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SCENARIOS FOR ^{14}C RELEASE TO THE ATMOSPHERE BY THE WORLD NUCLEAR INDUSTRY AND ESTIMATED RADIOLOGICAL IMPACTS*

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ABSTRACT

This paper presents an assessment of the radiation dose to the world population and the associated potential health effects from three scenarios of ^{14}C releases by the nuclear industry between 1975 and 2020. Measures of health impact are derived from source terms through the use of a multicompartment model of the global carbon cycle, dose-rate factors based on ^{14}C specific activity in various organs of man, and health-effect incidence factors recently recommended by the International Commission on Radiological Protection. The scenarios for worldwide ^{14}C releases considered are (1) a pessimistic scenario in which all the ^{14}C projected to be produced in fuel cycles is released, (2) an optimistic scenario that assumes a decontamination factor of 100 for fuel reprocessing, and (3) an intermediate scenario that simulates a phased improvement in effluent treatment technology at reprocessing plants. The estimates of cumulative potential health effects are based on integrations over infinite time. Comparisons with estimated effects from naturally formed ^{14}C are shown.

1. Introduction

Radioactive carbon-14 (^{14}C) is formed as a by-product of nuclear power generation, and a part of it is released to the environment. In

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recent years, concern about the quantity of ^{14}C released and its potential long-term hazard to man as a source of radiation exposure has prompted a number of assessments of existing and proposed nuclear fuel cycles and facilities.¹⁻⁸ While estimated releases of ^{14}C from presently operating nuclear power facilities are still quite small in comparison with natural and other man-made sources, potential growth in the world's demand for power and the introduction of new nuclear technologies, coupled with increased reprocessing of spent nuclear fuel elements, are virtually certain to raise the quantity of ^{14}C that is produced and potentially released.

Atmospheric releases of ^{14}C are often in the form of carbon dioxide gas and are carried into man's food chain by photosynthetic fixation. Because of the long radioactive half-life of ^{14}C (5730 years), less biologically viable chemical forms (carbon monoxide, methane, and other hydrocarbons) are also potential sources of $^{14}\text{CO}_2$ through eventual oxidation. Increased environmental specific activities (i.e., quantity of ^{14}C per gram of carbon) may persist for tens of thousands of years and constitute an incremental radiation exposure to many generations.

Throughout his history, man has been exposed to ^{14}C formed in the upper atmosphere by the interaction of cosmic neutrons with nitrogen, oxygen, and carbon compounds. Through photosynthesis, this natural source of ^{14}C has sustained specific activities of about 6.1 pCi per gram of carbon in man's exposure environment and, in particular, in the food chain.⁹ This specific activity is reproduced in the carbon in man's tissues and determines the strength of an internally distributed source of radioactivity, which delivers a radiation dose to the total body at the rate of approximately 1.3 mrem per year,¹⁰ or roughly 1% of the the rate of approximately 1.3 mrem per year,¹⁰ or roughly 1% of the total-body dose rate due to all naturally occurring radiation.¹¹

During the past century, the introduction of increasing quantities of ^{14}C -depleted carbon dioxide into the atmosphere by combustion of fossil fuels has diluted the ^{14}C and therefore reduced the specific activities of carbon fixed in the tissues of living things during this period (the so-called Suess effect¹²). The combustion of fossil fuels continues to increase exponentially, and the consequent increase in the level of CO_2 in the atmosphere and its possible influence on the world's

climatology have become factors of serious concern in the search for a national energy policy.¹³ In this paper, however, our consideration of the releases of CO₂ due to the combustion of fossil fuels will be limited to its effect on the radiological impacts of ¹⁴C.

The first objective of this study is to present our projection of the amount of ¹⁴C that the nuclear power industry is likely to produce and release to the atmosphere during the period 1975-2020. The second objective is to present estimates of radiation dose to the world population from the ¹⁴C released in our scenarios and to combine these population doses with health risk factors that have recently been recommended by the International Commission on Radiological Protection (ICRP). This paper is based on a more comprehensive report by Killough and Till that was published in *Nuclear Safety*.¹⁴

2. Scenarios for Release of ¹⁴C by the World Nuclear Power Industry

Our projections for nuclear energy growth were divided into two periods, the first period covering the 12 years from 1975 through 1986 and the second extending from 1987 to 2020. Nuclear energy growth during the first period is relatively easy to project because nuclear plants that will be operating during this time either have already been completed, are currently under construction, or have been committed for construction. Data for this period were taken from recently published listings of nuclear reactors throughout the world that are already built, under construction, or planned.¹⁵⁻¹⁸ Included in the listings are descriptions of the reactor type, generating capacity, date of availability, and location by country.

The forecast for nuclear growth beyond 1986 incorporates assumptions and data published by the Organization for Economic Cooperation and Development (OECD) and the International Atomic Energy Agency (IAEA),¹⁹ and by Hanrahan et al.²⁰ Projections in our study also incorporate estimates of the contribution from Eastern Bloc countries and China, which are based on data supplied by the Energy Research and Development Administration²¹ (now the Department of Energy).

2.1 Reactor Types and Fuel Reprocessing

The types of reactors considered in this study include pressurized-water reactors (PWR), boiling-water reactors (BWR), water-cooled graphite-moderated reactors (GMR), fast breeder reactors (FBR), high-temperature gas-cooled reactors (HTGR), and other reactors not included in these categories (e.g., advanced gas reactors and heavy-water-moderated reactors). Among the light-water-cooled reactors (LWR) constructed after 1986, 65% are assumed to be PWRs and 35% BWRs. The GMR, which is being constructed in the Soviet Union, is discussed separately because of its potential for producing and releasing significant amounts of ^{14}C to the environment, even though its contribution to the world's total nuclear energy production has been assumed to be small.

Advanced reactor designs, such as HTGRs and FBRs, are included in our scenario, although the future of these types of reactors is not certain at this time. It is possible, however that even without participation by the United States, liquid-metal fast breeder reactors (LMFBRs) will be developed elsewhere. On the basis of our scenario, we conclude that nonparticipation by the United States in the development of the breeder technology would not effect a substantial reduction in the total installed nuclear capacity throughout the world.

Figure 1 shows plots of the scenario developed in this study for world nuclear electrical generating capacity by reactor type between 1975 and 2020. Light-water reactors (PWRs and BWRs) will continue to dominate during most of this period, but fast breeder reactors will play a more important role during the last decade of the 45-year period as the contribution from LWRs diminishes. It is important to note that total installed nuclear capacity is assumed to be approaching a steady-state value in our scenario.

Reprocessing of the spent nuclear fuel from the reactors shown in Fig. 1 is projected in Fig. 2. Because of the uncertainty associated with fuel reprocessing at this writing, there are no reliable published data that project worldwide fuel reprocessing needs. Our scenario estimates the fuel reprocessing requirements on the basis of the factors shown in Table 1. These factors are expressed in units of metric tons of

Fig. 1. Scenario projecting the growth of nuclear energy world-wide.

Fig. 2. Scenario projecting fuel reprocessing world-wide.

Table 1. Fuel reprocessing by reactor type

Reactor	Reprocessed fuel, MTHM/GW(e)-year
PWR	33.5 ^a
BWR	40.2 ^a
GMR	40 ^b
FBR	36.8 ^c
HTGR	10.1 ^a
Others	40 ^b

^aC. W. Kee, A. G. Croff, and J. O. Blomeke, *Updated Projections of Radioactive Wastes to be Generated by the u.s. Nuclear Power Industry*, ERDA Report ORNL/TM-5427, Oak Ridge National Laboratory, NTIS, December 1976.

^bThis is an assumed value for this study.

^cV. J. Tennery et al., *Environmental Assessment of LMFBR Advanced Fuels: A Radiological Analysis of Fuel Reprocessing, Refabrication, and Transportation*, ERDA ORNL-5230, Oak Ridge National Laboratory, NTIS, November 1976.

Table 2. Source terms for ^{14}C released to the atmosphere

Type of reactor or fuel being reprocessed	Release rate of ^{14}C , Ci/GW(e)-year	
	Reactor	Reprocessing plant
PWR	5.0 ^a	18.8 ^a
BWR	4.7 ^a	17.6 ^a
GMR	100 ^b	15 ^c
FBR	~0 ^d	4.8 ^e
HTGR	~0 ^f	150 ^g
Others	5 ^c	30 ^c

^aW. Davis, Jr., *Carbon-14 Production in Nuclear Reactors*, NRC Report ORNL/NUREG/TM-12, Oak Ridge National Laboratory, NTIS, February 1977.

^bW. Davis, Jr., Calculated a source term of 800 Ci/GW(e)-year for GMRs based on the data of V. P. Rublevskii, A. S. Zykova, and A. D. Turkin, Atomic Power Stations as Sources of Carbon-14 Discharges (in Russian) in *Proceedings, Third International Congress of the International Radiation Protection Association, Washington, D.C., Sept. 9-14, 1973*, USAEC Report CONF-730907-P1, NTIS, 1974; paper translated into English and published as USAEC Report ORNL-tr-2976, NTIS, February 1974.

^cAn assumed value for this study.

^dU.S. Energy Research and Development Administration, *Final Environmental Statement: Liquid Metal Fast Breeder Reactor Program*, Report ERDA-1535, Vol. II, 1975.

^eV. J. Tennery et al., *Environmental Assessment of LMFBR Advanced Fuels: A Radiological Analysis of Fuel Reprocessing, Refabrication, and Transportation*, ERDA ORNL-5230, Oak Ridge National Laboratory, NTIS, November 1976.

^fH. Bonka et al., Contamination of the Environment by C-14 Produced in High Temperature Reactors, *Kerntechnik*, 15(7): 297-300 (1973).

^gJ. W. Snijder and S. V. Kaye, Process Behavior and Environmental Assessment of ^{14}C Releases from an HTGR Fuel Reprocessing Facility, in *Proceedings of ANS-AIChE Topical Meeting on Controlling Airborne Effluents from Fuel-Cycle Plants, Sun Valley, Idaho, August 5-6, 1976*; paper deposited as CONF-760806, NTIS, 1976.

influence the total from reactors plus reprocessing. At the same time, the 100-Ci value does recognize the potential for ^{14}C releases from this technology, contributing 29, 15, and 6% of the total ^{14}C in 1980, 2000, and 2020, respectively. We admit that this assumption is speculative and arbitrary, but we consider it preferable to analyses based entirely on ^{14}C release scenarios whose reactor components are overwhelmed by the GMR output.

Our other source terms have been adopted from Davis⁸ for LWR cycles; from the Energy Research and Development Administration²⁴ and Davis⁸ for FBRs (assumed to be negligible as for LMFBRs), and from Tennery et al.²² for FBR reprocessing; and from Bonka et al.¹ for HTGRs, and Snider and Kaye²⁵ for HTGR reprocessing. It should be emphasized that considerable uncertainty exists in the ^{14}C source terms assumed in this study because of the lack of quantitative data on ^{14}C present in gaseous effluent. Since ^{14}C formation in the fuel is strongly dependent upon the amount of nitrogen impurity, lower production rates can be realized if process precautions are taken to minimize nitrogen present during fabrication. In our calculations we assumed a capacity factor of 0.75 which is slightly greater than that assumed by some investigators, but it reflects expected improvements in reactor technology and reliability during the period of our scenario.

2.3 Projections for ^{14}C Release to the Atmosphere

We have focused our attention on three scenarios of ^{14}C release, which are distinguished from one another by their treatment of the decontamination factor (DF) that is applied to account for containment of the effluent during fuel reprocessing. For convenience in referring to them, we will designate these scenarios according to the following scheme:

- Scenario P (pessimistic) assumes no containment of ^{14}C during reprocessing (DF = 1).
- Scenario O (optimistic) is based on efficient containment of ^{14}C during reprocessing (DF = 100).

heavy metal (MTHM) per gigawatt-electric-year (GW(e)-year). We have relied on the estimates of Kee et al.¹⁶ for LWR and HTGR cycles and those of Tennerly et al.²² for LMFBRs. It is further assumed that commercial reprocessing of LWR fuel begins in 1980, GMR fuel in 1990, FBR fuel in 2000, HTGR fuel in 1995, and fuel from other reactor types in 1985. Our scenario suggests that in 2020 fuel reprocessing reaches an equilibrium with electrical power produced by nuclear reactors.

2.2 Source Terms for the Release of ^{14}C to the Atmosphere

Table 2 lists the source terms used in this study for ^{14}C releases to the atmosphere from reactors and reprocessing plants. In general, the potential for the largest releases exists at reprocessing plants, where fuel would be dissolved from the cladding and ^{14}C could escape as $^{14}\text{CO}_2$ in the gaseous effluent. The Russian-designed GMR technology is an exception, and additional elaboration of the source term for this reactor is needed.

Although source term data for GMRs are limited, Rublevskii et al.²³ reported the average for samples taken at the Beloyarsk Atomic Power Station [285 MW(t)] as 140 ± 50 mCi/day. On the basis of this value, Davis⁸ calculated that, for a 1000-MW(e) GMR, the release rate of ^{14}C to the atmosphere would be 800 ± 300 Ci/year at the reactor site. Therefore, although the contribution of GMRs to total world nuclear energy production may be small, their contribution to ^{14}C production is significant if the source term 800 Ci/GW(e)year is assumed. Our scenario predicts that GMRs represent only 2.9% of electrical nuclear energy in 1975, 1.2% in 1990, and 0.5% in 2010. If we adopted 800 Ci/GW(e)-year] as a source term, however, GMRs would contribute 79, 65, and 58% of the total quantity of ^{14}C released by reactors for these years, respectively.

The disproportionate quantity of ^{14}C that would be released by a small component of GMRs in our scenario inclines us to assume that major improvements will be made in GMR design, and in the calculations made for this study we have settled on a reduced source term of 100 Ci/GW(e)-year] for this type of reactor. At this value, the GMR source term does not dominate the ^{14}C release from all other reactors, nor does it greatly

- ° Scenario I (intermediate) incorporates a phased improvement in the effluent treatment technology at the reprocessing plant (DF varies in steps from 1 to 100).

Graphs of these scenarios appear in Figs. 3, 4, and 5, respectively. In each case, the rate of natural ^{14}C formation [2.7×10^4 Ci/year (ref. 9)] is plotted for comparison.

According to scenario P (Fig. 3), the total rate of release of ^{14}C to the atmosphere would surpass the natural background production rate by the year 2000 and would reach a steady-state level around 2015. This scenario indicates that the release of ^{14}C from the nuclear fuel cycle could exceed natural radiocarbon production by a factor of three if no effluent treatment systems for containment of ^{14}C are provided at reprocessing facilities.

Scenario O (Fig. 4) illustrates the effect of adding an effluent treatment system that would provide 99% containment at reprocessing plants (DF = 100). In this scenario, the ^{14}C released at reactors now becomes the dominant source. A steady-state release, attained between 2015 and 2020, is approximately 60% of the natural background production rate. An obvious conclusion is that requiring a DF of 100 at reprocessing plants without imposing restrictions on the ^{14}C production in reactors might not be advisable from the point of view of cost vs. benefit. If the total release of scenario O were deemed to lie below an acceptable limit (such as an international regulatory limit, although none exists at present), then the required DF could be decreased from the value of 100 used in the scenario to a smaller critical value determined by the requirement that the total remain below the limit. We hasten to add that we do not mean to advocate practices that would increase an existing release, nor are we suggesting that even small potential reductions be rejected out of hand. Our point, rather, is that policymakers should maintain an awareness of the diminishing returns of a vigorous policy of ^{14}C containment at the reprocessing plant without comparable reductions at the reactor.

In scenario I (Fig. 5), the DF at the reprocessing plants is increased in steps from 1 to 100. Some increase is to be expected as the

Fig. 3. Scenario P (Pessimistic) for ^{14}C released to the atmosphere by the nuclear industry. Decontamination factor for ^{14}C at the reprocessing plant assumed to be unity.

Fig. 4. Scenario 0 (Optimistic) for ^{14}C released to the atmosphere by the nuclear industry. Decontamination factor for ^{14}C at the reprocessing plant assumed to be 100.

Fig. 5. Scenario I (Intermediate) for ^{14}C released to the atmosphere by the nuclear industry. Decontamination factor for ^{14}C at the reprocessing plant increases in steps to simulate the advance of technology.

technology for ^{14}C effluent treatment improves with time. Our assumption in scenario I is that the DF increases from 1 to 10 in 1990 and from 10 to 100 in the year 2000; we concede that this assumption is an arbitrary one, but we do not consider it an unreasonable hypothesis. This scenario, in its general effect, is perhaps the most plausible of the three. The release of ^{14}C from reactors may also decrease as reactor design and quality control advance, but we have not allowed for such a decrease in scenario I.

2.4 Release of ^{14}C from Nuclear Explosives

Concern about the possible effects of man-made ^{14}C is hardly new. Testing of nuclear explosives, which began in the 1940s and has continued up to the present, has produced a significant amount of ^{14}C ; our estimate through 1974, based on yield data compiled recently by Carter and Moghissi,²⁶ is 6 million curies. Other data, summarized by Killough et al.,¹⁰ lead to a higher estimate (9.7 million curies). As a result of the testing, atmospheric carbon in the northern hemisphere reached a maximum specific activity in 1962 which was about twice that due to natural ^{14}C alone. Concern has been expressed about radiation-induced cancers and genetic effects that might accrue to present populations and future generations from the increased radiation exposure.²⁷

3. Dose Calculations

A global carbon cycling model developed by Killough²⁸ was used to predict CO_2 movement from the atmosphere. The simulation predicts a 90% reduction by the year 2019 (33 years) of the specific activity due to a pulse input of 1 Ci to the atmosphere in 1985; an additional 9% reduction (by radioactive decay and environmental processes) requires nearly 3000 years. Yet the dwindling 10% residue beyond the year 2019 will be responsible for a much larger fraction of the radiation dose commitment to the population over time than the 90% component that is more promptly removed. This disparity between the early component (90% reduction) and the long-lived component (remaining 10% reduction) presents a complex issue regarding the optimal length of integration of

the global population dose. Our decision is to integrate the dose to the point at which essentially all of the man-made ^{14}C is removed from the atmosphere. The rationale behind this calculational method is discussed later in the paper.

The assumed chemical form of the released ^{14}C is carbon dioxide, although other chemical species are known to appear, such as methane, ethane, and other hydrocarbons. In these latter forms, ^{14}C is unavailable for photosynthetic uptake in man's food chain until oxidation to CO_2 occurs. For methane, Ehhalt²⁹ gives estimates of the atmospheric mean residence time ranging from 0.7 to 6 years.

The steady-state dose rate to a human organ due to inhaled or ingested ^{14}C can be estimated from the specific activity of airborne or dietary carbon, respectively. Killough and Rohwer³⁰ give dose-rate factors for both intake pathways and a variety of organs. Their calculations show that ingestion accounts for more than 99% of the total intake of ^{14}C , provided both the inhalation and ingestion pathways have the same carbon specific activity.

If DRF denotes one of these dose-rate factors (in rem/year per Ci/gC), the dose rate to the corresponding organ of an individual is

$$\dot{D} = (\text{DRF})(\text{SpA}) \text{ rem/year} \quad , \quad (1)$$

where SpA is the specific activity of carbon (Ci/gC) in the individual's exposure environment. We assume that the specific activity of airborne carbon is equal to that in man's food chain (apart from an isotopic fractionation factor which can be neglected) and hence in his body tissues; we therefore define SpA as

$$\text{SpA} = 4.46[X/(X + Y)] \text{ Ci/gc} \quad , \quad (2)$$

where X and Y are grams of released ^{14}C and total nonradioactive carbon, respectively, in the atmosphere and 4.46 Ci/g is the specific activity of pure ^{14}C . The atmospheric levels X and Y are dynamic variables whose time histories are obtained from computer simulations based on a non-linear compartment model of the global carbon cycle, which we outline in the next section.

The population dose delivered between times t_0 and t_1 (years) is

$$D(t_0, t_1) = \int_{t_0}^{t_1} N(t) \cdot \dot{D}(t) \cdot dt \quad \text{man-rem} \quad (3)$$

where $N(t)$ denotes the number of individuals in the world population at time t and $\dot{D}(t)$ is obtained from Eqs. (1) and (2). The population dose commitment from the release is defined by Eq. (3) as the upper limit of integration, t_1 , tends to infinity. In order to perform a numerical calculation, the differential equations of the model are integrated numerically to compute the time histories of the atmospheric quantities X and Y , and hence the integral in Eq. (3). Since the numerical integration can only comprehend a finite time interval, the upper limit t_1 , is chosen as a point in the future when the nonradioactive carbon cycle may be assumed to have regained a state of near-equilibrium (a practical compromise influenced our choice of the year 4000). To continue the integration analytically to infinity, we assume a constant world population and use the equation

$$D(t_1, +\infty) = (DRF) \cdot N \cdot SpA(t_1) / \lambda^R \quad \text{man-rem}, \quad (4)$$

where N denotes the constant world population after time t_1 , and λ^R is the radioactive decay rate for ^{14}C ($= 1.21 \times 10^{-4} \text{ year}^{-1}$). The total population dose commitment is the sum of Eqs. (3) and (4).

3.1 Model of the Global Carbon Cycle

The dynamic model used in our calculations is a more recent version of the one described by Killough²⁸ and is shown schematically in Fig. 6. Its principal reservoirs are the atmosphere, the ocean, and the terrestrial biota, among which exchanges of nonradioactive carbon (^{12}C and ^{13}C) and radioactive ^{14}C are simulated. The ocean is subdivided into a well-mixed layer of surface water, 75 m in depth, and a deeper ocean compartment consisting of 25 layers with exchanges governed by first-order kinetics. With appropriate values assigned to the transfer coefficients, such an arrangement approximates diffusive transport and is similar to a model of carbon in the ocean studied by Oeschger et al.³¹ The model also

Fig. 6. A schematic presentation of the box-diffusion model of the global carbon cycle used for the environmental transport calculations for ¹⁴C in this article. The model is a more recent version of the one described by Killough.²⁸ Notation:

Y = nonradioactive carbon ¹²C and ¹³C (g)

X = ¹⁴C (g)

C = C(z, t) = concentration of carbon (g/m³) at depth z and time t

K = diffusion coefficient (m²/year)

takes into account the nonlinear variation of the carbonate-bicarbonate buffer factor with the total dissolved inorganic carbon in the ocean surface waters in computing the exchange between the ocean and the atmosphere. A buffering calculation similar to the one discussed by Keeling³² and by Bacastow and Keeling³³ was adapted to this application. The terrestrial biota are represented by a slow- and a rapid-turnover component with mean residence times of 41 and 2.2 years, respectively. A similar terrestrial submodel was employed by Bacastow and Keeling.³³ In our simulations, however, we imposed a growth limitation constraint which prevented the terrestrial biosphere from exceeding 1.5 times its preindustrial carbon biomass. Such a parameter is speculative, but simulations using more than twice that value gave only slightly different population dose estimates.

Exogenous inputs to the model are (1) the production rate of carbon dioxide from the combustion of fossil fuels, (2) the rate at which ^{14}C enters the system from the source under study (e.g., the release rate by the nuclear power industry as quantified by our scenarios), and (3) a function which represents world population levels in the recent past and in the future. We give some details about these inputs and their use in our simulations in the following paragraphs.

Each integration of the model's equations is initiated at a preindustrial point in time (we have used the year 1860) at which a state of near-equilibrium is assumed to have existed in the carbon cycle. Carbon dioxide from the combustion of fossil fuels is added to the system in accordance with historical data compiled by Keeling³⁴ and Rotty³⁵ through the year 1974. Future release rates are simulated by means of generalized logistic curves, as suggested by Keeling and Bacastow.³⁶

Estimating the radiation dose to future populations of the world from contemporary releases of ^{14}C involves projections of population growth which clearly are subject to considerable uncertainty. Estimates of the population dose commitment require integration to infinity, which in practical terms entails the assumption of a population scenario spanning about 46,000 years (8 half-lives of ^{14}C). Our approach has been to construct a reference scenario consisting of the United Nations

Population Bureau's "medium variant" projection,³⁷ which forecasts a rise to 12.2 billion by the year 2075. Beyond this date, we have projected the population to remain constant at that level.

3.2 Estimated Population Doses and Health Effects from ^{14}C

By means of simulations with the dynamic model of the global carbon cycle described previously, population doses corresponding to several sources of ^{14}C have been estimated. Three of these sources are the scenarios of release from the nuclear power industry that were discussed in a previous section. For comparison, we also consider the ^{14}C that is formed by natural processes in the upper atmosphere and the substantial quantity introduced into the atmosphere by the detonation of nuclear weapons during the past 30 years. Population doses from these sources are displayed in Table 3; each entry represents the integral of the population dose rate [Eq. (3)] from 1975 to the indicated date, except the weapons production, which is integrated from 1945.

Radiation-induced health effects were estimated from population doses by means of a linear model and risk factors which are derived from ICRP Publication 26 (ref. 38). This method assumes that the rate of induction of a particular health effect is proportional to the population dose rate, although a lag of years or generations may separate the realization of an effect from its antecedent induction. This lag is not considered in our calculations for the health effects that are presented in our tables and discussion. Table 4 displays such induction schedules for cancers and genetic effects associated with each of our three scenarios of nuclear power generation, natural radiocarbon, and the ^{14}C produced by nuclear explosives during the period 1945-1975.

It is artificial, of course, to perform these calculations assuming abrupt cessation of the ^{14}C release from the nuclear power industry in the year 2020. One must bear in mind that the estimates of impact apply only to the ^{14}C released before that date. Integrations of population dose rate are carried far into the future, however, since each curie released delivers its population dose over a period of tens of thousands of years. Note that in Table 3 the population dose to the year 2075

Table 3. Radiation dose to world population^a from natural and man-made ¹⁴C

Date	Nuclear power industry scenarios ^b			Natural ¹⁴ C formed 1975 to indicated date, before 2020 ^c	Nuclear weapons 1945 to indicated date ^d
	0	I	P		
1975					3.4×10^7
1990	1.1×10^5	1.8×10^5	2.4×10^5	2.8×10^6	5.3×10^7
2005	8.7×10^5	1.1×10^6	3.5×10^6	9.1×10^6	6.9×10^7
2025	3.8×10^6	4.3×10^6	2.1×10^7	2.2×10^7	9.2×10^7
2075	8.0×10^6	8.9×10^6	4.4×10^7	4.1×10^7	1.5×10^8
Infinite time	1.8×10^8	1.9×10^8	9.7×10^8	8.8×10^8	3.2×10^9

^aDose units are man-rem to total body.

^bFigures 3, 4, and 5, respectively.

^cRate of formation assumed to be 2.7×10^4 Ci/year (Ref. 9).

^dSource term derived from detonation data compiled by M. W. Carter and A. A. Moghissi, "Three Decades of Nuclear Testirg," *Health Phys.*, 33(1): 55-71 (1977).

Table 4. Cumulative induction of ^{14}C health effects^a from three nuclear power scenarios, natural formation, and nuclear weapons

Date	Scenario 0		Scenario I		Scenario P		Natural ^{14}C formed 1975 to in- dicated date before 2020		Nuclear weapons 1945 to indicated date	
	Cancer	Genetic	Cancer	Genetic	Cancer	Genetic	Cancer	Genetic	Cancer	Genetic
1975									4,000	2,600
1990	13	8	21	14	28	18	330	260	6,300	4,100
2005	100	67	130	85	410	270	1,100	700	8,100	5,300
2025	450	290	510	330	2,500	1,600	2,600	1,700	11,000	7,100
2075	900	620	1,100	690	5,200	3,400	4,800	3,200	18,000	12,000
Infinite time	21,000	14,000	22,000	15,000	110,000	75,000	100,000	68,000	380,000	250,000

^aCalculated from the population dose estimates of Table 3 and the ^{14}C risk factors published in International Commission on Radiological Protection, Recommendations of the International Commission on Radiological Protection (Adopted Jan. 17, 1977), ICRP Publication 26, *Annals of the ICRP*, 1(3): 2-47 (1977).

from each of the three nuclear power scenarios is less than 5% of the corresponding infinite-time dose commitment.

Comparisons are not entirely satisfactory, but they help to introduce some perspective. In Table 4, the natural ^{14}C accounted for is that which is formed during the period of release spanned by our scenarios (1975-2020). This comparison is analogous to comparing the release from the industry in a given year with one year's natural production (2.7×10^4 Ci). It is important to draw a distinction between this comparison and one involving the total specific activity of natural ^{14}C that is in an approximate steady state in man's exposure environment. This distinction is seen in Fig. 7, which shows the individual (or average) dose rate vs. time for each release scenario and that due to (1) the ^{14}C formed in nature since 1975 and terminated at 2020 like the scenarios (lower dashed curve) and (2) the natural ^{14}C in steady state (upper dashed curve). In the second case, credit is taken for radiocarbon that was formed long before 1975 as well as that formed afterward; this quantity corresponds to what is usually cited as the ^{14}C natural background dose rate ($\sim 10^{-3}$ rem/year). Each of the curves in Fig. 7 shows a dip due to the scenario of fossil-fuel carbon which was used in the simulations. The top curve (naturally produced ^{14}C in steady state) declines to a minimum and increases as the nonradioactive CO_2 in the atmosphere reaches a maximum and is eventually reduced by removal to the ocean and biotic reservoirs.

The cumulative induction of cancers and genetic effects from the three power scenarios, contemporary natural production, and weapons testing (Table 4) shows some interesting contrasts. According to the estimates of our models and data, the ^{14}C from weapons testing was already responsible for 4000 cancers and 2600 genetic effects by 1975, and for subsequent times this source dwarfs the other sources shown. But even the total of 380,000 cancers to which the population is already presumably committed from that source in the next 46,000 years (about 8 half-lives of ^{14}C) pales in comparison with the ~ 66 million* cancers

* 10^{-3} rem/year $\times 12.2 \times 10^9$ people $\times 46,000$ years $\times 118$ cancers per 10^6 man-rem ≈ 66 million cancers.

Fig. 7. Dose equivalent rates (mrem/year) to an individual from various sources of natural and man-made ^{14}C

induced during that same period of time by the steady-state natural radiocarbon - about 170 times as many as from the weapons testing. The same proportions apply to the genetic effects.

These comparisons provide us with levels of exposure which are accepted as inevitable because they cannot be reduced. Such an analysis of potential health effects from natural and weapons-produced ^{14}C could be used by international regulatory agencies as a basis for standards establishing acceptable levels of ^{14}C releases to the environment by the nuclear industry.

4. Conclusions

We draw several conclusions from the facts, hypotheses, and analyses presented in the foregoing sections.

First, our pessimistic scenario (P) projects a ^{14}C release rate by the nuclear industry that exceeds the natural production rate after the year 2000. This fact alone seems to us sufficient grounds for careful consideration of the industry's potential contribution to environmental levels of this ubiquitous and long-lived radionuclide, but in our opinion it justifies neither alarm nor precipitate action. The cumulative number of health effects estimated to result from this scenario would be significantly less than the number associated (by the same methods of calculation) with the ^{14}C released from nuclear weapons testing during the period 1945-1975 or with the steady-state level of naturally formed ^{14}C in man's exposure environment. The cumulative potential health effects from scenario P would, however, be comparable to those resulting from the natural ^{14}C formed during the period 1975-2020.

Our optimistic and intermediate scenarios (O and I) project that ^{14}C from the nuclear industry would attain a stationary level at approximately 37% of the natural production rate by 2020. Cumulative potential health effects from these scenarios (Table 4) are ~22% of those from natural ^{14}C formed during the period 1975-2020, ~6% of those from weapons testing, and <0.04% of those from natural ^{14}C at steady state in the environment.

A second and very important point is that there is relatively little difference between the projected impacts resulting from scenarios 0 and I. Therefore, we suggest that a phased reduction in ^{14}C effluent from reprocessing plants, such as the schedule of scenario I, is a more reasonable approach to controlling ^{14}C emissions from nuclear facilities if such a reduction is deemed necessary by national and international radiological protection agencies.

It is also essential to emphasize the potential importance of ^{14}C production in GMRs. We have incorporated the assumption that significant improvements will be made in GMR technology which will reduce the source term by approximately 88% before large-scale development of this reactor occurs. Should these improvements not be made, however, ^{14}C from a relatively small number of GMRs could be the dominant source of this radionuclide in the nuclear industry.

In verbal exchanges with nuclear scientists, we have often heard objections to the practice of integrating the ^{14}C population dose rate to infinity [Eqs. (3) and (4)] for the purpose of estimating health effects. They argue that individual risks are minute, and it is the accumulation of their product with a large number of people over tens of thousands of years that yields substantial numbers of health effects. Some advocate terminating the integration at some arbitrary point in time. To these objections we can only reply that the acceptance of a linear, no-threshold model for induction of these effects obliges us to carry out the calculation just as we have done it. A premature termination of the integration would fail to account for some of the induced health effects that are implied by such a hypothesis. Moreover, if a nonlinear response hypothesis were found to be appropriate for radiation-induced health effects, the low individual dose rates for ^{14}C would not necessarily permit us to neglect the integral to infinity; in such a circumstance, it would be necessary to consider simultaneously the total levels of radiation from all sources, natural and man-made, in order to estimate effects. These total levels might well exceed a given threshold or fall in a steep region of the response curve, while individual radionuclide contributions might not.³⁹ Whatever the uncertainties and shortcomings of the present method of projecting the impact

of ^{14}C releases, we cannot find in them any justification for shortening the dose integration period. We have tabulated our estimates of population doses and health effects for selected shorter integration times, because we believe the fraction of the total burden of risk borne by earlier generations is of interest. But we do not mean to suggest by having done so that these truncated quantities should be used to the exclusion of the infinite-time calculations.

Comparisons of potential health effects from ^{14}C produced by nuclear power generation with those associated with other sources, such as natural formation and nuclear explosives, provide some perspective, but it must be remembered that ^{14}C is only one of numerous radioactive effluents from nuclear fuel cycles. All need to be considered in assessing and comparing potential health impacts of various proposed mixes of nuclear technologies.

More generally, we must recognize that nonnuclear technologies will continue to be used for some time for generating electric power. A complete accounting of the cost of this power, in terms of potential health effects, requires that environmental studies be performed for the effluents of all contributing technologies, nuclear and nonnuclear alike, in order that integrated assessments can be carried out. Only then can scenarios based on various mixes of all available technologies be objectively compared with respect to their potential health consequences. Considerable research, particularly in the nonnuclear field, remains to be done before such assessments can be accomplished with reasonable precision. In the meantime, the nuclear industry must seek guidance from evaluations that are more limited in scope, such as the one outlined in this paper.

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