10^3

10^2

Discharge Rate, MCi/y

WORLD Kr-85

EC Kr-85

The predicted radiation exposure of the population

of the European Community resulting from

WORLD H-3

discharges of krypton-85, tritium, carbon-14 and iodine-129

from the nuclear power industry to the year 2000

EC H-3

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DIRECTORATE OF HEALTH PROTECTION
DIRECTORATE-GENERAL FOR SOCIAL AFFAIRS

10^{-1}

1975   1980   1985   1990   1995   2000

The predicted radiation exposure of the population of the European Community resulting from discharges of krypton-85, tritium, carbon-14 and iodine-129 from the nuclear power industry to the year 2000

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A B S T R A C T

The exposure of the population of the European Community from the
predicted discharges of krypton-85, tritium, carbon-14 and iodine-129 from
the Community and world nuclear power programmes up to the year 2000 is
assessed. These nuclides, owing to their relatively long half-lives and
their widespread dispersion, accumulate in the environment and represent
long term sources of irradiation to essentially the whole of the world
population. Consideration is given to the exposure of individuals and the
Community population as a whole from each of the four nuclides; the
relative significance of each nuclide in this context is evaluated. The
levels of exposure are compared with ICRP recommended dose limits and with
exposure from other sources such as natural background radiation. A
comparison is also made between the natural inventories of these nuclides
in the environment and those arising from discharges from the nuclear power
programmes. The assessment is based on the continued application, to the
end of this century, of current waste management practices; the implica-
tions and likelihood of the implementation of improved practices prior to
the year 2000 are also discussed.

1. Introduction

The generation of nuclear energy will, like all industrial processes, be accompanied by the production of waste material. Wastes will be generated at each stage of the nuclear fuel cycle and will be of varying form depending on the process from which they emanate. The waste arisings can be conveniently classified into airborne, liquid and solid categories, with further sub-division according to their chemical and physical characteristics; they will be contaminated with radioactivity at levels ranging from the trivial to a few megacuries per cubic metre of waste volume. The majority of the activity is isolated from the environment by engineered storage pending evaluation of ultimate disposal schemes or until radioactive decay has reduced the activity to a very low level. Only a very small fraction of the activity is discharged to the environment.

The basic principle underlying waste management procedures in the European Community derives from the ICRP system of dose limitation (1) which includes the recommendation that the radiation exposure of individuals and populations, and consequently the quantity of radioactive waste discharged to the environment, should be kept as low as reasonably achievable (2). These recommendations are incorporated into the Euratom Basic Standards on radiological protection. Although based on the same principles, the actual practice with regard to control of radioactive waste discharges differs considerably from country to country within the European Community. Typical procedures applied or being envisaged for application include evaluation of limits on a case by case basis, allocation of a stipulated fraction of ICRP dose limits to exposure from radioactive effluents (3), and limitation of population dose due to discharge of activity from a given installation (4). Each approach has its respective merits and disadvantages.

The present study is concerned primarily with the discharge to the environment of those nuclides which owing to the magnitude of their half-lives, their fairly rapid and widespread dispersion in the environment and the magnitude of their discharges, based on current waste management practices, will accumulate in the environment and may constitute significant long-term sources of irradiation to both regional and world populations. In general the limiting of doses to critical groups in

the vicinities of nuclear establishments will suffice to ensure the minimal exposure of the more distant population owing to such factors as increased dispersion at greater distance and attenuation of the short half-life component of the discharged activity by radioactive decay. While it may be unnecessary to limit the discharge of some long-lived nuclides because of local considerations, controls may need to be implemented to limit the accumulation of such nuclides in the general environment over extended time periods, particularly in the context of a rapidly expanding nuclear power programme.

An assessment of current waste management practices at various stages of the nuclear fuel cycle indicates that the discharges of krypton-85, tritium, carbon-14 and iodine-129 are those most likely to constitute significant long-term sources of irradiation in the context previously outlined. While the discharges of caesium-137 and plutonium may also be considered to fall into this category, only limited consideration is given to these nuclides in this report for the following reasons.

Current interest in caesium-137 in the European context is primarily related to its discharge to the marine environment from the fuel reprocessing plant at Windscale, and its subsequent dispersion in the Irish and North Seas. Preston (5) has recently reviewed this situation; the exposure of man from these discharges arises principally from consumption of contaminated fish and estimates indicate that the present level of annual collective dose* to the population of the United Kingdom is about 1500 man-rads, with a similar magnitude of collective dose accruing to the population of the remainder of Western Europe. Individual annual doses however, arising from consumption of locally-caught fish, represent the limiting factor with respect to these discharges. At present the median exposure of the critical group is a few percent of the appropriate ICRP recommended annual dose limit. As a consequence of the local situation being the more restrictive and of the intention to reduce the discharge rates of caesium-137 (5), the annual collective dose from these discharges is unlikely to increase significantly, at least beyond the near term, above the present levels, despite a rapidly expanding nuclear power industry. For this reason, no further consideration is

*Collective dose, together with other technical terms, is defined in the glossary.

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given to caesium-137 discharges in this report.

The behaviour and significance of plutonium discharges to the Irish
Sea from the United Kingdom nuclear power programme have recently been
discussed by Preston (5) and by Hetherington et al (6). These discharges,
from the fuel reprocessing and refabrication plants at Windscale, have
made by far the greatest contribution to the total plutonium discharges to
the environment from the nuclear fuel cycle in the United Kingdom. To
date approximately 10^4 Ci (α activity) of plutonium have been discharged
to the sea, of which about 95% has been rapidly lost from the water phase
and incorporated into bed sediments, with the residual few percent
remaining in the sea water and exhibiting a sea water distribution
analogous to that of discharged caesium. No evidence has been found for
a continuing increase in the level of plutonium in sediments in the
vicinity of the outfall, nor has evidence been found of any long-term
build-up in biological materials. These observations indicate that the
majority of plutonium is dispersed in association with the general
sediment transport processes in the area and that the small fraction of
plutonium remaining in the water phase probably represents the major
reservoir from which uptake into biological systems occur. While the
radiological significance of the plutonium so far discharged to the
Irish Sea has been shown to be negligible (5, 6) there remains a need
for further work on the bio-geochemistry of both plutonium and the other
actinides in order to demonstrate the long-term adequacy of the radiologi-
cal safety associated with these and future discharges. Of particular
importance in this context is the possibility of remobilisation of
plutonium from sediments into biological materials; no evidence has been
found to date however of such processes taking place in the sediment in
the Irish Sea. Taking account of the low radiological significance of
current discharges, together with the fact that local considerations are
probably the more restrictive with regard to limiting discharges, no
attempt has been made in this report to predict regional or global doses
from plutonium likely to be discharged from nuclear power programmes to
the end of this century.

Consideration has been restricted to krypton-85, tritium, carbon-14
and iodine-129, the discharges of which are essentially confined to two
stages of the fuel cycle, reactor operation and fuel reprocessing. The

doses to the population of the European Community from the discharges of these nuclides up to the end of this century have been evaluated, account being taken of the discharges from both the European Community and world nuclear power programmes. The assessment is based essentially on the continued application of current waste management practices to the end of the century, although some consideration is given to alternate waste management strategies. This approach is likely to result in upper limit estimates of dose.

2.   The nuclear power programme

Predictions of the rate of installation of nuclear capacity are prone
to large uncertainties in the short term, and even more so over periods
extending to the year 2000. In the past two years the marked dependence
of nuclear programmes on external events has been amply demonstrated. An
acceleration of the programme followed the rapid escalation of oil prices
in 1973/74 but this has since been followed by a significant slowdown,
brought about by the effects of energy conservation, a worldwide economic
recession and difficulties associated with the financing of such a capital
intensive programme in times of high interest rates. The results of this
current study will obviously be fairly sensitive to the magnitude of
installed nuclear capacity. However, the importance of uncertainties
in this area is likely to be small in relation to other factors. Moreover
the implications of changes in the nuclear programme can be assessed by
appropriate scaling.

Many predictions of the growth of nuclear power have been made both
at national and international levels. The most recent authoritative
prediction has been compiled by the OECD (7) and this forms the basis of
the power programme adopted in this study. Predictions of the world
nuclear power programme, apart from the USSR and Eastern Europe, up to the
year 2000 are given in reference 7 together with the distribution of
installed capacity up to 1990 among various geographical and political
regions. The regional distribution for the period 1990-2000 has been
derived from the total capacities assuming a pro-rata increase in each
region. Data for the nuclear power programme in the USSR and Eastern
Europe have been taken from a recent review by Parker and West (8). The
predicted installed capacities of nuclear power for the whole world and
the European Community are shown in Figure 1. Programmes for other
important regions are shown for comparison.

Consideration must also be given to the distribution of installed
capacity among the various reactor types because the reactor type has a
major influence on the yield and discharge of some nuclides. In reference
9, the breakdown of future power programmes into reactor types has been
considered in detail, and a variety of reactor strategies evolved. The
distribution derived in reference 9, on the basis of reasonably conserv-
ative extrapolations of present trends and announced plans has been

adopted for the purpose of this study. Data are given only up to 1990
and extrapolations of the indicated trends have been made to the year 2000.
The reactor distributions for the whole world and for the European
Community are shown in Figures 2 and 3 respectively, the latter being
derived from the world distribution with appropriate modifications. A
few points of clarification regarding Figures 2 and 3 are worthy of note:
the light water reactor (LWR) programme is assumed to comprise pressurised
water reactors (PWR) and boiling water reactors (BWR) in a ratio 3 : 2;
the high temperature reactor (HTR) programme is assumed to comprise equal
contributions from the low (U - Pu) and high (U - Th) enriched types; in
the absence of data the USSR and Eastern Europe programme is assumed to
comprise solely LWRs; no account has been taken in Figures 2 and 3 of the
recent decision in the United Kingdom to adopt the Steam Generating Heavy
Water Reactor (SGHWR) as the basis of the future thermal reactor programme.

It will subsequently be seen that the results of this study are in
general not particularly sensitive to the reactor type distribution. Where
such sensitivity occurs, the implications of the more extreme reactor type
distributions considered in reference 9 are discussed. Some consideration
is also given to the implications of introducing SGHWRs into the United
Kingdom nuclear power programme.

The rates of generation of nuclear energy (as heat) in the world and
in the European Community are shown in Figure 4 and have been derived
from the predicted installed capacities given in Figures 2 and 3 respect-
ively, the reactor thermal efficiencies in Table 1 (9), and an assumed
load factor of 0.7. A distinction is made between the energy generated
by fast and by thermal reactors, and it is to be noted that the rates of
energy generation are applicable to the end of the year in question. The
rates are probably overestimates, particularly for the later decades, due
to the likelihood of a decreasing load factor when the installed nuclear
capacity exceeds the base load.

Consideration is restricted in this study to the application of
nuclear power to the generation of electricity, no account having been
taken of other applications such as marine propulsion and process heat.
The magnitude of nuclear capacity installed for such applications prior
to the year 2000 is however unlikely to be sufficient to affect signifi-
cantly the results of this study.

3. <u>Nuclide generation and discharge to the environment</u>

The generation and discharge of krypton-85, tritium, carbon-14 and iodine-129 are considered in turn. In deriving discharge rates to the environment it is assumed that current waste management practices are to persist to the end of the century, this essentially representing an upper limit to the magnitude of the activity likely to be discharged. The implications of introducing new practices and new technology are subsequently considered.

3.1 <u>Krypton-85</u>

Krypton-85 is produced as a fission product during the irradiation of nuclear fuel. The generation of fission products during typical fuel irradiation cycles has been evaluated in references 10 and 11 for each of the reactor types. These data indicate that the yield of krypton-85 from all thermal reactors can adequately be represented by a single value of $1.1 \ 10^5$ Ci/GW(th)y. A somewhat lower value of $8.4 \ 10^4$ Ci/GW(th)y is applicable to fast reactors.

The discharge to the atmosphere of krypton-85 from reactors during normal operation will be very small and will arise as a result of trace amounts of uranium contaminating the primary circuit and the fuel cladding, or from operation of the reactor with leaking fuel elements. This mode of discharge is negligible in comparison to the discharge at fuel reprocessing plants where essentially the total krypton-85 content of the fuel will be discharged as an airborne effluent. The discharge rate of krypton-85 at reprocessing plants can therefore be assumed to be equal to its production rate in reactor fuel. It is to be noted that this assumption will be pessimistic, at least in the near term, due to the long delays occurring between fuel irradiation and subsequent reprocessing; this is a consequence of the very limited fuel reprocessing capacity currently available.

3.2 <u>Tritium</u>

Tritium is generated in nuclear reactors both as a fission product, via ternary fission, and as an activation product via neutron interactions with a variety of elements, in particular boron, lithium and deuterium. These elements are present in a variety of reactor materials, both intentionally and as impurities.

The production rates of both fission and activation product tritium per unit thermal energy generated in each of the reactor types are summarised in Table 2 (10-14). The major sources of activation product tritium are indicated in each case. No account has been taken of activation product tritium produced in the control rods as these in general represent a negligible source of tritium discharge to the environment. The variation of the generation rate of fission product tritium with thermal reactor type for typical fuel irradiation cycles is small and a single value of $7 \ 10^3$ Ci/GW(th)y can be adopted for all thermal reactors (10,11). A slightly higher value of $1 \ 10^4$ Ci/GW(th)y is applicable to fast reactors (10,11). The generation rate of activation product tritium is much more dependent on the reactor type. While production via this mode is in general much less than that via fission, the case of the HWR is a notable exception. In the HWR, activation of the deuterium in the heavy water moderator results in a production rate of tritium more than an order of magnitude greater than that via fission.

Tritium discharge to the environment can occur at reactors and reprocessing plants, and in Table 3 discharge rates per unit thermal energy generated from each are summarised. Both fission and activation product tritium contribute to the discharges from reactors. During reactor operation, fission product tritium is released from the fuel to the primary coolant by permeation through intact fuel cladding and by leakage from failed fuel elements. The magnitude of the release is dependent on the nature of the cladding and quality of the fuel. Tritium permeation through magnox and zircalloy clad fuels (BWR, PWR and HWR) is very small, whereas that through stainless steel clad fuel (AGR, FBR) is much larger, values ranging from up to 25% in the case of AGR up to essentially 100% for the FBR (13). A value of 1% (12,13) is commonly adopted for the percentage release from zircalloy clad fuels, this value encompassing both the release by permeation and by leakage from failed fuel. Release from HTR fuel, where the fuel particles are coated with pyrolytic carbon and in some cases a further coating of silicon carbide, is not well established although preliminary data have indicated a value of about 30% (15).

As well as a fraction of the fission product tritium, much of the activation product tritium also reaches the primary coolant, both by

virtue of production within the coolant itself and by diffusion from
other production sites. In general the major route for tritium discharge
from reactors is via the primary coolant, either directly by coolant
leakage or indirectly by processes such as coolant clean-up and permeation
of tritium across the primary or primary/secondary coolant boundaries
where these exist. The major exception concerns the HWR where the
moderator leakage is likely to determine the overall tritium discharge.
The presence of tritium in the primary coolants of reactors does not in
all cases however necessitate discharge to the environment. While tritium
appearing in MAGNOX, AGR, LWR and HWR coolants is likely to be discharged
in effluents, the majority of that in HTR and FBR coolants may well
accumulate in the coolant purification systems and, depending on waste
management practices, be isolated from the environment. In Table 3 only
upper limits are quoted for the tritium discharge from both HTRs and FBRs,
a consequence of uncertainties as to the type and performance of the
coolant purification systems to be implemented on these reactor types.
In reality the discharge rates are likely to be considerably smaller.

Tritium will be discharged from reactors in both liquid and airborne
effluents, the relative magnitude in each depending on the reactor type.
Limited data on the distribution between the two effluent streams indicate
that the airborne effluent comprises the following percentages of the total
tritium discharged from each reactor: 10% for AGR (12); 1% for PWR (12);
10-50% for BWR (12,16); and 90% for the CANDU version of HWR (17). The
remainder in each case appears in the liquid effluent. The form of the
tritium discharged in both effluent streams will be predominantly
tritiated water.

Tritium retained within the fuel elements during reactor operation
will subsequently be released to the process streams during fuel
reprocessing. Various data exist regarding the distribution of liberated
tritium among the various waste streams at reprocessing plants (12,18,19).
While the data show considerable variation they can be adequately
represented by a distribution in which 25% and 75% of the tritium through-
put respectively arise in the airborne and liquid effluent (ignoring the
few percent incorporated into the highly active waste stream and cladding
wastes). The tritium in the liquid effluent will be discharged in the
form of tritiated water; the form of tritium in the airborne effluent is

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not well defined although the majority would be expected to be in the form
of tritiated water vapour. For the purposes of this study it has been
pessimistically assumed that all the tritium discharged in the airborne
effluent is in the form of tritiated water vapour.

Inspection of Tables 2 and 3 indicates that the activation product
tritium makes only a small contribution to the overall tritium discharges;
taking account of the distribution of the nuclear power programmes among
the various reactor types (Figures 2 and 3) its contribution amounts to
somewhat less than 10% of that derived via fission. While the activation
product tritium is negligible in the overall context, it is of major sig-
nificance in determining the discharge rate at HWRs and PWRs themselves;
it comprises essentially 100% and about 80% of the total tritium discharged
from the HWR and PWR respectively.

The production rates of the fission product tritium in the fuel and
the tritium discharge rates from reprocessing plants (Table 3) are
sufficiently close as to adopt a simplifying assumption that the two are
equal; this is equivalent to assuming discharge rates from the reprocess-
ing plants of $7 \ 10^3$ Ci/GW(th)y and $1 \ 10^4$ Ci/GW(th)y for reprocessing of
thermal and fast reactor fuel respectively. The assumption is pessimistic
in significantly overestimating the discharge from reprocessing FBR fuel,
although only marginally so in the overall context due to the relatively
small contribution made by the FBR to the total nuclear programme by the
year 2000.

3.3 Carbon-14
    The production of carbon-14 by fission is negligible and its presence
in reactor systems is a consequence of activation processes. The dominant
modes of production are neutron activation of carbon-13, nitrogen-14 and
oxygen-17 via the following reactions.

$$^{13}C(n,\gamma)^{14}C \qquad \sigma = 9 \ 10^{-4} \text{ barns}$$
$$^{14}N(n,p)^{14}C \qquad \sigma = 1.8 \text{ barns}$$
$$^{17}O(n,\alpha)^{14}C \qquad \sigma = 0.24 \text{ barns}$$

The quoted cross sections are for thermal neutrons of velocity 2200 m/s
(equivalent to a neutron energy of 0.0253 eV).

The common occurrence of these nuclides in many reactor materials results in several sources of carbon-14 in each reactor type. Only very limited data exist on carbon-14 production in, and discharge from, nuclear reactors. Calculations have therefore been made of the major sources of carbon-14 production in the various reactor types. The calculated production rates are summarised in Table 4 where the production in the moderator, coolant and fuel is each considered separately.

In gas-cooled, graphite-moderated reactors (MAGNOX, AGR and HTR) the major source of production is the graphite moderator; comparable contributions arise from activation of the carbon-13 content of the graphite itself and from activation of the incorporated nitrogen-14 impurity. An impurity level of 10 ppm by weight (22,23) has been assumed. Production in the carbon dioxide coolant of MAGNOX and AGR reactors arises via activation of the carbon-13 and oxygen-17 content of the coolant together with activation of the nitrogen impurity in the coolant. At the level of impurity assumed (200 ppm by volume - the upper limit of commercial grade CO_2) nitrogen activation makes the greatest contribution to the production of carbon-14, being a factor of about four times greater than that arising via oxygen-17 activation; the contribution from carbon-13 activation in the coolant is negligible by comparison. Carbon-14 production in the helium coolant of the HTR is likely to be very small, a consequence of the nitrogen impurity level in the coolant being maintained at a very low level by the coolant purification systems.

The production of carbon-14 in the coolants of light water reactors (coolant and moderator being synonymous in these reactors) will arise predominantly through activation of the oxygen-17 content of the water. The production rates quoted in Table 4 have been derived from the measured discharge rates at PWRs and BWRs (20,21) assuming the discharges to have arisen solely from coolant activation and further that the measured discharges represented the total carbon-14 produced.

The final major source of production is the reactor fuel. In the case of metal MAGNOX fuel the sole production mode is the activation of the nitrogen-14 impurity; the typical impurity level is 50 ppm by weight (24). For the other reactor types, which utilise oxide fuel, production arises via oxygen-17 and nitrogen-14 activation. The nitrogen impurity

level in oxide fuels is typically 20 ppm by weight (25).

Predictions, based on the production rates in Table 4 have been made of carbon-14 discharge rates from both reactors and reprocessing plants. The discharge rates are summarised in Table 5 and are the values adopted for the purposes of this study. In the limited cases where measured discharge rates exist, in particular for discharges from PWRs and BWRs (20,21), the measured, as opposed to calculated, values have been adopted.

The discharges from MAGNOX and AGR reactors result from coolant leakage and comprise the carbon-14 produced in the coolant itself together with that released to the coolant due to the corrosion of the moderator. In the case of the HTR the discharge is assumed to arise as a result of the regeneration of the primary coolant purification system, moderator corrosion being the source of carbon-14 arising in the coolant; the discharge via leakage from the primary circuit would be expected to be small. The discharge from light water reactors will result from the leakage and removal of gases produced in the circulating coolant water.

Carbon-14 produced in reactor fuel may be discharged during fuel reprocessing. Numerous factors will determine the magnitude of the discharge, in particular the fraction of carbon-14 existing in the gaseous phase in the fuel element, the fraction incorporated into the cladding, the initial carbon impurity level in the fuel, the efficiency of off-gas treatment systems in removing CO and CO_2, and the fraction of carbon oxidised to CO or CO_2 during fuel dissolution. In the absence of data on carbon-14 discharges from reprocessing plants as well as on several of the factors listed above, it has been assumed that 10% of the carbon-14 contained in the fuel elements will be discharged during fuel reprocessing. It will subsequently be shown that the results of this study are not particularly sensitive to this assumption.

The previous considerations apply to the reprocessing of metal clad fuels; somewhat different assumptions are necessary with regard to the reprocessing of HTR fuel. The most likely process to be adopted for HTR fuel reprocessing is the grind-leach-burn process in which essentially 100% of the carbon content of the fuel element is burned and discharged to the atmosphere as CO or CO_2 (26). While the discharge rate quoted in Table 5 has been derived on the basis of the total discharge of the

carbon-14 content of the fuel element, it should be noted that schemes for the separation of the fuel particles from the graphite fuel element prior to the grind-leach-burn process have been proposed (27); their application could reduce the carbon-14 discharges via this route by more than an order of magnitude.

The assumptions adopted with regard to the carbon-14 discharges from FBRs and HWRs require further qualification. The production in FBRs of carbon-14, which may subsequently be discharged to the environment, is expected to be small compared to that in thermal reactors, a consequence of the much reduced neutron cross sections at fast neutron energies. No account has therefore been taken in this study of carbon-14 arising via this source. The discharge rate of carbon-14 from HWRs has been assumed for the purposes of this study to be intermediate between that for PWRs and BWRs, although preliminary estimates have indicated that the production rate in and the discharge rate from HWRs may be considerably in excess of those associated with LWRs. This results from the much larger mass of water (and hence oxygen-17) exposed to the neutron flux in the case of HWRs. Preliminary estimates indicate that the carbon-14 discharges from SGHWR and CANDU reactors respectively may be factors of about 10 and 40 times greater than the value given as appropriate to HWRs in Table 5; the larger value in the case of the CANDU, compared to that for the SGHWR, is a consequence of its larger moderator mass per unit reactor power and the use of nitrogen, compared to CO_2, as the vault gas (which fills the interspace between the pressure tubes and the calandria). The above factors have been derived on the assumption of equality between the discharge and production rate of carbon-14 in HWRs. The implications of much higher discharge rates from HWRs than adopted for the purposes of this study are subsequently discussed.

No account has been taken of the carbon-14 that may be discharged as a result of reactor decommissioning due to uncertainties as to the procedures likely to be adopted. Of particular significance in this context are the graphite moderators of MAGNOX and AGR reactors which at the end of an assumed 30 year reactor life may contain about 10^3 Ci per GW(th) of reactor power.

Owing to the few data available regarding the discharge rates of carbon-14, only limited comparison can be made between the values adopted in this study and those suggested by other authors. In contrast to the measurements by Kunz et al (20,21) of discharge rates from PWRs and BWRs of 2 and 5.3 Ci/GW(th)y respectively (the values adopted in this study), Rublevskii et al (28) have measured discharge rates of about 90 Ci/GW(th)y from LWRs in the USSR. The reason for the much higher value in the latter case is not apparent; possible causes may be different nitrogen impurity levels in the coolant or differing masses of coolant exposed to the neutron flux per unit reactor power. As the majority of the LWR programme in the European Community is based on the USA reactor design, the data of Kunz et al (20,21) are considered to be more appropriate. Magno et al (29) have estimated carbon-14 production rates of about 17 and 100 Ci/GW(th)y for LWRs and HTRs respectively. Their estimates are a factor of approximately 2 and 5 greater than the respective values adopted in this study. As no information is given by Magno et al as to their assumptions, particularly with regard to the nitrogen impurity levels assumed, no comment can be made as to the sources of the differences. Brooks et al (22) have evaluated the carbon-14 production rate in HTR fuel elements of the prismatic type which are incorporated in the General Atomic HTR design. Their current predictions revise earlier estimates which had suggested significantly higher production rates. Their results are presented in terms of carbon-14 production per fuel element; using design data for Fulton HTR (26) their predictions are equivalent to a production rate of approximately 40 Ci/GW(th)y. This value is based on a nitrogen impurity level in the graphite of 26 ppm, a value chosen solely for illustrative purposes. While the data on nitrogen impurity levels in graphite are limited, those which are available (23) are indicative of a level of 10 ppm by weight. Normalising the Brooks et al carbon-14 production rate to a 10 ppm nitrogen impurity level, the level assumed in this study, results in very close agreement with the value predicted in this current work. Bonka et al (30,31) have predicted a production rate of about 24 Ci/GW(th)y in HTRs of the pebble bed design which are under development in the FRG. The estimate is based solely on the activation of carbon-13 in the graphite, no account having been taken of the activation of any nitrogen impurity incorporated in the graphite; assuming a nitrogen impurity level of 10 ppm would result in an increase in the production

rate to about 60 Ci/GW(th)y. This value is approximately a factor of 3
greater than both that adopted in this study and that predicted by
Brooks et al after normalisation of the latter to a 10 ppm nitrogen
impurity level. The larger value is almost certainly a consequence of
the neutron flux in the pebble bed design of the HTR, the basis of the
prediction of Bonka et al, being a factor of approximately three times
greater than that in the prismatic style HTR; the latter was used as the
basis of the production rates calculated in the present work as well as
by Brooks et al. The prismatic style HTR is more likely to be widely
adopted, at least for electricity production, and is the style being
developed in the USA by General Atomic and in several European countries;
the pebble bed design is being developed in the FRG. As a consequence it
has been assumed in this study that the production rate evaluated for the
prismatic style is applicable to all HTRs.

Perhaps the greatest uncertainty associated with the prediction of
carbon-14 production rates is the magnitude of the nitrogen impurity
levels in a variety of reactor materials; by comparison the production
via the activation of oxygen-17 and carbon-13 can be quite accurately
assessed. While the nitrogen impurity levels adopted in this study are
felt in the case of the reactor fuels to be realistic, and in the case of
the CO_2 coolant to be at least conservative, much greater uncertainty
exists with regard to the impurity levels in the graphite moderators.
The production rates of carbon-14 in moderator graphite arising from
nitrogen activation should therefore be viewed with somewhat more caution
than the other production rates listed in Table 4.

Inspection of the discharge rates in Table 5 shows that the magnitude
of the total carbon-14 discharged from the nuclear programme will only be
moderately dependent on the distribution of installed reactor type. The
range of variation in the discharge rates associated with the various
reactor types is less than an order of magnitude. An even smaller
variation would result if the total carbon-14 produced in the reactor
fuel were assumed to be discharged at reprocessing plants, as opposed to
the value of 10% adopted. Note however should be taken of the considerably
higher discharge rates of carbon-14 that have been predicted, on the basis
of preliminary estimates, to be appropriate to HWRs.

The chemical form of the discharged carbon-14 will in general comprise carbon dioxide and carbon monoxide, the former being the more probable. The only exception involves the discharge from PWRs where the majority of the carbon (>80%) has been measured to be in the form of hydrocarbons, principally methane and ethane (20). Discharge in this form is due to the reducing nature of the primary coolant circuit. For the purpose of this study however it is assumed that all carbon-14 is discharged as carbon dioxide. While the implications of the assumption will be minor in the context of doses from the global circulation of activity it will lead to an overestimate of doses in the vicinity of LWRs.

3.4 Iodine-129

Iodine-129 is produced as a fission product during the irradiation of nuclear fuel. The variation of its production rate with reactor type, both thermal and fast, is small and a yield of 0.4 Ci/GW(th)y can be adopted for all reactor types (10,11). The discharge of iodine-129 from reactors will be negligible in comparison to that from reprocessing plants. A review of practice at Windscale (32) has indicated that 75% and 0.1% of the iodine-131 present in the fuel at the time of reprocessing are discharged to the sea and atmosphere respectively; similar discharge fractions would be likely to pertain for iodine-129. For the purposes of this present study discharge fractions of 75% and 1% of the iodine-129 have been assumed as representative. The more cautious choice of 1% discharge to the atmosphere is a reflection of the uncertainty with regard to present and future practice at reprocessing plants. The discharge percentages adopted as representative are essentially typical of a coastal sited reprocessing plant; different considerations would be likely to apply to an inland sited plant, in particular with regard to discharges to inland waters. In the latter case both the magnitude of the total iodine-129 discharge, as well as its distribution among the two effluent streams, may be very different from those adopted as representative for the purposes of this study.

A reduction in the fractional discharges might arise if shorter cooled fuel were to be processed, owing to the need to reduce the fractional discharge of the then much greater iodine-131 inventory. Significant economic benefits have been predicted to arise from minimising the cooling period, and hence the quantity of plutonium in the fuel cycle, for fast

reactor fuels. However the expected benefits will need to be carefully weighed against the increased waste management difficulties associated with such an action in order to ascertain the optimum approach. While a reduction in the fractional discharge of iodine-129 may not necessarily arise from the above consideration, a reduction resulting from the introduction of different waste management practices prior to the year 2000 cannot be dismissed. Consideration is therefore also given to the effect of a lower fractional discharge than cautiously assumed above.

3.5 Summary of discharge rates

The discharge, per unit energy generation, of the four nuclides considered are summarised in Table 6 for each of the reactor types. The location of the discharge and the medium into which it is made are also indicated. Discharges to the atmosphere are assumed to occur from elevated positions, at a height of 30 m and 100 m in the case of reactors and reprocessing plants respectively. These values are representative of the stack heights in the respective establishments. The discharge data in Table 6 and the power programmes contained in Figures 2 and 3 have been used to calculate the discharge rate of each nuclide to the year 2000. These discharge rates are shown in Figures 5 and 6 for both the world and European Community nuclear power programmes, and form the basic data from which the dose rates to the year 2000 are subsequently assessed.

4. The evaluation of doses arising from the discharges of krypton-85, tritium, carbon-14 and iodine-129

In assessing the doses from the discharges of these four nuclides consideration must be given to three distinct aspects. These comprise the doses to people within a few kilometres of the discharge point, the doses to people within several hundred kilometres who may constitute a regional group, and doses to the world population from the subsequent global circulation of discharged activity. A relatively small number of individuals in the first category will in general comprise the critical group and it is the dose to these individuals and the potential risk of somatic effects which are of interest. In the intermediate group both the dose to individuals and the exposure of the regional population group as a whole (collective dose) are likely to be of interest. In the case of the doses arising from the global circulation of the activity the individual exposures are in general trivial, and attention can be confined to the exposure of the population as a whole. With regard to the exposure of large populations, consideration needs to be given to both the genetically significant dose and collective somatic dose in the respective contexts of the possible genetic injury and the possible somatic effects that might occur in the population. While the ICRP have made recommendations on dose limits for individual exposure and on a genetic dose limit to a large population (1) no numerical recommendation has been made with regard to a maximum "somatically significant" dose for a population. The ICRP have pointed out that an improved knowledge of risk estimates would eventually allow national authorities to assess the acceptability of a somatic dose to a population; in the interim however it was felt that the dose limits for individuals would ensure that the number of somatic injuries that could occur in a population would remain at a low level (1).

Doses arising from global circulation will be determined essentially by the absolute magnitude of the total activity discharged and will only be moderately dependent on the distribution of discharged activity among the various locations. Conversely doses to populations within several hundred kilometres of discharge points will be very sensitive to the magnitude of the discharge at individual locations. This arises from almost all the activity, apart from carbon-14, being discharged at reprocessing plants, and from these plants being few in number. Assumptions must

therefore be made regarding the discharge at individual locations to enable the evaluation of doses to local and regional population groups.

Commercial fuel reprocessing capacity in the European Community is currently limited to plants at Windscale in the UK and at Cap de la Hague in France. The next major plant will probably be constructed in the FRG but is unlikely to be in operation before the early 1980s. For the purposes of this study it is assumed that one half of the European Community fuel reprocessing load to 1985 will be processed at one plant. During the period 1985-1990 this fraction is assumed to reduce to one-third, at which fraction it remains constant through to the year 2000. This assumption is equivalent to the reprocessing at one plant of the fuel from an installed reactor capacity of 65 GW(e) in 1985 increasing to 240 GW(e) in the year 2000, and this reprocessing load has been adopted as representative in the context of evaluating doses to people within several hundred kilometres of a reprocessing plant. It may however overestimate the reprocessing load at any one plant by up to a factor of two. This approach has been adopted with regard to the discharges of krypton-85, tritium and iodine-129 and the magnitude of their discharges from this single source can be derived by appropriate scaling of Figures 5 and 6. The situation with regard to carbon-14 is more complex and is discussed in greater detail later.

In the following sections consideration is given in turn to the evaluation of doses resulting from the global circulation of the discharges of each of the four nuclides from both the world and European Community nuclear power programmes. Doses to people within several hundred kilometres of the discharge point, resulting from the 'first pass' of activity discharged from the representative reprocessing plant outlined above are also evaluated. In the case of the airborne effluents the first pass dose arises from the downwind passage of discharged activity prior to the more widespread dispersal of the activity throughout the whole or part of the atmosphere. Similarly for liquid effluents the first pass dose arises prior to the more widespread dispersal of activity throughout the larger water masses of the world; in this case the transport processes and uses made of the aquatic medium into which the discharge is made will be instrumental in determining the magnitude of the first pass doses via this route.

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4.1 Doses resulting from the discharge of krypton-85

Krypton-85 decays with a half-life of 10.8 years by the emission of a
β particle of maximum energy 0.67 MeV, and a γ ray, with a branching ratio
of 0.41% of energy 0.515 MeV (33). Exposure to an extensive cloud of
krypton-85 at a uniform concentration of 1 pCi/g of air has been calculated,
in reference 34, to result in a dose of $2.5 \ 10^{-3}$ rad/y to the surface of
the skin and $2.1 \ 10^{-5}$ rad/y to shallow tissue and gonads. These dose rates
have been modified for the purposes of this study; the dose rate to the
surface of the skin has been modified by a factor of 0.6 to convert the
surface dose to a depth of 7 mg/cm^2 (35) and dose to shallow tissue and
gonads has been modified by a factor of 0.4 to make allowance for the
increased shielding during time spent indoors (36). The dose to the skin
arises mainly from the β component, while that to the gonads is attribu-
table mainly to the γ component. No account is taken of the additional
dose arising from the transport in the body of inhaled krypton-85, as
this has been shown to be small in comparison with the external radiation
dose to skin and whole body (37).

Gonad and skin dose rates per unit discharge rate of krypton-85 from
a stack of height 100 m are shown in Figure 7 as a function of the dis-
tance from the discharge point (first pass doses). The dose rates have
been derived from reference 38 and in their derivation account has been
taken of the non-uniform distribution of krypton-85 in the overhead cloud.
While the dose rates were derived specifically for dispersion conditions
typical of the UK they are likely to be broadly applicable in the temperate
latitudes, providing the topography is not exceptional. Gonad dose rates
to the year 2000, from the downwind passage of krypton-85 discharged from
the representative reprocessing plant, are given in Figure 8 for a range of
distances from the discharge point. The dose rates have been derived from
Figure 7 and the discharge rates associated with the representative plant.

The discontinuities in the curves in Figure 8 are a consequence of the
assumptions regarding the rate of fuel reprocessing in the representative
plant. While only the gonad doses are given, the doses to skin can be
derived by scaling by the appropriate factors given. Dose rates to 1985
are shown as solid lines and from 1985-2000 as dashed lines. This conven-
tion is adopted throughout where the dose rates are plotted as a function
of time and is a reflection of the greater uncertainty in the dose

predictions beyond 1985, as a consequence both of uncertainties in the magnitude of the power programme and of uncertainties as to the future waste management practice. It should be noted that the dose rates given in Figure 8, as well as in subsequent Figures, as appropriate to the year 1975 are likely to be significant overestimates due to delays in the installation and commissioning of reactors and to the limited amount of fuel reprocessing currently being undertaken throughout the world.

Dose rates to the year 2000 resulting from the global circulation of krypton-85 are shown in Figure 9, where the contribution from the European Community discharges is shown in relation to the total. The dose rates were evaluated using the krypton-85 discharge rates given in Figure 5 for both the European Community and world nuclear power programmes and the model for global circulation given in reference 39. Account was also taken of the discharge of krypton-85 prior to 1975. This model considers all krypton-85 to be discharged into the latitude band $35-60^{\circ}N$, and assumes uniform dispersion of the activity up to a height of 10 km. Transfer from this band to the troposphere of the Northern Hemisphere is assumed to occur with a mean life of 100 days (equivalent to a transfer coefficient of $3.65 \ y^{-1}$), and mixing between the Northern and Southern Hemispheres is assumed to proceed with a transfer coefficient of $0.5 \ y^{-1}$. The dose rates in Figure 9 are relatively insensitive to realistic variation of the numerical parameters adopted in the model. Typically the variation of the interhemispheric transfer coefficient from 0.1 to 1 y^{-1} would result in a variation in the dose rate of less than 50%.

Two points are of particular interest in relation to the dose rates from krypton-85. The first relates to the contribution which the European Community discharges make to the total dose rate arising from the global circulation of krypton-85. This contribution amounts to about 20% and indicates that little benefit would ensue from unilateral action in reducing the discharges of krypton-85. The second relates to the increasing significance with time of the dose rates from global circulation compared to those resulting from the first pass of the activity. From 1975 to the year 2000 the distance beyond which the dose rate from global circulation exceeds the first pass dose rate decreases from 180 km to 95 km. These data are obviously specific to the representative reprocessing plant considered. However as the fuel throughput assumed for this plant is

likely to represent an upper limit at any one plant, the relative sig-
nificance of the dose rate from global circulation may be even greater
than indicated above.

4.2 Doses resulting from the discharge of tritium

Tritiated water is as readily assimilated into biological systems as
ordinary water and it is this characteristic that is of particular signi-
ficance radiologically, not its inherent radiotoxicity which is low owing
to the very low energy (5.7 keV average) of the beta particle emitted
during radioactive decay. Tritiated water in body fluids at an equilibrium
concentration of 1 pCi/g delivers a dose rate of 10^{-4} rad/y to the whole
body, including the gonads (38). The radioactive half-life of tritium is
12.2 years.

Tritium discharge to the environment from the nuclear power industry
arises predominantly at reprocessing plants. Discharges from reprocessing
plants have therefore been used as a basis for evaluating doses to the end
of this century; some consideration is however given to the discharges
from reactors where these are likely to be of significance. Tritium is
discharged from reprocessing plants in two waste streams, liquid and
airborne, and the implications of each are considered in turn.

The discharge of tritium in airborne effluent leads to the irradiation
of man via two routes. These comprise the inhalation and skin absorption
of tritiated water vapour in air and the ingestion of foodstuffs and water
contaminated during the downwind passage of the radioactive cloud.
Contamination of foodstuffs and water arises principally from the washout
of the tritium in the cloud by rain. The dose rates for unit discharge
rate of tritiated water from a stack of height 100 m are shown in Figure
10 as a function of the distance from the discharge point. The doses via
inhalation and skin absorption have been averaged over dispersion con-
ditions typical of the temperate latitudes, and are based on a water intake
via these routes of 320 g/day (equivalent to an average water vapour
content in air of 8 g/m^3 which is typical of the UK). These doses are
relatively insensitive to the assumed water vapour content in air; this
results from any change in the water vapour level, and thus the magnitude
of water intake via these routes, being compensated by a corresponding but
inverse change in the concentration of tritium in the vapour. Ingestion

doses are much less certain than inhalation doses and are based on food-
stuffs and drinking water being contaminated at the same level as rain.
Approximately equal contributions to the daily water intake into the body
arise from foodstuffs and drinking water. The level of contamination in
rain, and hence the assumed levels in foodstuffs and in drinking water,
have been derived on the basis of rain occurring solely in the Pasquill
C and D weather categories, with rain being assumed to fall for 17% of the
time during the downwind passage of the cloud. Removal of tritium from
the cloud during rainfall has been evaluated using a washout coefficient
of 10^{-4} s^{-1} (40) and the tritium concentrations in rain are based on an
average rainfall of 75 cm/y. Account has also been taken of evaporation
and subsequent re-deposition of tritium removed from the cloud by rainfall.
Ingestion doses will be particularly sensitive to the fraction of food and
water derived locally, parameters which are likely to vary widely from
region to region. In this assessment it is assumed that 50% of the food
and water intake are contaminated at the mean level in an area contained
within a radius of 50 km from the point of intake, with the remaining 50%
being essentially uncontaminated. On this basis the inhalation dose is
the major contributor to the total dose out to about 10 km, the ingestion
route dominating beyond this distance. An extreme upper limit to the dose
from airborne discharge of tritiated water vapour can be obtained by
assuming all food and water to be contaminated at the same level as the
water vapour in the air at the point of intake. Doses derived on this
basis are shown in Figure 10 for comparison.

Doses to the year 2000 from the discharge of tritium to the atmos-
phere from the representative reprocessing plant are given in Figure 11 for
a range of distances from the discharge point. They have been derived from
Figure 10 and the discharge rates of tritium to the atmosphere associated
with the representative reprocessing plant. The tritium is assumed to be
discharged solely in the form of tritiated water vapour.

Doses to local or regional groups from the discharge of tritium in
liquid effluents are very sensitive to particular local or regional condi-
tions. Factors which determine this sensitivity include the nature of the
water body into which the discharge is made, the subsequent use made of the
water, and the rate of exchange with, and circulating behaviour of, atmos-
pheric water vapour. Owing to the marked dependence on local factors only

limited consideration is given in this study to the evaluation of representative local or regional doses associated with liquid discharges. Discharge to sea of tritium in liquid effluent, at least in the magnitude consistent with the predicted power programme to the year 2000, will be of very low radiological significance. This results from the very large volume of water available for dilution and the limited contribution made directly by the sea to man's total water intake. The major exposure pathway in this case is likely to arise from the exchange of water between the sea and atmospheric water vapour, followed by the subsequent deposition over land. Discharges to inland waters or rivers are however of much greater significance in the local and regional contexts, particularly where the water is subsequently used as a source of drinking water or for irrigation purposes. Although no assessment has been made in this study of the doses from discharges to rivers, assessments of other authors relating to discharges to specific areas are summarised.

Discharges of tritium to the Rhine are of particular importance in the European context because of the use made of the Rhine as a source of drinking water, particularly in the Netherlands. The International Commission for the Protection of the Rhine against Pollution has recently assessed the implications of the discharge of radioactive materials to the Rhine up to the year 2000 (41). The assessment is based on the discharges, from reactors only, associated with an installed reactor capacity in the Rhine catchment area by 1990-2000 of 100 GW(e). The installed capacity is assumed to comprise equal contributions from BWRs and PWRs. Tritium concentrations in the Rhine are derived from discharge rates of 2000 and 20 Ci/GW(e)y (equivalent to approximately 700 and 7 Ci/GW(th)y) from PWRs and BWRs respectively, values not inconsistent with those adopted in this study (Table 3), and an average Rhine flow at Lobith of 2200 m^3/s. Based on the pessimistic assumption that the tritium concentration in all routes of water intake to the body is equal to that predicted for the Rhine in the period 1990-2000, a whole body dose rate of 0.14 mrad/y would result. This value is based on a reactor programme comprising solely LWRs; somewhat different dose levels might arise if radically different reactor type distributions were assumed. This results from the tritium discharge rate from a reactor varying markedly with the reactor type (see Table 3); of particular importance in this respect are the HWR and the HTR, the significance of the latter depending critically on the waste management

procedures adopted for tritium contaminated water vapour removed in the
primary coolant purification system. The prediction of dose rates in
reference 41 is based solely on tritium discharged from reactors. If the
fuel from an installed reactor capacity of 100 GW(e) were also reprocessed
in the Rhine catchment area, and the tritium content of the fuel discharged
to the Rhine, the dose rate would be enhanced by a factor of 10 to 20.
Such discharges, however, would be unlikely to be made to a river which was
subsequently to be used as a major drinking water supply and other waste
management procedures would probably be adopted for the discharge or
disposal of such arisings. Grathwohl (12) has made an assessment of the
hypothetical contamination of German rivers based on the assumption that
all tritium discharged in liquid effluent from the FRG nuclear power
programme, from both reactors and reprocessing plants, will reach the
rivers and be diluted by the average volume flow. By the year 2000 the
average tritium concentration in river water predicted by Grathwohl (12)
is equivalent to a whole body dose rate of 0.7 mrad/y if all routes of
water intake into the body are assumed, pessimistically, to contain
tritium at this average concentration. In deriving this dose rate from
the tritium concentration given by Grathwohl, account was taken of the
reduction to unity of the quality factor for soft betas (42). The assess-
ment by Grathwohl is probably pessimistic in assuming a significant
fraction of tritium liberated from the fuel during reprocessing to be
discharged to river water.

The implications of tritium discharge in a global context have been
assessed on the assumption that the tritium is immediately dispersed
throughout the circulating waters of the hemisphere into which the dis-
charge is made. This assumption is adopted in the absence of much of the
data necessary for a detailed assessment and may result in underestimates
of dose in specific areas from which the rate of dispersion is slow. The
model adopted to evaluate the global circulation of tritium, subsequent to
the assumed immediate dispersion in the circulating waters, is shown in
Figure 12. Dose rates are evaluated assuming body fluids to be contamina-
ted at the same level as the circulating waters of the Northern Hemisphere
which comprise essentially the surface waters of the sea to a depth of 75 m
(volume of approximately 10^{22} cm^3). In evaluating the tritium concentra-
tion in the circulating waters account is taken of radioactive decay, the
interchange between the circulating waters of the Southern and Northern

Hemispheres, the interchange between these surface waters and the deeper
waters beneath the thermocline, as well as the interchange between the
deeper waters of the two hemispheres. The transfer coefficients adopted
to represent the transfer between the various compartments are indicated
in Figure 12. Variation in the transfer coefficient with the direction
of transfer is a consequence of the differing volumes of the respective
compartments. In Figure 13 the dose rates up to the year 2000 derived
using the above model are given for global circulation of the total
tritium discharged from the world and European Community nuclear power
programmes.

The dose rates arising from the first pass of tritiated water dis-
charged in airborne effluent are significantly greater out to large dis-
tances than the dose rate from global circulation, and only at distances
greater than 1000 km do the dose rates become comparable. By the year
2000 the first pass dose rates are predicted to be 0.2 mrad/y and 8 μrad/y
at downwind distances of 100 and 1000 km respectively (compared with the
dose rate from global circulation of 1.5 μrad/y). These first pass dose
rates are of course appropriate only to the representative reprocessing
plant considered and an assumed continuation of present waste management
practice. Their magnitude however is such that realistic assessments of
the local and regional doses from non-marine liquid discharges will be
required to ascertain the mode of discharge having the minimum impact in
specific cases.

4.3 Doses resulting from the discharge of carbon-14

The importance of carbon-14 discharge to the environment arises from
its incorporation into the carbon content of the biosphere. Carbon forms
the structural base of all organic matter and participates in almost all
biological and biochemical processes. It comprises about 18% of the total
body weight and is a major constituent of proteins and genetically signi-
ficant structures such as DNA and RNA. Carbon-14 decays, with a half-life
of 5730 years, by emission of a β particle with a mean energy of 50 keV.
The incorporation of carbon-14 into the body at a given specific activity
(pCi C-14/g C) will result in different doses to various organs by virtue
of their differing carbon content. A specific activity of 1 pCi/g of
carbon will result in doses of 0.76 mrad/y to fat, 0.1 mrad/y to the gonads,
and an average dose to the whole body of 0.17 mrad/y, fat being the

critical organ. The radiological significance of carbon-14 may be further enhanced by the transmutation of the carbon atom to a nitrogen atom during radioactive decay, particularly from a genetic viewpoint when the carbon-14 is incorporated into genetic structures. The limited data available however suggest that, compared with the absorbed energy from ionisation processes, the transmutation effects represent only a minor contribution to the radiological significance of carbon-14 (43).

The discharge of carbon-14, in the form of carbon dioxide, in airborne effluents will lead to the irradiation of man via two routes; these comprise the inhalation of the cloud as it passes downwind, and the ingestion of contaminated foodstuffs. The exchange rate between atmospheric carbon dioxide and living vegetation, as opposed to the humus, is assumed to be sufficiently rapid to consider the vegetation to be contaminated at the same specific activity as that of the carbon in the cloud. Gonad dose rates per unit discharge rate of carbon-14 from a 100 m stack are given in Figure 14, as a function of the distance from the discharge point, and the respective contributions from inhalation and ingestion are indicated. Doses to other body organs can be obtained by scaling by the appropriate factors given in Figure 14. The dispersion of the discharged activity has been evaluated in the same manner as for krypton-85, and the doses have been derived on the basis of the carbon-14 specific activity (pCi C-14/g C) in the body. This is derived as the weighted mean specific activity of the two routes of intake, weighting being applied according to the mass of carbon reaching the blood from each route. Values of 2.25 g/day and 300 g/day have been adopted for inhalation and ingestion respectively. The former value is probably a considerable overestimate of the intake via that route. The ingestion dose is obviously particularly sensitive to the area over which food is derived and for the purposes of this assessment it is assumed that 50% of food is derived from an area within 50 km of the point of intake, with the remainder being essentially uncontaminated. Ingestion doses based on all food being derived at the point of intake are also shown in Figure 14, these representing the upper limit to the possible doses.

The prediction of representative doses to the year 2000 from the first pass of discharged carbon-14 is complicated by the variety of sources contributing to the total discharge (Table 5). The largest

discharges of carbon-14 from a single location are likely to arise at HTR
fuel reprocessing plants and such discharges have been adopted here to
demonstrate the possible level of first pass doses to the year 2000. It
is assumed that all HTR fuel from the predicted European Community
programme is reprocessed at one plant; the carbon-14 discharges associ-
ated with such an assumption can be derived from the installed HTR ca-
pacity given in Figure 3 and the discharge rate associated with HTR fuel
reprocessing in Table 5. The assumption of a single plant, while result-
ing in an upper limit dose estimate, is not unrealistic in the context of
the predicted magnitude of installed HTRs in the European Community of
51 GW(e) by the year 2000. Furthermore a single plant would probably be
advantageous on economic grounds particularly if a Th-U fuel cycle were
adopted. On the basis of these assumptions gonad doses to the year 2000
from the first pass of discharged carbon-14 have been derived and are
shown in Figure 15 for a range of distances from the discharge point. The
predicted dose rates can however be scaled to accommodate different
assumptions regarding the magnitude of the HTR programme or the fraction
of the fuel reprocessed at a single plant.

The global circulation of carbon-14 discharged from the world and
European Community nuclear programmes (Figure 6) has been evaluated using
the circulation model outlined in Figure 16. It is assumed that all
carbon-14 is discharged as carbon dioxide into the troposphere in the
latitude band 35-60°N and that uniform dispersion occurs instantaneously
up to a height of 10 km. Transfer from this band to the whole troposphere
of the Northern Hemisphere is assumed to occur with a mean life of 100
days. Subsequent transfer from the troposphere and between other compart-
ments is indicated in Figure 16 together with the appropriate transfer
coefficients. The coefficients have been derived from numerous references
(44-55) and are representative of the range of values quoted. Dose rates
to the gonads have been evaluated on the assumption that the specific
activity of carbon-14 in the carbon content of body tissues is identical
to that in the troposphere. The assumption is justified by virtue of the
rapid exchange of atmospheric carbon dioxide with vegetation. Gonad dose
rates from the global circulation of carbon-14 to the year 2000 are given
in Figure 17 and the contribution to the total made by the European Com-
munity nuclear power programme is indicated. It should be noted that the
dose rates in Figure 17 refer to the latitude band 35-60°N and are

applicable to the European Community. Dose rates in the year 2000 at
other latitude bands in the Northern Hemisphere would be approximately
30% lower on the basis of the model adopted.

The sensitivity of the predicted dose rates in Figure 17, in relation
to the adopted carbon-14 discharge rates and the transfer coefficients
used in evaluating the global circulation of carbon-14, has been assessed.
Two aspects require consideration with regard to the assumed discharge
rates. The first concerns the assumption of 10% of carbon-14 produced in
metal-clad fuel being discharged at reprocessing plants; the assumption
of 100% discharge would only increase the predicted dose rates in Figure
17 by a factor of about 2. The second concerns the carbon-14 discharge
rate adopted for HWRs. As discussed in Section 3.3 preliminary estimates
have indicated that the carbon-14 discharge rates from HWRs may be more
than an order of magnitude greater than the value assumed in this study.
While such increased discharge rates may be of particular local signifi-
cance, especially in the context of nuclear parks, their impact on dose
rates from global circulation will be limited, a consequence of the
relatively small contribution made by HWRs to the total nuclear programme
(see Figure 2). Taking account of these preliminary estimates of carbon-14
discharge rates from HWRs would result in an increase in the predicted
dose rates from global circulation by up to a factor of 2. The dose
rates in Figure 17 are not particularly sensitive to variations in the
transfer coefficients given in Figure 16. Variation of these coefficients
within the bounds indicated in the literature (44-55) results in changes
in the dose rate from global circulation in the year 2000 by up to 30%.
This limited sensitivity is to some extent a consequence of the rapidly
expanding nuclear power programme assumed, since the dose rate is being
determined essentially by the current and previous few years' discharges.
A greater sensitivity would be experienced in the calculation of the dose
commitments from the global circulation of carbon-14 and further considera-
tion is given to this aspect later.

A factor not considered in the evaluation of carbon-14 dose rates is
the increasing atmospheric inventory of carbon-12 from the combustion of
fossil fuel depleted in carbon-14 (Suess effect). This will result in
lower isotopic concentrations of nuclear power generated carbon-14 in the
atmosphere and consequently lower doses. The impact of a fossil fuel

programme increasing at a rate of 4%/y on the calculated dose rates has been evaluated using the global circulation model in Figure 16. By the year 2000 the effect would be to reduce the calculated dose rates in Figures 15 and 17 by only a few per cent, which is negligible in relation to other uncertainties involved in the dose evaluation. Similar predictions as to the impact of an increased rate of use of fossil fuel have been made by other authors; for example Baxter and Walton (56) have predicted a reduction of about 10% in the carbon specific activity in the atmosphere during the period 1970-2000 based on the rate of use of fossil fuel increasing by about 4%/y.

4.4 Doses resulting from the discharge of iodine-129

Iodine-129 is of interest due to its extremely long half-life of 17 million years and to the significant fraction of its inventory in irradiated fuel that is currently discharged to the environment during fuel reprocessing. Exposure from iodine-129 incorporated into the body is solely of somatic interest; the critical organ for inhaled or ingested iodine in the transportable form is the thyroid gland which preferentially absorbs the element. Iodine-129 decays by emission of a β particle with an average energy per disintegration of 48 keV (33). The average dose rate to the thyroid has been estimated in reference 38 as $2 \ 10^{-7}$ rad/y for a specific activity of 1 pCi I-129/g I-127 in thyroid tissues, and is considered applicable for all age groups.

Iodine-129 is discharged from reprocessing plants in two waste streams, airborne and liquid, with 1% and 75% respectively of the throughput assumed to reach each stream. The implications of the discharge into each stream are considered in turn. The first pass doses from the airborne discharge of iodine-129 have been evaluated on the basis of a specific activity approach. Atmospheric dispersion of the discharged iodine-129 has been evaluated using a similar approach to that previously adopted for the other nuclides, and the iodine-129 specific activity has been derived assuming the average stable iodine-127 concentration in air to be 0.1 $\mu g/m^3$. This value is representative of the air in an inland region of the UK (57) and is assumed to be applicable to the European Community as a whole. Considerable local variation in the concentration would be expected however, with significantly higher values in some coastal areas. Thyroid doses have been conservatively evaluated on the assumption that the specific

activity of iodine-129 in the thyroid is the same as that in the atmosphere; implicit in this approach is the assumption that all iodine taken into the body is at the same specific activity as that in the atmosphere. The lack of consideration of the iodine contribution to the diet from food and water from relatively uncontaminated sources will result in these doses being overestimated. The dose rate per unit discharge rate of iodine-129 from a 100 m stack is given in Figure 18 as a function of the distance from the discharge point, and dose rates to the year 2000 resulting from the discharges associated with the representative reprocessing plant are given in Figure 19 for a range of downwind distances.

Doses to local or regional groups from the discharge of iodine-129 in liquid effluents will be very sensitive to particular local or regional conditions, and, as in the case of tritium in liquid discharges, no attempt has therefore been made to assess representative doses associated with such discharges. A few general points are however worthy of note. Doses resulting from discharges to rivers are likely to be significantly greater than those resulting from discharges to sea. This arises for several reasons including the smaller volumes of water available in rivers for dilution, the order of magnitude lower stable iodine concentration in river water (58) and the use made of river water for drinking and irrigation purposes.

The implications of the global circulation of iodine-129 have been assessed on the assumption that all of the discharged iodine-129 is immediately dispersed throughout the circulating waters of the hemisphere into which it is discharged. Dose rates have been derived assuming that the iodine-129 specific activity in the thyroid is the same as that in the circulating waters, the latter being derived on the basis of a stable iodine content of sea-water of 60 µg/kg (38). The model outlined in Figure 12 for tritium was also adopted to evaluate the global circulation of iodine-129. Account has been taken of the interchange between the circulating waters of the Southern and Northern Hemisphere, the interchange between the surface waters and the deep oceans, and the interchange between the deep oceans of each hemisphere. The transfer coefficients for transfer between the various compartments are indicated in Figure 12.

Dose rates from the global circulation of iodine-129 to the year 2000 are given in Figure 20 for both the European Community and world programmes.

The dose rates are, however, likely to be overestimated because of the assumed equality between the iodine-129 specific activity in the thyroid and the circulating waters.

Limited data on iodine transport (59) indicate mean lives of about 2 years and 20 years (transfer coefficients of 0.5 and 0.05 y^{-1}) respectively for the exchange of the atmospheric iodine content and the terrestrial biospheric iodine content with that of the hydrosphere. A significant time lag will therefore occur before the specific activity of iodine in the atmosphere and terrestrial biosphere equals that in the hydrosphere and the dose rates in Figure 20 are probably more appropriate to times of a few tens of years later. This probable overestimate in the predicted dose rates may be counteracted to some extent in specific areas by virtue of the assumption of instantaneous uniform dispersion in the circulating waters. Consideration of finite mixing times between the surface water of the various seas and oceans may result in significantly higher dose rates in some localised areas.

On the basis of the models adopted, the dose rates from global circulation in the year 2000 only become comparable with the first pass dose rates from airborne discharge at distances of a few hundred kilo- metres. The latter dose rates are, however, probably very pessimistic and the relative significance of the dose rate from global circulation may be somewhat greater. Furthermore a reduction in the fraction of the iodine-129 discharged may arise from the introduction of different waste management practices prior to the year 2000, with a consequent reduction in the predicted doses.

respect of local somatic doses, the average annual dose to the assumed
critical group reaching about 0.6% and 2% of the ICRP dose limit to the
skin by the year 1985 and 2000 respectively. The significance of the other
nuclides can be derived from Figure 21 and in each case is considerably
lower than that of krypton-85.

The annual doses to local groups by the year 2000 are such that on
radiological protection grounds there would be little justification, on
account of these doses alone, for reducing the discharges of the nuclides
considered by other than the simplest of procedures. Moreover the pre-
dicted dose rates in Figure 21 probably represent upper limits of doses
to local groups due to the somewhat pessimistic assumption adopted
regarding fuel throughput at the representative reprocessing plant
(corresponding to a reprocessing load equivalent to an installed nuclear
capacity of about 240 GW(e) by the year 2000). This assumption is likely
to result in a pessimism of up to a factor of 2 in the predicted dose
rates. It should be further stressed that doses of the predicted
magnitude will only accrue to a small number of people in the vicinities
of reprocessing plants, which in the European Community will be few in
number by the year 2000 (equivalent to 3 of the magnitude assumed for the
representative plant).

At greater distances from the discharge point both the dose and the
associated potential risk of somatic effects to an individual are very
much smaller and in general it is the exposure of the population group as
a whole that is of greater interest. Attention in the following is
directed primarily towards the genetic component of the exposure of the
population group although some consideration is also given to the somatic
doses. Gonad dose rates from the first pass of airborne activity dis-
charged from the representative reprocessing plant are given in Figure 22
as a function of the distance from the discharge point in the range 100-
1000 km. The gonad dose rates from the global circulation of the total
activity discharged from the world nuclear power programme are also shown
for comparison. The latter doses, being independent of the discharge
location, are shown as horizontal lines in Figure 22. Consideration has
been restricted to krypton-85, tritium and carbon-14, the gonad dose from
iodine-129 being negligible in comparison. The dose rates are expressed
as percentages of the ICRP provisional limit of 5 rad/generation
(0.17 rad/y) for genetic dose to the population as a whole from all

sources other than natural background and medical exposure (1). It is
worthy of note that in the UK the whole population must not receive an
average gonad dose in excess of 1 rad/generation from radioactive waste
disposal (60), and in the FRG the German Atomic Energy Commission in 1969
formulated a recommendation to allocate only one third of the ICRP limit
to the nuclear energy sector (41), that is a rounded value of 2 rad/
generation.

The dose rates from global circulation relate to the total activity
discharged from the world nuclear power programme and are appropriate to
the Northern Hemisphere, and in the cases of krypton-85 and carbon-14
specifically to the latitude band 35-60°N. Slightly smaller values are
applicable to the Southern Hemisphere, as well as in the remainder of the
Northern Hemisphere, in the cases of krypton-85 and carbon-14. The con-
tribution to these dose rates from the global circulation of activity
discharged from the European Community nuclear power programme amounts to
about 20%, this value to a good approximation reflecting the relative
magnitudes of the European Community and world nuclear power programmes.
The dose rates from the first pass of airborne activity are appropriate
to the discharges from the representative reprocessing plant; note should
be taken of the different assumption regarding the representative repro-
cessing plant in the case of carbon-14 discharges (Section 4.3). To
enable a comparison to be made between the dose rates from the first pass
of activity and those from the global circulation of the world discharges,
the distance of 1000 km has been assumed in this study to represent the
outer bound of a regional population group distributed around the repre-
sentative reprocessing plant. The average dose to such a group from the
first pass of activity will depend on the dose-distance relationship for
the nuclide considered and the surrounding population distribution; the
dose at a distance of 250 km has been taken as representative of the
average for the purposes of this assessment. Contributions to this
average first pass dose rate from discharges from other nuclear installa-
tions are considered insignificant in the context of the few reprocessing
plants likely to be operating within the European Community by the year
2000 and the pessimistic assumption adopted with regard to the fuel
throughput at the representative reprocessing plant.

Gonad dose rates resulting from the global circulation of world dis-
charges of krypton-85 and carbon-14 can be seen in Figure 22 to be

comparable within a factor of about 1.5 and to be an order of magnitude
greater than the dose rate associated with the global circulation of the
discharged tritium. The dose rate from the global circulation of both
krypton-85 and carbon-14 increases from about $2 \cdot 10^{-3}$% to about 10^{-2}% of
the ICRP genetic dose limit during the period 1985-2000. In the cases of
krypton-85 and carbon-14 the dose rates from the global circulation of the
world discharges of these nuclides are larger, and therefore of greater
significance, than the average dose rates to the assumed regional popula-
tion group from the first pass of activity discharged from the representa-
tive reprocessing plant; the doses from global circulation are greater by
factors of about 2 and 4 for krypton-85 and about 10 and 3 for carbon-14
for the years 1985 and 2000 respectively. The situation is somewhat
different in the case of tritium, the dose rate from the first pass of
activity being greater than that from global circulation by factors of
about 80 and 40 in 1985 and 2000 respectively; in this period the average
dose rate to the regional population group,from the first pass of tritium
discharged in airborne effluent from the representative reprocessing plant,
increases from about 10^{-2} to about $4 \cdot 10^{-2}$% of the ICRP genetic dose limit.

For completeness the somatic dose rates from the global circulation
of the world discharges, and from the first pass of activity discharged in
airborne effluent from the representative reprocessing plant, for each of
the four nuclides are given in Figure 23 as percentages of the appropriate
ICRP somatic dose limits (see page 33). The relative somatic and genetic
significance of the nuclides considered can be assessed by reference to
Figures 22 and 23.

The dose rates from the first pass of activity shown in Figures 21 -
23 apply solely to the discharge of airborne effluents from the representa-
tive reprocessing plant. Only limited consideration has been given to the
evaluation of representative first pass doses from the discharges of liquid
effluents, a consequence of their marked dependence on local and regional
conditions. While the discharges to sea of tritium and iodine-129, the
two nuclides discharged in both liquid and airborne effluents, are unlikely
to make more than a minimal contribution to the first pass doses, the
discharges of these nuclides to freshwater, if this is subsequently used
for drinking or irrigation purposes, may be of greater significance. Dose
rates resulting from the discharges of the latter type will be very
dependent on the characteristics and usage made of the water body to which

the discharge is made; an indication of the magnitude of the dose rates involved, however, has been derived from an assessment of liquid discharges to the Rhine from nuclear reactors in its catchment area (41). Based on an installed capacity of 100 GW(e) in the Rhine catchment area in the period 1990-2000, whole body dose rates of 0.14 mrad/y would result if all routes of water intake to the body were assumed to be contaminated at the same level as that in the river water. These dose rates apply to the discharges of tritium from reactors only; the further discharge to the Rhine of tritium liberated during the reprocessing of fuel from the above reactor capacity would enhance the dose rates by about an order of magnitude. Such discharges, however, to a water body used as a major source of drinking water would be unlikely, as other means of discharge, of lower radiological significance, would probably be available.

It is clear that the total gonad dose rates from the discharges of the nuclides considered are small. In the case of the assumed regional population group the average dose rate in the year 2000 from the first pass of activity amounts to about 0.1 mrad/y; that to the world population from the global circulation of the total activity discharged from the world nuclear programme amounts to a few tens of μrad/y. These dose rates represent very small fractions of the ICRP genetic dose limit of 5 rad/ generation (equivalent to 170 mrad/y). While it is a basic principle of radiological protection that doses should be reduced to as low as reason-ably achievable (2), the magnitude of the above doses are such that the application of very costly measures prior to the year 2000 to reduce the discharges of krypton-85, tritium and carbon-14 would appear to have little justification on radiological protection grounds.

5.2 Dose commitments, collective dose commitments and the relative significance of the discharges of krypton-85, tritium and carbon-14

The dose rates to members of the population of the European Community from the discharges of krypton-85, tritium, carbon-14 and iodine-129 have been summarised in Figures 21 - 23. While some measure of the relative significance of each nuclide discharged and of the doses from the first pass and global circulation of activity can be obtained from Figures 21 - 23, the relative significance can be more appropriately assessed by con-sideration of the dose commitments associated with the activity discharged per unit nuclear energy generated. This latter approach circumvents the inherent difficulty associated with the comparisons in Figure 21 - 23

where the doses from global circulation are composites of both current
discharges and previous discharge history. Comparison of the respective
dose commitments allows a direct appraisal to be made of the relative signi-
ficance of the nuclides discharged.

Gonad dose commitments from the first pass and global circulation of
activity discharged per GW(th)y of nuclear energy generated are given in
Figure 24. Consideration has been restricted to krypton-85, tritium and
carbon-14, the gonad dose from iodine-129 being negligible in comparison.
The dose commitments associated with the global circulation are shown as
horizontal lines, being essentially independent of the discharge location.
These values can be regarded, to a good approximation, as applicable to
the whole of the world population, although they were derived specifically
for the latitude band 35-60°N. The dose commitments from the first pass
of activity are given as a function of distance from the discharge point
and the values at a distance of 250 km can be considered as representative
of the average dose commitments to the assumed regional population group.
In some instances, particularly for carbon-14, the total discharge is
divided between two sources, the reactor and the reprocessing plant; for
simplicity in evaluating the dose commitments from the first pass of the
activity it has been assumed that the total discharge arises from one
location.

In terms of dose commitments to members of the population of the
European Community the values given in Figure 24 are appropriate to unit
nuclear energy generation within the European Community itself. If
consideration were to be given to unit nuclear energy generation in the
world as a whole, while the dose commitments to members of the population
of the European Community would be essentially the same from the global
circulation of activity, those associated with the first pass of activity
would be reduced by a factor of about 5, the ratio of the magnitude of the
world and European Community nuclear power programmes. This reduction is
a consequence of the negligible exposure of the population of the European
Community resulting from the first pass of activity discharged elsewhere
in the world.

The dose commitments given in Figure 24 are based on the discharges
per unit nuclear energy generation listed in Table 7 for each of the
nuclides considered. For krypton-85 the discharge associated with thermal

reactors has been adopted, thermal reactors comprising by far the major fraction of the nuclear programme. The tritium discharge adopted is equivalent to the production rate of fission product tritium in thermal reactors (see Table 6), no allowance being made for the small contribution from activation product tritium. The variation of carbon-14 discharge with reactor type (Table 6) is much greater than is the case for krypton-85 or tritium, and a mean value, appropriate to the distribution among reactor types of the installed world nuclear capacity in the year 2000 (Figure 2), has been adopted as representative. While the dose commitments associated with global circulation are based on the total activity discharged, the first pass dose commitments are based solely on activity discharged in airborne effluent, no allowance being made for any contribution arising from liquid effluents. This neglect of liquid effluents applies only to tritium, and furthermore is only likely to be of significance in those cases where discharge is made to a water body which is subsequently used as a major source of drinking water. While the first pass dose commitments associated with such discharges will be strongly dependent on the nature and usage of the water body to which the discharge is made, a value of $4 \ 10^{-7}$ rad/GW(th)y can be regarded as indicative of the order of magnitude involved. This value has been derived from an assessment of the tritium discharges from LWRs to the Rhine (41). It is to be noted that this value applies only to the discharge of tritium from reactors, the assumption being made that the much larger tritium arisings at reprocessing plants would not be discharged to a water body used directly for drinking water when other means of discharge, having a lower radiological significance, are likely to be available. The above value is comparable with the first pass dose commitments per unit energy generation associated with airborne discharges of tritium from a reprocessing plant (see Figure 24).

The lack of consideration of activation product tritium in deriving dose commitments is not significant if interest is confined to the average dose commitments associated with unit energy generation from an installed nuclear capacity distributed among the reactor types as shown in Figures 2 and 3. If interest is directed specifically towards the dose commitment associated with a given reactor type, activation product tritium can be of much greater significance. This is particularly so in the case of the HWR where consideration of the discharge of activation product tritium would

enhance the dose commitments given in Figure 24 for tritium by a factor of 2 or more, the exact magnitude depending on the fraction of the discharge appearing in airborne effluent. In a similar fashion consideration of the dose commitments from carbon-14 discharges associated with unit energy generation in specific reactor types would result in a wide variation about those values given in Figure 24, which are based on a mean carbon-14 discharge rate from an installed reactor programme. The variation of dose commitment with reactor type is summarised below; the dose commitment in each case is expressed as a ratio of the average value which has been derived from the mean carbon-14 discharge rate from the installed reactor programme in the year 2000.

Weighted mean	MAGNOX	AGR	PWR	BWR	HWR	HTR	FBR
1.0	1.29	1.6	0.63	1.47	1.04	5.6	-

It should be noted that the factor quoted above for the HWR is based on the assumption adopted in this study, that the carbon-14 discharge rate from HWRs is intermediate between those associated with PWRs and BWRs; preliminary estimates however indicate that values some 10 and 40 times greater than that given above for the HWR are more appropriate to the SGHWR and CANDU versions of the HWR respectively (see Section 3.3).

The dose commitments associated with the first pass of activity are assumed to be received within the period of the discharge. The dose commitments from the global circulation of activity have, in the cases of krypton-85 and tritium, been integrated essentially to infinity, although by far the major contributions arise within 30 years; in the case of carbon-14, due to its very long half-life of 5730 years, consideration has been given to the 30 year, 500 year and infinite dose commitments. The variation with time of the dose rate and dose commitment arising from the global circulation of carbon-14, discharged as a result of unit energy generation, is shown in Figure 25. The dose commitment in the first 30 years can be seen to be significantly greater than that in subsequent 30 year periods; an extension, to 500 years, of the time over which the dose commitments is integrated only results in a doubling of the initial 30 year value. While it is open to question as to whether it is sufficient to assess the significance of carbon-14 discharges on the basis of a 30 year

as opposed to the infinite dose commitment, in the remainder of this study attention is directed solely toward the 30 year value unless otherwise specified. The 30 year dose commitment is only moderately sensitive to the transfer coefficients adopted for the evaluation of the global circulation; a factor of about 2 encompasses its variation as a result of variation of the transfer coefficients within the bounds indicated in the literature.

The relative significance of the nuclides discharged can be assessed from Figure 24. In terms of global circulation comparable dose commitments result from krypton-85 and carbon-14 discharges, that associated with tritium being an order of magnitude lower. The situation is reversed in the case of the first pass of activity where the dose commitment from tritium discharge is an order of magnitude greater than those associated with either krypton-85 or carbon-14, the dose commitment from these last two nuclides again being comparable. It should be stressed that these comparisons are appropriate to mean discharge rates of the nuclides concerned from an installed nuclear programme comprising a variety of reactor types; the relative significance of the various nuclides may vary considerably if consideration is restricted to discharges from a specific reactor type.

While the relative significance of the various nuclides discharged can be adequately assessed from Figure 24, further consideration needs to be given to the respective magnitudes of the exposed populations to enable the relative significance of the dose commitments from the first pass and global circulation of discharged activity to be determined. In Table 8 the collective gonad dose commitments to the population of the European Community are given for each nuclide with the first pass and global circulation contributions indicated separately. The collective dose commitments are appropriate to the discharges of activity associated with unit energy generation; two distinct cases have been evaluated and they correspond to the collective dose commitment to the population of the European Community associated with unit energy generation in the European Community itself and with unit energy generation in the world as a whole, the distribution of energy generation in the latter case between the European Community and the rest of the world being on a pro-rata basis of installed nuclear capacity. The collective dose commitment from the first pass of activity, unlike that from global circulation, will obviously be

very dependent on the population distribution surrounding the discharge point. The population distribution of the Community in relation to the fuel reprocessing plant at Windscale (UK) has been adopted as the basis for evaluating the collective dose commitments from the first pass of discharged activity. While this population distribution is probably not untypical of that associated with the only other commerical fuel reprocessing plant in existence in Europe at this time (Cap de la Hague in France), consideration of the discharges from a site characterised by a radically different population distribution would necessitate a revision of the first pass collective dose commitments given in Table 8. The first pass collective dose commitments have been integrated out to a distance of 1000 km; the disregard of doses at greater distances is not significant in the context of collective dose commitment to the population of the European Community. The qualifications expounded earlier regarding the dose commitments given in Figure 24, such as the first pass dose commitments being based solely on airborne discharges, etc, apply equally to the collective dose commitments given in Table 8 and reference should be made to these qualifications.

If consideration is given to the collective dose commitment to the population of the European Community from activity discharged as a result of unit nuclear energy generation in the Community itself, the first pass of tritium, discharged as tritiated water in airborne effluent, can be seen in Table 8 to make the greatest contribution to the total collective dose commitment; its contribution amounts to about 70% of the total. In the context of the collective dose commitment to the population of the European Community as a result of unit nuclear energy generation in the world as a whole, the relative significance of the first pass of tritium is somewhat reduced. In this case the contribution from tritium amounts to about 40% of the total collective dose commitment and is essentially comparable with those contributions resulting from the global circulation of krypton-85 and carbon-14. The collective dose commitments from krypton-85 can be seen in Table 8 to be comparable with those from carbon-14, irrespective of whether consideration is given to unit energy generation in the Community itself or in the world as a whole. Consideration of tritium discharge in liquid effluents would, in those specific cases where the discharge was made to a water body used as a major drinking water supply, result in an increase in the relative significance of

tritium above that indicated in Table 8. A value of 5 man-rad/GW(th)y can be regarded as illustrative of the increase in the first pass collect- ive dose commitment associated with such discharges; the value has been derived from predictions of the tritium concentration in the Rhine resulting from reactor discharges (41) and an assumed population of 10 million people deriving their total water intake via the Rhine. The tritium concentrations in reference 41 are based solely on discharges from reactors (LWRs in particular); if tritium liberated during fuel reproces- sing were also discharged to the Rhine the collective dose commitment given above would be increased by about an order of magnitude. It should be noted that the collective dose commitments given above from tritium in liquid effluent are specific to unit energy generation in which a discharge is actually made to a water body used as a major supply of drinking water, such as the Rhine or the Meuse etc; the contributions to the collective dose commitment in terms of an average unit of energy generation in the Community would be smaller, the exact magnitude depending on the fraction of the installed nuclear capacity discharging tritium to such water courses.

The total collective dose commitments to the population of the European Community from the discharges of the three nuclides considered amount to about 15 and 5 man-rad/GW(th)y in the respective cases of unit energy generated in the Community itself and in the world as a whole. Taking account of the respective magnitudes of the world and Community nuclear power programmes (a ratio of 5:1) approximately equal contributions to the collective dose commitment to the population of the Community arise from discharges from within the Community itself and from discharges from elsewhere in the world. The important conclusion to be drawn from this near equality of the respective contributions is the very limited impact that would result from unilateral action within the Community to reduce the discharges of krypton-85, carbon-14 and tritium; a factor of 2 represents the maximum reduction achievable from such an action, and is a consequence of the global circulation of activity discharged from else- where in the world. If attention were, however, to be directed towards the reduction of the collective dose commitment to the population of the Community from Community discharges, the most profitable target for dis- charge reduction would appear to be tritium. A reduction in the tritium discharges by an order of magnitude would however, only result in a reduc-

tion in the collective dose commitment to the population of the Community
from the Community discharges by a factor of about 2.5. A somewhat greater
reduction factor may be appropriate to particular regional areas of the
Community where, by virtue of the reactor type installed (particularly in
the case of HWRs - see Table 3), greater than average tritium discharge
rates are associated with unit energy generation. The small reduction
factor indicated above demonstrates that the simultaneous reduction of the
discharges of all three nuclides would be required to achieve a significant
overall reduction. As previously noted, however, even this latter course
of action would have little virtue as an unilateral act.

It is pertinent to consider finally the relative significance of the
various nuclides in the world as opposed to the more restrictive European
Community context. Population dose commitments are given in Table 9
appropriate to unit generation of nuclear energy in the world. The values
are somewhat approximate, the first pass population dose commitment being
evaluated on the assumption that the population distribution surrounding
all discharge locations in the world is equivalent to that of the European
Community in relation to the fuel reprocessing plant at Windscale, and
further the population dose commitments from global circulation being
based on the whole world population receiving doses appropriate to the
$35-60^{\circ}$N latitude band. The contributions made by the global circulation
of activity are of greater significance in the world context due to the
much greater population exposed. The values in Table 9 indicate that
comparable contributions to the total population dose commitment are made
by each of krypton-85, carbon-14 and tritium, and further demonstrate that
the overall impact of these nuclides can only be reduced by concurrent
reduction of the discharges of all three.

It should be noted that the collective dose commitments given in
Tables 8 and 9 are appropriate to the average discharge rate of each of
the nuclides from a reactor programme comprising a variety of reactor
types. If consideration were given to unit nuclear energy generation in
specific reactor types similar changes to those predicted in the case of
dose commitment would occur in the collective dose commitments given in
Tables 8 and 9. Reference should be made to the earlier discussion of the
sensitivity of dose commitment to reactor type in which the reactor types
of significance in this respect are identified.

6. <u>Comparison of the doses from the discharge of krypton-85, tritium,</u>
<u>carbon-14 and iodine-129 with those from other routes of exposure</u>

Of the four nuclides considered, two of them exist naturally in the
environment in relatively significant quantities, being produced in the
interactions of the cosmic ray flux with the earth's atmosphere, and all
four are present artificially due to the atmospheric testing of nuclear
weapons. Prior to comparison with other routes of exposure it is relevant
to compare the magnitude of the discharges from the nuclear power industry
with the levels of these nuclides already existing in the environment.

6.1 <u>Comparison of the magnitudes of krypton-85, tritium, carbon-14 and</u>
<u>iodine-129 in the environment from nuclear power discharges with those</u>
<u>from natural processes and atmospheric testing of nuclear weapons</u>

Neither krypton-85 nor iodine-129 are produced in significant quanti-
ties by natural processes and their presence in the environment is a con-
sequence of weapons testing and discharges associated with the generation
of nuclear energy ('nuclear power' discharges). The total generation of
these nuclides from nuclear weapons ('bomb') testing has been estimated to
be about 3 MCi and 12 Ci respectively (36, 58), values which are only of
the same order of magnitude as the annual discharges of these nuclides from
the predicted European Community nuclear power programme from 1975. Their
levels in the environment will therefore be determined by the magnitude of
nuclear power discharges.

Carbon-14 exists in the environment both naturally and artificially.
The inventories in the troposphere and terrestrial biosphere of the North-
ern Hemisphere of natural and bomb carbon-14 are compared in Figure 26 with
the predicted inventory of carbon-14 from the nuclear power industry up to
the year 2000. The natural inventory is based on a specific activity of
carbon-14 in the biosphere, based on 19th Century wood, of 6.13 pCi/gC
(36). The variation with time of the bomb inventory has been derived
using the global circulation model outlined in Figure 16 assuming the
total bomb production of carbon-14, of 6.2 MCi (61), to have been dis-
charged to atmosphere in the year 1961. The gonad dose rates associated
with the various inventories are also compared in Figure 26; it should be
noted that the dose rate from nuclear power discharges refers to the
latitude band 35-60°N, whereas the other dose rates apply to the whole
of the Northern Hemisphere.

While the gonad dose rate from natural carbon-14 remains at its
equilibrium level, that from bomb carbon-14, despite the very long radio-
active half-life of carbon-14, falls fairly rapidly due to transfer among
the various compartments shown in Figure 16. By the year 2000 the dose
rate from nuclear power carbon-14 is comparable with that from bomb
carbon-14 and amounts to approximately 3% of the gonad dose rate of about
0.6 mrad/y associated with natural carbon-14. The significance of the
nuclear power discharges to the year 2000 is, therefore, small in relation
to the natural level of carbon-14 in the environment. Furthermore it
should be noted that the expanding rate of burning fossil fuels, which
are essentially free of carbon-14, is resulting in an increased inventory
of stable carbon in the atmosphere. This will result in a reduction in
the isotopic concentration (g carbon-14/g carbon) of natural carbon-14 in
the atmosphere and biosphere and consequently a pro-rata reduction in the
dose rate from natural carbon-14. Estimates of the decrease in the
isotopic concentration of carbon-14 as a result of this process are of the
order of up to 10% (56) by the year 2000. This predicted decrease in the
dose rate from natural carbon-14 is likely to more than compensate for any
contribution to the dose rate from nuclear power carbon-14 prior to the
year 2000. Adopting the most pessimistic assumptions with regard to
carbon-14 discharge rates and transfer coefficients in the environment, it
is difficult to envisage dose rates in the year 2000 from nuclear power
carbon-14 being more than a factor of 4 greater than those given in
Figure 26; even on this basis the dose rate still represents only about
12% of that resulting from natural carbon-14, and moreover is still com-
parable with the predicted decrease in the dose rate from natural carbon-14
by the year 2000.

Tritium exists in the environment both naturally and artificially and
the inventory of, and gonad dose rates from, natural, bomb and nuclear
power tritium in the circulating waters of the Northern Hemisphere up to
the year 2000 are given in Figure 27. The natural (18, 36, 63) and bomb
(18, 36, 62) inventories, and associated dose rates, are denoted by a
range of values in Figure 27. This is a reflection of the uncertainty in
the values and of the various values quoted in the literature. The varia-
tion of the inventory of bomb tritium with time was evaluated using the
model outlined in Figure 12 for global circulation of tritium; loss of
tritium from the circulating waters occurs by radioactive decay and

transfer to the deep oceans. Conversion of the natural and the bomb tritium inventory to dose rate is complicated by the apparent exponential variation of tritium concentration with latitude (63). The dose rates given for bomb and natural tritium in Figure 27 are based on an assumed uniform concentration in the circulating waters of the Northern Hemisphere and are probably typical of the dose rates in the mid-latitude bands, the region of current interest. The degree of uncertainty associated with the tritium inventory deriving from the nuclear power discharges is likely to be significantly lower than that associated with the natural and bomb inventories; on the assumption of the continued application of current waste management practices the uncertainty is solely a consequence of the generation rate of nuclear energy. A somewhat greater range of uncertainty will be associated with the corresponding dose rates owing to their derivation being based on a relatively simple model which assumes uniform dispersion of the tritium in the circulating waters, no account being taken of local variations.

The dose rate from the global circulation of tritium discharged from the nuclear power industry is predicted to become comparable with that from natural tritium at some time in the 1980s. The dose rate is nevertheless extremely small, amounting to only about 1 μrad/y by the year 2000. Regional dose rates from the first pass of the discharged tritium are, however of greater significance, typical dose rates being in the range of one to two orders of magnitude greater than that arising via global circulation.

6.2 Comparison of the doses with other routes of exposure

The average gonad dose rates to an assumed regional group in the European Community from the first pass, and to the whole European Community population from the global circulation, of the four nuclides considered are compared in Table 10 with average gonad dose rates from other routes of exposure. Separate consideration is given to irradiation by internal and external routes, carbon-14 and tritium contributing to the former and krypton-85 to the latter. The average gonad dose rates from the other routes of exposure have been taken from reference 64 and while they apply to the UK they have been assumed to be representative of the situation in the whole of the European Community. Two points regarding the comparison require further comment. The first concerns the temporal disparity in the comparison, the dose rates from the other routes being essentially current

values, while those appropriate to the discharged nuclides are for future
times. However as the total dose rate from other routes of exposure is
dominated by the contribution from the natural background, which is
essentially constant with time, the overall comparison remains valid. The
second point refers to the somewhat arbitrary nature of the quoted average
gonad dose rate to the regional group. The regional group was chosen for
illustrative purposes and is assumed to comprise individuals within 1000 km
of the representative reprocessing plant, the average dose rate to the
group being taken as appropriate to a distance of 250 km.

Inspection of Table 10 indicates that the average gonad dose rates to
the population of the European Community by the year 2000 from the dis-
charges of krypton-85, tritium, carbon-14 and iodine-129, from the world
nuclear power programme will represent small fractions of the total dose
rates from other routes of exposure, particularly natural background.
Moreover they will even represent small fractions of the variation in the
natural background dose rate with geographical location in the European
Community. This comparison further demonstrates the marginal significance
of the discharge of these nuclides prior to the year 2000.

The significance of the doses in the year 2000 can be further assessed
by comparison with possible occupational doses resulting from the envisaged
nuclear power programme. Only limited data exist on the occupational doses
associated with the overall nuclear fuel cycle, particularly with regard to
the contribution from fuel reprocessing. UNSCEAR (36) have reviewed the
available information which indicated occupational doses of 2.3 man-rad/
MW(e)y (equivalent to about 800 man-rad/GW(th)y), with some 70% and 30%
arising from fuel reprocessing and reactor operation respectively. Assuming
current practice to continue to the end of the century the average gonad
dose rate to the population of the European Community from occupational
exposure would reach approximately 5 mrad/y in the year 2000 (commensurate
with an installed capacity of about 720 GW(e) in the European Community).
While this value is probably much larger than will arise in practice, due
to the introduction of improved technology and practice prior to the year
2000, it indicates that effort would be more profitably spent in reducing
occupational doses than in reducing the discharges of the nuclides con-
sidered in this report.

7. Possible impact of future waste management practices

Although the dose rates predicted up to the year 2000 from the dis-
charges of the four nuclides considered have been shown to be small, both
in relation to the ICRP recommended dose limits (1) and the exposure via
other routes, considerable effort is being devoted throughout the world
to the development of procedures to reduce these discharges. The develop-
ment and evaluation of the performance and costs of such procedures are,
to a certain extent, a reflection of the ICRP recommendation to keep doses
as low as reasonably achievable, economic and social factors being taken
into account (2).

The discharges of krypton-85, tritium and iodine-129 occur primarily
at reprocessing plants. Typical overall reduction factors that might be
achieved by the reduction of the discharges from these plants alone are
about 10 for krypton-85 and 10^2 - 10^3 for iodine-129. In the case of
tritium about 10% (averaged over the reactor type distribution adopted in
this study) of the total discharge arises at reactors and the overall
reduction factor might therefore be about ten. Consideration will need
to be given to the simultaneous reduction of tritium discharges from both
reactors and reprocessing plants to achieve a significant reduction of
tritium discharges in some regional areas; this is particularly the case
for a regional nuclear programme comprising predominantly HWRs where the
discharge from the reactors may be comparable with or even greater than
that from fuel reprocessing. Carbon-14 is discharged in comparable quanti-
ties from both reactors and reprocessing plants. A significant reduction
in the overall level of carbon-14 discharges will therefore only be achie-
ved by the implementation of procedures at both types of installation.

Several methods have been suggested for the reduction of krypton-85
discharges, although at present only cryogenic distillation, selective
adsorption processes and cryogenic adsorption appear suitable for appli-
cation at reprocessing plants; the first two processes are the most pro-
mising (65, 66). Krypton-85 removed from the off-gas streams at reproces-
sing plants by such processes can be recovered and allowed to decay in
engineered storage. At present there is insufficient information to
assess the economic or technical feasibility of retaining tritium at repro-
cessing plants, although several processes have been considered (66). A
process appearing to have potential however is "voloxidation" (67, 68);
this involves the driving off of volatile fission products from the fuel

into a stream of air or oxygen, prior to fuel dissolution, so that these fission products can be collected in a relatively small volume and in a form suitable for isolation from the environment. Reduction of iodine-129 discharges can be achieved by a variety of processes either in isolation or in conjunction with each other, depending on the form of the iodine and decontamination factor required. Typical processes include wet collection/aqueous scrubbing, adsorption on charcoal and silver zeolite metallic filters and filtration. Little attention has yet been given to the measurement of carbon-14 discharges or to procedures for their reduction. Such a reduction may require the application of different procedures at reactors and reprocessing plants; procedures may also vary with reactor type. The chemical forms of carbon-14 discharged from LWRs are important in the latter context. In BWRs the chemical form is mainly carbon dioxide and monoxide while in PWRs it is primarily (>80%) hydrocarbons (20, 21). The long term isolation of carbon-14, which may be removed from the effluent streams at reactors and reprocessing plants, has also received little attention, although its incorporation into stable carbonates followed by ultimate disposal appears to be a feasible approach.

The timescale of the implementation of such procedures to the control of the discharges of the four nuclides on a world-wide basis cannot be predicted with any degree of confidence. In the United States the Environmental Protection Agency (EPA) has recently issued proposed standards for the uranium fuel cycle (69, 70) which included, among others, limits for the discharge to the "general environment" of krypton-85 and iodine-129 of 50,000 Ci and 5 mCi respectively for each gigawatt-year of electrical energy generated. These values are equivalent to discharge limits of about 17,000 Ci/GW(th)y and 1.7 mCi/GW(th)y respectively on the basis of a 33% conversion efficiency from thermal to electrical energy. These limits are based on cost-effectiveness arguments and thus correspond to the ICRP recommendation to keep doses as low as reasonably achievable (2). No standards are proposed for carbon-14 or tritium, inadequate information being available to assess the practicability of limiting such discharges; it was indicated however that as further information becomes available consideration would be given to the development of standards for these nuclides. The proposed standards for krypton-85 and iodine-129 are intended for application by 1983. The discharge limits are factors of about 6 and 200 lower for krypton-85 and iodine-129 respectively than

discharges typical of current practice.

The dose rates predicted in this report for the year 2000 from the global circulation of krypton-85 and iodine-129 would be reduced by about 30 - 40% (the magnitude of the USA nuclear programme in relation to the world programme) if these standards are implemented in the USA.

The probability that similar standards will be applied elsewhere in the world cannot be readily assessed although their application in the USA is likely to have some influence on practices adopted elsewhere. In this context it would seem reasonable to conclude that the doses predicted in this report, at least for the latter part of this century are likely to represent upper limits and in some cases represent considerable over-estimates.

8.   Summary and conclusions

The discharges of krypton-85, tritium, carbon-14 and iodine-129 are considered to comprise the most likely long-term sources of irradiation of both regional and world populations. This is because of their relatively long half-lives, their fairly rapid and widespread dispersion in the environment and the magnitude of their discharges based on the continued application of current waste management practices. The discharges of caesium-137 and plutonium may also be considered to fall into this category; these nuclides have however only received limited consideration in this report due to the intention to reduce the discharges from Windscale of the former (5) and because in both cases the discharge rates will be determined by local circumstances.

The predicted discharges up to the year 2000 of krypton-85, tritium, carbon-14 and iodine-129 to the environment have been shown to be of low radiological significance. Both the dose rates to individuals in the European Community and the exposure of the Community population as a whole by the year 2000 represent small fractions of the appropriate ICRP recommended dose limits; the dose rate to the most exposed individuals, who will be few in number, amounts to a few percent of the individual dose limit and in the case of exposure of the population as a whole the average gonad dose rate is somewhat less than 0.05% of the ICRP genetic dose limit. Dose rates in the years 1985 and 1975 are typically factors of about 5 and 30 respectively lower than those appropriate to the year 2000; values predicted for 1975 however are likely to be significant overestimates. This is because the installed reactor capacity is lower than expected and the discharge rates of the four nuclides are considerably lower than predicted owing to the long time delays between fuel irradiation and subsequent reprocessing. The long time delays are a result of the limited fuel reprocessing capacity currently available in the world.

The exposure of the population of the Community from these discharges up to the year 2000 also represents a small fraction of both the exposure from natural background radiation and the exposure via other routes such as medical irradiation. Of the four nuclides considered tritium and carbon-14 already exist in the environment in significant quantities, both naturally due to the interaction of the cosmic ray flux with the atmosphere and artificially due to the atmospheric testing of nuclear weapons. The inventory in the environment of tritium discharged from the nuclear power

industry is likely to become comparable with the natural inventory around the year 1990; that of carbon-14 from the same source, even by the year 2000, is unlikely to exceed more than a few percent of the natural carbon-14 inventory. Furthermore this small increase in the carbon-14 inventory is likely to be more than compensated for by the increasing inventory of stable carbon-12 in the environment arising from the increasing rate of burning fossil fuels which are essentially free of carbon-14; as a result the exposure of the population of the Community from carbon-14 may, despite the nuclear power discharges, be lower in the year 2000 than at present.

The discharges of krypton-85, tritium and carbon-14 are, within the range of uncertainty inherent in the evaluation of the dose rates from each nuclide, of comparable significance with regard to the gonad exposure of both the European Community and world populations. If attention is restricted to the exposure of the population of the Community solely from the Community discharges then tritium is marginally of greatest signifi- cance. The exposure via tritium arises predominantly during the first pass of discharged activity, whereas that from krypton-85 and carbon-14 results mainly from their global circulation in the atmosphere. The collective gonad dose commitments (integrated over a 30 year period) to the Community population from the discharges of these nuclides associated with unit nuclear energy generation in the Community alone and in the world as a whole are about 15 and 5 man-rad/GW(th)y respectively. In the broader context the collective gonad dose commitment to the world popula- tion from these discharges amounts to about 45 man-rad/GW(th)y.

The assessment of the implications of carbon-14 discharges is in some respects one of the most uncertain features of this current study, being based largely on theoretical predictions of generation and discharge rates from a variety of nuclear installations. While the predicted generation rates of carbon-14 are considered realistic, an increased programme of measuring carbon-14 discharges from both reactors and reprocessing plants would be of benefit in enabling a more definitive assessment to be made of the significance of this nuclide. Of particular importance in this respect are the discharges from HWRs which, on the basis of preliminary estimates, may be considerably in excess of those from other reactor types.

The evaluation of representative doses to the population of the

Community from the first pass of activity discharged into the aqueous
environment has received only limited consideration in this report due to
its marked dependence on the nature and use made of the water body to which
the discharge is made. The discharges to sea of tritium and iodine-129
will be of very low radiological significance in this respect; those to
inland waters may be of much greater significance particularly where
the water is subsequently used for drinking or irrigation purposes.
Typical of water bodies of the latter type in the Community are the Rhine
and the Meuse. An assessment of tritium discharges to the Rhine from
reactors installed in the Rhine basin has indicated that the use, in the
Netherlands, of the Rhine as a sole source of water intake would result
in individual gonad dose rates in the year 2000 of about 0.14 mrad/y (41).
The assessment is based solely on the discharges from reactors; dose
rates of more than an order of magnitude greater would result if tritium
released during the reprocessing of fuel from the same reactor capacity
were also discharged to the Rhine. Such discharges however would seem
unlikely since other disposal routes having a lower radiological signifi-
cance are probably available.

Considerable effort is being directed throughout the world to the
development of procedures to reduce the discharges of the nuclides
presently considered, thus reflecting, to a certain extent, the ICRP
recommendation to keep doses as low as reasonably achievable. The time-
scale of the implementation of such procedures on a worldwide basis cannot
be predicted with any degree of confidence. It is pertinent to note,
however, that the United States Environmental Protection Agency (EPA) has
recently issued proposed limits, intended for application in the USA by
1983, for the discharges of krypton-85 and iodine-129 associated with unit
nuclear energy generation (69); these limits are lower than current dis-
charge rates by factors of about 6 and 200 respectively. Consideration is
also being given to the development of standards for carbon-14 and tritium.
The application of the proposed standards in the USA, and the influence
this may have on practice elsewhere in the world, will result in the dose
rates predicted in this report, at least for the latter part of this
century, being overestimates.

Two points are worthy of particular note in the context of reducing
the discharges of these nuclides in the European Community. Unilateral
action by the Community to reduce these discharges would have only very

limited impact in terms of gonad exposure of the Community population; a
factor of 2 represents the upper limit to the exposure reduction achievable,
a consequence of the exposure from the global circulation of activity dis-
charged elsewhere in the world. The second point arises from the compar-
able significance of the discharges of krypton-85, tritium and carbon-14
which indicates that only limited benefit would ensue from reducing the
discharges of any one nuclide, simultaneous reduction in all three being
necessary to achieve a significant overall reduction in the exposure. The
above considerations apply to the reduction of the exposure of the Commun-
ity population as a whole. Somewhat greater reduction factors may be
achieved in some regional areas within the Community where, by nature of
the reactor type installed, greater than average discharge rates may be
associated with unit energy generation; of importance in this respect would
be a regional nuclear programme comprising mainly HWRs where both tritium
and possibly carbon-14 discharge rates may be significantly in excess of
the average values.

It is finally worth noting that the reduction of occupational
exposure, as opposed to the reduction of the discharges of the four
nuclides considered, may prove to be a more profitable approach to reducing
the genetically significant dose to the Community population resulting from
the application of nuclear power.

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Glossary

The curie (Ci) is the special unit of activity; one curie is numerically equal to $3.7 \cdot 10^{10}$ nuclear transformation per second.

The rad is the special unit of absorbed dose, equal to an absorbed energy of 10^{-2} joule per kilogram of tissue. Throughout this study doses are quoted in rads. For the nuclides considered here absorbed dose in rads and dose equivalent in rems are numerically equal.

Dose commitment:- In its most general form the dose commitment resulting from a specified procedure or operation is the integral over all time of the average dose rate to the exposed population resulting from the procedure. The concept is often used in a more restrictive sense by limiting the period of integration (e.g. a 30 year dose commitment).

Collective dose is the product of mean dose and the number of exposed people. The collective dose to the world population, as opposed to a regional or national population, is known as the population dose.

Collective dose commitment is the integration over time of the product of mean dose rate and number of exposed people. As in the case of dose commitment it can be used in the more restrictive sense by limiting the period of integration. If applied to the world population, as opposed to a regional or national population, it is known as the population dose commitment.

The critical group is that group representative of the more highly exposed individuals in the population and is as homogeneous as practicable with respect to radiation dose.

Somatic effects are those which become manifest in the exposed individual.

Genetic or hereditary effects are those which become manifest in future generations.

Genetically significant dose is the dose which, if received by every member of the population, would be expected to produce the same total genetic injury to the population as do the actual doses received by the various individuals.

Discharge of activity is used in the report to include activity that is conveyed intentionally to the environment as a result of a deliberate procedure, together with that which is unavoidably released via leakage etc.

<u>Rate</u> of discharge is used in the report in two distinct senses; these comprise the discharge rate per unit time and per unit energy generated.

TABLE 1

Thermal efficiencies of various reactor types (9)

Reactor	PWR	BWR	SGHWR	HWR	MAGNOX	AGR	HTR	FBR
Thermal Efficiency, %	33	34	32	29	30	42	40	40

PWR   -   Pressurised water reactor

BWR   -   Boiling water reactor

SGHWR   -   Steam generating heavy water reactor

HWR   -   Heavy water reactor

AGR   -   Advanced gas-cooled reactor

HTR   -   High temperature reactor

FBR   -   Fast breeder reactor

TABLE 2

Production rates of tritium in various reactor types

Reactor	Tritium production rate, Ci/GW(th)y		Major sources of activation product tritium
	via fission [a]	via activation [b]	
MAGNOX	$7 \ 10^3$	$1.9 \ 10^2$ [c]	Li - impurity in graphite moderator
AGR	$7 \ 10^3$	$1.9 \ 10^2$ (Ref 12) [d]	
PWR	$7 \ 10^3$	$3.3 \ 10^2$ (Ref 13)	B - dissolved in primary coolant
BWR	$7 \ 10^3$	5 (Ref 13)	D - impurity in light water coolant
HWR	$7 \ 10^3$	$2 \ 10^5$ (Ref 12,14)	D - heavy water moderator
HTR	$7 \ 10^3$	$1.4 \ 10^3$ (Ref 12,13)	He-3 - helium coolant Li - impurity in graphite moderator
FBR	$1 \ 10^4$	$< 7 \ 10^2$ (Ref 13)	B, Li - impurities in core and blanket fuel

Notes

a) Variation of the fission product tritium production rate with
    thermal reactor type for typical fuel irradiation cycles is small
    and a single value of $7 \ 10^3$ Ci/GW(th)y can be adopted for all
    thermal reactors (10,11). A slightly higher value is applicable
    to fast reactors (10,11).

b) No account has been taken of the tritium produced by the activa-
    tion of control rods as these do not contribute significantly to
    tritium discharges to the environment.

c) Activation product tritium generation rate in MAGNOX has been
    assumed to be equal to that in AGR.

d) Activation product tritium generation rate in AGR is a mean value
    averaged over the reactor life. In reality the generation rate
    is much larger initially and falls off with time due to the
    progressive burn-out of the lithium impurity.

TABLE 3

Discharge rates of tritium from reactors and reprocessing plants

Reactor	Tritium discharge rate, Ci/GW(th)y		
	At reactor [a]	At reprocessing plant [b]	Total
MAGNOX	$2.6 \ 10^2$	$6.9 \ 10^3$	$7.2 \ 10^3$
AGR	$1.9 \ 10^3$	$5.3 \ 10^3$	$7.2 \ 10^3$
PWR	$4 \ \ \ 10^2$	$6.9 \ 10^3$	$7.3 \ 10^3$
BWR	$7 \ \ \ 10^1$	$6.9 \ 10^3$	$7.0 \ 10^3$
HWR	$7 \ \ \ 10^3$ [c]	$6.9 \ 10^3$	$1.4 \ 10^4$
HTR	$< 3.4 \ 10^3$ [d]	$5 \ \ \ 10^3$	$< 8.4 \ 10^3$
FBR	$< 1 \ \ \ 10^4$ [d]	small [e]	$< 1 \ \ \ 10^4$

Notes

a) Comprises contributions from activation and fission product
    tritium, the latter by virtue of permeation through intact
    fuel cladding and leakage from failed fuel. The losses of
    fission product tritium from the fuel during reactor operation
    have been taken as 1% for MAGNOX, PWR, BWR and HWR (12,13);
    25% for AGR; 30% for HTR (15) and 100% for FBR (13). The
    following percentages of the total tritium discharged from
    reactors have been assumed to arise in airborne effluents: 10%
    for AGR (12); 1% for PWR (12); 10-50% for BWR (12,16); and 90%
    for the CANDU version of the HWR (17). The remainder in each
    case is assumed to appear in liquid effluent.

b) Discharge at reprocessing plant comprises that not lost from
    fuel during reactor operation. 25% and 75% of tritium through-
    put are assumed to be discharged in airborne and liquid
    effluent respectively.

c) Average value over reactor life and based on a heavy water
    moderator loss of 0.5% per year (12). Activation product
    tritium is major contributor to tritium discharges from HWRs.

d) Upper limits only are quoted owing to uncertainties as to
    efficiencies of coolant purification systems in removing
    tritium from the primary coolant.

e) A consequence of the assumption of essentially 100% of
    fission product tritium being released from the fuel during
    reactor operation.

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TABLE 4

Production of carbon-14 in nuclear reactors

Source of C-14		Carbon-14 production rates, Ci/GW(th)y [a]				
		MAGNOX	AGR	PWR	BWR	HTR [i]
Moderator	via C-13	25	40			7.0
	via O-17	–	–			–
	via N-14	39 [b]	62 [b]			10.9 [b]
	Total	64	102	– [g]	– [g]	18
Coolant	via C-13	– [c]	– [c]			–
	via O-17	0.6	0.6			–
	via N-14	0.7 [d]	2.4 [d]			–
	Total	0.9	3.0	2.0 [h]	5.3 [h]	–
Fuel	via O-17	–	1.5	0.9	0.9	0.8
	via N-14	26 [e]	5.9 [f]	3.6 [f]	3.6 [f]	3.3 [f]
	Total	26	7.4	4.5	4.5	4.1

Notes

a) All production rates are theoretical predictions other than
    for BWR and PWR coolants, these being derived from measured
    discharges (20,21).

b) Based on 10 ppm (by weight) N-14 impurity in graphite
    moderator (22,23).

c) Production via activation of C-13 negligible in comparison
    to that via activation of O-17 and N-14 (approximately 5%
    of that via O-17).

d) Based on 200 ppm (by volume) N-14 impurity in CO_2 coolant.

e) Based on 50 ppm (by weight) N-14 impurity in metal MAGNOX
    fuel (24).

f) Based on 20 ppm (by weight) N-14 impurity in oxide fuel (25).

g) Moderator and coolant synonymous in BWRs and PWRs; production
    rates have for convenience been assigned solely to the
    coolant.

h) Values based on measured discharge rates at PWRs and BWRs
    (20,21).

i) Values apply to prismatic style HTR; in pebble bed type
    values some three times greater may be expected.

TABLE 5

Predicted discharge rates of carbon-14 from nuclear reactors and reprocessing plants

Reactor	Predicted discharge rate of C-14 per unit energy generated, [a] Ci/GW(th)y		
	At the reactor	At the reprocessing plant [b]	Total
MAGNOX	2.5 [c]	2.6 [g]	5.1
AGR	5.6 [c]	0.7 [g]	6.3
PWR	2.0 [d]	0.5 [g]	2.5
BWR	5.3 [d]	0.5 [g]	5.8
HTR	0.9 [e]	21 [h]	22
HWR [f]	3.6 [f]	0.5 [f]	4.1 [f]

Notes

a) Discharge rates quoted are all theoretical predictions apart from those at PWR and BWR reactors which are measured values (20,21).

b) Discharge at reprocessing plants arises from C-14 content of the fuel and also in the case of HTR from the C-14 content of the graphite fuel element.

c) Discharges comprise the total C-14 produced in the CO_2 coolants together with that arising in the coolant as a result of graphite moderator corrosion (5% corrosion of moderator over 30 years reactor life assumed).

d) These discharge rates are measured values (20,21).

e) Discharge rate based on moderator/fuel element corrosion with accumulation of C-14 in helium coolant purification system, discharge to the environment assumed to result from regeneration of the purification system.

f) Discharge rates associated with HWR have been assumed in this study to be equal to the mean discharge rate from PWR and BWRs. Preliminary estimates have indicated that considerably greater discharge rates may be appropriate (see text).

g) Values based on 10% of the C-14 produced in the fuel being discharged, the remainder assumed to be isolated from the environment in other waste streams.

h) Based on reprocessing by grind-leach-burn process in which essentially 100% of the carbon content of the fuel element is burned and discharged as CO_2 (26).

TABLE 6

Summary of the rates adopted in this study for the discharge of
krypton-85, tritium, carbon-14 and iodine-129 associated
with unit energy generation in each of the reactor types

Reactor	Discharge rates, Ci/GW(th)y					
	Kr-85 a)	I-129 b)	H-3 c)		C-14 d)	
	at rep. plant	at rep. plant	at reactor	at rep. plant e,f)	at reactor	at rep. plant
MAGNOX	$1.1 \ 10^5$	0.3	$2.6 \ 10^2$	$7 \ 10^3$	2.5	2.6
AGR	$1.1 \ 10^5$	0.3	$1.9 \ 10^3$	$7 \ 10^3$	5.6	0.7
PWR	$1.1 \ 10^5$	0.3	$4 \ 10^2$	$7 \ 10^3$	2.0	0.5
BWR	$1.1 \ 10^5$	0.3	$7 \ 10^1$	$7 \ 10^3$	5.3	0.5
HWR	$1.1 \ 10^5$	0.3	$7 \ 10^3$	$7 \ 10^3$	3.6	0.5
HTR	$1.1 \ 10^5$	0.3	$< 3.4 \ 10^3$	$7 \ 10^3$	0.9	21
FBR	$8.4 \ 10^4$	0.3	$< 1 \ 10^4$	$1 \ 10^4$	-	-

Notes

a) Essentially 100% of the discharge occurs at the reprocessing plant, with little contribution at reactors. Discharge occurs in airborne effluent.

b) Discharge assumed to occur solely at reprocessing plants, with 75% and 1% of that produced in the fuel being discharged to sea and to atmosphere respectively. The value quoted refers to discharge to sea, a further $4 \ 10^{-3}$ Ci/GW(th)y is discharged in airborne effluent. The above values are representative of a coastal sited reprocessing plant. Different considerations may apply to an inland sited plant.

c) The distribution of the discharge between liquid and airborne effluent is summarised in Section 3.2 and Table 3.

d) The discharge is assumed to comprise solely CO_2.

e) Simplifying assumption has been made that discharge from reprocessing plant is equal to the production rate of fission product tritium (see Tables 2 and 3 and Section 3.2).

f) 75% and 25% of tritium discharged at reprocessing plant are in liquid and airborne effluent respectively. The above distribution among the two effluent streams is representative of a coastal sited reprocessing plant; different considerations would apply to an inland sited plant. Tritium discharged as liquid effluent will be in the form of tritiated water; that in the airborne effluent has been assumed, pessimistically, to comprise solely tritiated water.

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TABLE 7

Discharges of krypton-85, tritium and carbon-14 adopted in the evaluation of dose commitments associated with unit nuclear energy generated

Nuclide	Discharge, Ci/GW(th)y		
	Airborne [a]	Liquid	Total [b]
Kr-85 [c]	$1.1 \ 10^5$	-	$1.1 \ 10^5$
H-3 [d]	$1.8 \ 10^3$	$5.2 \ 10^3$	$7 \ 10^3$
C-14 [e]	4.0	-	4.0

Notes

a) Dose commitments from first pass of activity based solely on airborne discharges.

b) Dose commitments from global circulation of activity based on total discharges.

c) Values based on discharge from thermal reactors.

d) Values based on discharge of total fission product tritium produced in thermal reactor fuel, no account being taken of contribution from activation product tritium.

e) Value adopted is the mean discharge based on the distribution among the reactor types of the installed world nuclear capacity in the year 2000 (Figure 2).

TABLE 8

Collective dose commitments to the gonads of the European Community (EC) population from the discharge of krypton-85, tritium and carbon-14 associated with the generation of 1 GW(th)y of nuclear energy

Nuclide	Collective gonad dose commitment to the population of the EC, man-rad/GW(th)y [a]					
	Energy generated in EC			Energy generated in world		
	First pass	Global	Total	First pass	Global	Total
Kr-85	0.86	1.1	2.0	0.19	1.1	1.3
H-3	9.9	0.08	10	2.2	0.08	2.3
C-14	1.5	1.1 [b]	2.6	0.3	1.1 [b]	1.4
Total	12.3	2.3	14.6	2.7	2.3	5.0

Notes

a)   Population of European Community assumed constant at 1975 level.

b)   Applies to a 30 year collective dose commitment; infinite collective dose commitment is some 14 times greater.

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TABLE 9

Population gonad dose commitment from the discharge of

krypton-85, tritium and carbon-14 associated with the

generation of 1 GW(th)y of nuclear energy

Nuclide	Population gonad dose commitment, man-rad/GW(th)y a)		
	First pass	Global	Total
Kr-85	0.86	15	16
H-3	9.9	1.1	11
C-14	1.5	15 b)	16
Total	12	31	43

Notes

a) World population assumed constant at 1975 level.

b) Applies to 30 year population dose commitment; infinite population dose commitment is some 14 times greater.

TABLE 10

Comparison of gonad dose rates from other sources with those from the discharge of krypton-85, carbon-14, tritium and iodine-129

			Average gonad dose rate mrad/y		
			Internal	External	Total
Other routes of exposure a)	Natural background		21	66	87
	Medical irradiation		-	14	14
	Fallout		1.1 b)	1.1 b)	2.2
	Miscellaneous sources		0.6	0.1	0.7
	Occupational exposure		-	0.6	0.6
	Total other sources		22	82	104
Discharge of krypton-85, tritium, carbon-14 & iodine-129 from the world nuclear power programme	Average dose to regional group within EC from first pass of activity c)	(1985)	0.018	0.001	0.019
		(2000)	0.073	0.004	0.077
	Average dose to whole population of EC from global circulation of activity	(1985)	0.003	0.002	0.005
		(2000)	0.022	0.014	0.036

Notes

a) Values taken from reference 64 and are applicable to the UK population; they are assumed here to be representative of the whole of the European Community.

b) Division of dose rate associated with miscellaneous sources (eg, luminous devices) between internal and external irradiation is very approximate.

c) Average dose is to an assumed regional group within 1000 km of the representative reprocessing plant, (airborne discharges only). The first pass dose at a distance of 250 km has been adopted as the average dose to the regional group.
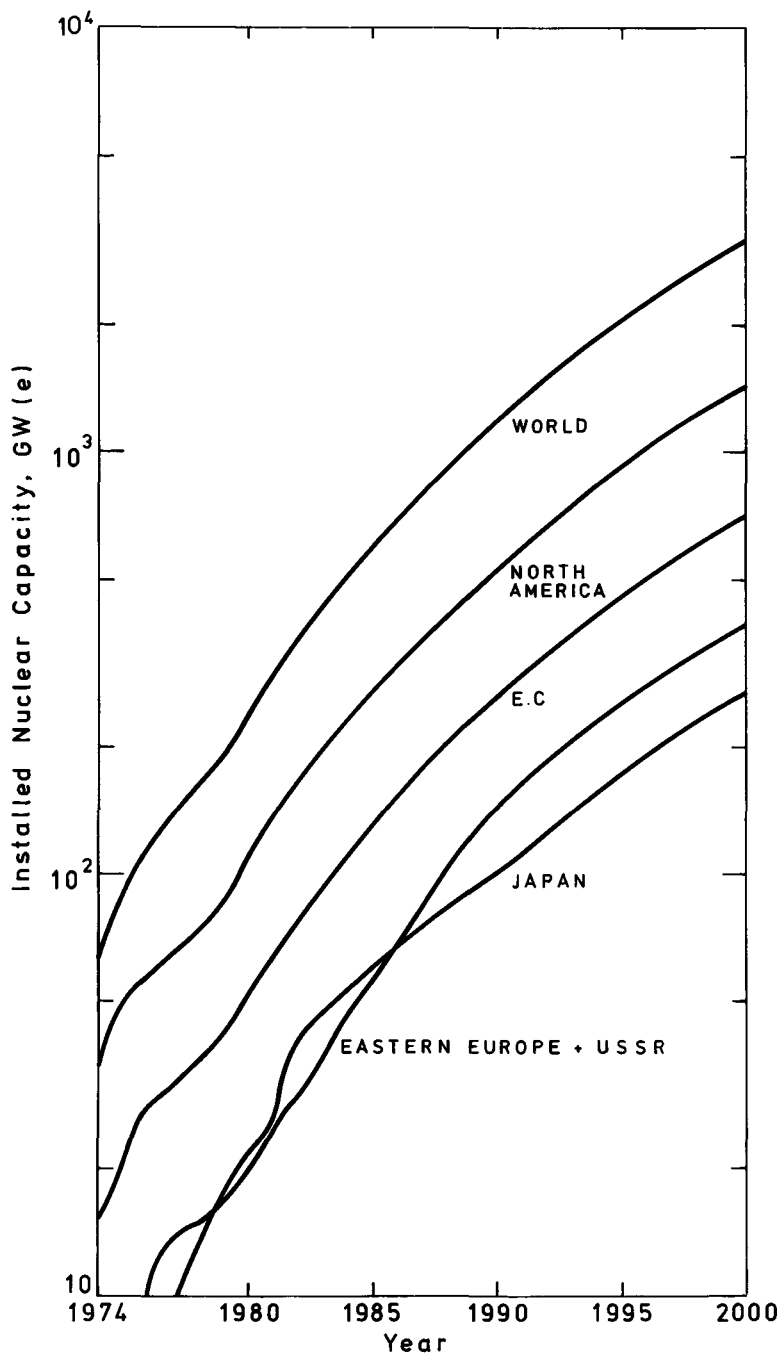
Figure 1

Predicted Nuclear Power Programmes to the Year 2000
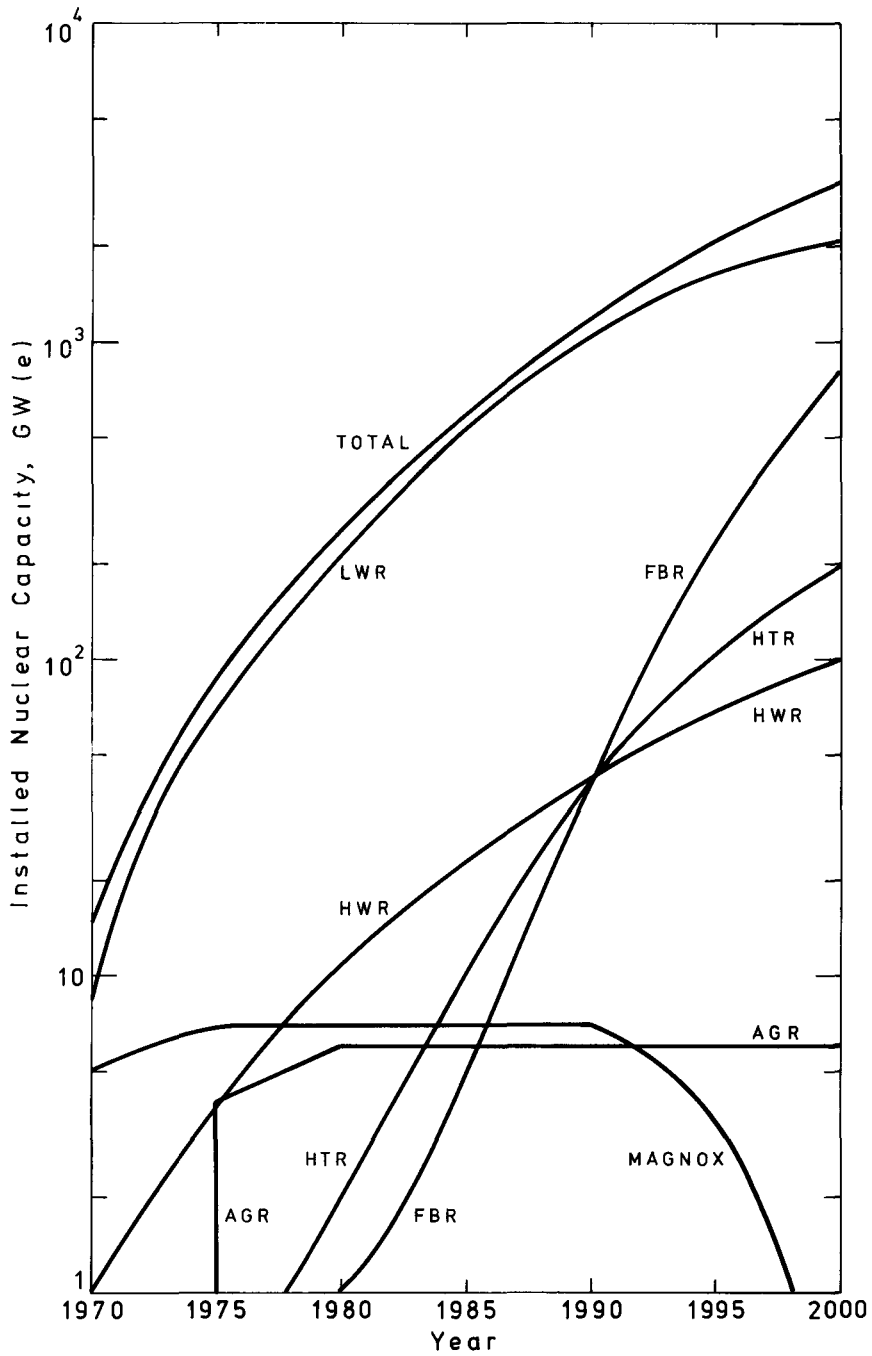
Figure 2
Distribution of the World Nuclear Power Programme
among the Various Reactor Types
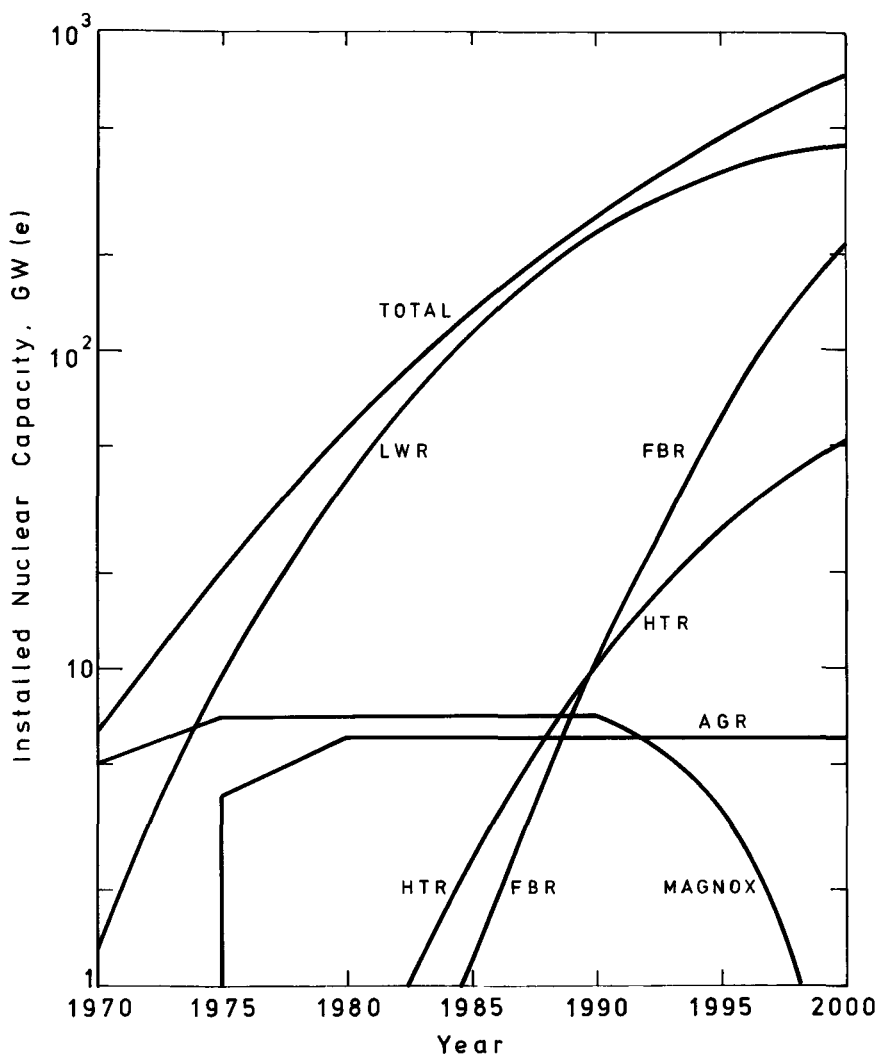
Figure 3
Distribution of the EC Nuclear Power Programme
among the Various Reactor Types
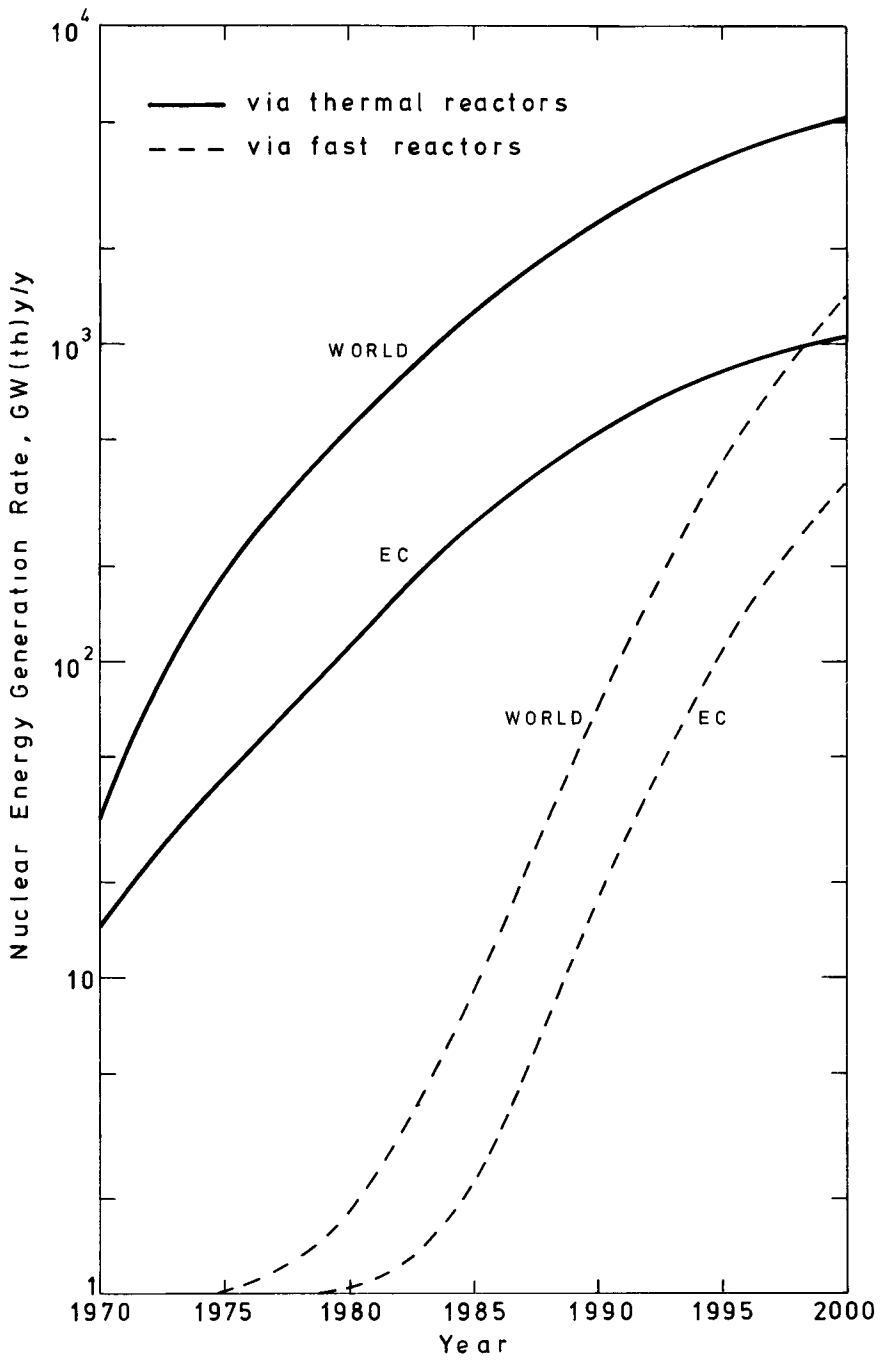
Figure 4

Predicted Generation Rate of Nuclear Energy in
the EC and in the World
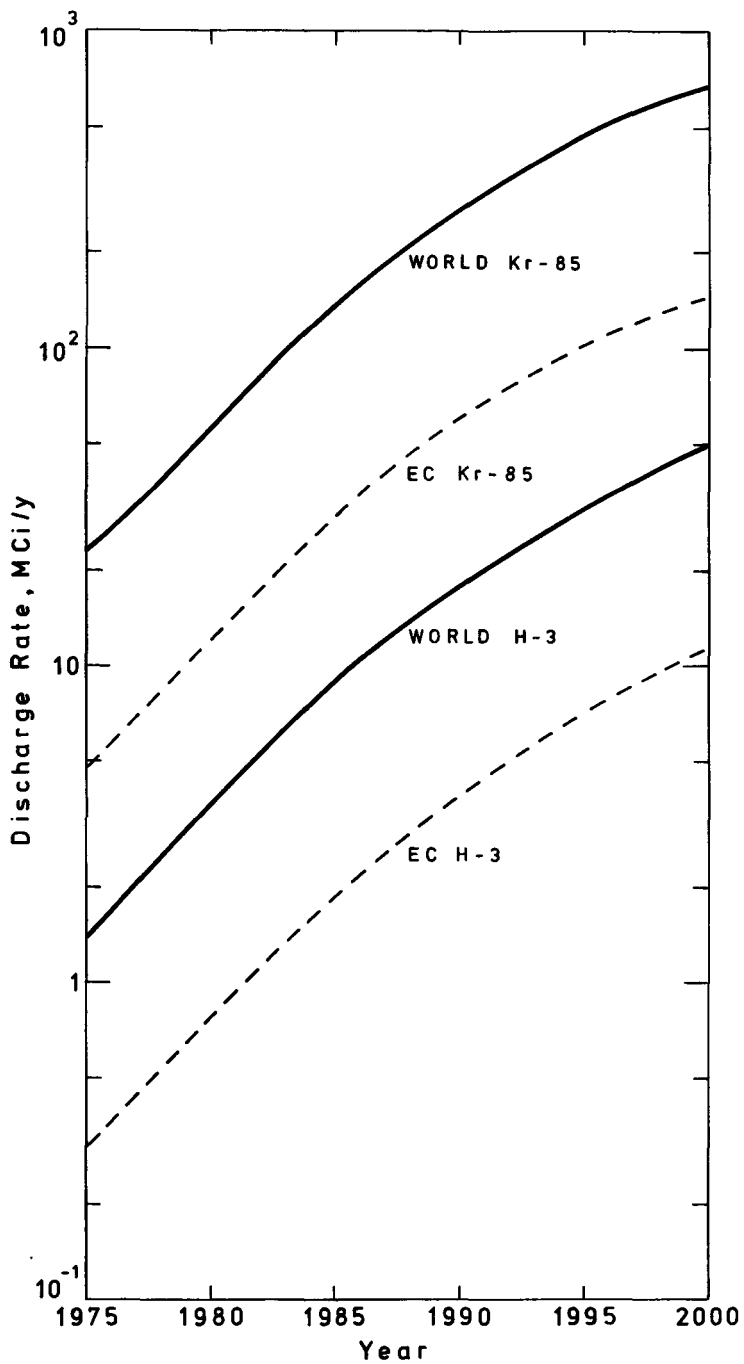
Figure 5
Predicted Discharge Rates of Kr-85 and H-3 from
the World and EC Nuclear Power Programmes
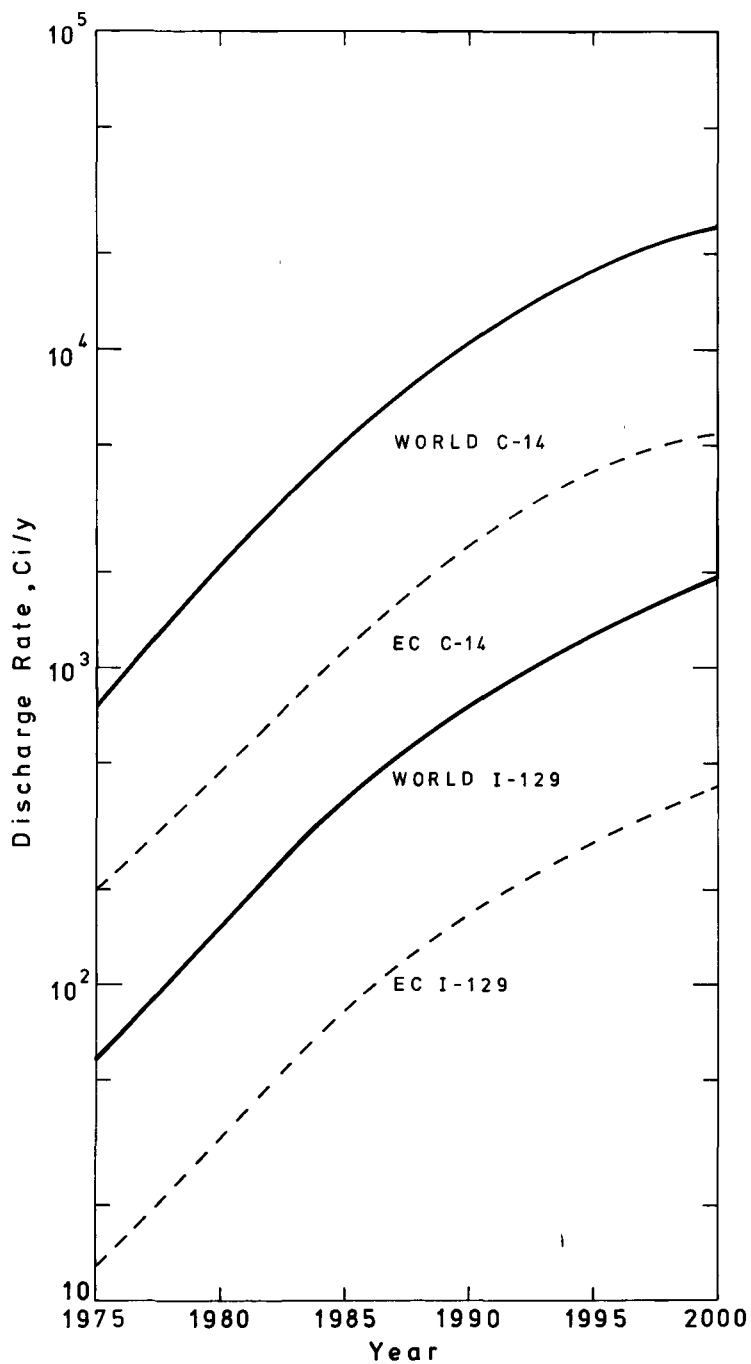
Figure 6
Predicted Discharge Rates of C-14 and I-129 from
the World and EC Nuclear Power Programmes
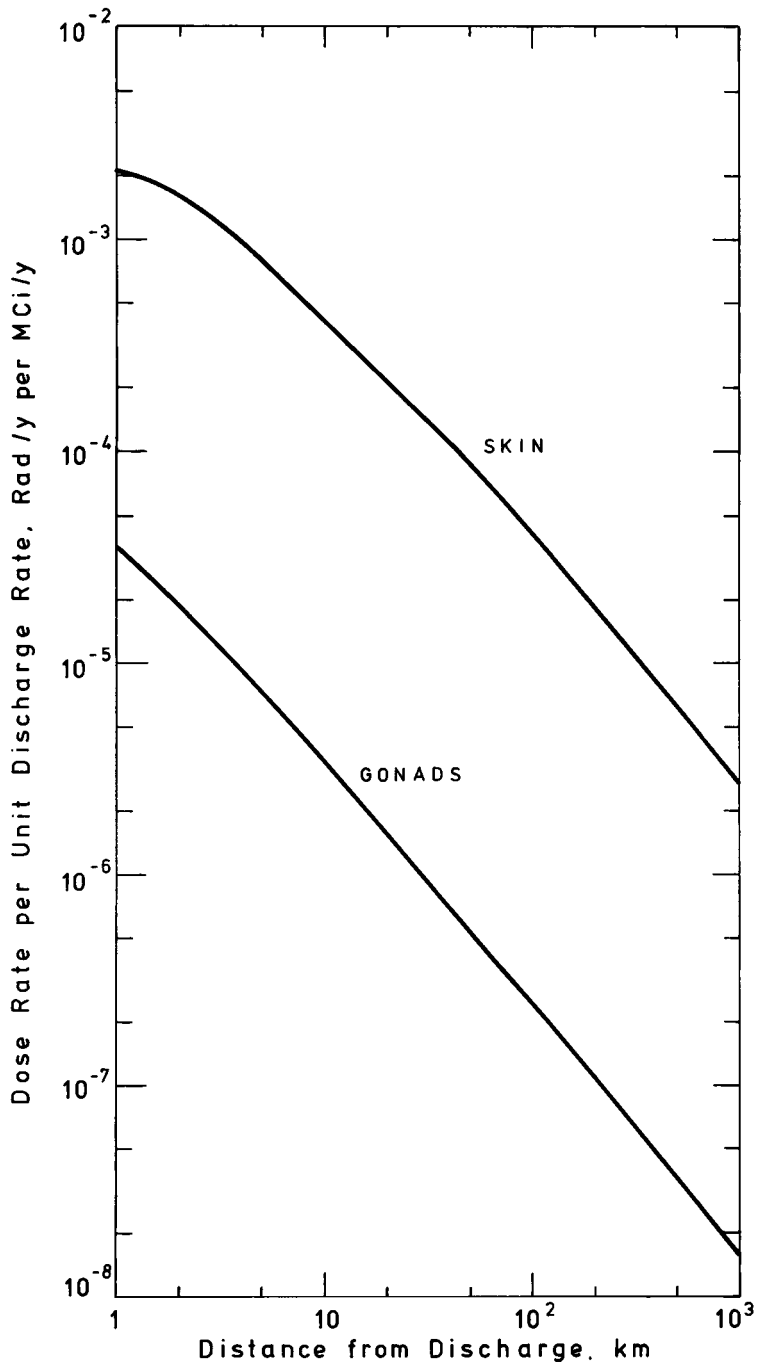
Figure 7

Dose Rates to the Skin and Gonads from the Discharge
of 1MCi/y of Kr-85 in Airborne Effluent from a Stack
of Height 100m.
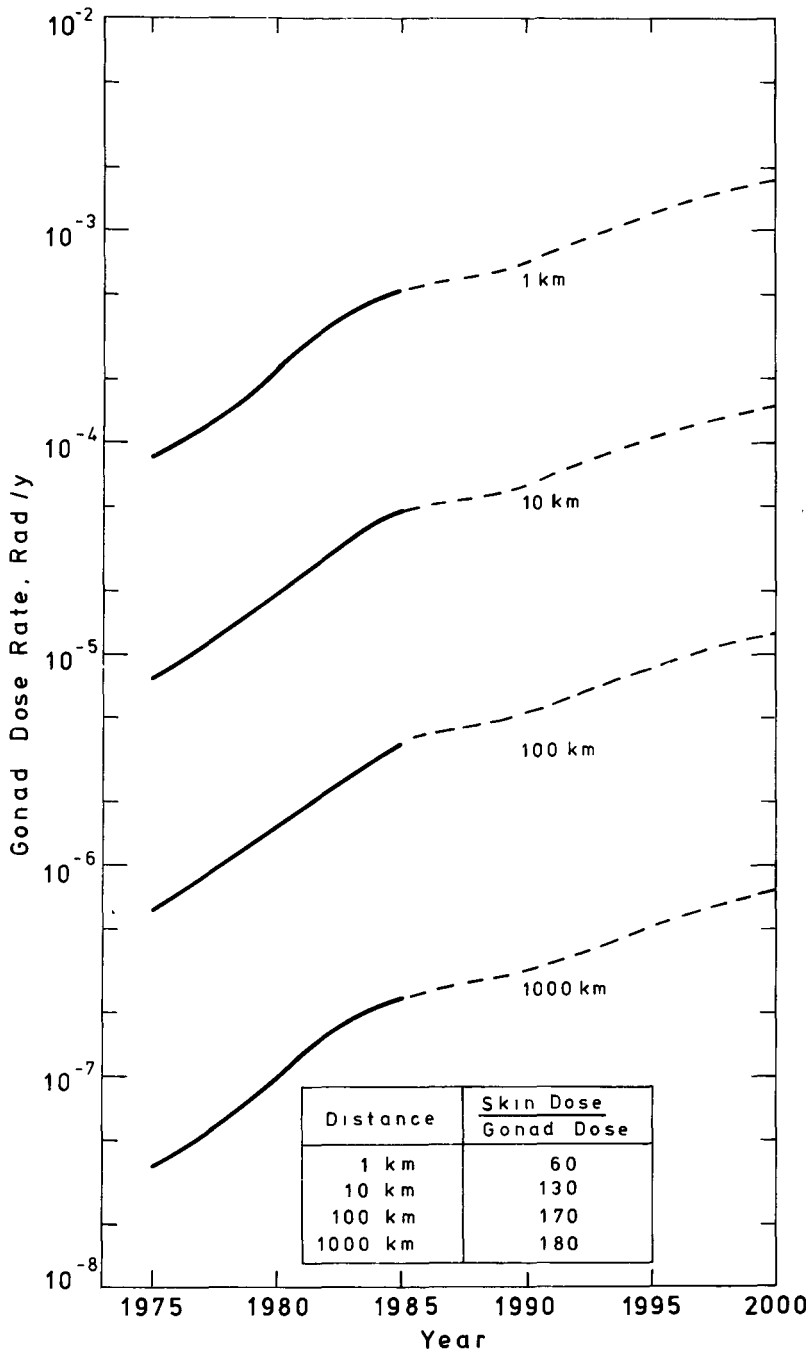
Figure 8

Dose Rates to the Year 2000 at Various Distances
from a Representative Reprocessing Plant Resulting
from the Airborne Discharge of Kr-85 from a Stack
of Height 100 m.
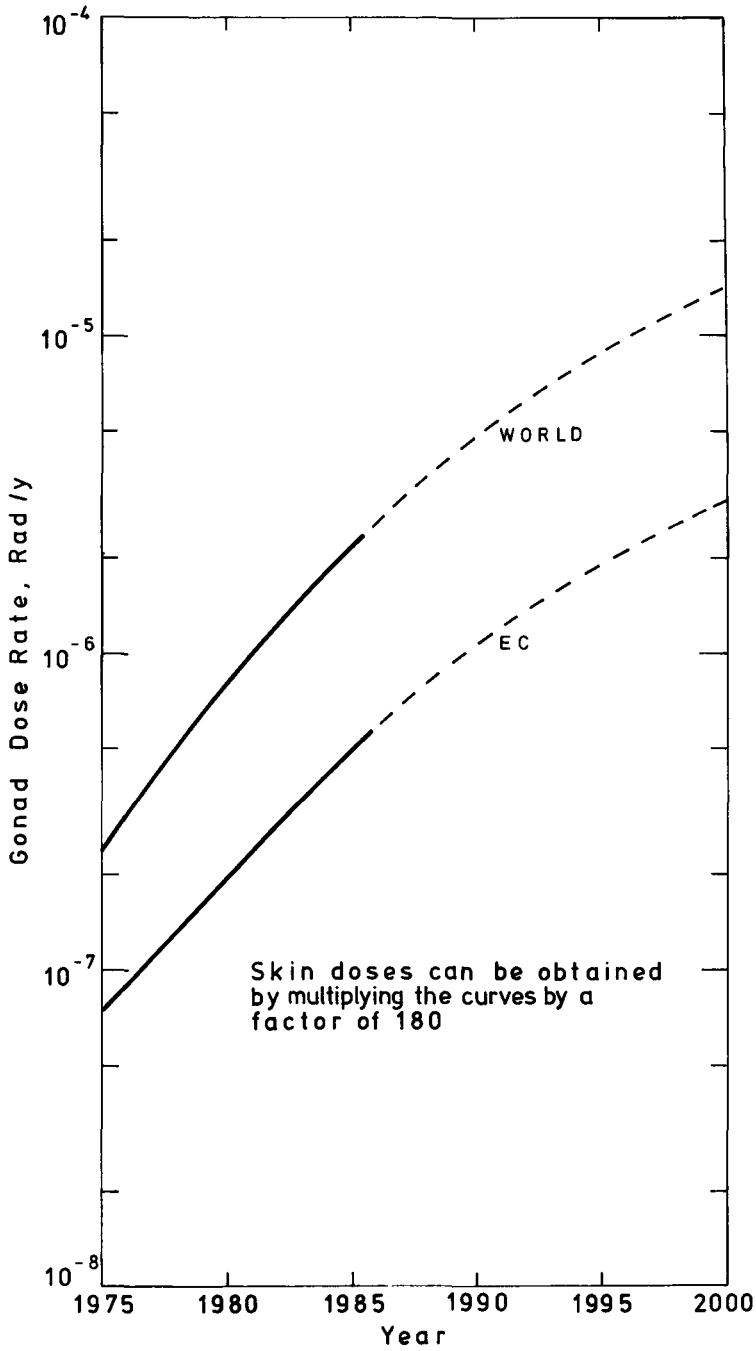
Figure 9

Dose rates to the Gonads in the Latitude Band 35-60°N
from the Global Circulation of Kr-85 Discharged
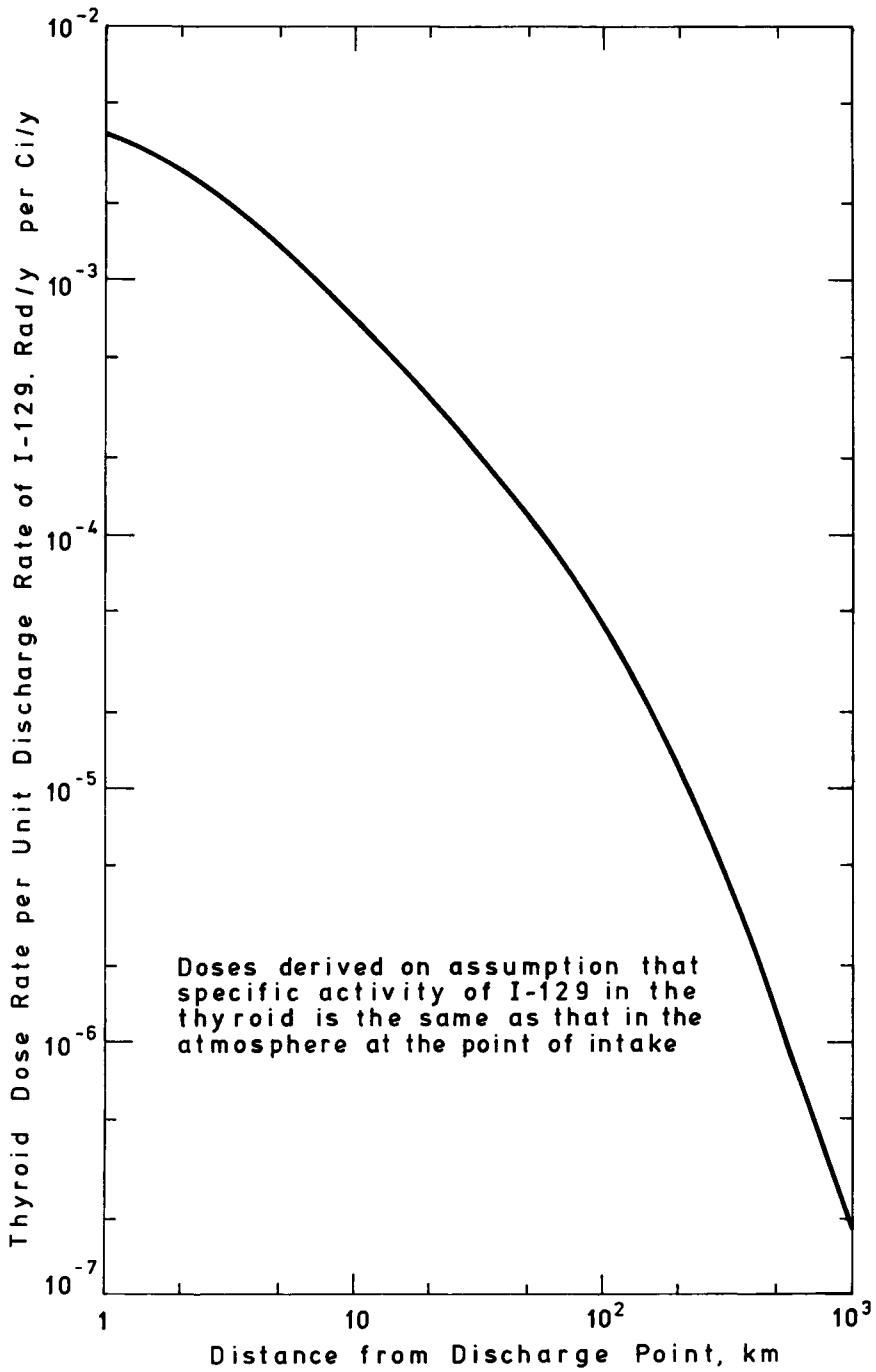from the World and EC Nuclear Power Programmes
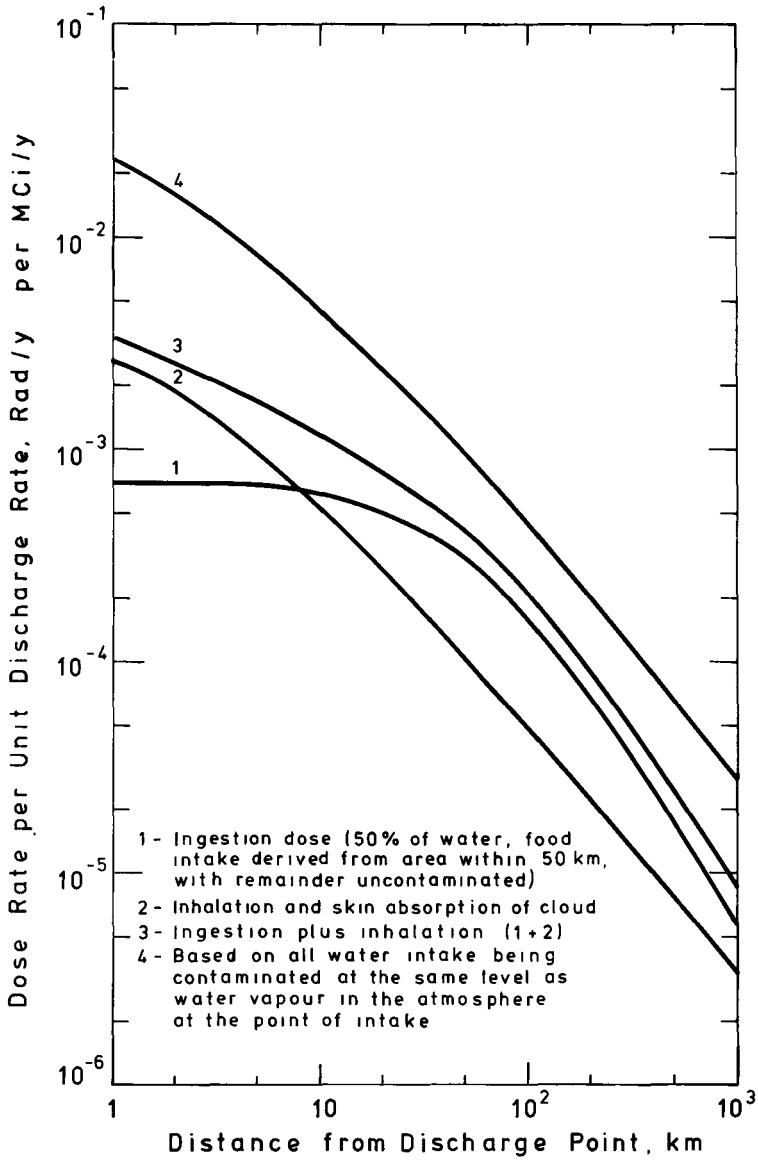
Figure 10

Dose Rate to the Whole Body from the Discharge of 1 MCi/y of Tritiated Water Vapour in Airborne Effluent from a Stack of Height 100 m.
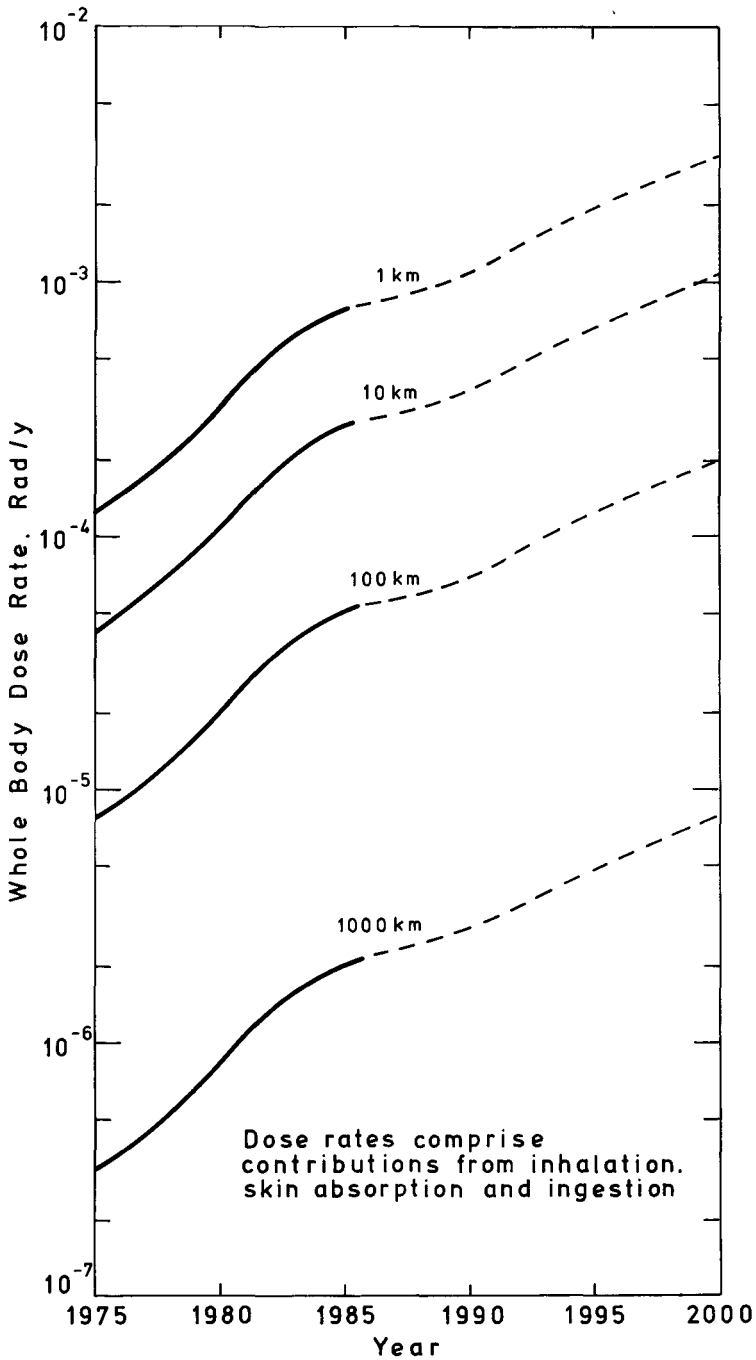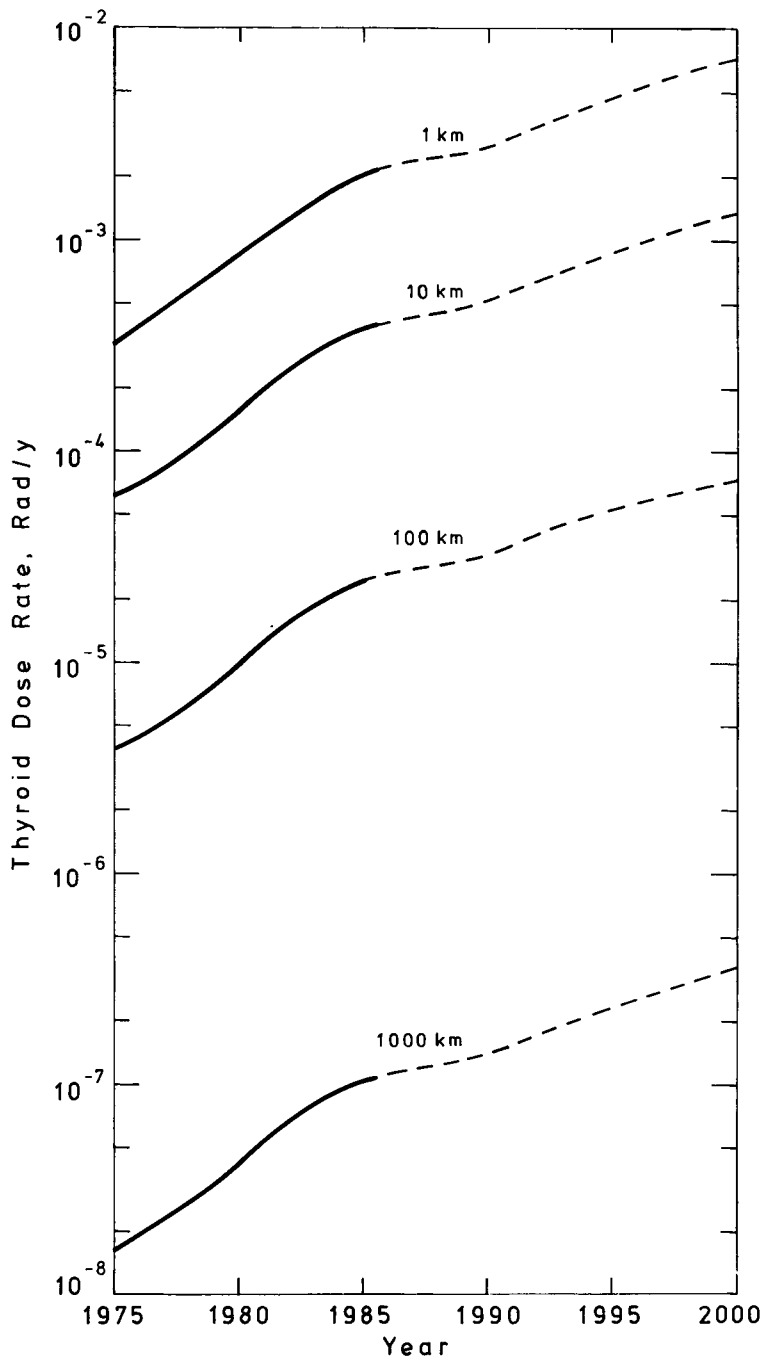
Figure 11
Dose Rates to the Year 2000 at Various Distances
from a Representative Reprocessing Plant Resulting
from the Airborne Discharge of Tritiated Water
Vapour from a Stack of Height 100 m.
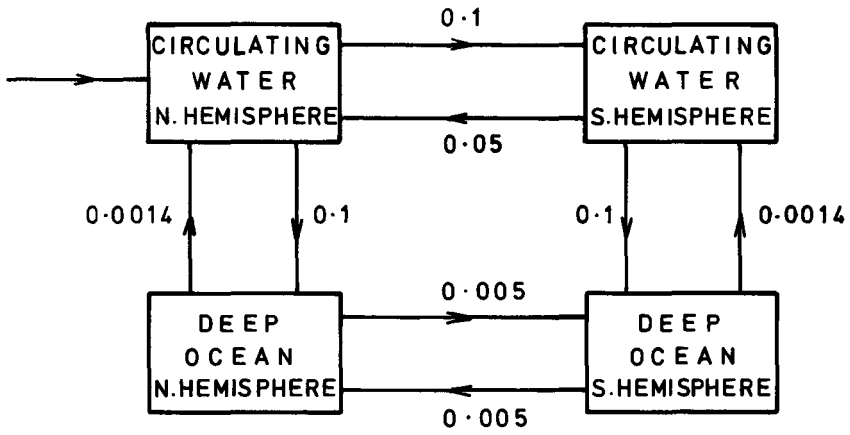
TRANSFER COEFFICIENTS ARE GIVEN
IN UNITS OF y^{-1}

Figure 12

The Model used for Global Circulation
of Tritium and Iodine - 129
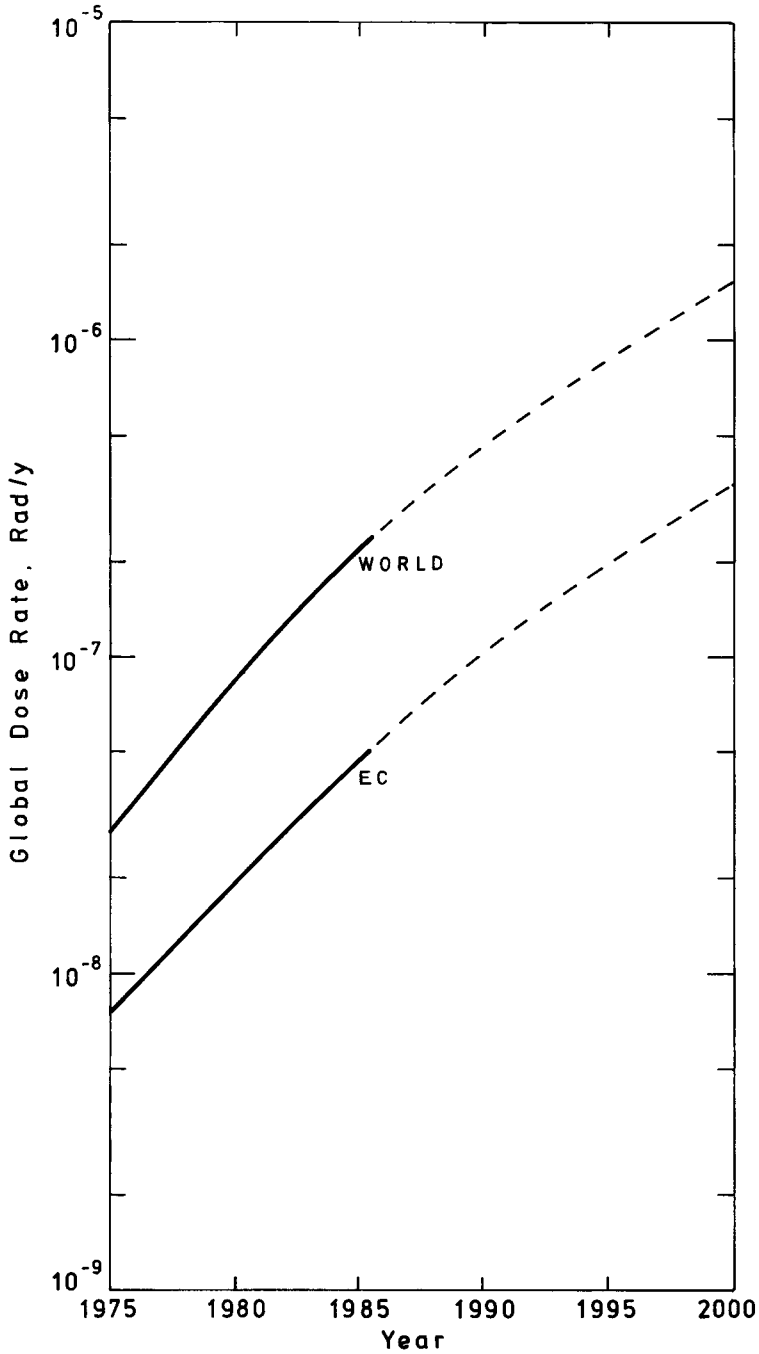
Figure 13
Dose Rates to the Whole Body from the Global
Circulation of Tritium Discharged from the EC
and World Nuclear Power Programmes
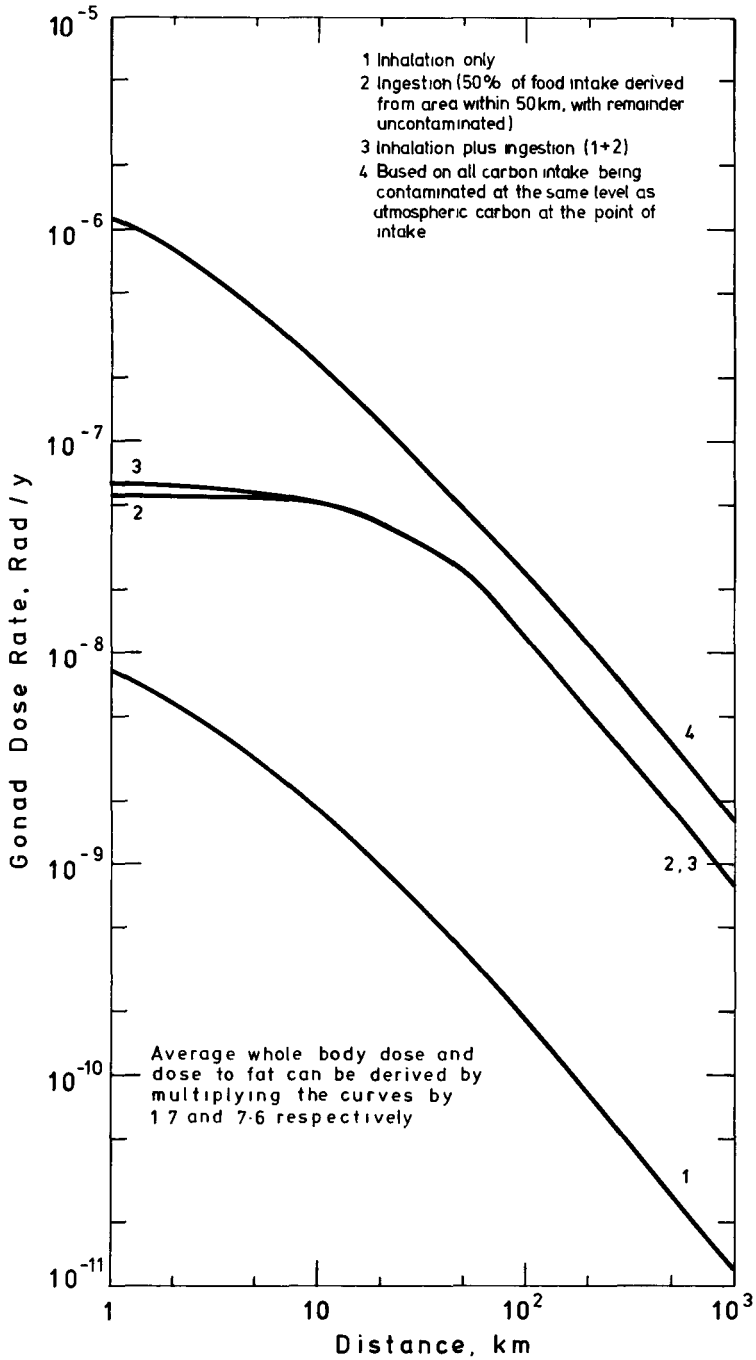
Figure 14

Dose Rate to the Gonads from the Discharge of 1Ci/y of $^{14}CO_2$ in Airborne Effluent from a Stack of Height 100 m

.
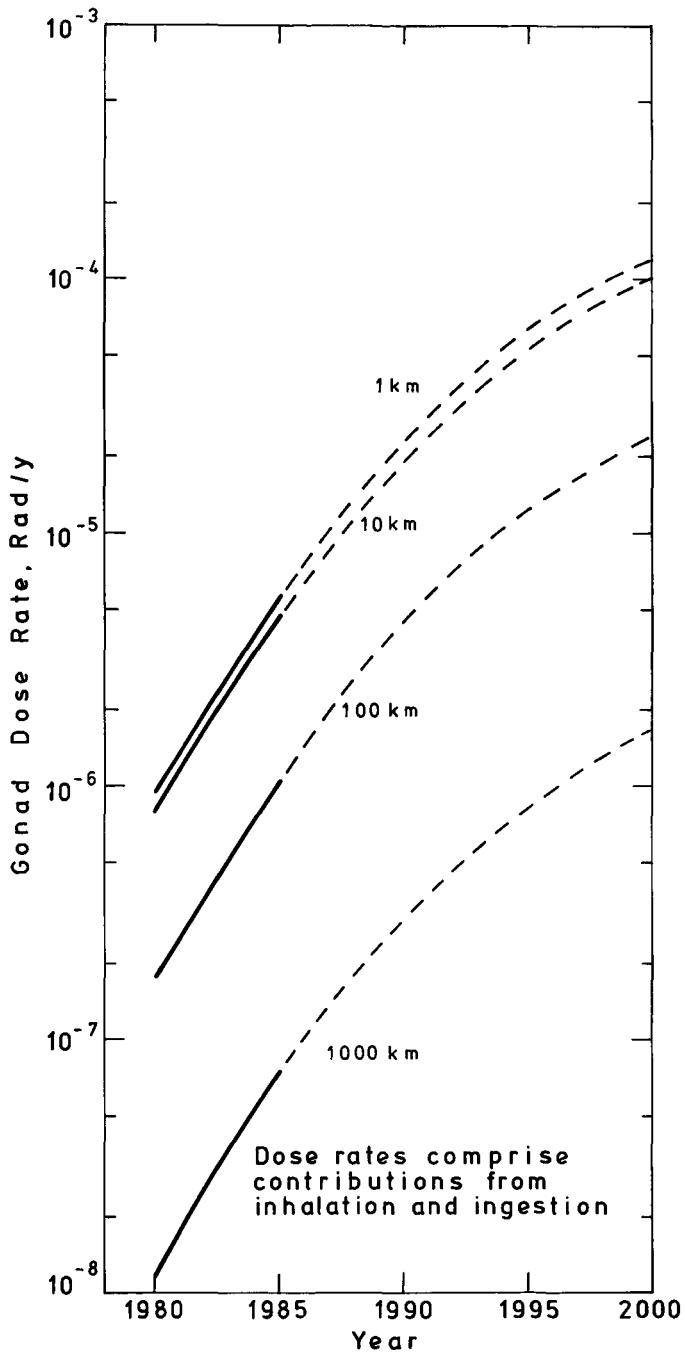
Figure 15

Dose Rates to the Year 2000 at Various Distances from a Representative Reprocessing Plant Resulting from the Airborne Discharge of $^{14}CO_2$ from a Stack of Height 100 m.
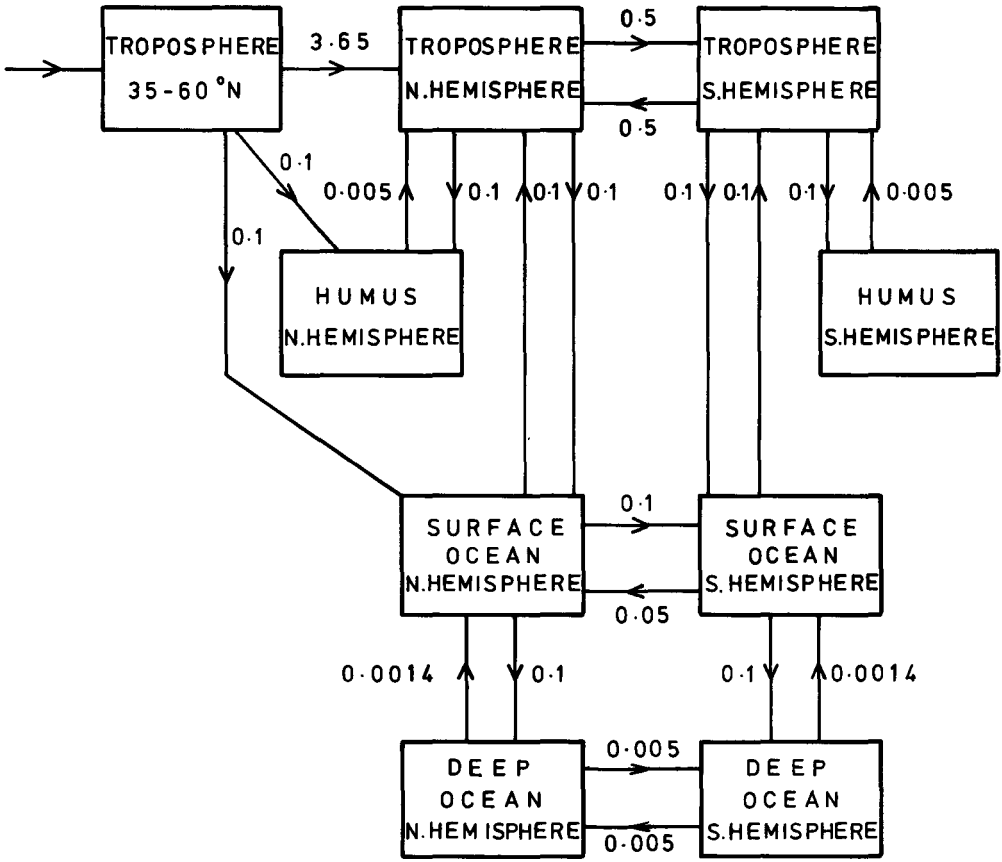
TRANSFER COEFFICIENTS ARE GIVEN IN UNITS OF Y^{-1}

Figure 16

Model used for Global Circulation of C-14

(the compartments marked troposphere also include the terrestrial biosphere)
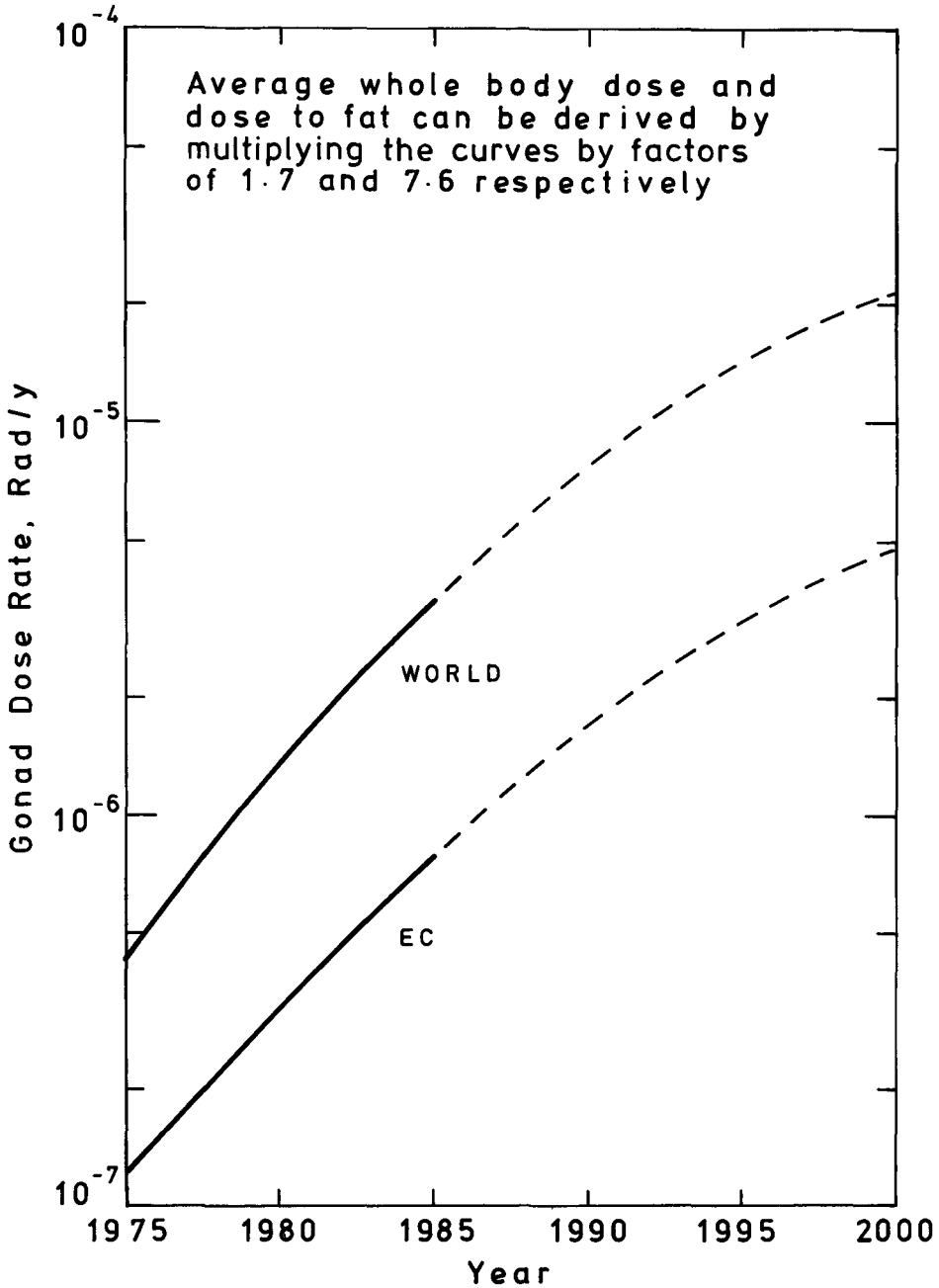
Figure 17
Dose Rates to the Gonads in the Latitude Band 35-60°N
from the Global Circulation of Carbon -14
Discharged from the World and EC Nuclear
Power Programmes

Doses derived on assumption that
specific activity of I-129 in the
thyroid is the same as that in the
atmosphere at the point of intake

Figure 18

Dose Rate to the Thyroid from the Discharge of 1Ci/y of
I-129 in Airborne Effluent from a Stack of Height 100 m

Figure 19

Dose Rates to the Year 2000 at Various Distances from a Representative Reprocessing Plant, Resulting from the Airborne Discharge of I-129 from a Stack of Height 100 m.
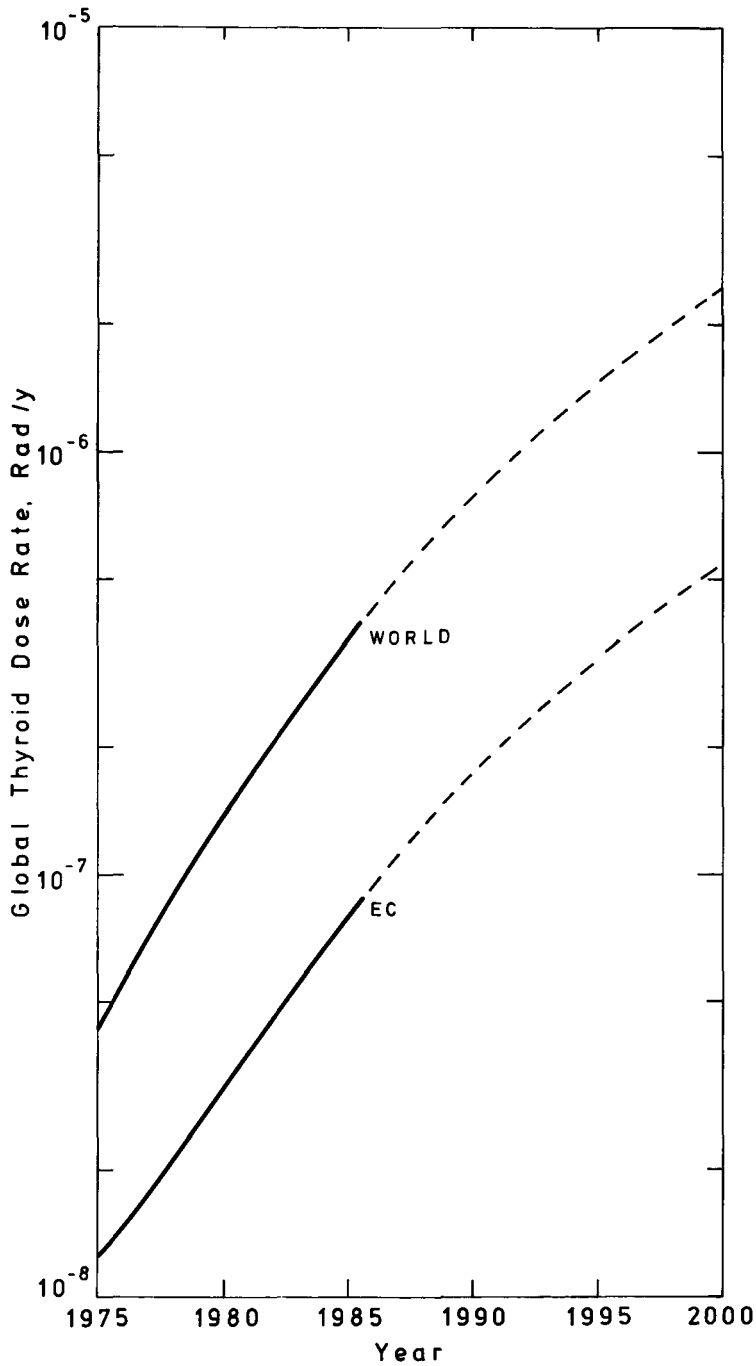
Figure 20

Dose rates to the thyroid from the Global Circulation
of I-129 Discharged from the EC and World
Nuclear Power Programmes
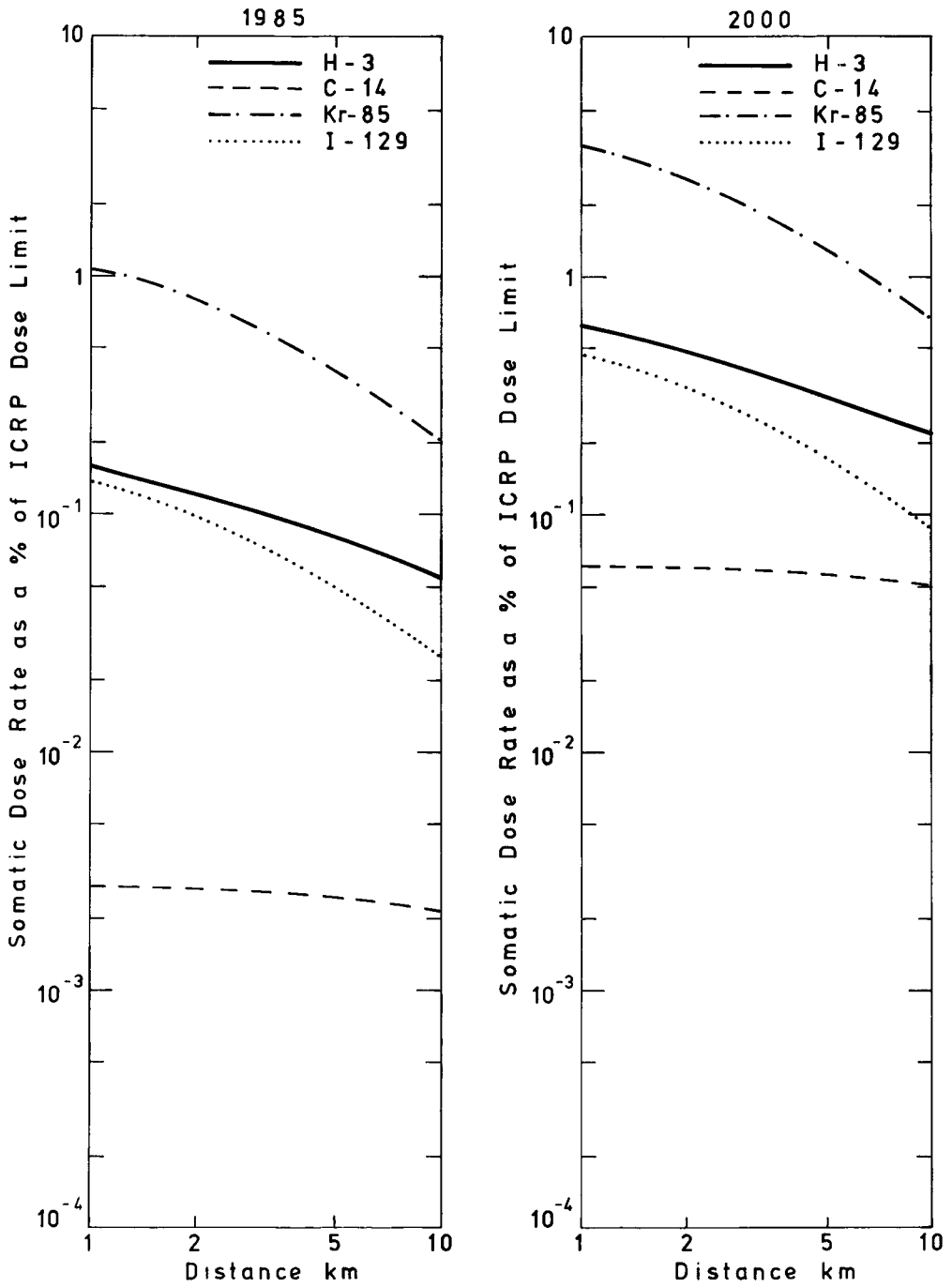
Figure 21
Somatic Dose Rates as % of the ICRP Dose Limits at Distances of
1-10km Resulting from Airborne Discharge from the Representative
Reprocessing Plants
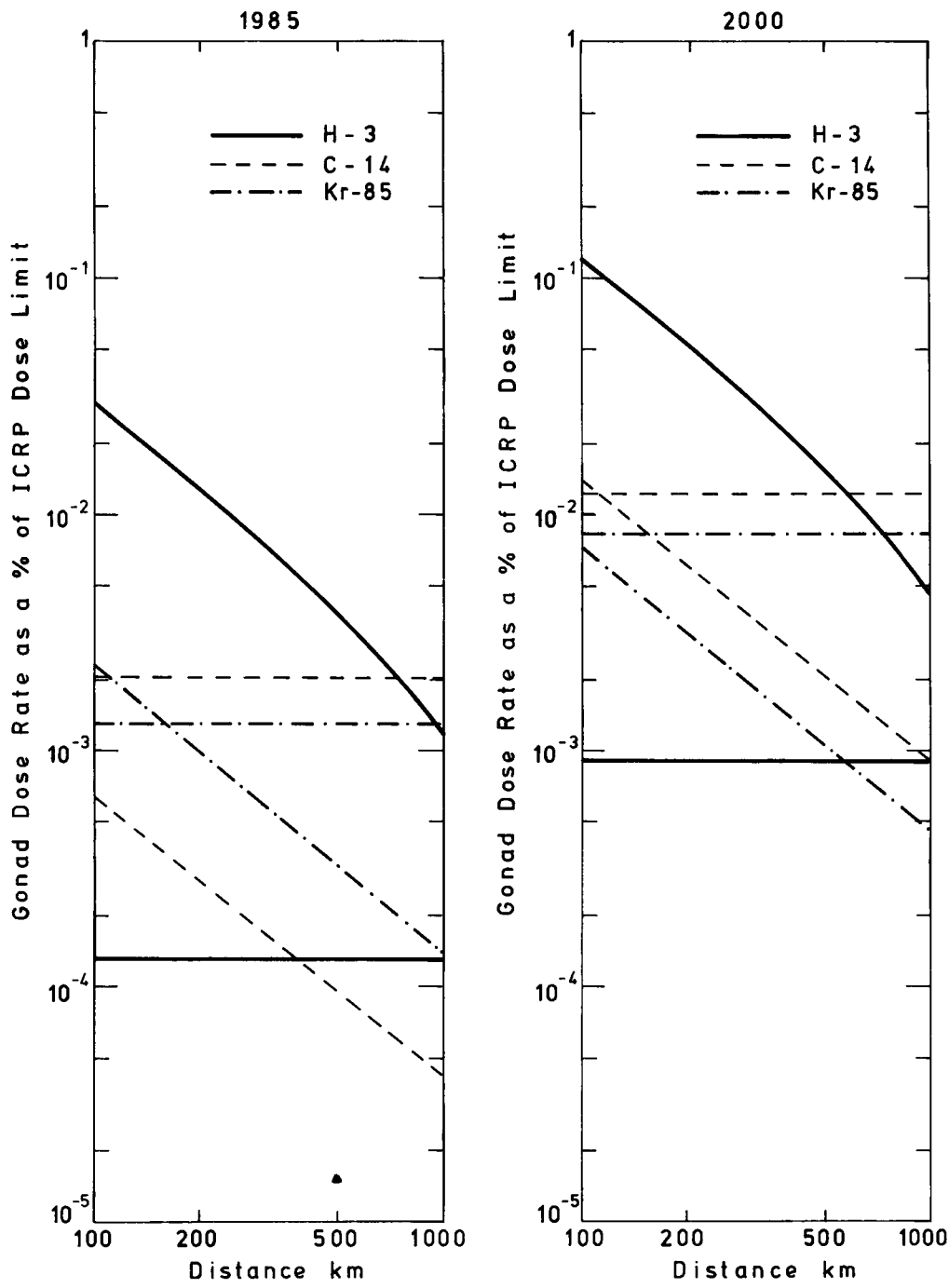
Figure 22
Comparison of First Pass Gonad Dose Rates to a Regional Group
with Gonad Dose Rates from Global Circulation, Doses being given
as Percentages of the ICRP Genetic Dose Limit
(Horizontal lines refer to doses from global circulation)
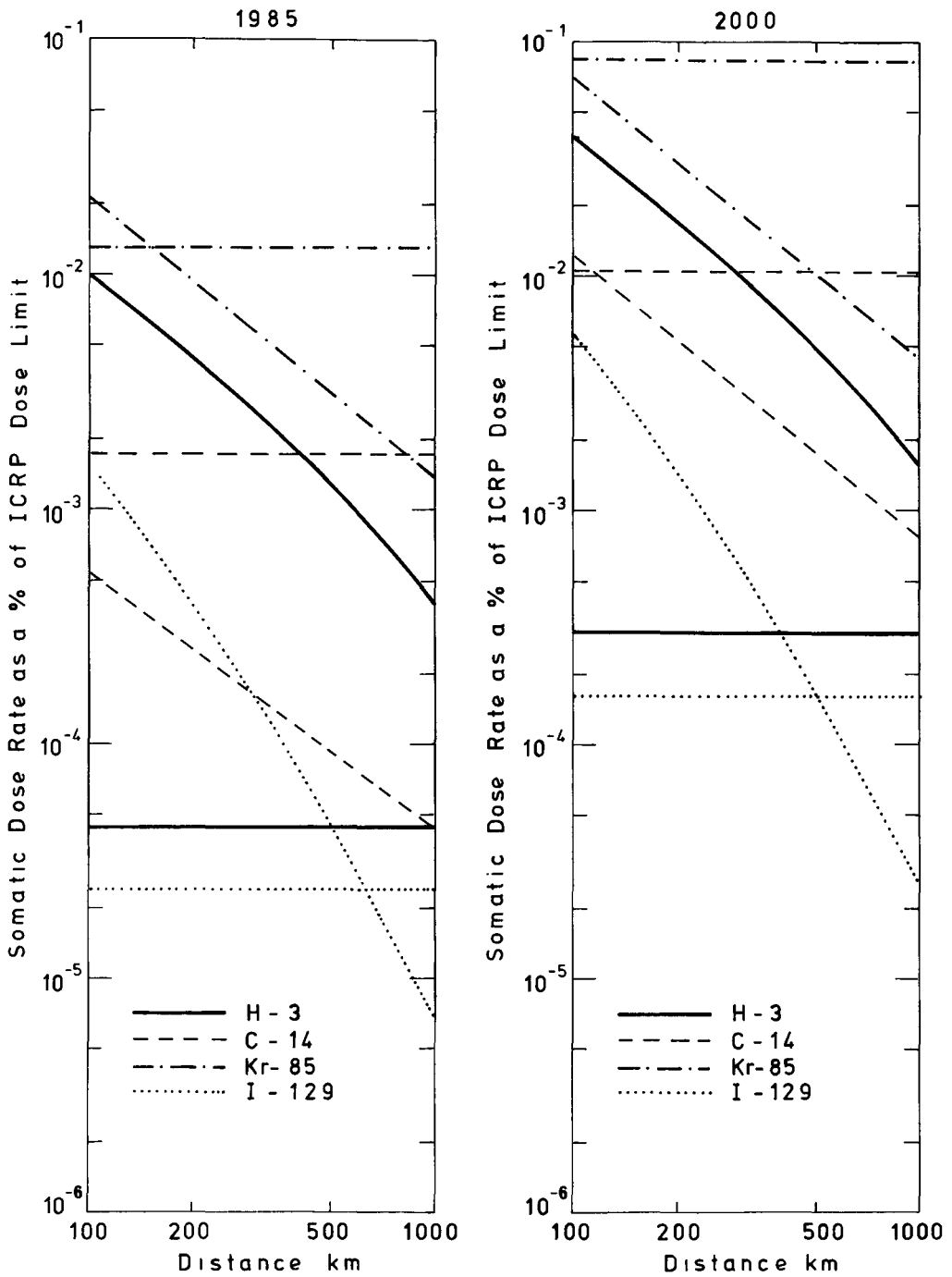
Figure 23
Comparison of First Pass Somatic Dose Rates to a Regional Group
with Somatic Dose Rates from Global Circulation, Doses being Expressed
as Percentages of the Appropriate ICRP Dose Limits
(Horizontal lines refer to doses from global circulation)
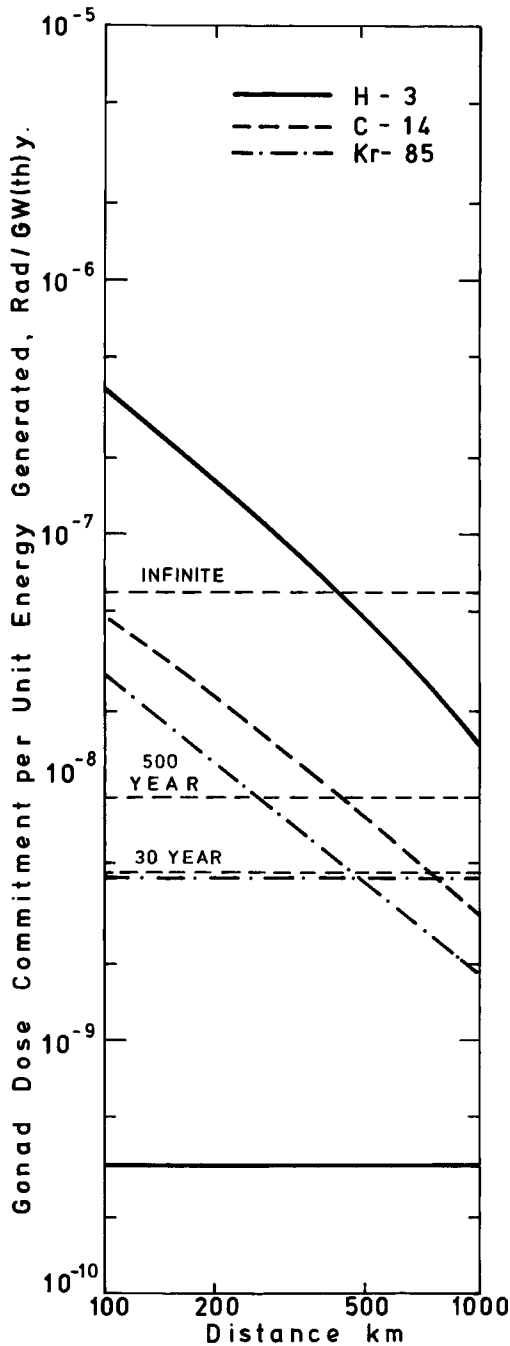
Figure 24
Gonad Dose Commitments from the First Pass
and Global Circulation of Activity Discharged
Commensurate with the Generation of 1 GW (th) y
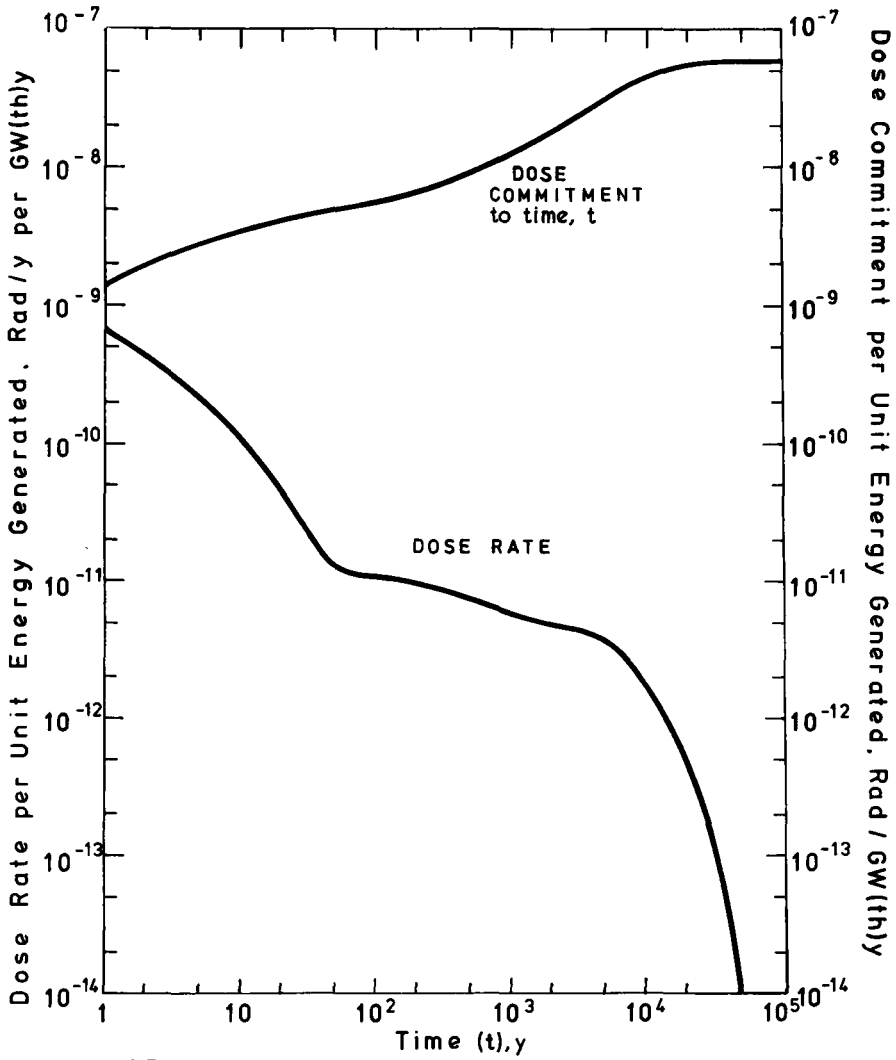of Nuclear Energy
(Horizontal lines refer to doses from global circulation)

Figure 25

Variation with Time of the Dose Rate and Dose
Commitment Associated with the Discharge of
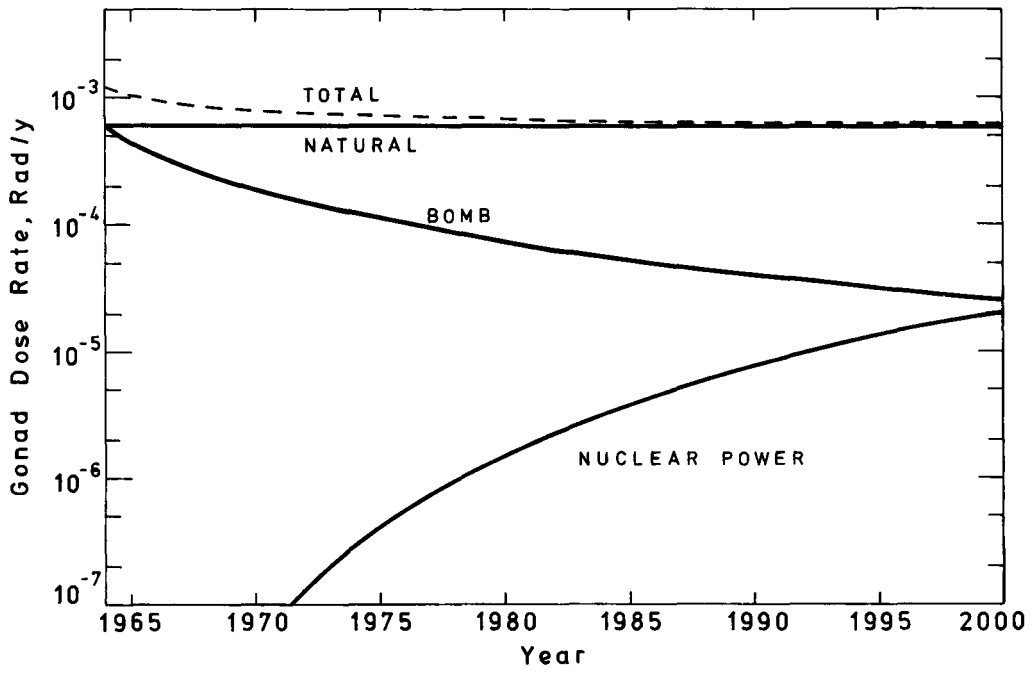Carbon-14 Resulting from the Generation of
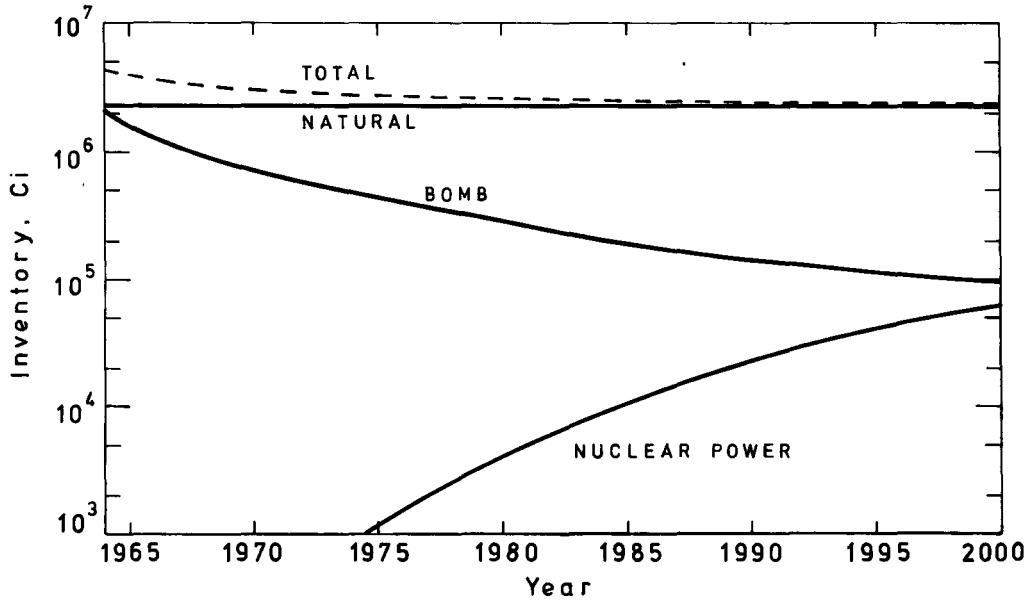1 GW(th)y of Nuclear Energy

Figure 26

Inventories of and Gonad Dose Rates from Natural, Bomb and Nuclear Power Produced Carbon-14 in the Troposphere and Terrestrial Biosphere of the Northern Hemisphere
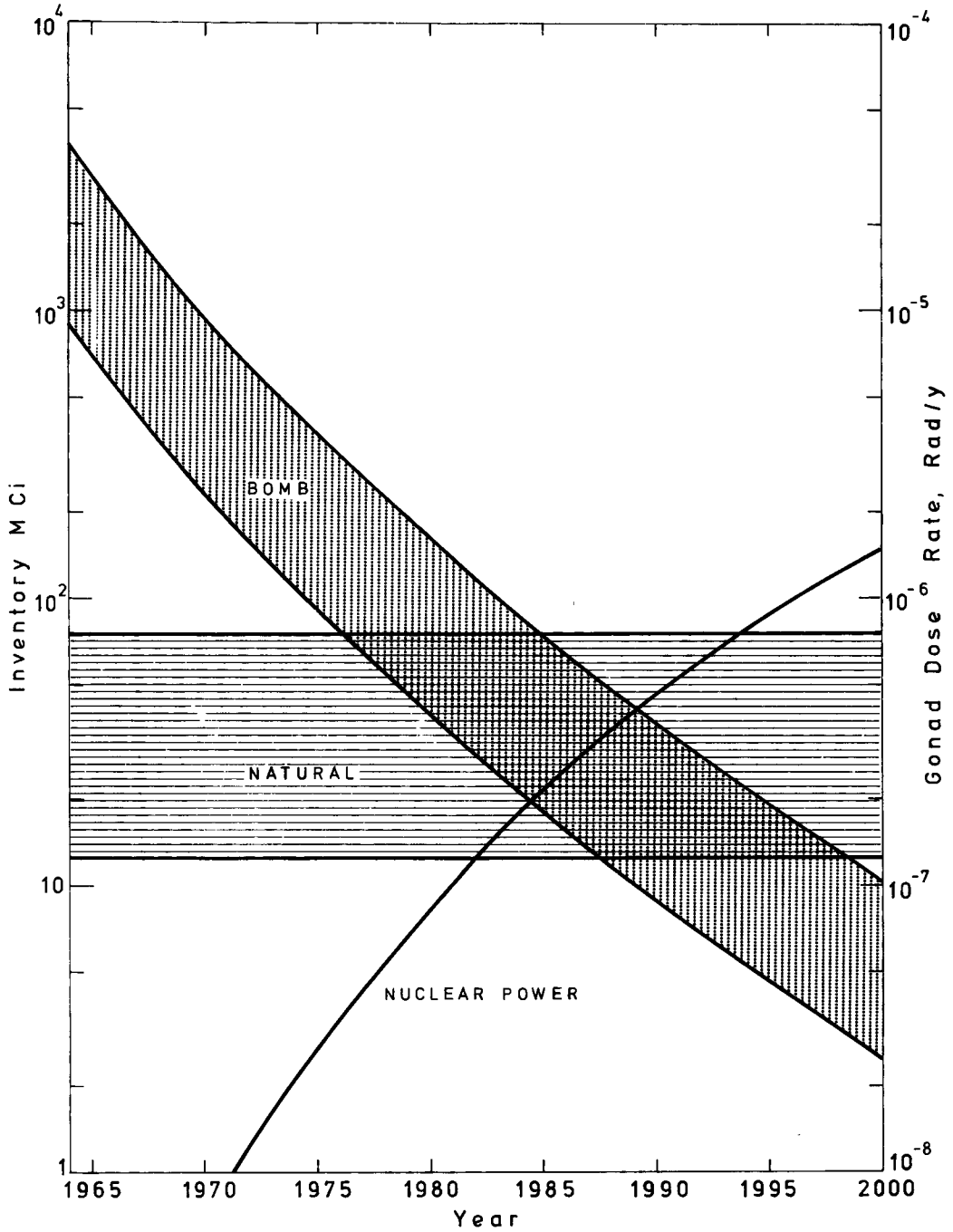
Figure 27

Inventories of and Gonad Dose Rates from Natural, Bomb and
Nuclear Power Produced Tritium in the Circulating Waters
of the Northern Hemisphere