of their carbon positions labelled. Turnover times of carbon in tissues of the human body are important in the field of medicine, particularly of benefit to drug metabolism studies.

The objectives of this research project are threefold, based on the following experimental approach:

1) a series of measurements of the ^{14}C concentration in a spectrum of human tissues as a function of age of the individual
2) a supplementary series of activity measurements of atmospheric CO_2 as an accurate assessment of the ^{14}C concentration in this reservoir, and as a check on any ^{14}C fluctuations caused by continued nuclear weapon testing
3) ^{14}C measurements of a limited number of foodstuffs. A systematic investigation of the ^{14}C levels of all the constituents of the diet is impracticable. Samples of uncertain relationship to atmospheric ^{14}C concentration - animals and marine life - require ^{14}C assay.

The intended objectives are:

(a) a model treatment of the data from 1), 2), and 3) above, to calculate residence times of carbon in different tissues,

(b) an examination of the results of such a treatment to search

for significant differences in residence time of tissue carbon between individuals of different age, and

(c) calculation of the expected dose rate to humans from the bomb ^{14}C burden, both now and in the future.

CHAPTER 2. EXPERIMENTAL METHODS IN RADIOCARBON ASSAY.

2.1 Introduction

The rigorous chemical and physical procedures adopted for the analysis of environmental ^{14}C are necessary for 2 reasons:

1) ^{14}C is a weak beta emitter (maximum energy 156 KeV., average energy 45 KeV.: Jenks and Sweeton 1952).

2) ^{14}C activities are low - < 27.0 d.p.m./g.carbon (i.e. $\simeq$ 12 picoCuries/g. carbon)

The decay characteristics of ^{14}C therefore require the analytical system to have a high efficiency of detection (E) while minimising the background count rate (B). For optimum sensitivity of activity measurement the parameter E^2/B should be as large as possible within these conditions. In addition, it is even more important that the counting equipment be stable electronically over long periods of time, since

(a) counting times are long ($\simeq$ 20 hours) to reduce the statistical error associated with the activity measurement, and

(b) background and reference samples can be counted only intermittently; thus the resultant data may be applied to gross sample activities only if counting conditions remain constant.

The 3 criteria for satisfactory measurement of low-level ^{14}C activities are therefore:

1) high ^{14}C detection efficiency

2) low background count rate

3) long-term electronic stability of the counting system.

Natural ^{14}C was first detected using a screen-wall Geiger counter (Anderson et al. 1947). The sample, in the form of elemental carbon, was coated on the internal walls of the detector. Background reduction was achieved initially with lead/iron shielding alone but later via addition of anticoincidence circuitry; using this latter technique, the sample counter is surrounded by a 'guard' ring of Geiger counters such that external (non-sample) pulses which register simultaneously in both guard and sample detectors are eliminated. The detection efficiency of the "solid carbon" method, however, was low ($< 5\%$) and experimental procedures laborious; in addition, due to atmospheric exposure of the necessarily large surface area of carbon required, samples were susceptible to contamination by airborne radionuclides, a feature soon highlighted by the increased 'fallout' levels produced during the nuclear era.

The advent of gas counting overcame the contamination problem, since operations were now to be performed in a high vacuum system. Counter operation was chosen in the proportional, rather than the Geiger, region due to the lower voltages and superior plateau characteristics (length $\simeq$ 500 v., slope $< 1\%$ per 100 v.) of the former at high working pressures (Anderson and Libby 1957). Furthermore, the pulse height measured in the proportional region is directly related to the incident particle energy; thus, with the development of pulse-height discrimination (Freedman and Anderson 1952), the background count rate could be reduced by selection of only the particular energy range of interest. No such correlation (pulse height with particle energy) applies to the Geiger region where all pulses are of equal height and background count rates can be reduced only via massive shielding and anticoincidence

arrangements. Of the gases developed for proportional counting of ^{14}C, three are in widespread use; CO_2, CH_4 and C_2H_2. Improvements in preparative methods (de Vries and Barendsen 1953, Suess 1954, Fergusson 1955, Burke and Meinschein 1955, Fairhall et al 1961) and advances in electronic circuitry and component design have produced counting efficiencies approaching 100% and backgrounds $\simeq$ 5 c.p.m. (i.e. $E^2/B \simeq 2000$).

Liquid scintillation counting, the alternative major method of low-level counting, was first applied to ^{14}C measurement by Arnold (1954). The inherent advantage of this technique lies in the reduction of sample volume with a corresponding increase therefore in the carbon content:volume ratio relative to gas counting (x 2000). Anticoincidence shielding of the type used in proportional counting is unnecessary, as the surface area of sample which is subtended to cosmic radiation is correspondingly reduced. Progress in this field has been achieved in 3 main areas:

1) the elimination of the photomultiplier 'noise' component of background, achieved by coincidence technique using 2 coaxial photomultiplier tubes
2) the removal of the discolouration frequently observed in scintillating liquids, causing a reduction in detection efficiency (quenching)
3) high-yield preparations, under routine laboratory conditions, of an organic solvent suitable for scintillation (e.g. benzene).

Through these advances (Rapkin 1964, Noakes et al. 1965) the E^2/B value has improved from ~ 150 in 1960 to ~ 800 in 1970; this together with the inclusion of automatic sample-changing facilities,

enabling sample, background, and reference activities to be measured almost 'simultaneously', has enhanced the value of the technique. The improved E^2/B value, however, remains lower than that of proportional gas counters due to the lower detection efficiency of liquid scintillation detectors. If the discriminator threshold, which is set above the thermal noise area of photomultiplier tubes, is lowered, it is possible to increase the detection efficiency of liquid scintillation counting but in this situation, the background increases and, more important, sample activities are subject to spurious noise pulses, a condition of electronic instability. A compromise between high detection efficiency and stability of performance is required, therefore, and the final discriminator setting ultimately determines the magnitude of E^2/B. Thus, for the activity measurement of small samples (< 2g. carbon) when maximum sensitivity of detection is essential, the use of liquid scintillation counting is severely restricted. Since the majority of samples available for this project were expected to contain ~ 1.5 g. carbon, proportional gas counting was considered to be superior and was chosen in preference to liquid scintillation counting. CO_2 is employed as the counter-filling gas for several reasons:

1) for accurate comparison of different sample activities, it is imperative that all gases are counted at the same gas gain (see 2.4.3). It is possible to achieve this condition for all gases by adjustment of the detector voltage to correct for the effects of any minor impurities. Since the characteristics of CO_2 are highly sensitive to these electronegative species (≥ 1 p.p.m. O_2, ≥ 0.1 p.p.m. Cl_2 : Fergusson 1955) the gas gain for each sample can be controlled precisely and reproducibly by normalisation of

the energy spectrum

2) it is more direct to use CO_2 itself as counting gas than to convert it further to CH_4 or C_2H_2 for activity measurement

3) handling/storage of CO_2 is carried out in relative safety in contrast to the potentially hazardous conditions under which C_2H_2 (explosive at pressures > 1.5 atmosphere) is used

4) the vapour pressure of CO_2 is negligible at liquid N_2 temperature (- 196°C.); thus possible fractionation effects (see 2.5) and sample handling losses are avoided cf. CH_4, vapour pressure $\simeq 1$ cm. Hg under similar conditions to CO_2

5) direct mass spectrometric analysis of the counting gas to determine fractionation effects is possible with CO_2 proportional counting but not with CH_4/C_2H_2 counting; in the latter cases, fractionation effects are determined from a sample of CO_2 which is extracted during each CH_4/C_2H_2 preparation, and may not be representative of the final counting gas.

Sophisticated vacuum technique and chemical procedures are required for CO_2 preparation. The laboratory processes performed are shown diagrammatically in Fig. 2.1. In this programme, samples measured for ^{14}C activity are divided into 5 categories:

1) Biospheric (human tissue, bone, aortae, food)

2) Atmospheric CO_2

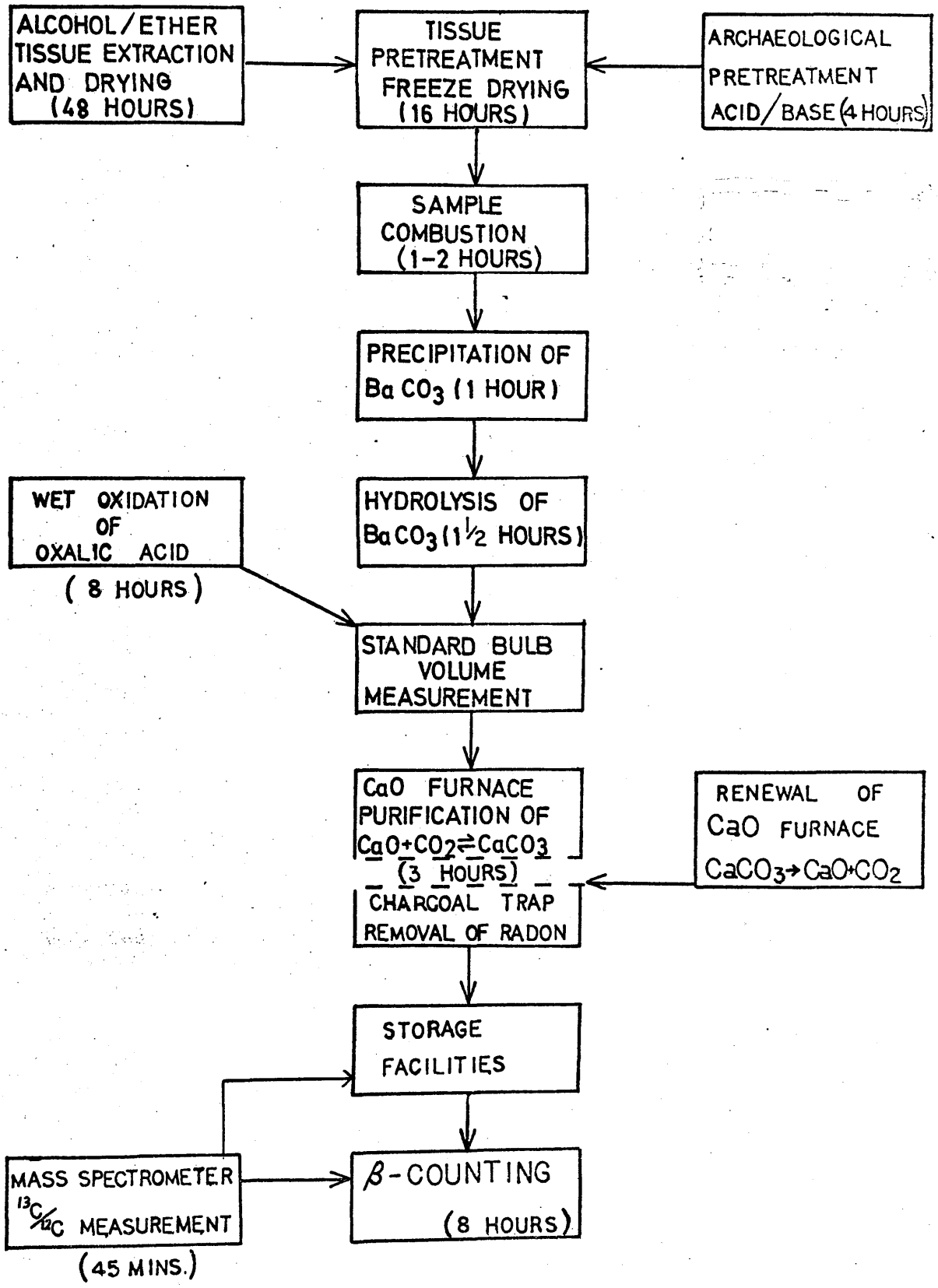
3) Archaeological (wood, charcoal, peat)

4) Backgrounds (samples containing only inactive carbon)

5) Reference standards

In every case, care must be taken to ensure that the carbon which is

FIG. 2.1 SCHEMATIC DIAGRAM OF LABORATORY PROCEDURE



ultimately counted as CO_2 originates totally from the sample. The effects of different sources of contamination on the sample types listed above are shown in Table 2.1 while special precautions for individual types are discussed in their corresponding sections. Background and reference samples are also treated elsewhere (2.6).

2.2 Sample Collection and Pretreatment

2.2.1 Biospheric samples

(a) Human tissues

Samples of different organs and of bone (10 - 20 g. wet weight) were collected at post-mortem examinations carried out in the Western Infirmary, Glasgow, and Law Hospital, Carluke, no later than 5 days after time of death. For each specimen, the age at death, sex, and cause of death were recorded. Preference for 'non-fixed' i.e. formaldehyde-free material was taken to avoid risk of contamination of tissue carbon with inactive carbon (formaldehyde : CH_2O). On the one occasion when samples were obtained 'fixed' (5 tissues), they were first boiled in distilled water for 15 - 30 mins. to remove water-soluble formaldehyde. Otherwise tissues were washed with distilled water to remove external traces of blood and thereafter were dissected free from extraneous fat, homogenised with 10 - 15 mls. distilled water to a purée texture, and freeze-dried overnight; 2 - 5 g. dried material were thus obtained ready for combustion.

(b) Tissue fractions

Although variations exist between tissues, the contents of dried tissue are composed essentially of protein (65%-85%) and of lipids (10%-30%), a group of compounds comprising several classes including,

TABLE 2.1 EFFECT OF CONTAMINATION FROM NON-CONTEMPORANEOUS CARBON ON DIFFERENT SAMPLES.

(a) Archaeological samples

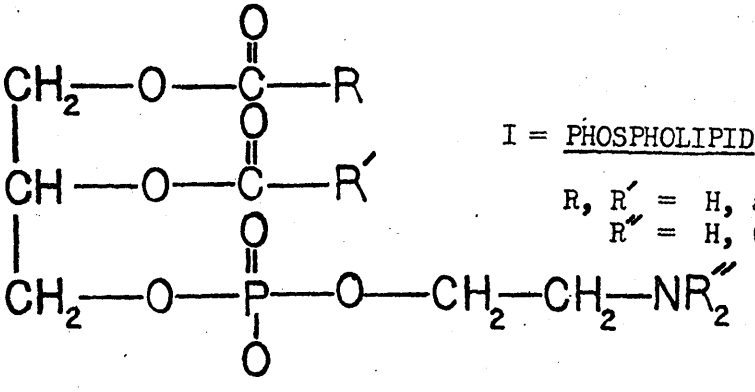
TRUE AGE (YEARS)	ERROR (YEARS) OF CONTAMINATION OF:				
	SAMPLE WITH MODERN CARBON				SAMPLE WITH INACTIVE CARBON
	1%	2%	5%	10%	
1,000	-57	-113	-280	-554	+80 years per 1% contamination
5,000	-143	-284	-692	-1331	" " " " "
10,000	-329	-641	-1519	-3370	" " " " "
20,000	-1219	-2278	-4824	-8167	" " " " "

(b) Contemporary samples

TRUE ^{14}C ACTIVITY (% above 1890 level)	ERROR ON SAMPLE ^{14}C ACTIVITY FROM CONTAMINATION OF:	
	SAMPLE WITH INACTIVE CARBON	STANDARD* WITH INACTIVE CARBON
10%	-1.1% per 1% contamination	+1.1% per 1% contamination
40%	-1.4% per " "	+1.4% " " "
50%	-1.5% " " "	+1.5% " " "
60%	-1.6% " " "	+1.6% " " "

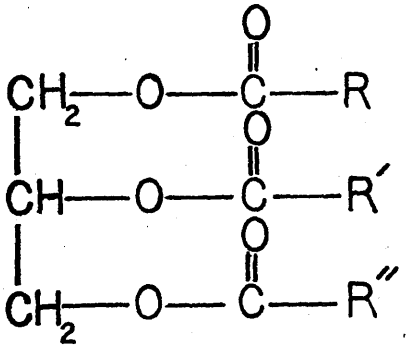
* standard ^{14}C activity related to 1890 level.

for example, phospholipids and triglycerides, each having a general formula shown in I and II respectively:



I = PHOSPHOLIPID

R, R′ = H, alkyl
R″ = H, CH_3



II = TRIGLYCERIDE

R, R′, R″ = alkyl

Other constituents which comprise the remaining percentage are carbohydrates, enzymes, hormones, vitamins, and inorganic salts (N.B. these percentage compositions do not apply to brain tissue or bone.) In this particular section, a series of freeze-dried tissues, ≃ 10 - 12 g., was treated to separate the lipid fraction from protein. One of the most widely used solvent mixtures for this purpose is Bloor's solvent - an ethanol:diethyl ether mixture in the ratio 3:1 v/v (Entenman 1961). Each dried tissue was first finely subdivided in a portion of hot ethanol/ether, using a pestle and mortar. The resulting slurry was added to 200 mls. solvent mixture and the solution refluxed for 1 hour. On filtration, the residue was further extracted for 1 hour with 200 mls. diethyl ether which replaced the

ethanol/ether mixture. The resulting proteinaceous material was filtered and oven-dried for a minimum of 48 hours while the 2 liquid extracts were combined and the solvent evaporated off under vacuum. A stream of N_2 was passed through the lipid to remove any last traces of solvent.

Solvent contamination of both protein and lipid fractions was investigated using the same extraction procedure for 3 tissues but with both ^{14}C-labelled ethanol and diethyl ether. The initial activities were such that a 1% solvent contamination level in the final extracts would increase their activities by 10 c.p.m. per counter fill of these samples. In fact the resultant ^{14}C activities measured for each protein sample and a pooled lipid extract failed to indicate the presence of solvent carbon [see Table 3.1(b)].

(c) Aortae

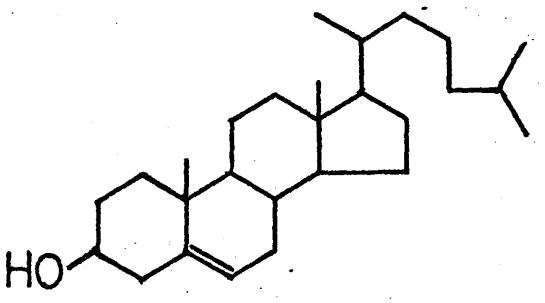
Aortae originally collected from victims of atherosclerosis in 1965 were forwarded with relevant details of their history by Prof. J.P. Strong, Dept. of Pathology, Louisiana State University, New Orleans, U.S.A. An additional more recent sample (June 1973) was supplied by Dr. W.A. Harland, Dept. of Pathology, Western Infirmary, Glasgow. The particular fraction of these arteries required for analysis - the lipids - is deposited on the intima (inner wall of the artery) and was visible in 2 forms:

1) fatty streaks and/or spots
2) fibrous plaques, an intimal thickening, firm and grey/pearly-white in colour. The composition of the lipid fraction varies with the extent of damage to the arterial wall

(Böttcher and Woodford 1962); thus in the arteries analysed in this work, the proportion of lipid constituents was approximately:

16 % phospholipids
25 % cholesterol (III)
42 % cholesterol esters of unsaturated fatty acids, predominantly lineolic acid, $C_{17}H_{31}CO_2H$
10% free fatty acids

III Cholesterol $C_{27}H_{46}O$



The solvent used for the extraction of total lipids from the intima was in this case a chloroform/methanol mixture. The arteries were opened longitudinally and washed with water to remove adhering blood. The 3 arterial layers, intima, media and adventitia were clearly visible, and the latter two were stripped from the intima. In the severely diseased aortae, each intima displayed considerable thickening and the separation of intima from media presented no difficulty. Separation of the two layers in samples affected only by fatty streaks, in contrast, was more difficult; the intima obtained in such cases frequently contained small quantities of medial tissue. After collection, the tissue was finely subdivided using scissors and extracted with a chloroform:methanol mixture (2:1 v/v) in a stoppered flask for

18 hours at room temperature. Almost total extraction of lipids is obtained by this method (Entenman 1961). The extract was filtered by gravity, the pieces of tissue were washed with small quantities of chloroform/methanol and the filtrate and washings combined. The extract was reduced to dryness under vacuum using a rotary evaporator; heat for the process was supplied by a hot water bath, the temperature of which did not exceed 40°C. Benzene:ethanol (1:1 v/v) was added in 50 ml. aliquots to reduce frothing and aid removal of water (Foote and Coles 1968). The residue was dissolved in a 200 ml. mixture of diethyl ether:hexane (1:1 v/v) and the solution washed with an equal volume of saline solution to remove non-lipid constituents (Entenman 1961). Prior to addition, the saline solution was heated to ensure a fine partition between the two phases. The organic layer was dried with Na_2SO_4, solvent was removed under vacuum and the pure extract weighed. Yields of lipid in the range 0.5 - 2.0 g. were obtained. Two sources of contamination were present in the arteries received from the U.S., viz.:

1) formaldehyde which prevents decay of the organic material during storage
2) Sudan III, a synthetic red dye used to stain lipid areas. A 2% solution(w/w) Sudan III ($C_{24}H_{20}N_4O$) in alcohol is prepared for this purpose.

Removal of the formaldehyde was achieved, if not during the initial washing, by the organic/aqueous phase separation; however, efforts to separate the dye from the lipid by solvent partitioning

proved fruitless. The extent of contamination, however, was estimated to be $< 1\%$ inactive carbon, by colorimetric comparison of the extracted stained lipids with several standards, each of which was prepared by addition of a known weight of dye in solution to a known weight of unstained lipids extracted from heart tissue. Solvent contamination of lipids, if present, was considered to be negligible, an assumption implied by the results of the ^{14}C tracer experiments of section (b).

(d) Bone

There are 2 basic components of bone; (a) the matrix which is rich in protein, mainly collagen, and (b) the mineral or inorganic fraction which is comprised essentially of phosphate and carbonate salts of calcium. The percentage composition of these constituents relative to dry bone is approximately:

50% $Ca_3(PO_4)_2.Ca(OH)_2$
20% $CaCO_3$
30% proteins (collagen)

In addition, normal bone contains both yellow bone marrow composed of connective tissue and large amounts of fat, and red marrow which is responsible for the production of red cells. Each carbon containing fraction, therefore, was isolated for ^{14}C activity measurement. A 20 g. bone sample (tibia) was collected together with soft tissues at one post-mortem examination. This bone was split into fragments $\sim 1cm^3$ and boiled in 2M NH_4OH which released the marrow fat into the aqueous phase. Subsequently, the fat was obtained from solution by benzene extraction followed

by distillation of the organic solvent. The residual solid material was washed and transferred to a closed system where it was digested in 2M HCl. CO_2 evolved from the carbonate fraction was collected in a series of traps containing $KOH/BaCl_2$ solution. Hydrolysis of the protein (collagen) fraction to its constituent α-amino acids also occurred during this stage but these acids remained dissolved in the bulk solution. Once hydrolysis was complete, the bulk solution was evaporated to dryness; the organic fraction remained absorbed on the calcium phosphate. Thereafter the total residue was combusted to obtain the collagen-derived CO_2.

(e) Food samples

The 2 types of foodstuffs analysed for ^{14}C activity were meat and fish samples. Meat samples (minced steak, lamb's heart, cow's liver) were freeze-dried and treated as in (b). Fish samples were freeze-dried after the majority of bones had been removed.

2.2.2 Atmospheric CO_2

Tropospheric CO_2 over the U.K. was collected monthly. A limited number of sites (3) was selected after consideration of the available counter time and of the general homogeneity of the 'bomb ^{14}C distribution at these latitudes. The locations of the sampling stations:

i) Chilton ($51^{\circ}31'N$, $1^{\circ}20'W$)

ii) Snowdon ($53^{\circ}03'N$, $4^{\circ}00'W$)

iii) Lerwick ($60^{\circ}08'N$, $1^{\circ}11'W$)

were chosen such that:

(a) the sites were isolated from areas of industrial activity

where the burning of fossil fuel releases inactive CO_2 and might cause local ^{14}C dilution effects as shown from atmospheric ^{14}C measurements in Glasgow (Ergin et al. 1970), (b) any local increase in ^{14}C concentration which might exist in the atmosphere close to a nuclear reactor would be revealed by the CO_2 activity at Chilton, in close proximity to the Atomic Energy Research Establishment, Harwell, and (c) a value of atmospheric ^{14}C activity would be obtained, representative of atmospheric ^{14}C levels in both the northern and southern hemispheres. Previous work indicates that these reservoirs are now equilibrated with respect to bomb ^{14}C (Rafter and O'Brien 1970).

A bulk solution of 4 ℓ. 4M KOH containing 5 g.Ba^{2+}/ℓ. was prepared for despatch to each sampling station. A concentration of 4M was selected from considerations of ionic strength, the amount of carbon necessary for an analysis, and difficulties in the handling of a caustic solution. Any CO_2 absorbed prior to exposure was precipitated as $BaCO_3$ which was filtered or decanted before use. At each site, using a static technique, tropospheric CO_2 was absorbed in 250 ml. aliquots of KOH solution contained in durable plastic basins of large surface area ($\simeq$ 100 cm^2). Exposure of KOH took place under well-ventilated conditions for periods of 1 month; protection from rain during this time was afforded by a wooden canopy and the level of solution was maintained by addition of distilled water. After exposure, the solutions, wax-sealed in plastic bottles, were returned to the laboratory where, for convenient storage, the total $BaCO_3$ was

precipitated (see 2.3.2), dried in an oven, and stored in sealed jars before analysis.

2.2.3 Archaeological samples

Special pretreatment methods are necessary for the removal from dating materials (wood, charcoal) of non-contemporaneous carbon which originates from the environment in which archaeological specimens are found - normally in earth. Most of the soil, pebbles, and rootlets were first removed manually from the sample fragments which were then washed in boiling distilled water; the superficial contaminants, carbonates and humic acids, were removed in boiling solutions of 5% HCl and 5% NaOH respectively. Distilled water was used to wash samples after each acid or base treatment; thus the total sequence of pretreatment solutions is:

boiling { distilled water
5% HCl
distilled water
5% NaOH
distilled water
5% HCl
distilled water

Normally each boiling was allowed to continue for 2 hours but this period was reduced for wood/charcoal samples in poor physical condition. Pretreated samples were oven-dried overnight before combustion.

2.3 Laboratory Preparation and Purification Procedures for CO_2

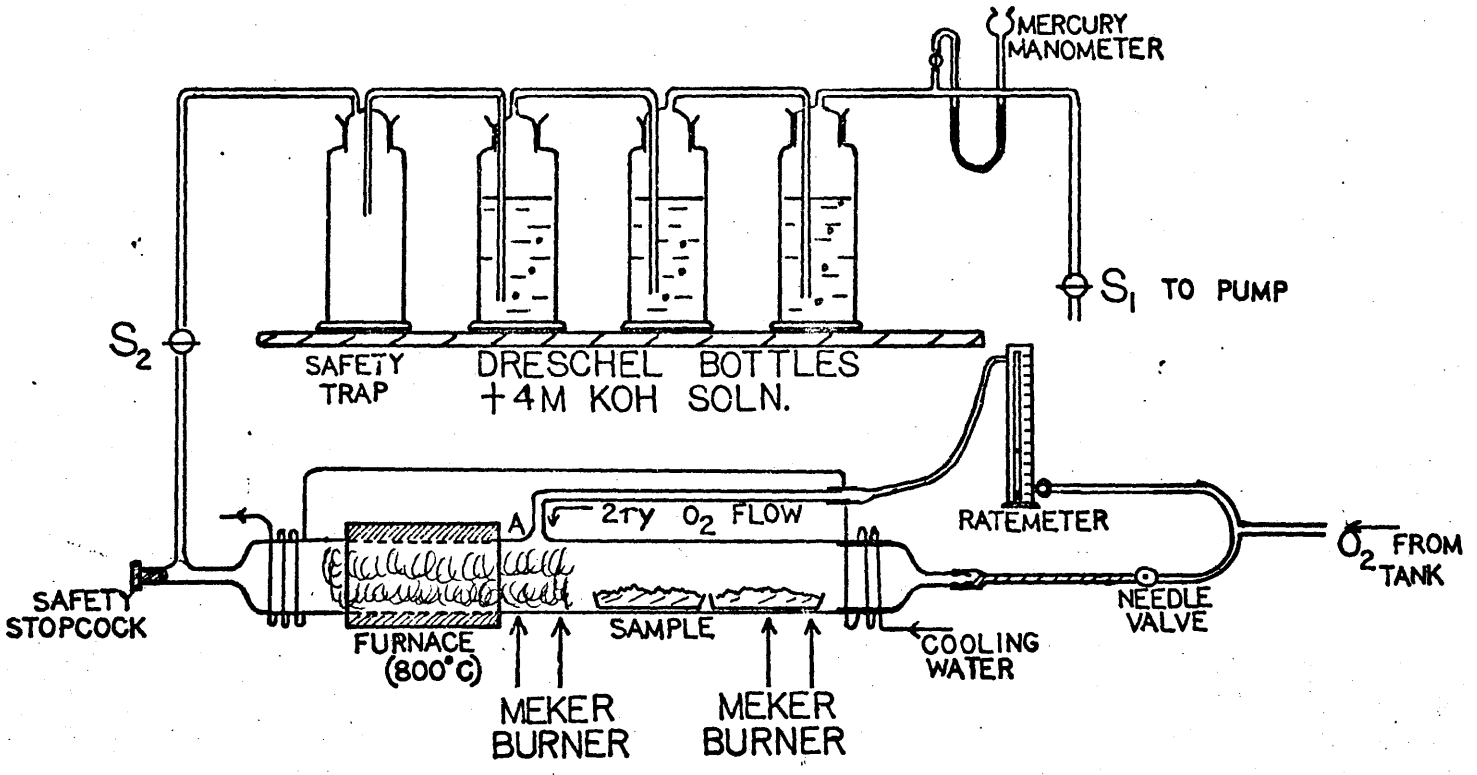
The following sections - combustion, precipitation of $BaCO_3$, and hydrolysis of $BaCO_3$ - describe the laboratory processes performed to obtain the preliminary yield of CO_2. The subsequent purification stage removes any residual electronegative species and regenerates CO_2 of the

high purity required for gas proportional counting.

2.3.1 Combustion

The combustion apparatus, shown in Fig. 2.2, is a modification of the system used by Rafter (1965). Quartz wool together with the side-arm flow at A replace CuO as a means of ensuring complete oxidation of the sample. Use of the latter oxidant resulted in the formation of $CuCl_2$ during some tissue combustions and eventually caused rupture of the combustion tube. Furthermore, chemical traps of $AgNO_3$ and $KMnO_4$ proved inefficient in removal of the relatively large yields of oxides of nitrogen and occasionally of sulphur. This preliminary purification stage was therefore replaced by absorption of CO_2 in KOH traps followed by precipitation of $BaCO_3$, filtration and regeneration of CO_2 by acid hydrolysis of $BaCO_3$ (Harkness 1970). Prior to a sample combustion, the tube with porcelain boats is roasted in a stream of oxygen for 20 mins. On cooling, the boats are packed with a known weight of sample, replaced in the combustion tube and the tube closed. Three Dreschel bottles are filled with 4M KOH solution while the first bottle is so positioned in case of accidental suck-back. The KOH solution is prepared from a bulk 8M KOH solution containing ~ 5 g. Ba^{2+}/ℓ. ; a portion of this solution is filtered through solid $BaCl_2$ before use and diluted with distilled water to 4M concentration. When the system is connected, the pump is switched on and the apparatus flushed with O_2 maintained at a negative pressure of $\sim$ 10 cms. Hg by stopcock S_1 partially opened (S_2 open). After 10 mins., a bunsen is applied under side-arm flow outlet, A, until the tube is glowing brightly; thereafter the second bunsen is applied under the porcelain boats at the end nearest the main-arm oxygen supply and the

FIG. 2.2 COMBUSTION SYSTEM



combustion initiated. The combustion rate is controlled by the O_2 flow rates in both the main and side arms; these, in turn, are adjusted by the needle valve (to 100 mls./min.) and ratemeter (to 250 mls./min.) respectively, during the initial stage of each combustion. Towards the final stage, the main-arm flow is increased to 200 mls./min. The combustion technique varies for each type of sample as can be seen from Table 2.2 which lists the characteristics of the most common sample types and the methods employed to obtain the highest combustion yields. Complete oxidation is ensured in most cases by the side-arm O_2 flow and the quartz wool maintained at $\simeq 600^{\circ}C$ by an electrical furnace. Pilot runs, in which oxalic acid was combusted, indicated combustion yields $> 90\%$. The evolved CO_2 is absorbed in KOH solution in traps 2 and 3 resulting in a cloudy appearance caused by precipitation of some of the CO_2 as $BaCO_3$; the KOH is of such a concentration (4M) that for a normal combustion rate, trap 4 remains clear, an indication that the flow rate is satisfactory. Once the sample is apparently combusted, the combustion tube is roasted in a main-arm O_2 flow rate increased to 200 mls./min. After 20 - 30 mins., the O_2 flow is stopped, S_1 is closed and traps 2, 3 and 4 are removed from the system for total precipitation of $BaCO_3$.

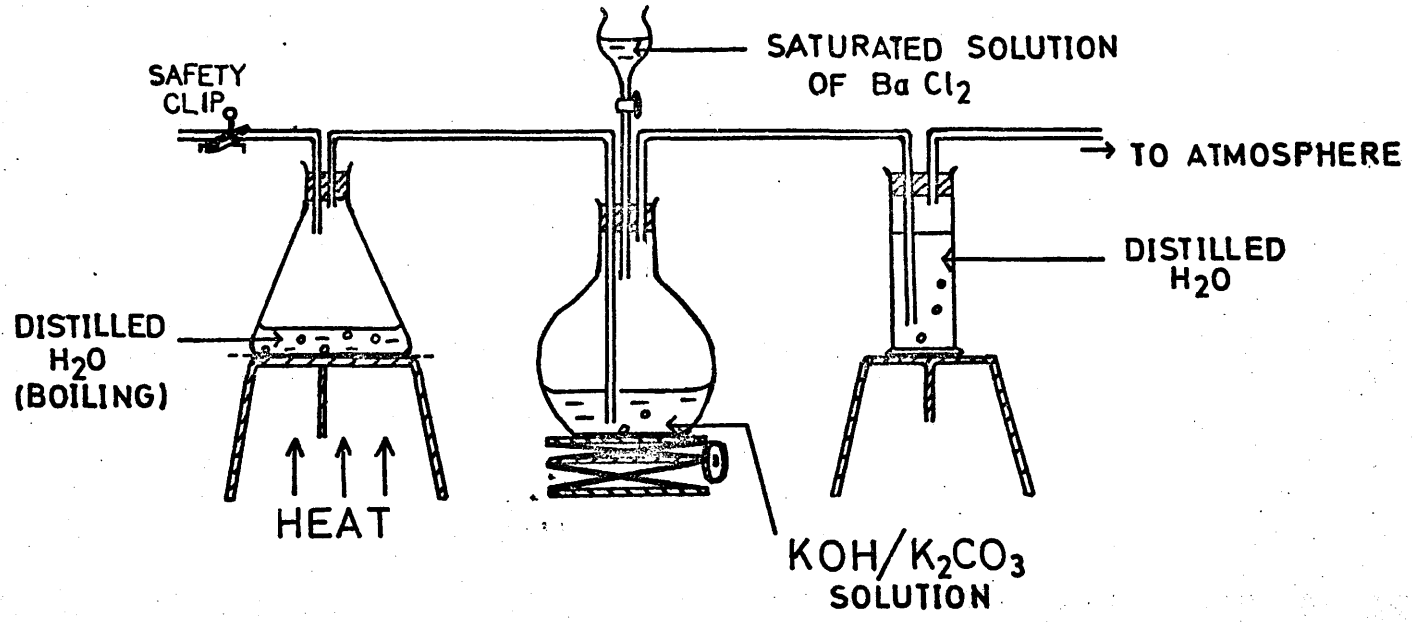
2.3.2 Precipitation of $BaCO_3$

As shown in Fig. 2.3, the precipitation of $BaCO_3$ from combustion/atmospheric KOH solution is performed in a closed system in which absorption of atmospheric CO_2 is prevented. Steam from boiling distilled water passes through the KOH solution to coagulate the solid by a combination of heat and agitation and hence improves the filtration time.

TABLE 2.2 COMBUSTION TECHNIQUES

SAMPLE TYPE	LENGTH OF COMBUSTION	COMMENTS
(a) charcoal, wood, anthracite	1 - 2 hrs.	Sample glows on applying second flame; thereafter sample glows without applied heat
(b) petroleum extract	2 - 2½ hrs.	Both extracts burn with controlled flame; after initial heating second burner is not required; prolonged roasting is necessary after sample flame dies down to aid oxidation of remaining 'soot-like' material
artery lipid	1 hr.	
(c) tissues	1½ - 2 hrs.	Second burner is applied intermittently; initial burning changes to a bright glow as in case (a)

FIG. 2.3 PRECIPITATION OF CO_2 AS $BaCO_3$



$BaCO_3$ is precipitated by addition, from the dropping funnel, of an excess of saturated $BaCl_2$ solution, and filtered when warm. Each sample is dried overnight in an oven at 110°C and weighed; any sample which is not required immediately is stored in sealed jars.

The remaining practical operations (hydrolysis, purification and counter filling) are performed in a high-vacuum manifold which prevents external contamination of sample gases. Furthermore, CO_2 can be transferred easily within this system from one section to another by distillation at liquid N_2 temperature when CO_2 exists in the solid state, its vapour pressure being $< 10^{-3}$ torr. Evacuation of the system is effected by 2 mercury diffusion pumps, each backed by its own rotary pump (one-stage and two-stage respectively). The manifold shown schematically in Fig. 2.4 is constructed so that time-consuming operations such as counter and 5ℓ. bulb evacuations can be performed simultaneously.

2.3.3 Hydrolysis of $BaCO_3$

CO_2 is regenerated from the carbonate at reduced pressure by addition of 95% H_3PO_4. The hydrolysis section, shown in Fig. 2.5, contains a water-cooled condenser as precaution against extensive frothing of samples in the reaction flask. Weighed sample $BaCO_3$ is powdered to increase the surface area exposed to acid and thereby ensure a fast, efficient process; the powder is added to the reaction flask plus stirrer, and covered with ~ 20 mls. distilled water. Two traps (T_1, T_2), each surrounded by a Dewar filled with a dry-ice/acetone mixture (-80°C), freeze out moisture from the evolved CO_2. Once the system is connected and sufficient time has elapsed for equilibration of the moisture traps with their cooling mixture, the

FIG. 2.4 BLOCK DIAGRAM OF HIGH VACUUM SYSTEM

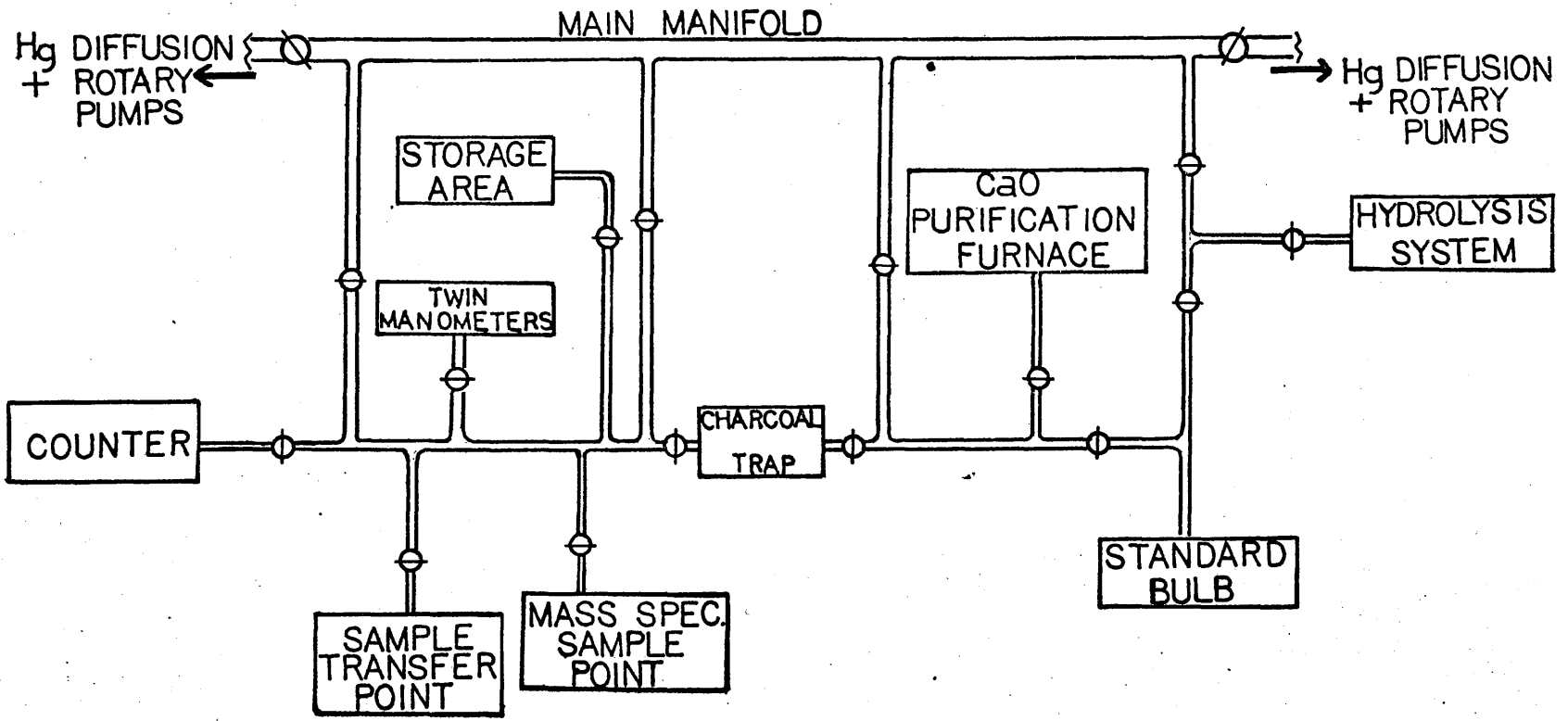
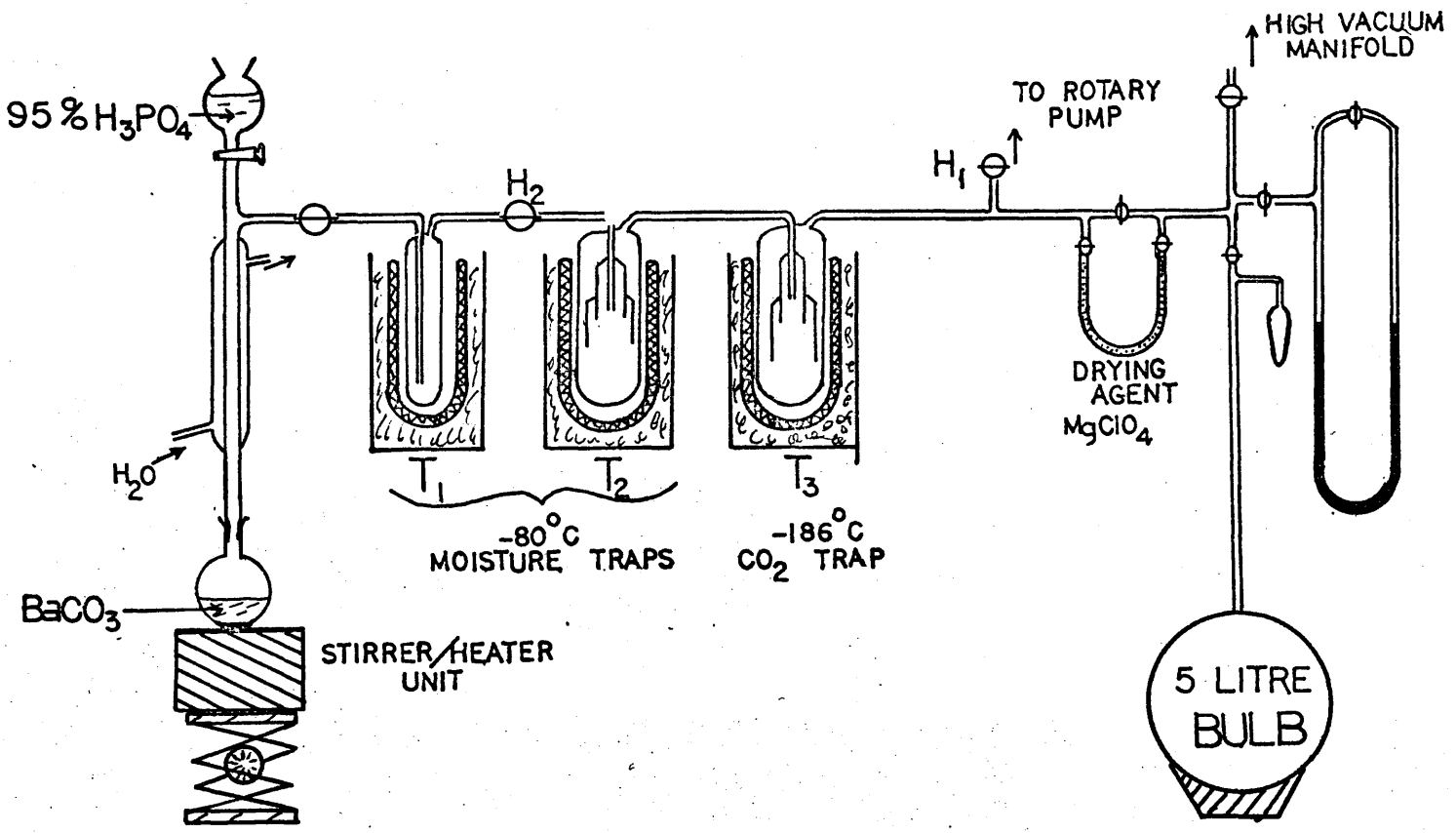


FIG. 2.5 HYDROLYSIS OF BARIUM CARBONATE



section is pumped through stopcock H_1 by rotary pump alone (H_2open). When the first signs of evaporation of the distilled water become apparent, H_1 is closed and liquid N_2 is placed under trap T_3. The non-volatile H_3PO_4 is added from the dropping funnel slowly to avoid excess frothing of the reaction mixture. When excess acid is present in the reaction flask, normally after 30 - 45 mins., the solution is stirred at maximum speed for a further 20 mins. to ensure complete hydrolysis. Thereafter H_2 is closed and traps T_2 and T_3 are evacuated to 10^{-2} torr. through H_1. The CO_2 is allowed to sublime through the drying agent ($MgClO_4$ pellets) contained in a U-tube and into the 5ℓ. standard bulb cold finger where it is condensed under liquid N_2. Both the U-tube and standard bulb are previously evacuated to $< 10^{-3}$ torr. during the hydrolysis. Once transferred, the CO_2 is pumped to 10^{-3} torr. and expanded into the standard bulb. The pressure of CO_2 is measured using a mercury manometer, room temperature is noted and the hydrolysis yield of CO_2 calculated. The resultant value is typically $\simeq 100\%$. After each hydrolysis, trap T_1 is removed, dried and replaced; distilled water is washed through the dropping funnel/condenser unit to remove traces of acid on the walls of the glass.

2.3.4 Purification of CO_2

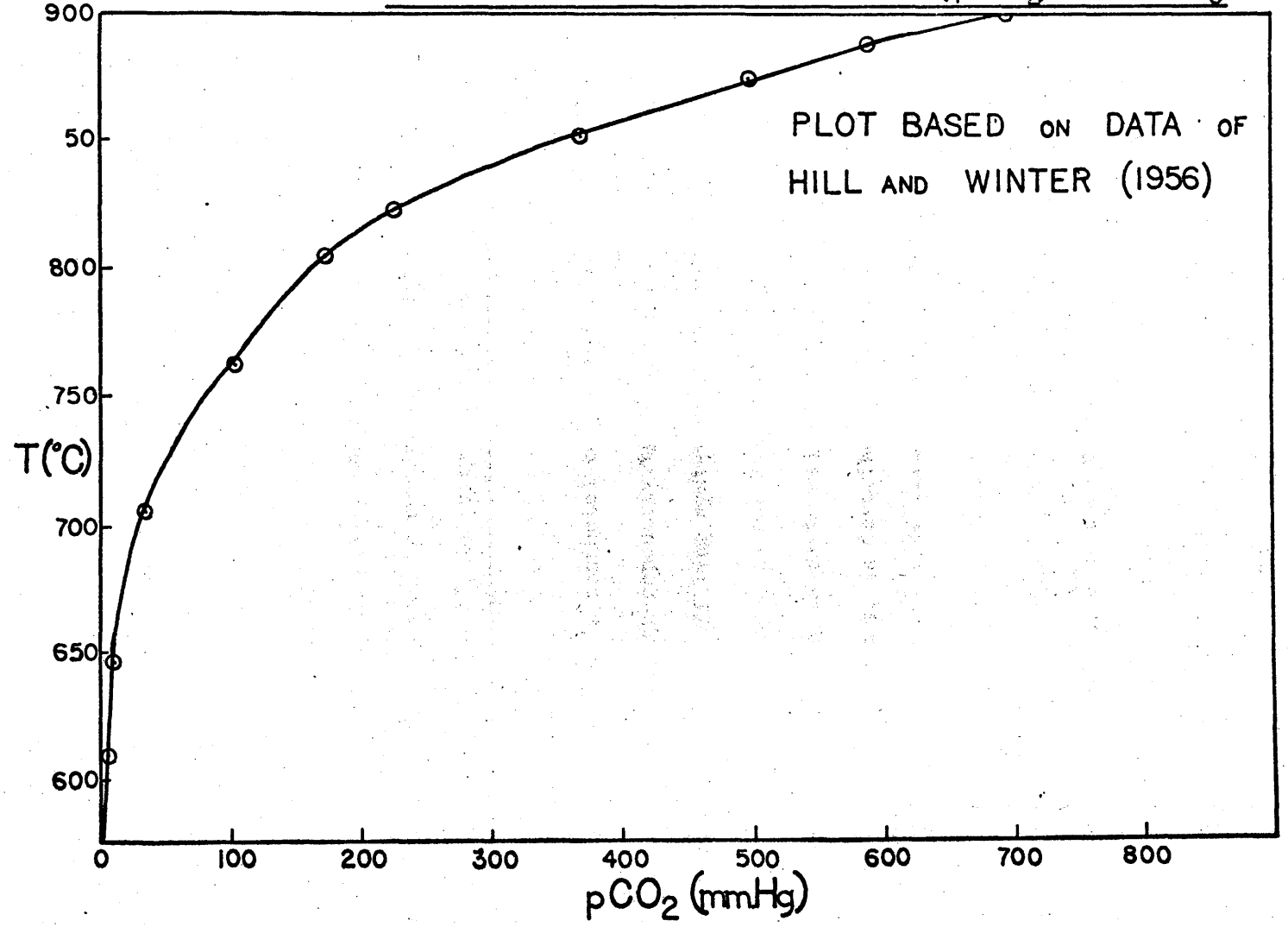
The effect of electronegative impurities on the counting performance of CO_2 has been demonstrated by Fergusson (1955) who also developed the purification technique initially used by de Vries and Barendsen (1953) to remove such impurities. Thus the initial difficulties experienced in the measurement of ^{14}C activities by proportional counting of CO_2 were overcome and led to a straightforward purification procedure for routine use. The treatment relies on the convenient temperature

dependence (400°C - 900°C) of the $CO_2/CaO/CaCO_3$ equilibrium system, represented as:

$$CaO + CO_2 \underset{T<400^{\circ}C}{\overset{T>800^{\circ}C}{\rightleftharpoons}} CaCO_3$$

Fig. 2.6 shows the dissociation pressure of $CaCO_3$ as a function of temperature, based on data from Hill and Winter (1956). CO_2 is passed from the standard bulb into the evacuated tube containing CaO heated to 700°C by a Gallenkamp energy regulated tube furnace (FS - 210). On cooling to 400°C, the tube is pumped to $< 10^{-3}$ torr.; the impurities not absorbed on the CaO are thus removed while the CO_2 is retained in $CaCO_3$ form ($pCO_2 \simeq 10^{-4}$ torr.). At 900°C, CO_2 is regenerated from $CaCO_3$ but impurities remain absorbed even at 1000°C. After each purification, the CaO is heated to $\simeq$ 1050°C; those impurities which are labile at this temperature plus any residual traces of CO_2 are removed in preparation for the next sample CO_2 by pumping to $< 0.3 \times 10^{-3}$ torr. The 3 - 4 hours required for the total (purification/cleaning) operation includes $\sim$1.5 hours taken by the furnace to cool from 700°C to 400°C. Excess moisture present in the CO_2 produced by hydrolysis decreases the rate of re-evolution of CO_2 resulting in the necessary renewal of CaO. Normally, however, renewal is only necessary after 40 - 50 gas purifications. CO_2 fresh from the CaO contains radon (α - emitter, 5.49 Mev, $t_{\frac{1}{2}}$ = 3.82 days), a daughter product of radium which exists as an impurity in the CaO. Since the amount of radon present in a CO_2 sample was found to increase with the duration of CO_2 absorption on the CaO, this time is kept to a minimum. Although Long (1965) reports almost total removal of radon from CO_2 by passage through an activated charcoal trap at - 40°C, a

FIG. 2.6 EFFECT OF TEMPORATURE ON THE DISSOCIATION PRESSURE (pCO_2) OF $CaCO_3$



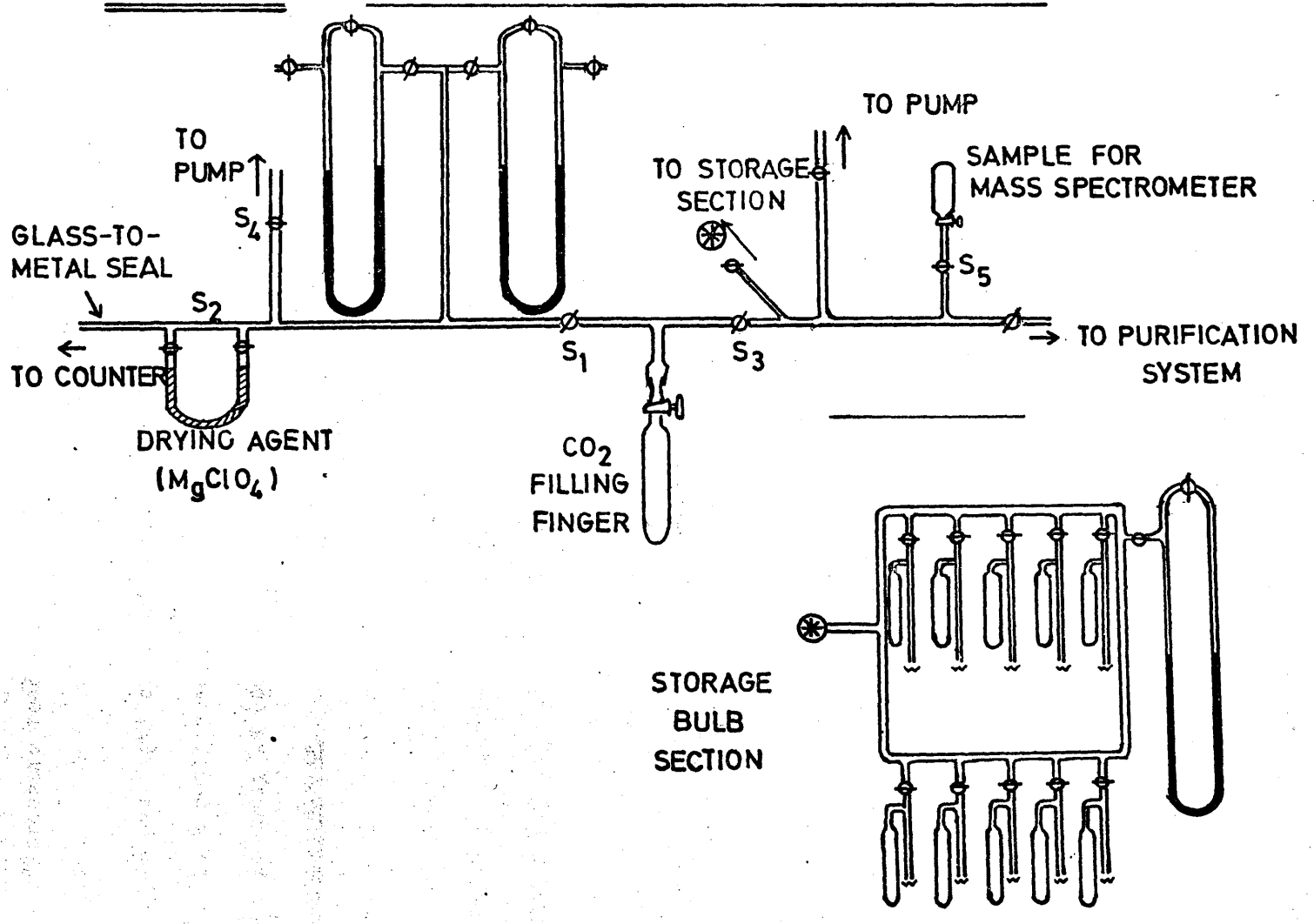
procedure lasting 2 hours, it is possible, with a similar trap at $0^{\circ}C$, to remove a high percentage of this contaminant with no time loss. The latter conditions are adopted here, since any residual radon can be allowed to decay to a negligible level within 2 - 3 weeks. Each CO_2 sample, on regeneration from the CaO furnace, passes through a charcoal trap immersed in a Dewar of crushed ice and is collected under liquid N_2 in the filling finger of a 5 ℓ. bulb. The CO_2 is stored in the bulb for a minimum of 2 weeks before its activity measurement. With a storage section of 10x5 ℓ. bulbs, it is possible to maintain a continuous supply of sample gases. After each CO_2 purification, the activated charcoal is degassed by pumping to 10^{-4} torr. at $150^{\circ}C$.

2.4 Routine Procedure for CO_2 Activity Measurement

2.4.1 Counter filling

The sample detector is connected to the vacuum manifold by 5 ft. of $\frac{1}{4}$"-bore oxygen-free, high-conductivity copper tubing ending in a glass-to-metal seal. The filling system is shown in Fig. 2.7. Prior to being filled, the counter and manometers are pumped to $< 3 \times 10^{-4}$ torr., a process which may be performed without interruption from other evacuation procedures, as described previously. Each sample gas is condensed from its storage bulb into the filling finger, with stopcock S_1 closed; before expansion into the counter, the CO_2 is pumped to 10^{-5} torr. under liquid N_2 (S_2, S_3 closed; S_4, S_4 open). The final counter filling pressure in each case corresponds to 760 mm. Hg at $15^{\circ}C$ to ensure that the same mass of carbon is counted each time. Thus when the counter pressure is slightly in excess of this value, S_1 is closed and S_3 opened; the remaining 'dry-ice' is expanded and condensed back into its storage bulb filling finger under liquid N_2. The temperature

FIG. 2.7 COUNTER FILLING SYSTEM



inside the sample detector is obtained using a gas thermometer equilibrated within the lead castle for at least 30 mins. prior to final pressure adjustment. CO_2 is leaked through S_1 (S_3 closed) until the required pressure readings in the two mercury manometers are obtained.

After an overnight count and before the gas is returned to its storage bulb, a small aliquot is extracted at S_5 for subsequent mass spectrometric analysis (see 2.5).

2.4.2 Counting system

Sample activities are measured using a Johnston Laboratories Inc. Beta-Logic Gas Proportional Counting System, models GC-12 and GC-13. The 2.6ℓ. sample detector (GC-12) is surrounded by a meson guard counter (GC-13) and the whole assembly is encased in a 4"-thickness of lead in which the gamma component of background radiation is absorbed. High-energy mesons which penetrate the lead shielding are largely eliminated from a sample activity measurement by employing sample/guard anticoincidence circuitry i.e. mesons counted simultaneously in both guard and sample detectors are automatically cancelled from a sample count.

(a) Guard counter

The guard counter is of the gas-flow Geiger type. It contains 12 independent anode wires, each anode separated from its neighbours by an earthed metal fin. The gas flow is supplied by a cylinder of Q-gas (98.7% helium, 1.3% isobutane), the flow being adjusted to an outlet pressure of 20 p.s.i. by a pressure regulator, and to a rate of 150 mls./min. controlled by a needle valve and ratemeter. Typical plateaus obtained

using this counter are > 300 V. in length with slopes $< 2.5\%/100$ V. while the working voltage is in the range 1.3 - 1.4 KV.

(b) Sample Detector

A diagram of both guard and sample counters is shown in Fig. 2.8. The sample detector, machined from brass and with a stainless steel anode wire, diameter 0.001 in., is designed to rest totally within the guard counter. A close-fitting door, also of lead, allows easy access to the counter assembly e.g. for the temperature measurement to enable the final pressure adjustment of sample CO_2. At counter pressures of 1 atmosphere, the working voltage is in the range 3.4 - 3.5 KV. Although this choice of filling pressure is essentially determined by counter volume and sample size, different operating conditions are possible, e.g. 100cms. filling pressure. Both coincidence and anticoincidence spectra exhibit excellent plateau characteristics:

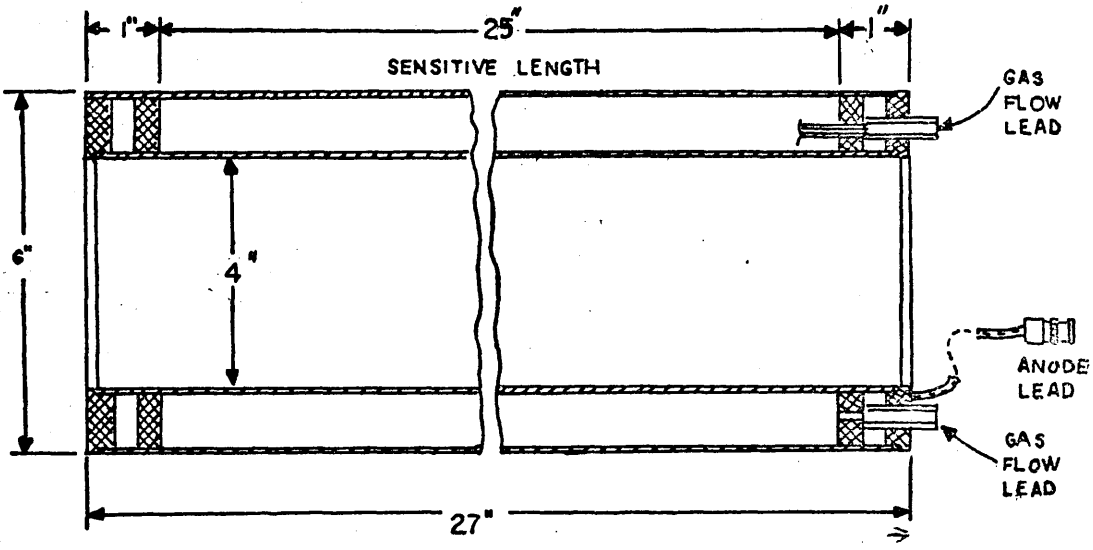
coincidence plateau : length $\sim$ 800V., slope $< 1.5\%/100$ V.

anticoincidence plateau : length $\sim$600 V., slope $< 1.0\%/100$ V.

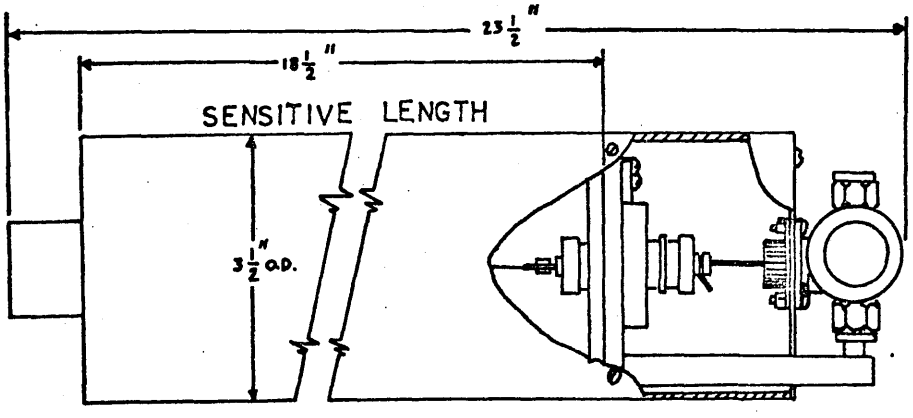
(c) Electronic console

Pulses from the sample detector are fed to a preamplifier and then to a series of 3 amplifier discriminator boards; the discriminators control the base line of 3 energy channels which receive the output pulses. The discriminator settings are adjusted for optimum ^{14}C detection and correspond to the following ranges of pulses leaving the preamplifier, assuming a gas gain of 2×10^3:

FIG. 2·8 SAMPLE AND GUARD COUNTERS
(cross-sectional view)



(a) GUARD COUNTER.



(b) SAMPLE COUNTER.

channel 1	2mV. - 20mV.
channel 2	20mV. - 400mV.
channel 3	> 400mV.

Channels 1 and 2 register ^{14}C pulses while ^{222}Rn is detected in the highest energy channel 3. The output pulses from the amplifier/discriminators are then fed to a diode matrix logic unit for time-coincidence analysis with the guard counter pulses. The diode matrix logic unit utilises information from the guard counter and the 3 discriminators to provide coincidence and anticoincidence of the 3 energy channels with the guard. The voltage to both counters is supplied by a fully transistorised dual voltage supply; 500 - 6100 V. and 500 - 4100 V. for the sample and guard detectors respectively. Pulses are shown on 4 decade scalers, each with a 5-digit register; in addition, 2 Sodeco print-out units with scalers coupled to an automatic timer and preset time interval enable long counting times to be split into several smaller periods, typically 20 mins. Print-out analysis therefore represents a valuable check on counter stability over the time of the total count. After a print-out, the registers are automatically reset. A block diagram of the essential features of the counting system is shown in Fig. 2.9.

2.4.3 Operating conditions and sampling procedure

The working voltage for a particular counter fill is obtained by analysis of detector voltage vs. coincidence meson count rate rather than the lower anticoincidence count rates. The resultant meson spectrum is a function of gas gain which in turn is sensitive to even low impurity levels in CO_2. Fig. 2.10 (a) and (b) contrast the meson spectra of pure/impure gases; the sharp peaks obtained in channels 1

FIG. 2.9 BLOCK DIAGRAM OF COUNTER ELECTRONICS.

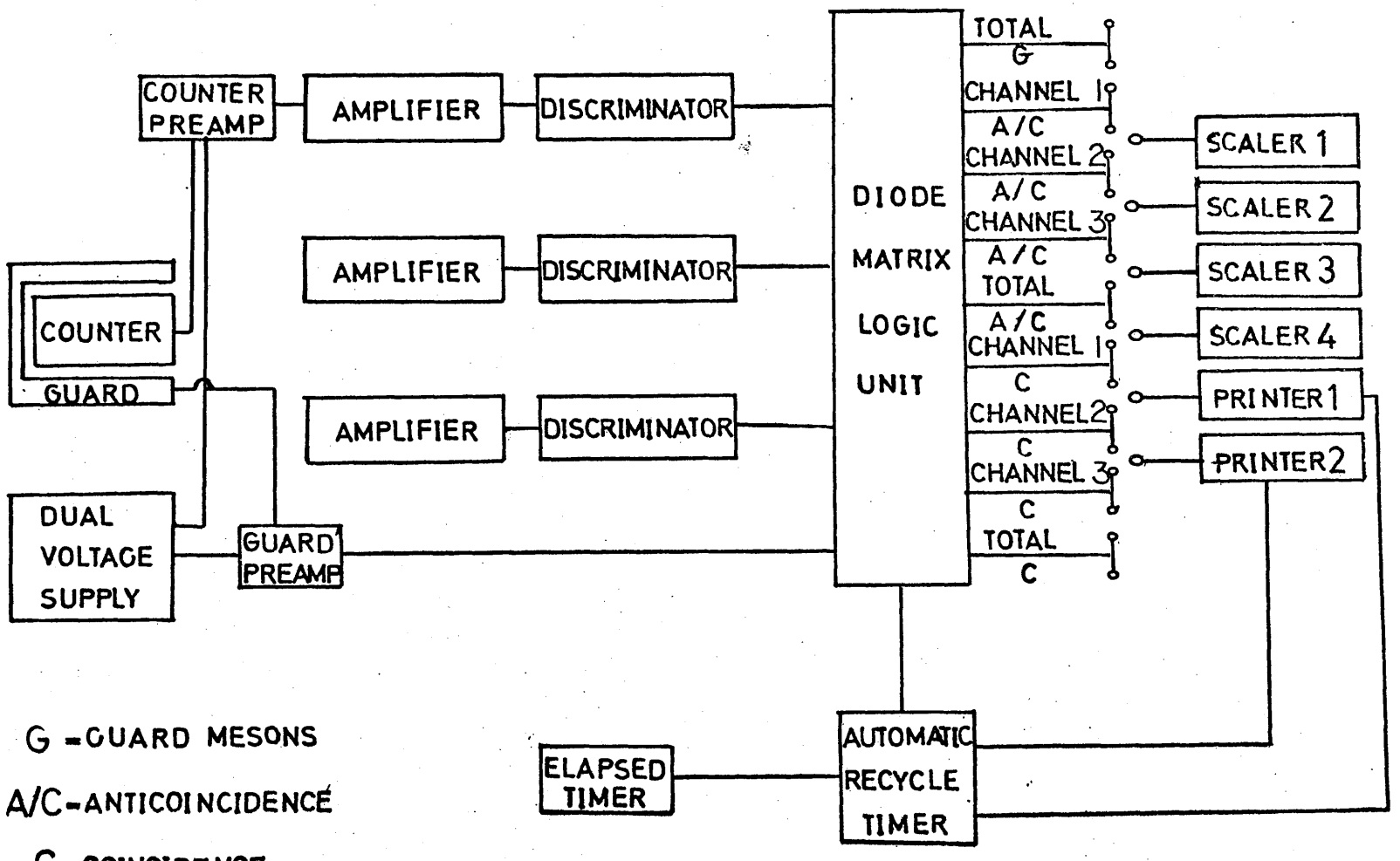
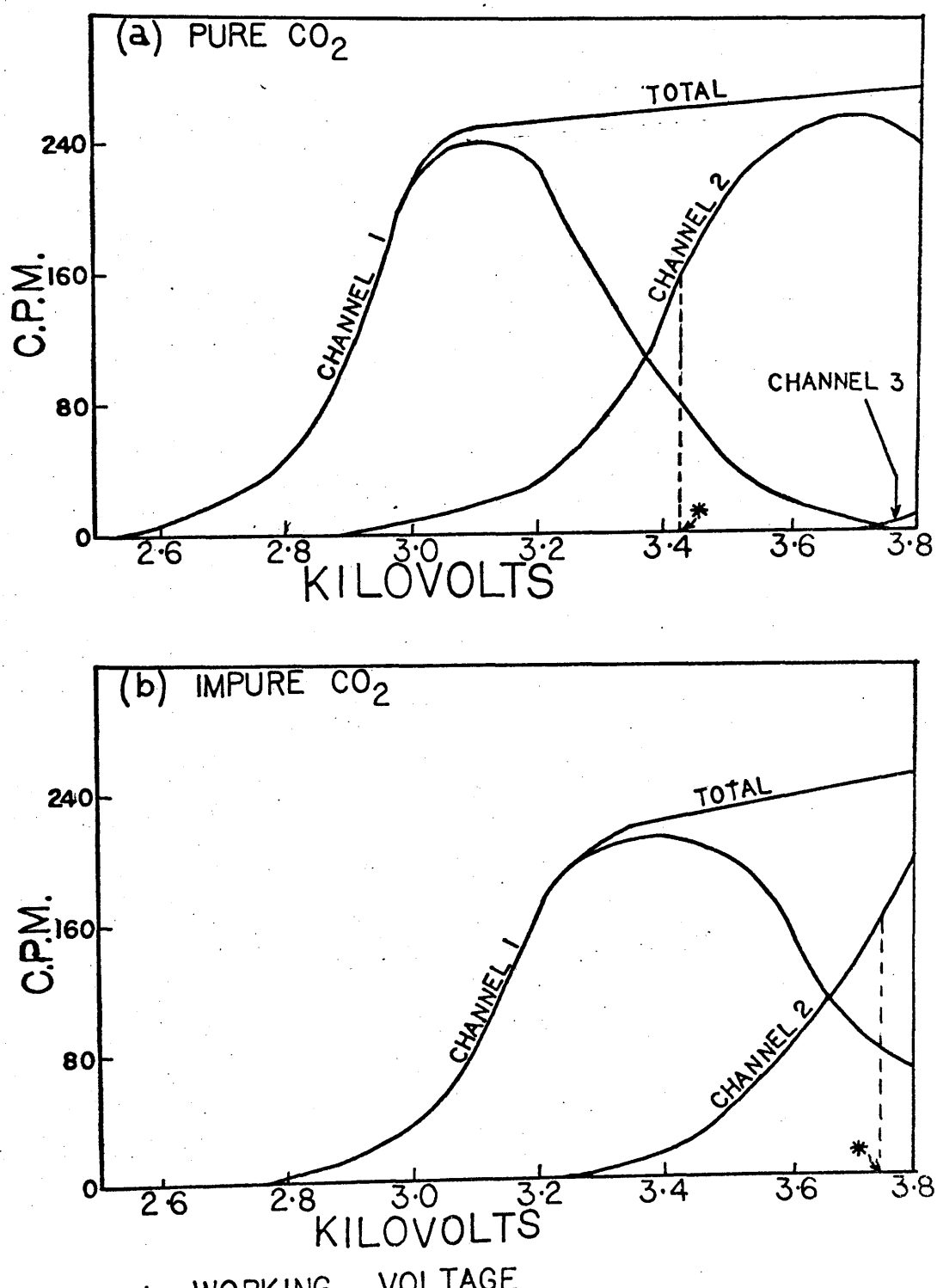


FIG. 2.10 CHARACTERISTIC COINCIDENCE SPECTRA



and 2 in (a) are characteristic of a pure gas with respect to counting while the broader peaks and lower peak-heights in (b) are caused by the presence of impurities. Provided that a CO_2 sample is pure, its working voltage is chosen within the area of steepest gradient of channel 1 and 2 count rates, C_1 and C_2 respectively, at the point where the ratio $C_1:C_2$ is 2:3. It is impossible to prevent small differences in gas purity of samples but a corresponding adjustment in voltage applied to each gas enables the 2:3 ratio and hence constant gas gain condition to be reproduced. A range in working voltage of 3.45 ± 0.03 KV. is regarded as acceptable; in a case where a voltage outside this range is necessary to obtain the same gas gain, the gas in question is repurified in the CaO furnace.

After the coincidence meson plateau has been plotted and the working voltage obtained, a 10 min. measurement is made of coincidence and guard count rates before the system is altered for the overnight anticoincidence count - normally of at least 18 hours' duration. At the end of this period, the coincidence and guard count rates are measured as before to ensure that the working voltage has not changed appreciably. In fact, the coincidence spectrum from most gases does move to higher voltage after an overnight count, but only by about $2\frac{1}{2}$ V. This effect is assumed to be caused by outgassing of the counter walls; however, the initial purity of the gas is restored at the next counter fill when the gas is pumped to 10^{-5} torr. A further distillation is not normally necessary. The guard count rate is monitored during the day.

A typical extract from the daily counting log is shown in Fig. 2.11. At least 2 overnight counts are performed for every sample gas to accumulate a minimum of 45,000 counts and thereby reduce overall counting

TABLE 2.11 TYPICAL EXTRACT FROM COUNTER LOG BOOK

SAMPLE: NBS Oxalic acid 5/S DATE: 7/1/72

FILLING PRESSURE: 77.55 cms. at 69.5°F.

VOLTAGE (KV.)	COUNTS PER 2 MINUTES					
	CO_1	CO_2	CO_3	CO_T	A/C_T	G
2.60	6	-	-	6	-	1381
2.80	82	1	-	83	4	1367
3.00	440	22	-	462	14	1373
3.20	363	138	-	501	32	1391
3.40	262	250	-	512	42	1365
3.50	106	428	-	534	39	1380
3.60	45	478	1	524	46	1377

WORKING VOLTAGE: 3.42KV. guard (day count rate) = 686 c.p.m.

10-MINUTE COUNT AT WORKING VOLTAGE

CO_1	CO_2	CO_3	CO_T	G	$\frac{CO_1}{CO_2}$
1002	1565	-	2567	6784	0.64

ON : 16.00 8/2

OFF: 10.30 9/2

COUNTING TIME: 1110 mins.

	AC_1	AC_2	AC_3	AC_T
TOTAL COUNT	5748	15956	63	21767
C.P.M.	5.18 ± 0.07	14.38 ± 0.11	0.06 ± 0.01	19.61 ± 0.13

10-MINUTE COINCIDENCE COUNT

CO_1	CO_2	CO_3	CO_T	G	$\frac{CO_1}{CO_2}$
1066	1524	1	2591	6846	0.70

ATMOSPHERIC PRESSURE (during counting period): 1038mbars.

uncertainty below 0.5%; if necessary, where 2 count rates differ by $> 2(\sigma_1 + \sigma_2)$ where σ_1, σ_2 are the statistical counting errors (one standard deviation), further counts are performed until there is agreement within the specified error limits. The stability of an overnight count is checked by inspection of the print-out tape; a print-out total differing from the mean by $> \pm 2\,\sigma_{mean}$ is neglected. Barometric pressure is averaged over the counting period and recorded.

2.5 Isotopic Fractionation of CO_2

In any chemical or physical process which occurs with $< 100\%$ yield and which involves at least 2 isotopes of an element, there exists the possibility of isotopic fractionation i.e. the preferential selection of either the light or heavy isotope as a consequence of its nuclear mass difference. The different themodynamic properties associated with this inequality result in different reaction rates and diffusion coefficients of isotopically substituted molecules. Thus for a non-quantitative laboratory preparation of CO_2, containing ^{12}C, ^{13}C and ^{14}C isotopes, there is likely to be a change in the original $^{13}C/^{12}C$ ratio. Similarly the $^{14}C/^{12}C$ ratio will be altered, but in this case by twice the former value, since the mass differences of ^{14}C and ^{13}C with respect to ^{12}C differ by a factor of 2 (Craig 1954).

2.5.1 Measuring technique

The fractionation effects in a sample of CO_2 are obtained via abundance ratio measurements of carbon and oxygen performed by mass spectrometric analysis of sample CO_2. The $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios are not measured directly but are deduced from the beam intensity ratios 45/44 and 46/(44 + 45) respectively, where

mass - 44 ions = $^{12}C^{16}O^{16}O$ (98.42%)

mass - 45 ions = $^{12}C^{16}O^{17}O$ (0.08%) + $^{13}C^{16}O^{16}O$ (1.1%)

mass - 46 ions = $^{12}C^{16}O^{18}O$ (0.4%) + $^{12}C^{17}O^{17}O$ + $^{13}C^{16}O^{17}O$ } ($\simeq$ 0%)

The values in parentheses represent the percentage relative abundances of the isotopic species (McCrea 1950). All isotopic analyses are performed using a double collecting, 90° deflection, 6 cm. radius Micromass 602B mass spectrometer (V.G. Micromass Ltd., Winsford, Cheshire). This spectrometer is fitted with twin ion collectors which permit direct measurement of the deviation in sample beam intensity ratio 45/44 and 46/(44 + 45) from the standard ratios. The enrichment of ^{13}C in a sample as a result of fractionation is expressed by the symbol $\delta^{13}C$ defined by the relationship:

$$\delta^{13}C = \left[\frac{R_{Sa}}{R_{Std}} - 1 \right] \times 1000 \text{ }^{o}/_{oo}$$

where R_{Sa} and R_{Std} are the $^{13}C/^{12}C$ ratios of the unknown and standard respectively. $\delta^{13}C$ represents, therefore, the per mil $^{13}C/^{12}C$ ratio enrichment in the sample relative to the standard - CO_2 produced from PDB "Belemnitella americana". As with ^{14}C activity measurements, absolute values are not necessary; only the deviation of isotopic ratio with respect to the standard is required. In practice, a secondary standard, previously intercalibrated with the belemnite standard, is employed. A double gas all-metal inlet system allows a rapid comparison between sample and standard. The dimensions of capillary leak and the inlet pressure ($\simeq$ 7 cms. Hg) are such that the inlet gas flow is viscous, preventing isotopic fractionation in the sample vessel (Brunnée

and Voshage 1964). Ratios are obtained on a digital output connected to a pen recorder.

About 6-8 successive differences between sample and standard $^{13}C/^{12}C$ ratio are obtained on the 45/44 ion beam. Only 4 differences are recorded for the 46/(44 + 45) ion beam; analysis of these enables a correction to be applied for ^{17}O contribution by $^{12}C^{16}O^{17}O$ to the mass-45 peak.

2.5.2 Calculation of $\delta^{13}C$

The values for sample 45/44 ratio, standard 45/44 ratio and their difference are averaged and expressed as R_1', R_o', and Δ' respectively. An adjustment is made to these values to correct for the slight amount of mixing of sample and standard gases in the inlet system. Thus the corrected ratios R_1 and R_o respectively are obtained. Δ, the corrected difference in the mass 45/44 ratio between sample and standard is calculated from the expression:

$$\Delta = \Delta' \times \frac{R_1 - R_o}{R_1' - R_o'}$$

The measured deviation $\delta^{13}C_m$ of sample from standard is:

$$\delta^{13}C_m = \Delta/R_o \times 1000\ ^o/_{oo}$$

but since $R = (^{13}C^{16}O^{16}O + ^{12}C^{16}O^{17}O)/\ ^{12}C^{16}O^{16}O$

a correction factor must be applied for the abundance of ^{17}O. Since enrichments for ^{17}O and ^{18}O differ by a factor of 2 (Craig 1957b) measurements of the 46/(44 + 45) ion beam ratio enables a correction to be applied to $\delta^{13}C_m$ via $\delta^{18}O$, where:

$$\delta^{18}O = \frac{\Delta''}{R''} \times 1000\ ^{o}/_{oo}$$

Δ'' = the mean of the difference in 46/(44 + 45) ratios of sample and standard and

R'' = the mean of the 46/(44 + 45) of standard

Thus the corrected value of $\delta^{13}C_m$

$$\delta^{13}C_{corr.} = 1.065 . \delta^{13}C_m - 0.0325 . \delta^{18}O$$

This value has been calculated relative to the working standard which was derived from the combustion of a sample of human brain. Before $\delta^{13}C_{sample}$ - defined with respect to the PDB standard - can be calculated, the $\delta^{13}C$ value of the working standard relative to PDB must be known. In fact, the calibration of brain CO_2 was performed by comparison with Solenhofen limestone, NBS reference sample No. 20. Using a value for NBS 20 relative to PDB of - 1.03 $^{o}/_{oo}$ (Craig 1957b), $\delta^{13}C_{brain}$ relative to PDB was calculated and found to be - 20.67 $^{o}/_{oo}$. Finally $\delta^{13}C_{sample}$ relative to PDB is calculated from the expression:

$$\delta^{13}C = \delta^{13}C_{sample}\ (^{o}/_{oo}) = \delta^{13}C_{corr.} + \delta^{13}C_{brain} + \delta^{13}C_{corr.}\ \delta^{13}C_{brain} . 10^{-3}$$

Appendix 1 gives details of the computer programme used to obtain $\delta^{13}C_{corr.}$ and $\delta^{18}O$ with associated statistical errors. Typical precision of measurement is 0.05 $^{o}/_{oo}$ ($\pm 1\sigma$).

2.6 Treatment of Sample ^{14}C Activity Measurements

The anticoincidence count rates obtained for each sample represent the gross activity of that particular sample and include a significant contribution from background radiation. To reduce the statistical uncertainty in the net activity of a sample, therefore, it is necessary

to measure the background count rate and its variation.

2.6.1 Background count rate measurement

The major sources of background radiation detected in the sample counter are:

(a) cosmic-ray mu-mesons which are not eliminated by anticoincidence shielding,

(b) secondary gamma rays produced essentially by interaction of mu-mesons with lead, and

(c) radioactive impurities in the counter materials.

The discriminator threshold of 2mV. eliminates counter electronic noise while teflon insulation reduces spurious pulses to a negligible level. Occasionally non-statistical background counts appear, caused by breakdown in the insulation of high tension cables. In such a situation, the source of trouble is located and the cable/plugs resoldered or, if necessary, renewed. For background measurement, suitable materials found to be sources of inactive carbon are (a) marble chips, (b) anthracite, (c) petroleum, (d) industrial Dri-Kold, and (e) tank CO_2. The pretreatment/preparation of these samples is summarised in Table 2.3. At least 2 separate background CO_2 samples are available at any one time, should a check for contamination of either gas with active CO_2 samples be necessary. Furthermore, the diverse methods of preparation of these gases ensures that different stages in the normal sample CO_2 preparation procedure can be checked for the possibility of contamination with laboratory CO_2 e.g. the precipitation/filtration of $BaCO_3$. Background gases are counted at least once every 14 days but normally once every 10 days; by accumulation of results over a period of months, a series of background data vs. atmospheric pressure is obtained. The

TABLE 2.3 PROCESSING OF BACKGROUND SAMPLES

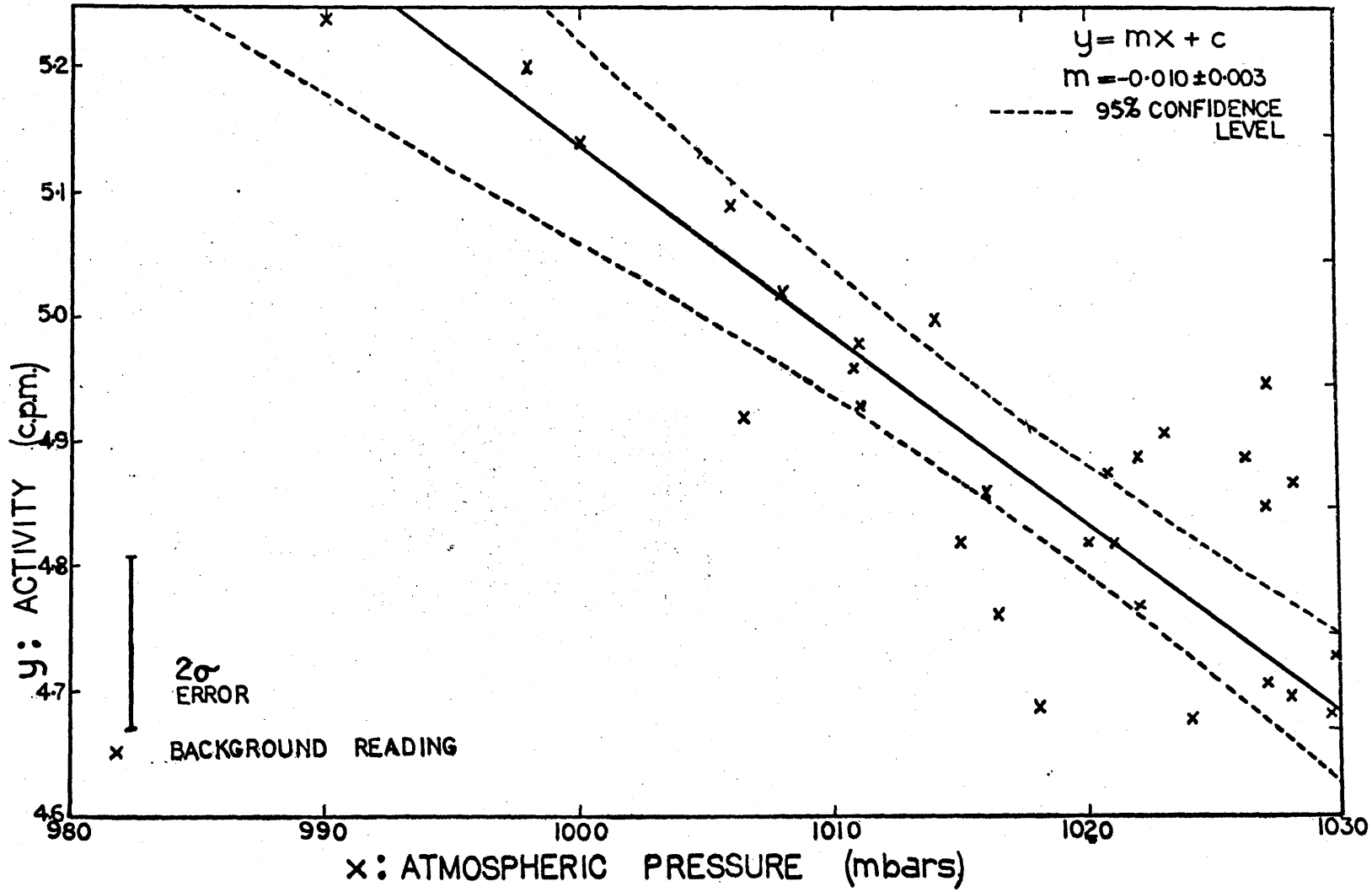
STARTING MATERIAL	PRETREATMENT	INITIAL STAGE OF PREPARATION
Marble chips	Outer layer (25%) removed by 2MHCl, washed in distilled water, dried	(i) Hydrolysis, or (ii) addition directly to purification furnace, pumped to 10^{-4}torr. at 400°C, heated to 900°C to obtain CO_2
Anthracite	Boiled in 2MHCl, washed in distilled water, dried	Combustion to CO_2
Petroleum	None	Combustion to CO_2
'Dri-kold' (dry ice)	Moisture removed in hydrolysis section	Standard bulb, purification
Industrial CO_2 (tank)	None	Standard bulb, purification

latter values range from 980 - 1035 mbars. pressure. The resultant information is subjected to linear regression analysis by the method of least squares; details of the procedure, performed by computer, are given in Appendix 2. An inverse relationship is obtained by such a treatment whereby the background count rate decreases by 0.010 c.p.m. per mbar. increase in atmospheric pressure; the line applicable to the six month period commencing August, 1972 is shown in Fig. 2.12, together with the statistical error associated with the linear plot (see Appendix 2). Such a relationship confirms that the main component of background radiation can be attributed to cosmic rays; a greater physical barrier is presented to the passage of cosmic rays/cosmic-ray derived particles by the earth's atmosphere during periods of high rather than low pressure.

2.6.2 Reference standard

Radiocarbon assay is not an absolute determination but rather a measurement of the per mil difference between a sample activity and that of a standard. It is therefore desirable that the reference material be universally applied to maintain consistency and reproducibility between different laboratories. Such a standard is the NBS oxalic acid standard, which is related in activity to 1890 wood (as described in the following subsection); the latter material is selected since it existed prior to the artificial perturbations of atmospheric ^{14}C concentration discussed in 1.4. CO_2 is prepared from the oxalic acid dihydrate by wet oxidation, performed in the hydrolysis section of the vacuum manifold; the reaction is allowed adequate time for completion to prevent isotopic fractionation of the CO_2 (Grey et al. 1969). A saturated solution of $KMnO_4$ in $0.5M H_2SO_4$ - the oxidising reagent - is slowly added to 16g. NBS oxalic acid covered with distilled water and the following reaction occurs:

FIG. 2.12 BACKGROUND ACTIVITY AS A FUNCTION OF ATMOSPHERIC PRESSURE (AUG. 1972 - FEB. 1973)



$$5(COOH)_2 \cdot 2H_2O + 2MnO_4^- + 16H^+ \longrightarrow 10CO_2 + 8H_2O + 2Mn^{2+} + 10H^+$$

After addition of excess permanganate (2-3 hours), the solution is stirred for a further 4 hour period; thereafter, purification of CO_2 is performed in the normal way (i.e. via the CaO tube/furnace). As in the case of background samples, the modern standard is counted regularly, on average once every 14 days, to reduce the statistical uncertainty in its activity and ultimately in the relative activity of a sample, while also representing a continual check on the stability of performance of the counter. Before the standard can be used in calculations of $\delta^{14}C/\Delta$ values (discussed in the next section), 2 corrections must be applied to its ^{14}C activity:

1) for isotopic fractionation, if any, via the equation:

$$A_{ox} = A'_{ox} \left[1 - \frac{2(19 + \delta^{13}C_{ox})}{1000} \right]$$

where A_{ox} = corrected ^{14}C activity of the NBS oxalic acid standard

A'_{ox} = measured " " " " " " " "

$\delta^{13}C_{ox}$ = experimentally measured $\delta^{13}C$ value of the standard, and

$-19^o/_{oo}$ = accepted value of the $\delta^{13}C$ " " " " (Craig, 1961)

2) for radioactive decay since 1958, the year of origin of the NBS oxalic acid standard, via the equation:

$$A_{corr} = A_{ox} \cdot \left[1 + \frac{0.12\ (t - t_o)}{1000} \right]$$

where 0.12 = decay rate of ^{14}C i.e. 0.12‰ per year

$(t - t_o)$ = number of years between the measurement of its activity and 1958 (t_o)

A_{ox} is defined as above, and

A_{corr} is the corrected standard activity.

The resultant activities are combined for periods of statistical agreement and their mean value used in the treatment of sample results. The values of the standard activities measured during the same time interval as in Fig. 2.12 are shown in Fig. 2.13. One exception to this averaging process occurred during an 8-week interval in early 1972 when, under conditions of apparent counter instability, a running mean of background and standard activity values was preferred. The periodicity of these measurements was correspondingly increased to improve the accuracy of the latter procedure.

2.6.3 Calculation of results

Net activities of both sample (A_s) and NBS oxalic acid standard (A_m) are related via the following formula established by Broecker and Olson (1959);

$$\delta^{14}C_{sample} = \left[\frac{f \times A_s}{0.95 \times A_m} - 1 \right] \times 1000 \text{ ‰}$$

The multiplication factor 0.95 adjusts the standard activity to correspond to the $^{14}C/_{12}C$ concentration of 1890 wood (see 1.4), while f, the dilution factor, is applied to those samples diluted with inactive CO_2:

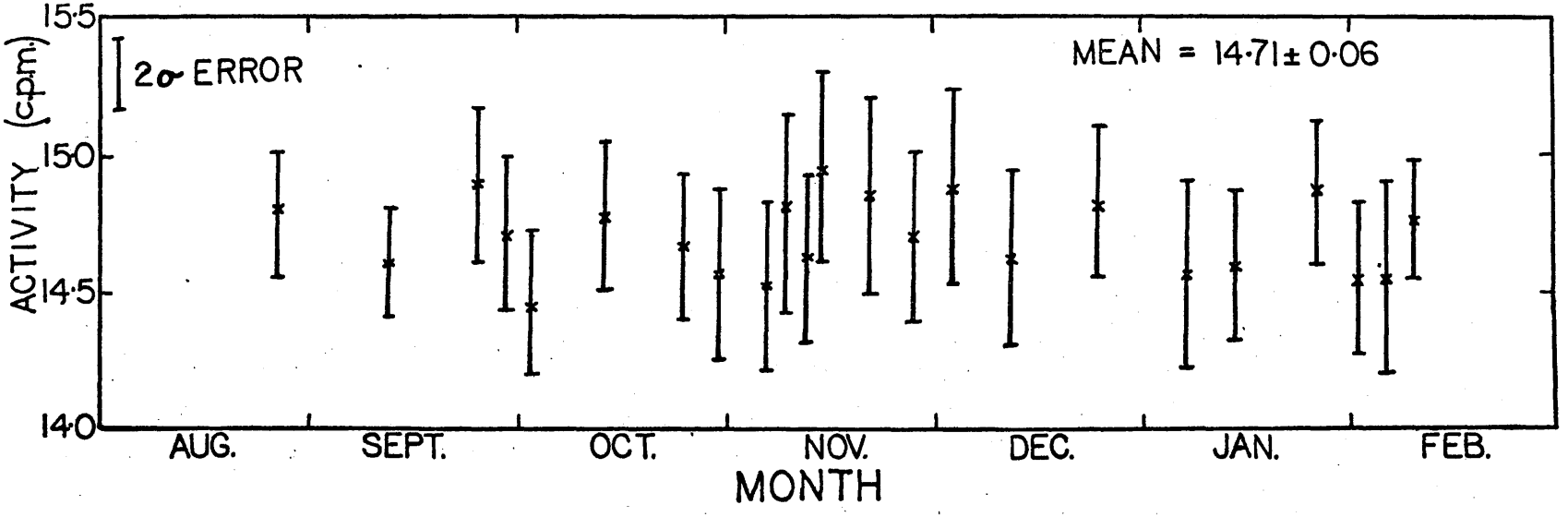
$$f = \frac{pCO_2 \text{ (sample + background)}}{pCO_2 \text{ (sample)}}$$

The parameter $\delta^{14}C_{sample}$ is uncorrected for isotopic fractionation of the sample itself; after the necessary correction via $\delta^{13}C_{sample}$, the final equation becomes:

$$\Delta(‰) = \delta^{14}C_{sample} - (2\,\delta^{13}C + 50)(1 + \frac{\delta^{14}C}{1000})$$

from Broecker and Olson (1961). Δ represents the per mil difference in ^{14}C activity between sample and standard, after fractionation effects have been considered. The errors on $\delta^{14}C$ and Δ, values expressed

FIG. 2.13 NET ^{14}C ACTIVITY MEASUREMENTS OF OXALIC ACID STANDARD (AUG. 1972 – FEB. 1973)



below at the $\pm 1\sigma$ confidence level i.e. one standard deviation, are based on the statistical uncertainty of sample, background, and standard count rates, and on the precision of each $\delta^{13}C$ measurement, viz:

$$\sigma(\delta^{14}C) = \pm \frac{A_m \cdot f \cdot 1000}{0.95 A_m} \sqrt{\left\{ \left(\frac{\sigma_s}{A_s}\right)^2 + \left(\frac{\sigma_m}{A_m}\right)^2 + \left(\frac{\sigma_f}{f}\right)^2 \right\}}$$

and $$\sigma(\Delta) = \pm \sqrt{\left[1 - \frac{(2\delta^{13}C + 50)}{1000}\right]^2 \sigma^2(\delta^{14}C) + 4\left[1 + \frac{\delta^{14}C}{1000}\right]^2 \sigma^2(\delta^{13}C)}$$

from Callow et al. (1965).

2.6.4 Age determination

^{14}C ages are still calculated relative to the Libby half-life of 5,568 years, a resolution adopted at the 1962 Cambridge Conference on Radiocarbon Dating to avoid confusion with initial radiocarbon dates (Godwin 1962). However, these values can be converted to dates based on the 5,730 year half-life through multiplication by the factor 1.03.

A sample age, T years, is calculated from the equation:

$$T = 8033 \log_e \left[\frac{1}{1 + (\Delta \times 10^{-3})}\right]$$

where $8033 = t_{\frac{1}{2}}/0.693$

Limits of age are fixed by the error on Δ, as follows:

$$(T + t_1,\ T - t_1) = 8033 \log_e \frac{1}{1 + \left[\Delta \pm \sigma(\Delta)\right] \times 10^{-3}}$$

Furthermore, ^{14}C ages are normally quoted in years B.P. (before present) as stipulated in the journal Radiocarbon, the present being taken as 1950.

2.6.5 Correction of a sample's activity measurement for the presence of ^{222}Rn plus daughter products

Occasionally a contribution to the gross activity of a sample from radon and associated daughter products was observed, even after

2 weeks. To avoid wastage of counting runs by rejection of such count rates, the relationship between ^{222}Rn alpha pulses occurring in anticoincidence channel 3 (A/C_3) and the resultant increase in counts observed in $A/C_1 + A/C_2$ was determined using samples of predetermined activity which were subsequently seeded with ^{222}Rn. A residual alpha count rate in A/C_3 (0.04 c.p.m.) was apparent from numerous counting sequences. These pulses, which were subtracted from the gross A/C_3 count rate, were assumed to result from traces of daughter products of the U and Th series present in the counter materials. A similar effect, but to a greater extent, was noted by Fergusson (1955). Treatment of the A/C_3 count rate in excess of this value is performed as follows:

Let $A_{corr.}$ = the true sample activity (c.p.m.) i.e. in the absence of ^{222}Rn

A/C_T = the total anticoincidence count rate with ^{222}Rn present (c.p.m.)

i.e. $A/C_T = A/C_1 + A/C_2 + A/C_3$ where A/C_1, A/C_2, and A/C_3 are the individual channel count rates (c.p.m.)

R, the contribution in channels $A/C_1 + A/C_2$ from ^{222}Rn plus daughter products in A/C_3 i.e. the net β/α ratio

$$R = \frac{A/C_1 + A/C_2}{A/C_3 - 0.04}$$

R was determined experimentally under normal CO_2 counting conditions (filling pressure, working voltage), to be 1.557 ± 0.036. The total correction to be subtracted from A/C_T is, therefore:

$$(R + 1)(A/C_3 - 0.04) \text{ c.p.m.}$$

i.e. $A_{corr.} = A/C_T - (R + 1)(A/C_3 - 0.04) - 0.04$ c.p.m.

The error on $A_{corr.}$, at the 1 σ confidence level, is given by:

$$\pm \sigma_{A_{corr.}} = \pm\sqrt{\sigma^2_{A/C_T} + \sigma^2_C} \quad \text{(the error on 0.04 is negligible)}$$

where $C = (R + 1)(A/C_3 - 0.04)$

and $$\pm \sigma_C = \pm\sqrt{\left(\frac{\sigma_R}{R+1}\right)^2 + \left(\frac{\sigma_{A/C_3}}{A/C_3 - 0.04}\right)^2} \cdot (R + 1)(A/C_3 - 0.04)$$

Since the error on $(R + 1)$ is negligible compared to $(A/C_3 - 0.04)$, σ_C reduces to:

$$\pm \sigma_C = \pm \sigma_{A/C_3} \cdot (R + 1)$$

2.6.6 Intercalibration of the counting system

Several interlaboratory calibration samples were measured to check the validity of the CO_2 preparation and counting technique; good agreement within statistical error was obtained with both modern and archaeological specimens (Table 2.4). As a check on the continuing reliability of the counting system, some of the latter samples were repeated throughout the research period.

TABLE 2.4 INTERCALIBRATION SAMPLES.

(a) Archaeological

SAMPLE/TIME OF ANALYSIS		AGE (YEARS B.P. ± 1σ)	
		THIS LABORATORY	OTHER LABORATORIES
Kilphedir Hut Circles	1971	2215 ± 61	2100 ± 80 (L)
	1972	2045 ± 67	
Wood Calder	1973	2578 ± 58	2569 ± 80 (SRRC)
			2585 ± 100 (S)
Oxbow Wood	1971	4120 ± 107	
	1972	4154 ± 69	4280 ± 100 (S)
	1973	4149 ± 107	
Chesil Beach Peat	1973	3876 ± 90	4023 ± 40 (SRRC)
Cyprus Charcoal (a)	1972	5223 ± 90	Archaeological
(b)	1972	5267 ± 112	estimate ca. 5000

(L): Lamont Radiocarbon Laboratory; (S): Stockholm Radiocarbon Laboratory; (SRRC): Scottish Research Reactor Centre, East Kilbride.

(b) Contemporary

SAMPLE/TIME OF ANALYSIS	Δ ± 2σ	
	THIS LABORATORY	W.S.U. (assuming $\delta^{13}C = -25‰$)
W.S.U. 1189 - Cow heart (1971)	51.5 ± 2.3	48.2 ± 3.3
W.S.U. 1187 - Cow cartilage (1971)	31.5 ± 1.8	31.8 ± 3.8
W.S.U. 1168 - Cow muscle (1971)	58.3 ± 1.9	60.7 ± 5.6

W.S.U.: Washington State University Radiocarbon Laboratory.

CHAPTER 3. ^{14}C RESULTS : $\delta^{14}C$, $\delta^{13}C$, Δ.

The following tables contain data accumulated over the research period; apart from explanatory notes on individual sections, discussion of results is withheld until the subsequent chapter. In circumstances where a $\delta^{13}C$ measurement was not available, due either to escape of the sample CO_2 during storage or to collection of a diluted sample rather than the pure sample gas, a mean $\delta^{13}C$ value is recorded in parentheses. For these tissues, the mean of the $\delta^{13}C$ values of the corresponding tissue in other specimens is used in the calculation of the Δ values; where such a mean $\delta^{13}C$ value does not exist, the average of all tissue $\delta^{13}C$ values is used. The former choice was made since there appeared to be less variation between $\delta^{13}C$ measurements of the same tissue of different individuals than the corresponding values of different tissues of the same individual. A $\pm 1\sigma$ error is quoted for $\delta^{14}C$ and Δ results, while the 1σ error for a $\delta^{13}C$ measurement is 0.05% except for mean $\delta^{13}C$ values when a $\pm 1\ ^{o}/_{oo}$ ($\pm 1\sigma$) error is assumed. $\delta^{14}C$ and Δ values are quoted in per cent rather than per mil units as defined by Broecker (see 2.6.3) since samples derived from the bomb ^{14}C era are represented more appropriately by the former order of magnitude.

3.1 Human tissue ^{14}C measurements

In each of the tabulated series, the sex, age, date and cause of death of the individual accompanies the results.

(a) Whole tissue series

(i) Male, 50 years old; died January 1971: cerebral haemorrhage

(i) Male, 50 years old

Tissue	$\delta^{14}C(\%)$	$\delta^{13}C(^{o}/_{oo})$	Δ (%)
Liver	44.29 ± 0.80	-21.72	43.34 ± 0.80
Muscle	50.98 ± 1.24	(-22.46)	50.21 ± 1.27
Heart	53.31 ± 1.84	(-21.60)	52.27 ± 1.85
Testes	38.25 ± 1.01	-23.18	37.75 ± 1.01
Kidney	45.14 ± 0.84	-22.96	44.55 ± 0.84

(ii) Male, 72 years old; died March, 1971 : bronchial pneumonia

Tissue	$\delta^{14}C(\%)$	$\delta^{13}C(^{o}/_{oo})$	Δ (%)
Brain	51.51 ± 1.04	-21.36	50.41 ± 1.04
Muscle	52.21 ± 1.10	-24.07	51.93 ± 1.10
Pancreas	54.39 ± 0.93	-25.92	54.67 ± 0.93
Lung	51.86 ± 0.98	-22.76	51.18 ± 0.98
Spleen	52.42 ± 1.04	-21.99	51.50 ± 1.04
Liver	53.96 ± 0.99	-22.53	53.20 ± 0.99
Heart	51.65 ± 0.98	-21.72	50.66 ± 0.98
Kidney	55.51 ± 0.94	-24.09	55.23 ± 0.94
Testes	49.93 ± 0.98	-24.45	49.77 ± 0.98
Bone Marrow fat	48.28 ± 0.84	-27.04	48.88 ± 0.84
Collagen	10.94 ± 2.74	(-22.46)	10.38 ± 2.74

(iii) Female, 64 years old; died April, 1971 : pulmonary embolism

Tissue	$\delta^{14}C(\%)$	$\delta^{13}C(^{o}/_{oo})$	$\Delta(\%)$
Muscle	48.43 ± 0.99	-24.11	48.17 ± 0.99
Brain	49.15 ± 0.94	-24.86	49.11 ± 0.94
Fat	46.89 ± 1.23	-24.90	46.86 ± 1.23
Heart	42.47 ± 1.44	(-21.70)	41.53 ± 1.48
Kidney	50.30 ± 0.99	-22.42	49.52 ± 0.99
Spleen	46.44 ± 1.22	-22.11	45.59 ± 1.21
Ovaries	48.22 ± 1.43	(-22.46)	47.47 ± 1.45

(iv) Male, 39 years old; died August, 1971 : coronary artery disease

Tissue	$\delta^{14}C(\%)$	$\delta^{13}C(^{o}/_{oo})$	$\Delta(\%)$
Liver	42.97 ± 1.18	(-22.53)	42.26 ± 1.21
Brain	49.31 ± 0.88	-21.09	48.14 ± 0.88
Spleen	39.50 ± 0.97	(-21.70)	38.58 ± 1.00
Thyroid	38.58 ± 1.50	(-22.46)	37.88 ± 1.52
Pancreas	46.10 ± 1.16	(-24.65)	46.00 ± 1.20
Heart	40.83 ± 1.21	-21.24	39.77 ± 1.21

(v) Male, 42 years old; died September, 1971 : rheumatic heart disease

Tissue	$\delta^{14}C(\%)$	$\delta^{13}C(^{o}/_{oo})$	$\Delta(\%)$
Heart	52.30 ± 1.50	(-21.60)	51.26 ± 1.52
Kidney	34.54 ± 0.88	(-22.58)	33.89 ± 0.92
Liver	48.47 ± 0.91	(-22.53)	47.74 ± 0.95
Brain	52.73 ± 1.00	(-22.42)	51.94 ± 1.04
Lung	38.48 ± 0.99	(-22.47)	37.78 ± 1.02
Thyroid	44.45 ± 0.92	-21.10	43.32 ± 0.92
Spleen	44.40 ± 2.51	(-21.70)	43.45 ± 2.51

(vi) Male, 21 years old; died September, 1971: road traffic accident

Tissue	$\delta^{14}C(\%)$	$\delta^{13}C(^{o}/_{oo})$	$\Delta(\%)$
Heart	43.32 ± 1.36	(-21.60)	42.35 ± 1.38
Spleen	46.85 ± 0.80	-22.13	46.01 ± 0.80
Liver	55.06 ± 0.89	-23.34	54.55 ± 0.89
Thyroid	44.18 ± 1.53	(-22.10)	43.34 ± 1.55
Kidney	51.98 ± 1.62	(-22.58)	51.24 ± 1.64
Testes	56.38 ± 1.28	(-23.71)	55.98 ± 1.32
Lung	54.66 ± 1.60	(-22.47)	53.88 ± 1.62
Muscle	56.83 ± 1.27	-21.99	55.89 ± 1.27
Pancreas	52.30 ± 1.12	-24.74	52.22 ± 1.12

(vii) Female, 21 years old; died September, 1971: sudden (acute diabetes)

Tissue	$\delta^{14}C(\%)$	$\delta^{13}C(^{o}/_{oo})$	$\Delta(\%)$
Kidney	53.02 ± 1.18	-25.26	53.10 ± 1.18
Muscle	52.43 ± 1.28	(-22.46)	51.66 ± 1.31
Spleen	55.24 ± 1.58	-23.50	54.77 ± 1.58
Heart	55.58 ± 1.31	-21.38	54.45 ± 1.31
Liver	55.50 ± 1.04	-24.02	55.20 ± 1.04
Lung	51.85 ± 1.10	-22.45	51.08 ± 1.10
Pancreas	55.17 ± 1.07	-23.28	54.64 ± 1.07
Thyroid	51.57 ± 1.11	-22.10	50.69 ± 1.11
Brain	53.07 ± 1.10	-22.37	52.26 ± 1.10
Ovaries	51. 3 ± 1.96	(-22.46)	50.56 ± 1.96

(viii) Male, 5 years old; died October, 1971: road traffic accident

Tissue	$\delta^{14}C$(‰)	$\delta^{13}C$(‰)	Δ(‰)
Muscle	53.49 ± 1.04	-21.71	52.48 ± 1.04
Kidney	51.16 ± 1.43	(-22.58)	50.43 ± 1.45
Spleen	45.84 ± 0.77	(-21.70)	44.88 ± 0.82
Brain	51.70 ± 0.91	-21.09	50.51 ± 0.91
Pancreas	53.57 ± 1.11	-24.65	53.46 ± 1.15
Liver	53.42 ± 0.85	-22.83	52.75 ± 0.85

(ix) Male, 37 years old; died April, 1972: cardiac failure

Tissue	$\delta^{14}C$(‰)	$\delta^{13}C$(‰)	Δ(‰)
Testis	50.20 ± 1.76	-23.51	49.75 ± 1.76
Liver	49.13 ± 0.90	-22.51	48.39 ± 0.90
Heart	48.65 ± 1.04	-20.36	47.27 ± 1.04

(b) Whole tissue; protein, lipid fraction

In most cases, there was insufficient material from a lipid extraction for its ^{14}C analysis and only the protein fraction was carried through to its activity measurement. Included in this section are the 3 samples which were pretreated (i.e. protein extraction) in ^{14}C-solvent.

(i) Male, 67 years old; died January, 1973: cardiac failure

	Tissue	$\delta^{14}C$(‰)	$\delta^{13}C$(‰)	Δ(‰)
	Kidney (W)	47.53 ± 0.84	-21.78	46.58 ± 0.84
*	Kidney (P)	49.77 ± 0.91	-20.54	48.46 ± 0.91
	Heart (W)	47.71 ± 0.84	-21.89	46.79 ± 0.84
*	Heart (L)	51.21 ± 0.84	-24.58	51.08 ± 0.8
*	Heart (P)	46.38 ± 0.83	-21.80	45.44 ± 0.83

(i) Male, 67 years old (continued)

Tissue	$\delta^{14}C(‰)$	$\delta^{13}C(°/oo)$	Δ (‰)
Liver (W)	50.21 ± 0.84	-22.40	49.43 ± 0.84
Liver (P)	50.17 ± 0.91	(-22.53)	49.43 ± 0.95
Liver (L)	49.43 ± 1.21	(-22.53)	48.69 ± 1.24

(* = ^{14}C solvent used) W = whole tissue; P = protein; L = lipid

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(ii) Female, 87 years old; died January, 1973 : cardiac failure

Tissue	$\delta^{14}C(‰)$	$\delta^{13}C(°/oo)$	Δ (‰)
Liver (W)	48.76 ± 0.86	-22.36	47.97 ± 0.86
Liver (P)	50.42 ± 0.98	-20.66	49.11 ± 0.98
Kidney (W)	47.31 ± 0.86	-21.34	46.23 ± 0.87
Kidney (P)	49.19 ± 0.80	-20.55	47.86 ± 0.80
Spleen (P)	52.41 ± 0.91	-20.83	51.14 ± 0.91

(iii) Male, 64 years old; died November, 1972 : cardiac failure

Tissue	$\delta^{14}C(‰)$	$\delta^{13}C(°/oo)$	Δ (‰)
Kidney (W)	47.58 ± 0.90	-20.84	46.28 ± 0.90
Kidney (P)	49.44 ± 1.00	-21.48	48.39 ± 1.00
Liver (W)	48.58 ± 0.84	-21.26	47.47 ± 0.84
Liver (P)	49.93 ± 0.93	-20.91	48.70 ± 0.93
Liver (L)	47.24 ± 1.14	-24.99	47.24 ± 1.14
Spleen (W)	44.10 ± 0.90	(-21.70)	43.15 ± 0.95
Spleen (P)	44.03 ± 0.92	-20.51	42.75 ± 0.92
Lung (W)	44.83 ± 1.20	-22.19	44.01 ± 1.20
Lung (P)	47.29 ± 2.21	(-22.47)	46.54 ± 2.21
Heart (P)	42.17 ± 0.90	-20.36	40.85 ± 0.90

(iv) Male, 61 years old; died October, 1972 : carcenoma of the lung

Tissue	$\delta^{14}C(\%)$	$\delta^{13}C(‰)$	$\Delta(\%)$
Heart (W)	51.05 ± 0.77	-22.78	50.38 ± 0.77
Heart (P)	46.04 ± 0.97	-21.13	44.91 ± 0.97
Kidney (W)	46.54 ± 0.84	-20.84	45.32 ± 0.84
Kidney (P)	44.39 ± 0.97	(-22.58)	43.69 ± 1.02
Spleen (W)	44.28 ± 0.90	-22.02	43.42 ± 0.90
Spleen (P)	47.47 ± 0.97	-20.84	46.24 ± 0.97
Liver (W)	49.22 ± 0.91	(-22.53)	48.48 ± 0.95
Liver (P)	45.81 ± 1.06	-22.32	45.03 ± 1.06

(c) Tumour tissue

All individuals concerned in this section died from cancer of one of the particular tissues analysed. For the 66 year-old male, an undiseased portion of liver was compared with the diseased part, while the spleen from the 63 year-old male was 'healthy'.

Patient	Date of death	Tissue	$\delta^{14}C(\%)$	$\delta^{13}C(‰)$	$\Delta(\%)$
Male/66	March 1973	Liver (normal)	51.28 ± 0.92	-20.76	50.00 ± 0.92
		Liver (diseased)	55.99 ± 1.32	(-22.53)	55.22 ± 1.35
Male/63	February 1973	Spleen (normal)	52.03 ± 0.85	(-21.70)	51.03 ± 0.90
		Liver (diseased)	53.78 ± 1.21	(-22.53)	53.02 ± 1.24
Male/59	February 1973	Kidney (diseased)	49.37 ± 0.78	(-20.70)	48.09 ± 0.79

(d) Aortae samples

Ten aortae were received from the Department of Pathology, Louisiana State University, New Orleans; of these, 7 intimae were found to be contaminated by tracer levels of ^{14}C activity i.e. the measured ^{14}C activity levels were higher than the maximum atmospheric ^{14}C bomb-level and were assumed to be the result of an administered dose of ^{14}C, although it was not possible to substantiate this assumption. The modern sample of aorta, from which both the intima and adventitia were analysed for ^{14}C content, was obtained from the Western Infirmary, Glasgow.

Details of Patient	$\delta^{14}C(\%)$	$\delta^{13}C(‰)$	$\Delta(\%)$
Male/68, died 1963: Multiple atherosclerosis	5.84 ± 0.61	-20.24	4.83 ± 0.61
Male/67, died 1964: Thyroid carcenoma	10.70 ± 0.88	(-20.26)	9.65 ± 0.91
Male/69, died 1964: Coronary occlusion	18.92 ± 0.82	-20.61	17.88 ± 0.82
Female/86, died June 1973: Myocardial infarction			
intima	47.45 ± 0.90	-23.95	47.14 ± 0.90
adventitia	32.65 ± 0.83	-21.08	31.61 ± 0.83

3.2 Dietary samples

(i) Marine origin : obtained fresh - March, 1973 except salmon which was tinned

Sample	$\delta^{14}C$(%)	$\delta^{13}C$(‰)	Δ(%)
Herring	14.10 ± 0.83	-19.73	12.90 ± 0.83
Whiting	17.59 ± 0.83	-17.30	15.78 ± 0.83
Smoked Herring	14.30 ± 0.90	-19.38	13.02 ± 0.90
Cod	14.57 ± 0.97	-17.75	12.91 ± 0.97
Plaice	28.96 ± 0.84	-15.29	26.46 ± 0.84
Haddock	18.20 ± 0.83	-18.34	16.63 ± 0.83
Salmon	14.88 ± 0.69	-22.11	14.22 ± 0.69

(ii) Meat: obtained fresh - January, 1972. Protein and lipid fractions were also analysed for ^{14}C content.

Sample	$\delta^{14}C$(%)	$\delta^{13}C$(‰)	Δ(%)
Lamb's heart - whole	44.38 ± 0.97	-28.29	45.33 ± 0.98
lipids	49.35 ± 1.10	-31.13	51.18 ± 1.11
protein	46.44 ± 1.07	-25.50	46.59 ± 1.07
Lamb's kidney - whole	54.49 ± 2.43	-29.94	56.02 ± 2.47
lipids	50.72 ± 1.23	-25.85	50.98 ± 1.23
protein	59.54 ± 1.28	-24.99	59.54 ± 1.28
Cow's liver - whole	43.80 ± 1.04	-26.50	44.23 ± 1.04
lipids	60.02 ± 0.99	-28.74	61.22 ± 1.00
protein	47.90 ± 1.09	-24.81	47.62 ± 1.09

3.3 Atmospheric ^{14}C activity

(i) Lerwick

Date of exposure	$\delta^{14}C(\%)$	$\delta^{13}C(‰)$	$\Delta(\%)$
April, 1970	53.02 ± 1.27	-15.26	50.04 ± 1.27
May, 1970	51.03 ± 0.85	-15.32	48.11 ± 0.85
June, 1970	45.85 ± 1.26	-14.99	42.93 ± 1.26
July, 1970	62.81 ± 1.12	-15.11	59.59 ± 1.12
November, 1970	55.56 ± 1.12	-17.55	53.24 ± 1.12
March, 1971	54.25 ± 1.00	-16.81	51.72 ± 1.00
June, 1971	58.08 ± 1.01	-18.78	56.11 ± 1.01
July, 1971	53.26 ± 1.22	-18.30	51.21 ± 1.22
September, 1971	54.40 ± 1.15	-19.38	52.66 ± 1.15
April/May, 1972	49.30 ± 0.84	(-16.21)	46.68 ± 0.84
July, 1972	51.84 ± 0.77	-14.78	48.74 ± 0.77
October/November 1972	46.74 ± 0.83	-16.01	44.10 ± 0.83
February, 1973	44.81 ± 0.83	-16.09	42.23 ± 0.83
May, 1973	45.67 ± 0.97	(-16.21)	43.11 ± 0.97

(ii) Cwm Dyli

Date of exposure	$\delta^{14}C(\%)$	$\delta^{13}C(‰)$	$\Delta(\%)$
May, 1970	49.41 ± 1.04	-16.24	46.79 ± 1.04
November, 1970	62.46 ± 1.06	-16.44	59.68 ± 1.06
March, 1971	51.48 ± 1.00	-17.23	49.13 ± 1.00
April, 1971	52.01 ± 0.92	-17.38	49.69 ± 0.92
June, 1971	53.30 ± 1.00	-15.43	50.37 ±1.00
July, 1971	55.80 ± 1.15	-14.18	52.43 ± 1.15

(ii) Cwm Dyli (continued)

Date of exposure	^{14}C(%)	^{13}C(°/oo)	(%)
September, 1971	51.58 ± 0.87	(-16.02)	48.86 ± 0.91
December, 1972	44.92 ± 0.83	-15.81	42.26 ± 0.83
March, 1973	45.45 ± 0.90	(-16.02)	42.84 ± 0.93
June, 1973	47.10 ± 0.90	(-16.02)	44.46 ± 0.93

(iii) Harwell

Date of exposure	^{14}C(%)	^{13}C(°/oo)	(%)
March, 1971	47.16 ± 0.99	-20.76	45.91 ± 0.99
June, 1971	63.34 ± 1.02	-18.73	61.29 ± 1.02
September, 1971	58.41 ± 0.78	-19.83	56.77 ± 0.78
August/September, 1972	57.75 ± 0.91	-20.42	56.31 ± 0.91
January, 1973	46.88 ± 0.83	-21.76	45.93 ± 0.83
May, 1973	46.10 ± 0.83	(-20.69)	44.84 ± 0.87

CHAPTER 4. DISCUSSION OF ^{14}C DATA.

4.1 Preliminary observations

(a) Tissue Δresults The large number of tissue ^{14}C activity measurements permits the assessment of a representative range of Δ values for each tissue and consequently facilitates the recognition of atypical results. A prominent feature of the tissue ^{14}C data is the variation, outwith the statistical error of measurement, of Δvalues for the tissues of any individual. These "internal" differences vary from approximately a 4.5% minimum, Table 3.1 (a) (vii), to an 18% maximum, Table 3.1 (a) (v). Excluded from this comparison for separate consideration is the Δ value of the bone collagen sample, Table 3.1 (a) (ii), since simple interpretation of this result suggests a significant difference between the turnover rates of carbon in bone collagen and in other tissues.

Tropospheric ^{14}C is transferred to animal and human tissues via assimilation of atmospheric CO_2 by plants and subsequently through the food chain; thus comparison of the ^{14}C content of tropospheric CO_2 and human tissue carbon gives an approximate estimate of the relative rates of turnover of carbon in different tissues. In the case of the collagen sample therefore, the Δvalue is significantly lower than any atmospheric ^{14}C concentration since 1958, and is indicative of a rate of carbon turnover slower than in any other tissue sampled. This conclusion is in agreement with the results of ^{14}C activity measurement of collagen performed at other laboratories (Libby et al. 1964, Berger and Libby 1966, ibid. 1967). By similar consideration, 2 tissues with particularly low Δvalues, viz.:

testis, Table 3.1 (a) (ii), $\Delta = 37.75 \pm 1.01\%$

kidney, Table 3.1 (a) (v), $\Delta = 33.89 \pm 0.92\%$

appear to reflect a comparatively slow carbon turnover rate.

Preliminary consideration of the internal variations in ^{14}C concentrations leads to 3 possible reasons for scatter:

(1) different rates of turnover of carbon in different tissues. Variations in ^{14}C content of tissues within any one individual may indeed reflect different residence times of body carbon, a possibility which is discussed subsequently in detail. The Δ results indicate that these variations are not consistent throughout the whole series of human tissue ^{14}C activity measurement. Table 4.1 allows comparison of the Δ values of the 6 tissues most frequently analysed in all individuals; thus the ^{14}C content of heart and spleen are highest in the 21 year-old female, but lowest in the 39 year-old male. While such a direct comparison between individuals of different age is not necessarily valid, it is hoped that any future treatment of this data may account for such deviations.

(2) different composition of tissues with respect to protein/lipid content. The relative amount of lipid carbon in tissues, with the exception of brain white matter (30% protein, 60% lipid), is much smaller than that of protein carbon. Thus variable lipid concentration in different tissues could produce variations in composite values (i.e. whole tissue), but only if the turnover of lipid carbon differs appreciably from that of protein carbon. However, comparison of the ^{14}C content of protein and lipid fractions with those of the corresponding whole tissue, Tables 3.1(b), does not support this possibility. Moreover, the ^{14}C content of a collective sample of adipose tissue, Table 3.1(a) (iii) — expected to be less mobile than internal lipid —is of the same order of magnitude as those of other tissues. Thus it seems unlikely that inhomogeneity of lipid

TABLE 4.1 COMPARISON OF Δ RESULTS OF THE MAJOR TISSUES ANALYSED

TISSUE	Δ							
	M/50	M/72	F/64	M/39	M/42	M/21	F/21	M/5
Heart	52.3	50.7	41.5	39.8	51.3	42.4	54.5	(-)
Kidney	44.6	55.2	49.5	(-)	33.9	51.2	53.1	50.4
Liver	43.3	53.2	(-)	42.3	47.7	54.6	55.2	52.8
Muscle	50.2	51.9	48.2	(-)	(-)	55.9	51.7	52.5
Brain	(-)	50.4	49.1	48.1	51.9	(-)	52.3	50.5
Spleen	(-)	51.5	45.6	38.6	43.5	46.0	54.8	44.9
Range of values	9%	~5%	8%	9.5%	~18%	13.5%	~3%	~8%
Mean	47.6	52.2	46.8	42.2	48.6	50.0	53.6	50.6

(-): ^{14}C activity measurement not performed

Values quoted to 1st decimal place without statistical error.

distribution is the major factor responsible for the variation of values of the tissues of any one individual.

(3) different rates of turnover of carbon within a single tissue i.e. the rate of turnover of carbon in different parts of the same tissue may vary. Thus for example, the organic carbon of surface layers of a tissue may turn over at a relatively fast rate compared to carbon present in the inner sections of that tissue. While this possibility may exist, its influence on ^{14}C activity measurement would, in effect, represent a sampling problem. The method of sample selection (cross-sectional dissection) was, however, consistently maintained; since, in addition, samples were efficiently homogenised during pretreatment, the resultant ^{14}C data should be negligibly influenced by variations of this nature.

Thus of the 3 possibilities, (1) is most likely to produce the observed differences in Δ values. Consequently, in the future treatment of these data, it will be assumed that the rate of carbon turnover in different organs of the body can vary.

Initial inspection of the ^{14}C data of cancered tissues reveals no significant variation of Δ values from those of normal, healthy material. In contrast, the relatively low ^{14}C concentrations obtained in analyses of the arterial lipid extracts compared with the high tropospheric ^{14}C activities of the corresponding time period (1963-1964) indicate a turnover rate of this material of the same magnitude as that of bone collagen. A more detailed treatment of past and present ^{14}C data of arteries is necessary here, however, rather than a direct comparison of Δ values which is complicated by the fact that present day tropospheric ^{14}C activities are considerably different from those of the earlier decade.

(b) Environmental ^{14}C data In general, the ^{14}C content of the dietary

samples analysed reflects the environment in which these foodstuffs originated. Thus ^{14}C concentrations of fish may be compared to the surface ocean ^{14}C activity (northern hemisphere, Fig. 4.1) while the ^{14}C activities of meat products are compared with the tropospheric ^{14}C concentrations of the same time period.

With respect to atmospheric activities, variations, both with time and location, are apparent in the ^{14}C measurements performed in this study. The general trend, however, evaluated from all 3 sampling stations, indicates an average decrease in ^{14}C concentration of 2% per year. This decrease is still subject to short-term fluctuations which may be attributed to the continued release of ^{14}C as a result of nuclear weapon tests; while the majority of these explosions since 1970 have been in the low-yield category, (~20 Ktons), there have been 5 high-yield explosions (Table 1.2), one of which occurred in the northern hemisphere. The time at which each explosion took place is included in Fig. 4.1; thus the enhanced exchange, in late spring, of CO_2 between stratosphere and troposphere (Fairhall and Young 1970) is still in evidence, responsible for the ^{14}C concentration maxima observed in the troposphere during the summer months of the last 3 years. While the reason for the variation in atmospheric ^{14}C activity with location is less apparent, the results stress the need for a representative sampling programme which involves more than one station; however, there is no evidence of any major leakage of ^{14}C at the nuclear reactor site at Harwell.

The variations observed in both tissue and atmospheric ^{14}C content justify the relatively large number of measurements performed in these areas of sampling. While comparison of tissue and atmospheric ^{14}C concentrations is suitable for simple qualitative treatment of the data, a more complex approach is necessary to quantify Δ values in terms of residence times of

FIG. 4.1 ENVIRONMENTAL ^{14}C LEVELS.

The curves shown on the opposite page are constructed from data quoted in the reference sources below:

Tropospheric CO_2 - N. Hemisphere

Münnich and Vogel (1958)
Nydal (1966)
Thommeret and Thommeret (1966)
Berger and Libby (1967)
Münnich and Roether (1967)
Nydal (1967)
Stenberg and Olsson (1967)
Nydal (1968)
Young and Fairhall (1968)
Ergin et al. (1970)
Ergin et al. (1972)
Gulliksen and Nydal (1972)

Tropospheric CO_2 - S. Hemisphere

Rafter (1965)
Rafter and O'Brien (1970)
Rafter and O'Brien (1972)

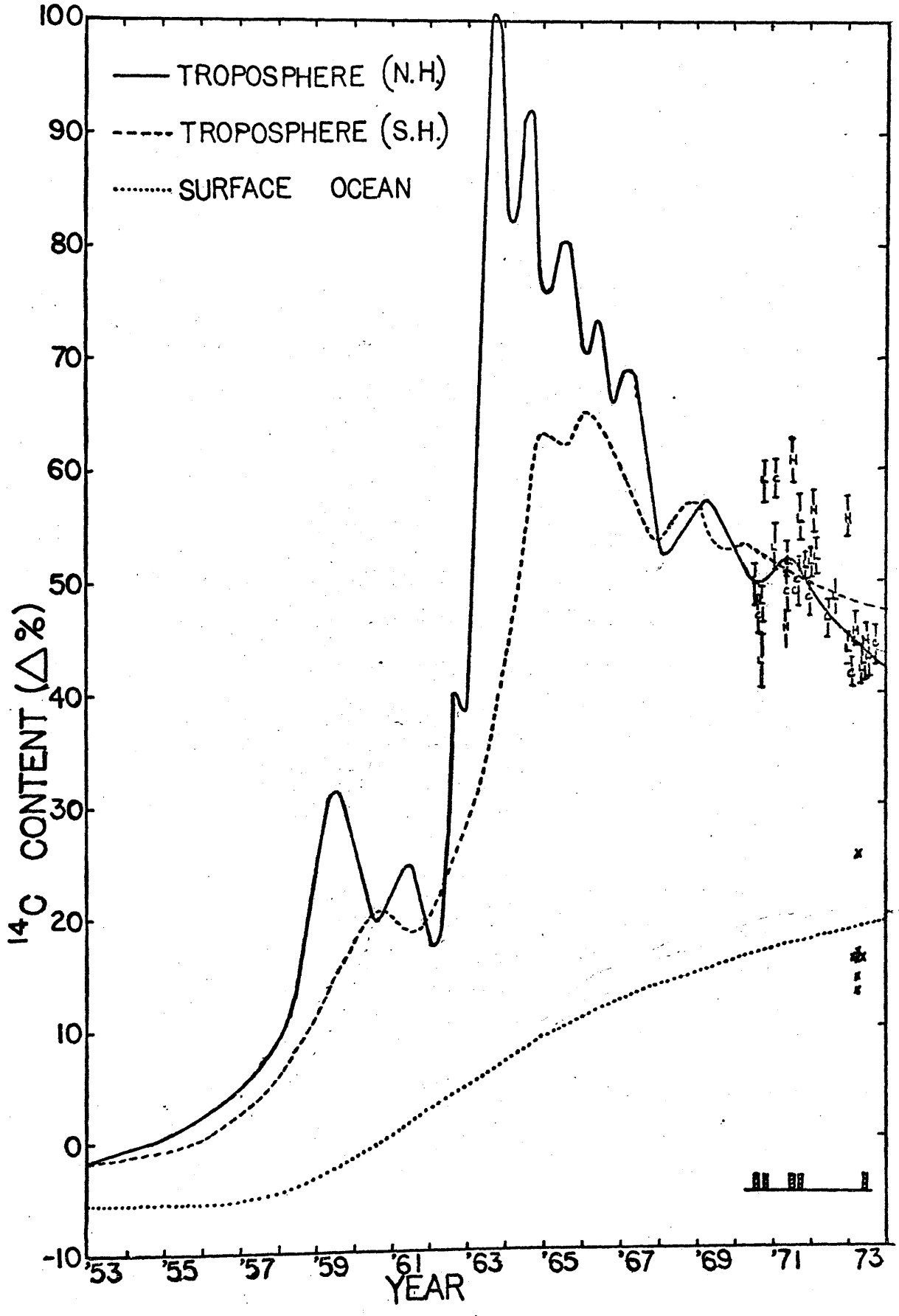
Surface Ocean CO_2

Broecker and Olson (1961)
Nydal (1967)
Bien and Suess (1967)
Young and Fairhall (1968)
Rafter and O'Brien (1970)
Rafter and O'Brien (1972)

This work: H = Harwell, L = Lerwick, C = Cwm Dyli } Tropospheric CO_2

x = fish samples

A = High yield nuclear weapon tests (> 1Mton).


TROPOSPHERE (N.H.)
TROPOSPHERE (S.H.)
SURFACE OCEAN
^{14}C CONTENT (Δ %)
100
90
80
70
60
50
40
30
20
10
0
-10
'53
'55
'57
'59
'61
'63
'65
'67
'69
'71
73
YEAR

carbon in tissues.

4.2 Basis for Theoretical Model of Carbon Turnover in Human Tissues

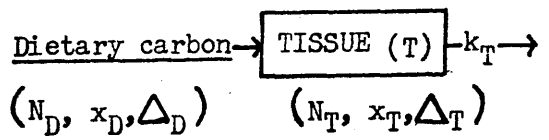
The distribution and transport of bomb-produced ^{14}C throughout the dynamic carbon cycle has been evaluated by several workers (Chapter 1) with the aid of box-model calculations similar to those described in 1.5. Many of these models contain at least 6 boxes (Plesset and Latter 1960, Nydal 1967) and are necessarily complex because of the marked disequilibrium in world-wide ^{14}C concentrations soon after the major testing of nuclear weapons in 1961-1962. In many cases, the biosphere is not considered as an independent reservoir but instead is combined with the larger reservoirs of either the surface ocean (Nydal 1967) or the troposphere/atmosphere (Nydal et al. 1971); this assumption is possible since the relatively small volume of the biospheric reservoir has a negligible effect on the other reservoirs of the box-model. From similar considerations, in any model designed to investigate the kinetics of carbon exchange within a section of the biosphere, inclusion of the considerably larger reservoirs will have a masking effect on the specific objective - determination of the rate of carbon turnover in human tissues. This latter situation is therefore more constructively described via simpler theoretical models, especially since the marked disequilibrium of world-wide ^{14}C concentrations no longer exists. For such a model to be relevant, consideration must be given to those parts of the dynamic carbon cycle which are closely associated with the transfer of carbon in humans. Provided that adequate data are then available to support the box-model calculations, the desired solution is possible.

For these reasons, a single compartment model is considered appropriate for the treatment of tissue carbon turnover. This system incorporates as the reservoir tissue carbon with an input of dietary carbon, since essentially 100% of carbon in the human body is ultimately derived from food

consumption. It is apparent that such a model, in which transfer of carbon from the diet to each tissue is considered to be a process independent of other tissues, certainly simplifies the true state of metabolism in the body. Thus it is well established that a state of "dynamic equilibrium" exists whereby protein, carbohydrate, and lipid components of the body may be synthesised from any one or more of the corresponding fractions present in the diet or even in a tissue itself via numerous metabolic pathways. In this situation, first postulated by Schoenheimer (1942), cellular protein is in constant exchange with the immediate environment i.e. plasma protein, irrespective of whether or not the cells of a given tissue divide. This rapid interchange of dietary and cellular amino acids was revealed using ^{15}N-labelled amino acids. The results obtained from such a single compartment model treatment therefore must be interpreted carefully within the theoretical confines of the model.

4.3 Single Compartment Model for Carbon Turnover in Tissues

4.3.1 Basic model The following diagram illustrates a single compartment system similar to that defined by Shipley and Clark (1972):



Definition of terms:

Let N_D^i = the no. of dietary carbon atoms transferred to any tissue in time 'i'

x_D^i = the $^{14}C/_{12}C$ ratio of the diet, averaged over period 'i'

$\therefore N_D^i . x_D^i$ = the no. of ^{14}C atoms transferred to that tissue in time 'i'

where 'i' is a suitable small increment of time.

Similarly,

N_T^i = the no. of tissue carbon atoms at time 'i'

x_T^i = the $^{14}C/_{12_C}$ activity of a tissue at time 'i'

k_T = the first order rate constant for turnover of tissue carbon, defined by the equation $-\frac{dN_T}{dt} = N_T^o k_T^i$

where N_T^o = the original no. of tissue carbon atoms.

Consider the carbon content of a tissue after the small increment of time 'i' i.e. at time 't+i', where 't' is the initial time:

$$N_T^{t+i} = N_T^i + N_D^{t+i} - N_T^i(1 - e^{-k_T i})$$

where N_T^{t+i} = the no. of tissue carbon atoms at time 't+i'

N_T^t = the no. of tissue carbon atoms at time 't'.

In this form,

N_D^{t+i} = the no. of dietary carbon atoms transferred to a tissue in time 'i', while

$N_T^t(1 - e^{-k_T i})$ = the no. of tissue carbon atoms at time 't' which have been removed via turnover in time 'i'

i.e. N_D^{t+i} and $N_T^t(1 - e^{-k_T i})$ are the input to and output from a tissue respectively. With regard to the ^{14}C balance, the equation is:

$$N_T^{t+i} x_T^{t+i} = N_T^t x_T^t + N_D^{t+i} x_D^{t+i} - N_T^t x_T^t(1 - e^{-k_T i}) \quad \text{------ (A)}$$

In this case x_D is the mean $^{14}C/_{12_C}$ activity of the diet over time period 'i'. The rate constant k_T applies strictly to the kinetics of ^{12}C exchange but may also be used for ^{14}C atom transfer provided that isotope effects in the carbon exchange processes of this model are included in the evaluation of 'x' values i.e. the 'x' values must be corrected for isotopic fractionation. Subsequently, 'x' values will be shown to be directly related to Δ values and therefore this condition is fulfilled.

For a fully grown tissue at time 't', $N_T^{t+i} = N_T^t$

$\therefore$ the stationary state applies and

$$N_D^{t+i} = N_T^t(1 - e^{-k_T i})$$

Substitution for N_D^{t+i} in equation (A) gives the following equation:

$$N_T^{t+i} x_T^{t+i} = N_T^t x_T^t + N_T^t(1 - e^{-k_T i}) x_D^{t+i} - N_T^t x_T^t (1 - e^{-k_T i})$$

Dividing through by N_T^{t+i}, $= N_T^t$:

$$x_T^{t+i} = x_T^t + (1 - e^{-k_T i})(x_D^{t+i} - x_T^t)$$

For the general case,

$$x_T^{t+ni} = x_T^t + \sum_{n=1}^{n}(1 - e^{-k_T i})\left\{x_D^{t+ni} - x_T^{t+(n-1)i}\right\}$$

or, $$x_T^{ni} = x_T^o + \sum_{n=1}^{n}(1 - e^{-k_T i})\left\{x_D^{ni} - x_T^{(n-1)i}\right\}$$

where, initially $x_T^t = x_T^o = x_T^{(n-1)}$ when n=1

If the initial time is taken at a period prior to the effect of nuclear weapon tests, x_T^{ni} shows the build-up of bomb ^{14}C in human tissues.

Finally, since

$$x_{sample} = {}^{14}C/_{12}C \text{ sample}$$

$$\Delta_{sample} = \left[\frac{x_{sample}}{x_{standard}} - 1\right] . 100\%$$

$$\therefore x_{sample} = \left[\frac{\Delta_{sample}}{100} + 1\right] . x_{standard}$$

$x_{standard}$ = $^{14}C/_{12}C$ activity of the modern oxalic acid standard

= constant (see 2.6.2)

Thus Δ values may be substituted directly for 'x' values, and the final equation becomes:

$$\Delta_T^{ni} = \Delta_T^{o} + \sum_{n=1}^{n}\left\{(1 - e^{-k_T i})\left[\Delta_D^{ni} - \Delta_T^{(n-1)i}\right]\right\} \text{- - - - (4.1)}$$

For a given residence time of tissue τ_T ($= 1/k_T$) and with 'i' a fixed, small increment of time, $(1 - e^{-k_T i})$ is constant and the ^{14}C concentration in a tissue is found to be dependent on the cumulative difference between the ^{14}C activity of the tissue and the mean ^{14}C activity of dietary carbon over the subsequent time period. Δ_T^{o}, the original ^{14}C content of a fully grown tissue, is taken as the ^{14}C concentration of that tissue in 1953. Provided that Δ_D^{ni} values are known for each increment of time 'i' since 1953, each Δ_T^{ni} value may be calculated and substituted as $\Delta_T^{(n-1)i}$ in equation 4.1 to obtain the subsequent Δ_T term.

Comments on the validity of the model Several comments are justified:

(a) the final equation 4.1 is representative of a system in which ^{14}C activities change by increments rather than in a continuous manner. This approach is somewhat necessitated by the periodic nature of atmospheric and biospheric sampling. However, provided that the time period 'i' is relatively small compared to the residence time of tissue carbon, τ_T, the model tends towards a continuous system. Thus for this work, a value of 'i' of 6 months is considered appropriate.

(b) the model and the derivation of equation 4.1 make no allowance for a change in carbon residence time during the mature lifetime of any tissue. However, this fact may be used to advantage, when τ_T values of the same tissue but in individuals of different age are compared.

(c) similar models may be constructed in which the input to the tissue reservoir - i.e. dietary carbon - is substituted by either (i) the

atmospheric CO_2, or (ii) blood plasma carbon. The former case is oversimplified, however, in its assumption of a direct relationship between the ^{14}C concentrations in atmospheric and tissue carbon. Thus a model similar to (i) was proposed by Jansen (1972) but he points out that corrections are necessary before this model can be realistically applied to the evaluation of residence times of human tissue carbon. Harkness and Walton (1969) stress the need to acknowledge the contribution to the diet made by food of marine origin, a source in which the ^{14}C activity is considerably below that of the atmosphere. In case (ii) - blood plasma input - a detailed knowledge of ^{14}C activities of blood plasma is required. Comment on this latter model is reserved for discussion in 4.4.1.

(d) Δ_T^o is defined as the ^{14}C content of a tissue prior to the effect of nuclear weapon tests, and is taken as the ^{14}C concentration of a tissue in 1953. In this case $\Delta_T^o < 0$ due to the Suess effect; thus a more appropriate value of -2.5% is employed to account for the latter effect.

4.3.2 Special treatments of the single compartment model

(A) Growth of tissue In the derivation of equation (1), the assumption of steady-state conditions was applied i.e. that input of carbon equals output of carbon, since the tissues considered in such a treatment are fully grown. In the situation where tissues are in a state of growth, however, this equality is not valid and a modified approach to that used in 4.3.1 is therefore necessary. Use is made here of the general shape of growth curve obtained for the majority of body tissues; this curve, to a first approximation, may be considered as a combination of 2 linear portions of growth. The first linear increase in tissue size

occurs until the age of 11 years when the majority of tissues attain about 50 % of their mature weight; the latter increase occurs until 20 years of age. Thus each of the two periods of growth is described by the following equation:

$$N_T^{ni} = N_T^o + n(N_T^i - N_T^o) \quad \text{where n is an integer.}$$

N_T^o in this case represents the number of tissue carbon atoms prior to each period of linear growth i.e. at birth and at 11 years of age. The equations for carbon transfer are similar to those of the basic model apart from the condition of stationary state; thus for the ^{14}C budget,

$$N_T^i \Delta_T^i = N_T^o \Delta_T^o - N_T^o \Delta_T^o (1 - e^{-k_T i}) + N_D^i \Delta_D^i \quad ---- (B)$$

Here, $$N_D^i = (N_T^i - N_T^o) + N_T^o (1 - e^{-k_T i})$$

and, for the general case,

$$N_D^{ni} = \left[N_T^{ni} - N_T^{(n-1)i} \right] + N_T^{(n-1)i} (1 - e^{-k_T i})$$

$\left[N_T^{ni} - N_T^{(n-1)i} \right]$ represents the net increase in carbon atoms of a tissue in time 'i' and is constant for each increment of linear growth. Substitution for N_D^i in the above equation (B) gives:

$$\Delta_T^i = \frac{N_T^o}{N_T^i} \Delta_T^o - \frac{N_T^o (1 - e^{-k_T i})}{N_T^i} \Delta_T^o + \frac{(N_T^i - N_T^o)}{N_T^i} \Delta_D^i + \frac{N_T^o (1 - e^{-k_T i})}{N_T^i} \Delta_D^i$$

The above equation may be adjusted to give the following:

$$\Delta_T^i = \Delta_T^o - \Delta_T^o + \frac{N_T^o}{N_T^i} \Delta_T^o + \frac{(N_T^i - N_T^o)}{N_T^i} \Delta_D^i + \frac{N_T^o (1 - e^{-k_T i})}{N_T^i} (\Delta_D^i - \Delta_T^o)$$

which reduces to:

$$\Delta_T^i = \Delta_T^o + \frac{(N_T^i - N_T^o) + N_T^o (1 - e^{-k_T i})}{N_T^i} (\Delta_D^i - \Delta_T^o)$$

For the general case, the final equation becomes:

$$\Delta_T^{ni} = \Delta_T^{o} + \sum_{n=1}^{n} \left\{ \frac{N_T^{ni} - N_T^{(n-1)i} + N_T^{(n-1)i}(1 - e^{-k_T i})}{N_T^{ni}} \right\} \left[\Delta_D^{ni} - \Delta_T^{(n-1)i} \right] \quad \text{------ (4.2)}$$

The N_T^o value employed in the derivation of this equation is not based on the true number of carbon atoms at birth but on the quantity predicted by the assumed linear relationship. The latter number is obtained as a fraction of the mature tissue; under these conditions, therefore, the 6-monthly increment in tissue size is $0.015N_T^{40i}$ for the first 11 years of growth, and $0.025N_T^{40i}$ for the next 9 years.

The previous treatment of tissue growth pertains to the majority of organs in the body, with the exceptions of neural and reproductive tissues. In the former case, the growth curve indicates a rapid period of growth during the initial 5 years of childhood after which time the brain is approximately 90% of its mature size. Thus the stationary state model is applied to brain. On the other hand, reproductive tissue remains at about 10% of its mature size until the age of 15; thereafter the remaining 5 years' growth follows a linear pattern. In this situation, model equation 4.1 is used to determine Δ_T values at the end of the 15-year period according to different γ values; this data, in turn, is used as 'Δ_T^o' in model equation 4.2, applied to a 5-year linear growth increase. Similarly for cancered tissues, a short-term increase in size (over 5 years) is considered to be more applicable than the mature tissue model. 'Δ_T^o' values in this case are obtained from the appropriate Δ_T data of normal tissue.

(B) Accumulation of arterial lipid deposit Atherosclerosis, or 'hardening of the arteries', is a common illness in man, while its pathogenesis has consistently eluded medical researchers. In this disease, there is

an abnormal deposition of cholesterol and other lipids with progressive hardening of arteries due to calcification. The extreme effects of this disease result in arterial lesions, irregular blood clotting which leads to blockages of arteries, and ultimately in many cases, death. The exact machanism by which lipid is deposited in the vessel wall is still unknown, although many theories have been postulated. Thus Bowyer and Gresham (1970) discuss the mechanism of accumulation of lipids in terms of

(a) deposition of blood components, either soluble lipoprotein or formed cells

(b) "in situ" synthesis

(c) inadequate breakdown and clearance of lipid derived from either (a) or (b), and

(d) abnormal redistribution of lipid within the arterial wall during metabolism.

The studies of Newman and Zilversmit (1962) on the metabolism of arterial lipids indicate that in aortic lesions of rabbits fed on a high cholesterol diet, cholesterol and cholesteryl ester appear to accumulate at rapidly increasing rates and are derived primarily from the circulating blood; on the other hand, phospholipids which accumulate in the arterial wall appear to be derived from local synthesis. This latter finding is in contrast to that of Harper et al. (1953) who concluded from their extensive tracer studies, using ^{32}P, of phospholipid turnover rates in blood and tissue of animals, that the latter lipid component enters the blood almost exclusively from the liver. A rapid turnover of fatty acid between liver and tissue via blood plasma was also found. Table 4.2 shows the proportion of the various lipid fractions in the atherosclerotic lesion in comparison with those of blood serum (Weinhouse and Hirsch 1940). These figures suggest that the lipids deposited in the intima are the result of non-selective

TABLE 4.2 PROPORTION OF DIFFERENT LIPID FRACTIONS IN BLOOD PLASMA, INTIMA, AND AN ATHEROSCLEROTIC PLAQUE

LIPID	BLOOD PLASMA (%)	INTIMA (%)	EARLY PLAQUE (%)
Free cholesterol	14.1	14.2	16.2
Cholesteryl esters	38.3	38.6	38.5
Phospholipids	22.8	20.1	19.0
Neutral fat, etc.	23.3	27.1	26.3

from Weinhouse and Hirsch (1940)

infiltration and precipitation of the various lipids directly from the plasma. Other mechanisms to account for lipid accumulation have also been postulated (Hueper 1944, ibid. 1945, Hirsch and Weinhouse 1943). Thus an intense research effort has already been concentrated on atherosclerosis with experimental investigation normally confined to animals. Two major generalisations from the bulk of this work may be made:

(i) although atherosclerosis is not caused by any single effect, as a result of a combination of exogenous and endogenous factors, a diet of high-cholesterol, high-fat content is a major causal influence in the development of excess cholesterol levels and of atherosclerosis

(ii) the 'hardening' process is, within limits, a reversible lesion since substitution of a low-fat, low-cholesterol diet apparently results in reduction of the causal effects.

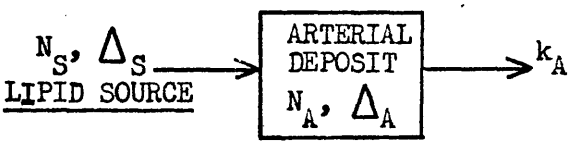
These findings are based on the results of experimental work involving animals but may be applicable to man himself. Similarities and differences between the disease in humans and in experimental animals have been recorded (Duff and McMillan 1951) although criticism may be levelled at the common use of the rabbit in the study of the disease (Katz and Stamler 1953) owing to the predominantly vegetarian diet of this animal.

Experimental investigation of atherosclerosis in humans is, however, restricted; diagnosis of the presence, let alone quantification of the extent, of the disease is virtually impossible except by post-mortem examination or from obvious clinical manifestations of major blockages in veins or arteries. Thus most research in this field is confined to

(a) population groups known by experience to have either high or low mortality rates attributable to atherosclerosis as shown by post-mortem evidence (Kimura 1956), and

(b) carefully controlled clinical investigation (Jolliffe et al. 1959).

On the basis of the previous considerations — in particular the extensive evidence accumulated which links diet to serum lipid levels and, as a secondary effect, to the prevalence and incidence of coronary atherosclerosis — the following single compartment model is proposed:



At present, the lipid source is unspecified and, as in special case (A), this system is non-stationary, the build-up of arterial lipids increasing with time. However, in this situation, at zero time there is no deposit; thus the initial amount of material after time 'i'

$$N_A^i = N_S^i$$

N is defined as before while A and S represent arterial deposit and lipid source respectively. Similarly the corresponding ^{14}C budget is:

after time 'i', $N_A^i \Delta_A^i = N_A^i \Delta_A^i$

and, after '2i', $N_A^{2i} \Delta_A^{2i} = N_A^i \Delta_A^i - N_A^i(1 - e^{-k_A i})\Delta_A^i + N_S^{2i} \Delta_S^{2i}$ ----- (C)

Numerous pathological findings (e.g. Eggen and Solberg 1968) indicate a linear incidence in the number of atherosclerotic lesions with time from the age of about 20-25 years; therefore the following relationship holds:

$$N_A^{ni} = nN_A^i$$

Hence equation (C) yields

$$\Delta_A^{2i} = \frac{N_A^i}{N_A^{2i}} \Delta_A^i - \frac{N_A^i(1 - e^{-k_A i})}{N_A^{2i}} \Delta_A^i + \frac{N_S^{2i}}{N_A^{2i}} \Delta_S^{2i} \text{ ----- (D)}$$

$$\text{but} \quad N_A^{2i} = N_A^i - N_A^i(1 - e^{-k_A i}) + N_S^{2i}$$

$$\therefore N_S^{2i} = N_A^{2i} - N_A^i + N_A^i(1 - e^{-k_A i})$$

$$= N_A^i + N_A^i(1 - e^{-k_A i})$$

Substitution for N_S^{2i} in equation (D) leads to the following relationship between the lipid deposit and source:

$$\Delta_A^{2i} = \frac{N_A^i}{N_A^{2i}}\Delta_A^i - \frac{N_A^i}{N_A^{2i}}\Delta_A^i(1 - e^{-k_A i}) + \frac{N_A^i}{N_A^{2i}}\Delta_S^{2i}\left\{1 + (1 - e^{-k_A i})\right\}$$

which may be modified to a form similar to that of equations 4.1 and 4.2, viz.:

$$\Delta_A^{2i} = \Delta_A^i + \frac{N_A^i}{N_A^{2i}}\left\{1 + (1 - e^{-k_A i})\right\}(\Delta_S^{2i} - \Delta_A^i)$$

[illegible] n=2 [illegible]

$$\Delta_A^{ni} = \Delta_A^i + \sum_{n=2}^{n}\left\{\frac{1 + (1 - e^{-k_A i})}{n}\right\}\left\{\Delta^{ni} - \Delta^{(n-1)i}\right\} \quad \text{---} \quad (4.3)$$

In equation 4.3, k_A $(=1/\tau_A)$ refers to the rate constant for turnover of the annual deposit. Δ_S has until now been undefined, since the lipids found in the deposit are known to be of exogenous and endogenous origins. The proportion of each source is estimated at

30% dietary

70% endogenous (after Kaplan et al. 1963)

and although most tissues are capable of the preparation of cholesterol, the major sites of biosynthesis are liver and the gastrointestinal tract (Ho et al. 1970). Thus each term is split into 2 components, viz.:

$\Delta_S^{ni} = 0.3\Delta_D^{ni} + 0.7\Delta_T^{ni}$ where

Δ_S^{ni} = the mean ^{14}C activity of dietary lipids over the nth 'i' period

Δ_T^{ni} = the mean ^{14}C activity of the biosynthesised lipid component over the corresponding time interval.

4.4 Evaluation of Each Model Equation

(a) Tissue models Both models and their associated equations 4.1 and 4.2 are based on transfer of carbon from diet to tissue. Although a comprehensive survey of ^{14}C activities in the diet is not available, relation-

ships exist between most foodstuffs and environmental ^{14}C concentrations which preclude the necessity for their comprehensive ^{14}C activity measurements e.g. fish - marine environment, vegetational samples - atmospheric environment. The remainder of the diet is essentially composed of food of animal origin i.e. meat and dairy products. Nydal and Lovseth (1965) measured the ^{14}C activity of milk and noted its close resemblance to the cow's diet, which consisted mainly of grass. Thus milk and dairy products (cheese, butter) may also be linked in ^{14}C content to vegetation and ultimately to tropospheric ^{14}C concentrations whereas the ^{14}C activity of animal tissues might be expected to depend on the turnover of carbon in animals. It is reasonable to assume that these turnover rates will be of the same order of magnitude as those of human tissues; however, since the mean life of an animal is less than 2 years (determined from statistics on agricultural stock and meat production in Britain) an average Δvalue for each animal was taken to be equivalent to the ^{14}C concentration in the troposphere of the previous year. The ^{14}C concentrations of dietary materials, with the exception of fish (directly related to oceanic ^{14}C levels), are therefore related by a finite lag time to tropospheric $^{14}CO_2$ activities, as shown in Table 4.3. Since Δvalues of tropospheric CO_2 are readily available from past measurements and from this present study, it is possible to assign Δvalues to each foodstuff in terms of the tropospheric ^{14}C concentration. The major task remaining is the quantitative determination of the constituents of the human diet in order that the final composite ^{14}C activity of diet may be calculated for each increment of time. A comprehensive survey of the dietary habits of United Kingdom inhabitants was performed, based on detailed information and statistics on the food supplies moving into consumption in this country; this data is available

TABLE 4.3 RELATIONSHIP IN ^{14}C ACTIVITY BETWEEN DIETARY SAMPLES AND ENVIRONMENTAL LEVELS.

FOODSTUFF (Δ_D)	RELATION TO ENVIRONMENTAL Δ VALUE
Milk Milk (processed/cream) Cheese Butter Eggs	$\Delta_D^{ni} = \Delta_T^{ni}$
Margarine/other fats	2/3 animal oil: $\Delta_D^{ni} = \Delta_T^{(n-2)i}$
Beef and veal Mutton and lamb	$\Delta_D^{ni} = \Delta_T^{(n-2)i}$
Pork Bacon and ham	$\Delta_D^{ni} = \Delta_T^{(n-1)i}$
Poultry	$\Delta_D^{ni} = \Delta_T^{(n-1)i}$
Offals Other meats	$\Delta_D^{ni} = \Delta_T^{(n-2)i}$
Fresh/frozen fish	$\Delta_D^{ni} = \Delta_S^{ni}$
Canned fish	$\Delta_D^{ni} = \Delta_S^{(n-1)i}$
Fresh green vegetables	$\Delta_D^{ni} = \Delta_T^{ni}$
Other vegetables	$\Delta_D^{ni} = \Delta_T^{(n-1)i}$
Flour/bread Cereals Sugar/preserves	Δ_D^{ni} = previous July: Δ_T
Fresh fruit	$\Delta_D^{ni} = \Delta_T^{ni}$
Citrus fruit Canned/bottled fruit Dried fruit Cakes/biscuits	Δ_D^{ni} = previous July: Δ_T ; maximum time of photosynthesis.

T = troposphere; S = surface ocean; i = 6 months.

from the Ministry of Agriculture, Food and Fisheries Annual Statistics (found in the journal 'Trade and Industry').

Dietary survey A variety of data was accumulated to compile figures which relate to the percentage protein, fat, and carbohydrate content of the typical diet of a British householder.

(i) Production/disposal of foodstuffs The production and stock figures for processed food and feeding stuffs were collected and compared, where possible, with corresponding disposal figures so that the size of the standing stock could be assessed; the figures show that, in general, there is no more than 1 year's storage time of food stocks and that in most cases, this period is only 3 months or less (Appendix 3, Table 1).

(ii) Estimated food supplies per head of population These figures, which apply to the average householder during the past decade, were analysed to check that no significant changes in U.K. dietary habits had occurred. Table 4.4 (calculated from the data in Table 2 of Appendix 3) indicates a negligible difference in the percentage quantities of each class of food commodity.

(iii) Landings of fish of British taking Table 3, Appendix 3, lists the most important landings of fish in terms of weight. The main fish types are cod, haddock, plaice and whiting of demersal landings, and herring and mackerel of pelagic landings.

(iv) U.K. sources of supply for foods and feeding stuffs From data quoted by the Ministry of Agriculture, Food and Fisheries (MAFF) (see Table 4, Appendix 3), each commodity was subdivided according to a geographical origin of either the northern or southern hemispheres. Values are calculated as a percentage of each commodity in terms of hemisphere and are quoted in Table 4.5 for the year 1970 with a comparison of the average figures for the years 1964-1966.

TABLE 4.4 ESTIMATED FOOD SUPPLIES PER HEAD OF POPULATION

percentage of total food supplies

COMMODITY	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
Cereal products and sugar	22.6	22.5	22.2	22.1	21.4	21.4	21.3	20.8	20.7	21.0
Meat	11.2	11.6	12.0	11.9	11.7	11.7	11.7	12.0	12.0	12.0
Fish	1.4	1.4	1.5	1.4	1.5	1.5	1.4	1.5	1.5	1.5
Dairy products	24.5	24.7	24.8	24.7	24.8	24.9	24.8	25.2	24.9	24.9
Butter/fats	4.3	4.3	4.4	4.4	4.5	4.3	4.3	4.3	4.4	4.4
Fruit and vegetables	35.0	34.5	34.0	34.6	35.0	35.1	35.3	35.1	35.5	35.2
Other foods (tea, coffee)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

TABLE 4.5 SOURCE OF SUPPLY OF FOODS

(values quoted as % of each commodity)

COMMODITY	AMOUNT SUPPLIED BY S.HEMISPHERE		VALUES USED FOR CALCULATIONS
	1964-1966	1970	(%)
Wheat + flour	7	13	10
Cereal(maize)	1.8	2	1.9
Mutton + lamb	52	59	55
Beef and veal	18	7	13
Offals	15	20	17
Canned meat	4	2	3
Fish	1	1	1
Sugar	33	30	31
Butter	49	47	48
Cheese	30	23	27
Dried fruit	23	16	20
Citrus fruit	28	16	22
Canned/bottled fruit	47	44	46

(v) National Food Survey - household food consumption A statistical analysis of household food consumption is performed annually by MAFF and presented according to (a) composition of household, and (b) income of the head of the household. Since consideration here of each set of figures in both sections is impractical, 2 sets of data relevant to this research were selected from each series as shown in Table 4.6. Each component of the diet is primarily quoted in oz. per week but this quantity has been converted subsequently to a percentage weight of the total diet per week. Thus for example, consumption of fish comprises ~1.7% by weight of the total diet, with slight variations of this value between different groups. A mean percentage figure is used in Table 4.7 and combined with values for the nutritive content of each commodity in terms of protein + amino acid, fat, and carbohydrate components. This latter information, quoted as a percentage of each foodstuff (Table 4.7 - column 3), represents in most cases an average figure prepared from a more comprehensive list of nutritive contents of food (see Table 5, Appendix 3).

From columns 2 and 3 of Table 4.7, the weight of each fraction (protein + amino acid, fat, and carbohydrate) present in each commodity was calculated and each fraction of the diet was summed separately. From the latter values, the percentage amount of the total protein + amino acid, fat, and carbohydrate content of the diet supplied by each foodstuff was calculated as shown in Table 4.7.

Finally, the mean percentage values quoted in Tables 4.5 and 4.7 were combined in Table 4.8 to produce the fraction of total protein + amino acid, fat, and carbohydrate supplied by each foodstuff with respect to geographical source of the food (northern and southern hemisphere). Thus for example, 3.6% of the protein content of the diet is derived from cheese produced in the northern hemisphere while a corresponding figure of 1.2%

TABLE 4.6 DETAILED HOUSEHOLD FOOD CONSUMPTION

Data extracted from information on all households over the year 1971.

A = old age pensioner; B = 2 adults, aged 35-54, no children: C = 3 adults, 2 children; D = 2 adults, aged 55, no children.

Column 1 - oz. per person per week; column 2 - % age of each commodity in the total diet.

COMMODITY	A		B		C		D	
	1	2	1	2	1	2	1	2
Milk	87.08	24.9	85.88	20.9	76.27	23.5	85.19	22.4
Milk (processed/ cream)	5.33	1.5	8.95	2.2	7.23	2.2	5.52	1.4
Cheese	3.96	1.1	4.99	1.2	3.41	1.0	4.14	1.1
Butter	5.32	1.5	6.28	1.5	4.36	1.3	6.18	1.6
Margarine	4.11	1.2	3.47	0.8	3.89	1.2	4.74	1.2
Other fats	2.49	0.7	3.08	0.7	2.35	0.7	3.20	0.8
Eggs	8.48	2.4	9.40	2.3	7.80	2.3	7.80	2.5
Carcase meat	16.87	4.8	24.20	5.9	12.75	3.9	20.24	5.3
Bacon/ham	5.13	1.5	6.97	1.7	4.58	1.4	6.46	1.7
All other meats	14.70	4.2	25.62	6.5	17.91	5.5	17.50	4.6
Fish	6.11	1.7	6.82	1.7	4.92	1.5	7.55	2.0
Fresh fruit	19.27	5.5	24.93	6.1	15.30	4.7	23.43	6.2
Other fruit	5.51	1.6	8.62	2.1	5.55	1.7	7.86	2.0

TABLE 4.6 (continued)

COMMODITY	A		B		C		D	
	1	2	1	2	1	2	1	2
Potatoes	36.51	10.4	45.12	11.0	40.82	12.6	42.25	11.1
Fresh green veg.	14.43	4.1	21.42	5.2	9.47	2.9	17.72	4.7
Other vegetables	22.87	6.5	32.79	8.0	25.69	7.9	24.76	6.5
Bread/flour	43.41	12.4	44.90	10.9	43.17	13.3	44.05	11.6
Cakes/biscuits	12.78	3.7	13.36	3.2	10.82	3.3	12.66	3.3
Other cereals	9.11	2.6	6.81	1.7	7.87	2.4	8.83	2.3
Sugar/preserves	21.63	6.2	22.27	5.4	17.79	5.5	23.13	6.1
Others (tea/coffee)		1.5		1.0		1.1		1.6

TABLE 4.7 ESTIMATE OF THE PERCENRAGE CONTRIBUTION OF EACH FOODSTUFF TO TOTAL PROTEIN AND AMINO ACID (P+A), FAT (F), AND CARBOHYDRATE (C) CONTENT OF THE DIET

(see text for explanation)

Commodity	Wt. of each commodity per 100g. dietary intake(D_i)	% age nutrient content of each commodity (P+A)/F/C·	Wt. of each fraction in each commodity $P_i/F_i/C_i$	% $100 \times \frac{P_i}{\Sigma P_i} : \frac{F_i}{\Sigma F_i} : \frac{C_i}{\Sigma C_i}$
Milk	22.9	4.6/ 3.7/ 5.0	1.05/0.85/1.15	13.8/10.2/5.5
Milk (processed/ cream	1.8	8.5/ 7.9/ 9.7	0.15/0.14/0.17	2.0/ 1.7/0.8
Cheese	1.1	34.0/27.0/ 2.5	0.37/0.30/0.03	4.8/ 3.6/0.1
Butter	1.4	1.2/81.0/ -	0.01/1.13/ -	0.1/13.5/ -
Eggs	2.4	16.0/11.5/ 0.8	0.38/0.28/0.02	4.9/ 3.4/0.1
Margarine/other fats	1.9	0.6/95.0/ 0.2	0.01/1.81/ -	0.1/21.7/ -
Beef and veal	2.3	27.5/12.4/ -	0.63/0.29/ -	8.2/ 3.5/ -
Mutton and lamb	1.6	23.0/29.1/ -	0.37/0.47/ -	4.8/ 5.6/ -
Pork	1.0	34.2/30.0/ -	0.24/0.30/ -	3.1/ 3.6/ -
Bacon and ham	1.5	31.3/50.0/ 6.3	0.47/0.75/0.09	6.1/ 9.0/0.4
Poultry	1.6	28.8/ 5.0/ 1.3	0.46/0.08/0.02	6.0/ 1.0/0.1
Offals	0.3	25.3/20.0/ -	0.08/0.06/ -	1.0/ 0.7/ -
Other meats	3.5	20.0/25.0/ -	0.70/0.88/ -	9.1/10.6/ -
Fresh/frozen fish	1.1	25.0/10.0/ -	0.28/0.11/ -	3.6/ 1.3/ -
Canned fish	0.6	21.8/ 8.2/ -	0.13/0.05/ -	1.7/ 0.6/ -
Potatoes	11.7	2.2/ 0.1/14.5	0.26/0.01/1.64	3.4/ 0.1/7.8
Fresh green vegetables	4.0	3.5/ 0.2/ 4.5	0.14/0.01/0.18	1.8/ 0.1/0.9
Other vegetables	7.2	3.0/ 0.3/ 6.3	0.22/ - /0.45	2.9/ - /2.1

TABLE 4.7 (continued)

Commodity	Wt. of each commodity per 100g. dietary intake (D_i)	% age nutrient content of each commodity (P+A)/F/C	Wt. of each fraction in each commodity $P_i/F_i/C_i$	% 100 x $\frac{P_i}{\Sigma P}:\frac{F_i}{\Sigma F}:\frac{C_i}{\Sigma C}$
Fresh fruit	3.7	0.7/ 0.2/12.0	0.03/0.01/0.44	0.4/0.1/2.1
Citrus fruit	1.9	1.1/ 0.1/ 8.9	0.02/ - /0.17	0.3/ - /0.8
Canned/bottled fruit	1.4	0.8/ 0.1/19.2	0.01/ - /0.27	0.1/ - /1.3
Dried fruit	0.3	4.0/ 0.5/66.7	0.01/0.02/0.20	0.1/0.2/1.0
Sugar/preserves	5.7	0.1/ 0.1/91.5	0.01/0.01/5.22	0.1/0.1/24.9
Flour/bread	12.3	10.3/ 2.8/54.5	1.27/0.34/6.70	16.6/4.1/31.9
Cereals	2.3	9.1/ 0.4/85.3	0.21/0.01/1.96	2.7/0.1/9.3
Cakes/biscuits	3.3	5.5/13.0/69.4	0.18/0.43/2.29	2.3/5.2/10.9
Others (tea/coffee)	1.2	- / - / -	- / - / -	- / - / -
			7.69/8.34/21.0	100/100/100

TABLE 4.8 EFFECT OF SOURCE OF SUPPLY ON CONTRIBUTIONS OF EACH COMMODITY TO DIETARY PROTEIN + AMINO ACID, FAT, AND CARBOHYDRATE

COMMODITY	$\frac{P_i}{\Sigma P}\ \frac{F_i}{\Sigma F}\ \frac{C_i}{\Sigma C}$	SOURCE OF SUPPLY		PROTEIN		FAT		CARBOHYDRATE	
		N.H.	S.H.	N.H.	S.H.	N.H.	S.H.	N.H.	S.H.
Milk	13.8/10.2/5.5	100	-	13.8	-	10.2	-	5.5	-
Milk (processed/ cream)	2.0/ 1.7/0.8	100	-	2.0	-	1.7	-	0.8	-
Cheese	4.8/ 3.6/0.1	74	26	3.6	1.2	2.7	0.9	0.1	-
Butter	0.1/13.5/ -	52	48	0.05	0.05	7.0	6.5	-	-
Eggs	4.9/ 3.4/0.1	100	-	4.9	-	3.4	-	0.1	-
Margarine/other fat	0.1/21.7/ -	100	-	0.1	-	21.7	-	-	-
Beef and veal	8.2/ 3.5/ -	87	13	7.1	1.1	3.0	0.5	-	-
Mutton and lamb	4.8/ 5.6/ -	45	55	2.2	2.6	2.5	3.1	-	-
Pork	3.1/ 3.6/ -	100	-	3.1	-	3.6	-	-	-
Bacon and ham	6.1/ 9.0/0.4	100	-	6.1	-	9.0	-	0.4	-
Poultry	6.0/ 1.0/0.1	100	-	6.0	-	1.0	-	0.1	-
Offals	1.0/ 0.7/ -	85	15	0.9	0.1	0.6	0.1	-	-
Other meats	9.1/10.6/ -	98	2	8.9	0.2	10.4	0.2	-	-
Fresh/frozen fish	3.6/ 1.3/ -	99	1	3.6	-	1.3	-	-	-
Canned fish	1.7/ 0.6/ -	99	1	1.68	0.02	0.59	0.01	-	-
Potatoes	3.4/ 0.1/7.8	100	-	3.4	-	0.1	-	-	-
Fresh green veg.	1.8/ 0.1/ 0.9	100	-	1.8	-	0.1	-	0.9	-
Other vegetables	2.9/ - /2.1	100	-	2.9	-	-	-	2.1	-

TABLE 4.8 (continued)

COMMODITY	$\frac{P_i}{\Sigma P_i} : \frac{F_i}{\Sigma F_i} : \frac{C_i}{\Sigma C_i}$	SOURCE OF SUPPLY		PROTEIN		FAT		CARBOHYDRATE	
		N.H.	S.H.	N.H.	S.H.	N.H.	S.H.	N.H.	S.H.
Fresh fruit	0.4/0.1/2.1	100	-	0.4	-	0.1	-	2.1	-
Citrus fruit	0.3/ - /0.8	78	22	0.2	0.1	-	-	0.6	0.2
Canned/bottled fruit	0.1/ - /1.3	54	46	0.05	0.05	-	-	0.7	0.6
Dried fruit	0.1/0.2/1.0	80	20	0.08	0.02	0.16	0.04	0.8	0.2
Sugar/preserves	0.1/0.1/24.9	69	31	0.07	0.03	0.07	0.03	17.2	7.7
Flour/bread	16.6/4.1/31.9	90	10	14.9	1.7	3.7	0.4	28.7	3.2
Cereals	2.7/0.1/9.3	98	2	2.6	0.1	0.1	-	9.1	0.2
Cakes/biscuits	2.3/5.2/10.9	90	10	2.1	0.2	4.7	0.5	9.8	1.1

is obtained for the southern hemisphere.

To relate the ^{14}C concentration of each foodstuff and its fractions to either a corresponding tropospheric or surface ocean ^{14}C activity, Table 4.3 is used. In this way, the ^{14}C content of the diet may be estimated over any desired time period 'i'. On the assumption that dry tissue is composed of ~75% protein and 25% lipid of dietary origins, but with half the latter percentage derived from converted carbohydrate, a 'weighting' factor for each dietary fraction is obtained. Thus

$$\Delta_D^{ni} = 0.24\Delta_{TN}^{ni} + 0.19\Delta_{TN}^{(n-1)i} + 0.16\Delta_{TN}^{(n-2)i} + 0.28\Delta_{TN}^{J} + 0.02\Delta_{TS}^{ni} + 0.035\Delta_{TS}^{(n-2)i} + 0.035\Delta_{TS}^{J} + 0.03\Delta_{M}^{ni} + 0.01\Delta_{M}^{(n-1)i} \quad -- (I)$$

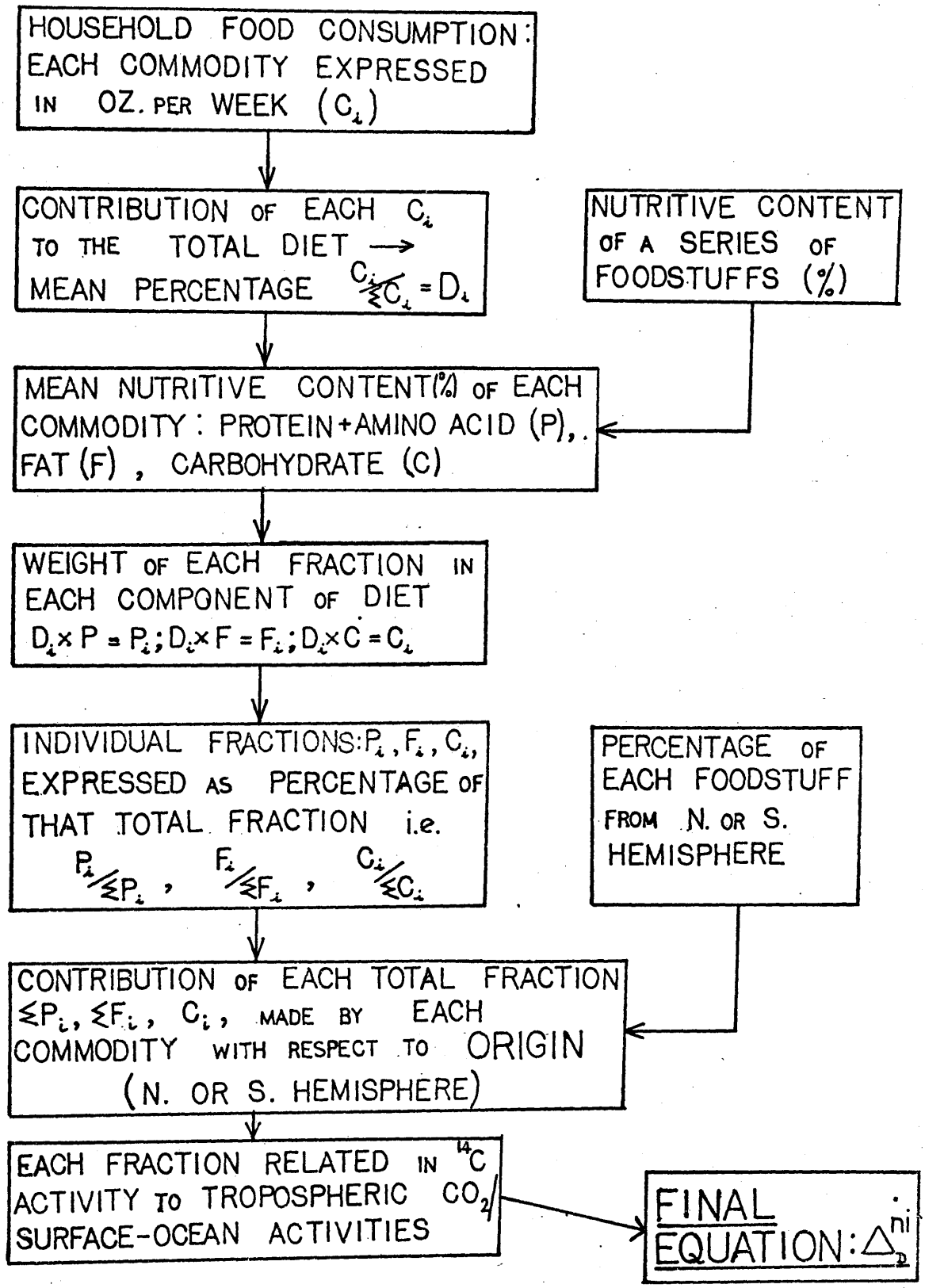
In the above equation, transcripts TN, TS, and M represent the northern troposphere, southern troposphere, and surface ocean respectively; 'ni', '(n-1)i', and '(n-2)' are used according to Table 4.3, and J refers to the preceding period of maximum photosynthesis. The total procedure discussed previously is shown schematically in Fig. 4.2.

(b) Arterial deposit model In the derivation of an equation similar to equation (I) above, to enable calculation of corresponding Δ_D^{ni} values, certain dietary factors relevant to the development of atherosclerosis were noted.

(i) dietary cholesterol Wilson and Lindsey (1965) estimate that approximately 60% - 80% of serum cholesterol is produced by the body itself (cf. 70%, the value used in this study) while numerous other investigations (e.g. Connor et al. 1964) indicate a direct relationship between dietary cholesterol and serum lipid levels.

(ii) quantity of fat Intake of total fat also appears to exert a strong influence on serum lipid levels. Populations with diets high in total fat usually have high serum cholesterol levels (U.S.A., Finland)

FIG. 4.2
PROCEDURE INVOLVED IN DIETARY ANALYSIS



while reduction of total fat intake is consistently associated with a fall in serum cholesterol levels (Italy, Japan) (Connor et al. 1964, Hegsted et al. 1965).

(iii) quality of fat Keys and Blackburn (1963) noted that changes in serum lipids and cholesterol appeared to be dependent on the degree of saturation or unsaturation of the dietary fats, rather than to their source. Thus dietary saturated fatty acids and cholesterol increased the serum cholesterol concentrations while polyunsaturated fatty acids tended to reduce the latter. In general, it was found that "vegetable" fat lowers serum lipid levels but "animal" fat increases these levels (Hardinge and Stare 1954, Bronte-Stewart et al. 1956).

(iv) dietary carbohydrate was not found to be a major influence on blood cholesterol reduction (McGandy et al. 1966) nor was the latter level shown to be influenced by the amount of protein in the diet (Keys and Anderson 1957).

In addition to the above considerations, Hellman et al. (1954) showed that plasma cholesterol derived from the diet is eventually indistinguishable from that synthesised in the body; thus it could be assumed that there is no preferential uptake of either component by a tissue in the transport of plasma cholesterol to that tissue.

From the above observations, the build-up of the lipid deposit in the arteries is assumed to originate in part from a dietary source, in particular the fat content. Each component of the diet, therefore, is attributed a 'weighting' factor dependent on the percentage of saturated and unsaturated fats and cholesterol in different foodstuffs. From these figures, listed in Table 4.9, and the data in column 2 of Table 4.7, a similar procedure to that employed in the previous section is adopted as shown in Tables 4.10 and 4.11; in this case:

TABLE 4.9 CHOLESTEROL, TOTAL FAT, AND SATURATED FATTY ACID CONTENT OF VARIOUS FOODSTUFFS

Foodstuff	% age cholesterol content	% age total fat content	% age satd. fatty acid content
Milk	0.011	3.7	2.2
Cheese	0.110	27.0	16.2
Butter	0.250	81.0	48.6
Eggs	0.550	11.5	4.3
Poultry	0.06	5.0	2.6
Carcase meat	0.07	24.0	12.5
Offals	0.35	20.0	10.4
Bacon and ham	0.07	50.0	22.0
Fish	0.07	10.0	3.2
Margarine/ other fats	0.08	95.0	37.1
Bread/cakes	—	2.8	—

TABLE 4.10 PERCENTAGE OF TOTAL CHOLESTEROL, TOTAL FAT, AND SATURATED FATTY ACIDS IN DIETARY FOODSTUFFS

Commodity	Wt of each commodity in 100g. diet	Wt. of cholesterol in each commodity (x 10^2)	% age total cholesterol in each commodity	Wt of total fat in each commodity	% age total fat in each commodity	Wt of satd. fatty acid in each commodity	% age total satd. fatty acid in each commodity
Milk (plus processed/ cream)	24.7	0.272	8.4	0.99	12.3	0.54	14.5
Cheese	1.1	0.121	3.7	0.30	3.7	0.18	4.8
Butter	1.5	0.375	11.5	1.13	14.1	0.73	19.6
Eggs	2.4	1.320	40.5	0.28	3.5	0.10	2.7
Poultry	1.6	0.096	3.0	0.08	1.0	0.04	1.1
Carcase meat	8.4	0.588	18.1	1.94	24.2	1.05	28.3
Offals	0.3	0.105	3.2	0.06	0.7	0.03	0.8
Bacon and ham	1.5	0.105	3.2	0.75	9.3	0.33	8.9
Fish	1.7	0.119	3.7	0.16	2.0	0.05	1.3
Margarine/fats	1.9	0.152	4.7	1.81	22.5	0.67	18.0
Bread/cakes	13.8	—	—	0.54	6.7	—	—
	TOTAL 3.253		TOTAL 8.04		TOTAL 3.72		

TABLE 4.11 EFFECT OF SOURCE OF SUPPLY ON VALUES QUOTED IN TABLE 4.10

Commodity	Source of supply		CHOLESTEROL CONTRIBUTION		TOTAL FAT CONTRIBUTION		S.F.A. CONTRIBUTION	
	%N.H.	%S.H.	% N.H.	% S.H.	% N.H.	% S.H.	% N.H.	% S.H.
Milk (including processed/cream)	100	-	8.4	-	12.3	-	14.5	-
Cheese	73	27	2.8	0.9	2.8	0.9	3.5	1.3
Butter	52	48	6.0	5.5	7.3	6.8	10.2	9.4
Eggs	100	-	40.5	-	3.5	-	2.7	-
Poultry	100	-	3.0	-	1.0	-	1.1	-
Carcase meat	73	27	13.2	4.9	17.7	6.5	20.7	7.6
Offals	83	17	2.7	0.5	0.6	0.1	0.65	0.15
Bacon and ham	100	-	3.2	-	9.3	-	8.9	-
Fish	99	1	3.7	-	2.0	-	1.3	-
Margarine/ other fats	100	-	4.7	-	22.5	-	18.0	-
Bread/cakes	90	10	-	-	6.0	0.7	-	-

$$\Delta_D^{ni} = 0.48\Delta_{TN}^{ni} + 0.09\Delta_{TN}^{(n-1)i} + 0.28\Delta_{TN}^{(n-2)i} + 0.095\Delta_{TS}^{ni} + 0.035\Delta_{TS}^{(n-2)i} + 0.02\Delta_M^{ni} \quad \text{- - - - - (II)}$$

Δ_{TN}, Δ_{TS}, Δ_M are defined as in equation (I). Hence the value of Δ_S^{ni}, the ^{14}C content of the arterial lipid source at any time, may be calculated from the expression quoted in 4.3.2, viz.:

$$\Delta_S^{ni} = 0.3\Delta_D^{ni} + 0.7\Delta_T^{ni}$$

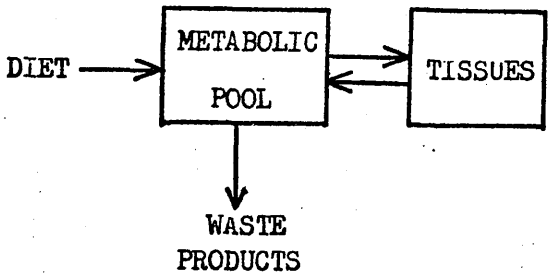
Values of Δ_T^{ni} are obtained from the results of the tissue model analysis which gives Δ_T i.e. the Δ value of a tissue at half-yearly intervals (see Fig. 4.6). In this case the graph chosen corresponds to the Δ value which produces the best correlation between predicted and measured Δ values of liver, the endogenous source of lipid; the latter tissue is considered alone in the absence of ^{14}C activity measurements of the GI tract.

4.4 Estimation of the Limitations Involved in Each Model Evaluation

There are 2 major sources of error involved in prediction of tissue Δ values, both of which are worthy of consideration prior to analysis of the results of each model treatment.

(a) the assumptions necessary in the derivation of each model equation The single compartment treatment of the tissue Δ data implies that the tissues concerned are independent of each other with respect to exchange of carbon. However, it is well documented that such a simplification certainly does not represent the true state of metabolism in the body. Thus dietary protein, on digestion, is degraded into its constituent amino acids which subsequently intermingle with the breakdown products of tissues themselves, including amino acids. Besides this direct source of tissue protein, the complex biochemical reactions of the body allow the interaction of carbon units of variable size derived from lipid, carbohydrate and protein components of the body. Furthermore, storage of excess dietary constituents

occurs e.g. carbohydrate is stored as glycogen in muscle and liver tissue, a factor not included in the single compartment model. It is therefore important to determine the effect on the final γ values obtained using the single compartment model created by neglect of such considerations. A more realistic representation of carbon transport within the body tissues is given by the following 2-box model:



The metabolic pool is described by Sprinson and Rittenberg (1949) as a mixture of compounds, derived either from the diet or from breakdown of tissue material, employed by an animal for the synthesis of new tissue constituents; thus the metabolic pool is a mechanism for transfer of amino acids from one tissue to another. Consideration of the above model reveals the basic difference from the single compartment treatment to be the input of carbon into a tissue; the latter quantity includes carbon from other tissues' constituents besides the dietary sources. Nevertheless, the ultimate value obtained for the turnover time of carbon in any tissue as evaluated by the single compartment analysis is inaccurate only if an appreciable quantity of carbon has access to the metabolic pool and, in addition, possesses a relatively long residence time compared to that tissue. The ^{14}C activities of the tissues analysed in this study, however, indicate that, with the exception of bone collagen, no single source of carbon consistently possesses a Δ value significantly different from the bulk of ^{14}C activity measurements. Muscle, for example, the protein of which constitutes 50% of total body protein and therefore represents a

potential influence on metabolic pool ^{14}C activities, shows no deviation in Δ value from those of other major organs. Thus the simplification inherent in the single compartment kinetic treatment of tissue ^{14}C levels is not unjustified.

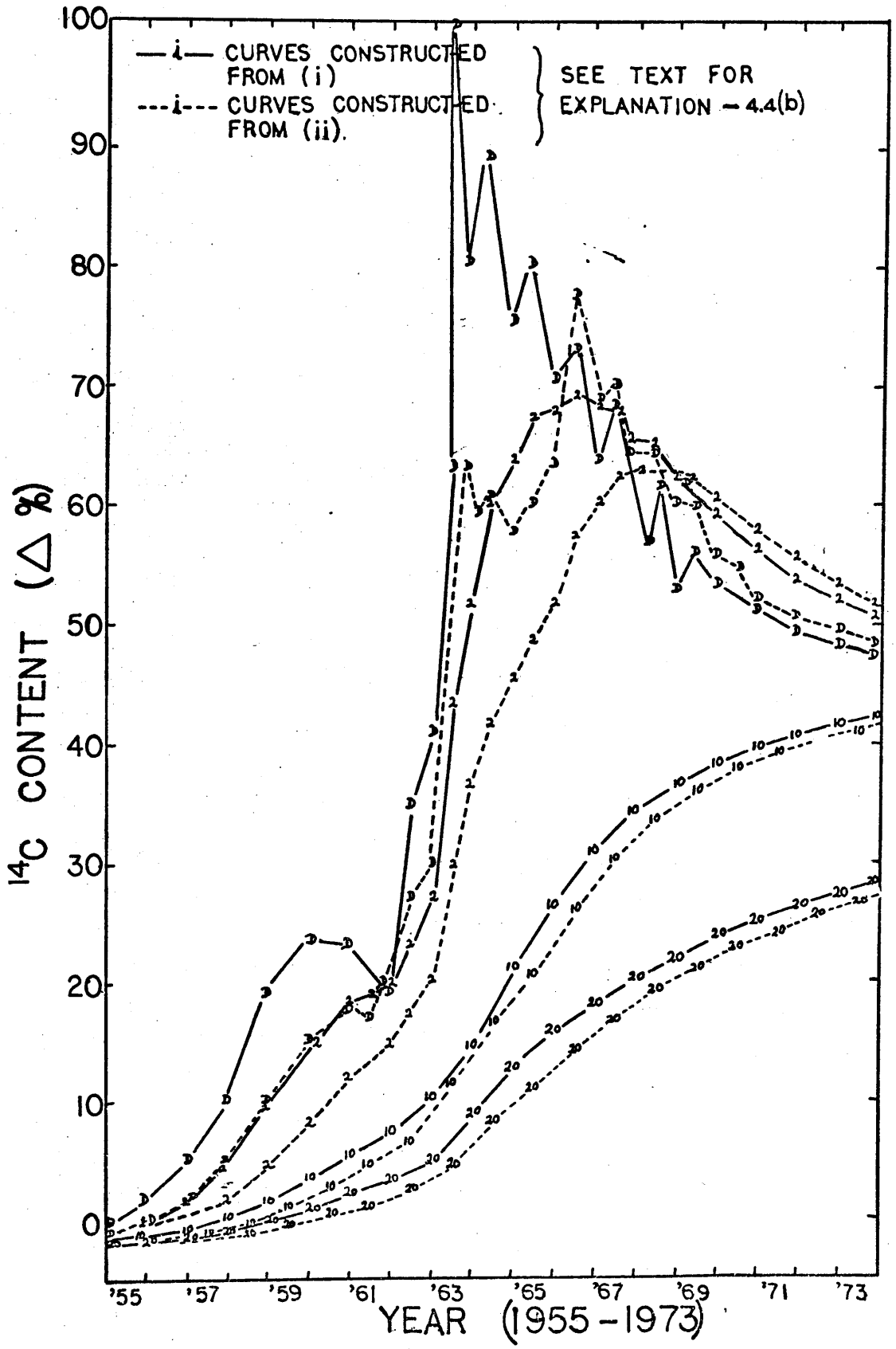
(b) the assumptions necessary in the evaluation of the theoretically predicted families of curves of Δ_T from Δ_D data. The major discrepancy in this case is associated with the relationships given in Table 4.3, in particular the correlation between the ^{14}C content of meat and atmospheric ^{14}C levels. However, the effect of this error on the final γ values may be assessed by comparison of relatively extreme situations of the dietary equations (I) and (II), viz.:

(i) where $\Delta_D^{ni} = \Delta_{TN}^{ni}$ i.e. no marine component of diet is considered

(ii) where Δ_D^{ni} is recalculated for a case in which $\Delta_{meat}^{ni} = \Delta_{TN}^{(n-6)i}$. This latter relationship is implied by ^{14}C activity measurements of North American cattle (Chatters, private communication) although most animals analysed were >5 years old. This treatment, therefore, accomodates a diet which contains only that small percentage of meat derived from relatively long-lived animals.

Both families of curves calculated for each set of Δ_D data are shown in Fig. 4.3 where, for the sake of clarity, only those curves which represent $\gamma = 0$, 2, 10, and 20 are represented. The major discrepancy between curves of the same γ value is seen to lie in the years immediately following a major pulse of $^{14}CO_2$ into the atmosphere, in agreement with the observation of Harkness and Walton (1969), and is greatest for small γ values i.e. for tissues in which the carbon turns over rapidly. In addition, Fig. 4.3 indicates an attenuation of differences between corresponding sets of Δ_T data with increase in time since the major disturbance of the $^{14}C/12_C$ equilibrium conditions such that at the time period of

FIG. 4.3 EFFECT OF DIFFERENT Δ_D^{ni} ON PREDICTED Δ_T CURVES



tissue analysis in this study, variations between corresponding curves do not exceed ~2%. This latter difference is equivalent to a time displacement of ± 1 year which must be considered a maximum in view of both situations (i) and (ii) described. In these circumstances, and since the statistical uncertainty of ^{14}C activity measurement is included in each quoted Δ_T value, any error involved in the prediction of the ^{14}C content of tissues is assumed to be associated with time rather than with ^{14}C activity. Thus in the comparison of theoretically predicted with experimentally determined Δ_T values, a time displacement of ± 1 year is included.

4.5 Determination of the Mean Residence Times of Tissue Carbon

Appendix 4 contains the computer programmes employed to provide the data for the families of curves shown in Figs. 4.4 - 4.6; the diagrams represent the predicted ^{14}C contents of both mature and growing tissue for different τ values of carbon. $\tau = 1/k_T$, is the mean residence time/turnover time of carbon in a tissue where removal of material is assumed to occur under conditions of first order kinetics. $\tau = 0$, $k = \infty$, signifies that carbon in a tissue turns over at a rate fast enough that $\Delta_T^{ni} = \Delta_D^{ni}$. Since this equality exists for $\tau = 0$ within the limitations of the model, replacement of the equivalent amount of total carbon in a tissue may occur in days or months (< 6 months) for such a residence time. For the contrasting case of $\tau = \infty$, no turnover of carbon occurs in either mature or growing tissues; thus in the former case,

$$\Delta_T^{ni} = \Delta_T^{o} = -2.5\%, \text{ the prebomb } ^{14}C \text{ level}$$

whereas for a growing tissue,

$$\Delta_T^{ni} = \frac{\Delta_T^{o} + \sum_{n=1}^{n} \Delta_D^{ni}}{N_T^{o} + n(N_T^{i} - N_T^{o})}$$

In kinetic experiments using isotopic tracers, a commonly determined

FIG. 4.4 PREDICTED ^{14}C LEVELS IN HUMAN TISSUES (1955 - 1973)

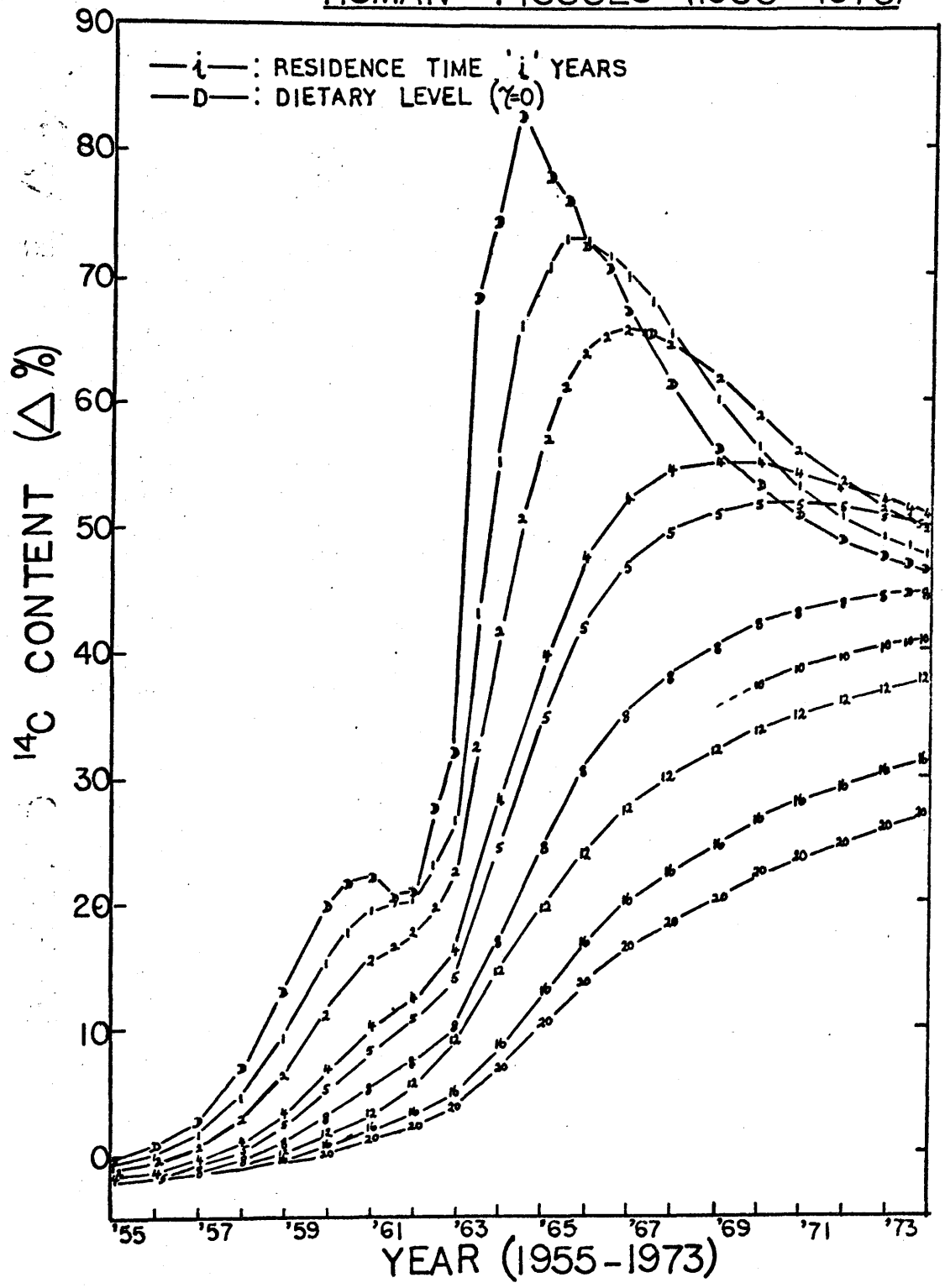


FIG. 4.5 PREDICTED ^{14}C LEVELS IN HUMAN TISSUES:— NON-STATIONARY MODEL

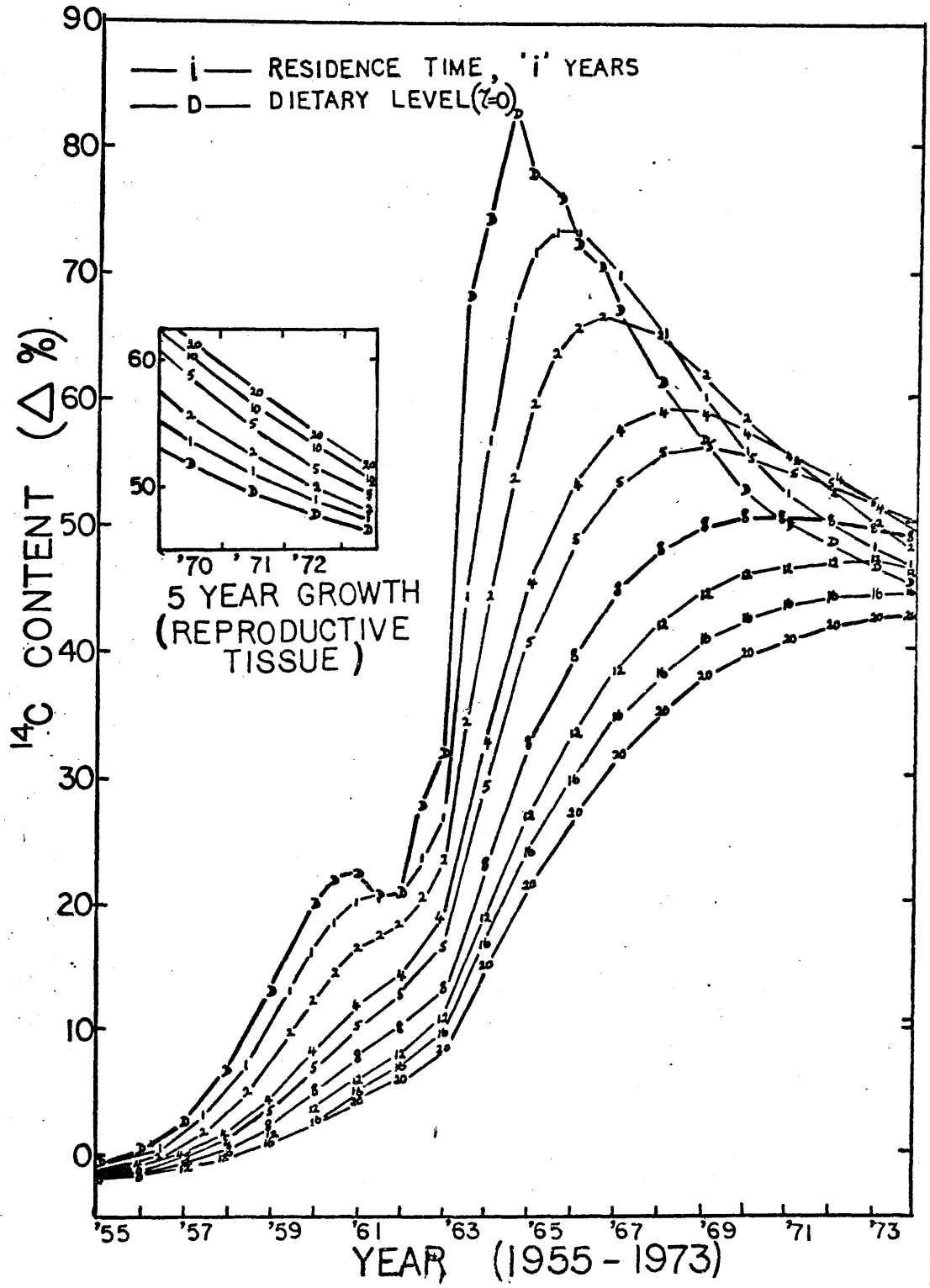
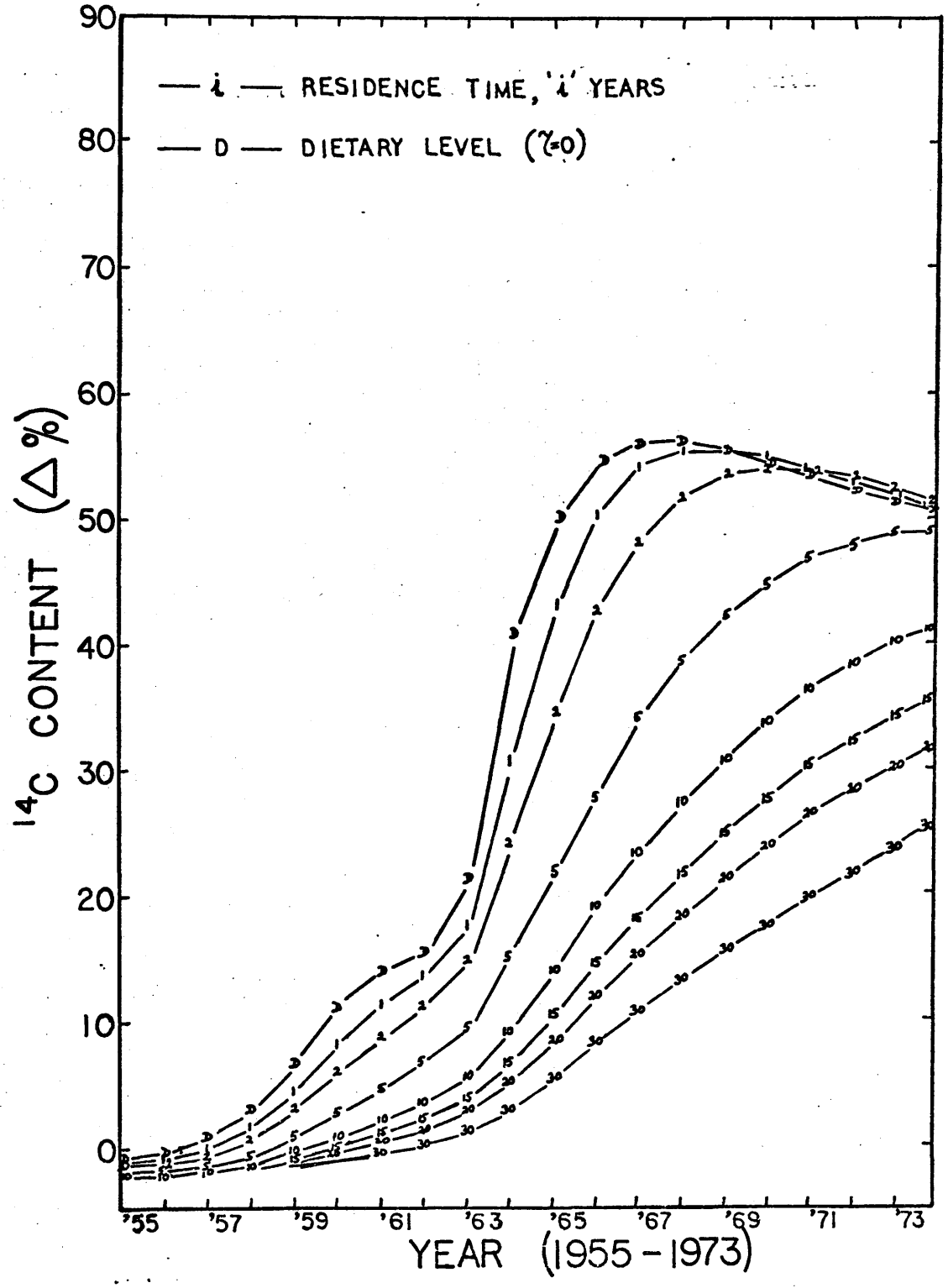


FIG. 4.6 PREDICTED ^{14}C LEVELS IN ARTERIAL LIPID DEPOSIT



parameter is $t_{\frac{1}{2}}$, or half-life, the time required for the original material to be removed/renewed. For first-order kinetics, the relationship between γ and $t_{\frac{1}{2}}$ is given by the equation

$$\gamma = \frac{t_{\frac{1}{2}}}{\log_e 2} = 1.44\ t_{\frac{1}{2}}$$

Collation of experimentally determined and theoretically predicted Δ values of tissue and arterial deposit carbon enables an estimate of the residence time of carbon in that material, as shown in Tables 4.12, (i) - (xiv). Although the final value/range of values of γ covers a considerable range in most cases, the figures are based on both the time displacement mentioned previously and the $\pm 2\sigma$ error of ^{14}C activity measurement. Table 4.13, on the other hand, is constructed in such a manner that more emphasis is attached to the γ values determined by comparison of the actual measured with theoretically predicted Δ data, although the total ranges remain the same. Presentation of this latter table also allows an immediate comparison of γ values of the same tissue of different individuals. In approximately 50% of these samples, 2 possible choices of residence time are found; this situation arises as a result of the approach to equilibrium conditions of tissue and dietary ^{14}C levels and is more a function of the extent of the original disturbance of the pre-bomb $^{14}C/_{12}C$ distribution than of the model itself.

For the 5 year-old child, the errors involved in the assumption of linear growth are particularly great since an exponential growth of tissue during the first 3 years of childhood is more applicable than the former situation. For this reason, the ^{14}C content of the tissues of the 5 year-old are not subjected to model analysis. Rather, direct comparison of the measured ^{14}C activities of the tissues indicates a strong similarity to

TABLE 4.12 ESTIMATES OF RESIDENCE TIMES OF CARBON IN THE BODY

(i) Male, 50 years old

Tissue	$\Delta \pm 2\sigma$	γ (years)
Liver	43.3 ± 1.6	7-9
Muscle	50.2 ± 2.5	0-1/5-6
Heart	52.3 ± 3.7	0-6
Testis	37.8 ± 2.0	9-11
Kidney	43.6 ± 1.7	7-8

(ii) Male, 72 years old

Tissue	$\Delta \pm 2\sigma$	γ (years)
Brain	50.4 ± 2.1	0-1/5-6
Muscle	51.9 ± 2.2	0-5
Pancreas	54.7 ± 1.9	0-4
Lung	51.2 ± 2.0	0-6
Spleen	51.5 ± 2.1	0-5
Liver	53.2 ± 2.0	0-5
Heart	50.7 ± 2.0	0-1/4-6
Kidney	55.2 ± 1.9	1-4
Testis	49.8 ± 2.0	0-1/5-6
Bone marrow fat	48.9 ± 1.7	0-1/6
Bone collagen	10.4 ± 5.5	30

(iii) Female, 64 years old

Tissue	$\Delta \pm 2\sigma$	γ (years)
Muscle	48.2 ± 2.0	0-1/5-7
Brain	49.2 ± 2.0	0-1/5-6
Adipose tissue	46.9 ± 2.5	0/6-7
Heart	41.5 ± 3.0	7-10
Kidney	49.5 ± 2.0	0-1/5-6
Spleen	45.6 ± 2.4	0/6-8
Ovary	47.5 ± 2.9	0-1/6-7

(iv) Male, 39 years old

Tissue	$\Delta \pm 2\sigma$	γ (years)
Liver	42.3 ± 2.4	7-10
Brain	48.1 ± 1.8	0-1/6-7
Spleen	38.6 ± 2.0	9-11
Thyroid	37.9 ± 3.0	9-12
Pancreas	46.0 ± 2.4	0-1/6-8
Heart	39.8 ± 2.4	9-11

(v) Male, 42 years old

Tissue	$\Delta \pm 2\sigma$	γ (years)
Heart	51.3 ± 3.0	0-6
Kidney	33.9 ± 1.8	11-14
Liver	47.7 ± 1.9	0-1/6-7
Brain	51.9 ± 2.1	0-5
Lung	37.8 ± 2.0	10-12
Thyroid	43.3 ± 1.8	7-9
Spleen	43.5 ± 5.0	0-1/6-10

(vi) Male, 21 years old

Tissue	$\Delta \pm 2\sigma$	γ(years)
Heart	42.4 ± 2.8	14-25
Spleen	46.0 ± 1.6	11-16
Liver	54.6 ± 1.8	1-6
Thyroid	43.3 ± 3.1	12-25
Kidney	51.2 ± 3.3	0-12
Testis	56.0 ± 2.6	1-30
Lung	53.9 ± 3.2	0-8
Muscle	55.9 ± 2.5	1-6
Pancreas	52.2 ± 2.2	0-8

(vii) Female, 21 years old

Tissue	$\Delta \pm 2\sigma$	γ(years)
Kidney	53.1 ± 2.4	0-8
Muscle	51.7 ± 2.6	0-9
Spleen	54.8 ± 3.2	0-7
Heart	54.5 ± 2.6	0-7
Liver	55.2 ± 2.1	1-6
Lung	51.1 ± 2.2	0-10
Pancreas	54.6 ± 2.1	1-7
Thyroid	50.7 ± 2.2	0-11
Brain	52.3 ± 2.2	0-5
Ovary	50.6 ± 2.0	0-20

(viii) Male, 37 years old

Tissue	$\Delta \pm 2\sigma$	γ (years)
Testis	49.8 ± 3.5	0-6
Liver	48.4 ± 1.8	0-2/5-7
Heart	47.3 ± 2.1	0-1/6-7

(ix) Male, 67 years old

Tissue	$\Delta \pm 2\sigma$	γ (years)
Kidney (W)	46.6 ± 1.6	0-1/6-8
Kidney (P)	48.5 ± 1.8	0-7
Heart (W)	46.8 ± 1.7	0-1/6-7
Heart (P)	45.4 ± 1.7	0-1/7-8
Heart (L)	51.1 ± 1.7	1-6
Liver (W)	49.4 ± 1.7	0-6
Liver (P)	49.4 ± 1.9	0-7
Liver (L)	48.7 ± 2.5	0-7

(x) Female, 87 years old

Tissue	$\Delta \pm 2\sigma$	γ (years)
Liver (W)	48.0 ± 1.7	0-1/6-7
Liver (P)	49.1 ± 2.0	0-7
Kidney (W)	46.2 ± 1.7	0-1/6-8
Kidney (P)	47.9 ± 1.6	0-1/6-7
Spleen (P)	51.1 ± 1.8	0-6

(xi) Male, 64 years old

Tissue	$\Delta \pm 2\sigma$	γ (years)
Kidney (W)	46.3 ± 1.8	0-1/6-8
Kidney (P)	48.4 ± 2.0	0-3/5-7
Liver (W)	47.5 ± 1.7	0-1/6-7
Liver (P)	48.7 ± 1.9	0-3/5-7
Liver (L)	47.2 ± 2.3	0-1/6-7
Spleen (W)	43.2 ± 1.9	7-9
Spleen (P)	42.8 ± 1.8	8-10
Lung (P)	44.0 ± 2.4	7-9
Lung (P)	46.5 ± 4.4	0-9
Heart (P)	40.9 ± 1.8	9-10

(xii) Male, 61 years old

Tissue	$\Delta \pm 2\sigma$	γ (years)
Heart (W)	50.4 ± 1.5	0-6
Heart (P)	44.9 ± 1.9	0/7-9
Kidney (W)	45.3 ± 1.7	0/6-8
Kidney (P)	43.7 ± 2.0	7-9
Spleen (W)	43.4 ± 1.8	7-9
Spleen (P)	46.2 ± 1.9	0-1/6-8
Liver (W)	48.5 ± 1.9	0-3/5-7
Liver (P)	45.0 ± 2.1	0/7-9

(xiii) Cancered tissues

Donor	Tissue	$\Delta \pm 2\sigma$	γ(years)
Male/66 years old	Liver (normal)	50.0 ± 1.8	0-4
Male	" (diseased)	55.2 ± 2.7	4-30
Male/59 years old	Kidney (diseased)	48.1 ± 1.6	0-10
Male/63 years old	Spleen (normal)	51.0 ± 1.8	1-6
	Liver(diseased)	53.0 ± 2.5	2-30

(xiv) Aorta samples

Donor	Tissue	$\Delta \pm 2\sigma$	γ(years)
Male/68 years old	lipid extract	4.8 ± 1.2	8-30
Male/67 years old	lipid extract	9.7 ± 1.8	5-25
Male/69 years old	lipid extract	17.9 ± 1.6	2-10
Female/86 years old	lipid extract	47.1 ± 1.8	5-8
	adventitia	31.6 ± 1.7	18-25

TABLE 4.13 MORE DETAILED INTERPRETATION OF Δ VALUES OF TISSUES

Donor		Liver	Kidney	Spleen	Heart	Muscle
M/50	whole	8 ± 1	7 ± 1	-	$(0-1)^{+5}$	$0^{+1}/(5-6)$
M/72	whole	$(1-4)_{-1}$	$(1-3)^{+1}$	$(0-1)/5^{+0}_{-3}$	$(0-1)/(5-6)_{-1}$	$(0-1)^{+4}$
F/64	whole	-	$0^{+1}/(5-6)$	$7\pm1/0$	$(8-9)\pm1$	$0^{+1}/6\pm1$
M/39	whole	$(8-9)\pm1$	-	$(10-11)_{-1}$	$(9-10)^{+1}$	-
M/42	whole	$0^{+1}/6^{+1}$	$(12-14)_{-1}$	$(0-1)/8\pm2$	$(0-1)/5^{+1}_{-3}$	-
M/64	whole	$(0-1)/6^{+1}$	$0^{+1}/7\pm1$	$(8-9)_{-1}$	-	-
	protein	$(0-1)^{+2}/6\pm1$	$(0-1)^{+2}/6\pm1$	$(8-9)^{+1}$	(9-10)	-
	lipid	$0^{+1}/(6-7)$	-	-	-	-
M/61	whole	$(0-1)^{+2}/6\pm1$	$0/(7-8)_{-1}$	$(8-9)_{-1}$	$(1-5)\pm1$	-
	protein	$0/(7-8)^{+1}$	8 ± 1	$0^{+1}/7\pm1$	$0/8\pm1$	-
M/67	whole	$(0-1)/(5-6)_{-3}$	$0^{+1}/7\pm1$	-	$0^{+1}/7_{-1}$	-
	protein	$(0-1)/^{+1}_{(5-6)_{-3}}$	$(0-1)/6^{+1}_{-4}$	-	$0^{+1}/7_{-1}$	-
	lipid	$(0-1)/6^{+1}_{-4}$	-	-	-	-
F/87	whole	$(0-1)/6^{+1}$	$0^{+1}/7\pm1$	-	-	-
	protein	$(0-1)/(5-6)^{+1}_{-3}$	$(0-1)/6^{+1}$	-	-	-
M/21	whole	$(2-5)\pm1$	$(0-2)^{+1}/8\pm4$	$(12-14)^{+2}_{-1}$	$(18-20)^{+5}_{-4}$	$(2-4)^{+2}_{-1}$

TABLE 4.13 (continued)

Donor	Liver	Kidney	Spleen	Heart	Muscle
F/21 whole	$(2\text{-}4)^{+2}_{-1}$	$(1\text{-}5)^{+3}_{-1}$	$(2\text{-}5)^{+2}$	$(2\text{-}5)^{+4}$	$(0\text{-}5)^{+4}$
M/37 whole	$(0\text{-}1)^{+1}/6\pm1$	-	-	$0^{+1}/(6\text{-}7)$	-

Donor	Lung	Brain	Pancreas	Thyroid	Testis/Ovary
M/50 whole	-	-	-	-	$(10\text{-}11)_{-1}$
M/72 whole	$(0\text{-}1)/5^{+1}_{-3}$	$(0\text{-}1)/(5\text{-}6)$	$(1\text{-}4)_{-1}$	-	$0^{+1}/(5\text{-}6)$
F/64 whole	-	$0^{+1}/6_{-1}$		-	$0/6^{+1}$
M/39 whole	-	$0^{+1}/6^{+1}$	$(0\text{-}1)/7\pm1$	$(10\text{-}11)\pm1$	-
M/42 whole	$(10\text{-}11)^{+1}$	$(0\text{-}2)/5_{-2}$	-	8 ± 1	-
M/64 whole	8 ± 1	-	-	-	-
protein	$0/7^{+2}_{-6}$	-	-	-	-
M/21 whole	$(2\text{-}5)^{+3}_{-2}$	-	$(1\text{-}5)^{+3}_{-1}$	$(16\text{-}20)^{+5}_{-4}$	$(4\text{-}25)^{+5}_{-3}$
F/21 whole	$(0\text{-}2)/8\pm4$	$(1\text{-}5)_{-1}$	$(2\text{-}5)^{+2}_{-1}$	$(0\text{-}2)^{+9}$	$(0\text{-}4)^{+16}$
M/37	-	-	-	-	$(0\text{-}1)/(5\text{-}6)_{-3}$

dietary ^{14}C levels of the 18-month period prior to death. The ^{14}C content of spleen, however, is closer to contemporary atmospheric ^{14}C activities; while this result may be explained by the relatively small size of this tissue in comparison to other major organs, the observed Δ value suggests that the different dietary pattern of a child favours a more direct correlation between atmospheric and tissue ^{14}C activities.

4.6 Discussion of the Residence Times of Tissue Carbon

4.6.1 Tissue τ results The τ values listed in Table 4.13 show a considerable variation within each organ type. Although in most cases whole tissue carbon has been analysed for ^{14}C activity, comparison of these results with the corresponding data for protein and lipid fractions shows that, for the purposes of this research at least, residence times of carbon in whole tissue may also be applied to the protein moeity. This extrapolation is further justified by the following observations:

(a) the high percentage of protein in all tissues except brain, but

(b) brain tissue, which comprises almost equivalent amounts of lipid and protein, shows no significant variation in Δ value from other organs analysed.

Although the model for prediction of Δ values of cancered tissue is insensitive at the particular time of sample ^{14}C activity measurement, no significant differences exist between residence times of carbon in normal and cancered material, both of which appear to be derived from similar metabolic sources. For the remainder of the τ data, 2 major comments may be made:

(i) there are a considerable number of tissues which contain carbon of mean residence time > 5 years and hence demonstrate the presence

in them of 'long-term' carbon

(ii) from Table 4.13, 2 values/ranges of value of the mean turnover time of carbon emerge for most tissues, certainly in the organs most abundantly analysed.

Further consideration of the Δ_T data of the tissues of the 21 year-old individuals helps to differentiate between the 2 choices and favours the conclusion that the carbon content possesses a finite residence time, at least $>$ 2 years. Besides heart, spleen, and thyroid carbon of the 21 year-old male, all of which reveal, from their Δ_T values, the presence of long-lived carbon ($\tau > 5$ years), the ^{14}C activities of the bulk of the remaining material are notably higher than contemporary dietary ^{14}C levels. Figs. 4.4 and 4.5 illustrate that there is a negligible variation between corresponding Δ_T curves predicted for τ = 0-2 years. Alternatively, if carbon in a tissue possesses a residence time $\leq$ 2 years, no difference is to be expected in the observed Δ value of that tissue between a 21 year-old and older individuals. Thus the consistently higher ^{14}C contents of tissue carbon of the former donor implies a τ value of at least 2-5 years. This argument plus the fact that long residence times alone have been detected, are invoked to justify a preference for the upper choice of residence time. Accordingly, Fig. 4.7 shows the histogram of τ values of the major organs, based on the upper value/range of values of turnover times of Table 4.13, where applicable. Finally, Table 4.14 summarises the mean residence time of soft tissue carbon estimated in this study for each organ. Taking all results except that of bone collagen into consideration, a representative value of the mean turnover time of all soft tissue carbon in the body is taken as 6 $\pm$ 4 years. Furthermore, no relationship between ^{14}C content/

FIG. 4.7 HISTOGRAMS OF TISSUE RESIDENCE TIMES

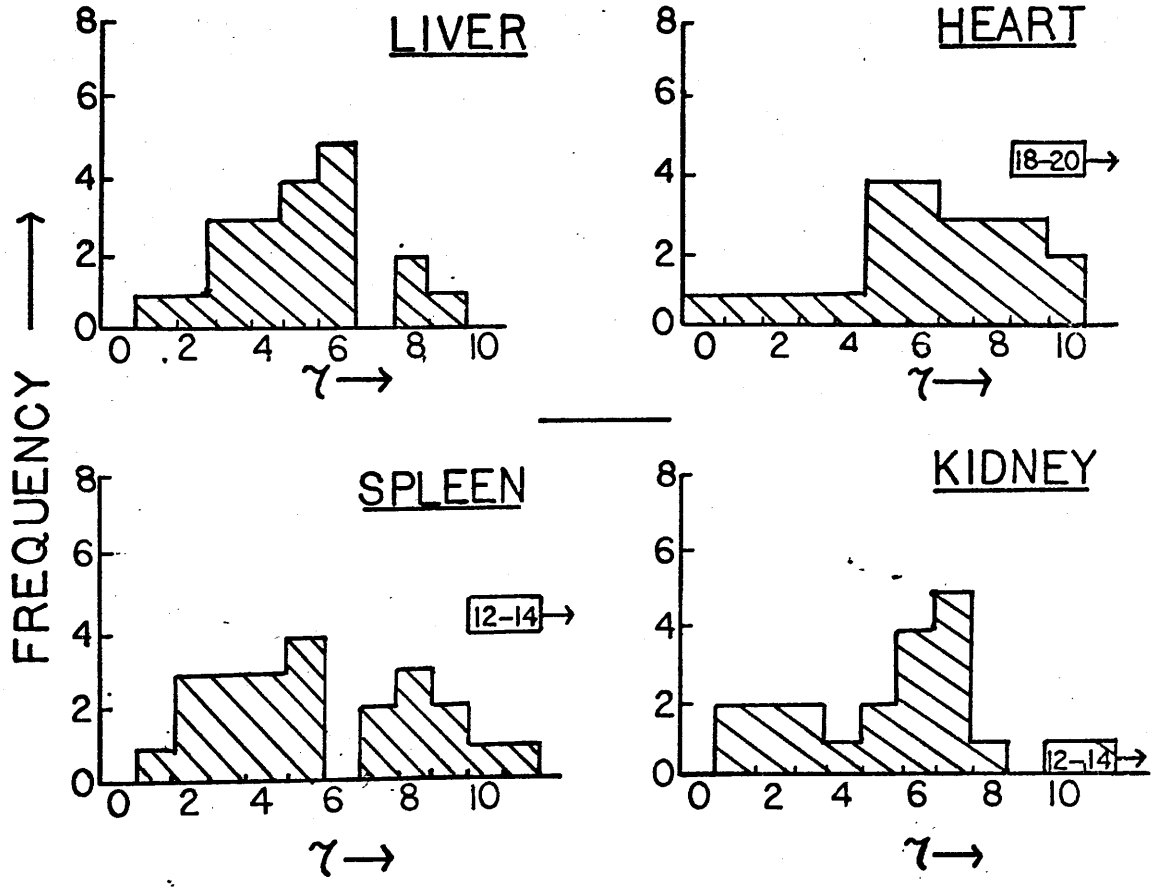


TABLE 4.14 SUMMARY OF RESIDENCE TIMES OF CARBON IN SOFT TISSUES

TISSUE	MEAN RESIDENCE TIME (years)
Heart	6 ± 4
Spleen	2-9
Liver	(5-6) ± 2
Kidney	(6-7) ± 1
Muscle	4 ± 2
Brain	5-6
Lung	8 ± 3
Pancreas	5 ± 2
Testis/Ovary	6 ± 4
Thyroid	10 ± 2

turnover time of carbon in each tissue and age of donor is apparent from the ^{14}C activity measurements performed in this study.

Very few relevant data are available for comparison with the findings of this research. Early measurements by Libby, Berger, and collaborators, of the ^{14}C content of blood and tissue carbon (Libby et al. 1964, Berger et al. 1965, Berger and Libby 1966, ibid. 1967) are difficult to assess in terms of carbon residence times owing to the large increase, $\simeq 60\%$, in atmospheric ^{14}C activity at the period of sampling. However, with ^{14}C data on the tissues of persons from both hemispheres, these workers demonstrated that incorporation of ^{14}C into brain protein and lipid fractions, and liver, heart, plasma, and erythrocyte proteins reflected the ^{14}C content of the atmosphere several months earlier. Cartilage carbon, on the other hand, was shown to be metabolically inert in adult humans. Nydal et al. (1971) measured the ^{14}C activity of whole blood and hair samples in the same individuals over a period of 7 years; the major conclusion of this research was the estimation of the mean residence time of carbon in humans to be 10 years, somewhat higher than the representative figure found in this present study. Perhaps the most appropriate data for comparison with the results reported here, however, are the ^{14}C activity measurements of whole tissue performed by Harkness and Walton (1972) under similar sampling conditions. Their Δ_T values are subjected to the model treatment applied to mature tissues and the resultant estimates of carbon residence times are shown in Table 4.15, presented in a similar form to that of Table 4.13. Although, in several samples, a choice of values/range of γ values is apparent even at this sampling period, there is good agreement with the results listed in Table 4.14.

With respect to the investigation of tissue metabolism outside

TABLE 4.15 COMPARISON OF DATA OF HARKNESS AND WALTON (1972) WITH THE THEORETICALLY PREDICTED CURVES OF FIGURE 4.

TISSUE	MEAN RESIDENCE TIME
	τ (years)
Brain	$(0\text{-}3)^{+1}$
Liver	0/5
Kidney	0/5
Uterus	6-7
Ovary	(0-1)/4
Muscle	$(0\text{-}2)^{+2}$
Fat	5-6
Bone marrow	7-8
Bone collagen	$(15\text{-}17)^{+2}_{-1}$

the field of bomb ^{14}C, the use of isotopic tracers has long been established, particularly for fat and protein metabolism, as described by Schoenheimer (1942). Through the use of ^{15}N, the latter worker and colleagues demonstrated the rapid incorporation of amino acids into the proteins of plasma, intestine, liver, spleen, and bone marrow; on the other hand, bone, skin, and muscle incorporated only small amounts of ^{15}N-amino acid per unit weight of tissue (Shemin and Rittenberg 1944, Sprinson and Rittenberg 1949). Subsequent research, using tritium, proved that tissue proteins were heterogeneous with regard to rates of metabolism; the half-life of the long-lived component of brain, for example, was found to be about 150 days, while bone contained a tissue component with $t_{\frac{1}{2}} > 300$ days (Thompson and Ballou 1956). It should be noted that the majority of such experiments were conducted over a period of days, or at the most, months.

During such a time period, 3 types of protein turnover could be distinguished and were found to vary with different cells/tissues:

(a) replacement of whole cells by mitosis, the process of cell division,

(b) renewal of subcellular protein, and

(c) turnover of the soluble constituents of the cell without actual renewal of microscopic structures e.g. nuclear protein.

For experiments with tracers performed over a short period of time, each of the stated processes requires consideration (Neuberger and Richards 1964). On the other hand, differences of several days or months in the turnover of either protein or whole tissue cannot be distinguished by the use of bomb ^{14}C; the latter tracer is best applied to the detection of long residence times and, in this situation, distinction between different types of turnover is not critical. This

fact may be confirmed by comparison of the ^{14}C contents of liver, spleen, and kidney —tissues with high mitotic rates —with that of brain and muscle, where cell division is virtually absent; no appreciable difference in the interpretation of the observed Δ_T data is apparent. Thus while 'normal' kinetic experiments using tracers are designed to distinguish differences of metabolic activity in terms of days, the short-term nature of such work is ill-equipped to detect the presence of carbon with mean turnover time in the order of years. An important exception to this situation is the demonstration of metabolic inertness of most of body collagen (Thompson and Ballou 1956). The application of bomb ^{14}C as a biological tracer is, in contrast, best suited for the detection of carbon of long residence time i.e. >10 years. In this respect, it is surprising to note the number of tissues which fall into this latter category. Despite the obvious ambiguity in many of the determinations of γ, about 25% of all tissues analysed indicate unquestionably the presence of long-lived carbon ($\geqslant 8$ years).

In consideration of these results and of the conclusions of the areas of research discussed previously, it is apparent that, as far as the sensitivity of bomb ^{14}C is concerned, there are basically 2 types of carbon detectable:

(a) a metabolically 'active' fraction, of residence time $\simeq$ 0-1 yrs. and (b) a metabolically 'inactive' fraction, of residence time >10 yrs. The terms 'active' and 'inactive' are purely relative. The former component corresponds to that material which is readily identified by normal kinetic experiments and there is no apparent reason why this fraction should not be present in the tissues sampled in this study; a simple calculation based on metabolism studies indicates that the major

portion of body protein probably possesses such a turnover. Dietary protein utilised in the synthesis of body protein is estimated to be ~35g. per day for a 70kg. man (Munro 1969) whereas the corresponding figure for the total non-skeletal protein is ~8000g. (Forbes et al. 1953). Manipulation of both figures shows that an amount of protein equivalent to total soft tissue protein is replaced in less than 300 days, but on the assumption that this protein is metabolically homogeneous. For every component with a turnover less than this value, therefore, there is a corresponding fraction with residence time greater than the mean γ value. Although there are proteins of widely different rates of breakdown and renewal within the classification metabolically 'active' (Neuberger and Richards 1964), for the purposes of bomb ^{14}C, one category is adequate. With regard to the inactive component - case (b) - in view of the results of turnover studies of collagen (Neuberger et al. 1951, Gerber et al. 1960, Thompson and Ballou 1956) in agreement with the long residence time of bone collagen recorded in this study, there is a temptation to propose body collagen as the major component of soft tissue which contains long-lived carbon.

Collagen is the major structural protein of mammals, and comprises 20-25% of total body protein in man (Neuberger and Richards 1964). Unlike the highly soluble globular proteins, collagen in its most common form is insoluble and fibrous in nature. This protein exists in the extracellular compartment of connective tissue which, in turn, is found in every organ of the body. Different forms of collagen, with characteristic chemical and metabolic properties, have been identified, even in the same protein fraction. Gerber et al. (1960) demonstrated the existence of long- and short-lived components

in bone. This finding is in agreement with the ^{14}C activity measurement of bone collagen in the 72 year-old male of the present research; the Δ value obtained indicates that the collagen fraction is not totally inert since a small amount of bomb ^{14}C has been incorporated. Extensive studies on the turnover of collagen in different tissues of the rat by Kao et al. (1961) revealed the greatest turnover rate of this protein to be in the non-pregnant uterus, while collagen of aorta was found to be as 'inert as that in cartilage'.

For tissues with particularly low Δ_T values, non-representative of the bulk of ^{14}C activity measurements, a simple calculation may be performed to obtain the minimum percentage of 'inactive' component required to produce the observed ^{14}C content in each tissue. For the calculation, each tissue is assumed to contain a metabolically active ($\gamma = 0$) and totally inactive ($\gamma = \infty$) component. The ^{14}C content of each fraction is given by the corresponding dietary and pre-bomb ^{14}C levels respectively. In such a situation, the minimum percentage of metabolically inactive carbon which yields the measured ^{14}C activities can be calculated. The estimates obtained in this way are listed in Table 4.16; the range includes possible discrepancies in the dietary ^{14}C content (i.e. $\pm$ 1 year).

Although the majority of calculated percentages are found to be $< 10\%$, the fraction of collagen in the tissues concerned is considerably smaller than the hypothetical values (e.g. 0.1% collagen in liver, 3% in kidney, 4% in lungs - Bartley et al. 1968). Whatever the source of long-lived carbon readily detectable in many tissues, proof of existence of such a component represents an important contribution to the quantitative interpretation of isotopic tracer experiments in terms of the turnover rates of groups of proteins as opposed to

TABLE 4.16 ESTIMATES OF THE POSSIBLE PERCENTAGE OF INERT CARBON IN CERTAIN TISSUES

TISSUE DESCRIPTION		POSSIBLE FRACTION OF INERT CARBON (%)
Male/50	Liver	8-11
	Testis	18-22
	Heart	5.5-8.5
Female/64	Heart	8-14
	Spleen	0-4.5
Male/39	Liver	5.5-10
	Spleen	14-18
	Thyroid	13-19.5
	Heart	11-15.5
Male/42	Kidney	24-28
	Lung	16-20
	Thyroid	4-7.5
	Spleen	0-8
Male/21	Heart	4.5-10
	Spleen	0-3
	Thyroid	2-8.5
Male/64	Spleen	4.5-8.5
	Kidney (protein)	2.5-7.0

individual species. In the former case, contamination by as much as 25% non-representative carbon may lead to highly erroneous conclusions.

4.6.2 Discussion of δ^{13} data of the lipid extracts · In the previous section, the potential of bomb ^{14}C as a biological tracer was shown to be most constructively applied to the detection of carbon of long residence time. The application of bomb ^{14}C to the interpretation of the ^{14}C activity measurements of the lipids extracted from the intima is therefore particularly valuable. Since the pretreatment of intima results in the extraction of total lipids rather than cholesterol itself, a further appraisal of the content of this extract is considered pertinent prior to subsequent discussion of the observed residence times.

Although the lipid extract is composed of different classes of lipid, the percentage composition of each class is found to maintain a consistent level. Chemical species of lipid which accumulate in human atherosclerotic lesions have been shown in repeated assays to consist predominantly of cholesterol and cholesteryl esters (Lang and Insull 1970) while the proportion of each major lipid class, i.e. cholesterol/cholesteryl ester, phospholipid, and triglyceride, of the lipid-rich inclusions in the intima are significantly different from lipids of the other arterial layers. Comparison of grossly visible fatty streaks and fibrous plaque lesions with adjacent normal intima and media has shown that these lesions accumulate lipids of all 3 major classes but, as previously mentioned, with cholesterol, especially the esters, being the most predominant (Insull and Bartsch 1966). As atherosclerosis progresses from the fatty streak to plaques and complicated lesions, the proportion of arterial lipid content which is composed of free cholesterol and its esters increases while the

phospholipids decrease; triglycerides and free fatty acids remain essentially unchanged from the values observed in normal arteries (Böttcher and Woodford 1962 , Insull and Bartsch 1966).

Although the data presented in Table 4.12(xiv) again show a wide range of values, the final γ estimates, with respect to the model treatment and especially the input data, Δ_S, represent minimum values of the mean turnover time of carbon in the deposit. In the event of a rapid increase in lipids deposited during the years immediately preceding death — the intuitive situation — the ^{14}C content of the extract is expected to contain more contemporary carbon than that predicted by the linear model; in this system, residence times would appear longer than those quoted in Table 4.12(xiv). In addition, the family of curves of predicted Δ_A values, shown in Fig. 4.6, are based on a carbon input which comprises a 70% endogenous source. For the latter reservoir, a mean residence time of carbon is taken as 6 years i.e. the upper choice of the turnover time of liver carbon. For a faster turnover of this reservoir, e.g. $\gamma = 0$, a family of curves similar to Fig. 4.5 is obtained, which results again in longer residence times than those listed. Thus it seems likely that, on the basis of the model treatment, the mean residence time of carbon in the lipid extract of heavily diseased aortas is >10 years. This value, applied to cholesterol/cholesteryl esters alone, contrasts with the results of tracer experiments (Goodman 1970) which indicate that arterial and serum cholesterol levels equilibrate fairly rapidly. However, the restriction of short-term tracer work applies to the quantitative interpretation of arterial/intimal metabolism as well as to the tissues of the previous section.

Discussion of the ^{14}C activities measured in the arterial deposit

would not be complete without reference to a further possible mechanism of lipid accumulation in the arterial wall — 'in situ' synthesis. By this mechanism, the assumption inherent in the model i.e. that deposition of carbon occurs from blood plasma, breaks down. This latter assumption is based on numerous experimental observations on the bulk of cholesterol and its esters as present in atherosclerotic lesions (e.g. Lofland et al. 1968, Newman and Zilversmit 1962). In situ synthesis, on the other hand, is invoked to explain the accumulation of phospholipid in the arterial wall (Zilversmit 1970). However, this mechanism affects the ultimate interpretation of γ values only if the precursors of the lipid fraction contain a large percentage of carbon of lower ^{14}C activity i.e. pre-bomb carbon. The most likely identity of such a source of carbon in this situation is collagen or some similar component in connective tissue. The results of Kao et al. (1961) certainly indicate the metabolic inertness of aortic collagen. This factor may be employed to explain the low ^{14}C content detected in carbon of adventitia which was analysed without pretreatment; hence the collagen fraction is not eliminated as in the case of the lipid extracts.

From the assumption that collagen, or at least some source of inert carbon, is the precursor of the lipids analysed, a calculation similar to that performed in the preceding discussion is repeated at this stage to determine data corresponding to that shown in Table 4.16 i.e. in this case the percentage of inert carbon possible in the lipid deposit. The results of the present analysis are shown in Table 4.17 and indicate that values, in all cases except for the intimal extract of the 87 year-old female, are too high to correspond to that of the phospholipid component, the most likely candidate for in situ

TABLE 4.17 ESTIMATE OF POSSIBLE PERCENTAGE OF INERT CARBON IN LIPID EXTRACT

SAMPLE DESCRIPTION		POSSIBLE FRACTION OF INERT CARBON (%)
Male/68	lipid extract	70-85
Male/67	lipid extract	70-80
Male/69	lipid extract	50-60
Female/86	lipid extract	7-12
	adventitia	38-40

synthesis.

It would be presumptious to develop a theory on the pathogenesis of atherosclerosis on the basis of the limited data and the method of ^{14}C activity measurement i.e. total lipid extraction. However, the low values obtained are highly significant in that the only type of carbon known to possess a very slow turnover rate — in the order of years — is that of collagen. Thus 2 possible conclusions may be drawn from the ^{14}C analysis of arterial lipid extracts, each in itself an important basis for further, more detailed research into the origins and treatment of atherosclerosis:

(1) the turnover of lipids in the deposit is extremely slow. Therefore medical treatment to reverse the process of lipid accumulation by metabolic means must be considered as a long-term project i.e. over a period of years

(2) collagen, or some similar component of connective tissue may play a significant, though as yet unknown, role in the origin of the lipid deposit associated with the development of atherosclerosis.

CHAPTER 5. HUMAN RADIATION BURDEN FROM ARTIFICIALLY PRODUCED ^{14}C.

5.1 Environmental Radioactivity

Man is exposed continuously to ionising radiation of natural origin. Since the advent of the nuclear era, however, radioactive fall-out from nuclear weapon tests has resulted in a significant increment in the mean radiation dose received by the world population. ^{14}C, as a component source of both background and artificially produced radioactivity, is worthy of consideration since direct pathways are available for incorporation of this radioactive isotope of carbon into all key molecules of body tissue. In addition, the dose contribution attributable to natural ^{14}C provides a convenient reference for comparison with the dose received from the man-made burden.

Table 5.1 summarises the individual contributions to the absorbed dose received by three of the most critical areas of the body; in consideration of the radiation hazard to humans from low doses, the gonads, bone-marrow and bone-lining cells are important tissues with respect to induction of genetic damage, leukaemia and bone tumours respectively. The major contribution to external radiation arises from decay of isotopes which possess a non-uniform world-wide distribution, namely the γ-emitters of the natural decay series; hence the values quoted in Table 5.1 apply to a "normal" area. Terrestrial radiation may be regarded as the product of decay of 2 classes of radioactive species,

(i) cosmogenic radionuclides, formed continuously by the interaction of cosmic-ray secondaries with matter, and

(ii) primary radionuclides which have survived since the earth's formation together with their daughter isotopes.

TABLE 5.1 DOSE RATES DUE TO INTERNAL AND EXTERNAL IRRADIATION FROM NATURAL SOURCES.

SOURCE OF IONISING RADIATION	DOSE RATE (mrad./year)		
	GONADS	BONE-LINING CELLS	BONE MARROW
EXTERNAL			
Cosmic rays : ionising component	28	28	28
neutron component	0.35	0.35	0.35
Terrestrial radiation (including air)	44	44	44
INTERNAL			
^{3}H	0.001	0.001	0.001
^{14}C	0.69	0.74	0.69
^{40}K	19	15	15
^{87}Rb	0.3	0.6	0.6
^{210}Po	0.6	1.6	0.3
^{220}Rn	0.003	0.05	0.05
^{222}Rn	0.07	0.08	0.08
^{226}Ra	0.02	0.6	0.1
^{228}Ra	0.03	0.8	0.1
^{238}U	0.03	0.3	0.06
TOTAL (rounded)	93	92	89

^{14}C , with its relatively high rate of production (~ 2.5 atoms/cm.^{2}/sec.) and long half-life, is the major contributor to the former class in which 20 radioactive species have been detected (Lal and Suess 1968). Table 5.1 indicates the dose contribution from decay of this radioisotope to be about 3% of the internal and 1% of the total natural radiation dose.

Radioactive fallout from nuclear weapon tests, particularly those which occurred in the years 1961-1962, represents the major man-made source of environmental radioactivity and is discussed with reference to ^{14}C production in Chapter 1 (1.4). Rates of transfer of radioactive debris from stratosphere to troposphere and of deposition on land are of importance in determination of the radiation hazard from nuclear explosions, since most of the radioactive material produced in explosions >1 Mton is injected into the stratosphere. In the latter reservoir, the mean residence time of ^{90}Sr has been determined as 1.6 years (Fabian et al. 1968) compared to 4 years, the corresponding value obtained for excess ^{14}C (Walton et al. 1970). On the other hand, particulate material in the troposphere is rapidly removed via wet deposition (Junge 1963) so that the mean residence time of nuclear debris in this reservoir is only about 30 days (United Nations 1972a) cf. ^{14}C, mean residence time $\simeq$8 years prior to transfer to the biosphere (Walton et al. 1970). The major radioisotopes produced in fallout are listed in Table 5.2 together with relevant information on their uptake by man. Besides short-lived γ-emitters of which ^{95}Zr and ^{140}Ba are potentially most hazardous, ^{137}Cs is the predominant source of external irradiation.

5.2 Calculation of the Absorbed Radiation Dose Attributable to Bomb ^{14}C.

5.2.1 Annual absorbed dose for the period 1955-1973 Determination of

TABLE 5.2 NUCLEAR WEAPON FALLOUT — IMPORTANT RADIOISOTOPES AND THEIR PROPERTIES

RADIOISOTOPES AND MODE OF DECAY	HALF-LIFE	TOTAL PRODUCTION TO 1970 (MCi)	MAJOR MODE OF UPTAKE BY MAN	SITE OF BODY IRRADIATION
^{3}H β_{max} 0.018 Mev.	12.8 y.	1900	water	whole body
^{14}C β_{max} 0.156 MeV.	5730 y.	6.2	terrestrial food chain	whole body
^{55}Fe electron capture	2.6 y.	50	terrestrial food chain marine food chain	65% red blood cells 35% soft tissue
^{137}Cs β_{max} 1.176 MeV.	30 y.	19.7*	milk	80% muscle 9% bone
^{131}I β_{max} 0.806 MeV.	8 days	-	ingestion/inhalation	thyroid
^{239}Pu α 5.160 MeV.	2.4×10^{4} y.	0.3	inhalation	lymph nodes/lung/liver/bone
^{85}Kr γ 0.514 MeV. β_{max} 0.670 MeV.	10.8 y.	3	(inhalation)	skin/subcutaneous tissue (external)
^{90}Sr β_{max} 0.546 MeV.	28 y.	12.4*	milk	bone

* UKAEA (1973). All other information obtained from United Nations (1972a).

the dose contribution from any radioactive species deposited within the body requires a knowledge of

(a) the concentration and distribution of the isotope in the target medium, and

(b) the characteristics of energy loss of the emitted radioactive particle(s).

The present study enables not only a direct estimate of recent ^{14}C concentrations in tissues but also a good assessment of future body levels of this isotope. In addition, normal participation of ^{14}C in the carbon cycle - particularly its uptake by and subsequent turnover in man - ensures essentially a uniform isotopic distribution throughout any particular organ. The range of almost all β-particles emitted from radioisotopes within the body is such that all energy dissipation is confined to the tissue region in which the radionuclide was contained. This property is particularly applicable to the low-energy β-particle emitted from ^{14}C - maximum range $\simeq 300\mu$ in soft tissue. Thus on the basis that ^{14}C is distributed homogeneously in the tissue under investigation and that the range of β-particles is small compared to the dimensions of the medium, the absorbed dose rate attributable to ^{14}C, D_a,

$$D_a = A \times \bar{E}_\beta \times 1.6 \times 10^{-5} \times c \times 10^{-2} \text{ mrad./min.}$$

where A = activity of ^{14}C (d.p.m. per g. carbon)

c = % carbon in a tissue.

$\bar{E}_\beta$ = mean energy of the emitted β-particle (MeV.),

1.6×10^{-5} = conversion factor, to convert MeV/g. to mrad.

For the calculation of the absorbed dose rate from natural ^{14}C, $A = 13.56 \pm 0.06$ (Karlen et al. 1964) and $\bar{E}_\beta$ is taken to be 0.05 MeV. The average content of carbon in the whole body is estimated at 18% by

weight, but more accurate values for particular regions of the body are:

soft tissue, including bone marrow 12% (United Nations 1962)

bone - - - - - - - - - - - - - - - - 13% (ICRP 1960)

From these percentages, the annual radiation dose contributed by natural ^{14}C is determined to be 0.69 mrad. and 0.74 mrad. to soft tissue/bone marrow and bone-lining cells respectively.

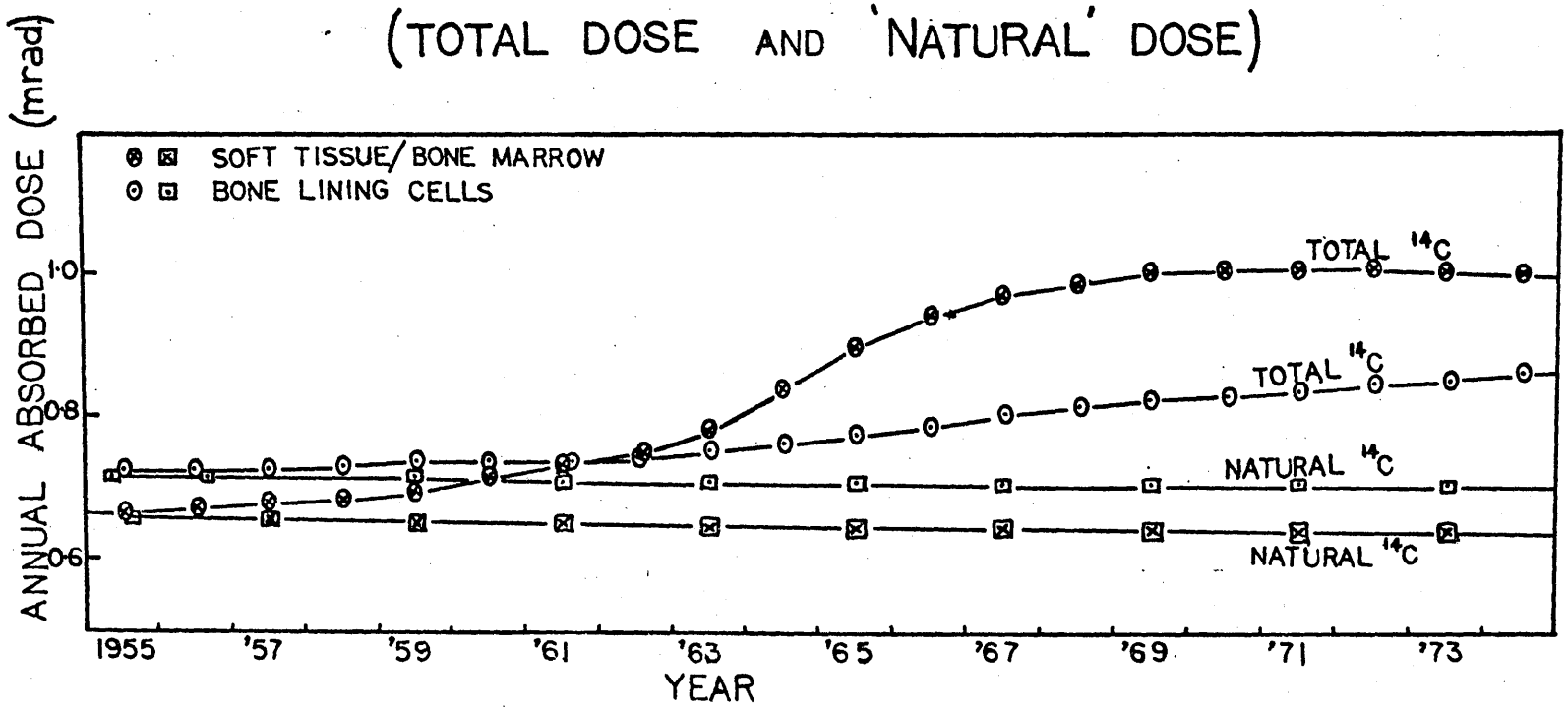
Analysis of concentrations of artificially produced ^{14}C in the environment is performed in such a way that ^{14}C activities are related to the natural level; thus a similar treatment is appropriate for the calculation of absorbed dose rates. From a knowledge of the absorbed radiation dose attributable to natural ^{14}C, environmental doses received from decay of this radionuclide may be calculated directly via Δvalues. The ^{14}C activity of a tissue sample expressed as Δ represents the per mil deviation of its $^{14}C/^{12}C$ concentration from the corresponding 1890 level; similarly the absorbed dose from ^{14}C for such a sample may be obtained via the equation:

$$D_S = D_N \cdot \left[1 + \frac{\Delta_S}{1000}\right] \qquad \text{- - - - - - - - (5.1)}$$

where D_S and D_N represent the annual absorbed radiation doses attributable to ^{14}C in sample and 1890 (i.e. natural ^{14}C) wood respectively.

From estimates in the previous chapter of turnover times of carbon in different tissues of the body, $\tau = 6$ years is taken as a representative figure for the mean residence time of carbon in soft tissue and is used here for absorbed dose evaluation. Insertion into equation (5.1) of the annual Δ values predicted by the single compartment model and plotted in Fig. 4.4 yields the annual absorbed dose attributable to ^{14}C, both the natural and artificial components. The latter quantity is plotted for each year 1955-1973 as shown in Fig. 5.1. A similar

FIG. 5.1 ANNUAL ABSORBED DOSE FROM ^{14}C
(TOTAL DOSE AND 'NATURAL' DOSE)



treatment for bone-lining cells is performed for $\gamma = 30$ years and the resultant values are plotted also in Fig. 5.1. In order to provide a comparison of the latter curves with pre-bomb dose levels, the absorbed dose from natural ^{14}C has been calculated for the corresponding time period and is based on predictions of the atmospheric ^{14}C (Baxter and Walton 1970b). The doses from natural ^{14}C estimated in this manner appear as the lower curves in Fig. 5.1. Comparison of Figs. 4.4 and 4.5, i.e. the ^{14}C content of mature and growing tissues, indicates a minimal error in the extension of soft tissue dose calculations performed for adult humans to the situation where steady-state assumptions are not applicable. In the case of bone collagen however, such an extrapolation is not valid; however for the purposes of an approximate dose estimate, a linear increase in bone collagen with no turnover of carbon may be assumed. In this situation the annual absorbed dose for a 20 year-old is equivalent to the average of each annual dose contribution received prior to this age. Thus the maximum annual absorbed dose from ^{14}C in the bone-lining cells will be delivered in 1984 to individuals born in 1965 and will amount to 1.07 mrad. Data calculated in this section are strictly applicable to persons living in the northern hemisphere but may be applied with minimal error to persons in the southern hemisphere for determinations of accumulated radiation doses (see section 5.2.2)

5.2.2 Annual absorbed doses for the period 1974-2025 Evaluation of future absorbed dose contributions from bomb ^{14}C requires a knowledge of values of Δ_T for insertion in equation 5.1; this data, in turn, may be assessed from future dietary and hence future atmospheric and surface ocean ^{14}C activities (as seen in equation I, chapter 4). Model predictions of the latter quantities have been performed by Gulliksen

and Nydal (1972) and are expressed mathematically as a function of time as shown below:

for troposphere, $\Delta_A = 85e^{-0.06t} - 45e^{-1.8t}$, where for t=0 in 1963 $\Delta_A = 40\%$

and for surface ocean, $\Delta_s = -5 - 27e^{-0.34t} + 33e^{-0.06t} + 3e^{-1.8t}$, where for t = 0 in 1963, $\Delta_s = 4\%$

From the data obtained by insertion of appropriate 't' values into these equations, the mean annual ^{14}C content of the diet was evaluated for the years 1975-2025 and combined with values of $\tau = 6$ years and 20 years, the mean residence time of carbon in soft tissues and bone collagen respectively, in the calculation of future concentrations of ^{14}C in the human body. Predicted values of tropospheric, dietary and tissue ^{14}C content are shown in Fig. 5.2. Minor modifications of the dietary habits of the population are not expected to affect final Δ_T values significantly; rather the major uncertainty in the latter estimates is associated with the error in predictions of future tropospheric and, to a lesser extent, surface ocean ^{14}C activities. Provided that there is no further major artificial production of this radioisotope, Fig. 5.2 indicates that the ^{14}C content of the atmosphere will return to within 2% of the natural level by the year 2025, essentially via (a) exchange of carbon with the oceans and (b) dilution with inactive CO_2 (Suess effect). The corresponding annual absorbed radiation doses are calculated as previously and the resultant data are plotted in Fig. 5.3. With the aid of the theoretical predictions made by Baxter and Walton (1970b) concerning the decrease in tropospheric ^{14}C activity for the years 1975-2025, corresponding absorbed doses attributable to natural ^{14}C alone enhances an appreciation of the impact of bomb ^{14}C on the total dose received from this radioisotope; thus although future

FIG. 5.2 PREDICTED ^{14}C CONTENT OF TROPOSPHERE, DIET, AND TISSUES (1974-2025)

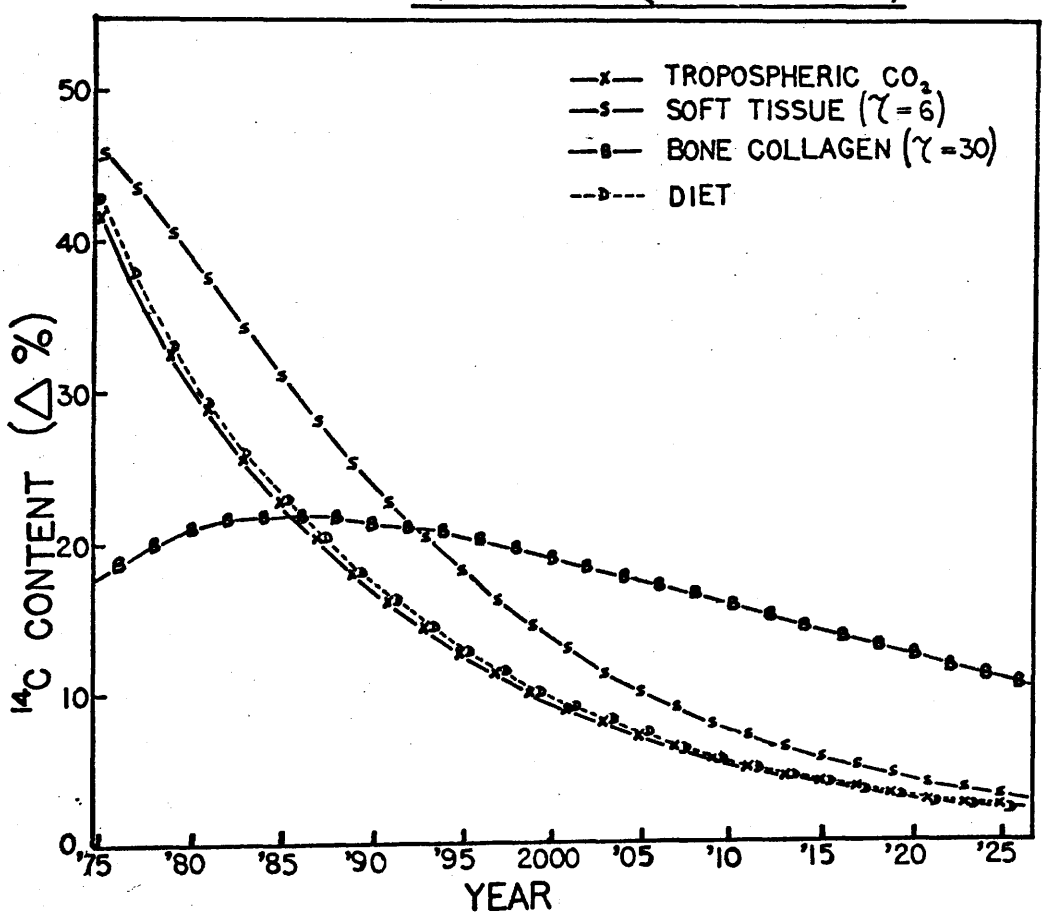
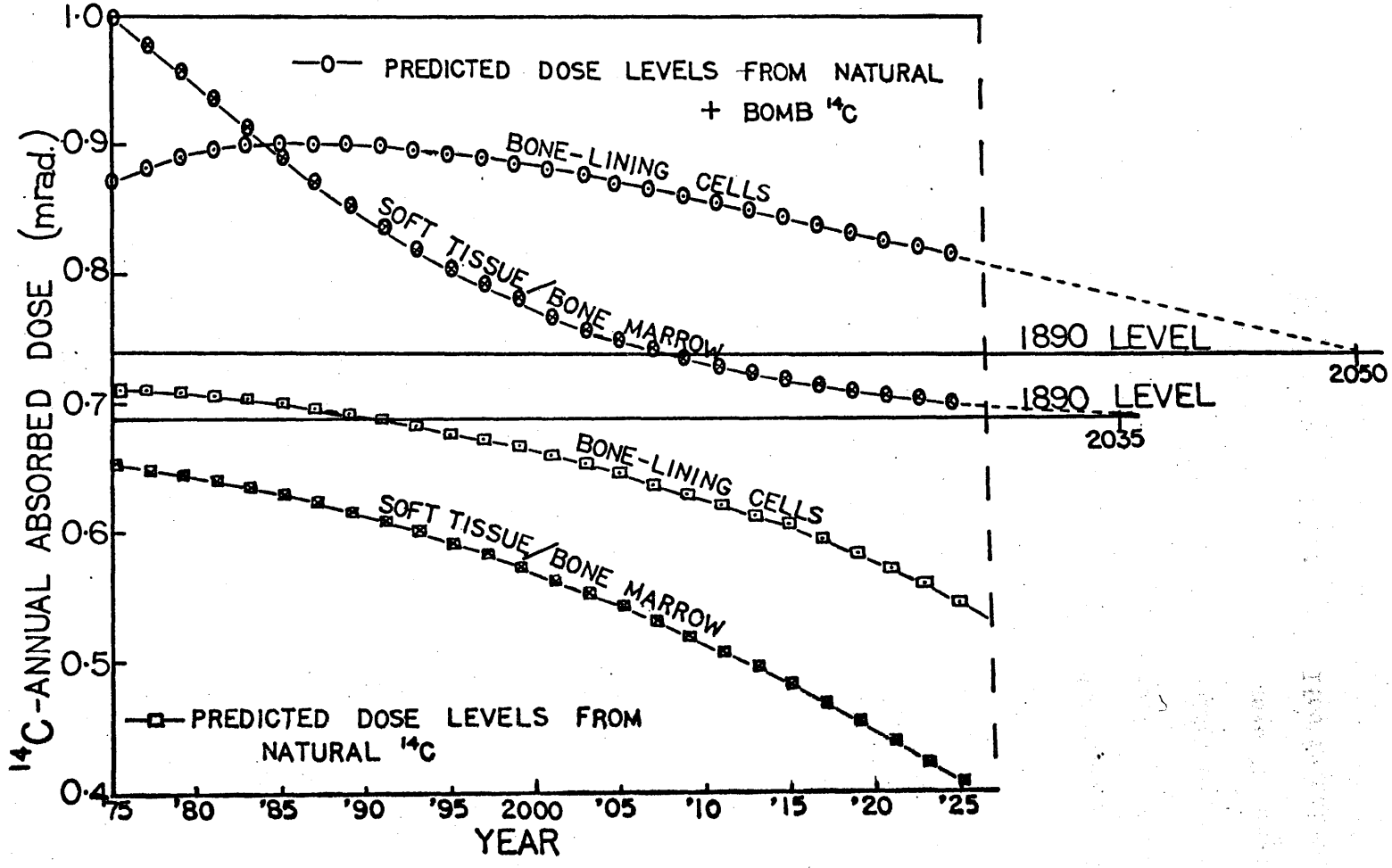


FIG. 5.3 FUTURE DOSE LEVELS TO SOFT TISSUE AND BONE-LINING CELLS (1975-2025)



environmental ^{14}C levels will approach pre-bomb concentrations again by the first half of next century, Fig. 5.3 shows that there is still an appreciable contribution to this dose level from artificially produced ^{14}C.

5.2.3 Accumulated absorbed doses due to environmental ^{14}C In the evaluation of non-threshold biological effects of radiation e.g. genetic damage, the absorbed dose accumulated over several years is of greater relevance than annual absorbed doses. Mutations produced in reproductive cells are cumulative and the number of new radiation-induced mutations that an individual will transmit to offspring depends on the total amount of radiation received by the reproductive organs from his/her own conception to the time each of his/her offspring is conceived. Thus for the determination of the radiation-induced genetic damage to each generation and of significance to subsequent generations, the dose received from ^{14}C decay in the reproductive organs over a period of 30 years (Penrose 1955) is considered; similarly for late somatic effects e.g. leukaemia, 60 years is applicable. Table 5.3 illustrates particular examples of the 30-year accumulated dose to soft tissue/bone marrow and bone-lining cells from both natural and total (i.e. natural and bomb-produced) ^{14}C. The maximum 60-year dose to bone-lining cells is accumulated from birth in 1965 until 2025 and is included in Table 5.3. Absorbed doses directly attributable to bomb ^{14}C may be obtained via the differences between each column of data for both tissues considered; resultant values are shown in Table 5.4. Nydal et al. (1971) calculated the absorbed dose from bomb ^{14}C over the 30-year period 1970-2000 to be 11 mrad. and 7 mrad. to bone-lining cells and soft tissue/bone marrow respectively; however these figures are based on different values of the annual dose from natural ^{14}C. Recalculation of these workers' results using the more

TABLE 5.3 ACCUMULATED ABSORBED DOSES DUE TO ENVIRONMENTAL ^{14}C

PERIOD UNDER CONSIDERATION	30 YEAR ACCUMULATED DOSE (mrad.)			
	SOFT TISSUE/BONE MARROW		BONE-LINING CELLS	
	TOTAL ^{14}C (natural + bomb)	NATURAL ^{14}C	TOTAL ^{14}C	NATURAL ^{14}C
pre 1890	20.58	20.58	22.29	22.29
1925 - 1954	19.80	19.80	21.81	21.81
1955 - 1984	26.78	19.52	24.56	21.40
1964 - 1993	27.90*	19.09	26.04	21.09
1970 - 1999	27.01	18.70	26.55*	20.86
1985 - 2014	23.58	16.93	26.33	19.76
1965 - 2024	bone growth during initial 20 years		64.20*	39.40

* maximum value in each category.

TABLE 5.4 ACCUMULATED ABSORBED DOSES DUE TO BOMB ^{14}C

PERIOD UNDER CONSIDERATION	ACCUMULATED DOSE (mrad.)	
	SOFT TISSUE/ BONE MARROW	BONE-LINING CELLS
pre 1890	-	-
1925-1954	-	-
1955-1984	7.26	3.16
1964-1993	8.81*	4.95
1970-1999	8.31	5.69
1985-2014	6.65	6.57*
1965-2024	60-year dose	24.80*

* maximum doses.

recent values of the latter quantity yields 7.24 mrad. for bone-lining cells and 6.70 mrad. for soft tissue/bone marrow. Although no allowance is made for differences in turnover times of carbon in the body, the adjusted values are in reasonable agreement with the results obtained in this study.

The total absorbed dose attributable to any radioisotope is obtained by integration of the dose over that period of time during which there is a significant contribution to the world population. The resultant quantity, known as the dose commitment, is important in consideration of the long-term genetic threat represented by the isotope under consideration. The method of calculation of the dose commitment, D_C from bomb ^{14}C is via the formula

$$D_C = (T \times A/N)D_N \text{(United Nations 1972a)}$$

where T = mean life of a ^{14}C atom $\simeq$ 8300 years

A = total quantity of artificially produced ^{14}C

= 6.2 MCi. (Fairhall et al. 1968) and

N = steady-state inventory of natural $^{14}C \simeq$ 280 MCi.

From these values, D_C is evaluated as 140 mrad. and 170 mrad. to soft tissue/bone marrow and bone-lining cells respectively. These figures tend to overestimate the potential radiation hazard from bomb ^{14}C, however, as a result of total neglect of the Suess effect which, in the absence of an artificial source of ^{14}C, would be expressed in the troposphere as a decrease of approximately 50% below the natural level by the year 2025. The total accumulated absorbed dose from bomb ^{14}C considered to be important with respect to this study, therefore, is that obtained by summation of all annual absorbed doses due to this radioisotope in excess of that delivered by the corresponding pre-1890 level. Such a summation is performed for each year until 2050 in the case of bone-

lining cells, and 2035 for soft tissue/bone marrow; these temporal limits are obtained by linear extrapolation of the upper curves of Fig. 5.3. The accumulated dose from bomb ^{14}C evaluated in this way corresponds to $\simeq$ 10 mrad. and $\simeq$ 8.5 mrad. delivered to soft tissue/bone marrow and bone-lining cells respectively. Although this treatment yields quantities well below the dose-commitments from bomb ^{14}C as calculated in the UNSCEAR report (1972a), the former values are more relevant for discussion of the additional radiation hazard provided by the man-made burden. Table 5.5 allows comparison of the dose-commitments of other major artificially produced radioisotopes with the accumulated doses determined in this research project. For the fission products ^{90}Sr and ^{137}Cs, the total dose received in the northern hemisphere population exceeds that of the southern hemisphere as a consequence of the rapid rate of deposition of these radioactive species in the former location relative to inter-hemispheric mixing rates. With the exception of ^{14}C, essentially all of the total dose from radioactive fallout produced in nuclear weapon tests carried out prior to 1970 will be delivered to the population by the year 2000 as a result of radioactive decay and environmental processes e.g. erosion, dispersion, which prevent uptake of fission products by man. ^{14}C decay, on the other hand, is responsible for the loss of $<$ 1% of total bomb ^{14}C; in addition, this radioisotope is retained in the dynamic carbon cycle where it is available for transfer to man. Thus the dilution effect of fossil CO_2 is the major influence responsible for the 'reduced' radiation dose attributable to artificially produced ^{14}C.

5.3 Radiation hazard associated with ^{14}C

5.3.1 General considerations Although the maximum per caput absorbed dose attributable to bomb ^{14}C accumulated over 30 years represents

TABLE 5.5 DOSE COMMITMENT FROM RADIOACTIVE FALLOUT

PRODUCED IN NUCLEAR WEAPON TESTS PRIOR TO 1971

SOURCE OF RADIATION	DOSE COMMITMENT (mrad.)					
	NORTHERN HEMISPHERE			WORLD POPULATION		
	GONADS	BONE-LINING CELLS	BONE MARROW	GONADS	BONE-LINING CELLS	BONE MARROW
EXTERNAL						
Short-lived isotopes	65	65	65	44	44	44
^{137}Cs	59	59	59	40	40	40
^{85}Kr	2×10^{-4}	2×10^{-4}	2×10^{-4}	2×10^{-4}	2×10^{-4}	2×10^{-4}
INTERNAL						
^{3}H	4	4	4	4	4	4
^{14}C	10(140)	8.5(170)	10(140)	10(140)	8.5(170)	10(140)
* ^{14}C	8(12)	4(15)	8(12)	8(12)	4(15)	8(12) *
^{55}Fe	1	1	0.6	0.7	0.7	0.4
^{90}Sr	-	85	62	-	57	42
^{137}Cs	26	26	26	7	7	7
^{239}Pu	-	0.2	-	-	0.1	-

* Dose to the year 2000.

Other isotopes and ( ) ^{14}C data from United Nations (1972a).

≃ 30%-45% of the corresponding dose contributed by natural ^{14}C, artificial production of this radioisotope was cause for concern among several eminent scientists, notably Pauling, soon after completion of the initial weapons testing. Significance was attached particularly to the potential radiation hazard from ^{14}C with respect to genetic damage and certain late somatic effects for which there appears to be no threshold radiation dose. Experimental investigation of this topic reveals a direct linear relationship between total dose accumulated in an organism and mutation frequency, in the low dose range down to 25R as well as in the high (Uphoff and Stern 1949). Experiments performed at exposure doses lower than 25R are necessarily tedious and rarely performed although Glass and Ritterhoff (1961) noted an induced mutation frequency in Drosphila melanogaster significantly above the spontaneous level of mutation with an X-ray dose as low as 5R. However, the lack of evidence to suggest otherwise leads to the assumption, for radiation genetic consideration at least, that this linear relationship extends to zero dosage. Acceptance of such an assumption results in the general opinion among geneticists that mutation frequency with any dose above zero R, no matter how low, is increased. Thus there is no small radiation dose that can be regarded as entirely harmless biologically i.e. there is no threshold dose for genetic damage from ionising radiation.

Genetic material comprises chromosomes, long threadlike structures within the cell nucleus, and genes, the funtional units of which chromosomes are composed. Information required by a particular cell for control of its metabolism and self-replication processes is contained in the DNA component of chromosomes and is encoded in the special arrangement of pyrimidine-and purine-base pairs linked together by hydrogen bonds. The DNA content of a mammalian diploid cell is ≃ 9×10^{-12} g. (Veatch and

Okada 1969) while the molecular weight of this macromolecule is estimated to be $>5 \times 10^9$ (Lett et al. 1967); thus few DNA molecules are contained in each cell.

Cell reproductive death and hereditary changes in surviving cells are possibly the two most important visible expressions of biological damage from ionising radiation. However, at the cellular level, ionising radiation can give rise to 2 types of mutation:

(i) gene, or point mutations i.e. alteration of the normal function of individual genes, and

(ii) chromosome aberrations i.e. changes in the structure/number of chromosomes via rearrangement or loss of blocks of genes.

Both changes may occur in either somatic cells, with consequences only to the individual concerned, or in germ cells, with consequences to immediate offspring and future generations. For β-decay processes, there exists an additional mechanism associated with the daughter nucleus which may upset the normal cellular balance and be responsible for mutations similar to those resulting from the ionising radiation itself. Thus with regard to biological damage by ^{14}C decay, 2 mechanisms are available:

(i) the ionising radiation associated with the β-particle, β_{max} = 0.156 MeV., and

(ii) the transmutation effect of ^{14}C associated with the daughter nucleus ^{14}N.

The factors involved in each process are discussed separately with particular emphasis on possible damage to genetic material. More information is available on the former process since the biological effects produced by β-irradiation and other types of ionising radiation are qualitatively similar and as such have been the subject of intense research since the discovery of X-rays by Roentgen in 1895.

5.3.2 Biological effects of ionising radiation at the molecular and cellular levels. The processes involved with cellular damage produced by ionising radiation may be classified into 3 levels of effect,

(a) initial absorption of radiation by the surrounding medium,

(b) radiochemical reactions and the resultant production of new stable species, and

(c) manifestation of damage via biochemical/physiological reactions.

Since body tissue comprises ~75%-85% by weight of water, the major component of radiation energy is transferred directly to water with the resultant formation of radicals and other primary products as shown in the following equation:

$H_2O \rightsquigarrow e^-_{(aq)}, {}^{\bullet}H, {}^{\bullet}OH, H_2, H_2O_2, H_2O^+$ (Allen 1961)

The solute constituent of the cell, essentially organic molecules, may be altered either by direct transfer of radiation energy or via interaction with primary water radicals. Thus when a living cell is subjected to ionising radiation, its DNA content may be damaged directly or, more likely, by attack by radicals produced in the vicinity of the DNA. Of the species which interact with this macromolecule, the .OH radical is the most reactive rate constant $\left[k_{(.OH + DNA)} = 6 \times 10^8 \text{ moles}^{-1} \text{ sec.}^{-1}\right]$ (Myers et al. 1968) while the major site of attack is determined experimentally to be the purine and pyrimidine bases (Scholes et al. 1960)

Radiation-induced chemical changes which occur in DNA include

(a) cleavage of bonds between bases or sugar and phosphate, with resultant strand breakage

(b) modification of nucleic acid bases, and

(c) DNA-DNA, DNA-RNA, and DNA-protein cross-linkages (Cerutti 1974)

These alterations, of which the latter is least documented, are reflected

in modified physical properties of DNA, either physical e.g. molecular weight change produced by single- and double-strand breakage, or chemical e.g. release of inorganic phosphate (Scholes and Weiss 1952). With respect to DNA strand cleavage, single- (SSB) or double-strand (DSB) breaks have both been detected, though normally in the ratio SSB/DSB ≃ 10 (Freifelder 1965, Veatch and Okada 1969)

Single-strand breaks The .OH radical is responsible for ≃ 70% of this damage in DNA (Ward and Kuo 1973). Estimates of the number of single-strand breaks induced in mammalian DNA by ionising radiation are commonly found in the range 7 - 10 SSB/cell/rad (Roots and Okada 1972, Painter 1970) although the radiosensitivity of DNA in terms of the number of radiation-induced single-strand breaks per DNA unit per rad is comparable in all organisms studied i.e. viruses, bacteria and mammalian cells (Sawada and Okada 1972). In terms of the energy requirements for DNA strand breakage, the efficiency of single-strand breaks in mammalian cells is found to range from 44eV. (Ormerod and Stevens 1971) to 70eV. (Lett et al. 1967)

Double-strand breaks While single-strand breaks have been investigated in the DNA of both microorganisms (Freifelder and Freifelder 1966) and mammalian cells (Sawada and Okada 1970), double-strand breaks have been studied only recently and by a technique which uses radiation sensitisers e.g. 5-bromodeoxyuridine. Kaplan et al. (1962) observed that incorporation of this latter deoxyribonucleoside increased the yield of double-strand breaks per unit dose and to an extent which was proportional to radiation-induced lethality; this correlation was interpreted by these workers to imply that double-strand breakage is the major radiochemical lesion which results in loss of cell viability. Approximately 1 DSB/cell/rad is found in mammalian cells (Veatch and Okada

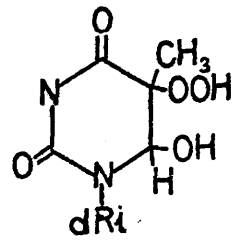
1969) with the efficiency of double-strand cleavage estimated at 600eV. per break (Corry and Cole 1968).

Chromosome aberrations Evidence obtained in the dose-response curves for in vitro X-irradiation of mammalian cells, suggests that chromosome aberrations are responsible for radiation-induced cell lethality (Dewey et al. 1971). In addition, recent research on this topic indicates that radiation damage expressed ultimately as chromosome aberrations involves DNA, although the responsible lesions in DNA have not yet been identified conclusively. Thus the presence or absence of oxygen, change in LET (see Appendix 5), and cell-cycle stage all have a comparable effect on the rate of formation of both DNA strand breaks and chromosome aberrations (Okada 1970). Unfortunately, although DNA is considered to be the major lethal target of the cell, no quantitative relationship between radiation-induced damage at the DNA level and mutational events exists such that predictions may be made about mutational responses observed with both different dose rates and cell stages in mammals. However, the number of chromatid and chromosome breaks in mammalian cells ranges from 0.002-0.24/cell/rad and 0.002-0.01/cell/rad respectively. Comparison of these figures with the corresponding values for DNA single-strand or double-strand breaks leads to the conclusion that either (a) the extent of DNA damage is insignificant with respect to cell lethality, or (b) some or all of the DNA damage is repaired (Painter 1970).

Ormerod and Stevens (1971) provide experimental evidence of the rapid repair of $\simeq$ 85% of single-strand breaks produced in mammalian DNA after an irradiation dose $>$ 5 Krads.; the residual 15% appeared to be irrepairable. The majority of evidence of repair is based on the results of a sedimentation technique developed for determination of the

molecular weight of DNA fragments (McGrath and Williams 1967); hence by this method there is no proof that repair of DNA strands ensures participation in normal DNA replication. However, Rasmussen et al. (1970) obtained experimental evidence of normal replication of the repaired DNA of human diploid cells. Thus single-strand breaks do not appear to be the main radiation-induced chemical lesion which results in heritable damage to cells. Although Dean et al. (1966) discovered the repair of both single- and double-strand breaks in the bacterial strain Micrococcus radiodurans, repair of the latter damage in mammalian DNA remains a controversial issue. However reconstitution of chromosome aberrations has been recognised in mammalian systems (Dewey and Humphrey 1964).

Recent research is orientated towards investigation of radiation-induced heterocyclic base damage. Hariharan and Cerutti (1971) studied the γ-ray induced damage of thymine incorporated in the DNA of Micrococcus radiodurans and discovered that damaged thymine is released from DNA together with several molecules of undamaged thymine. These workers conclude therefore that the extensive degradation which accompanies removal of damaged residues may be significant in relation to the biological effects of ionising radiation. Thymine is the base most thoroughly investigated for damage which does not involve strand breakage. On the basis of results obtained with polynucleotide model compounds containing saturated pyrimidine residues Cerutti (1974) postulates that a possible ring-saturated in vivo radiation product of thymine might be:



dRi = deoxyribose

and that this altered base could disrupt the ordered conformation of double-stranded DNA with significant consequences to the biological function of the nucleus. Whatever the identity of such base damage, Painter (1970) estimates the number of damaged bases to be 5-15 per rad.

Table 5.6 contains a summary of the major research outputs discussed in the preceding paragraphs. The contents of this table are combined with the 30-year accumulated absorbed doses attributable to both natural and artificially produced ^{14}C; in the latter case, the maximum 30-year dose is taken. The resultant figures shown in Fig. 5.7 represent the probability per cell that a particular category of cell damage is induced. Repair of damage is assumed to occur only for single-strand breaks at an efficiency of 85% (Ormerod and Stevens 1971); thus the remainder of data contained in Table 5.7 must be regarded as maximum estimates. Since damage from ionising radiation at the cellular level has not yet been identified in terms of the incidence of heritable mutations, a specific assumption as to the critical lesion must be made as a basis for prediction of the possible number of abnormal offspring. For this reason chromosome breaks are considered to be the biological damage from ionising radiation at the cellular level which are expressed as genetic mutations. Such an assumption is not too unreasonable by reference to the spontaneous mutation rate. An estimated 2%-4% of disease is attributed to spontaneous mutation (United Nations 1972b) while an absorbed dose of 100 rads is regarded as the doubling dose for chronic exposure of the human population to ionising radiation i.e. the dose required to double the spontaneous mutation rate. These figures lead to the result that the 30-year accumulated dose to humans from ^{14}C of natural origin (i.e. the pre-1890 level) yields a probability of $\simeq 6 \times 10^{-6}$ that offspring will possess deleterious traits, a value within

TABLE 5.6 SUMMARY OF DAMAGE TO MAMMALIAN CELLS FROM IONISING RADIATION

BIOLOGICAL ENTITY	DAMAGE INCURRED
Single-strand breaks	10/cell/rad
Double-strand breaks	1/cell/rad
Chromatid breaks	0.002 - 0.24/cell/rad
Chromosome breaks	0.002 - 0.01/cell/rad
Damaged bases	5 - 15/cell/rad

TABLE 5.7 ESTIMATES OF BIOLOGICAL DAMAGE TO REPRODUCTIVE CELLS FROM ^{14}C β- IRRADIATION (30-YEAR ACCUMULATED DOSE)*

LOCATION OF DAMAGE IN CELL	EXTENT OF DAMAGE (PROBABILITY/CELL)	
	NATURAL ^{14}C	BOMB ^{14}C
Single-strand breaks	0.03	0.01
Double-strand breaks	0.02	0.006
Chromatid breaks	4.2×10^{-5} - 5.0×10^{-3}	1.2×10^{-5} - 1.4×10^{-3}
Chromosome breaks	4.2×10^{-5} - 2.1×10^{-4}	1.2×10^{-5} - 0.6×10^{-4}
Damaged bases	0.1 - 0.3	0.03 - 0.09

* Calculations performed on bomb ^{14}C contribution: maximum 30-year absorbed dose.

an order of magnitude of the lower estimate of the number of chromosome breaks under similar radiation conditions. The existence of a mutation in the subsequent generation requires only one genetically abnormal parent germ cell. Hence the number of mutant individuals produced in such a situation depends on the birth rate and on the world population taken as 3% and 2.5×10^9 respectively. Calculations performed on the basis of chromosome breaks as the critical lesion lead to the conclusion that approximately 3000-16,000 live-born per generation will possess some form of disorder directly attributable to ^{14}C of natural origin. In the same manner, the corresponding maximum figure from artificial production of ^{14}C is $\approx$ 1000-4500 live-born/generation. The total radiation burden from bomb ^{14}C may be determined from the average 30-year dose attributable to this radioisotope and in excess of the pre-1890 dose level. The former value amounts to about 1/6 of the latter and results in a total radiation burden of 1500 - 7500 individuals with deleterious traits extending over the period 1955-2035. With regard to all the assumptions involved in the evaluation of the latter range, the resultant estimate must be regarded as a maximum - possibly an order of magnitude too high. In addition, no information on the types of abnormalities may be postulated using the preceding approach.

5.3.3 The transmutation effect of ^{14}C decay The transmutation effect with regard to ^{14}C is normally associated with 3 properties of the decay process, viz.:

(i) nuclear recoil

(ii) the modified valence state and

(iii) the excited electronic state of the daughter nucleus ^{14}N.

From momentum considerations, the maximum recoil energy is always considerably lower than the energy associated with the β- particle

because the daughter nucleus is much heavier relative to the emitted particle. The recoil energy, E_r, of any atom formed in a β- decay process is given by the equation

$$E_r = 548 \frac{E_\beta}{M} + 536 \frac{E_\beta^2}{M} \qquad \text{(Libby 1947)}$$

where E_β = energy of the emitted β- particle (MeV.) and

M = the mass of the atom formed.

Thus for ^{14}C decay, insertion of the appropriate values M=14, and E_{max} = 0.156MeV. yields a maximum recoil energy of $\simeq$ 7eV. Although strictly applicable to the maximum β-energy, the above equation may be used to determine the mean recoil energy; the corresponding value of the latter quantity is therefore approximately 2eV. Chemical bond energies occur in the range 1-5eV. and ^{14}N recoil thus represents a potential mechanism of cleavage of one of the newly formed bonds - in particular the C-N bond of 2.1eV. (Pauling 1948). Working on the basis of this hypothesis, Wolfgang et al. (1956) investigated experimentally the self-irradiation products of doubly-labelled ^{14}C-ethane and obtained a value of 47$\pm$2% for the complete retention of ^{14}C-ethylamine i.e. ^{14}C decay results in 53% cleavage of the C-N bond. The observed retention is in approximate agreement with the theoretically predicted value of 60$\pm$2% (Wolfsberg 1956), although the excess quantity of bond rupture was attributed to the excited electronic state of ^{14}N immediately after ^{14}C decay. Similar experiments were performed on ^{14}C-benzene and self-irradiation products were examined for the quantity of pyridine formed by ^{14}C decay. Regardless of the experimental phase employed, the yield of pyridine, equivalent to bond retention, was found to be 58$\pm$4% compared to the theoretical yield of 60% calculated on the basis of simple consideration of momentum conservation (Skorobogatov and Nefedov 1966). In general, the extent of bond

breakage is difficult to predict from momentum considerations alone while complex quantum mechanical calculations are required to evaluate theoretically the additional effect of electronic excitation associated with the newly-formed ^{14}N. Thus Manning and Monk (1962) compared experimentally the amount of bond rupture in the ^{14}C-containing alkyl groups of toluene and ethylbenzene induced by ^{14}C decay; the stabilising influence of the benzene ring on the excited electronic state of ^{14}N was demonstrated by the fact that more bond rupture occurred in the decay of ^{14}C-ethyl benzene. Although the individual components of the transmutation effect of ^{14}C are difficult to compare quantitatively, Kačena (1968) performed a theoretical assessment of the contribution to the total decay process from nuclear recoil and electronic excitation. Analysis of the results of this study together with experimental evidence on bond rupture allowed the conclusion that most of the biological effects of the β-decay of incorporated radioisotopes can be attributed to the change in atomic number of the residual atom with resultant modification of atomic arrangements and loss of specificity of the biologically active structure.

In the determination of the total transmutation effect of an isotope, distinction between β- particle and nuclide decay effects becomes progressively more difficult as the energy of the emitted β-particle diminishes (Strauss 1958). Thus only ^{32}P, with a relatively large β- emission energy (β max = 1.71MeV.), has been studied extensively in connection with the transmutation effect of radioisotopes which may be incorporated in DNA, particularly with regard to induced cell lethality and mutation. Initial research performed on microorganisms pointed to the existence of a significant mutagenic effect (Hershey et al. 1951) while subsequent work involving insects proved

less conclusive. Whereas King (1953) and Bateman (1955) were unable to detect a mutagenic effect of ^{32}P in Drosophila melanogaster, Oftedal (1959) observed a large increase in mutation frequency above that expected for β-irradiation alone. At the present time, the bulk of evidence is in favour of a transmutation effect of ^{32}P (Krisch and Zelle 1969).

With regard to similar experiments performed using ^{14}C and ^{3}H, conclusions are in disagreement; McQuade and Friedkin (1960) observed a positive effect in tritiated thymidine incorporated in the DNA of plant cells, while Williams and Scully (1961) were unable to detect any transmutation effect. In the latter case, however, these workers did not carry out their own radiation controls, a common drawback in the interpretation of experimental observations in this field of research. The difficulties involved in the use of ^{3}H and ^{14}C arise for two reasons:

(i) both radioisotopes are weak β-emitters which necessitates high activities in order to obtain statistically significant comparisons with control experiments, and

(ii) the difficulty in separation of the mutagenic effect from damage attributable to β-ionisation.

Purdom (1965) cultured larvae on a medium containing generally labelled glucose-^{14}C, also providing his own radiation controls with ^{60}Co γ-irradiation. This worker concluded that the number of sex-linked recessive lethals measured could be explained as damage induced by β-radiation alone, but that a mutagenic effectiveness for ^{14}C transmutation in the X-chromosome DNA in male germ cells of 0.01 could not be discounted. On the other hand, Kuzin et al. (1964) performed similar experiments but using a 1:1 mixture of glycine-^{14}C together with glucose-^{14}C, and arrived at a different conclusion; incorporated

^{14}C appeared to be 2.3-2.9 times more effective in the induction of recessive lethals than an equivalent dose of chronic external γ-radiation. Pluchennik (1965) studied the kinetics of the mutation process in a species of yeast as induced by decay of incorporated ^{14}C; comparison of the observed effect with that produced by a similar X-ray radiation dose indicated that ^{14}C is 2-4 times more effective. This author accepted the latter result as proof of the important role of the transmutation effect of ^{14}C. In more recent years Aleksandrov et al. (1971)have investigated the rate of mutation in a strain of yeast grown in the presence of either ^{14}C-thymine or ^{14}C-thymidine; DNA is known to incorporate thymidine (Reichard and Estborn 1951) but not thymine (Plentl and Schoenheimer 1944). Since thymidine incorporation resulted in a greater mutation rate relative to that from thymine, these workers reason that the difference between the 2 values is a measure of the mutation directly attributable to the mutagenic effect of ^{14}C as opposed to β-irradiation damage, which is assumed to be equivalent for both thymine and thymidine. From these experimental findings, Aleksandrov et al. estimate that the natural ^{14}C content in the DNA is responsible for $\simeq 4\%$ of the spontaneous mutations in the strain of yeast studied. Perhaps the most convincing experimental evidence opposed to the existence of a transmutation effect of ^{14}C is the recent work of Lee et al. (1972) on the transmutation of ^{14}C within the thymidine component of DNA in Drosophila melanogaster. A special technique developed by these workers to separate a possible transmutation effect from that caused by β-ionisation was used in conjunction with a general labelling process. Although a positive result was obtained in the third generation offspring in similar experiments using ^{32}P (Lee et al. 1967), no statistically significant evidence

of a similar property of ^{14}C was found in the latest investigation on this theme. Nevertheless Lee et al. state that, on the basis of their results, a mutagenic effect due to transmutation from specifically-labelled DNA (as opposed to a general label) cannot be discounted.

Thus the lack of conclusive proof for or against a transmutation effect associated with ^{14}C is perhaps a reflection of the difficulties involved in such experiments with low-energy radioactivity. For the purposes of this study, a transmutation effect is assumed and an approach similar to that of Totter et al. (1958) is employed to calculate the possible radiation damage from decay of natural and artificially produced ^{14}C.

The DNA content of a mammalian diploid cell = 8.6×10^{-12} g.

(Veatch and Okada 1969)

the carbon content of each DNA molecule $\simeq 37\%$

$\therefore$ the number of Catoms/DNA/cell $= \dfrac{0.37 \times 8.6 \times 6.023 \times 10^{11}}{12}$.

The isotopic concentration of ^{14}C of natural origin

$= 0.8$ ^{14}C atoms per 10^{12} C atoms

$\therefore$ the number of ^{14}C atoms/DNA/cell $= \dfrac{0.37 \times 8.6 \times 6.023 \times 0.8 \times 10^{-1}}{12}$

Probability of decay $= -dN/dt = N\lambda$

where N = number of ^{14}C atoms, and

λ = decay constant for $^{14}C = \dfrac{0.693}{5730}$ years^{-1}

$\therefore$ probability of decay/DNA/cell/generation

$$= \frac{0.37 \times 8.6 \times 6.023 \times 0.8 \times 0.693 \times 30 \times 10^{-1}}{12 \times 5730}$$

$$= 4.64 \times 10^{-4} \text{ decays/DNA/cell/generation.}$$

The above value represents the probability of a decay process in the DNA content of each cell in the course of 30 years (1 generation). However, the location of each ^{14}C atom in a DNA molecule is likely to be

critical with respect to a mutation. Thus on the basis that a mutation occurs for every decay of ^{14}C situated at a tertiary site in the molecule - approximately 1 in 3 carbon atoms occupies a tertiary site in DNA - the probability of a mutant individual per cell per generation,

$$P = \frac{4.64 \times 10^{-4}}{3} = 1.55 \times 10^{-4} \text{ mutations/cell/generation}$$

By a similar reasoning to that adopted in the preceding section, multiplication of this probability by the mean birth rate and world population yields the number of individuals per generation with deleterious traits induced by the decay of ^{14}C of natural origin

no. of mutants/generation = 12,000 individuals

A similar calculation applied to artificially produced ^{14}C in excess of that prior to 1890 yields the total radiation burden from this source of:

no. of mutants in excess of the normal (i.e. pre-1890) incidence from artificially produced ^{14}C = 5,500 individuals

Comparison of these two estimates with those predicted in the preceding section indicates that the transmutation effect from ^{14}C is of similar magnitude provided that the assumptions employed in both calculations are accurate.

5.3.4 Evaluation of estimates of the radiation burden from ^{14}C The preceding discussion and calculations indicate the potential damage at the molecular and cellular levels that may be caused by ^{14}C of both natural and artificial origins, and also includes an attempt at assessment of the possible number of genetically determined disorders attributable to this radioisotope. The assumptions involved in the latter determinations are necessarily numerous and do not allow

identification of visible expressions, if any, of these mutations. Thus for a more pertinent consideration of the social implications of the artificial production of ^{14}C, reference is made to the results of experiments centred on observed genetic effects of radiation i.e. different types of mutations. Adequate human data in this field of research is limited, and reference must be made to results obtained in radiation experiments performed on other species — in particular insects, bacteria, and unicellular organisms. However, in an effort to reduce the error in extrapolation of radiation effects observed in other species to man himself, experiments are now orientated towards the investigation of radiation effects produced in mammals e.g. mice, since the genetic material of these animals in terms of quality and quantity is more closely related to that of humans.

A common method of radiation burden evaluation is based on estimated rates of spontaneous mutation; the latter phenomenon, known for over half a century, has been discovered in every species of plant or animal studied, although no specific cause has yet been identified. Regardless of mechanism, an estimated 4% of all live-born children are derived from mutational defects involving natural selection processes (United Nations 1972b). Leipunsky (1957) and Sakharov (1958) estimated that 10% and 5% respectively of the latter quantity may be attributable to natural radiation which contributes a dose of $\simeq$ 0.16R.- 0.18R. On the basis of these percentages, each worker predicted independently the number of diseases of genetic origin caused by ^{14}C which would result from a given weapon yield. These predicted values are shown in Table 5.8(a) together with corresponding estimates of the number of induced leukaemia victims which were assumed to possess a non-threshold incidence level of 1-2 cases per 10^6 individuals per roentgen of

TABLE 5.8 (a) ESTIMATED RADIATION BURDEN FROM ^{14}C PRODUCED IN A 1MTON NUCLEAR EXPLOSION

REFERENCE	TISSUE/BONE DOSE (RAD)	TOTAL NO. OF MUTANTS	TOTAL NO. OF LEUKEMIA CASES
Leipunsky (1957)	5×10^{-3}	60,000	18,000
Sakharov (1958)	7×10^{-4}	22,000	2,200-4,00

TABLE 5.8 (b) GENETIC DAMAGE FROM RADIATION

Genetic defects produced by a 0.1 roentgen exposure to the gonads of the world population (2×10^9) Crow (1957)

CATEGORY	NO. OF MUTANTS
I Gross physical/mental defects	80,000
II Stillbirths/childhood deaths	320,000
III Embryonic/neonatal deaths	700,000

TABLE 5.8 (c) GENETIC HAZARD FROM ^{14}C Pauling (1958)

CATEGORY	TOTAL NO. OF CASES FROM ONE YEAR'S TESTING (30 MTONS)	TOTAL NO. OF CASES/MTON
I	34	3
II	1300	7
III	300	13

exposure. The resultant quantities represent a significant hazard to the world poulation from ^{14}C despite the time period involved i.e. the mean lifetime of ^{14}C = 8300 years. Crow (1957) predicted the number of genetic disorders induced by a radiation exposure of 0.1 roentgen, which is equivalent to about 10 times the annual dose received from natural radiation; estimates for 3 different, though not necessarily mutually exclusive, categories of damage are listed in Table 5.8(b). These calculations are based on the natural incidence of diseases in each category and on a "doubling dose" = 50 roentgens exposure estimate lower than the recently accepted value of 100 rads for chronic radiation exposure. The doubling dose is considered to produce deleterious effects in a population and therefore provides a convenient reference for comparison with doses received from other radiation sources. With regard to the state of uncertainty at that time concerning biological effects of radiation, the values quoted in Table 5.8(b) were considered to be of the correct order of magnitude only. Pauling (1958) applied Crow's figures to the evaluation of the radiation hazard from bomb ^{14}C released in one year, i.e. in weapon tests which totalled $\simeq$30 Mtons, and thus obtained the values given in Table 5.8(c). In addition, Pauling considered the possibility of genetic damage as a result of the transmutation effect of ^{14}C incorporated in DNA but concluded that β-irradiation is the predominant mechanism for induction of genetic damage. On the other hand, Totter et al. (1958) compared the possible β-irradiation induced damage from ^{14}C, also based on Crow's analysis, with the possible mutagenic effect of the $^{14}C \longrightarrow {}^{14}N$ transition in DNA. In this case, these workers concluded on the assumption that the ratio: $\frac{\text{mutation}}{\text{transmutation}} = 1$, that the extent of damage produced by both effects may be of similar magnitude.

These early estimates of the potential radiation damage from bomb ^{14}C represent some of the first evaluations to be made on this topic soon after the advent of the nuclear era. However, a considerable accumulation of data has occured since these predictions and now enables more valid risk estimates to be made. On this theme, the United Nations Scientific Committee on the Effects of Atomic Radiation (1972) compiled a table of estimates of the incidence of genetic disorders in man calculated with repect to damage to the germ cells most at risk i.e. spermatogonia and oöcytes. In addition, these risk estimates are based on the expected rates of induction of damage at low doses and under conditions of chronic exposure; thus the data described is most applicable to ^{14}C considerations and major categories are shown in Table 5.9. The contents of this table represent the conclusions of numerous experiments but are still based on certain necessary assumptions — in particular the process of linear extrapolation of data from other species to man. Observed mutation induction frequencies for the mouse are applied to humans but consideration is given to the size of the human genome relative to the mouse. The size of the mouse genome, i.e. the total number of functional units capable of mutating, is estimated at 25,000. However, since the number of nucleotide pairs per diploid cell is 4.7×10^9 in the mouse and 5.6×10^9 in man (Vendrely and Vendrely 1949), allowance for this difference leads to a figure of 30,000 for the size of the human genome. Thus in relating the mutation induction rate from mouse to man, the 20% increase in size of mutational unit is taken into consideration. Most of the results used to derive Total I in Table 5.9 are based on genetic experiments involving mice. However, a further method of estimation of the total number of mutations is related to the natural incidence of spontaneous mutations and to the

TABLE 5.9 RISK ESTIMATES OF INDUCTION OF GENETIC DAMAGE IN MAN

BIOLOGICAL MANIFESTATION OF RADIATION DAMAGE	RATE OF INDUCTION PER 10^6/RAD	EXPRESSION IN THE 1st GENERATION PER 10^6 CONCEPTIONS AFTER SPERMATOGONIAL IRRADIATION
Recessive point mutations	1500 (36)(sperm.)	30 - 75
Dominant visibles	2 (sperm.)	2
Reciprocal translocations	15 (sperm.)	2 congenitally malformed 19 unrecognised early embryonic losses 9 unrecognised abortions
X-chromosome losses	8 (oöcytes)	8 early embryonic losses and/or abortions
TOTAL I	1517 (53)(sperm.)	-
TOTAL II *	300	6 - 15

sperm. = spermatogonia; (36) is a lower estimate of this type of genetic damage (see text)

* TOTAL II calculated from spontaneous mutation rate.

radiation doubling dose as discussed previously. A 3% natural mutation rate is assumed while the doubling dose for chronic radiation exposure is fixed at 100 rads. On the basis of these values, the rate of increase in mutations of the zygotes — formed by union of male and female germ cells — is determined as 300 per million per rad of low dose radiation to the males of a parental generation. Although the degree of dominance among these mutations is uncertain, a range of 2-5%, applied directly to man from observations in Drosophila, is taken as an upper limit for the average dominance in man; this latter genetic characteristic is expressed as deleterious traits among live-born in the first generation immediately following radiation exposure, while the remainder of mutations are spread over subsequent generations. Application of the contents of Table 5.9 to the present topic and to the accumulated dose to the reproductive organs attributable to ^{14}C of natural and man-made origin, yields the corresponding estimates of the radiation burden to man from this radioisotope as shown in Table 5.10. In this instance, the maximum 30-year accumulated dose due to bomb ^{14}C is treated. Multiplication of Total I for bomb ^{14}C by the number of conceptions per generation yields a value of ~680 individuals with severe deleterious traits of which 20-40 are expressed in the first generation. Similarly, for the total radiation dose due to bomb ^{14}C delivered to the population over a period of ~80 years, a total of ~1100 severe mutations is obtained with a corresponding figure of ~40-70 for expression in the first generation offspring. It should be noted that mutations resulting in minor deleterious effects probably outnumber considerably those discussed above, on the basis of experiments with insects; however, such effects were not included in the compilation of Table 5.9 and have therefore not been considered in

TABLE 5.10 ESTIMATED RADIATION BURDEN TO MAN DUE TO 30-YEAR ACCUMULATED DOSES FROM ^{14}C

BIOLOGICAL END POINT OF RADIATION-INDUCED DAMAGE	NATURAL ^{14}C (21 mrad.)		BOMB ^{14}C (6 mrad.)*	
	RATE OF INDUCTION PER 10^6 CELLS (SPERM.)**	EXPRESSION IN 1st GENERATION PER 10^6 CONCEPTIONS	RATE OF INDUCTION PER 10^6 CELLS (SPERM.)**	EXPRESSION IN 1st GENERATION PER 10^6 CONCEPTIONS
Recessive point mutations	30	0.6 - 1.5	9	0.2 - 0.45
Dominant visibles	0.04	0.04	0.01	0.01
Reciprocal translocations	0.15	(i) 0.02	.0.045	(i) 0.005
		(ii) 0.20		(ii) 0.055
		(iii) 0.10		(iii) 0.025
Genetic damage TOTAL I	30		9	
Genetic damage TOTAL II	6.2	0.13 - 0.32	1.8	0.04 - 0.09

* maximum 30-year dose

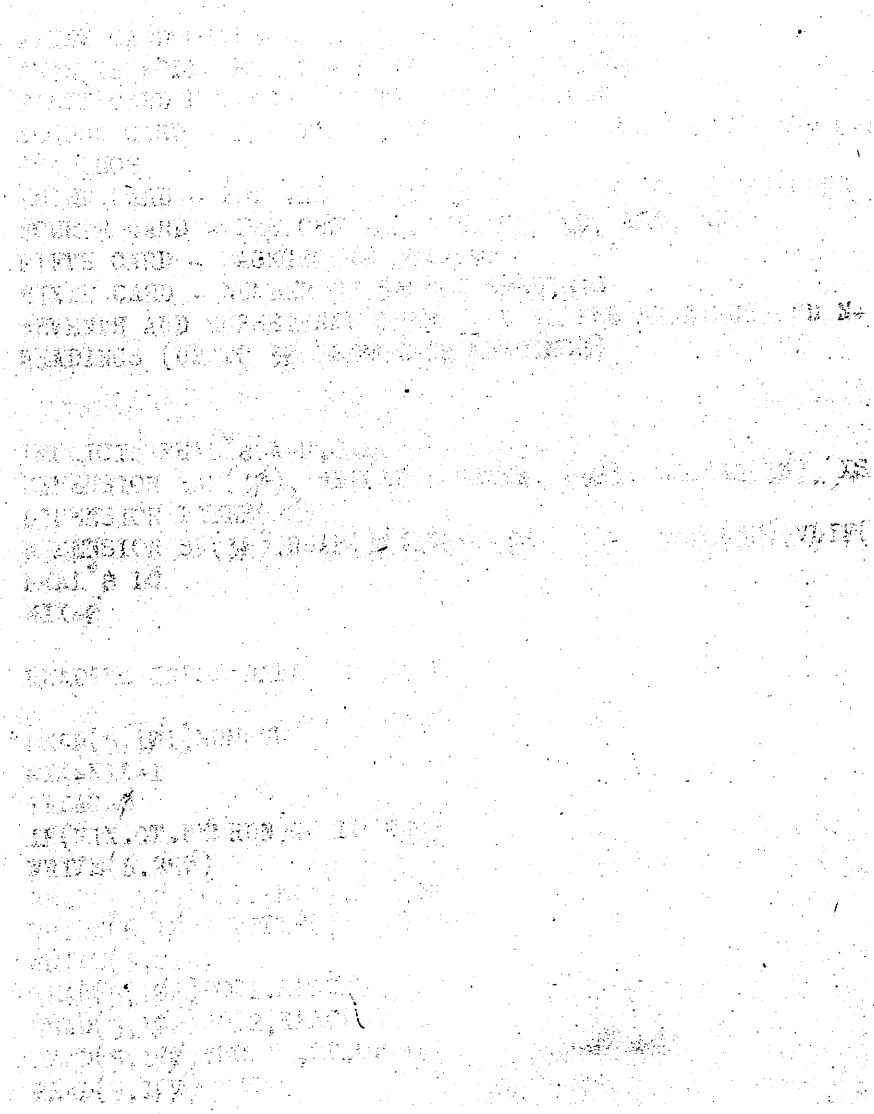
** sperm. = spermatogonia

this evaluation. Nevertheless the results indicate that the impact of bomb ^{14}C on the frequency of mutations with serious genetic consequences is not as marked as had been anticipated at the onset of the nuclear era (Pauling 1958), but is considerably dampened by the input of inactive CO_2 to the atmosphere from fossil fuel consumption. The relatively low values for the genetic hazard obtained in this section in comparison with that of 5.3.2 appear to indicate the importance of repair processes in the reduction of damage from ^{14}C decay.

With respect to late somatic effects, in particular an increase in the number of leukemia and cancer victims from the effects of ^{14}C decay, there is a notable lack of experimental observations at low doses and under chronic exposure conditions. In the range of exposure doses considered, however, a linear relationship between radiation dose and effect is frequently obtained (United Nations 1972b), such that a non-threshold incidence of the diseases is assumed for the purposes of radiation hazard evaluation. On the basis of studies of Hiroshima and Nagasaki survivors (Ishimaru et al. 1971), and of men therapeutically exposed to radiation for ankylosing spondylitis of the spine, an incidence of 1-2 cases of leukaemia per rad per 10^6 individuals exposed is assumed (Pizzarello and Witcofski 1972). Thus from this figure an estimate of the number of leukaemia victims which results from decay of bomb ^{14}C may be determined. In this way a total of 20-40 persons may be affected over a period of ~100 years, the length of time during which the dose due to bomb ^{14}C is higher than the natural ^{14}C dose. It can be seen that the potential genetic damage attributable to bomb ^{14}C is considerably higher than the corresponding late somatic effects.

However, while the values obtained for the number of individuals affected by the release of ^{14}C during nuclear weapon tests are

significant and therefore must remain a topic for moral debate, the conclusion of this research is that the threat to the world population from genetic damage due to this radionuclide is negligible.



APPENDIX 1. COMPUTER PROGRAMME FOR THE CALCULATION OF $\delta^{13}C$ VALUES.

The following programme, written in Fortram language, was used for the calculation of $\delta^{13}C_{sample}$ relative to PDB "Belemnitella americana" and associated statistical error (see 2.5).

```
C
C       FIRST CARD GIVES NUMRUN - NUMBER OF RUNS
C       THIS IS FOLLOWED BY NUMRUN SETS OF CARDS
C       FIRST CARD OF EACH SET IS TITLE OF RUN
C       SECOND CARD - POT VALUE, RATIO FACTOR FOR SAMPLE AND REFERENCE
        READINGS
C       THIRD CARD - POT VALUE AND RATIO FACTOR FOR BACKGROUND
C       FOURTH CARD - FACTORS VMC, CB, CP, LC, ACC, ACO
C       FIFTH CARD - BACKGROUND READING
C       SIXTH CARD - NUMBER OF SAMPLE READINGS
C       SEVENTH AND SUBSEQUENT CARDS - N SAMPLE READINGS AND N+1 REFERENCE
C       READINGS (UP TO 30 REFERENCE READINGS)
C
C
        IMPLICIT REAL*8(A-H,O-Z)
        DIMENSION SAM(30), REF(30), DELTA1 (30), DELTA2(30), XSAM(30),XREF(30)
        DIMENSION TITLE(20)
        DIMENSION SP(30),RSAM(30),RREF(30)    ,    REFM(30),VDIF(30)
        REAL*8 LC
        NIX=0
C
C       READING INPUT DATA
C
        READ(5,101)NUMRUN
 1111   NIX=NIX+1
        IFLAG=0
        IF(NIX.GT.NUMRUN)GO TO 9999
        WRITE(6,250)
 2222   READ(5,103)(TITLE(J),J=1,20)
        WRITE(6,104)(TITLE(J),J=1,20)
        WRITE(6,218)
        READ(5,102)POT1,RFACT1
        READ(5,102)POT2,RFACT2
        READ(5,100)VMC    ,CB,CP,LC        ,ACC,ACO
        READ(5,100)BCKG
        READ(5,101)N
        NN=N+1
        READ(5,100)(SAM(J),J=1,N)
        READ(5,100)(REF(J),J=1,NN)
        WRITE(6,210)
        WRITE(6,211)
        WRITE(6,200)POT1
        WRITE(6,201)RFACT1
```

```
      WRITE(6,202)POT2
      WRITE(6,203)RFACT2
      WRITE(6,219)VMC,CB,CP,LC
      WRITE(6,602)BCKG                ,ACC,ACO
      WRITE(6,204)N
      WRITE(6,205)
      DO 99J=1,NN
      WRITE(6,206)REF(J)
      IF(J,EQ,NN)GO TO 99
      WRITE(6,207)SAM(J)
   99 CONTINUE
C
C     CONSTANTS FOR PROGRAM
C
      CORC1=1.0682
      CORC2=0.0342
      CORO1=1.0014
      CORO2=0.0089
      CONC1=0.97924
      CONC2=2.76
      CONO1=0.9851
      CONO2=-14.90
C
C     CALCULATION
C
      WRITE(6,212)
      WRITE(6,213)
      SUM1=0.0
      SUM2=0.0
      ASUM=0.0
      BSUM=0.0
      CSUM=0.0
      YSUM=0.0
      ZSUM=0.0
      VSUM=0.0
      WSUM=0.0
      DO 50 J=1,N
      SUM1=SUM1+SAM(J)
   50 CONTINUE
      DO 51 J=1,NN
      SUM2=SUM2+REF(J)
   51 CONTINUE
      XMA=SUM1/N
      XMB=SUM2/NN
      DO 52 J=1,N
      ZA=XMA-SAM(J)
      ZA=ZA*ZA
      ZSUM=ZSUM+ZA
   52 CONTINUE
      ZSUM=ZSUM/(N-1)
      ZSUM=DSQRT(ZSUM)
      DO 53 J=1,NN
      ZB=XMB-REF(J)
      ZB=ZB*ZB
      YSUM=YSUM+ZB
   53 CONTINUE
      YSUM=YSUM/(NN-1)
      YSUM=DSQRT(YSUM)
```

Note: These constants were predetermined on the mass spectrometer before sample $\delta^{13}C$ measurement.

```
      DO 6Ø J=1,N
      JJ=J+1
      REFM(J)=REF(J) + REF(JJ)
      REFM(J)=REF (J)/2.Ø
   6Ø CONTINUE
      DO 61 J=1,N
      VDIF(J)=SAM(J)  -  REFM(J)
      VSUM=VSUM + VDIF(J)
   61 CONTINUE
      VMA=VSUM/N
      DO 62 J=1,N
      VA=VMA  -  VDIF(J)
      VA=VA*VA
       WSUM=WSUM + VA
   62 CONTINUE
      WSUM=WSUM/(N-1)
      WSUM=DSQRT(WSUM)
      WRITE(6,29Ø)XMA,ZSUM
      WRITE(6,291)XMB,YSUM
      WRITE(6,292)VMA,WSUM
      DO 1 J=1,N
      AA=SAM(J)*1.ØE-Ø6
      XSAM(J)=(POT1+AA)*RFACT1
    1 CONTINUE
      DO 2 J=1,NN
      BB=REF(J)*1.ØE-Ø6
      XREF(J)=(POT1+BB) RFACT1
    2 CONTINUE
      RB=(POT2 + BCKG*1.ØE-Ø6)*RFACT2
      DO 3 J=1,N
      JJ=J+1
      SP(J)=XREF(J)+XREF(JJ)
      SP(J)=SP(J)/2.Ø
    3 CONTINUE
      F5=CB/CP
      FACT5=1.+F5
      FACT6=F5*FACT5
      DO 9Ø J=1,N
      G1=FACT5+FACT6*RB/SP(J)
      G2=FACT5+FACT6*RB/XSAM(J)
      BC5=G1/G2
      RSAM(J)=(XSAM(J)+LC)*BC5
      RREF(J)=(SP  (J)+LC)*BC5
   9Ø CONTINUE
      WRITE(6,723)
      DO 92 J=1,N
      DELTA1(J)=(RSAM(J)-RREF(J))*1ØØØ.Ø/RREF(J)
      ASUM=ASUM+DELTA1(J)
      WRITE(6,726)DELTA1(J)
   92 CONTINUE
      DLMEAN=ASUM/N
      DO 5 J=1,N
    6 SS=DLMEAN-DELTA1(J)
      SS=SS*SS
      CSUM=CSUM+SS
    5 CONTINUE
```

```
      ABC=CSUM/(N-1)
      SIGMA=DSQRT(ABC)
      WRITE(6,724)DLMEAN,SIGMA
      IF(IFLAG.EQ.1)GO TO 9Ø3
      D1=DLMEAN
      S1=SIGMA
      IFLAG=1
      GO TO 9Ø4
 9Ø3  CONTINUE
      D2=DLMEAN
      S2=SIGMA
      GO TO 9Ø6
 9Ø4  CONTINUE
       TO TO 2222
 9Ø6  RDC=D1*VMC*ACC
      RDO=D2*VMC*ACO
      RDO1=RDO
      DCM=CORC1*RDC-CORC2*RDO
  38  DOM=CORO1*RDO+CORO2*DCM
      IF(DABS(DOM-RDO1)-Ø.ØØØ1)43,43,4Ø
  4Ø  DCM=CORC1*RDC-CORC2*DCM
      RDO1=DOM
      GO TO 38
  43  DCC=CONC1*DCM+CONC2
      DOC=CONO1*DCM+CONO2
      WRITE(6,47)DCC,DOC
      WRITE(6,295)
C     FORMAT STATEMENTS
  47  FORMAT(////1H ,'FINAL VALUE OF DCC = ',F1Ø.4,6X,'FINAL VALUE OF DO
     IC=',F1Ø.4)
 1ØØ  FORMAT(BF1Ø.4)
 1Ø1  FORMAT(I2)
 1Ø2  FORMAT(2F1Ø.4)
 1Ø3  FORMAT(2ØA4)
 1Ø4  FORMAT(1H ,2ØA4)
 2ØØ  FORMAT(//1H ,'POT VALUE FOR SAMPLE AND REFERENCE=',F1Ø.4)
 2Ø1  FORMAT(1H ,'RATIO FACTOR FOR SAMPLE AND REFERENCE=',F1Ø.4)
 2Ø2  FORMAT (1H , 'POT VALUE FOR BACKGROUND=',F1Ø.4)
 2Ø3  FORMAT(1H , 'RATIO FACTOR FOR BACKGROUND=',F1Ø.4)
 2Ø4  FORMAT(1H ,'NUMBER OF SAMPLE READINGS=',I4)
 2Ø5  FORMAT(////1H ,'SAMPLE READINGS      REFERENCE READINGS')
 2Ø6  FORMAT(1H ,2ØX,F1Ø.1)
 2Ø7  FORMAT(1H ,F1Ø.4)
 2Ø8  FORMAT(1HØ,'MEAN VALUE OF DELTA=',F1Ø.4,'  AND ERROR=',F1Ø.4)
 2Ø9  FORMAT(1HØ,'DELTA(M)=',F1Ø.4)
 21Ø  FORMAT(////1H ,'INPUT DATA')
 211  FORMAT(1H ,15('*')
 212  FORMAT(////////1H ,'RESULTS')
 213  FORMAT(1H ,1Ø('*')
 214  FORMAT(1HØ,'F=',F1Ø.4)
 216  FORMAT(///1H ,'VALUES OF DELTA AVERAGING SAMPLE READINGS')
 218  FORMAT(1HØ,26('-')
 219  FORMAT(1H , 'VMC=',F1Ø.4,1ØX,'CB=',F1Ø.4,1ØX,'CP=',F1Ø.4,1ØX,'LC=',
     1F1Ø.4,1ØX,'ACC=',F1Ø.4,1ØX,'ACO=',F1Ø.4)
 25Ø  FORMAT(1H1,'NEW PASS'////)
```

```
  29Ø FORMAT(//1HØ,'MEAN AND STANDARD DEVIATION OF SAMPLE
     READINGS=',
    1  2(F1Ø.2,5X))
  291 FORMAT(1HØ,'MEAN AND STANDARD DEVIATION OF REFERENCE
     READINGS=',
    1  2(F1Ø.2,5X))
  292 FORMAT(1HØ,'MEAN AND STANDARD DEVIATION OF SAMPLE
     READING - REFERE
    1NCE READING=',2(F1Ø.2,5X))
  295 FORMAT(///1H ,12Ø('*'))
  6Ø2 FORMAT(1H ,'BACKGROUND READING=',F1Ø.4)
  723 FORMAT(///1H 'VALUES OF DELTA')
  724 FORMAT(//1H ,'MEAN VALUE AND STANDARD DEVIATION OF DELTA=',
     2F1Ø.4)
  726 FORMAT(1H ,15X,F12.4)
C
      GO TO 1111
 9999 STOP
      END
```

APPENDIX 2. LINEAR REGRESSION ANALYSIS: BACKGROUND COUNT RATE AS A FUNCTION OF BAROMETRIC PRESSURE.

As noted in section 2.6.1, an inverse relationship is observed between the background count rate and barometric pressure. Sets of n pairs of values (x_i, y_i), where x_i is the barometric pressure and y_i the measured background count rate, were submitted for regression analysis. The underlying mathematical relationship between the 2 variables is of the form:

$$Y = \alpha + \beta X$$

which represents the 'true' regression line. Y is the 'true' value of y for a given x. Since barometric pressure can be measured relatively accurately compared with y, the total error is associated with the measurement of y values which are assumed to follow a normal distribution about the 'true' regression line. The actual regression line shown in Fig. 2.12 is given by the equation:

$$y = a + bx$$

where y = the mean count rate for a given x, and

b = the regression coefficient.

Each pair of points satisfies the relation:

$$y_i = a + bx_i + e_i$$

where e_i is called the residual. Values of a and b are found such that the sum of squares of the residuals is a minimum

$$\text{i.e. } \sum_{i=1}^{n} e_i^2 = \sum (y_i - a - bx_i)^2$$

In fact, b is given by the following equation:

$$b = \frac{n\sum(x_i y_i) - \sum x_i \sum y_i}{n\sum x_i^2 - (\sum x_i)^2}$$

and $$a = \frac{\Sigma y_i - b\Sigma x_i}{n}$$

The error associated with the background count rate determined in this way is less than that for any one experimentally measured observation and is obtained by the following procedure (after Natrella 1969):

(1) Choose the desired confidence level, $1-\alpha$. Here $\alpha = 0.05$.

(2) Obtain: $$S_y = \frac{\Sigma y_i^2 - \frac{(\Sigma y_i)^2}{n} - b^2.\Sigma x_i^2 - \frac{(\Sigma x_i)^2}{n}}{n-2}$$

(3) Obtain $F_{1-\alpha}$ for (2,n-2) degrees of freedom

(4) Choose a number of values of x (within the range of the data).

(5) At each selected x of the regression line, calculate y:

$$y = \frac{\Sigma y_i}{n} + b\left(x - \frac{\Sigma x_i}{n}\right)$$

and $$W = \sqrt{2F}.S_y\sqrt{\frac{1}{n} + \frac{(x - \bar{x}_i)}{S_1}}$$

where $\bar{x}_i = \Sigma x_i/n$ and $S_1 = \Sigma x_i^2 - (\Sigma x_i)^2/n$.

(6) Plot all points $y \pm W$ and join them up on either side of the regression line to give the 95% confidence band for the line.

The computer programme used to obtain the regression line and the parameters necessary for evaluation of the confidence limits appears below:

```
begin comment  This programme works out m and c for the equation
               y = mx + c by least squares from n pairs of x and
               y and gives the root mean square error
               (sqrt ([v↑2]/(n-2)) plus the individual deviations
               in y ;
integer  n, i, p;
```

```
real  sx, sy, sxy, sx2, sy2, m, c, d;
open(20);  open(70);

start:  n:=read(20);

begin array  x,y, e [1:n];
sx:=sy:=sxy:=sx2:=sy2:=0.0;
for i:=1 step 1 until n do
begin  x[i] := read(20);
       y[i] := read(20)
end;
for i:=1 step 1 until n do
begin sx:= sx + x[i];
      sy:= sy + y[i];
     sxy:=sxy + x[i] Xy[i];
     sy2:=sy2 + y[i]↑2;
     sx2:=sx2 + x[i]↑2
end;
d:=nXsx2 -sx↑2;   m:= (n X sxy -sx X sy)/d;
c:= (sx2 X sy - sx X sxy)/d;
d:= sqt ((sy2 - sy X c - sxy X m)/(n - 2));

for i:=1 step 1 until n do
begin

e[i]  :=y[i];
y[i]  := y[i]  - m X x[i]  - c
end
```

```
write text (70, [[4c] m*=*]);
write (70, format ([-d ddddd₁₀-nd]), m);
write text (70, [[3s]c*=*]);
write (70, format([-d.ddddd₁₀-nd]), c);
write text (70, [[3s] rms*error*=*]);
write (70, format ([-d.ddddd₁₀-nd]), d);
write text (70, [[3c][6s]y*obs[8s]y*calc [7s]deviation[2c]]);
for i := 1 step 1 until n do
  begin
    write (70, format ([2s -d.dddd₁₀-nd]), e[i]);
    write (70, format ([3s -d.dddd₁₀-nd]), m × x[i] + c);
    write (70, format ([3s -d.dddd₁₀-ndc]), y[i])

comment  if another set of data is to follow punch 1 otherwise 0;

p := read (20);
if p = 1 then goto start;
close (70);
close (20);
comment The data tape consists of n followed by n pairs of
    values of x and y.  A 1 is punched after each set of n
    pairs if another set follows, and a zero after the
    final set;

  end
end   →
```

APPENDIX 3. DIETARY SURVEY OF UNITED KINGDOM RESIDENTS - STATISTICS OF FOOD SUPPLY AND CONSUMPTION.

The following tables contain relevant material selected from annual tables of statistics supplied by the Ministry of Agriculture, Fisheries and Food (MAFF) and peblished in the journal 'Trade and Industry'. The National Food Survey, on which most of this information is based, is conducted on behalf of MAFF and is a continuous sampling inquiry into the domestic food consumption, expenditure and nutrition of private households in Great Britain. It is the only official inquiry which obtains direct measurements of the quantities and varieties of food purchased by housewives.

TABLE 1. PRODUCTION AND DISPOSAL OF STOCKS (monthly averages)

(a) Cereals and cereal products — Stocks taken at end of period. — Thousand tons.

	WHEAT AND FLOUR						OATS			BARLEY		
YEAR	Sales of home grown wheat	Wheat milled		Stocks	Flour Produced	Flour Disposals	Sales of home grown oats	Oats milled	Stocks	Sales of home grown barley	Disposals for brewing	Stocks
		Home produced	Imported									
1968	148	139	273	1019	302	311	9	10	45	152	163	649
1969	133	123	302	938	307	316	9	10	60	115	120	763
1970	138	133	286	1000	308	315	9	10	52	132	137	783
1971	134	125	291	1075	310	317	9	10	49	127	138	827

(b) Animal feedingstuffs — Thousand tons

	MAIZE		OILCAKE AND MEAL			WHEAT MILLING OFFALS		
	Disposals	Stocks	Production	Disposals	Stocks	Disposals	Production	Stocks
1968	310	238	30	109	157	117	111	22
1969	266	181	33	109	162	127	121	26
1970	255	244	31	115	127	117	113	23
1971	144	238	30	102	136	111	108	32

(c) (i) Cattle and sheep on agricultural holdings.

Thousands

YEAR	CATTLE								SHEEP				
	Total	Cows & heifers in milk	Cows in calf but not in milk	Heifers in calf with 1st calf	Bulls & bull calves for service	Other cattle			Total	Ewes for breeding	Rams for service	Other sheep	
						>2 years	1-2 years	<1 year				>1 year	<1 year
1968													
June	12,151	3,815	562	826	90	923	2,581	3,351	28,004	11,415	327	3,475	12,787
Dec.	12,094	3,048	1,484	672	93	918	2,498	3,381	19,667	10,513	352	2,991	5,811
1969													
June	12,374	3,894	592	822	91	879	2,623	3,474	26,604	10,946	313	3,323	12,022
Dec.	12,296	3,087	1,477	678	92	917	2,598	3,449	19,157	9,969	327	2,862	6,000
1970													
June	12,581	3,946	597	863	92	861	2,658	3,564	26,080	10,544	302	3,292	11,943
Dec.	12,442	3,180	1,490	675	93	848	2,566	3,589	18,499	9,683	319	2,768	5,730
1971													
June	12,804	4,036	575	831	94	873	2,736	3,659	25,981	10,422	300	3,206	12,053
Dec.	12,926	3,252	1,509	706	96	876	2,771	3,719	18,749	9,927	325	2,679	5,818

(ii) Animals slaughtered and meat produced.

Thousands

YEAR	Steers and heifers	Cows and bulls	Calves	Ewes and rams	Other sheep and lambs
1968	234	60	40	119	913
1969	219	63	35	113	755
1970	241	66	30	109	846
1971	240	68	22	102	854

(d) (i) Pigs and poultry on agricultural holdings. Thousands

YEAR	PIGS					
	Total	Sows for breeding	Boars used for service	Other pigs		
				>5 months	2-5 months	<2 months
1968						
June	7,387	887	44	1,149	3,309	1,998
Dec.	7,969	917	44	1,287	3,681	2,038
1969						
June	7,783	915	44	1,188	3,526	2,111
Dec.	8,126	921	44	1,242	3,815	2,103
1970						
June	8,088	953	45	1,249	3,672	2,169
Dec.	8,546	986	46	1,277	3,972	2,265
1971						
June	8,724	984	46	1,275	4,646	2,374
Dec.	8,882	958	44	1,357	4,248	2,275

(ii) Pigs slaughtered, and production of bacon/ham Thousands

YEAR	Sows and boars	Other pigs			Bacon and Ham	
		Used for bacon	Used partly for bacon	Other uses	Production	Disposals
1968	26	224	253	578	18.0	51.8
1969	32	241	276	620	19.5	51.6
1970	27	256	295	621	20.6	52.0
1971	30	294	368	639	24.0	54.7

(e) Potatoes, sugar, butter, cheese, canned fruit, canned vegetables.

Thousand tons

YEAR	Potatoes		Sugar(refined)		Butter		Cheese		Canned fruit		Canned vegetables	
	Disposals	Stocks	Disposals	Stocks	Production	Stocks	Production	Stocks	Production	Stocks	Production	Stocks
1968	430	2,587	235	816	4.2	50.6	9.8	70.7	8.4	39.8	59.4	177.7
1969	414	2,177	238	903	4.6	29.8	9.9	57.9	8.6	44.4	65.6	167.8
1970	403	3,381	238	865	5.2	18.2	10.6	44.9	7.7	45.9	67.1	196.3
1971	456	3,444	239	949	5.4	22.4	12.8	56.0	6.5	46.1	64.7	254.5

(f) Fish, frozen and cured

Thousand tons

Year	British Landings	Disposals
1968	70.2	87.8
1969	72.8	87.4
1970	74.1	88.2
1971	74.7	86.7

TABLE 2 ESTIMATED FOOD SUPPLIES PER HEAD OF POPULATION (1960 - 1969)

lb. per head per annum.

CLASS TYPE AND CONSTITUENTS	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
CEREAL PRODUCTS AND SUGAR										
Flour	165.9	164.0	160.5	161.1	155.5	154.1	153.4	147.0	145.0	145.7
Rice	2.6	2.8	3.4	3.0	3.0	3.1	2.8	2.5	3.2	3.2
Oat Products	3.4	3.3	3.3	3.4	3.1	3.1	2.9	2.7	2.8	2.7
Other cereals	5.7	5. 8	6.0	6.1	6.3	5.8	6.3	6.3	6.6	6.9
Starch and other farinaceous foods	2.7	2.6	3.0	3.1	3.3	3.1	3.5	2.7	4.0	4.2
Sugar	112.0	113.6	111.1	111.5	107.6	107.8	109.0	106.9	105.8	107.2
MEAT AND FISH										
Fresh and frozen meat	90.9	93.4	97.0	97.8	93.6	92.6	93.2	93.9	91.6	93.0
Offal	8.6	9.1	9.4	9.6	9.8	9.6	9.8	9.9	10.1	8.2
Imported canned meats	8.5	8.7	8.2	7.7	7.8	6.8	7.1	8.0	7.9	7.0
Bacon and Ham	25.0	25.2	26.1	25.1	25.2	25.7	25.1	24.6	25.2	25.0
Poultry	11.7	14.1	14.9	14.9	15.8	16.6	17.6	18.9	20.9	21.9
Fresh, frozen and cured fish	16.1	16.1	16.8	15.5	16.9	17.1	16.0	15.9	16.7	16.1
Imported canned fish	2.6	2.1	3.2	2.6	3.2	2.8	2.6	3.0	3.2	2.6

TABLE 2 (cont'd)

lb. per head per annum

CLASS TYPE AND CONSTITUENTS	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
DAIRY PRODUCTS										
Liquid milk (pints)	249.1	250.2	251.1	251.7	251.8	250.9	250.9	250.7	248.4	246.4
Cream (40% fat content)	1.3	1.6	1.7	2.0	2.1	2.3	2.5	2.7	2.8	3.0
Cheese	9.9	10.1	10.3	10.2	10.6	10.1	10.4	10.7	11.0	11.3
Condensed milk	7.1	7.9	7.8	7.6	7.1	7.5	7.7	8.3	8.2	8.5
Milk powder	4.3	3.9	4.3	4.4	4.6	4.1	4.4	4.0	3.9	4.0
Eggs in shell	237	243	242	237	248	248	245	248	252	248
Egg products	21	21	21	22	22	19	24	26	23	23
FATS										
Butter	18.3	19.6	20.2	19.1	19.7	19.4	20.0	20.5	19.7	19.6
Margarine	14.7	13.3	13.1	13.3	13.3	12.0	12.1	11.7	11.3	11.8
Lard and cooking fat	12.9	11.9	13.1	14.1	14.7	13.4	12.4	12.2	11.9	12.0
Other edible oils and fats	9.6	10.9	11.0	11.2	11.1	11.5	12.0	11.4	13.7	13.4
FRUIT AND VEGETABLES										
Fresh citrus fruit	20.7	19.8	20.1	18.1	20.5	19.1	20.0	19.8	20.2	20.1
Other fresh fruit	53.1	49.8	52.0	53.4	53.2	54.1	54.3	48.0	51.7	53.2
Canned and bottled fruit	16.9	17.9	18.8	18.8	19.4	18.8	18.7	19.0	18.9	19.0
Dried fruit	6.0	6.6	6.8	6.2	5.6	5.6	5.3	5.2	5.4	5.2
Potatoes	223.7	226.7	213.6	227.0	223.6	221.8	224.0	223.5	226.5	217.7
Fresh tomatoes	15.0	15.0	13.9	13.2	14.2	13.1	13.2	13.6	13.4	13.6
Other fresh veg.	99.4	95.0	95.2	93.0	100.7	101.5	101.0	101.3	160.9	100.2
Canned vegetables	10.8	11.6	12.8	13.7	13.1	13.5	16.0	15.4	14.9	17.2
Pulses	8.1	6.0	7.7	8.2	6.7	7.6	7.1	7.2	6.9	7.5

TABLE 2 (cont'd)

lb. per head per annum

CLASS TYPE AND CONSTITUENTS	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
OTHER FOODS										
Tea	9.3	9.8	9.5	9.5	9.3	8.9	8.7	9.1	8.8	8.5
Coffee	2.1	2.1	2.7	2.9	2.5	2.7	2.9	3.1	3.1	3.6
Cocoa powder	1.3	1.1	1.2	1.3	1.2	1.4	1.4	1.2	1.1	1.1

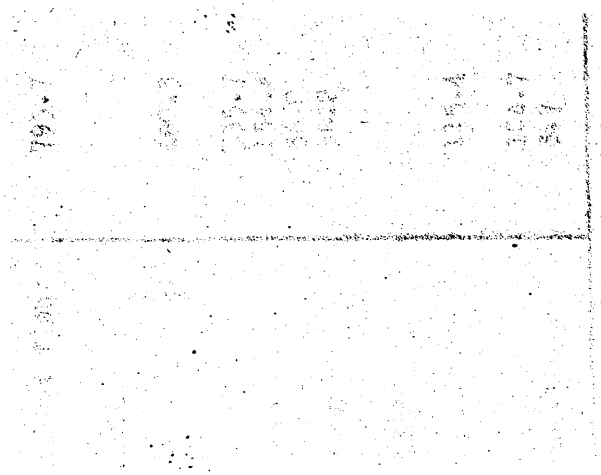


TABLE 3 LANDINGS OF FISH OF BRITISH TAKING

Landed weight (Thousand tons)

	1960	1965	1969
Total wet fish	795.7	875.9	883.4
Demersal			
Total	680.3	718.5	711.7
Cod	335.7	311.2	373.0
Haddock	134.4	165.8	140.6
Plaice	36.0	39.1	40.8
Whiting	38.2	46.7	31.0
Pelagic			
Total	115.4	157.4	171.7
Herring	104.7	96.5	121.0
Mackerel	3.7	3.0	3.3

TABLE 4 SOURCES OF SUPPLY FOR FOODS AND FEEDING STUFFS

COMMODITY AND SOURCE OF SUPPLY	AVERAGE OF YEARS 1964-1966		1970	
	x1000 tons	% age of total supplies	x1000 tons	% age of total supplies
WHEAT AND FLOUR				
Australia	606	7	1,169	13
Canada	2,164	27	1,569	17
U.S.A.	428	5	673	7
Other countries	1,173	15	1,544	17
Home production	3,753	46	4,169	46
TOTAL SUPPLIES	8,124	100	9,124	100
BARLEY				
Canada	176	2	657	8
Other countries	72	1	529	6
Home production	8,017	97	7,410	86
TOTAL SUPPLIES	8,265	100	8,596	100
OATS				
Total imports	25	2	9	1
Home production	1,213	98	1,198	99
TOTAL SUPPLIES	1,238	100	1,207	100
MAIZE AND MAIZE MEAL				
Argentina	73	2	200	6
France	37	1	422	14
Netherlands	336	10	219	7
South Africa	284	9	304	10
U.S.A.	2,034	61	1,527	49
Other countries	580	17	417	14
Home production	-	-	-	-
TOTAL SUPPLIES	3,344	100	3,089	100
POTATOES				
Total imports	296	4	497	6
Home production	6,962	96	7,364	94
TOTAL SUPPLIES	7,258	100	7,861	100

TABLE 4 (cont'd)

COMMODITY AND SOURCE OF SUPPLY	AVERAGE OF YEARS 1964-1966		1970	
	x1000 tons	% age of total supplies	x1000 tons	% age of total supplies
CHEESE				
Canada	14	5	13	5
New Zealand	77	30	65	23
Irish Republic	10	4	20	7
Netherlands	13	5	14	5
Other countries	33	13	42	15
Home production	110	43	128	45
TOTAL SUPPLIES	257	100	282	100
EGGS IN SHELL				
Total imports	14	2	11	1
Home production	827	98	868	99
TOTAL SUPPLIES	841	100	879	100
CONDENSED MILK				
Irish Republic	1	-	1	-
Netherlands	4	2	10	5
Other countries	2	1	1	1
Home production	199	97	202	94
TOTAL SUPPLIES	206	100	214	100
DRIED MILK				
New Zealand	31	20	17	11
Irish Republic	10	7	17	11
Austria	10	7	3	2
Other countries	20	13	11	6
Home production	79	53	113	70
TOTAL SUPPLIES	150	100	161	100
DRIED FRUIT				
Australia	32	23	22	16
Greece	45	32	54	39
Iran	6	4	8	6
Turkey	23	17	18	13
U.S.A.	14	10	16	12
Other countries	19	14	20	14
Home production	-	-	-	-
TOTAL SUPPLIES	139	100	138	100

TABLE4 (cont'd)

COMMODITY AND SOURCE OF SUPPLY	AVERAGE OF YEARS 1964-1966		1970	
	x1000 tons	% age of total supplies	x1000 tons	% age of total supplies
BEEF AND VEAL				
Australia	81	7	31	2
Irish Republic	50	4	103	9
Argentina	125	11	58	5
Other countries	71	6	70	6
Home production	819	72	933	78
TOTAL SUPPLIES	1,146	100	1,195	100
MUTTON AND LAMB				
Australia	19	3	32	6
New Zealand	286	49	291	53
Other countries	29	5	3	-
Home production	250	43	223	41
TOTAL SUPPLIES	584	100	549	100
PORK				
Total imports	14	2	11	2
Home production	592	98	614	98
TOTAL SUPPLIES	606	100	625	100
OFFAL				
Australia	17	7	22	9
New Zealand	20	8	27	11
Denmark	14	5	5	2
U.S.A.	22	9	21	9
Other countries	32	12	20	9
Home production	154	59	140	60
TOTAL SUPPLIES	259	100	235	100
BACON AND HAM				
Denmark	296	48	283	45
Poland	51	8	46	7
Other countries	48	8	49	8
Home production	221	36	247	40
TOTAL SUPPLIES	616	100	625	100
POULTRY MEAT				
Total imports	10	2	6	1
Home production	399	98	570	99
TOTAL SUPPLIES	409	100	576	100

TABLE 4 (cont'd)

COMMODITY AND SOURCE OF SUPPLY	AVERAGE OF YEARS 1964-1966		1970	
	x1000 tons	% age of total supplies	x1000 tons	% age of total supplies
CANNED MEAT				
Australia	12	7	8	5
Argentina	13	8	33	20
Brazil	1	1	2	1
Denmark	37	22	49	29
Kenya	3	2	3	2
Netherlands	39	23	32	19
Paraguay	5	3	3	2
Poland	11	6	9	5
South and S.W.Africa	5	3	-	
Tanzania	1	1	3	2
Yugoslavia	12	7	10	6
Other countries	29	17	15	9
TOTAL SUPPLIES	168	100	167	100
OILCAKE AND MEAL				
Canada	218	14	160	12
India	337	21	192	14
Netherlands	10	1	76	6
Nigeria	132	8	162	12
U.S.A.	9	1	18	1
Other countries	350	22	364	27
Home production	524	33	377	28
TOTAL SUPPLIES	1,580	100	1,349	100
OILS AND FATS				
Commonwealth & W. Africa	275	20	152	10
Canada	105	8	114	8
Malaysia	56	4	86	6
Singapore			87	6
Netherlands	45	3	91	6
Norway	62	5	81	6
U.S.A.	197	15	205	14
Other countries	459	34	443	31
Home Production	146	11	180	13
TOTAL SUPPLIES	1,345	100	1,439	100

TABLE 4 (cont'd)

COMMODITY AND SOURCE OF SUPPLY	AVERAGE OF YEARS 1964-1966		1970		
	x1000 tons	% age of total supplies	x1000 tons	% age of total supplies	
FISH					
Total imports	187	17	182	16	
Home landings	883	83	941	84	
TOTAL SUPPLIES	1,070	100	1,123	100	
CANNED FISH					
Canada	7	10	4	7	
Japan	26	35	19	33	
Norway	4	5	3	5	
Portugal	7	10	4	7	
South & S.W. Africa	13	18	11	19	
U.S.A.	7	10	5	9	
U.S.S.R.	3	4	2	4	
Other countries	6	8	9	16	
Home production	(7)	-	(1)	-	(included in previous section)
TOTAL SUPPLIES	73	100	57	100	
SUGAR					
Australia	403	14	327	11	
Commonwealth West Indies	507	17	512	18	
Fiji	140	5	131	5	
Guyana	88	3	164	6	
Mauritius	400	14	386	14	
Other countries	546	18	453	16	
Home production	845	29	838	30	
TOTAL SUPPLIES	2,929	100	2,811	100	
BUTTER					
Australia	73	15	65	14	
New Zealand	170	34	155	33	
Irish Republic	19	4	33	7	
Denmark	97	20	83	18	
Other countries	97	20	63	14	
Home production	32	7	64	14	
TOTAL SUPPLIES	488	100	463	100	

TABLE 4 (cont'd)

COMMODITY AND SOURCE OF SUPPLY	AVERAGE OF YEARS 1964-1966		1970	
	x1000 tons	% age of total supplies	x1000 tons	% age of total supplies
CITRUS FRUIT				
Brazil	31	6	13	2
Cyprus	35	7	46	8
Israel	143	28	220	38
Morocco	20	4	35	6
South Africa	114	22	84	14
Spain	130	25	126	22
Other countries	42	8	57	10
Home production	-	-	-	-
TOTAL SUPPLIES	515	100	581	100
CANNED AND BOTTLED FRUIT				
Australia	85	19	85	18
Japan	23	5	19	4
South Africa	124	28	126	26
Spain	12	3	28	6
Other countries	106	23	129	27
Home production	97	22	93	19
TOTAL SUPPLIES	447	100	480	100
CANNED VEGETABLES				
Italy	66	8	65	6
Other countries	81	10	146	15
Home production	670	82	804	79
TOTAL SUPPLIES	817	100	1,015	100

TABLE 5 NUTRITIVE CONTENT OF VARIOUS FOODSTUFFS *

Values given in % of each commodity

Foodstuff	P / F / C / A
MILK	
whole fresh	3.7/3.7/5.0/0.9
evaporated	6.9/7.9/9.7/1.6
condensed	8.1/8.7/54.3/1.9
dried whole	26.4/27.5/38.2/6.2
CHEESE	
cheddar	25.0/32.0/2.0/5.8
Camembert	17.5/24.6/1.8/4.1
cottage, creamed	13.6/4.2/2.9/3.2
Edam	27.5/20.4/3.9/6.4
Gruyere	28.9/31.8/1.8/6.7
Swiss	27.5/27.9/1.8/6.4
BUTTER	1.0/81.0/ - /0.2
MARGARINE	0.6/90.0/ - / -
LARD	- /100/ - / -
EGGS	12.9/11.5/0.8/3.1
SUGAR	- / - /99.5/ -
PRESERVES	
general	0.5/ - /99.0/ -
marmalade	0.9/0.4/70.0/ -
treacle	1.2/ - /67.2/ -
MEAT	
bacon	23.5/58.7/2.2/1.6
Beef(brisket)	18.2/39.4/ - /3.9
(lean)	35.1/7.6/ - /7.5
beef rib (roast)	26.8/6.3/ - /5.7
(steak)	25.5/17.0/ - /5.7
stew (raw)	32.5/13.5/ - /6.9
ham	32.9/18.3/ - /6.7
veal	33.2/15.0/ - /6.7
(chop)	22.7/35.9/ - /4.6
lamb	22.4/27.0/ - /4.6
(chop)	25.6/15.6/ - /5.2
pork	29.4/25.6/ - /6.0
(chop)	27.3/20.0/ - /5.6
sausages (beef)	11.3/41.2/ - / -
(pork)	17.5/44.0/ - / -
heart	19.3/4.2/0.8/4.4
kidney	19.4/10.4/1.2/4.0
liver	23.0/10.0/11.6/5.6
brain	10.4/8.6/0.8/2.1
chicken	20.2/15.8/ - /4.2

TABLE 5 (cont'd)

Values given in % of each commodity

Foodstuff	P / F / C / A
FISH	
Cod	27.5/5.3/ - /3.7
haddock	19.6/0.1/ - /4.1
herring	24.5/16.7/ - /5.1
smoked herring	22.2/12.9/ - / -
mackerel	21.8/7.3/ - /4.5
salmon	27.0/7.4/ - /5.6
shrimp	18.8/0.8/1.5/3.9
trout	21.5/11.4/ - /4.5
VEGETABLES	
brussel sprouts	4.2/0.4/6.4/0.6
cabbage	1.1/0.2/4.1/0.1
carrots	0.9/0.2/7.1/0.1
cauliflower	2.3/0.2/4.1/0.4
lettuce	1.2/0.2/2.9/ -
peas	5.4/0.4/12.1/0.7
green beans	1.6/0.2/5.4/0.2
mushrooms	2.4/0.1/2.4/0.6
onions	1.2/0.1/6.5/0.1
turnip	0.8/0.2/6.0/ -
tomatoes	1.1/0.2/5.1/0.1
potatoes	1.9/0.1/14.5/0.3
frozen brussel sprouts	3.2/0.2/6.5/0.4
frozen peas	5.1/0.3/11.8/0.7
frozen green beans	1.6/0.1/5.7/0.2
tinned peas	4.7/0.4/16.8/0.6
tinned carrots	0.8/0.3/6.7/ -
tinned green beans	1.4/0.2/5.2/0.2
tinned mushrooms	1.1/0.2/2.3/0.3
FRUIT	
apple	0.2/0.6/14.5/ -
apricots (tinned)	0.6/0.1/22.0/ -
banana	1.1/0.2/22.2/ -
cherries (c/s)	0.8/0.2/22.7/ -
grapefruit	0.5/0.1/10.8/ -
fruit cocktail (c/s)	0.4/0.1/19.7/ -
grapes	0.6/0.3/17.3/ -
lemons	1.1/0.3/8.2/ -
oranges	1.0/0.2/12.2/ -
peaches raw	0.6/0.1/9.7/ -
peaches (c/s)	0.4/0.1/20.1/ -
pears raw	0.7/0.4/15.3/ -
pears (c/s)	0.2/0.2/19.6/ -
pineapple (c/s)	0.3/0.1/19.4/ -
prunes	0.8/0.2/45.1/ -
raisins	2.5/0.2/77.4/ -
currants	1.7/0.1/13.1/ -
rhubarb	0.6/0.1/3.7/ -
strawberries	0.7/0.5/8.4/ -

TABLE 5 (cont'd)

Values given in % of each commodity

Foodstuff	P / F / C / A
FLOUR	10.0/1.0/76.1/1.6
BREAD	
white	8.7/3.0/50.4/1.4
brown	10.4/3.0/47.8/1.7
rolls	9.7/3.1/59.4/1.7
CEREALS	
barley	10.3/3.4/82.8/1.6
oatmeal	16.7/2.2/68.9/3.0
breakfast cereals	7.5/0.4/85.9/1.6
CAKES/BISCUITS	
chocolate fudge	5.5/24.0/65.5/ -
vanilla fudge	3.8/24.6/68.1/ -
coffee cake	6.3/9.6/52.4/ -
Devil's food mix	4.8/11.7/77.0/ -
gingerbread	5.4/10.4/78.4/ -
oatmeal biscuits	7.0/16.3/70.2/ -
chocolate chip	5.1/19.3/72.0/ -
tea biscuits	6.7/12.7/77.8/ -

Note : P = protein

F = fat

C = carbohydrate

A = amino acid

c/s = canned and sweetened

* Sources of reference: McCance and Widdowson 1960.

MAFF 1961.

U.S. Dept. of Agriculture 1963.

APPENDIX 4. COMPUTER PROGRAMMES USED IN THE EVALUATION OF THE MODEL EQUATIONS OF CHAPTER 4.

The following programmes, in Fortran language, were used to derive the families of curves of Δ_T shown in Figs. 4.2 - 4.4.

(a) Tissue - stationary state (Mrs. F. Williams) Information required by the computer includes the mean ^{14}C content (as Δ) of atmospheric CO_2 and surface ocean water for each 6-month period from 1953 - 1973. For each γ value given, Δ_T is calculated for every 6-monthly increment under investigation (1955 - 1973).

```
      DIMENSION DIET(2ØØ),TISSUE(2ØØ),ATMOS(2ØØ),FISH(2ØØ)
      DIMENSION TITLE(2Ø),TAU(2Ø)
      READ(5,18)TITLE
      WRITE(6,19)TITLE
      READ(5,1)NUMRUN
      WRITE(6,2Ø)NUMRUN
      READ(5,1)N
      READ(5,2)(TAU(KJ),KJ=1,NUMRUN)
      READ(5,2)C1,C2,C3,C4,C5,C6,C7,C8
      NN=N + 6
      READ(5,2)(ATMOS(J),J=1,NN)
      READ(5,2)(FISH(J),J=7,NN)
      READ(5,2)ZERO
      WRITE(6,1Ø)
      WRITE(6,11)N
      WRITE(6,12)(TAU(KJ),KJ=1,NUMRUN)
      WRITE(6,13)C1.C2,C3,C4,C5,C6,C7,C8
      WRITE(6,14)
      WRITE(6,15)(ATMOS(J),J=1,NN)
      WRITE(6,16)
      WRITE(6,15)(FISH(J),J=7,NN)
      WRITE(6,17)ZERO
      WRITE(6,21)
      DO 1ØØØ IRUN=1,NUMRUN
C
      FACT=-0.5/TAU(IRUN)
      FACT=1.0-EXP(FACT)
      DO 1ØØ J=7,NN
      J1=J-1
      F1=C1*ATMOS(J-6)
      F2=C2*ATMOS(J-5)
      F3=C3*ATMOS(J-4)
      F4=C4*ATMOS(J-3)
      F5=C5*ATMOS(J-2)
      F6=C6*ATMOS(J-1)
```

```
      F7=C7*ATMOS(J)
      F8=C8*FISH(J-1)
      F9=C9*FISH(J)
      DIET(J)=F1 + F2 + F3 + F4 + F5 + F6 + F7 + F8 + F9
      IF(J.EQ.7)GO TO 1Ø1
      TISSUE(J)=FACT*(DIET(J)-TISSUE(J1))   + TISSUE(J1)
      GO TO 1ØØ
  1Ø1 TISSUE (J)=FACT*(DIET(J)-ZERO)    + ZERO
  1ØØ CONTINUE
      IF(IRUN.GT.1)GO TO 4Ø
      WRITE(6,29)
      DO 3Ø J=7,NN
      WRITE(6,31)DIET(J)
   3Ø CONTINUE
   4Ø WRITE(6,41)TAU(IRUN)
      DO 32 j=7,NN
      WRITE(6,31)TISSUE(J)
   32 CONTINUE
 1ØØØ CONTINUE
C
    1 FORMAT(8I3)
    2 FORMAT(8F1Ø.4)
   1Ø FORMAT(//1HØ,'INPUT DATA'/1H ,2Ø('*')
   11 FORMAT(//1HØ,'NUMBER OF HALF YEAR INTERVALS STUDIED=',I4)
   12 FORMAT(//1HØ,'VALUES OF TAU=',1ØF1Ø.4)
   13 FORMAT(//1HØ,6X,'C1',8X,'C2',8X,'C3',8X,'C4',8X,'C5',8X,'C6',8X,
     + 'C7',8X,'C8',8X,'C9'/1H ,2X,8F1Ø.4)
   14 FORMAT(//1H ,'VALUES OF DELTA(ATMOS)')
   15 FORMAT(1HØ,12F1Ø.4)
   16 FORMAT(//1HØ,'VALUES OF FISH')
   17 FORMAT(//1HØ,'VALUE OF ZERO TISSUE=',F1Ø.4)
   18 FORMAT(2ØA4)
   19 FORMAT(1H1,2ØA4/1H ,8Ø('*'))
   2Ø FORMAT(//1HØ,'NUMBER OF PASSES OF DATA=',I4)
   21 FORMAT(1H1,'RESULTS'/1H ,8('*'))
   29 FORMAT(///1HØ,'VALUES OF DIET')
   31 FORMAT(1H ,18X,F1Ø.4)
   41 FORMAT(///1HØ,'VALUES OF TISSUE',2ØX,'TAU=',F1Ø.4)
      END
```

(b) Tissue - non-stationary (Mr. H.M.Blauer) Input data includes each 6-monthly dietary ^{14}C content (as Δ), the initial size of tissue expressed as a fraction of the mature size, and the corresponding increment in size over 6 months, also given as a fraction of the mature size.

```
      REAL NI, NO, K
      INTEGER Z, YR BORN, P, AGE, A, B, C, YR DIED
      DIMENSION DELTA P(2ØØ), DELTA T(2ØØ), yr born(2ØØ), TAU(7)
```

```
    1 READ(5,1Ø) NI,NO,AGE
   1Ø FORMAT(2F1Ø.Ø,5X,I5)
      READ(5,20) N
   2Ø FORMAT(I3)
      READ(5,3Ø) TAU
   3Ø FORMAT(7F1Ø.Ø)
      READ(5,4Ø) A
   4Ø FORMAT(I3)
      READ(5,5Ø)(DELTA P(I), I=1,A)
   5Ø FORMAT(F1Ø.Ø)
      READ(5,6Ø) B
   6Ø FORMAT(I3)
      READ(5,7Ø)(DELTA T(I), YR BORN(I), I=1,B)
   7Ø FORMAT(F1Ø.Ø,I1Ø)
      WRITE(6,8Ø)
   8Ø FORMAT(//6X,'DELTA',15X,'TAU',16X,'AGE',14X,'YEAR DIED')
      DO 3ØØ J=1,7
      K=1/TAU(J)
      EFG=EXP(-0.5*K)
      DO 250  M=1,B
      SUM=Ø.Ø
      DELTA O= DELTA T(M)
      C=2*M-2
      YR DIED= YR BORN(M)
      DO 2ØØ  P=1,N
      IF(P+C.GT.A) GO TO 3ØØ
      SUM=SUM+(NI-(NO*EFG)+(P-1)*(NI-NO)*(1-EFG))*DELTA P(P+C)*EXP(-0.5
      *1K(N-P))
      I1=MOD(P,2)
      IF(I1.NE.Ø) YR DIED=YR DIED+1
  2ØØ CONTINUE
      IF(YR DIED.GT.1973) GO TO 3ØØ
      DELTA=NO*DELTA O*EXP(-Ø.5*K*N)+SUM
      WRITE(6,19Ø) DELTA, TAU(J), AGE, YR DIED
  19Ø FORMAT(' ',F15.8,5X,F15.8,1ØX,I3,I2Ø)
  25Ø CONTINUE
  3ØØ CONTINUE
      READ(5,45Ø) Z
  45Ø FORMAT(I1)
      IF(Z.EQ.1)  GO TO 5ØØ
      GO TO 6ØØ
  5ØØ WRITE(6,51Ø)
  51Ø FORMAT(///' NEXT TISSUE')
      GO TO 1
  6ØØ STOP
      END
```

(c) Arterial lipid accumulation model (Mr. H.M.Blauer) Input data includes annual Δ_S values and age of individual concerned plus year died.

```
      INTEGER AGE, YR BORN, C, P, YR DIED
      DIMENSION TAU(6),AGE(7),DELTA P(2ØØ),YR BORN(2ØØ)
      READ(5,1Ø) TAU
   1Ø FORMAT(6F1Ø.Ø)
      READ(5,2Ø) AGE
   2Ø FORMAT(6I1Ø)
      READ(5,3Ø)(DELTA P(I), YR BORN(I), I=1,8Ø)
   3Ø FORMAT(F1Ø.Ø,I1Ø)
      WRITE(6,8Ø)
   8Ø FORMAT(//6X' DELTA',15X,'TAU',16X,'AGE',14X,'YEAR DIED')
      DO 4ØØ L=1,6
      IF(AGE(L),EQ.8Ø) I=1
      IF(AGE(L),EQ.7Ø) I=11
      IF(AGE(L),EQ.6Ø) I=21
      IF(AGE(L),EQ.5Ø) I=31
      IF(AGE(L),EQ.4Ø) I=41
      IF(AGE(L),EQ.3Ø) I=51
      N=61-1
      DO 3ØØ  J=1,6
      K=1/TAU(J)
      EFG=EXP(-1K)
      Q=Ø.Ø
      YR STRT=YR BORN(I)-1
      DO 25Ø P=1,N
      Q=Q+(P-(P-1)*EFG)*EXP(-(N-P)*1K)
  25Ø CONTINUE
      DO 2ØØ M=1,21
      YR STRT=YR STRT+1
      YR DIED=YR STRT
      SUM=Ø.Ø
      C=M-1
      DO 15Ø P=I,6Ø
      IF(P+C.GT.8Ø) GO TO 3ØØ
      SUM=SUM+(P-1)*EFG*DELTA P(P+C)*EXP(-(N-P)*1K)
      I1=MOD(P,2)
      IF(I1.NE.Ø) YR DIED=YR DIED+1
  15Ø CONTINUE
      DELTA  A=(1/Q)*SUM
      YR DIED=YR DIED+1
      WRITE(6,19Ø) DELTA A, TAU(J), AGE(L), YR DIED
  19Ø FORMAT(/,F15.8,5X,F15.8,1ØX,I3,I2Ø)
  2ØØ CONTINUE
  3ØØ CONTINUE
  4ØØ CONTINUE
      STOP
      END
```

APPENDIX 5. COMMON QUANTITIES USED IN RADIATION BIOLOGY

The first quantitative unit of dose — the roentgen — is used to define a quantity of X- or γ-irradiation in terms of the number of ion pairs produced per unit volume of air. Thus 1 roentgen (1R) of X- or γ-rays produces 2.1×10^9 ion pairs/cm^3. of air; this unit is therefore one of radiation exposure and, by definition, applies only to X- or γ-ray exposure.

Since in most situations the dose absorbed by an irradiated object is required rather than the exposure dose, the International Commission on Radiological Units (ICRU) introduced in 1954 the rad as the unit of absorbed radiation dose. One rad is equivalent to the absorption of 100 ergs per g. of any medium. Exposure of 1g. of air to 1R of X- or γ-rays results in an absorbed dose of 0.87 rad while for water and soft tissue, the exposure dose in roentgens and the absorbed dose in rads are almost equivalent numerically:

exposure dose, 1roentgen = 0.97 rad, absorbed dose

Electrons with energies <0.1 MeV. (e.g. the β-particle emitted from ^{14}C during its decay) lose their energy by inelastic collisions with electrons of the stopping medium. The density of ionisation produced during this process is of importance with regard to the extent of biological damage incurred. The quantity which describes the behaviour of any radiation is known as the linear energy transfer (LET) and is the rate of loss of energy of the radioactive particle with distance travelled. LET is directly proportional to electron density and is therefore highest for solids. In addition, radiations of equal energy, but which possess different LET characteristics differ

in the extent of biological damage induced. Thus in order to sum doses of radiations with different qualities, a weighting factor known as the quality factor (Q.F.) is employed. The resultant dose is defined as the dose equivalent, expressed in rems (originally roentgen-equivalent-man). One rem is the radiation dose which is considered to produce the same biological damage as 1R of X-rays, while dose equivalent and absorbed dose are related via the equation:

dose equivalent (rems) = absorbed dose (rads) x Q.F.

A list of quality factors is given below:

RADIATION	Q.F.	R.B.E.
X-rays, γ-rays, electrons, β-particles of energy $>$ 0.03 MeV.	1.0	1.0
β-particles of energy $<$ 0.03 MeV.	1.7	1.0
Naturally occurring α-particles	10	10
Heavy recoil nuclei	20	20

In the field of radiobiology, a factor similar to the quality factor is used — known as the relative biological effectiveness (RBE). RBE is defined as the following ratio:

$$\text{RBE} = \frac{\text{Dose in rads to produce a given effect with therapy X-rays}}{\text{Dose in rads to produce the same effect with sample radiation}}$$

RBE values are also included in the above table.

For the purposes of radiation protection, the International Commission on Radiological Protection (ICRP) adopted the following dose equivalent values which they consider should not be exceeded in the course of normal employment (see next page).

Exposed part of body	Maximum permissible doses for adults
Gonads, red bone marrow, whole body (if subjected to uniform radiation)	5(N - 18) rems/year N = age of individual
Skin and bone (except hands, forearms, feet and ankles), thyroid	30 rems/year
Other single organs	15 rems/year
Hands, forearms, feet, ankles	75 rems/year

Since the quality factor for ^{14}C, Q.F. = 1, the above values may be compared directly with annual doses from ^{14}C shown in Figs. 5.1 and 5.3.

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