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ORNL/TM-5284

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Progress Report on Evaluation of Potential Impact of ^{14}C Releases from an HTGR Reprocessing Facility

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MASTER

Environmental Sciences Division Publication No. 838

OAK RIDGE NATIONAL LABORATORY

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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy ~~\$5.50~~ 5.00; Microfiche \$2.25

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Contract No. W-7405-eng-26

Environmental Sciences Division

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¹⁴C RELEASES FROM AN HTGR REPROCESSING FACILITY

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JULY 1976

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Foreword

The release of ^{14}C into the atmosphere from HTGR fuel reprocessing facilities has long been considered a potential source of difficulty in licensing such facilities. Some preliminary work on this problem has been done by General Atomic Company (GAC)^a and Oak Ridge National Laboratory's (ORNL) Chemical Technology Division. The GAC work was inconclusive with respect to the environmental acceptability of ^{14}C releases from HTGR reprocessing. The GAC report concluded that the amount of ^{14}C released into the atmosphere during the period 1985 and 2035 from reprocessing plants would be considerably less than the amount from natural production during the same period; and that the amount produced would also be considerably less than the amount of ^{14}C produced by weapons testing during the 1950s and 1960s. The report also concluded that ^{14}C was rapidly removed from the atmosphere, eventually ending up in deep ocean reservoirs. One of the report's recommendations was the investigation of methods of carbon fixation as part of the reprocessing development work.

The pursuit of carbon fixation as a serious alternative to atmospheric release could introduce a significant financial perturbation into the development program. Therefore, a more definitive assessment of the need for carbon fixation was felt to be desirable. Furthermore, it was felt that this assessment should include an investigation by professional environmental researchers, rather than reflecting only the point of view of reprocessing development engineers, as had been the case with

^aGA-A13174, Ref. 4 in the References section of this report.

previous ORNL and GAC studies. In addition to their expertise in the relevant basic sciences, the environmental scientists bring to the study a familiarity with the language and concerns of those who will be involved in the licensing of reprocessing plants.

Early in FY 1975 a two-phase program was undertaken to study the ^{14}C problem in depth. This work was funded from Subtask 310 of the Thorium Utilization Program and is being accomplished in the ORNL Environmental Sciences Division. The two phases are (1) a regional assessment (within 50 miles of the reprocessing plant), which was completed at the end of FY 1975; and (2) an assessment of the worldwide impact of ^{14}C releases, scheduled for completion during FY 1976. The principal objective of this program is to establish a defensible ORNL position on ^{14}C releases to guide the reprocessing development program. This document reports results for the first phase of the study; a final report will be published at the end of FY 1976.

The starting point of the assessment described in this report is an assumed release of $^{14}\text{CO}_2$ to the atmosphere. In-plant engineering studies which might lead to the mitigation of the spread of ^{14}C from a reprocessing facility were considered to be outside the scope of this report. Calculated radiation doses to individuals and the population within 50 miles of the facility are presented; these doses are based on new dosimetric factors for ^{14}C computed for the study from recently published metabolic and dosimetric data. To predict time-averaged concentrations of ^{14}C in the air at various locations for dosimetric calculations, Oak Ridge area meteorology was used with a Gaussian plume atmospheric dispersion model. Other aspects of the study, however, such as

the regional distribution of population and food-production sources, are not site specific.

The uptake and retention of ^{14}C by vegetation near the reprocessing facility were studied with a plant carbon assimilation model. Combinations of meteorological conditions leading to occurrences of elevated ambient concentrations of ^{14}C were simulated with a Monte Carlo technique, with probability distributions appropriate to the hypothesized meteorology. The results of these calculations suggest that plant tissues might reach a specific activity in excess of the time-averaged ambient specific activity. At present, however, this result should be regarded as tentative and lacking direct experimental confirmation; but it serves to raise a question whose importance to the HTGR technology calls for further investigation.

The dose estimates presented in this report are probably higher than those that would result from comparable site-specific analyses applied to many potential real sites. But within the context of the generic type of assessment described here, the models, analytical methods, and data bases are believed to be representative of the best information that is currently available.

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ABSTRACT

KILLOUGH, G. G., K. R. Dixon, N. T. Edwards, B. D. Murphy, P. S. Rohwer, W. F. Harris, and S. V. Kaye. 1976. Progress report on evaluation of potential impact of ^{14}C releases from an HTGR reprocessing facility. ORNL/TM-5284. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 80 pp.

The potential radiological impacts of atmospheric releases of $^{14}\text{CO}_2$ are assessed for a model HTGR reprocessing facility. Two off-gas systems were considered: (1) a 300-ft stack with no thermal output, and (2) a 1000-ft stack with a stack gas temperature of 80°C and heat output of 4.2×10^7 Btu/hr. Meteorological data for the Oak Ridge area were used with an assumed annual release rate of 5000 Ci as input to an atmospheric transport model, which in turn was used to predict air concentrations of ^{14}C at points of habitation and food production in the local area (within 50 miles) of the facility. The total-body dose rates estimated for the average resident living in the local area were 0.107 mrem/yr for the 300-ft stack and 0.063 mrem/yr for the 1000-ft stack. The estimated total-body dose to the "fence-post man" was 87 mrem/yr for the 300-ft stack and 5.5 mrem/yr for the 1000-ft stack. Population doses were computed for a population of 10^6 individuals uniformly distributed within the 50-mile local area of the facility; these were 110 man-rem for the 300-ft stack and 63 man-rem for the 1000-ft stack. The results of these dose calculations suggest that a 1000-ft stack would be very effective in reducing the estimated doses from the levels predicted for the 300-ft stack.

An atmospheric transport model was used to drive a plant growth carbon assimilation model in order to investigate the adequacy of the assumption of tissue equilibration with time-averaged ambient specific activity

as a basis for dose estimates. Simulation runs with these models suggest that in the presence of frequent fluctuations of large amplitude in the ambient air $^{14}\text{CO}_2$ concentrations, specific activity in plant tissue can exceed conventionally calculated time-averaged specific activity.

The significance of elevated plant specific activity to dose estimation must be evaluated together with other factors such as variation among local meteorologies, time of harvest and amount and type of plant consumed.

1.0 REVIEW AND ANALYSIS OF LITERATURE RELATED TO TRANSPORT AND DOSIMETRY OF ^{14}C

1.1 Introduction and Scope

Before an accurate assessment can be made of the fate of ^{14}C released into the atmosphere by man's activities, the amounts of natural ^{12}C and ^{14}C that are now present in the various world reservoirs must be determined. Also, the transfer rates of carbon between these reservoirs must be estimated. These estimates require measurements of carbon reservoirs, production and decay rates of various types of biota in the sea and on land, and the areal extent of each type. In Sec. 1.2 a survey of relevant literature is given, and uncertainties in the existing information are discussed.

The dosimetry of ^{14}C in man may be approached via metabolic models or specific activity calculations. The latter approach is appropriate for the present assessment and is developed in Sec. 1.3. Dose-rate factors based on recently published dosimetric information are derived in Sec. 1.3 and used for all dose calculations in this report.

1.2 Global Carbon Cycling

1.2.1 Distribution of ^{12}C and ^{14}C among environmental reservoirs

Some of the earliest estimates of world carbon budgets were made by Schroeder¹ who reviewed earlier studies by Liebig² and Ebermayer.³ The bases for these budgets were annual hay production in Europe, production of various food crops in different parts of the earth, and estimates of organic production in a Bavarian forest. Even though such estimates

required very broad assumptions, world carbon budgets have recently been constructed using much of their data, which was collected in the nineteenth century. For example, a recent report by Brooks, et al.⁴ used data from Fairhall and Young⁵ which can be traced back through Goldschmidt,⁶ Schroeder,¹ Ebermayer,³ and Liebig.²

Through the use of computer modeling it is now possible to simulate global carbon cycling, and from such modeling efforts, to identify areas requiring more data and research. In recent years data have been gathered by numerous investigators on production rates and reservoir sizes of most environments of the world. For example, one of the major objectives of the International Biological Program was to measure organic matter production in major environments of the world. Through such integrated team efforts more realistic world carbon budgets are becoming available as data gathered in recent years are analyzed and published (Olson⁷; Lieth⁸).

Conceptual models of the world carbon cycle published in the last 20 years consist of five to twelve compartments depending usually upon the amount of data available to the modeler. Craig⁹ published a five-compartment model of ^{12}C and ^{14}C using carbon data which can be traced back to the late 1800's. A seven-compartment model developed by Machta¹⁰ gives little consideration to the contribution of the terrestrial exchange of plants and dead organic matter and other parts of the model are oversimplified. The 10-reservoir model of Bolin¹¹ is a more comprehensive model, but like all models of global carbon cycling suffers from lack of complete data. Cramer and Myers¹² have perhaps the most complete model exchange of C between the sea and the atmosphere. Smil and Milton¹³ emphasized carbon emissions from fossil fuel combustion in their eight

reservoir model and predicted changes in levels of carbon in the various reservoirs between the years 1960 and 2020. Nydal¹⁴ constructed a 10-reservoir world carbon model which treats northern and southern hemispheres separately, a feature especially adaptable to studying ^{14}C releases from nuclear testing.

All of the models described above are hampered by a lack of complete data sets and the lack of a coordinated approach to compiling all of the available sources of data.

Data used in some of the models mentioned above are compared in Tables 1 and 2. Carbon pool sizes for specific reservoirs (Table 1) are not as variable as carbon transfers between compartments (Table 2). These discrepancies among values of carbon flux are due to insufficient data in many cases and are often values which are generated by the particular model for balance purposes, and in many cases the values are little more than educated guesses. One of the most complete data sets given in Table 1, that of Fairhall and Young,⁵ contains estimates of ^{14}C pool sizes as does that of Plesset and Latter.¹⁵ Data for ^{12}C of Fairhall and Young⁵ represent much earlier estimates dating back to the 1800's. Because of changing land use and improved measurement techniques, more recently constructed world carbon budgets should provide better estimates of both ^{12}C and ^{14}C pool sizes. Data in Table 1 reported by SCEP¹⁶ represent intensive synthesis effort by numerous scientists from several disciplines. The accuracy of the estimates given is suspect, as was admitted by the SCEP working group, but are probably the best estimates that are currently available. The SCEP group recommended that an organized information system be developed and maintained to eliminate uncertainties in comparing

Table 1. A comparison of estimates of world reservoir sizes of ^{12}C and natural ^{14}C before nuclear testing. Values are given in 10^9 metric tons for ^{12}C and in metric tons for ^{14}C (shown in parentheses).

Atmospheric	Ocean			Terrestrial		Reference ^a
	Mixed Layer	Deep Ocean	Marine Biosphere	Biosphere	Dead Organic	
683	703		2	82 ^b	1498 ^c	SCEP ¹⁶
700	500	34500	3010 (Includes dead organic)	450	700	Bolin ¹¹
600	2700	33000				Machta ¹⁰
642 (0.825)	770 (0.958)	37000 (41.74)		306 (0.379)	1097 (1.279)	Plesset and Latter ¹⁵
680 (0.953)	1820 (1.65)	38000 (45.07)	3 (0.0046)	310 (0.418)	1100 (1.487)	Fairhall and Young ⁵

^aComplete citations are given in the List of References at the end of this report.

^bIncludes leaves, litter, short-lived animals, algae.

^cIncludes wood, large roots, and upper soil humus.

Table 2. A comparison of estimates of the carbon fluxes among reservoirs. Values are in 10^9 metric tons/year.

	SCEP ¹⁶	Bolin ¹¹	Machta ¹⁰	Plesset and Latter ¹⁵
Stratosphere to troposphere	—	—	45	—
Troposphere to stratosphere	—	—	44	—
Troposphere to mixed layer	21	—	275	92
Troposphere to terrestrial biosphere	56	—	—	—
Mixed layer to troposphere	—	—	270	91
Mixed layer to deep ocean	—	40	54	43
Mixed layer to marine biosphere	—	40	—	—
Deep ocean to mixed layer	—	45	21	43
Marine biota to mixed layer	—	35	20	—
Marine biota to deep ocean	—	5	—	—
Terrestrial biota to troposphere	—	—	310	—
Terrestrial biota to dead organic	—	25	—	214
Dead organic to troposphere	—	—	250	2

techniques and results from scattered sources. They also recognized the importance of including changing land use, such as deforestation, in development of budget models with which to assess carbon cycling.

1.2.2 Estimates of introduction of excess ^{14}C into the atmosphere from nuclear tests and its distribution

Carbon-14 concentration in the atmosphere began to increase in the 1950's in both the northern and southern hemisphere as a result of low-yield releases from nuclear testing (Fig. 1). This trend continued until mid-1959. The moratorium on atmospheric testing resulted in a slight decrease in ^{14}C levels in the northern hemisphere with a continued rise in ^{14}C concentration in the southern hemisphere. Detonation of nuclear devices in the atmosphere began again in 1961 and 1962, and the resumption is reflected in the peak ^{14}C concentrations in the atmosphere of the northern hemisphere in 1963. Low yield releases since 1962 are not reflected in measurements of atmospheric ^{14}C , probably because of the rapid movement of ^{14}C from the northern (where tests were conducted) to the southern hemisphere. By 1970, ^{14}C concentrations in the southern hemisphere had almost equilibrated with the northern hemisphere at about 54% above natural (pre-1950) ^{14}C concentrations.

A thorough investigation of the cycling of ^{14}C from nuclear testing is the appropriate course to follow in order to assess global cycling of ^{14}C released from nuclear facilities. A first step in this investigation is to quantify the ^{14}C released into the atmosphere from the nuclear tests. According to Walton et al.,¹⁷ a yield of 510.8 megatons had released 2130.6 kg of ^{14}C into the atmosphere (Table 3) by 1962. Nearly 90% of this ^{14}C release was from air tests and less than 10% from surface tests.

Fig. 1. Atmospheric levels of excess ^{14}C in the northern and southern hemispheres between 1953 and 1970 compared with excess ^{14}C levels in plants and milk products.

Table 3. Estimated ^{14}C yields to the atmosphere from nuclear testing between 1945 and 1969. Data through 1962 are from Walton et al.¹⁷ and data from 1967-69 are from Telegadas.¹⁸

Period	Air Tests		Surface Tests		Total	
	Yield (M ton)	^{14}C Atoms $\times 10^{27}$	Yield (M ton)	^{14}C Atoms $\times 10^{27}$	^{14}C Atoms $\times 10^{27}$	^{14}C kg
1945-51	0.19	0.038	0.57	0.057	0.095	2.21
1952-54	1.0	0.2	59.0	5.9	6.1	141.74
1955-56	11.0	2.2	17.0	1.7	3.9	90.62
1957-58	57.0	11.4	28.0	2.8	14.2	329.95
1959-60	Test Moratorium					
1961	120.0	24.0			24.0	557.66
1962	217.0	43.4			43.4	1008.43
1967	3.0	0.6			0.6	13.94
1968	4.0	0.8			0.8	18.59
1969	<u>3.0</u>	<u>0.6</u>			<u>0.6</u>	<u>13.94</u>
Total	416.19	83.24	104.57	10.46	93.7	2177.5

An additional 46.9 kg of ^{14}C were released from nuclear device testing in the air between 1967 and 1969 (Telegadas¹⁸) for a total release through 1969 of 2177.5 kg of ^{14}C . These values were calculated with the assumption that a one-megaton total-yield air burst introduces 2×10^{26} ^{14}C atoms into the atmosphere while a one-megaton yield surface burst introduces one-half this amount (Walton et al.,¹⁷ Telegadas¹⁸). Fairhall and Young⁵ report a much smaller estimate of total ^{14}C yield (1256 kg) from nuclear tests through 1962 than is reported here and elsewhere. All calculations in the present report which involve ^{14}C yield data from weapon tests are based on the theoretical ^{14}C yields summarized in Table 3.

If we assume a pre-1950 specific activity in the atmosphere of 1.41×10^{-12} g ^{14}C /g ^{12}C (Fairhall and Young⁵) and a total of 63×10^{16} g ^{12}C in the atmosphere, we calculate that the natural (pre-1950) ^{14}C was ≈ 958 kg. Data from Telegadas¹⁸ show the excess ^{14}C (above 1950 natural levels) in the troposphere to be ≈ 425 kg by the end of 1962 and 470 kg by the end of 1969. Thus only $\approx 22\%$ ($470/2178$) of the ^{14}C released into the atmosphere between 1945 and 1969 from nuclear tests was still in the troposphere in 1969. This is comparable to an estimate by Walton et al.²⁰ of 20% of the excess ^{14}C remaining in the troposphere by July 1968. Therefore, the remaining 78% (1710 kg) must be in other reservoirs of the earth. Walton et al.²⁰ could account for only about 610 kg in other reservoirs (150 kg in the surface ocean, 260 kg in the biosphere, and 200 kg in the stratosphere). They placed the remaining 1100 kg in the deep ocean. Thus they assumed that over 50% of the total excess ^{14}C released from nuclear test had reached the deep ocean by 1969. This estimate of deep ocean excess ^{14}C is probably too high as the result of possible underestimation

of ^{14}C retained in the terrestrial biosphere components (especially forests).

1.2.3 Analysis of the distribution of excess ^{14}C in the terrestrial biota

From available estimates of carbon pool sizes and production rates of the various terrestrial biosphere components (SCEP¹⁶) and specific activities of these components (Baxter and Farmer²¹; Harkness and Walton²²; Tauber²³; and Godwin and Willis²⁴) the amounts of natural ^{14}C and excess ^{14}C present in the terrestrial biota were calculated (Table 4). For example, ^{14}C concentrations in Danish cereals were $\approx 35\%$ above natural concentrations in 1962 (Tauber²³) thus raising the specific activity to about $1.84 \times 10^{-12} \text{ g } ^{14}\text{C/g } ^{12}\text{C}$. Multiplying 1.84×10^{-12} times the organic carbon pool in agricultural crops gives 303 kg of ^{14}C or 79 kg excess ^{14}C above the pre-1950 natural level of 224 kg. Carbon-14 is accumulated in growth rings of trees with levels of ^{14}C activity in a particular growth ring equilibrated with the levels of ^{14}C in the atmosphere which existed during the time the ring was growing (Baxter and Farmer²¹ and Godwin and Willis²⁴). Thus, it is necessary to calculate the amount of ^{14}C in forest and woody vegetation on a cumulative basis. The annual net primary production values for forest (SCEP¹⁶) were multiplied by ^{14}C specific activities for each year and accumulated to give the values in Table 4. Using the above procedures we calculate that excess ^{14}C in the terrestrial biosphere was 356 kg in 1962 and 747 kg in 1969. This 1969 value is nearly 3 times higher than the value given by Walton et al.²⁰ for the terrestrial biosphere for the same year. Fairhall and Young⁵ reported

Table 4. Carbon pools and production for the various components of the terrestrial biosphere (SCEP¹⁶) and estimates of ¹⁴C content of the oceans in 1969. Pre-1950 levels of ¹⁴C are based on specific activities taken from Fairhall and Young⁵ and ¹⁴C amounts in the terrestrial components are based on specific activities calculated from Fig. 1. Atmospheric ¹⁴C estimates are from Telegadas.¹⁸ Values in parenthesis represent a lower bounds estimate for forests in which 44% of each year's NPP has a long residence time and 56% of each year's NPP has a short (3 yrs) residence time (after SCEP¹⁶).

	Organic Carbon Pool (10 ⁹ metric tons)	Net Primary Production (10 ⁹ metric tons/yr)	Natural ¹⁴ C pre-1950 (kg)	Excess ¹⁴ C (kg)	
				1962	1969
Atmosphere	680		958		
Stratosphere				828	200
Troposphere				426	469
Terrestrial Biosphere					
Forest and woodland (includes detritus)	1012	36	1387	43	173
Agricultural	165	6	224	79	123
Other (grassland, desert, etc.)	<u>483</u>	<u>14</u>	<u>538</u>	<u>196</u>	<u>305</u>
Total terrestrial	1580	56	2149	318	601
Ocean				530 ^a [121 ^b]	762 ^a [815 ^c]
Estimated yield of ¹⁴ C from weapon tests (through 1962 and 1969)				2140	2178

^aTotal in atmosphere + terrestrial minus estimated yield from weapon tests.

^bFrom Fairhall and Young.⁵

^cMeasured ¹⁴C activity in sea water from Fairhall.²⁶

only 23 kg of excess ^{14}C in the terrestrial biosphere in 1962 as compared to our estimate of 356 kg. Our estimate does not subtract forest mortality and decay from forest net primary production and thus may be considered too high by the amount transferred annually to detritus, which is decomposed very slowly and released back into the atmosphere as $^{14}\text{CO}_2$. However, Olson⁷ has stated that even the highest values for terrestrial net primary production seem more likely to underestimate rather than overestimate. A recent estimate of forest and woodland net primary production by Olson²⁵ puts the value at 59.4×10^9 metric tons of carbon per year (an amount considerably higher than the 36×10^9 value used in our calculations). If our estimates of excess ^{14}C in the terrestrial biosphere and detritus are added to other world reservoir estimates by Walton et al.,²⁰ we calculate that $\approx 65\%$ of the ^{14}C released from nuclear tests through 1969 can be accounted for in the atmosphere, terrestrial biomass, and terrestrial detritus. This leaves $\approx 35\%$ (762 kg) of ^{14}C in the oceans at the end of 1969. This is relatively close to A. W. Fairhall's²⁶ estimate of 3.5×10^{28} ^{14}C atoms, which is equivalent to ≈ 815 kg. Fairhall's estimate is based on extensive measurements of ^{14}C in sea water. If careful consideration is given to high levels of ^{14}C activity of the biota and soil in the immediate vicinity of nuclear test sites, estimates of excess ^{14}C in the deep ocean or other reservoirs may need adjustments. For example, Koranda²⁷ reported relatively high concentrations of ^{14}C in the biota and soil near the detonation sites in the Pacific Proving Grounds (where nuclear devices were tested from 1948 to 1958), at times up to 12 years after the end of testing. Koranda reports that on Runit Island, outer growth rings contained concentrations of ^{14}C 78%

above natural, leaves-125%, litter-204% and soil-292%. Thus, budgeting of ^{14}C from any source must consider the ^{14}C content in the immediate environment of the release before global budgets from such releases can be considered reliable.

1.3 Dosimetry Models and Parameters

1.3.1 Reference individual for dose calculations

The reference individual for whom doses are calculated is an adult male whose anatomical and physiological properties are defined and quantified by the Task Group on Reference Man of the International Commission on Radiological Protection (ICRP) in ICRP Publication 23.²⁸ This document represents a distillation of biological information from many hundreds of sources and defines reference human beings to replace the older Standard Man²⁹ concept. It seems probable that future ICRP Publications will present recommendations based on the dosimetry of Reference Man, and accordingly, information from ICRP Publication 23 has been utilized wherever possible. Table 5 presents a selection of Reference Man parameters.

1.3.2 General equations of internal dosimetry

In general, we may express the dose rate to an organ of the body which results from a given burden of a radionuclide in that organ, as

$$\dot{D}(t) = S q(t) \text{ rem/day} \quad (1)$$

where

$\dot{D}(t)$ = the dose rate (rem/day) at time t to the reference organ;

S = the dose per unit residence of the radionuclide in the reference organ (rem/ $\mu\text{Ci-day}$);

Table 5. Selected data for Reference Man²⁸

Organ	Weight (g)	Carbon Content (g)
Total Body	7.0×10^4	1.6×10^4
Skeleton		
Cortical Bone	4.0×10^3	5.5×10^2
Trabecular Bone	1.0×10^3	1.3×10^2
Red Marrow	1.5×10^3	6.2×10^2
Yellow Marrow	1.5×10^3	9.5×10^2
Lungs	1.0×10^3	1.0×10^2
Liver	1.8×10^3	2.6×10^2
Kidneys	3.1×10^2	4.0×10^1
Spleen	1.8×10^2	2.0×10^1
Thyroid	2.0×10^1	2.1
Testes	3.5×10^1	3.1
G. I. Tract		
Stomach	1.5×10^2	1.8×10^1
Small Intestine	6.4×10^2	7.4×10^1
Upper Large Intestine	2.1×10^2	2.4×10^1
Lower Large Intestine	1.6×10^2	1.9×10^1
Adipose Fat	1.2×10^4	8.0×10^3

		Air Breathed per Day (l)
"light activity"	8 h working	9600
	8 h nonoccupational activity	9600
	8 h resting	3600
Total		2.3×10^4

Carbon Ingested per Day (g)	300
-----------------------------	-----

$q(t)$ = activity burden of the radionuclide in the organ (μCi);

t = time (days).

The factor S , which depends on the radionuclide and on the mass and geometry of the organ, will be taken as a constant in this discussion.

The value of S , in the present context, is given by the equation

$$S = \frac{51.2\epsilon}{m} \text{ rem}/\mu\text{Ci-day} \quad (2)$$

where

$$51.2 = \frac{3.2 \times 10^9 \left(\frac{\text{dis/day}}{\mu\text{Ci}} \right) \times 1.6 \times 10^{-6} \left(\frac{\text{erg}}{\text{MeV}} \right)}{100 \text{ (erg/g tissue/rad)}};$$

ϵ = the effective absorbed energy per disintegration (MeV/dis)

(rem/rad);

m = mass of the reference organ (g).

Carbon-14 is a beta emitter with $\epsilon = 0.05$ (MeV/dis)(rem/rad). Reference 29 includes in the effective absorbed energy, ϵ , a relative damage factor $n = 5$ when the reference organ is bone; but a different approach to the dosimetry of skeletal tissues will be taken in this report, and accordingly $\epsilon = 0.05$ MeV will be used in Eq. (2) for all organs. Thus the dose may be computed from Eq. (1) by integration:

$$D(T) = S \int_0^T q(t) dt \quad (3)$$

where

$D(t)$ = dose accumulated by the reference organ between time zero and time T (rem);

T = time at which dose integration ends (days).

The integral on the right of Eq. (3) is the residence ($\mu\text{Ci-days}$) of the radionuclide in the reference organ.

1.3.3 Review of metabolic models

The dynamic quantity $q(t)$ of Eq. (1) depends on the particular history of uptake of the radionuclide by the reference organ and on the organ's metabolic processes with respect to the radionuclide. A model which explicitly incorporates the dynamics of the organ's removal of activity will be referred to as a "metabolic model" in this discussion.

Recent ICRP documents^{28,29,30} have given metabolic models which represent the reference organ either (1) by a single compartment with first-order removal and a production (uptake) mechanism which is independent of the compartment's burden of activity or (2) by a combination of two or more such compartments arranged in parallel. In either case, we may speak of a number M of compartments, assumed to satisfy the differential equation

$$dq_j/dt = -(\lambda^r + \lambda_j^b) q_j + f c_j I(t) \quad (4)$$

where

$q_j(t)$ = activity of the radionuclide (μCi) present in the j -th compartment of the reference organ at time t ;

λ^r = radioactive decay constant (day^{-1});

λ_j^b = metabolic removal rate constant (day^{-1}) for activity in the j -th compartment of the reference organ;

f = fraction of intake reaching the reference organ;

c_j = fraction of material reaching the reference organ that is

deposited in the j -th compartment;

$I(t)$ = rate of intake into the body of activity at time t
($\mu\text{Ci/day}$).

Reference 29 presents ^{14}C metabolic models for total body, skeleton, and body fat; each such model consists of a single compartment ($M = 1$). ICRP Publication 10 (Ref. 30) and the extension of this report, 10A (Ref. 31) emphasizes the dependence of the metabolism of ^{14}C upon the particular compound in which it occurs and presents two multiple-compartment models ($M > 1$) for total-body retention, one for ^{14}C -labelled bicarbonate and the other for glycine labelled at the C2 position. One compartment of the former model is associated with the skeleton. Bernard³² cites experimental data which he interprets as supporting a mean residence time of approximately 40 days for ^{14}C in total body, and he concludes that the ICRP Publication 10 metabolic models need one or more additional long-term compartments to be consistent with such a residence time. Rohwer et al.³¹ discuss this point in the context of the uncertainty which it poses for the application of these metabolic models to ^{14}C dose calculations for environmental assessments; they indicate a discrepancy of three orders of magnitude in inhalation doses calculated with retention functions based on these models.

1.3.4 The specific activity method

When steady-state concentrations of ^{14}C -labelled carbon dioxide may be assumed, metabolic models may be avoided through the use of specific activity calculations. With this approach, it is assumed that the ^{14}C activity per gram of carbon (specific activity) in human tissue approaches

a steady-state value which is determined by the prevailing specific activity in the air that an individual breathes and in the local atmosphere at each point of production of his dietary inputs. In particular, if a man lives at a geographic point at which the atmospheric specific activity of ^{14}C in stable carbon is constant and if all of his food is produced on site, then the specific activity of his body tissues is assumed to equal the local atmospheric value when equilibrium is achieved. This hypothesis, based on observations of organisms under conditions of constant or slowly-varying atmospheric specific activity, can be challenged with regard to its appropriateness for an exposure environment in which the isotopic ratio experiences narrow-pulse fluctuations of large amplitude. A model of carbon assimilation by plants has been designed to aid in investigating this question in connection with vegetation grown near the facility, where sporadic occurrences of high ^{14}C concentration create just such an exposure environment. The model is discussed in Secs. 2.2.4, 2.2.5, and 2.2.6. Our approach to the dosimetry for purposes of the present assessment, however, will be to retain the equilibrium hypothesis, with the understanding that doses computed on this basis might be subject to eventual adjustment by factors which take into account estimates of the specific activity in vegetation produces near the release point.

In making conversions from the specific activity of ^{14}C (Ci/gC) to activity concentration in the air (Ci/m^3) it will be assumed throughout this section that ^{12}C is present in the atmosphere in the concentration 0.16 gC/m^3 . This reference value corresponds to the assumption that airborne carbon is present exclusively as CO_2 in the concentration 300 parts per million by volume (STP).

1.3.5 Relative contributions of inhalation and ingestion to the dose

The exposure modes considered are inhalation and ingestion, with associated uptake fractions f_a and f_w , respectively (the factor f in Eq. (4) stands for the appropriate choice of these if uptake is restricted to a single mode). For the simple case of a reference individual whose total diet is produced at the location of his habitation, analysis indicates that at least 99 percent of the steady-state ^{14}C dose rate to an organ is attributable to the ingestion exposure mode. The following argument derives a more general relation, which will be needed again in Sec. 3.

Suppose the reference individual breathes air at a concentration Q_0 Ci/m^3 ($= Q_0 \text{ } \mu\text{Ci/ml}$). Reference Man breathes 2.3×10^7 ml of air per day. His uptake rate via inhalation is thus

$$(2.3 \times 10^7 \text{ ml/day}) \times (Q_0 \text{ } \mu\text{Ci/ml}) \times f_a \quad \mu\text{Ci/day}.$$

Suppose further that his diet is produced at a location where the air concentration of ^{14}C is Q_1 Ci/m^3 . Reference Man ingests 300 g of carbon per day; therefore, his ingestion uptake rate is

$$\begin{aligned} & \frac{300 \text{ gC/day}}{0.16 \text{ gC/m}^3} \times (Q_1 \text{ Ci/m}^3) \times (10^6 \text{ } \mu\text{Ci/Ci}) \times f_w \\ & = 1.88 \times 10^9 Q_1 f_w \quad \mu\text{Ci/day}. \end{aligned}$$

(In practice, Q_1 will represent a suitable average of air concentrations of ^{14}C at the various points of production of the reference individual's diet.) The fraction F of the uptake of ^{14}C which is attributable to inhalation is

$$F = \frac{2.30 \times 10^7 \times f_a Q_0 \text{ } \mu\text{Ci/day inhaled}}{[2.30 \times 10^7 f_a Q_0 + 1.88 \times 10^9 f_w Q_1] \text{ } \mu\text{Ci/day total}} \quad (5)$$

Publication 2 of the ICRP²⁹ provides values for f_a and f_w for several organs, but more generally that publication assumes that these fractions are related by the equation

$$f_a = (0.5 + 0.25/f_1) f_w ,$$

where f_1 is the fraction of the radionuclide passing from the G. I. tract to the blood. This equation is, in fact, based on the lung model for particulate matter, which assumes 25 percent retention of such matter in the lungs and mechanical removal of 50 percent, which is swallowed. This model is inappropriate for CO_2 gas, however, and the implied ratio $f_a/f_w = 0.75$ ($f_1 = 1$ for carbon) is probably conservative: Bernard³² makes an argument which would support a value $f_a/f_w \sim 0.01$ for CO_2 gas. Utilization of the conservative value gives

$$F_0 = \frac{2.30 \times 10^7 \times 0.75}{2.30 \times 10^7 \times 0.75 + 1.88 \times 10^9} = 9.09 \times 10^{-3} ,$$

while $f_a/f_w = 0.01$ implies $F_0 = 1.22 \times 10^{-4}$. The notation F_0 has been used to mean the fraction computed from Eq. (5) with $Q_0 = Q_1$. This value is also used to compute the separate contributions, $\dot{D}_a$ and $\dot{D}_w$, due to inhalation and ingestion, respectively, to the total dose rate $\dot{D}$ when the two exposure modes are associated with different concentrations Q_0 and Q_1 . We have

$$\dot{D}_a = F_0 (\text{DRF}) Q_0 \text{ mrem/yr}$$

$$\dot{D}_w = (1 - F_0) (\text{DRF}) Q_1 \text{ mrem/yr} ,$$

where (DRF) stands for a dose-rate factor (mrem/yr per Ci/m³) which is calculated for the special case of equal Q_0 and Q_1 . Such dose-rate factors are given in Table 6 for several reference organs.

The values of F_0 calculated above indicate that the inhalation exposure mode contributes negligibly to the total dose when inhalation and ingestion are associated with the same atmospheric concentration. When the reference individual breathes air at an elevated concentration, however, the inhalation component can become significant in relation to the total dose if his dietary intake does not rise correspondingly.

1.3.6 Calculation of dose-rate factors for various internal organs

If the reference organ is irradiated by sources of activity in other tissues, Eq. (1) must be extended as follows:

$$\dot{D}_{\text{target} \leftarrow \text{source}} = S_{\text{target} \leftarrow \text{source}} q_{\text{source}} \text{ rem/day} \quad (6)$$

where

$\dot{D}_{\text{target} \leftarrow \text{source}}$ = component of the dose rate (rem/day) attributed to irradiation of the target organ by the activity in the source organ;

$S_{\text{target} \leftarrow \text{source}}$ = dose to target organ per unit residence of the radionuclide activity in the source organ (rem/ μ Ci-day);

q_{source} = activity burden of the radionuclide in the source organ (μ Ci).

The total dose rate is then computed by summing Eq. (6) over all source organs. In Eq. (6) the source and target organs may be identical. Quite

Table 6. Dose Rate Factors for ^{14}C Computed from Snyder et al.³⁴

Reference Organ	Dose Rate ^a ($\frac{\text{mrem/yr}}{\text{Ci/m}^3}$)
Total Body	1.31×10^{12}
Skeleton	
Endosteal Cells	2.08×10^{12}
Red Marrow	2.28×10^{12}
Bone	8.11×10^{11}
Lung	5.75×10^{11}
Liver	8.30×10^{11}
Kidneys	7.42×10^{11}
Spleen	6.38×10^{11}
Thyroid	6.03×10^{11}
Testes	5.10×10^{11}
G. I. Tract	1.03×10^{12b}
Adipose Fat	3.81×10^{12}
Skin Dose from Immersion in Infinite Cloud	4.83×10^{8c}

^aDilution in 0.16 grams of ^{12}C per cubic meter is assumed (300 ppm CO_2 by volume).

^bDose is delivered by contents of lower large intestine plus ^{14}C content of the wall. Specific activities in contents and wall were assumed to be equal. The model used to estimate the dose due to the contents was that of Dolphin and Eve.³⁵

^cComputed with the EXREM III code, Trubey and Kaye.³⁶

often, the only significant contribution to the dose will result from the activity in the target organ itself, but other contributions can be significant.

Dose rate factors are given in Table 6 for a number of reference organs. For all internal organs except the G. I. tract and body fat the dosimetric information provided by Snyder et al.³⁴ has been utilized. This reference provides tabulations of factors $S_{\text{target} \rightarrow \text{source}}$ for substitution into Eq. (6). The tabulation covers 60 radionuclides, including ^{14}C , and for each nuclide, S factors for 22 source and 24 target tissues are given. These factors were computed for an anthropomorphic phantom with biological and physiological parameters which closely approximate corresponding values for the ICRP's Reference Man.²⁸ In the internal dose calculations for Table 6, the source and target organs are identical except for skeletal tissues, in which the dose rates for endosteal cells and red marrow include components of irradiation by bone and marrow. The S factors were not used in the calculation of dose rates to body fat and the G. I. tract; the methods applied to these tissues are discussed in Secs. 1.3.6.3 and 1.3.6.2, respectively.

The dose rate factors in Table 6 for total body, lung, liver, kidneys, spleen, thyroid, and testes were calculated by the following method. Let Q denote the local activity concentration of ^{14}C in the air (Ci/m^3). If one assumes dilution in 0.16 grams of stable carbon per cubic meter of air, the ^{14}C activity per gram of carbon is

$$Q/(0.16 + 0.223Q) \text{ Ci/g C} ;$$

where $0.223 = \text{g C/Ci } ^{14}\text{C}$. Except at very high concentrations ($0.223Q > 10^{-2}$), the approximation $Q/0.16 \text{ Ci/g C}$ may be used. If an organ of man is in steady-state equilibrium with this atmospheric specific activity, its burden q (μCi) of ^{14}C is given by

$$q = 10^6 M_C Q/0.16 = (6.25 \times 10^6) M_C Q \mu\text{Ci}$$

where $10^6 = \mu\text{Ci/Ci}$ and M_C = grams of carbon in the organ. The dose rate $\dot{D}$ (mrem/yr) is [from Eq. (1)]

$$\begin{aligned} \dot{D} &= S q (3.65 \times 10^5) \text{ mrem/yr} \\ &= (2.28 \times 10^{12}) M_C Q S \text{ mrem/yr} \end{aligned} \quad (7)$$

where 3.65×10^5 converts from rem/day to mrem/yr. With $Q = 1 \text{ Ci/m}^3$ this formula has been applied to the calculation of those dose-rate factors listed above.

1.3.6.1 Skeletal tissues

ICRP Publication 11³⁷ has suggested a more detailed approach to the dosimetry of skeletal tissues than was advocated in Ref. 29. Reference 37 notes the identification of endosteal osteogenic tissues and red marrow as possible tissues at risk with respect to radiation-related bone tumor and leukemia, respectively. These tissues receive significant components of their doses from other skeletal tissues. With the appropriate S factors of Snyder et al.,³⁴ Eq. (7) is applied to each source tissue individually and the partial contributions summed to give the total dose rate. The following table summarizes the source-target relationships:

Source	Cortical Bone	Cancellous Bone	Red Marrow	Yellow Marrow
Target Organ				
Bone	X	X	X	
Red Marrow	X	X	X	
Endosteal Cells	X	X	X	X

1.3.6.2 Body fat

Body fat is not included as a reference tissue by Snyder et al.³⁴ because of the difficulty of mathematically defining a mass with indefinite boundaries for the purpose of making Monte Carlo calculations. In Publication 2 of the ICRP,²⁹ however, body fat is defined as a reference tissue and from a dosimetric point of view becomes the critical organ for ^{14}C . Reference Man's adipose fat weighs 12 kg, of which approximately 8 kg is carbon. Equation (7) may be used to estimate the dose-rate factor, with $Q = 1$ and S computed from Eq. (2).

1.3.6.3 Gastrointestinal tract

The G. I. tract presents a special problem, in that its segments are irradiated not only by the ^{14}C in their tissues but also by their migrating contents. Thus two components of the dose to each segment had to be computed from Eq. (7) with Eq. (2) substituted for S and m standing for the mass in grams of the segment. The second required a dynamic model of mass transport and mass and activity absorption from the gut. For this purpose, the model proposed by Dolphin and Eve³⁵ was chosen; 95 percent activity absorption in the small intestine was assumed, with no activity absorption in the other segments. The following table shows, for each segment of

the G. I. tract, the dose-rate factor for each of the two components of the dose. The lower large intestine is seen to receive the largest dose.

Segment	Dose Rate $\left(\frac{\text{mrem/yr}}{\text{Ci/m}^3}\right)$		
	Contents	^{14}C in Tissue	Total
Stomach	1.57×10^{11}	7.01×10^{11}	8.58×10^{11}
Small intestine	9.99×10^{10}	6.75×10^{11}	7.75×10^{11}
Upper large intestine	1.70×10^{11}	6.67×10^{11}	8.37×10^{11}
Lower large intestine	3.33×10^{11}	6.94×10^{11}	1.03×10^{12}

1.3.7 External dose

The EXREM III³⁶ computer code was used to compute an estimate of the external dose rate at the skin surface which would result from immersion in an infinite cloud of $^{14}\text{CO}_2$. From this information, the dose-rate factor 4.83×10^8 mrem/yr per Ci/m^3 (Table 2) was derived. It is assumed that no significant skin penetration by the 50 keV beta particles will occur.

2.0 PREDICTIONS OF ^{14}C TRANSPORT AND CYCLING IN A MODEL ECOSYSTEM BORDERING A HTGR REPROCESSING FACILITY

This section discusses the hypothesized rates of release of ^{14}C from the model HTGR fuel reprocessing facility, the atmospheric dispersion model and meteorology which were used to estimate time-averaged concentrations of ^{14}C at ground level at various points within 50 miles of the facility, and the plant carbon assimilation modeling which was applied to the estimation of the ^{14}C specific activity in vegetation near the facility

in response to the sporadic nature of the resultant ground level concentrations. The atmospheric dispersion model and the dosimetric information presented in Sec. 1.3 constitute the basis for the estimation of radiation doses to an individual at the facility's boundary and to a population in the region.

2.1 Source Term

Only the routine continuous release situation was considered for analysis in this report. All ^{14}C effluents from the reprocessing facility were assumed to be released to the atmosphere through a tall stack as carbon dioxide gas; because of this assumed mode of release, no accidental releases or releases to surface waters were hypothesized. The assumed release rate used for transport and dosimetry evaluations was 5,000 Ci/yr $= 1.59 \times 10^{-4}$ Ci/sec.

2.2 Carbon-14 Transport Calculations

The atmospheric transport of ^{14}C as a gaseous effluent from a HTGR fuel reprocessing plant was calculated using meteorological data for the Oak Ridge area. It should be emphasized that these data were used for this analysis because of their immediate availability in the kind of detail that was needed; it is not suggested that the Oak Ridge area is representative of a modal set of meteorological conditions.

2.2.1 The Atmospheric Transport Model

The Atmospheric Transport Model (ATM) of Mills and Reeves³⁸ based on the Gaussian plume model (Gifford³⁹) formed the basis of the atmospheric transport calculations. The version described in the original publication

uses time averaged climatological data and averages concentrations over each 22.5° compass sector.

2.2.2 Hourly version of the Atmospheric Transport Model

A special modification of the ATM was prepared to predict short-term average concentrations resulting from a specified stability class, wind speed, and wind direction. In this version of the ATM, wind direction, wind speed, and stability class are considered fixed, and the ground-level concentration is calculated as a function of downwind distance. Such a fixed set of conditions might last for approximately one hour. Thus by running this modified version of the model for all the significant speed and stability conditions associated with the prevalent wind direction, one can construct an hour by hour concentration history which would be typical of points in the direction of the prevalent wind vector (throughout the growing season, for example).

2.2.3 Atmospheric data

Speed-stability wind rose data for the Oak Ridge area were obtained from TVA. The data are monthly averages and these were used in the climatological model. We have found from an analysis of TVA data that the important stability classes are A, D, E and F for the Oak Ridge area. With respect to plant uptake of ^{14}C , stability class A (very unstable) is quite important because it results in high concentrations at close distances. Since photosynthetic incorporation of ^{14}C occurs only during the daytime, it is important to identify the frequency of daytime class A stability.

2.2.3.1 Plume rise

Two different reprocessing plant designs were studied which have different stack heights and different parameters for the exiting gases (Table 7).

The first case is represented by a present generation plant design with a 300 ft stack and exit gases assumed to be at ambient temperature. There is a small amount of momentum rise associated with this gas. We have followed the procedure of Briggs⁴⁰ and have used the most conservative estimate of plume rise in all cases.

The second case is represented by a future generation of plant using a 1000 ft stack with exit gases at 80°C. The higher stack and elevated off-gas temperature gives a plume rise which is quite dependent on wind speed and atmospheric stability. However, for low wind speeds the parameters for the future generation plant can more than double the effective stack height (Briggs⁴⁰). The ATM uses the Briggs formulation and calculates plume rise according to the prevailing meteorological parameters.

For buoyant plumes and the greater stack height, the increase in effective source height reduces close-in ground level concentration values substantially. These relationships are illustrated in Fig. 2, which shows the effective height increment obtained as a function of the temperature difference between the stack gas and the surrounding air; and Fig. 3, which shows the maximum ground level concentration as a function of effective source height.

2.2.3.2 Dispersion parameters

The best-known dispersion parameters are those generally referred to as the Pasquill-Gifford ones. These parameters were not intended

Table 7. Stack parameters used to calculate atmospheric dispersion of ^{14}C released from a model HTGR fuel reprocessing plant.

	Present Generation	Future Generation
Stack Height	300 ft	1000 ft
Heat Output in Stack Gases	Zero	0.42×10^8 Btu/hr
Stack Ejection Velocity	44 ft/sec (STP)	50 ft/sec (STP)
Internal Diameter of Stack	4.92 ft	11.92 ft
Stack Gas Temperature	Ambient	80°C

Fig. 2. Increase in effective height of stack as a function of exit gas temperature (wind speed = 1 m/sec).

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Fig. 3. Maximum ground level concentration as a function of effective source height (Class A stability, wind speed = 1 m/sec).

originally for use at distances greater than approximately ten kilometers. They are, however, frequently used at greater distances. Recently, some investigators have constructed dispersion parameters which are valid at greater distances. Hosker⁴¹ describes the more recent dispersion parameters and we have followed his procedures in choosing our parameters.

2.2.3.3 Wind stability and speed classes

Local temperature profile data obtained by TVA and classified by atmospheric stability (U.S.A.E.C. Regulatory Guide 1.21, Revision 1, June 1974) supplied the necessary climatological input to the air model. In this scheme there are seven stability classes ranging from 1 (extremely unstable) to 7 (extremely stable) with number 4 corresponding to neutral conditions. These correspond in essence to the Pasquill-Gifford classes A through F. In using the ATM for Oak Ridge area stability data, we have consolidated the two most stable classes. An important fact which is evident in the TVA data is that the very unstable condition (Pasquill-Gifford Class A) is quite prevalent in the Oak Ridge area during the warmer months. This condition will be responsible for much of the elevated ¹⁴C concentration in those areas near the plant.

The TVA data used the following values to typify six wind speed classes:

<u>Class</u>	<u>Wind Speed (m/sec)</u>
1	0.9
2	2.4
3	4.4
4	6.9
5	9.5
6	14.0

2.2.3.4 Basis for calculating time averages

The data set resulting from TVA measurements in the Oak Ridge area was in the form of a speed-stability wind rose on a monthly basis, and contained the relative frequency of occurrence of a given stability class together with a given wind speed class and the compass sector from which the wind blows. The ATM sums the contributions from all relevant events in proportion to the frequencies with which they occur to calculate a time-averaged concentration at a specified point.

2.2.3.5 Calculation of exposure history on an hour by hour basis

An analysis of the stability-speed wind rose allowed the identification of the most prevalent wind speed-stability combinations which occur in the Oak Ridge area. Calculation of ground level concentration along the wind vector yielded maximum concentrations for these conditions. Further analysis of the wind rose data identified the wind direction associated most frequently with these occurrences. The resulting ground level concentrations were combined with the frequency of occurrence of the relevant wind direction. For a given location, the occurrences of high level concentrations of $^{14}\text{CO}_2$ associated with the set of wind speed-stability combinations will be termed plume events. By using a Monte Carlo technique, hour by hour plume events could be generated for a typical growing season; these plume events were used to drive the Carbon Assimilation Model (CAM).

The most frequently occurring stability classes in the Oak Ridge area were Pasquill-Gifford Classes A, D, E, and F. Wind speed classes

1, 2, 3, and 4 were important, although all speed classes were not important for all stability classes. Most frequently the wind was from the Southwest. We have analyzed conditions which refer to the case of a southwesterly wind having the stability and speed characteristics noted above. Such a combination would be expected to yield the maximum opportunity for assimilation of ^{14}C in growing plants. Because of different plume rise characteristics the concentration pattern downwind of the stack was significantly different for the two types of plant design. An example of an important meteorological condition which illustrates this difference is given in Fig. 4, which shows the centerline plume ground concentration for the A stability class and wind speed class 1 in the case of both designs.

2.2.3.6 Diurnal pattern of stability classes

The meteorological data represented the frequency of occurrence of the six stability classes together with wind speed and wind direction. These data represent the fractions of the time during the month which are associated with the respective conditions. The recognition that some stability conditions are daytime and some nocturnal can help to extend the usefulness of these meteorological data.

In calculating ground level concentrations for input to the Carbon Assimilation Model the diurnal character of the wind stability classes was taken into account. Stability classes A, B, and C can be considered to be daylight occurrences, whereas classes E and F are nocturnal⁴²; class D was equally apportioned between daylight and nighttime hours. Thus in estimating ground level concentration histories of $^{14}\text{CO}_2$ during

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Fig. 4. Plume centerline concentration for the two HTGR fuel reprocessing plant designs as described in Table 7. The atmospheric conditions are those which produce high concentrations near the stack, and the advantages of a high stack and heated plume are demonstrated.

daylight hours (i.e., when photosynthesis is taking place), one should choose those meteorological conditions which are primarily daytime in character. It follows that the a priori monthly probabilities should be adjusted accordingly for daylight hours.

The climatology of a location, as reflected in the frequency of occurrence of the various stability classes, can have a marked effect on close-by ground level concentrations. This effect can be appreciated when one notes that for the 300-ft stack (see Fig. 4) the maximum ground level concentration occurs at less than 1 km from the source for an A stability condition; for a D condition, it is found to occur at a point between 1.5 and 2.0 km from the source and to be 4 to 5 times lower. The climatology of Oak Ridge, Tennessee, shows much class A stability throughout the summer months (about 20%) and will therefore lead to increased concentrations at nearby locations. A site such as Springfield, Illinois, shows much less evidence of class A stability, and preliminary estimates indicate a corresponding decrease in the average seasonal concentration by an approximate factor of 5.

It is of interest to compare our predicted concentrations with those of other investigators whenever such comparisons are possible. One opportunity is provided by a recent study based on Oak Ridge area meteorology. Using meteorological data compiled by the U. S. Weather Bureau at Oak Ridge, Binford et al.⁴³ calculated an annual X/Q of 1.72×10^{-7} sec/m³ for a point 2.1 miles NE of stack 7911 on the Oak Ridge Reservation; this value is based on an effective stack height of 80.8 meters with no compensation for plume rise due to higher-than-ambient exit gas temperatures. Our corresponding X/Q for the 100-meter stack (effective stack height

117 meters) at a point 2.9 miles NE is $1.12 \times 10^{-7} \text{ sec/m}^3$, which is in good agreement with the number reported by Binford et al. when the disparate effective stack heights are taken into consideration.

2.2.4 Description of Carbon Assimilation Model (CAM)

Specific activity of ^{14}C in plants tends to follow atmospheric ^{14}C specific activity where the ambient $^{14}\text{CO}_2$ has been mixed uniformly in the atmosphere (Fig. 1). Extrapolation of atmospheric ^{14}C specific activity to plants under these conditions would seem reasonable. It is suggested, however, that this hypothesis of equilibration of plant tissue with ambient specific activity should be reexamined in situations where ambient levels of ^{14}C are subject to frequent fluctuations of relatively large and varying amplitude. Such an exposure environment exists for vegetation growing near a nuclear facility which releases ^{14}C into the atmosphere. In particular, the time-averaged ^{14}C specific activity in the ambient air needs to be compared with the ultimate specific activity in the plant tissues; the latter quantity is the result of a possibly different averaging process, reflecting varying rates of carbon uptake and history of plume events. The goal might be viewed as the estimation of a ratio $S_p/\bar{S}_a$, where S_p denotes the specific activity in a plant's tissue and $\bar{S}_a$ stands for the time-averaged ambient atmospheric specific activity for the growing season, restricted to daylight hours. If the value of this ratio at the end of the growing season is viewed as a transfer factor, with respect to ^{14}C in man's food chain, then a value larger than unity would suggest an amplification effect, whereas a value of one is compatible with the equilibrium hypothesis;

a value less than one would indicate an apparent attenuation. Such a quantity is in no way intended to suggest a departure from mass conservation or an unusual isotopic discrimination; it should be thought of, rather, as a means of adjusting the more conveniently calculated ambient time average to take into account the varying exposure environment and metabolic factors of the plant.

In this section, we describe the plant growth Carbon Assimilation Model (CAM), which was designed to facilitate the study of the specific activity in the plant as it responds to plume events of high ambient concentration of ^{14}C similar to those that would occur near a fuel reprocessing plant. A listing of the model's computer implementation, together with a table of the principal program variables and their symbolic counterparts from the mathematical formulation, is given in the Appendix.

The CAM is a model of plant carbon dynamics representing a hypothetical vegetable crop species based on the plant growth model of Dixon⁴⁴. The CAM is modified to operate on an hourly time scale and simulates the dynamics of both ^{14}C and ^{12}C .

A description of the general form of the plant carbon dynamics model is followed by a more detailed description of the plant growth model which assimilates ^{14}C .

The carbon dynamics are considered separately for roots, leaves and stems since these variables are included in several process models. We consider here only the carbon dynamics of leaves, which receive the greatest proportion of photosynthate. Operationally there are two sets of equations, one set for ^{14}C and a second set for ^{12}C . For each plant

component, the total carbon pool is the sum of ^{14}C and ^{12}C . The leaf carbon mass balance equations are

$$^{14}\dot{C}_L = ^{14}G_L - ^{14}M_L - ^{14}R_L$$

for ^{14}C , and

$$^{12}\dot{C}_L = ^{12}G_L - ^{12}M_L - ^{12}R_L$$

for ^{12}C , where

$^{14}\dot{C}_L$ = mass balance rate of ^{14}C in leaves ($\text{g m}^{-2}\text{hr}^{-1}$),

$^{12}\dot{C}_L$ = mass balance rate of ^{12}C in leaves ($\text{g m}^{-2}\text{hr}^{-1}$),

$^{14}G_L$ = growth rate of ^{14}C in leaves ($\text{g m}^{-2}\text{hr}^{-1}$),

$^{12}G_L$ = growth rate of ^{12}C in leaves ($\text{g m}^{-2}\text{hr}^{-1}$),

$^{14}M_L$ = mortality rate of ^{14}C in leaves ($\text{g m}^{-2}\text{hr}^{-1}$),

$^{12}M_L$ = mortality rate of ^{12}C in leaves ($\text{g m}^{-2}\text{hr}^{-1}$),

$^{14}R_L$ = respiration rate of ^{14}C in leaves ($\text{g m}^{-2}\text{hr}^{-1}$),

$^{12}R_L$ = respiration rate of ^{12}C in leaves ($\text{g m}^{-2}\text{hr}^{-1}$).

Total leaf carbon then is expressed as

$$C_{TL} = \int ^{14}\dot{C}_L dt = \int ^{12}\dot{C}_L dt$$

where

C_{TL} = total leaf carbon (g/m^2)

$$^{14}\text{C}_L = ^{14}\text{C in leaves (g/m}^2)$$

$$^{12}\text{C}_L = ^{12}\text{C in leaves (g/m}^2)$$

The set of equations for each form of carbon is solved numerically with the Runge-Kutta integration method using the Continuous System Modeling Program (CSMP III) simulation language⁴⁵. The state variable of primary interest is the specific activity of ^{14}C in plant leaves (S_p) which is calculated as $4.46 \text{ Ci/g } ^{14}\text{C} \times (^{14}\text{C}_L/\text{C}_{TL})$.

2.2.4.1 Plant growth rate

The expression for photosynthesis in the plant growth model is based on an analogous equation for a gaseous diffusion system (Penman and Schofield⁴⁶):

$$\text{net flux} = \frac{\text{CO}_2 \text{ concentration gradient}}{\text{transfer resistance}}$$

In terms of the model, the net volume flux of CO_2 exchange ($\text{cm}^3 \text{cm}^{-2} \text{s}^{-1}$) is

$$F_v = \frac{\text{CO}_{2a} - \text{CO}_{2c}}{r_{\text{CO}_2}},$$

where

CO_{2a} = ambient CO_2 concentration (cm^3/cm^3),

CO_{2c} = CO_2 concentration at chloroplast surface (cm^3/cm^3), and

r_{CO_2} = total CO_2 transfer resistance (s/cm).

The total CO_2 transfer resistance consists of separate resistance terms for stomatal resistance and internal leaf resistance. Of the two, stomatal resistance normally dominates:

$$r_{\text{CO}_2} = r_s + r_i$$

where r_s is stomatal resistance and r_i is internal leaf resistance. The latter quantity is written as a function of temperature and light intensity.

$$r_i = P_1 e^{-b_1 T} \cdot e^{-b_2 Ix} + P_5$$

where

P_1 = maximum resistance (s/cm)

T = average hourly temperature ($^{\circ}\text{C}$)

Ix = average light intensity in the canopy ($\text{cal cm}^{-2}\text{min}^{-1}$)

P_5 = minimum resistance (s/cm)

and b_1 and b_2 are constants. The average light intensity in the canopy is a function of leaf area index:

$$Ix = I_0 e^{-k \cdot \text{LAI}}$$

where

I_0 = the light intensity above the canopy

k = attenuation constant

LAI = leaf area index (m^2/m^2)

Leaf area index (LAI) is a dynamic function of total leaf carbon (C_{TL}) and an empirical ratio of leaf area to leaf weight:

$$\frac{d}{dt} (LAI) = \left[\frac{d}{dt} (f_{10} \cdot C_{TL}) \right] \left[1 - \frac{(LAI)}{(LAI)_{max}} \right],$$

where

f_{10} = leaf area to leaf weight ratio (m^2/g),

C_{TL} = total leaf carbon, and

LAI_{max} = maximum leaf area index (m^2/m^2).

The function f_{10} is a cubic polynomial function of time fitted to the empirical data of Hughes⁴⁷. The total net volume flux can be expressed as independent fluxes of ^{14}C and ^{12}C :

$$\begin{aligned} F_v &= [(^{12}CO_{2a} - ^{12}CO_{2c}) + (^{14}CO_{2a} - ^{14}CO_{2c})]/r_{CO_2} \\ &= ^{12}F_v + ^{14}F_v \end{aligned}$$

The ambient CO_2 concentration is estimated to be $3.4 \times 10^{-4} \text{ cm}^3 \text{ cm}^{-3}$ at the time of the HTGR fuel economy from the model of Bolin and Eriksson⁴⁸. The calculation of ground-level $^{14}CO_2$ concentrations was presented in Sec. 2.2.3.5 and the incorporation of these data in the plant growth model is described in Sec. 2.2.5. The $^{12}CO_2$ concentration at the leaf chloroplast is written as an empirical function of temperature (Wuenschel and Kozlowski⁴⁹):

$$^{12}CO_{2c} = \begin{cases} 2.5 \times 10^{-4} - 8.33 \times 10^{-6} (T-20) & T \geq 20 \\ 2.5 \times 10^{-4} & T < 20 \end{cases}$$

where T is the average hourly temperature.

Concentrations of $^{14}\text{CO}_2$ at the chloroplast during a non-plume event are assumed to be proportional to the normal ambient concentrations of $^{14}\text{CO}_2$. These values of $^{14}\text{CO}_{2c}$ are calculated by multiplying $^{12}\text{CO}_{2c}$ by the pre-1950 ^{14}C to total carbon ratio of 1.41×10^{-2} times a 30% increase from residual ^{14}C due to bomb testing (Fairhall and Young⁵). During a plume event, the ^{14}C concentration at the chloroplast is less certain. We make the assumption of an instantaneous build-up of $^{14}\text{CO}_2$ at the chloroplast proportional to the ambient $^{14}\text{CO}_2$ concentration during a plume event:

$$^{14}\text{CO}_{2c} = ^{12}\text{CO}_{2c} \cdot ^{14}\text{CO}_{2a}/^{12}\text{CO}_{2a}$$

The net mass flux of carbon exchange in $\text{gC cm}^{-2} \text{ hr}^{-1}$ is calculated from the net volume flux of CO_2 exchange by multiplying by a set of coefficients:

$$n_{Fm} = n_{Fv} \cdot \rho \cdot 3.6 \times 10^3$$

where

$$n_{Fv} = \text{net volume flux } (\text{cm}^3 \cdot \text{cm}^{-2} \cdot \text{s}^{-1}),$$

$$\rho = \text{density of pure } \text{CO}_2 \text{ at ambient temperature and pressure } (\text{g/cm}^3).$$

For ^{12}C the coefficient ρ is written as a function of temperature (Sestak, et al.⁵⁰):

$$\rho = 1.977 \times 10^{-3} - 6.5 \times 10^{-6} \cdot T,$$

where T is the average hourly temperature. For ^{14}C , ρ is calculated as the ρ for ^{12}C times the isotopic ratio of $1.045 \text{ g } ^{14}\text{CO}_2/\text{g } ^{12}\text{CO}_2$.

The total growth rate of the crop species in $\text{gC m}^{-2} \text{h}^{-1}$ is calculated by multiplying the net mass flux of carbon by the leaf area index of the crop:

$$n_{G_T} = n_{F_m} \cdot \text{LAI} \cdot c \cdot 10^4,$$

where

n_{F_m} = net mass flux of carbon exchange ($\text{g} \cdot \text{cm}^{-2} \cdot \text{h}^{-1}$),

LAI = leaf area index (m^2/m^2),

c = stoichiometric coefficient to convert CO_2 to C (g/g).

The coefficient c is derived from the summary equation for photosynthesis (Sestak, et al.⁵⁰):

Since six molecules of CO_2 are required to make a single molecule of glucose, the constant c is calculated by using the fractional molecular weights of carbon to CO_2 and sugar ($\text{C}_6\text{H}_{10}\text{O}_5$):

$$\frac{6 \cdot \text{molecular weight of carbon/molecular weight of sugar}}{6 \cdot \text{molecular weight of carbon/molecular weight of CO}_2}$$

For ^{12}C , the value of c is 0.2716 and for ^{14}C it is 0.2644. The growth rate of leaves (n_{G_L}) is assumed to be a specified fraction of n_{G_T} .

2.2.4.2 Leaf mortality rate

The total leaf mortality rate (M_{TL}) is written as a function of total leaf carbon. For each carbon isotope, the rate of leaf mortality is expressed as the isotope fraction of total leaf carbon times the total mortality rate. The total mortality rate (Dixon⁵¹) is

$$M_{TL} = C_{TL} \cdot \gamma_1 / [1 + e^{(2.2/\gamma_3)(\gamma_2 - t)}]$$

where

γ_1 = maximum leaf fall rate constant (hr^{-1})

γ_2 = time of maximum leaf fall (hr)

γ_3 = time between 0.1 and 0.5 total leaf fall (hr)

The individual isotope leaf mortality rates are

$$^{14}M_L = (^{14}C_L / C_{TL}) M_{TL}$$

for ^{14}C and

$$^{12}M_L = (^{12}C_L / C_{TL}) M_{TL}$$

for ^{12}C .

2.2.4.3 Leaf Respiration Rates

Leaf respiration rate, as with leaf mortality, is a function of total leaf carbon. Since photorespiration is considered implicitly in the calculation of photosynthesis, only dark respiration is calculated. The dark respiration rate for total leaf carbon is:

$$R_{TL} = LAI \cdot 10^4 \cdot R_{std} \cdot 2^{(T-22)/10},$$

where

R_{std} = standard dark respiration rate ($\text{gC cm}^{-2} \text{ hr}^{-1}$), and

T = average hourly temperature ($^{\circ}\text{C}$).

The respiration rates for each carbon isotope are expressed by

$$^{14}R_L = (^{14}C_L/C_{TL}) R_{TL}$$

for ^{14}C and

$$^{12}R_L = (^{12}C_L/C_{TL}) R_{TL}$$

for ^{12}C .

2.2.5 Incorporation of ^{14}C Concentration in the Carbon Assimilation Model (CAM)

A first step in the incorporation of ^{14}C concentration into the CAM is to calculate the natural ambient ^{14}C concentration in the year 1985 - the assumed on-line date for the HTGR reprocessing facility. The estimated ^{14}C to total carbon ratio in 1985 is 1.83×10^{-12} (Fairhall and Young⁵). Multiplying this value by the projected⁴⁶ CO_2 concentration in 1985 of $3.4 \times 10^{-4} \text{ cm}^3/\text{cm}^3$ yields an estimated 1985 natural ambient $^{14}CO_2$ concentration of $6.2 \times 10^{-16} \text{ cm}^3/\text{cm}^3$.

The above ambient calculations of $^{14}CO_2$ as Ci/m^3 presented in Sec. 2.2.3.5 provide the basis for calculating hourly above-background $^{14}CO_2$ concentrations as fractional volume. The maximum plume event concentrations are added to the natural ambient concentration for each daytime stability class-wind speed class combination for two stack heights (Table 8) to provide estimates of total $^{14}CO_2$ atmospheric concentrations. It is convenient to express these concentrations as a vector $c = (c_1, c_2, \dots, c_6)$ in which the first five components are the concentrations in a column of Table 8 and the sixth component is the natural ambient concentrations.

Also needed for calculation of hourly $^{14}CO_2$ concentrations are the daytime fractional occurrences of each stability class and wind speed combination (Table 9). These tabled values also can be expressed as a matrix. We can write:

Table 8. Maximum ground level concentrations of $^{14}\text{CO}_2$ for two stack heights expressed as fraction by volume (cm^3/cm^3).

Stability Class	Wind Speed Class	Distance from Stack				
		500 m ^a	1 km		10 km	
		300 ft Stack	300 ft Stack	1000 ft Stack	300 ft Stack	1000 ft Stack
1	1	1.3×10^{-12}	5.7×10^{-13}	6.2×10^{-16}	1.5×10^{-14}	1.0×10^{-14}
1	2	5.1×10^{-13}	2.1×10^{-13}	3.3×10^{-15}	5.8×10^{-15}	4.8×10^{-15}
1	3	3.0×10^{-13}	1.2×10^{-13}	1.0×10^{-14}	3.5×10^{-15}	2.9×10^{-15}
4	3	4.4×10^{-15}	1.4×10^{-13}	6.6×10^{-16}	3.6×10^{-14}	9.2×10^{-15}
4	4	3.7×10^{-15}	9.5×10^{-14}	6.2×10^{-16}	2.3×10^{-14}	7.8×10^{-15}

^aGround level concentrations at 500 m from a 1000 ft stack are not significantly higher than background concentrations.

Table 9. Fractional daytime occurrence of important stability classes and wind speed conditions.

Stability Class	Wind Speed Class	April	May	June	July	August	September	October
1	1	0.0	0.0136	0.0479	0.0821	0.0080	0.0084	0.0056
1	2	0.0286	0.0272	0.0592	0.0238	0.0486	0.0641	0.0084
1	3	0.0344	0.0218	0.0310	0.0207	0.0703	0.0615	0.0224
4	3	0.0072	0.0095	0.0198	0.0223	0.0027	0.0097	0.0070
4	4	0.0230	0.0149	0.0	0.0103	0.0094	0.0209	0.0112
Conditions other than above		0.9068	0.9130	0.8421	0.8408	0.8610	0.8354	0.9454

$$P = ||P_{ij}|| \quad i = 1, 2, \dots, 6; j = 1, 2, \dots, 7$$

where i is the stability class - wind speed class and j is the month (April through October).

A cumulative probability distribution is calculated for each month and written in matrix notation as $A = ||a_{ij}||$ where:

$$a_{ij} = \begin{cases} P_{1j} & i = 1 \\ a_{i-1,j} + P_{ij} & i > 1 \end{cases}$$

and i and j are defined as before.

Since the stability class and wind speed class combinations are defined by month (Table 9) and the carbon assimilation model uses a time-step of an hour, it is necessary to define j according to sequential hours per month:

$$j = \begin{cases} 1 & 2160 \leq t < 2940 \\ 2 & 2904 \leq t < 3648 \\ 3 & 3648 \leq t < 4368 \\ 4 & 4368 \leq t < 5112 \\ 5 & 5112 \leq t < 5856 \\ 6 & 5856 \leq t < 6576 \\ 7 & 6576 \leq t < 8760 \end{cases}$$

Finally a value of ground-level $^{14}\text{CO}_2$ (from the vector c) is obtained each hour by sampling the cumulative probability distribution of the month in which the current hour falls. A uniform distribution random number generator with random variable x is used such that for each month j :

$$^{14}\text{CO}_{2a} = \begin{cases} c_1 & 0 \leq x \leq a_{1,j} \\ c_2 & a_{1,j} < x \leq a_{2,j} \\ c_3 & a_{2,j} < x \leq a_{3,j} \\ c_4 & a_{3,j} < x \leq a_{4,j} \\ c_5 & a_{4,j} < x \leq a_{5,j} \\ c_6 & a_{5,j} < x \leq 1 \end{cases}$$

If x corresponds to a nighttime hour, however, the uptake rates for ^{12}C and ^{14}C are set to zero.

2.2.6 Estimates of ^{14}C Assimilation

Rates of carbon assimilation increase whenever the ambient CO_2 concentrations are increased. Because the net assimilation rates are much higher than respiration or mortality rates at the beginning of the growing season, the assimilated ^{14}C is retained in the plant; near the end of the growing season, this trend is reversed. In order to show the response of plants to the plume events, the results of a simulation during five days in July are shown in Fig. 5. Included in this figure are the hours of day and night, the plume events, and the carbon-14 in plant leaves. Note that whenever a plume event occurs in daylight the carbon-14 in leaves increases. No accumulation occurs at night since the photosynthetic process requires light to function. Plume events do occur at night but with different probabilities than in the daytime.

For the specific case using Oak Ridge area meteorological conditions, CAM predicted a maximum specific activity in plant leaves (S_p) of 1.84×10^{-9} Ci/gC at a point 500 m from the 300-ft stack. Figure 6 shows a plot of S_p superimposed on a bar graph of the monthly averages of the ambient

Fig. 5. Ground level atmospheric concentrations of $^{14}\text{CO}_2$ (solid line) and ^{14}C content in leaves (cashed line) simulated for five days during the growing season at 500 m from the 300-ft stack. The hours of dark and daylight are represented by solid and clear bars, respectively.

Fig. 6. Simulated history of specific activity of ^{14}C in plant leaves (plotted points). The solid bars show the monthly averaged specific activity in the ambient air during daylight hours, and the dashed line represents the corresponding average for the growing season.

specific activity during daylight hours. The dashed line represents the ambient seasonal daylight average, $\bar{S}_a$. The increased frequency of plume events during June and July accounts for the steep rise in leaf specific activity, shown in Fig. 6, to its maximum, which occurs in the latter half of July. Afterward, this quantity recedes toward the seasonal average in response to the decreasing frequency of plume events, and accordingly, the ratio $S_p/\bar{S}_a$ decreases from its maximum (≈ 2) and returns to values near unity during September.

For the simulation plotted in Fig. 6, the calculated seasonal $^{14}\text{CO}_2$ concentration is $6.22 \times 10^{-14} \text{ cm}^3/\text{cm}^3$. This value is divided by $3.4 \times 10^{-4} \text{ cm}^3/\text{cm}^3$, the estimated 1985 atmospheric CO_2 concentration, to obtain the $^{14}\text{CO}_2/^{12}\text{CO}_2$ ratio of 1.83×10^{-10} . Multiplying this value by the isotopic density ratio 1.116 yields a ratio of $2.04 \times 10^{-10} \text{ g }^{14}\text{C/gC}$ in the atmosphere. This value times $4.46 \text{ Ci/g }^{14}\text{C}$ gives an average specific activity of $9.10 \times 10^{-10} \text{ Ci/gC}$. If we assume that vegetation is in equilibrium with the average atmospheric specific activity, the specific activity in plant tissue would also equal $9.10 \times 10^{-10} \text{ Ci/gC}$. The maximum ^{14}C specific activity in plant leaves (S_p) based on the CAM simulation is $1.84 \times 10^{-9} \text{ Ci/gC}$, from which we calculate $\max(S_p/\bar{S}_a) = 2.02$.

We emphasize that information obtained from the model in this simulation is highly tentative, and such numeric transfer factors as might be inferred from it must be considered preliminary until validation experiments can be performed. If the validity of the model were stipulated, the appropriate transfer factor for vegetation raised under these exposure conditions would depend upon the distribution of harvest times in the growing season, and this would be specific to the particular kind of plant.

Moreover, a composite transfer factor for the carbon that man ingests would have to take into account specific factors for all vegetation links in his food chain, including forage and silage crops consumed by beef and poultry.

Because of the lack of direct experimental corroboration of the model's predictions, the evidence is judged insufficient at this time to support the recommendation of any transfer factor greater than unity for use in dose estimates to man from the ingestion of ^{14}C .

3. RADIOLOGICAL IMPACTS TO INDIVIDUALS AND POPULATIONS IN THE VICINITY OF A HTGR REPROCESSING FACILITY

3.1 Exposure Scenarios

Dose estimates were computed (1) for a hypothetical maximally exposed individual (fence-post man), (2) an average individual within approximately 50 miles of the facility site, and (3) for a population of 10^6 individuals uniformly distributed over the same area.

The two modes of release discussed in Sec. 2.2.3.1 involved a 300-ft stack with no thermal discharge and a 1000-ft stack with a specified thermal discharge accompanying the ^{14}C release. For the sake of brevity, we shall refer to these cases simply as the "300-ft stack" and "1000-ft stack" cases, respectively.

In each of these cases, two grids have been superimposed upon the region around the facility. The first, or "large grid," fits into an approximately square area 100 miles x 100 miles, with the facility located at the center, and with sides oriented north-south and east-west. The grid is a network of $11 \times 11 = 121$ points spaced at north-south or

east-west increments of 10 mi. The second, or "small grid," is similarly oriented with respect to a square 10 mi x 10 mi and consists of $21 \times 21 = 441$ points spaced at intervals of 0.5 mi. The facility was assumed to occupy the central square mile of each grid, with the stack in the exact center.

The atmospheric transport methodology of Sec. 2.2 was used to predict, for the hypothesized release from each stack, the resulting time-averaged ground-level air concentrations of ^{14}C at each point of both grids. Because of the organization of the computer data file containing the meteorological information, these concentrations were averaged with respect to the 24-hour day; both annual and growing-season (April through October) averages were calculated. A special computation was undertaken to furnish, for selected points, concentrations which represent growing-season averages for daylight hours only (with daylight defined as geometric sunrise to sunset). These special values were used to derive conversion factors for extrapolating the daylight-averaged concentrations to averages over the regions covered by the small and large grids; in addition, the special points were chosen to include the location of the maximally exposed individual ("fence-post" man). Inhalation dose components were estimated from the annual average concentrations; uptake by ingestion, however, is dependent upon photosynthesis, and the seasonal daylight average concentrations are therefore appropriate for estimating the ingestion component, which ordinarily accounts for more than 99 percent of the dose.

It is appropriate to point out that significant differences between these two seasonal averages (daylight vs 24-hour) exist in the Oak Ridge meteorology and should be examined in any meteorology which is used for

this type of assessment. The difference between annual and seasonal concentrations, when averaged over the large grid, was not significant for either stack, but was pronounced at points close to the stack.

The dose-rate factors of Table 6 are based on the assumption that a steady-state ambient specific activity of ^{14}C produces the same specific activity in man's tissues, provided all dietary intakes are exposed to the same ambient levels that he breathes. Extrapolation from this model permits a mixture of intakes at different specific activities.

The maximally exposed individual was assumed to live at the grid point where the highest concentrations occurred and to raise all food on site. In the Oak Ridge area meteorology, a radial drawn from the stack in the northeast direction defines a corridor of high concentration, which contains the maximum grid point for each stack height. For the 300-ft stack, the concentrations are highest at the grid point closest to the stack (0.707 miles), and in the case of the 1000-ft stack, the maximum point is the next point to the northeast (1.41 miles). The concentrations at these points were used to calculate dose estimates for the maximally exposed individual. These estimates are presented in Sec. 3.2.

The basic assumptions taken in calculating averaged dose estimates for the area covered by either grid were the following:

- (1) Population is geographically uniformly distributed.
- (2) Each individual receives a dietary intake of 300 grams of carbon per day, the sources of which are uniformly distributed over the large grid area.

Area-averaged concentrations were therefore computed as arithmetic means of time-averaged concentrations at the grid points of the area in question,

and the results were applied to calculating the corresponding area-averaged dose estimates. Components due to inhalation and ingestion were analyzed, but only the latter are significant for the exposure situations of interest. We note, however, that an average resident of the small grid has an inhalation component that accounts for 30 percent of the total dose, if we assume the conservative ratio of uptake fractions $f_a/f_w = 0.75$; this effect derives from the locally elevated concentration of ^{14}C in the air he breathes, whereas his dietary uptake is the same as that of the average large-grid resident. But the differential effect diminishes rapidly as distance from the stack increases. Average doses to area inhabitants are given in Sec. 3.3.

For each stack, the dose (man-rem) to population in the large-grid area was estimated for one year of operation of the reprocessing facility; a population of 10^6 persons was assumed for this calculation. These doses represent integrations of the respective dose rates over the one year of operation; they do not contain the component that would be delivered over the long term by the residual increment in world-wide atmospheric specific activity contributed by the ^{14}C release during the single year of operation.

All dose estimates given in Secs. 3.2, 3.3, and 3.4 apply to total body. Dose rates or doses to other organs may be calculated by the appropriate ratio of dose rate factors from Table 2.

The population doses are presented in Sec. 3.4.

3.2 Dose to the Maximally Exposed Individual

With the models under discussion, the maximum inhalation dose would result from continuous habitation where the annual 24-hour average air

concentration of ^{14}C is maximum, and the largest ingestion dose would come from the direct consumption of vegetation produced at the point where the daylight seasonal average concentration is greatest, and from eating the meat and drinking the milk of cattle fed on vegetation produced at the same location. For the 300-ft stack, both concentrations are maximum at the nearest point of the small grid northeast of the stack (0.707 miles, $35^\circ 55' 26''$ N by $84^\circ 19' 28''$ W); in the case of the 1000-ft stack, both are maximum at the second small-grid point northeast of the stack (1.41 miles, $35^\circ 55' 52''$ N by $84^\circ 18' 56''$ W). Each of these points will be referred to as the "maximum point" for its respective stack. The coordinates of the stack, in each case, are $35^\circ 55' 0''$ N by $84^\circ 20' 0''$ W.

The following table displays the two concentrations and the resulting dose rates to the fence-post man for each stack height. Natural background concentration and dose rate are shown for comparison. Parenthesized dose rates are for 1 Ci/yr (= 1/5000 of the assumed release rate).

	24-Hour Annual Concentration (Ci/m ³)	Daylight Seasonal Concentration (Ci/m ³)	Total Body Dose Rate (mrem/yr)
300-ft stack	3.19×10^{-11}	6.66×10^{-11}	$\frac{87}{(1.7 \times 10^{-2})}$
1000-ft stack	1.79×10^{-12}	4.17×10^{-12}	$\frac{5.5}{(1.1 \times 10^{-3})}$
Natural ^{14}C	9.76×10^{-13}	9.76×10^{-13}	1.3

The 24-hr annual concentrations are presented for comparison purposes, but more than 99 percent of each dose rate is attributable to the

ingestion mode, which depends on the daylight seasonal concentration.

Thus to the precision shown, each dose rate may be calculated as the product of the daylight seasonal concentration and the dose rate factor 1.31×10^{12} mrem/yr per Ci/m³ from Table 6.

3.3 Average Individual Within the 10- and 100-mile Squares

Doses to the average adult individual in each grid system have been estimated. The average small-grid resident is of some interest because a conservative assumption regarding the inhalation uptake fraction ($f_a/f_w = 0.75$) results in an inhalation component that is approximately 30 per cent of the total dose.

The following table shows, for each stack, the inhalation, ingestion, and total dose rates to total body for the average resident of the small grid versus two assumed uptake ratios f_a/f_w . The first ratio (ICRP Publication 2²⁹) is conservative and probably inappropriate; the second was derived from Bernard³² and is believed to be a more realistic representation. This point was discussed in Sec. 1.3.5.

f_a/f_w	Total-Body Dose Rate (mrem/yr)			
	Inhalation	Ingestion	Total	Total/5000 Ci
300-ft Stack				
0.75	4.79×10^{-2}	0.106	0.154	3.08×10^{-5}
0.01	6.42×10^{-4}	0.107	0.108	2.16×10^{-5}
1000-ft Stack				
0.75	3.84×10^{-3}	6.24×10^{-2}	6.62×10^{-2}	1.32×10^{-5}
0.01	5.14×10^{-5}	6.30×10^{-2}	6.32×10^{-2}	1.26×10^{-5}

It is clear from the table that if the latter assumption is taken, the component of dose due to inhalation remains minor for the average resident of the small grid.

The total-body dose rates (mrem/yr) for the average resident of the large-grid area are as follows (parenthesized values are mrem/yr per Ci/yr of release):

300-ft stack	0.11	(2.2×10^{-5})
1000-ft stack	6.3×10^{-2}	(1.3×10^{-5})
Natural ^{14}C	1.3	

For the average resident of the large-grid area, the inhalation component of the dose is negligible.

3.4 Local Population Dose

Estimates of dose to the local (large-grid) population (man-rem) were computed from the average dose rates of Sec. 3.3. These population dose estimates reflect one year of operation of the reprocessing facility. A population of 10^6 individuals has been assumed, which is uniformly distributed over the large grid area and which receives dietary carbon intakes in equal proportions from uniformly distributed sources (assumptions (1) and (2) from Sec. 3.1).

The population dose estimates are as follows:

	man-rem	man-rem/Ci
300-ft stack	110	2.2×10^{-2}
1000-ft stack	63	1.3×10^{-2}
Natural ^{14}C	1300	

These population doses should not be interpreted as total dose commitments to the local population from one year of operation of the facility; such a commitment would contain the component that would be delivered over the longer term by the residual increment in the world-wide atmospheric ^{14}C specific activity that is contributed by the release during the year of operation. A large fraction of the release eventually goes into the deep ocean and is retained there with a mean residence time of centuries, but a portion remains airborne, subject only to radioactive decay and dilution by the increasing inventory of ^{12}C . This airborne fraction of ^{14}C , distributed world wide, delivers its dose to populations over a period of thousands of years.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The information presented in this report leads to a number of conclusions and recommendations. Some recommendations suggest further research; others are applicable to site-specific assessments that might be performed for HTGR and other facilities which release ^{14}C into the atmosphere.

In Sec. 1.2.2, calculations of amounts of natural and excess ^{14}C present in terrestrial biota were described, and it was pointed out that the resulting estimates were somewhat higher than corresponding values reported in the literature. Taken together, estimates of terrestrial distribution in the present analysis and the more precisely measured oceanic distribution are in acceptable agreement with theoretically calculated yields from weapons testing. The question which remains to be investigated is whether this biospheric partitioning significantly alters previous

estimates of dose commitment to the world's population. We recommend that existing dose estimates be reviewed in the light of this question.

Internal dose-rate factors for several reference organs of man were computed from recently published information and presented in Sec. 1.3.6. These factors are based on the ^{14}C specific activity in man's tissues. Their use for steady-state dose rate calculations is believed to be preferable to the adoption of corresponding estimates based on existing metabolic models, specifically those of ICRP Publications 2²⁹ and 10.³⁰

Atmospheric transport calculations have been carried out to predict concentrations of releases ^{14}C over the local area surrounding the model facility. The resulting concentrations depend on the particular meteorology (which, for this study, was that of the Oak Ridge area), and they are also functions of several stack and release parameters (release rate, stack height and diameter, and exhaust gas temperature and velocity) for which specific values were chosen. In particular, calculations were done with two stack heights and exit-gas temperatures, and the results indicated a significant reduction in the fence post dose when a 1000-ft stack with 80°C gas temperature replaces a 300-ft stack releasing gas at ambient temperature. The dependence of the maximum dose on these parameters needs to be explored further in order to provide information for stack design and release control engineering.

The dependence of the dose on the specific meteorology also needs to be examined. There is reason to believe that the Oak Ridge meteorology tends to lead to a larger fence post dose because of its higher frequency of daytime Class A (unstable) conditions. To the extent practicable, a range of fence post concentrations should be estimated for near-extreme meteorologies.

For the Oak Ridge meteorology, calculations revealed that replacing the 24-hour annual average ^{14}C concentration in the air by an average taken with respect to daylight hours during the growing season increases the fence post ingestion dose component by a factor of about two. It is suggested that the latter average is the more appropriate basis for the estimation of the ingestion dose, whereas the former should be used for the inhalation exposure mode.

The possibility of restricting some fraction of the ^{14}C release to nighttime hours might be considered. Calculations for this report assumed a uniform release rate throughout each day and night of the year. Thus some reduction in local dose rates is possible by an increase in the nocturnal fraction of the release. But such a procedure would in no way reduce the global impact of the release.

Finally, calculations done with a plant growth carbon assimilation model (CAM) have suggested the possibility that in the presence of frequent meteorological events that produce sporadic high ^{14}C concentrations, the time-averaged ambient specific activity may underestimate the maximum specific activity likely to occur in the tissue of a plant growing in such an exposure environment. Published information is inadequate to corroborate or reject this result, and the relevance of the the question to the estimation of the transfer of ^{14}C to man through his food chain indicates a need for continuing efforts to validate the model.

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APPENDIX

LISTING OF CARBON ASSIMILATION MODEL

AND

GLOSSARY OF VARIABLES AND PARAMETERS

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* *****CAN***** (CARBON ASSIMILATION MODEL)
* A MODEL OF CARBON-12 AND CARBON-14 DYNAMICS IN VEGETATION
* DATE: JULY 1, 1975
* AUTHOR: KENNETH R. DIXON
* ENVIRONMENTAL SCIENCES DIVISION
* OAK RIDGE NATIONAL LABORATORY
* OAK RIDGE, TENNESSEE 37830
/ COMMON/C1/ APD(5,7),PD(5,7)
  FIXED I,J,K,M
INITIAL
  NOSORT
*
* READ IN MONTHLY WIND SPEED - STABILITY CLASS PROBABILITIES
*
  READ (5,100) ((PD(I,J),J=1,7),I=1,5)
  100 FORMAT (7F10.5)
INCON      LC120=1.0,          SC120=4825.,   RC120=2490.
INCON      LC140=1.83E-12,    SC140=6.03E-9,   RC140=3.11E-9
PARAMETER  ISTAR=5.0E-6,     LAIMAX=5.0
PARAMETER  P1=200.,          P3=0.9
PARAMETER  C1202A=3.4E-4,    P18=7.434E-5
PARAMETER  P5=15.0,          RH20=3.5
PARAMETER  C12CNV=.2714,     C14CNV=.2642
PARAMETER  P13=6.166E-05,    LRESTD=1.45E-8
PARAMETER  TRNP=1800.,       TAB=7224.
PARAMETER  GAMMA1=.005,      GAMMA2=7239.84
PARAMETER  GAMMA3=1248.
CONSTANT   B1=0.1689,        B2=23.5668
CONSTANT   FA=1.87E-2,       FB=3.96E-5
CONSTANT   PC=1.95E-8,       PE=3.0E-12
CONSTANT   PI=3.14159,       K2=.138
CONSTANT   PSMA=2.895,       PSMB=9.284
CONSTANT   TOFF=2880.
DYNAMIC
  TM=AMOD(TIME,8760.)
*
* STORE GROUND-LEVEL C1402A EXPOSURE DATA FOR ONE STACK HEIGHT
* AND DISTANCE
STORAGE EX(5)
TABLE      EX(1)=1.29E-12,EX(2)=5.14E-13,EX(3)=3.05E-13,...
           EX(4)=4.42E-15,EX(5)=3.66E-15
*
* DETERMINE MONTH BY HOURS
*
PROCEDURE M=MNTH(TM)
  IF(TM.LT.2904) GO TO 31
  IF(TM.LT.3648) GO TO 32
  IF(TM.LT.4368) GO TO 33
  IF(TM.LT.5112) GO TO 34
  IF(TM.LT.5856) GO TO 35
  IF(TM.LT.6576) GO TO 36
  IF(TM.LT.8760) GO TO 37
  GO TO 37
31  M=1
    GO TO 38
32  M=2
    GO TO 38
33  M=3

```

```

      GO TO 38
34  M=4
      GO TO 38
35  M=5
      GO TO 38
36  M=6
      GO TO 38
37  M=7
38  CONTINUE
ENDPRO
*
* CALCULATE LIGHT AND TEMPERATURE
*
      TERM5=(ISTAR/2.0)*SIN((2*PI*(18-TM))/24)
      IH=(ISTAR/6.0)+TERM5
      IT=INSW(IH,0.0,IH)
      TERM1=15.3*SIN((2*PI*(7320-TM))/8760)
      TERM2=5.5*SIN((2*PI*(TM-8))/24)
      TH=11.4+TERM1+TERM2
      TT=INSW(TH,0.0,TH)
      EXT=K2*LAI
      IX=IT*EXP(-K2*LAI)
*
* CALCULATE CO2 CONCENTRATION AT THE CHLOROPLAST
*
PROCEDURE C12O2C=SLO(TH)
      IF (TH .LT. 20.) GO TO 7
      C12O2C=.000250-8.33E-6*(TH-20.)
      GO TO 8
7      C12O2C=.000250
8      CONTINUE
ENDPRO
      C14O2C=C12O2C*C14O2A/C12O2A
*
* CALL AMBIENT CO2 CONCENTRATION FROM FUNCTION CHEX
*
      C14O2A=CHEX(M)
      CC14A=INTGRL(0.0,C14O2A)
*
* CALCULATE TOTAL GROWTH
*
PROCEDURE RNP12,RNP14=PHOTO(LRT,C12O2C,C14O2A)
      IF ((TM .LT. TRNP).OR.(TM .GT. TAB)) GO TO 3
      IF (IT .EQ. 0.0) GO TO 3
      RNP12=(C12O2A-C12O2C)/LRT
      RNP14=(C14O2A-C14O2C)/LRT
      GO TO 4
3      RNP12=0.0
      RNP14=0.0
4      CONTINUE
ENDPRO
      LRT=LRS+LRI
      LRS=1.7*RH2O
      TERM3=EXP(-B2*IX)
      TERM4=EXP(-B1*TT)
      LRI=(P1*TERM3*TERM4)+P5
      C12O2D=1.977E-3-6.5E-6*TT
      C14O2D=1.045*C12O2D
      RGR12=RNP12*LAI*3.6E7*C12O2D*C12CNV

```

RGR14=RNP14*LAI*3.6E7*C14O2D*C14CNV

*
* ALLOCATE GROWTH TO LEAVES, STEMS, AND ROOTS
*

RLG12=F3*(1-F1)*RGR12
RLG14=P3*(1-F1)*RGR14
RSG12=(1-P3)*(1-F1)*RGR12
RSG14=(1-P3)*(1-F1)*RGR14
RRG12=F1*RGR12
RRG14=F1*RGR14

PROCEDURE F1=TRANS2(TM)
IF (TM.LT. 4944.) GO TO 18
IF (TM.LT. 6912.) GO TO 19
IF (TM.LT. 8136.) GO TO 20
GO TO 21
18 F1=0.0
GO TO 22
19 F1=0.00004065*(TM-4944)
GO TO 22
20 F1=.08-0.00006533*(TM-6912)
GO TO 22
21 F1=0.0
22 CONTINUE

ENDPRO

*
* CALCULATE LEAF MORTALITY RATE
*

Q=(2.2/GAMMA3)*(GAMMA2-TM)
TERM6=EXP(Q)
RLMT=TLC*GAMMA1/(1+TERM6)
RLM12=LC12*RLMT/TLC
RLM14=LC14*RLMT/TLC

*
* CALCULATE LEAF RESPIRATION
*

PROCEDURE LRSPT,LRSP12,LRSP14=BRTH(IT,LAI)
IF (IT.EQ. 0.0) GO TO 5
LRSP12=0.0
LRSP14=0.0
GO TO 6
5 LEXTMP=(TM-22.)/10.
LRSPT=LAI*1.E4*LRESTD*2**LEXTMP
LRSP12=LC12*LRSPT/TLC
LRSP14=LC14*LRSPT/TLC
6 CONTINUE

ENDPRO

*
* CALCULATE LEAF CARBON
*

LC12D=RLG12-RLM12-LRSP12
LC14D=RLG14-RLM14-LRSP14
TLCD=LC12D+LC14D
LC12=INTGRL(LC120,LC12D)
LC14=INTGRL(LC140,LC14D)
CRATIO=LC14/TLC
TLC=LC12+LC14

```

*
* CALCULATE LEAF AREA INDEX
*
PROCEDURE F10,F11,LAIDOT,F10DOT=XXX(LAI,TLCD,TLC)
  IF(TM.LT.TRNP) GO TO 11
  IF(TM.LT.TOFF) GO TO 12
  F11=PA+PB*(TM-TOFF)-PC*(TM-TOFF)**2+PE*(TM-TOFF)**3
  F10DOT=PB-2*PC*(TM-TOFF)+3*PE*(TM-TOFF)**2
  IF(TM.GE.6000.) F10DOT=0.0
  Z=6000.-TM
  F10=F11
  IF(Z.GT.0.0) XSAVE=F11
  IF(Z.LE.0.0) F10=XSAVE
10  CONTINUE
  LAIDOT=(F10*TLCD+TLC*F10DOT)*(LAIMAX-LAI)/LAIMAX
  GO TO 13
11  LAIDOT=0.0
  GO TO 13
12  F10=.025
  F10DOT=0.0
  GO TO 10
13  CONTINUE
ENDPRO
  LAI=INTGRL(0.24,LAIDOT)
*
* CALCULATE STEM MORTALITY RATE
*
  RSMT=P13*TSC*PSMA/(PSMB+TH)
  RSM12=SC12*RSMT/TSC
  RSM14=SC14*RSMT/TSC
*
* CALCULATE STEM CARBON
*
  SC12D=RSG12-RSM12
  SC14D=RSG14-RSM14
  SC12=INTGRL(SC120,SC12D)
  SC14=INTGRL(SC140,SC14D)
  TSC=SC12+SC14
*
* CALCULATE ROOT MORTALITY RATE
*
  RRMT=P18*TRC
  RRM12=RC12*RRMT/TRC
  RRM14=RC14*RRMT/TRC
*
* CALCULATE ROOT CARBON
*
  RC12D=RRG12-RRM12
  RC14D=RRG14-RRM14
  RC12=INTGRL(RC120,RC12D)
  RC14=INTGRL(RC140,RC14D)
  TRC=RC12+RC14

```

*
* CALCULATE TOTAL PLANT CARBON
*

TPC=TLC+TSC+TRC

*
TIMER DELT=1.0, DELMIN=1.E-6, OUTDEL=60.0, PINTIM=8760.

OUTPUT RGR12

OUTPUT CRATIO

OUTPUT RGR14

OUTPUT C14O2A

OUTPUT LAI

OUTPUT LC14

OUTPUT TLC

OUTPUT CC14A

END

*

* MONTHLY WIND SPEED - STABILITY CLASS PROBABILITIES

*

INPUT

0.0	.01358	.04788	.08206	.00804	.00844	.00560
.02860	.02716	.05924	.02382	.04860	.06406	.00840
.03440	.02176	.03104	.02068	.07028	.06146	.02242
.00715	.00949	.01978	.02226	.00271	.00974	.00700
.02297	.01488	0.0	.01034	.00944	.02089	.01121

ENDINPUT

STOP

C

C MONTE CARLO ROUTINE TO OBTAIN HOURLY C14O2A VALUES

C

FUNCTION CHEX(N)

COMMON

COMMON/C1/APD(5,7),PD(5,7)

DO 200 J=1,7

APD(1,J)=PD(1,J)

DO 200 I=2,5

K=I-1

APD(I,J)=APD(K,J)+PD(I,J)

200 CONTINUE

X=RNDRGEN(1,333)

IF(X.GT.APD(5,N)) GO TO 99

IF(X.GT.APD(4,N)) GO TO 90

IF(X.GT.APD(3,N)) GO TO 80

IF(X.GT.APD(2,N)) GO TO 70

IF(X.GT.APD(1,N)) GO TO 60

CONC=EX(1)

GO TO 105

60 CONC=EX(2)

GO TO 105

70 CONC=EX(3)

GO TO 105

80 CONC=EX(4)

GO TO 105

90 CONC=EX(5)

GO TO 105

99 CONC=6.20E-16

105 CONTINUE

CHEX=CONC

RETURN

END

GLOSSARY OF VARIABLES AND PARAMETERS

Variables

Algebraic Symbol	Code Name	Description	Units
C_{TP}	TPC	total plant carbon	g/m^2
C_{TL}	TLC	total leaf carbon	g/m^2
$^{14}C_L$	LC14	^{14}C mass in leaves	g/m^2
$^{12}C_L$	LC12	^{12}C mass in leaves	g/m^2
C_{TS}	TSC	total stem carbon	g/m^2
$^{14}C_S$	SC14	^{14}C mass in stems	g/m^2
$^{12}C_S$	SC12	^{12}C mass in stems	g/m^2
C_{TR}	TRC	total root carbon	g/m^2
$^{14}C_R$	RC14	^{14}C mass in roots	g/m^2
$^{12}C_R$	RC12	^{12}C mass in roots	g/m^2
$^{14}G_T$	RGR14	total growth rate of ^{14}C	$g \cdot m^{-2} \cdot h^{-1}$
$^{12}G_T$	RGR12	total growth rate of ^{12}C	$g \cdot m^{-2} \cdot h^{-1}$
$^{14}G_L$	RLG14	growth rate of leaf ^{14}C	$g \cdot m^{-2} \cdot h^{-1}$
$^{12}G_L$	RLG12	growth rate of leaf ^{12}C	$g \cdot m^{-2} \cdot h^{-1}$
$^{14}G_S$	RSG14	growth rate of stem ^{14}C	$g \cdot m^{-2} \cdot h^{-1}$
$^{12}G_S$	RSG12	growth rate of stem ^{12}C	$g \cdot m^{-2} \cdot h^{-1}$
$^{14}G_R$	RRG14	growth rate of root ^{14}C	$g \cdot m^{-2} \cdot h^{-1}$
$^{12}G_R$	RRG12	growth rate of root ^{12}C	$g \cdot m^{-2} \cdot h^{-1}$
M_{TL}	RLMT	total leaf C mortality rate	$g \cdot m^{-2} \cdot h^{-1}$
$^{14}M_L$	RLM14	mortality rate of leaf ^{14}C	$g \cdot m^{-2} \cdot h^{-1}$
$^{12}M_L$	RLM12	mortality rate of leaf ^{12}C	$g \cdot m^{-2} \cdot h^{-1}$
M_{TS}	RSMT	total stem C mortality rate	$g \cdot m^{-2} \cdot h^{-1}$

Algebraic Symbol	Code Name	Description	Units
$^{14}M_S$	RSM14	mortality rate of stem ^{14}C	$g \cdot m^{-2} \cdot h^{-1}$
$^{12}M_S$	RSM12	mortality rate of stem ^{12}C	$g \cdot m^{-2} \cdot h^{-1}$
M_{TR}	RRMT	total root C mortality rate	$g \cdot m^{-2} \cdot h^{-1}$
$^{14}M_R$	RRM14	mortality rate of root ^{14}C	$g \cdot m^{-2} \cdot h^{-1}$
$^{12}M_R$	RRM12	mortality rate of root ^{12}C	$g \cdot m^{-2} \cdot hr^{-1}$
R_{TL}	LRSPT	total leaf C respiration rate	$g \cdot m^{-2} \cdot hr^{-1}$
$^{14}R_L$	LRSP14	respiration rate of leaf ^{14}C	$g \cdot m^{-2} \cdot hr^{-1}$
$^{12}R_L$	LRSP12	respiration rate of leaf ^{12}C	$g \cdot m^{-2} \cdot hr^{-1}$
R_{TS}	SRSP12	total stem C respiration rate	$g \cdot m^{-2} \cdot hr^{-1}$
$^{14}R_S$	SRSP14	respiration rate of stem ^{14}C	$g \cdot m^{-2} \cdot hr^{-1}$
$^{12}R_S$	SRSP12	respiration rate of stem ^{12}C	$g \cdot m^{-2} \cdot hr^{-1}$
R_{TR}	RRSPT	total root C respiration rate	$g \cdot m^{-2} \cdot hr^{-1}$
$^{14}R_R$	RRSP14	respiration rate of root ^{14}C	$g \cdot m^{-2} \cdot hr^{-1}$
$^{12}R_R$	RRSP12	respiration rate of root ^{12}C	$g \cdot m^{-2} \cdot hr^{-1}$
$^{14}F_v$	RNP14	net volume flux of $^{14}CO_2$	$cm^3 \cdot cm^{-2} \cdot s^{-1}$
$^{12}F_v$	RNP12	net volume flux of $^{12}CO_2$	$cm^3 \cdot cm^{-2} \cdot s^{-1}$
$^{14}CO_{2a}$	C1402A	ambient concentration of $^{14}CO_2$	cm^3/cm^3
$^{14}CO_{2c}$	C1402C	$^{14}CO_2$ conc. at the chloroplast	cm^3/cm^3
$^{12}CO_{2c}$	C1202C	$^{12}CO_2$ conc. at the chloroplast	cm^3/cm^3
$^{14}F_m$		net mass flux of ^{14}C exchange	$g \cdot cm^{-2} \cdot hr^{-1}$
$^{12}F_m$		net mass flux of ^{12}C exchange	$g \cdot cm^{-2} \cdot hr^{-1}$
LAI	LAI	leaf area index	m^2/m^2
ρ	C1202D	density of pure $^{12}CO_2$	g/cm^3
	C1402D	density of pure $^{14}CO_2$	g/cm^3

Algebraic Symbol	Code Name	Description	Units
$^{14}\dot{C}_L$	LC14D	mass balance rate of leaf ^{14}C	$\text{g}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$
$^{12}\dot{C}_L$	LC12D	mass balance rate of leaf ^{12}C	$\text{g}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$
$\dot{C}_{\text{TL}}$	TLCD	mass balance rate of total leaf C	$\text{g}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$
r_{CO_2}	LRT	total CO_2 transfer resistance	s/cm
r_i	LRI	apparent mesophyll CO_2 dif- fusion resistance	s/cm
r_s	LRS	stomatal CO_2 diffusion resistance	s/cm
I_o	IH	average hourly incident radiation	$\text{cal}\cdot\text{cm}^{-2}\cdot\text{min}^{-1}$
T	TH	average hourly air temperature	$^{\circ}\text{C}$
I_x	IX	average hourly radiant flux in canopy	$\text{cal}\cdot\text{cm}^{-2}\cdot\text{min}^{-1}$
	CRATIO	ratio of leaf ^{14}C to total leaf C	-
	F1	fraction of photosynthate allocated to roots	-
f_{10}	F10	leaf area to leaf weight ratio	m^2/g

Parameters

Algebraic Symbol	Code Name	Description	Value	Units
$^{12}\text{CO}_{2a}$	C1202A	ambient concentration of $^{12}\text{CO}_2$	3.4×10^{-4}	cm^3/cm^3
C	C12CNV	stoichiometric coefficient to convert $^{12}\text{CO}_2$ to ^{12}C	.2714	g/g
	C14CNV	stoichiometric coefficient to convert $^{14}\text{CO}_2$ to ^{14}C	.2642	g/g
	ISTAR	maximum average hourly incident radiation	5.0×10^{-6}	$\text{cal} \cdot \text{cm}^{-2} \cdot \text{min}^{-1}$
	P1	maximum apparent mesophyll resistance	200	s/cm
	P3	fraction of aboveground photo- synthates allocated to leaves	0.9	-
	P5	minimum apparent mesophyll resistance	15	s/cm
	P13	maximum hourly stem mortality rate coefficient	6.166×10^{-5}	hr^{-1}
	P18	root mortality rate constant	7.43×10^{-5}	hr^{-1}
	RH20	leaf transpiration resistance	3.5	s/cm
	TRNP	time of start of growing season	1800	hr
R_{std}	TAB	time of end of growing season	7224	hr
	LAIMAX	maximum leaf area index	5.0	m^2/m^2
	LRESIU	standard leaf respiration rate	1.45×10^{-6}	$\text{g} \cdot \text{cm}^{-2} \cdot \text{hr}^{-1}$
γ_1	GAMMA1	maximum hourly leaf mortality rate coefficient	.005	hr^{-1}
γ_2	GAMMA2	time of maximum leaf fall	7239.84	hr
γ_3	GAMMA3	time between 0.1 and 0.5 total leaf fall	1248.00	hr

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