UNITED NATIONS ENVIRONMENT PROGRAMME

REGIONAL SEAS

Radioactivity in the South Pacific

UNEP Regional Seas Reports and Studies No. 40

Prepared in co-operation with

SPC SPEC ESCAP

UNEP 1984

PREFACE

Twelve years ago the United Nations Conference on the Human Environment (Stockholm, 5-16 June 1972) adopted the Action Plan for the Human Environment, including the General Principles for Assessment and Control of Marine Pollution. In the light of the results of the Stockholm Conference, the United Nations General Assembly decided to establish the United Nations Environment Programme (UNEP) to "serve as a focal point for environmental action and co-ordination within the United Nations system" (General Assembly resolution 2997(XXVII) of 15 December 1972). The organizations of the United Nations system were invited "to adopt the measures that may be required to undertake concerted and co-ordinated programmes with regard to international environmental problems", and the "intergovernmental and non-governmental organizations that have an interest in the field of the environment" were also invited "to lend their full support and collaboration to the United Nations with a view to achieving the largest possible degree of co-operation and co-ordination". Subsequently, the Governing Council of UNEP chose "Oceans" as one of the priority areas in which it would focus efforts to fulfil its catalytic and co-ordinating role.

The Regional Seas Programme was initiated by UNEP in 1974. Since then the Governing Council of UNEP has repeatedly endorsed a regional approach to the control of marine pollution and the management of marine and coastal resources and has requested the development of regional action plans.

The Regional Seas Programme at present includes eleven regions [1/] and has over 120 coastal States participating in it. It is conceived as an action-oriented programme having concern not only for the consequences but also for the causes of environmental degradation and encompassing a comprehensive approach to combating environmental problems through the management of marine and coastal areas. Each regional action plan is formulated according to the needs of the region as perceived by the Governments concerned. It is designed to link assessment of the quality of the marine environment and the causes of its deterioration with activities for the management and development of the marine and coastal environment. The action plans promote the parallel development of regional legal agreements and of action-oriented programme activities [2/].

The idea for a regional South Pacific environment management programme came from the South Pacific Commission (SPC) in 1974. Consultations between SPC and UNEP led, in 1975, to the suggestion of organizing a South Pacific Conference on the Human Environment. The South Pacific Bureau for Economic Co-operation (SPEC) and the Economic and Social Commission for Asia and the Pacific (ESCAP) soon joined SPC's initiative and UNEP supported the development of what became known as the South Pacific Regional Environment Programme (SPREP) as part of its Regional Seas Programme.

A Co-ordinating Group, consisting of representatives from SPC, SPEC, ESCAP and UNEP, was established in 1980 to co-ordinate the preparations for the Conference.

1/ Mediterranean, Kuwait Action Plan Region, West and Central Africa, Wider Caribbean, East Asian Seas, South-East Pacific, South Pacific, Red Sea and Gulf of Aden, East Africa, South-West Atlantic and South Asian Seas.

2/ UNEP: Achievements and planned development of UNEP's Regional Seas Programme and comparable programmes sponsored by other bodies. UNEP Regional Seas Reports and Studies No. 1. UNEP, 1982.

The Conference on the Human Environment in the South Pacific was convenved in Rarotonga (8-11 March 1982). It adopted: the South Pacific Declaration on Natural Resources and Environment of the South Pacific Region; and agreed on the administrative and financial arrangements needed to support the implementation of the Action Plan and on the workplan for the next phase of SPREP [3/].

At the request of the States and Territories of the South Pacific Region, negotiations were initiated to develop, in the framework of the Action Plan, a Convention for the Protection and Development of the Natural Resources and Environment of the South Pacific Region with specific protocols related to (i) prevention of pollution by dumping and (ii) co-operation in combating oil pollution emergencies. In order to facilitate the negotiation of these legal instruments, the present document, reviewing the problems of radioactivity in the South Pacific Region, was drawn up.

The document was prepared by a group of consultants acting in their personal capacity. The Group consisted of Dr. Mike Bacon (USA), Professor Gérard Lambert (France), Dr. Athol Rafter (New Zealand), Dr. James Samisoni (Fiji) and Mr. Don Stevens (Australia), and worked under the Chairmanship of Dr. Mike Bacon. The sponsors of the study would like to express their gratitude to the chairman and the members of the group, as well as to the scientist who reviewed the draft of the document.

3/ SPC/SPEC/ESCAP/UNEP: Action Plan for managing the natural resources and environment of the South Pacific Region. UNEP Regional Seas Reports and Studies No. 29. UNEP, 1983.

C O N T E N T S

CHAPTER 1

SUMMARY OF THE REPORT

1.1 INTRODUCTION

In November 1982 the Technical Group on Radioactivity in the South Pacific Region was created and assigned the task of reviewing radioactivity and its regional impact. The project was motivated largely by the concern expressed in the Region over existing and proposed activities that might release radioactive materials to the environment. Of particular concern are the nuclear explosions presently being conducted in Polynesia and proposals to include the Pacific Ocean in strategies for radioactive waste management.

This Report is the outcome of the Technical Group's efforts. The subject is vast, and the Report is necessarily lengthy and, in places, somewhat technical. The Report can be said to have three overall objectives: (i) to provide the general reader with some basic information needed to understand the scientific issues (Chapters 3 and 4), (ii) to provide an overview of the radiation environment in which Pacific people live (Chapters 5 - 7), and (iii) to give an evaluation, from the scientific point of view, of some of the issues that are presently of greatest concern in the Region (Chapters 8 and 9).

1.2 IONIZING RADIATIONS AND THEIR POSSIBLE HARMFUL EFFECTS

Chapters 3 and 4 of the Report were written with the aim of providing the general reader with an introduction to some of the basic concepts and terms used in nuclear science and the properties and effects of ionizing radiations. The most important terms introduced in Chapter 3 are the absorbed dose, measured in units called the gray, and the dose equivalent, measured in units called the sievert. The absorbed dose is the amount of energy that is absorbed in a substance (for example, a living tissue) as radiation passes through it. The dose equivalent is equal to the absorbed dose multiplied by a factor that takes into account the different properties of the different types of ionizing radiation (alpha, beta, gamma, or X-radiations).

It is especially important to understand the concept of the dose equivalent, because it is used very extensively throughout the remainder of the Report. Use of the dose equivalent provides a basis for comparing exposures of people to different sources of ionizing radiation, for comparing exposures received by different groups of people in different geographical areas, and for assessing objectively the impact of radionuclide releases to the environment. It is extremely important to recognize that it is the dose equivalent that is the important consideration in assessing the effects of ionizing radiation, not the origin of the radiation. The potential harm to living things from ionizing radiation depends on the size of the dose equivalents received by them as influenced by the type of radiation (that is, whether it is

alpha, beta, gamma or X-radiation) and its energy. It makes no difference whether the ionizing radiation derives from a natural or an artificial source.

Chapter 4, provides a review of what is known about the harmful effects of ionizing radiation on living things and explains the role of various international bodies in the field of radiation protection, most notably the International Commission on Radiological Protection (ICRP). The Technical Group takes note in that Chapter of the expanding use of X-rays for medical diagnosis in the Region, and it sees a need for countries in the Region to consider the enactment of radiation control legislation. Similar legislation has been adopted by developed countries and some developing countries so as to establish proper standards of radiation protection for workers and members of the public and acceptable levels of radiation dose for persons and the environment. In the preparation of such legislation, consideration might be given to setting an upper limit for the contribution which any one source of ionizing radiation might be permitted to make to persons as members of the public. Dose limits adopted in such legislation would provide a basis against which radiation doses to persons in the Region could be monitored and possible harmful effects of the doses assessed. The detailed requirements of such legislation could appropriately be based on the recommendations of the International Commission on Radiological Protection, on codes of practice of other competent international authorities, such as the World Health Organization and the International Atomic Energy Agency, and on the experience gained in this field by other countries.

In discussing the known harmful effects produced in living things by exposure to ionizing radiation, an important distinction is made between what are called stochastic and non-stochastic effects. For some effects, it has been shown that their severity depends on the size of radiation dose received and that for these effects a threshold or minimum dose is required for their occurence. These are called non-stochastic effects. The size of the threshold dose is different for different effects and for different species of living things. For other effects, particularly many late effects, the chances of the effects occurring rather than their severity depends on the size of the radiation dose to living cells. As a group these are called stochastic effects. For them it has not been possible to show by scientific research whether or not a threshold dose exists for their occurrence. So as not to underestimate the chances of stochastic effects occurring in living things, it is the current radiation protection practice to assume that no threshold dose exists for them. In the preparation of this Report, the Technical Group applied this concept in its consideration of possible harmful effects of ionizing radiation.

1.3 EXPOSURES TO IONIZING RADIATION IN THE SOUTH PACIFIC REGION

Ionizing radiations originate both in sources that occur naturally and in sources created by human technology. Natural sources of ionizing radiation have been present in the environment since the beginning of the earth's history. They include cosmic rays that come from outer space and natural radionuclides that occur on earth. Barring a nuclear war or major nuclear reactor accidents, natural sources are likely always to be the main environmental contributor to human radiation exposure. Artificial sources of ionizing radiation in the environment are due almost exclusively to atmospheric nuclear explosions and nuclear electric power production, the former being by far the most important.

The Technical Group spent a considerable amount of its effort reviewing the information available on human exposure to sources of ionizing radiation in the environment. That work is reported in Chapters 5 and 6. Much of the information given in those chapters is based on the most recent report of the United Nations

Scientific Committee on the Effects of Atomic Radiation which derived global averages for exposure to natural and artificial ionizing radiation. In addition the Group reviewed data relating specifically to the exposures of populations living in the South Pacific Region with the aim of determining how the average exposures to ionizing radiation in the Region compare with the global averages.

In the case of natural radiation, the world population as a whole receives an average annual effective dose equivalent of 2000 microsievert. This is an average figure, and there is a large variation from place to place on earth, depending on a number of environmental factors, and from person to person depending on living habits. The exposure is received in a variety of ways: by external exposure to cosmic rays and radioactive elements (potassium, thorium and uranium) in soils, by the consumption of food containing natural radionuclides, and by the breathing in of radon-222 and other radionuclides that are naturally present in the air. For the South Pacific Region the Technical Group concluded that, on average, the annual effective dose equivalent from natural sources of ionizing radiation is approximately 1000 microsievert, only half the world average. The lower-than-average exposures in the Region are the result of several factors: (1) the low concentrations of radioactive elements in the coralline soils that occur in much of the region, (2) the lower concentrations of radon-222 in air over the ocean compared with concentrations over the continents, and (3) the fact that most people in the region live in well-ventilated houses and spend much of their time outdoors, thus avoiding exposure to the elevated levels of radon that often occur in indoor air. The Technical Group also concluded that exposure to artificial sources of ionizing radiation, mainly the radionuclides formed during nuclear weapons tests in the atmosphere, is on the average lower, perhaps two to three times lower, in the South Pacific Region than it is for the world as a whole. This is because most of the population of the Region lives in the Southern Hemisphere, whereas the greater part of the fallout from atmospheric testing was delivered in the Northern Hemisphere. In general the contribution to total radiation exposure due to artificial radionuclides is small and is much less than the variability that exists in exposure to natural sources of radiation.

Although average doses from both natural and artificial ionizing radiation, in the Region are substantially lower than in most other parts of the world, there are certain islands in the Region where populations receive unusually high radiation exposures. Niue Island in the South Pacific is a documented example of an area of unusually high natural radioactivity, and in Chapter 5 the Technical Group calls attention to some data suggesting that part of Guam might also be such an area. Unusually high levels of artificial radioactivity are found at some atolls in the Marshall Islands that were contaminated by local fallout from the US weapons tests.

Chapter 7 discusses in detail the exposures that arise from the use of sources of ionizing radiation in medicine and other activities. In most developed countries the radiation doses to populations from the medical diagnostic uses of ionizing radiation are the largest of all the doses from artificial sources. The Technical Group is not aware of any assessments of the radiation doses to the populations of any of the countries in the Region from the medical uses of sources of ionizing radiation. However, it is reasonable to assume that there will be an increase, and more diversity, in the use of sources of ionizing radiation for medical purposes in the South Pacific Region as health services develop further. In many countries in the Region the special facilities necessary for these purposes are becoming more readily available in the major population centers, and it is to be expected that, with time, the facilities will be provided in less densely populated areas. As these developments occur, it will be important for the countries of the region to ensure that the resulting radiation doses to their populations are minimised. The Technical Group sees value in the development of a regional program through which

special technical services to oversee standards with respect to the medical uses of ionizing radiation would be available.

1.4 PRESENT AND PROPOSED ACTIVITIES INVOLVING RADIOACTIVE MATERIALS IN THE SOUTH PACIFIC REGION

After a brief review in Chapter 8 of radioactivity in the Pacific Ocean, the Report proceeds in Chapter 9 to a discussion of activities presently conducted in the Region, or proposed for the future, that might result in the release of radionuclides to the environment. The activities that are presently of greatest concern and most likely to influence the setting of environmental policy in the near future are the underground nuclear explosions presently being conducted in Polynesia by France as part of its weapons development program and the proposed use of the Pacific Ocean for the disposal of radioactive wastes.

The first section of Chapter 9 deals with the subject of radioactive waste. Much of the emphasis in that section is on the ocean dumping of packaged low-level waste, because there has already been a considerable development on a scientific basis for setting limits on such disposal and because there exist well developed international mechanisms for control and surveillance. Furthermore, a specific proposal has been issued by Japan to initiate in the near future a program of low-level waste disposal at a site in the western North Pacific, and this proposal has been the focus of considerable debate in the Region over the general issue of ocean dumping.

Significant amounts of radionuclides are continually delivered to the ocean by natural processes (Chapter 8). These constitute a small hazard to human health. The scientific task is to determine how much additional radioactivity will be added to the ocean by various human activities (such as ocean dumping) and to estimate the associated hazard. These additional radioactivity levels and their associated hazard may then be compared on the one hand with the corresponding quantities arising from natural radioactivity in the ocean and on the other hand with the hazards estimated to arise from the maximum permissible level of radiation dose recommended for members of the public by the ICRP. Because of this, a conservative but flexible approach should be taken.

The IAEA in 1978 provided a general assessment of the problem of ocean dumping. Its task was to set limits on the release rates of radionuclides on the seafloor so that a definition of high-level waste (not suitable for dumping) could be formulated as required by the London Dumping Convention. In its assessment the IAEA used quantitative predictions of the dose equivalent to people as a measure of the impact of dumping. The IAEA scientists recognized that present scientific knowledge does not allow exact predictions of seawater concentrations resulting from radionuclide releases to be made. They also recognized the possibility that some radioactivity could be transferred from the seafloor to human populations by completely unforeseen pathways. Because of these uncertainties, they adopted a conservative approach based on pessimistic assumptions about what might happen in extreme circumstances, not on realistic assumptions about what would most likely happen under ordinary circumstances. Thus the doses predicted by their calculations are, by intention, most probably overestimated. For this reason the resulting release-rate limits contain built-in safety factors. The Technical Group is satisfied that a very high level of conservatism was adopted in the IAEA assessment and believes that the release-rate limits set by IAEA are restrictive enough that dumping carried out within the IAEA guidelines should pose extremely little risk to human health or environmental safety.

The Japanese proposal for dumping of low-level waste in the North Pacific is also

discussed extensively in Chapter 9. The proposed full-scale operation would involve dumping at a rate no greater than one percent of the release-rate limit set by the IAEA, and, on the basis of the IAEA work and the confirmatory calculations made by Japanese scientists, the Technical Group believes that the proposed Japan dumping operation would pose extremely little risk to human or environmental health and well-being. This evaluation was made on the basis of a draft Japanese assessment of the proposal. The Technical Group understands that a final report on the proposal is in preparation. That report will require careful public review to ensure that the proposal complies with all the principles of the London Dumping Convention and with its associated requirements.

It does not necessarily follow from the above conclusion regarding the safety of the particular Japan dumping proposal that dumping of radioactive waste in the ocean should be advocated generally as a procedure to be preferred over land-based options. This cannot be clearly decided on the basis of present scientific knowledge alone. Continued evaluation of all the alternatives is required. The problem of the management of wastes, both radioactive and non-radioactive, will always exist, and scientific understanding of the environment will always continue to be revised. The Technical Group feels it is important that policies and practices remain flexible enough to respond to changed circumstances and improved scientific knowledge. At any moment in time, policy decisions should be based on the best scientific information then available, but there will always be need in the end for the exercise of good judgement and common sense.

Regarding the program of underground nuclear weapons tests by France, the Technical Group makes note of the difficulty of giving an informed evaluation because of the high level of secrecy that surrounds the activity. This is in sharp contrast to civilian activities, such as radioactive waste disposal, which are subject to international surveillance, scientific review, and public scrutiny.

The present procedure of testing underground avoids the previous pollution of the atmosphere by radioactive debris and is considered safer, with regard to human health, than is testing above ground. Crude approximations of the amounts of radionuclides that might be accumulating underground at the test site indicate that they are unlikely to be large enough to be cause for alarm, but neither are they altogether negligible. One should be particularly concerned of the possible long-term effects, such as leakage of radionuclides into the ocean, especially if the testing program and the accumulations of radionuclides underground are to continue into the future. The Technical Group believes that past environmental safety assessments and publication of results have been inadequate, and it urges prompt publication of results and distribution to concerned governments in the Region. For example, the Technical Group notes with interest that, after some 50 underground nuclear tests since 1974 in the Tuamotu Islands, France has decided to conduct future underground tests in shafts bored in the lagoon rather than in the rim of the atolls as used previously. The Technical Group believes that this decision could only have been taken after a thorough scientific evaluation of the need for the change. The Technical Group urges that the scientific evaluation which led to this decision be promptly published and distributed.

Overall the Technical Group concludes that the present nuclear weapons testing and the proposed low-level waste disposal involve only a small, quite possibly a non-existent, risk to human health and the environment in the South Pacific Region. The Group believes that there is little scientific basis for judging these activities to be unacceptable. However, this conclusion does not in any way deny that important legal, political, and moral principles might very well be involved in and dominate the evaluation of them. Through its Report the Technical Group attempts to provide factual scientific information and interpretation that, it is hoped, will contribute to informed debate on these important issues.

CHAPTER 2

BACKGROUND TO THE REPORT

The Technical Group on Radioactivity in the South Pacific Region was formed in November 1982 and charged with the task of preparing a review of natural and artificial radioactivity in the Region. Formation of the Group took place following the Conference on the Human Environment in the South Pacific (Rarotonga, Cook Islands, 8-11 March 1982), where concern was expressed about the problems related to radionuclides, such as the testing of nuclear devices and the storage and release of nuclear wastes, occurring in the Pacific regional environment. This subject was given high priority in the Action Plan for the South Pacific Regional Environment Programme (SPREP).

According to its terms of reference, the Technical Group, under the supervision and guidance of the South Pacific Commission, was to prepare a review on natural and artificial radioactivity in the South Pacific Region, supported with bibliographic references and covering:

- the origin and source of natural and artificial radioactivity in the Region;
- the inputs of artificial radioactivity into the Pacific (including a historical review);
- the past and present levels of natural and artificial radioactivity in Pacific waters, soils, and ecosystems (including past, present, and foreseeable trends);
- the effects of natural and artificial radioactivity on the Pacific ecosystems, including human populations.

The Technical Group held its first meeting at SPC headquarters in Noumea, New Caledonia, 17-21 January 1983. At that time an interim report was prepared in the form of a working outline, which was distributed to governments in February for comment. A second and final meeting of the Technical Group was held at Noumea, 4-9 July 1983, with the support of the SPREP Secretariat. A draft of the present Report was completed at that meeting.

It was originally desired that the review by the Technical Group would be in the form of a short report written in layman's language. As the Group proceeded with its work, however, it became apparent that the subject was too vast and the issues too complex to be treated adequately in that form. Consequently, the present lengthy Report resulted. In writing the Report, however, the Group made a sincere attempt to keep in mind the needs of the general reader and to avoid as much as possible the use of technical jargon. Chapters 3 and 4 in particular are aimed at the general reader who may have little prior knowledge of radioactivity or of ionizing radiations. For convenience a Glossary of Terms is appended to the Report.

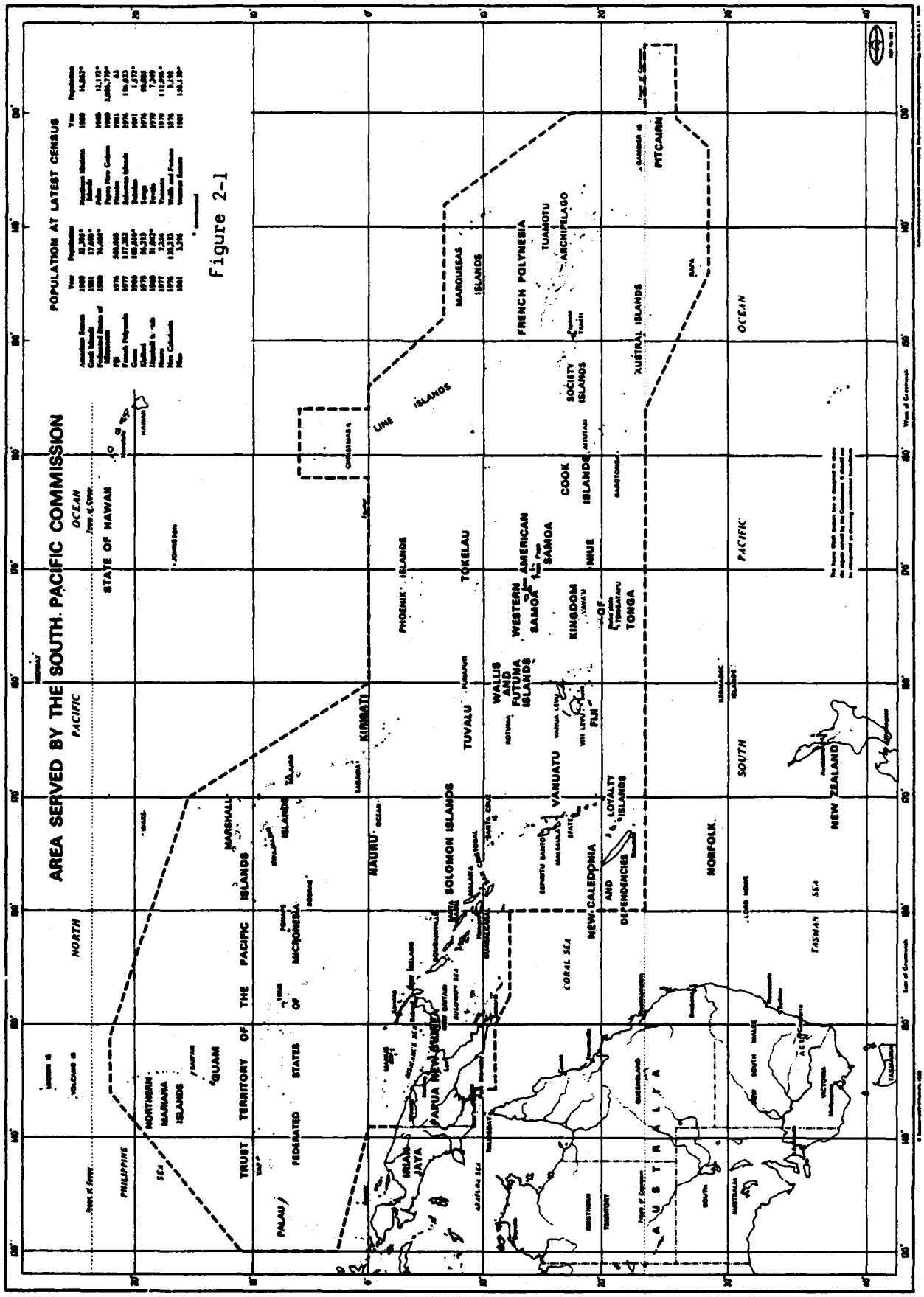
In considering the scope of its Report the Technical Group decided that for completeness and for achieving a proper perspective it should expand its coverage slightly to include all sources of ionizing radiation to which people are commonly exposed. Thus, in addition to discussing natural and artificial radionuclides, the Report also discusses exposures to cosmic rays and machines that give off X-rays.

For the purposes of this Report, the South Pacific Region is taken to be the entire area of the South Pacific Commission, which includes the islands north of the equator in Micronesia (see figure 2-1).

This Report appears at a time when a newer unit of radioactivity, the becquerel, is replacing an older unit, the curie (see Chapter 3, Section 3.4). One curie is equal to 3.7×10^{10} becquerel. Throughout the early chapters of the Report, activity is expressed in the units of becquerel. However, in the preparation of Chapters 8 and 9, which discuss radioactivity in the ocean, radioactive waste disposal, and the London Dumping Convention, it was decided to retain the use of the curie, because the documents related to the Convention all make use of the older unit. In some cases where published figures have been reproduced in the Report, other units of radioactivity will be found. These are explained in the figure captions or the accompanying text.

The Membership of the Technical Group on Radioactivity in the South Pacific Region consisted of M.P. Bacon (Co-ordinator), G. Lambert, T.A. Rafter, J.I. Samisoni, and D.J. Stevens.

During its work the Technical Group received information and helpful comments from individuals too numerous to list here. Special thanks are given to the South Pacific Commission for its hospitality and to SPREP Co-ordinator, Dr Jeremy Carew-Reid, and the staff of the SPREP Secretariat for encouragement and support and for overcoming the many problems involved in the production of this first edition of the report.


AREA SERVED BY THE SOUTH PACIFIC COMMISSION
POPULATION AT LATEST CENSUS
PACIFIC OCEAN
NORTH PACIFIC OCEAN
SOUTH PACIFIC OCEAN
STATE OF HAWAII
JOHNSTON
LINE ISLANDS
CHRISTMAS I.
PHOENIX ISLANDS
MARQUESAS ISLANDS
FRENCH POLYNESIA
TUAMOTU ARCHIPELAGO
SOCIETY ISLANDS
AUSTRAL ISLANDS
PITCAIRN
COOK ISLANDS
NIUE
WESTERN SAMOA
AMERICAN SAMOA
TOKELAU
WALLIS AND FUTUNA ISLANDS
KINGDOM OF TONGA
FIJI
TUVALU
KIRIBATI
NAURU
MARSHALL ISLANDS
MICRONESIA
TRUST TERRITORY OF THE PACIFIC ISLANDS
FEDERATED STATES OF
PALAU
NORTHERN MARIANA ISLANDS
GUAM
PHILIPPINE SEA
SOLOMON ISLANDS
VANUATU
NEW CALEDONIA AND DEPENDENCIES
LOYALTY ISLANDS
NORFOLK
NEW ZEALAND
CORAL SEA
TASMAN SEA
PAPUA NEW GUINEA
IRIAN JAYA
AUSTRALIA
Figure 2-1

CHAPTER 3

BASIC CONCEPTS AND TERMS

3.1 ELEMENTS AND ATOMS

All substances are made of one or more elements. At present there are just over 100 known elements, of which 92 occur in nature. The remainder can be made by technical procedures developed in recent years. Most of the known elements exist in more than one form called isotopes of a given element. The isotopes of all the elements are referred to by the more general term nuclide. There are, in total, about 2000 nuclides of the different elements. Radioactive nuclides are called radionuclides (section 3.3). Some radionuclides occur naturally and others can be made by artificial means. Different elements can be mixed, and in the mixture each element retains its own properties (for example, a mixture of gold and silver). Two or more elements can also combine to form a chemical compound. Elements lose their individual properties when they combine to form compounds. For example, the elements hydrogen and oxygen (both gases) in chemical combination form water; table salt is a chemical compound of the element sodium (a metal) and chlorine (a gas); and, although living things contain other elements in chemical combination, they are mainly compounds of the elements hydrogen, oxygen, carbon, and nitrogen.

Elements themselves are made up of atoms, the atom being the smallest unit into which an element can be divided and still keep its properties. Atoms have their own particular internal structures. They can be divided into component particles (sub-atomic particles), but these particles do not have the properties of the element to which the atoms belong.

3.2 STRUCTURE OF THE ATOM

An atom is an extremely small unit of an element both in weight and size. For example, there are about 6×10^{23} atoms in one gram of the lightest element hydrogen and about 2.5×10^{21} atoms in one gram of the heaviest naturally occurring element uranium. Each atom has a central core, its nucleus, which is surrounded by a number of much smaller sub-atomic particles, electrons, which move in paths around the nucleus. Most of the weight of an atom is in its nucleus, which is made up of two different sub-atomic particles called protons and neutrons, except in the case of the simplest hydrogen atom, which has only one proton and no neutrons in its nucleus. Protons have a positive electric charge, whereas neutrons have no electric charge. The weight of a proton and of a neutron is very small and about the same for each. The diameter of the nucleus of an atom is also very small, about 10^{-12} centimetre. For the different elements, the number of protons in the nucleus differs. This number is called the atomic number of the element. It is one way by which an element can be identified, because the number of protons in the nucleus of an atom determines the chemical properties of the element.

Each electron orbiting around a nucleus of an atom weighs about one two-thousandth of the weight of a proton or neutron. An electron has a negative electric charge equal in size to the positive charge of a proton. Because the number of protons in the nucleus of an atom and the number of electrons in its orbits is the same, and because a proton and an electron have equal and opposite electric charge, atoms have no net electric charge; that is, they are electrically neutral units. The overall diameter of an atom, as fixed by the orbits of its electrons, is about 10^{-8} centimetre, about 10,000 times greater than the diameter of its nucleus. The total number of protons and neutrons in the nucleus is another of the features by which the form of an element can be identified. This total number is called the mass number of the particular form of the element, the form being known as a nuclide or as an isotope of the element.

For a particular element, the number of neutrons in the nucleus is different from the number of neutrons in a different isotope of the same element. Different isotopes of an element have the same atomic number because the number of protons in the nucleus of each of their atoms is the same. The mass numbers of different isotopes of a particular element are different, however, because of the difference in the number of neutrons in their nuclei. Different isotopes of an element have the same chemical properties. Further, if an element is part of, or is used by, living things, its different isotopes behave in the same way in those living things.

For easy reference, a nuclide or isotope of an element can be identified in several ways. In strictly scientific terms it would be sufficient to refer to its atomic number and its mass number. It is the usual practice, however, to identify a nuclide or isotope by naming the element and attaching to the name the mass number of the particular nuclide or isotope. The names of all elements have, for convenience, been abbreviated to symbols (one or two letters of the alphabet). Accordingly, nuclides or isotopes can be identified by their symbols and mass numbers. The terminology used in this Report is illustrated by the following examples. The element uranium (symbol U) has atomic number 92; that is, the nucleus of each atom of uranium contains 92 protons, and each atom has 92 electrons. There are several isotopes of uranium. The most common, that which is most abundant naturally in soil and seawater, for example, has mass number 238; that is, each of its atoms has 92 protons and 146 neutrons in its nucleus. This nuclide or isotope is called uranium-238, and this can be written ^{238}U or U-238*. Another isotope of uranium, that which is used as fuel in nuclear reactors, is uranium-235 (U-235), the nuclei of its atoms each containing 92 protons, as given by the atomic number of uranium, and 143 neutrons. There are other isotopes of uranium which can be identified in a similar way. Further examples are the three isotopes of the element hydrogen (H), atomic number one. The nucleus of each of the atoms of the simplest and most abundant isotope of this element contains only a proton and no neutrons. It has a mass number of 1 and is identified as H-1 (hydrogen-1). A second isotope of hydrogen is H-2, usually called deuterium, and sometimes given the symbol D, the nucleus of each of its atoms containing one proton and one neutron. A third isotope of hydrogen is H-3 (usually called tritium, T). The nucleus of each atom of this isotope contains one proton and two neutrons.

---

* In this Report a nuclide or isotope will usually be identified by naming the element and giving the mass number (for example, uranium-238).

3.3 RADIONUCLIDES

The atoms of most isotopes of the elements which occur naturally are stable; that is, they do not change with time, although they may combine to form chemical compounds. On the other hand, the atoms of some isotopes of elements which occur naturally, and of most of the nuclides produced artificially, are unstable. Each nucleus of an unstable nuclide will sooner or later change, following a set pattern and giving off energy in the form of radiation. This process is called radioactive decay, radioactive disintegration, or radioactive transition. Nuclides which are unstable in this way are said to be radioactive and the nuclides are called radionuclides or radioisotopes. They have the property of radioactivity. The set pattern of radioactive decay of a radionuclide is identified by the rate at which its nuclei disintegrate and by the type and energy of the radiation given off.

Radioactive decay results in nuclei which, most often, are those of a different element. An important feature of all radioactive decay processes is that they cannot be changed, stopped or slowed down by any known physical or chemical means (for example, by heat, pressure or chemical combination).

For some radionuclides, stable (non-radioactive) nuclei of an element different from the original nuclide will be produced in a single step of radioactive decay. It is the practice to call the original radionuclide the parent in the radioactive decay process and the resulting nuclide its daughter product. Some radionuclides, however, are members of a chain or family of radionuclides which are produced by a series of radioactive decays progressing from one radionuclide to the next and resulting finally in a stable end-product. Such radioactive decay chains may involve only two steps in the series or, as in the case with some parent radionuclides which occur naturally, they may involve many steps. In either case, if the parent radionuclide continues to be present, there will be a gradual build-up of all members of the decay chain including the stable end-product. If the various nuclides in a radioactive decay chain remain with the parent of the chain, in time a state of balance (or equilibrium) is reached when all the radionuclides in the chain decay at the same rate and are present in proportions which depend on the half-lives of the successive daughter radionuclides. Figure 3-1 gives three examples of the processes of radioactive decay outlined above. In this Report, the radiation given out in the radioactive decay of certain naturally occurring and artificially produced radionuclides is of particular importance.

3.4 ACTIVITY

Because the different radionuclides disintegrate in different ways, both with respect to their rates of decay and to the type and energy of the radiation given off in the process, it is not very useful to measure amounts of them simply by their weights (for example, in grams). In practice, the amount of a radionuclide is measured in terms of the rate at which its nuclei are undergoing decay or disintegration. The quantity measured is called the activity of the radionuclide. The unit of activity used most often in this Report is the becquerel (Bq), named after the French scientist who, in 1896, first identified in natural uranium the property which is now known as radioactivity. An amount of a radionuclide has an activity of one becquerel if one of its nuclei is disintegrating each second. The becquerel is a very small unit of activity. The need to use a quantity other than the weight of a radionuclide to give its amount is illustrated by the following. Ten megabecquerels (10 MBq) of pure cobalt-60, an artificially produced radionuclide, weighs less than 2.5 thousandths of a gram, whereas the same activity of naturally occurring uranium-238 weighs more than 500 kilograms.

The becquerel and its multiples have only recently replaced an older unit of activity, the curie (Ci) and its sub-multiples. An activity of 1 curie is 3.7×10^{10} becquerel. In the preparation of this Report, it has been necessary to use information from a number of published reports, some of which expressed the activity of radionuclides in the older unit, the curie. For uniformity, activities expressed in curie have, in most cases, been changed to the new units, the becquerel, using the above equivalence between the two units. However, in the preparation of Chapters 8 and 9, which discuss radioactivity in the ocean, radioactive waste disposal, and the international agreement known as the London Dumping Convention, the use of the curie is retained, because the documents related to the Convention all make use of the older unit.

3.5 CONCENTRATION AND DEPOSIT DENSITY OF RADIONUCLIDES

In considering the possible harmful effects on living things of radionuclides in the environment, it is often necessary, and appropriate, to measure or to compare quantities other than simply the total activity of a radionuclide in a substance. For this reason, concentrations of radionuclides in a variety of substances and the deposit density of radionuclides on the earth's surface are used. In the following paragraphs examples are given of units of measurement which are used in later chapters to report concentrations and deposit densities of radionuclides in the environment.

The concentration of a radionuclide in a substance can be given in several ways. Firstly, it can be measured as the activity per unit volume of a substance. For example, the concentration of tritium (hydrogen-3), a naturally occurring as well as an artificially produced radionuclide in the environment, can be measured in becquerel per cubic metre of air or water (Bq m^{-3}). With respect to iodine-131 and strontium-90, two of the radionuclides present in fallout from nuclear explosions on or above ground, it is appropriate for the purpose of assessing any harmful effects of them on persons to measure their concentrations in fresh milk in becquerel per litre of milk (Bq l^{-1}). Secondly, the concentration of a radionuclide may be measured as its activity per unit weight of a substance. For example, the concentration of potassium-40, a naturally occurring radionuclide, can be measured in becquerel per kilogram of soil or human tissue (Bq kg^{-1}). A third approach is to measure the concentration of a radionuclide as its activity per unit weight of the same element, for example, with respect to potassium-40, in becquerel per gram of total potassium in a substance (Bq $(gK)^{-1}$). A variation of this method is to measure the concentration of a radionuclide as its activity per unit weight of a stable nuclide of another element which is used by living things in a way similar to the way the radionuclide is used. For example, for strontium-90 and caesium-137, both radionuclides present in fallout from nuclear explosions, concentrations can be measured, respectively, in millibecquerel of strontium-90 per gram of calcium in bone (mBq $(gCa)^{-1}$) and becquerel of caesium-137 per gram of potassium in meat or fish (Bq $(g\ K)^{-1}$). With respect to the deposit of radionuclides on the earth's surface, including the oceans, the deposit density, that is, the amount of the radionuclide which falls on a given area, can be measured as the activity per unit area. For example, the deposit densities of iodine-131 and strontium-90 can be measured in becquerel per square metre (Bq m^{-2}).

3.6 RADIOACTIVE HALF-LIFE

The number of radioactive nuclei, and the activity of a particular radionuclide, decrease with time at a rate which is identified with the radionuclide. In scientific terms, this unique feature of the decay of a radionuclide is given by a

quantity called its decay constant. For practical purposes, and for this Report, a more convenient way of giving the rate of change is by using the half-life of the radionuclide.

The half-life of a radionuclide is the length of time required for half of its unstable nuclei, present at a stated starting time, to undergo radioactive decay. Subsequently, in the same length of time, half of the unstable nuclei remaining will in turn decay, and so on. For example, if, for a radionuclide of half-life eight days (the case for iodine-131), there are one million atoms of the radionuclide present now, eight days from now 500,000 nuclei of atoms of the radionuclide will have decayed (half the original number), leaving 500,000 unstable nuclei. In the next eight days, half of those remaining unstable nuclei will decay, that is 250,000, leaving 250,000 unstable nuclei (one-quarter the original number). After the next eight days, half of that number will in turn decay, leaving 125,000 (one-eighth of the original number), and so on.

The half-life of a radionuclide cannot be changed by any known physical or chemical means. The half-lives of the different radionuclides range from small fractions of a second to many thousands of millions of years. Using appropriate equipment and procedures in scientific laboratories, the half-lives of most radionuclides have been measured accurately and published in the scientific literature. With this information, the accurate measurement of the half-life of an unknown radionuclide is one way by which it can be identified.

By fairly simple arithmetic, the half-life of a radionuclide may be used not only to calculate the number of nuclei remaining after one or more half-lives but also the number of those nuclei present at intermediate times or at earlier times. If the activity, activity concentration or deposit density of a radionuclide is known at a particular time, the values of those quantities at any past or future time can be calculated precisely if the radionuclide and its half-life are also known. Figure 3-2 shows how the numbers of unstable nuclei and their activity change with time.

3.7 IONIZING RADIATIONS

Radionuclides in their radioactive decay emit energy as various types of radiation: alpha and beta radiations (both sub-atomic particles) and gamma radiation (bundles, or quanta, of electromagnetic radiation). Radionuclides in the environment can result in exposure of living things to the radiations emitted. When a substance is exposed to alpha, beta or gamma radiations, some or all of the energy of the radiations is absorbed (deposited) in the substance as the result of interaction between the radiations and atoms of the substance. The harm which radionuclides may cause to living things results from the absorption, in its cells, of the energy of alpha, beta or gamma radiation. Ionization is the main process by which the energy of the radiations emitted by radionuclides is absorbed. Thus the radiations as a group are referred to as ionizing radiations. In the ionization process, the radiation knocks electrons out of the orbits of atoms of substances which it penetrates, leaving each atom so affected temporarily short of an electron and therefore electrically positive. An atom affected in this way is called a positive ion. The electron knocked out either exists in the substance for a short time by itself or temporarily adds itself to the electrons in the orbits of another atom. In either case, a negative ion is formed. Thus ionization produces an equal number of positive and negative ions, that is, a number of ion pairs. Alpha, beta and gamma radiations are different in form and in how they lose their energy in passing through substances.

Alpha radiation is a stream of small particles, the nuclei of helium atoms, and

therefore made up of two positively charged protons and two zero-charged neutrons in combination. Alpha radiation travels relatively slowly and loses its energy in a short distance in a substance. It is said to have a short range or path in a substance. It can only pass through a few centimetres of air, it is completely stopped by even a thin sheet of paper, and it can pass through only a few hundredths of a millimetre of human tissue. It cannot penetrate the dead outer layer of cells which forms the surface skin of a person. It does, however, produce a large amount of ionization over the short distance it travels in a substance. Because of the low penetrating power of alpha radiations, a radionuclide which emits alpha radiation alone cannot harm a living thing unless the radionuclide is within it and is incorporated in living cells so that the alpha radiation irradiates them.

Beta radiation is a stream of charged electrons, each of which has a very small weight. The electrons have energy because of the high speed with which they are emitted by a radionuclide in its radioactive decay. Beta radiation produces in a substance less ionization per unit length of travel than alpha radiation, but its penetrating power and its range in a substance are greater than for alpha radiation. The range of beta radiation in a substance depends on its energy, a property identified with the radionuclide which emits it, and on the nature of the substance. Beta radiation can penetrate up to a few metres of air and up to about a centimetre of human tissue. A radionuclide which emits beta radiation alone can cause irradiation exposure to a small depth in living things if the radionuclide is on or close to them. However, because of the low penetrating power of beta radiations, thin protective barriers can absorb all the beta radiation before it reaches the outer surface of living things. If a radionuclide which only emits beta radiation enters living things, the energy of its radiation will be absorbed in cells and tissue near the location of the radionuclide.

Gamma radiation is a different type of ionizing radiation*. It carries its energy in bundles, or quanta. It belongs to the large family of electromagnetic radiations, which includes radiowaves, radar radiations, microwaves, infra-red radiations emitted by objects because of their temperatures, visible light, ultra-violet light as in sunlight, X-rays and gamma rays. Gamma radiation has energy but does not have weight or electric charge. Unlike alpha and beta radiations, it does not have a fixed range in a substance but instead loses its energy continuously as it passes through the substance, causing ionization as it goes. By the use of thick protective barriers, particularly of heavy material such as lead and concrete, energy of gamma radiation can be readily absorbed. A radionuclide which emits gamma radiation* can irradiate cells and tissues of living things both when it is external to or within them.

X-rays, which, as discussed later in this Chapter, are given off by some types of electrically operated equipment, behave in a similar way to gamma radiation in their passage through a substance.

3.8 ABSORBED DOSE AND DOSE EQUIVALENT

(a) Absorbed radiation dose - Unit Gray

The energy absorbed when alpha, beta or gamma radiations or X-rays pass through a substance is referred to as the absorbed radiation dose (the absorbed dose) of

---

* Some radionuclides which, in their decay, emit alpha or beta radiations, also emit gamma radiation (see Table 3-1).

radiation in the substance. The unit of absorbed dose used in this Report is the gray (Gy) and its sub-multiples. The gray has recently replaced an older unit, the rad, as the unit of absorbed dose. It is primarily through absorbed doses to living things, or through another type of radiation dose (dose equivalent) discussed in the following paragraph, that an attempt can be made to assess or compare the possible harmful effects on living things of radionuclides and ionizing radiations in the environment.

(b) Dose equivalent - Unit Sievert (absorbed dose x quality factor)

Scientific research has shown that absorbed doses in living things from different radionuclides and different types of ionizing radiations are not sufficient by themselves to assess the severity or chances of harmful effects of ionizing radiations in living things. The quantity used for such assessments is the dose equivalent, of which the unit used in this Report is the sievert (Sv) and its sub-multiples. The sievert recently replaced an older unit, the rem, as the unit of dose equivalent. Dose equivalents are calculated by multiplying absorbed doses by a number called the quality factor. The quality factor relates to the amount of ionization the different radiations cause per unit length of their paths in a substance. For alpha radiation, which causes a large amount of ionization per unit length of its path in a substance, the quality factor is 20. For beta and gamma radiations and for X-rays the quality factor is 1. It follows that, for beta and gamma radiations and for X-rays, dose equivalents are numerically the same as corresponding absorbed doses, whereas for alpha radiations dose equivalents are 20 times greater than the corresponding absorbed doses. In this Report, unless otherwise indicated, the term dose is used subsequently to mean dose equivalent, values of it being measured in sievert and its sub-multiples.

It is extremely important to recognize that it is the dose equivalent that is the important consideration in assessing the effects of ionizing radiation, not the origin of the radiation. The potential harm to living things from ionizing radiation depends on the type of radiation (that is, whether it is alpha, beta, gamma or X-radiation) and its energy. It makes no difference whether the ionizing radiation comes from a natural or an artificial source.

There are two types of radiation exposure by which living things can receive a dose of radiation: external exposure and internal exposure.

External exposure of cells and tissues of living things arises from a source of ionizing radiation which is external to them. In some external exposures the whole body receives uniform doses of radiation to all organs and tissues. This is essentially the case when the external exposure is due to high-energy gamma radiation emitted by radionuclides in the environment. In some external exposures, the dose of radiation involves only part of the body or is highly non-uniform. This would be the case for some exposure to radionuclides which might only emit beta radiation. As indicated above, because alpha radiations are so readily absorbed, radionuclides in the environment which emit alpha radiations only are not a source of external exposure. Internal exposure, on the other hand, results from a radionuclide within a living thing. The amount and distribution of the radiation doses to organs and tissues of living things, as the result of internal exposure to radionuclides, will depend on how the radionuclides are used by living things, on their radioactive half-lives and on the radiations they emit.

In addition to absorbed dose and dose equivalent already discussed, it is necessary in this Report to use three other ways to express radiation dose: effective dose equivalent, collective dose equivalent and collective effective dose equivalent commitment. These quantities are explained in the following paragraphs.

(c) Effective dose equivalent - Unit Sievert (dose equivalent x a factor)

The radiation dose received by persons from a given source of ionizing radiation (natural or artificial) will, in most cases, not be the same for each organ or tissue of their bodies. Simply adding together the separate doses to individual organs and tissues does not give a true picture of the possible harmful effects of the non-uniform radiation exposure. In these circumstances, each dose equivalent must be multiplied by an appropriate factor before adding the doses together. The effective dose equivalent then obtained expresses the non-uniform doses as a uniform whole body dose which would produce the same overall harmful effects. When effective dose equivalents from different sources of ionizing radiation are calculated in this way, they can be compared directly one with the other. The unit of effective dose equivalent is the sievert, the same unit as for dose equivalent itself. The factors used in calculating the effective dose equivalent were assigned by the International Commission on Radiological Protection (ICRP, 1977) and were used by the United Nations Scientific Committee on the effects of Atomic Radiation in its most recent report (UNSCEAR, 1982). The factors relate specifically to such organs and tissues as gonads, breast, bone marrow, lungs, thyroid, and bone itself and to other organs and tissues less likely to be affected by radiation doses.

(d) Collective dose equivalent - Unit Man Sievert

To assess the possible harmful effects of ionizing radiation, it is sometimes helpful to calculate another quantity of radiation dose called the collective dose equivalent. This dose is simply the total of the radiation dose equivalents to a given organ or tissue received by all the persons in a population group exposed to a source of ionizing radiation. The number in a group may be small (for example, those living near a nuclear reactor) or large (for example, the total population of a country, a region, or the whole world). Collective dose equivalents are frequently calculated by multiplying together the number of persons in a population group and the average dose equivalent to the organ or tissue for which it is desired to calculate the collective dose. Collective dose equivalents are often calculated for groups of people whom it is thought may be at greatest risk from a particular release of radioactivity to the environment. The unit in which collective dose equivalents are expressed is the man-sievert.

(e) Effective dose equivalent commitmment - Unit Sievert

Over a period of time, the concentrations or deposit densities of artificial radionuclides in the environment, in food and water consumed, and in persons change with time or location due, for example, to the non-uniform distribution of the radionuclides or the decrease in their activities because of radioactive decay. The assessment of annual effective dose equivalents or collective dose equivalents may not be the best way to represent the possible harmful effects for a population group (world, regional, or national) of a radiation exposure over a long time, particularly if the radionuclides are long-lived. For these circumstances another type of radiation dose assessment has been established by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 1982). The radiation dose calculated is the effective dose equivalent commitment. The calculation is complex, but this dose has the merit of taking account of the various environmental and time-related factors which affect the radiation dose to be received over an infinite period of time because of the release of radioactivity into the environment. The calculation gives the radiation dose to be received by a population group (including children yet to be born) from a given practice which involves the members of that group in a radiation exposure. It differs from a collective dose equivalent in that it represents the radiation dose input to

individuals in a population group. The effective dose equivalent commitment obtained (say the effective dose equivalent commitment from nuclear bomb tests in the atmosphere) can be compared with the annual effective dose equivalent for the same population from natural sources of ionizing radiation, which essentially does not change with time. The unit of effective dose equivalent commitment is the sievert. The absorbed dose commitment can also be calculated. In this case, the unit used is the gray.

3.9 PATHWAYS OF EXTERNAL AND INTERNAL EXPOSURE

In assessing the possible harmful effects of environmental exposure of living things to sources of ionizing radiation, it is necessary to identify a number of pathways by which exposures may occur and thus give rise to radiation doses to organs and tissues. It is important to appreciate that, to assess possible harmful effects of sources of ionizing radiation, it is necessary to determine the radiation doses in particular organs and tissues. Figure 3-3 shows five pathways by which either external or internal exposure to sources of ionizing radiation result in radiation doses to organs and tissues. In the following paragraphs examples of these pathways are given.

Pathways 1, 2 and 3 in Figure 3-3 all lead to external exposures. An example of exposure by Pathway 1 is the radiation dose the organs and tissues of living things receive from naturally occurring cosmic rays which reach the earth from outer space (section 3.10.1.1). A second example is the radiation dose to organs and tissues of persons undergoing an X-ray examination for medical diagnostic purposes. An example of exposure by Pathway 2 is that of persons who are in or near a cloud (or plume) of a radioactive gas or vapor released to the atmosphere. The size of the radiation dose to living things exposed in this way depends on the radionuclides in the cloud, on the activities and concentrations, and on the length of time of the exposure. If the radionuclides released to the atmosphere are deposited on the earth's surface as fallout (section 3.10.2), those radionuclides may become a source of external exposure to living things in the area of the deposit (Pathway 3). A build-up of overlying soil or the emplacement of solid building materials, such as brick and concrete, between the deposit and the living things reduces the radiation doses, because some of the energy of the ionizing radiations emitted by the radionuclides is absorbed by those materials. The size of the radiation doses also depends on the radionuclides deposited, on their activities and deposit densities, on the distance of the living things from the radioactive contamination, and on the length of time of the exposure. From what has already been said, radionuclides which emit alpha radiation alone will not cause external exposure by any of the Pathways 1, 2, or 3.

Pathways 4 and 5 (Figure 3-3) result in internal exposure. Pathway 4 represents an internal exposure from radionuclides in the air. If living things breathe the radionuclides into their lungs, radiation doses will be received by lung tissue, some of the radionuclides in the lungs may reach the blood stream and be distributed internally, and some of them may reach the stomach from the nose and subsequently be distributed internally. The size of the radiation doses depends on the radionuclides breathed in, on their activities, on their concentrations, on the size of the particles they are associated with, and on the length of time the living things breathe in the radioactively contaminated air. Pathway 5 shows how internal exposure arises from radionuclides in food and drinking water and results in radiation doses to organs and tissues of living things. The eating of radioactively contaminated food and the drinking of radioactively contaminated water make radionuclides available for internal distribution. The sizes of the radiation doses to organs and tissues depend on the radionuclides involved, on their activities and concentrations and on the amount of food or water drunk.

It is important to appreciate, in the case of exposure by Pathways 4 and 5, that different radionuclides which get into living things will be used in different ways. Some radionuclides, because they are isotopes of elements which are normally used by the living things, concentrate, along with the stable isotopes of the elements, in particular organs or tissues. For example, the fission-product radioisotopes of iodine (section 3.10.2) taken in by persons will concentrate in their thyroids, along with the stable iodine in their diet, where the major part of the radiation doses from them will be received. Some radionuclides in food and water may not be nuclides of elements which are normally used by living things. These may go to a particular organ or tissue because they are similar chemically to an element which is normally used by living things. For example, the fission product radionuclides of strontium taken in by persons will concentrate in bone along with stable (non-radioactive) calcium in the diet, because strontium and calcium are chemically similar. Then again, some radionuclides are distributed more or less uniformly throughout living things when taken in through food or water. For example,tritium, the fission-product radioisotopes of caesium, and the naturally occurring radionuclide potassium-40, when taken in by persons in food or water, will be distributed fairly uniformly throughout their soft tissue.

3.10 SOURCES OF IONIZING RADIATION

Living things are exposed to a number of sources of ionizing radiation. Some occur naturally and have been present in the environment since the beginning of the earth's history. Others are artificial; that is, they result from human actions. Later Chapters discuss the radiation doses to living things in the South Pacific Region from the various sources of exposure to ionizing radiation. The aim in this section is to identify the sources and to indicate their origins.

3.10.1 Natural Sources

As will be discussed in Chapter 5, there are three natural sources of radiation exposure: cosmic rays, cosmogenic radionuclides, and primordial radionuclides.

3.10.1.1 Cosmic rays

High-energy radiations (mainly protons) enter the solar system from outer space. Some of them reach the earth's surface. These radiations are primary cosmic rays. Their protons also act on the nuclei of atoms in the earth's atmosphere, and other sub-atomic particles, called secondary cosmic rays (mainly protons and neutrons), are produced. Some of the secondary cosmic rays reach the earth, and others act on nuclei of atoms in the air and on the earth to give a number of different radionuclides known as the cosmogenic radionuclides. The primary and secondary cosmic rays which reach the earth's surface give radiation doses to persons by external irradiation (Pathway 1, Figure 3-3). Cosmic rays will continue to be a major source of radiation dose to persons.

3.10.1.2 Cosmogenic radionuclides

Nuclear changes (called nuclear transmutations) result from the interactions between stable nuclei of atoms in the air and on the earth and the sub-atomic particles (mainly neutrons and protons) in secondary cosmic rays. As a result, many radionuclides are continually produced in the earth's environment. These are the naturally occurring cosmogenic radionuclides. In a general way, nuclear transmutations can be represented as follows:

Target Nuclei	+ Bombarding Sub-Atomic Particles	⟶	Product Nuclei	+ Sub-Atomic Particles or Gamma Radiation

An example of such a nuclear transmutation which goes on in the air is the production of radioactive carbon-14 from stable nitrogen-14.

$$\text{Nitrogen-14} + \text{Neutron} \longrightarrow \text{Carbon-14} + \text{Proton}$$

UNSCEAR (1982) lists only four of the cosmogenic radionuclides as being significant sources of radiation exposure of living things: tritium, beryllium-7, carbon-14, and sodium-22. The radiation dose each year to living things from these cosmogenic radionuclides is almost all due to internal irradiation.

3.10.1.3 Primordial radionuclides

Natural radionuclides have been present on the earth and in its waters since its formation, estimated to be about 4500 million years ago. These radionuclides, called the primordial radionuclides, can be divided into two groups. There are the few which undergo one-step radioactive decay to form stable nuclides, for example, potassium-40 and rubidium-87. Then there is the large number which are members of the three natural radioactive decay series of which uranium-238, uranium-235, and thorium-232 are the parents. Potassium-40, rubidium-87 and the parents of the three natural radioactive decay series all have very long half-lives (Table 3-1).

Among the primordial radionuclides which decay in a single step, only potassium-40 (Figure 3-1(a)) and rubidium-87 are significant contributors to the natural radiation doses to living things (UNSCEAR, 1982). Those two radionuclides, in addition to being in the earth's environment, are present in the human body and in many other living things and therefore cause internal irradiation. Unlike rubidium-87, which only gives off beta radiation in its decay, potassium-40 emits both beta and gamma rays. As a consequence potassium-40 is also a source of external irradiation of living things.

Naturally occurring uranium and thorium are widely distributed in the earth, in its waters, and in living things. Uranium-238, uranium-235, and thorium-232 are the parent radionuclides of three radioactive decay series. They decay through a series of radioactive daughter products to give finally a non-radioactive end-product. The half-lives of many of the daughter products of the series are short. The member radionuclides of each of the series may be present in an equilibrium state along with the parent of its decay series. However, members of a series can become separated from some of the other members and from the parents of the series. Whereas some members of the three series emit only alpha or beta radiation, others emit gamma radiation as well. The decay series of uranium-238 and thorium-232 are shown in Figures 5-1 and 5-2, respectively. The uranium-235 decay series is not a significant contributor to the annual natural radiation dose to persons (UNSCEAR, 1982).

3.10.2 Artificial Sources

There are a number of artificial sources which actually, or potentially, expose persons and other living things to radiation doses. Of primary importance are the artificial radionuclides and X-rays.

A large number of radionuclides can be made by one of the following processes:

nuclear transmutation, nuclear fission, or nuclear transmutation followed by radioactive decay. Controlled nuclear transmutations using neutrons as the bombarding sub-atomic particles are carried out in nuclear reactors to prepare a large number of artificial radionuclides which have applications in medicine, industry and scientific research. Neutron-induced transmutations also produce artificial radionuclides in the constructional components of nuclear reactors. For example, iron-55, a radionuclide of iron, is produced in reactor components made of the stable isotope of iron (iron-54) as the result of neutron bombardment during the operation of the reactor.

$$\text{Iron-54} + \text{Neutron} \longrightarrow \text{Iron-55} + \text{Gamma Radiation}$$

Similarly, some nuclei of deuterium (hydrogen-2) are present in small amounts in the cooling water used in nuclear reactors, and this stable nuclide is converted by neutron transmutation to radioactive tritium (hydrogen-3).

$$\text{Hydrogen-2} + \text{Neutron} \longrightarrow \text{Hydrogen-3} + \text{Gamma Radiation}$$

Neutron-induced radionuclides are also formed as a result of nuclear explosions. In these explosions neutrons are produced, and some of the neutrons cause nuclear transmutations in the constructional components of the bombs and in the stable nuclides of elements present in the immediate neighbourhood of the explosion; for example, in the nuclides in the air and in the earth within the range of the neutrons released at the time of the explosion.

Nuclear transmutations caused by neutrons are of particular importance in this Report. Artificial radionuclides can also be produced by nuclear transmutations involving other bombarding sub-atomic particles, such as alpha particles, protons, deuterons (the nuclei of hydrogen-2), and gamma radiation. For such transmutations to occur, the bombarding particles and the gamma radiation must have very high energies. These energies are normally achieved only in a scientific laboratory using machines developed for scientific research. Because it is possible for alpha and gamma radiations to cause nuclear transmutations, it is important to point out that those radiations when given off in the decay of radionuclides (either natural or artificial) have insufficient energy to produce nuclear transmutations.

A second process by which artificial radionuclides are produced is nuclear fission. When neutrons enter the nuclei of some nuclides, the nuclei split or fission. Nuclides which have this property are called fissile nuclides. In the fission process, the nuclei split into two fission fragments of approximately equal weight, give off a few neutrons (called prompt neutrons), and release energy.

$$\underset{\text{Nucleus}}{\text{Fissile}} + \text{Neutron} \longrightarrow \underset{\text{Fragments}}{\text{2 Fission}} + \text{Neutrons} + \text{Energy}$$

There are about 36 different ways in which the nuclei of a particular fissile nuclide split when fission occurs, giving about 72 different fission fragments. These fragments, which are radioactive, within a very short time give off more neutrons (called delayed neutrons) and beta radiation to form a mixture of nuclides which are mostly radioactive. The radionuclides in this mixture are called fission products.

$$\text{Fission Fragments} \longrightarrow \text{Fission Products} + \text{Neutrons} + \text{Beta Radiation}$$

The different fission products have a wide range of half-lives. More than 200

different radionuclides have been identified among fission products. The fission products that will be discussed in later chapters are listed in Table 3-1.

Only a few nuclides, some of the isotopes of uranium, thorium, and plutonium, are fissile. For the purpose of this Report, it is only necessary to consider uranium-235, uranium-238 and plutonium-239. The first two occur in nature, whereas plutonium-239 is artificially produced. The rate of fission depends on the energy of the neutrons which bombard the fissile nuclei. Fission occurs in uranium-235 and plutonium-239 at all neutron energies, the rate being greater for neutrons of low rather than high energy. On the other hand, fission occurs in uranium-238 nuclei only if the bombarding neutrons have high energy. Uranium-235 is present as only 0.7 percent of naturally occurring uranium, the remaining uranium being almost totally uranium-238. If uranium 235 is to be used as the fissile material, it is necessary to increase the percentage of it in its mixture with uranium-238.

Although there are many different ways in which the fissile nuclei can be split, the amount of energy released per nucleus undergoing fission does not vary much. Neutrons which are released in the fission of each nucleus can cause fission in the neighboring fissile nuclei. This continuing fission process is known as a chain reaction, which will continue as long as there are sufficient fissile nuclei and neutrons available. Such chain reactions are the basis of the operation of a nuclear reactor and of the explosion of a nuclear (atomic) bomb. There are, however, important differences between these two chain reactions.

In a nuclear reactor, the rate at which the chain-reaction goes on is controlled by the concentration of the fissile nuclide present in the fuel and by the number of neutrons which are available to continue the chain reaction. In one type of nuclear reactor, at present the one most commonly used to generate electricity, uranium-235 is the fissile nuclide at a concentration of no more than about four percent with respect to the associated uranium-238. In such reactors the fissile uranium-235, along with the uranium-238, is put in the core of the reactor in a number of fuel rods, which are sealed metal tubes. The fission chain reaction in the fuel is controlled by increasing or decreasing the number of neutrons, produced by fission, that are available to cause further fissions. This is done by moving out of, or into, the space between the fuel rods non-fissile, neutron-absorbing material in the form of control rods. If the control rods are fully inserted between the fuel rods, the nuclear chain reaction stops, because insufficient neutrons are available to keep it going. The fission process in the fuel of a nuclear reactor goes on so slowly that only about one-third of the fuel has to be removed as spent fuel and replaced each year.

A nuclear bomb, on the other hand, is designed and constructed so that the chain reaction in the fissile nuclides contained within the bomb casing goes on very rapidly. The whole fission process is completed in a very small fraction of a second, and there is a sudden release of the large amount of energy resulting from the splitting of a large number of fissile nuclei. To achieve this rapid completion of the total fission process in a nuclear bomb in which uranium-235 is used, it is necessary for the uranium-235 to be very highly enriched (usually greater than about 90 percent in relation to the accompanying uranium-238) and for as few as possible of the neutrons produced in the splitting of the fissile nuclei to escape without causing further fission.

There are some features in common in the use of the fission process in a nuclear reactor and in a nuclear bomb. Firstly, a very large amount of energy is produced (over a long period in a reactor, but extremely rapidly in a bomb). In a reactor for the production of electricity, the heat produced by controlled fission in the fuel rods is used to convert water into steam to drive an electricity-generating

turbine. In an explosion of a nuclear bomb, the energy appears as a short duration flash of very bright light, as very high temperatures in surrounding materials, and as blast and shock waves. Secondly, in the operation of a reactor and in the explosion of a nuclear bomb, the same wide variety of radioactive fission products is formed. A reactor is constructed so as to keep the fission products within the metal tubes of the fuel rods and within the thick steel container (the pressure vessel) in which the reactor core is sealed. With the explosion of a nuclear bomb, the fission products are released to the immediate surroundings of the explosion. If the explosion occurs on or above the ground, the radioactive fission products are transported and distributed in the environment. If the explosion is underground, the aim is usually to contain the fission products within the hole (shaft) in which the bomb is exploded. The third feature common to the operation of a nuclear reactor and the explosion of a nuclear bomb is the production of a number of radionuclides by nuclear transmutations, mostly by neutron bombardment of stable nuclei of elements used in the construction of the reactor or bomb and in nearby material. In a reactor, by design and construction, most of those radionuclides are retained within the reactor. In the explosion of a nuclear bomb, however, the radionuclides produced by nuclear transmutation will, along with the fission products, become the total radioactive debris of the explosion.

It is important to appreciate that the design and construction of nuclear reactors exclude the possibility of a nuclear-bomb-type explosion occurring in the fissile fuel. During routine operation, however, there do occur small, controlled releases of radioactive gases to the atmosphere. There have only been a few accidents in the operation of nuclear reactors in which radionuclides, particularly some fission products, have been released in small amounts to the environment. Those accidents have, in general, been due to component failure, human operational error, or both, resulting in some escape to the environment of the radionuclides which the reactor is designed and constructed to retain.

With respect to nuclear bombs, it is necessary to refer to those in which the explosion results not only from fission, but also from the even larger amount of energy released when the nuclei of light nuclides such as hydrogen, deuterium, and tritium are made to combine (to fuse). This nuclear process is called fusion, and the explosion is called a thermonuclear explosion, because fusion is achieved by raising the nuclei of the light atoms to extremely high temperatures to give them sufficient energy to fuse together. In a thermonuclear bomb (sometimes called a hydrogen bomb) the high temperature necessary for fusion is obtained by the explosion of an associated nuclear fission bomb as an initiator, or trigger, for the thermonuclear explosion. Consequently, the explosion of a thermonuclear bomb results in radioactive fission products (from the fission trigger), in radionuclides produced by nuclear transmutations in surrounding material, and in radioactive tritium either as an unfused residue or as a product of the fusion process. All those radionuclides will be transported and distributed in a manner similar to those produced by nuclear fission bombs except that, for a thermonuclear explosion on or above ground, their transport and distribution in the environment will depend on the height to which they are carried above the surface of the earth by the explosion.

The third group of man-made radionuclides to be considered is that produced by the combination of the process of nuclear transmutation followed by radioactive decay. A number of man-made radionuclides fall into this group, the most relevant for this Report being isotopes of plutonium and neptunium. All isotopes of plutonium are radioactive, and they are all man-made. A radioisotope of this element which is important when considering environmental radioactivity is plutonium-239. Apart from being an artificial radionuclide, plutonium-239 is fissile at all energies of neutrons and has great potential as a fuel for nuclear reactors and for use in the construction of nuclear and thermonuclear bombs. Plutonium-239 has a long

radioactive half-life, 2.44×10^4 years. Another radioisotope of plutonium, plutonium-241, is also fissile at all neutron energies, but it has a comparatively short half-life of 14.4 years. In radioactive decay, plutonium-239 gives off only alpha radiation, and it is therefore not a source of external irradiation to living things. Its potential for harmful effects arises from its intake by living things and its incorporation in living cells. For persons, the most important hazard of plutonium-239 is the breathing into the lungs of particles containing the radionuclide. Plutonium-239 is produced primarily by the transmutation by neutrons of uranium-238, which is present with uranium-235 in nuclear fuel of a reactor or in a nuclear or thermonuclear bomb, and by a series of subsequent steps of radioactive decay of the radionuclide produced by that transmutation. Uranium-238 is transmuted to another radionuclide of uranium, uranium-239, which has a half-life of 23.5 minutes and decays, giving off beta radiation, to form neptunium-239. Neptunium-239 is also radioactive and decays with a half-life of 2.35 days, giving off beta radiation, to form plutonium-239. It will be seen later in the Chapter that processes have been developed, and are in use, to recover the plutonium-239 produced in the fuel rods removed from a nuclear reactor (the spent fuel). The plutonium-239 recovered can be used as fuel in nuclear reactors or as the fissile material in nuclear and thermonuclear bombs.

X-rays are a man-made source of ionizing radiation which do not originate in the nuclei of radionuclides but which are produced as the result of interactions between atoms and high speed electrons which are accelerated to the necessary speeds in some types of electrically operated equipment. X-rays are used extensively for medical and dental diagnostic purposes, and in these uses they give rise to radiation doses to patients, to the medical specialists and dentists who use the equipment, and to the technical staff who assist in their use. It will be seen in Chapter 7 that, at least in technologically developed countries, X-rays used for medical and dental purposes are the major man-made source of radiation doses to persons. X-rays are also used in industry and scientific research and are a source of radiation dose to those working with them in these applications.

Additionally, X-rays are produced as an unwanted by-product in some electrically operated equipment in which electrons are accelerated to high speeds. An example is some types of colour television receivers, which can give a very small dose of ionizing radiation to viewers (see Chapter 7, Section 7.4.2).

3.11 RADIOACTIVE WASTES

The problem of managing wastes has existed since people first lived on earth. Waste management problems have, with time, become more complex as populations have increased in numbers and become more concentrated and as technological developments have produced larger quantities and different types of wastes, some creating new potential hazards to the health and well-being of living things and to the environment. Although considerable progress has been made in the management of the variety of wastes now produced on earth, much remains to be done to achieve uniformly high standards of waste management in all countries. With respect to radioactive waste, the Nuclear Energy Agency of the Organization for Economic Cooperation and Development recently pointed out (OECD/NEA, 1982): "Although relative newcomers to the scene, the wastes that probably receive most attention from the scientific community, from governments and from the general public are radioactive wastes. Extensive guidelines for their management have been established at the local, regional and international level, and countries with commitments to nuclear power have programs to demonstrate and implement technology for the safe management of the wastes that are produced." Radioactive wastes are produced in many operations. The more important sources of them are the preparation of fuel for

nuclear reactors, the operation of those reactors, the spent fuel removed from them, the manufacture and explosion of nuclear and thermonuclear bombs, and the preparation and use of radionuclides for medical, industrial, and scientific purposes. Although different radioactive wastes have distinct characteristics, experience already gained in the management of other potentially hazardous wastes is of some assistance in developing effective management practices for radioactive wastes. The activity of radioactive wastes and, therefore, their potential for harm, decreases according to the half-lives of the radionuclides they contain.

Radioactive wastes may be in the form of solids, liquids or gases. The wastes, in practice, fall into two classes: low-level radioactive wastes and high-level radioactive wastes*.
There is, however, no precise scientific definition which distinguishes these two classes of wastes. Much of the waste from the technological procedures listed above is low-level radioactive waste because the total activity in becquerel of the radionuclides in it is low or because the concentration of the radionuclides in it in becquerel per kilogram or in becquerel per litre is low. For low-level radioactive wastes, the quantity to be managed in terms of total weight or volume is usually high. On the other hand, high-level radioactive wastes, which are most often small in volume, contain high activities of radionuclides at high concentrations. In the classification of radioactive wastes for the purpose of taking a particular waste management action, it is usual and appropriate to consider the particular radionuclides in the wastes and their radioactive half-lives, as well as the activities and concentrations of radionuclides present. The approach to the classification of radioactive wastes for waste management action is illustrated by the definition by the International Atomic Energy Agency, as required by the Convention on the Prevention of Marine Pollution by the Dumping of Wastes and other Matter (the London Dumping Convention), of high level radioactive waste unsuitable for dumping at sea (see Chapter 9, Section 9.1.1.1).

In the management of radioactive wastes it is necessary to distinguish clearly between their disposal and their storage. In this Report disposal means either the planned release of wastes to the environment or their permanent placement in a designated site with the intention of making them not retrievable. Thus radioactive gases at low levels of radioactivity are disposed of to the air as planned releases; low-level liquid radioactive wastes are released into rivers, lakes, the sea, and often, as in the case of medical and research uses of radionuclides, into the local sewerage system; and solid low-level radioactive wastes are buried on land or dumped in the sea. Various methods of disposing of high-level radioactive wastes in solid forms are being studied. An important feature of these methods of disposal is the way in which the high-level wastes are made into a solid form. Sites under investigation for the disposal of solidified radioactive wastes are rock formations (for example, granite and salt deposits) deep underground and on or under the floor of the deep oceans. The aim of all disposal methods, whether for low- or high-level radioactive wastes, is to limit, to an acceptable level, the amount of radionuclides in the wastes which reach living things and the environment. Storage, on the other hand, means the placing or holding of the radioactive wastes in a store from which they can be recovered either in the short or long term. Storage may be on or below the surface of the earth. The wastes in storage may be in the form of solids, liquids or gases. Solids are most often compacted to reduce their bulk and enclosed in an outer container. Liquids are usually concentrated and stored in large tanks or in small drums. Gases are compressed and stored in pressure-resistant cylinders.

Sometimes radioactive wastes are classified in three ways: low-, intermediate-, and high-level radioactive wastes.

Having regard for the possible environmental impacts of waste management actions, essential requirements of all procedures to be used for the disposal or storage of radioactive wastes include a full evaluation of the merits of the site, of the possible modes of release and dispersal of radionuclides in the waters, and programs to monitor the environment to confirm the effectiveness of the disposal or storage procedure.

In current practice, the term high-level radioactive waste is used almost exclusively to describe the high activity and high concentration of the various radionuclides in spent nuclear fuel. Accordingly, unless otherwise identified in this Report, the term high-level radioactive waste is used in that sense. The spent fuel rods removed from nuclear reactors contain radioactive products of nuclear fission in the fuel, some unused fissile nuclides (for example uranium-235), and other radionuclides, such as plutonium-239, produced in the fuel by nuclear reactions. When the spent fuel is first removed from a reactor, the activity in becquerel of the radionuclides in it is very high, and it generates a large amount of heat as the result of absorption, within the fuel rods, of ionizing radiations given off by the radionuclides they contain. On removal, spent fuel is placed in storage in large water-filled tanks (called cooling ponds) at the reactor site. Such ponds, which are typically six to eight metres deep, are usually constructed of concrete (mostly double-walled) and lined with stainless steel. During storage in the cooling pond, the heat produced in the spent fuel is removed by the water, and the activity of the radionuclides in the fuel decreases considerably with rapid decay of the short-lived radioactive fission products present.

After the initial period of storage of spent fuel at the reactor site, three options are available for its subsequent management. The first is to continue storage on a long-term basis in cooling ponds, either at the reactor site or in a central national repository specially designed for the purpose, until a decision is made about the future management of the spent fuel. This option is at present being followed in a number of countries in which nuclear reactors are used to generate electricity. After extended storage, two alternatives are available for the future management of the spent fuel. On the one hand, suitably sealed in outer containers, the spent fuel could be disposed of as radioactive waste. This alternative has not yet been put into practice, but the technological requirements for the safe disposal of spent fuel in this way are being assessed in some countries. The other approach is to use chemical methods to reprocess the spent fuel to recover from it the unused part of the fissile nuclides. The fissile nuclides recovered are uranium-235, which, for nuclear reactors which use fuel enriched in that fissile nuclide would be at a higher concentration than uranium-235 in natural uranium, and plutonium-239 produced in the fuel, by the process outlined above, while the fuel was in the reactor. The fissile nuclides would be available for re-use as fuel for nuclear reactors and, in the case of plutonium-239, for the making of nuclear and thermonuclear bombs. The reprocessing of spent fuel is undertaken at present in only a few countries, but a number of others have reprocessing plants under construction or at the planning stage.

In reprocessing, radioactive wastes are produced. These include low-level radioactive wastes, of which some are released to the air, while the remainder, in solid or liquid form, are put in storage or are disposed of. However, the greater part of the activity of radionuclides in the wastes resulting from reprocessing of spent nuclear fuel is in the high-level radioactive waste component which contains many long-lived radionuclides. When first produced these high-level radioactive wastes are in liquid form. It is the current practice to store them for a time in double-walled stainless steel tanks. The heat produced in the wastes as the result of the radioactive decay of their radionuclides is removed by circulating cooling water through stainless-steel coils immersed in the liquid waste. The storage in

this way of high-level liquid radioactive wastes from the reprocessing of spent nuclear fuel is now a proven safe technical procedure. No leakages from such storage tanks have been reported over the years for which the practice has been followed. This high standard of performance is in contrast to leakages and problems which occurred when, earlier, high-level liquid radioactive wastes from the reprocessing of spent fuel were stored in a different chemical form in tanks not made of stainless steel.

Because many of the radionuclides in high-level liquid wastes have extremely long half-lives, their storage in the way outlined is not suitable for their management in the long term. The intention is ultimately to dispose of them. Currently, notably in France, high-level liquid radioactive wastes are being converted into a solid form by incorporating them in glass blocks for disposal. Other solid forms in which these wastes may be incorporated are being investigated to obtain a solid form with improved characteristics compared with glass for the retention of the radioactive wastes over a very long time.

Several methods for the disposal of solidified high-level radioactive wastes are under investigation. These include the disposal of the solidified wastes in deep underground rock deposits, in deep underground salt deposits, and on or under the bottom of deep oceans. The intention of all these disposal proposals is to isolate the radionuclides in the wastes from living things and their environment, particularly by preventing the transfer of the radionuclides from their solid form to food by circulating water. To date, no disposals of solidified, high-level radioactive wastes from the reprocessing of spent nuclear fuel have been carried out. The glass blocks in which such wastes have been incorporated are, at present, being held in special storage facilities in the countries where they are produced. The heat still being developed in the blocks is removed by cooling procedures such as forced air circulation or water cooling.

3.12 CHARACTERISTICS OF RADIONUCLIDES

For the convenience of readers, Table 3-1 summarizes the characteristics of many of the radionuclides discussed in later Chapters. The radionuclides included are primarily those which UNSCEAR (1982) considers the potentially important contributors to environmental irradiation. As already pointed out, a large number of radionuclides are used for medical, industrial and scientific purposes. Examples of those radionuclides will be given in Chapter 7, in which the medical, industrial and scientific applications of radionuclides are discussed.

TABLE 3-1

CHARACTERISTICS OF IMPORTANT RADIONUCLIDES IN THE ENVIRONMENT

Radionuclide	Abbreviation	Radioactive Half-life (1)	Type of Ionizing Radiation Emitted	Main Source (Origin) of the Radionuclide in Environment (2)
Hydrogen-3 (Tritium)	H-3	12.3 y	Beta	Natural (C), Artificial (NT)
Beryllium-7	Be-7	53.6 d	Beta	Natural (C)
Carbon-14	C-14	5730 y	Beta	Natural (C), Artificial (NT)
Sodium-22	Na-22	2.62 y	Beta + gamma	Natural (C)
Manganese-54	Mn-54	312.7 d	Gamma	Artificial (NT)
Iron-55	Fe-55	2.7 y	Gamma	Artificial (NT)
Potassium-40	K-40	1.28×10^{9} y	Beta + gamma	Natural (P)
Krypton-85	Kr-85	10.72 y	Beta	Artificial (FP)
Rubidium-87	Rb-87	4.9×10^{10} y	Beta	Natural (P)
Strontium-89	Sr-89	50.5 d	Beta	Artificial (FP)
Strontium-90	Sr-90	28.6 y	Beta	Artificial (FP)
Zirconium-95	Zr-95	63.9 d	Beta + gamma	Artificial (FP)
Ruthenium-103	Ru-103	39.4 d	Beta + gamma	Artificial (FP)
Ruthenium-106	Ru-106	368 d	Beta	Artificial (FP)
Iodine-129	I-129	1.57×10^{7} y	Beta + gamma	Artificial (FP)
Iodine-131	I-131	8.04 d	Beta + gamma	Artificial (FP)
Caesium-137	Cs-137	30.2 y	Beta + gamma	Artificial (FP)
Barium-140	Ba-140	12.8 d	Beta	Artificial (FP)
Cerium-141	Ce-141	32.5 d	Beta + gamma	Artificial (FP)
Cerium-144	Ce-144	284 d	Beta + gamma	Artificial (FP)
Uranium-235 (decay series of 12 principal nuclides)	U-235	7.1×10^{8} y	Alpha + gamma	Natural (P)
Thorium-232 (decay series of 12 principal nuclides)	Th-232	1.41×10^{10} y	Alpha + Gamma	Natural (P)
Radon-220	Rn-220	55 s	Alpha + gamma	Natural (daughter product of Th-232 series)
Uranium-238 (decay series of 15 principal nuclides)	U-238	4.47×10^{9} y	Alpha + gamma	Natural (P)
Thorium-230	Th-230	8×10^{4} y	Alpha	Natural products of U-238 series)
Radium-226	Ra-226	1600 y	Alpha + gamma	
Radon-222	Rn-222	3.82 d	Alpha + gamma	
Lead-210	Pb-210	22.3 y	Beta + gamma	
Polonium-210	Po-210	138.4 d	Alpha	

Table 3-1 (Continued)

Radionuclide	Abbreviation	Radioactive Half-life (1)	Type of Ionizing Radiation Emitted	Main Source (Origin) of the Radionuclide in Environment (2)
Neptunium-237	Np-237	2.1×10^6 y	Alpha	Artificial (NT followed by decay)
Plutonium-238	Pu-238	88 y	Alpha	
Plutonium-239	Pu-239	2.44×10^4 y	Alpha	
Plutonium-240	Pu-240	6537 y	Alpha	
Plutonium-241	Pu-241	14.4 y	Beta	
Americium-241	Am-241	433 y	Alpha	

(1) Half-lives expressed in y (years), d (days) and s (seconds).
(2) Abbreviations of origins of radionuclides :
C (cosmogenic), NT (nuclear transmutation), P (primordial), FP (fission product). Thus Natural (C) means the radionuclide is naturally occurring and cosmogenic.

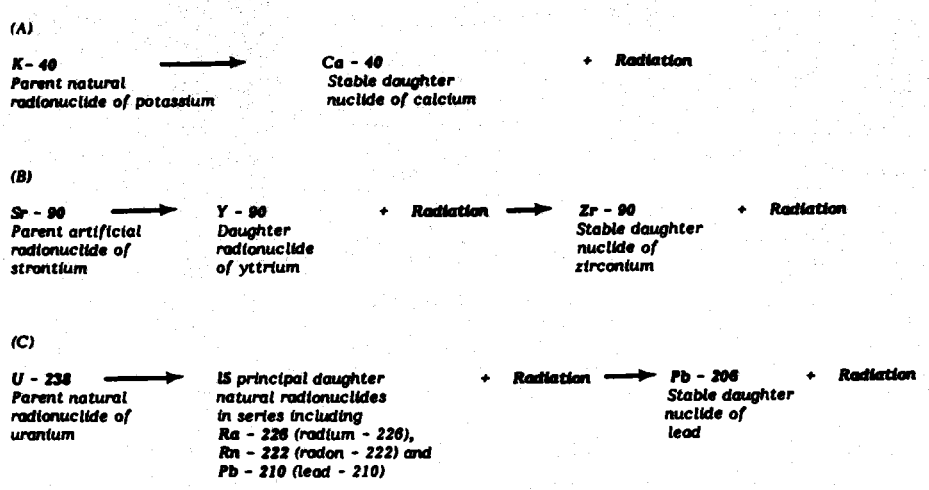


Figure 3-1. Examples of radioactive decay processes:
(A) - single step decay
(B) - two-step decay chain
(C) - many steps in long decay chain

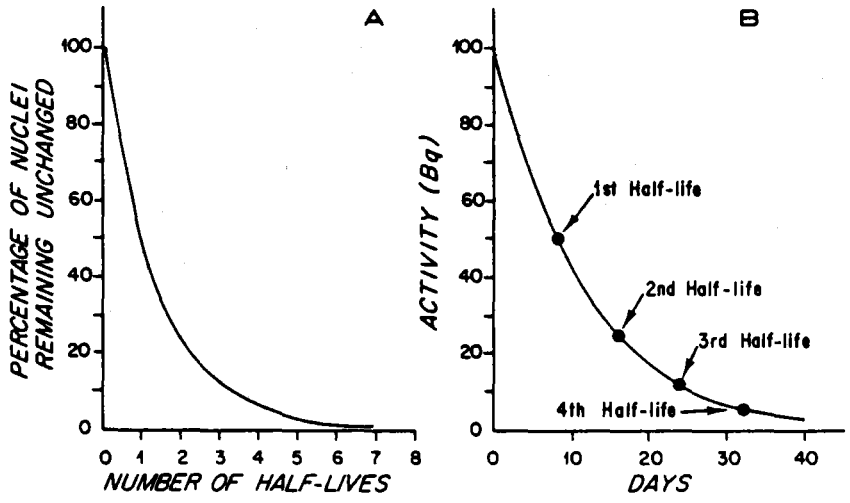


Figure 3-2. (A) Percentage of radioactive nuclei remaining with decay of radionuclide

(B) Change of activity with time of iodine-131, half-life 8 days

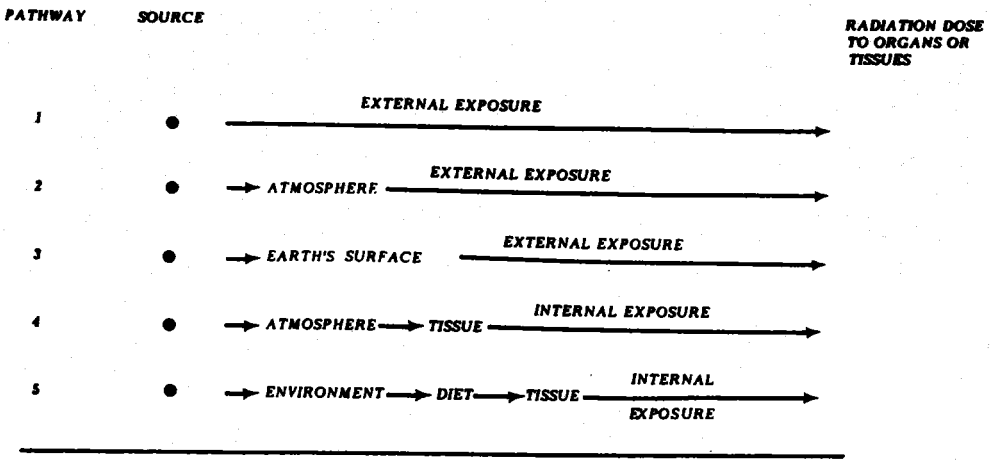


Figure 3-3. Pathways of external and internal exposure

3.13 REFERENCES

International Commission on Radiological Protection. Recommendations of the International Commission on Radiological Protection. ICRP Publication 26. Annals of the ICRP1: No. 3 (1977).

Organisation for Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA), 1982. Disposal of Radioactive Waste - An Overview of the Principles Involved. Paris.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1982. Ionizing Radiation: Sources and Biological Effects, Report to the General Assembly, with Annexes, 773 pp.

CHAPTER 4

POSSIBLE HARMFUL EFFECTS OF EXPOSURE TO IONIZING RADIATIONS

4.1 INTRODUCTION

X-rays were discovered in 1895, and the property now known as radioactivity was identified in uranium in 1896. In the following few years, other naturally occurring radionuclides of the uranium-238 series, for example, radium-226 and polonium-210, were isolated. X-rays are a type of ionizing radiation produced in some electrically operated equipment, and radionuclides continuously give off ionizing radiations in their radioactive decay. The different sources of ionizing radiations were quickly put to use, particularly for medical and scientific research purposes. Because of ignorance of possible harmful effects of exposure to ionizing radiations, a number of persons who worked with them in the early years suffered radiation injuries. It is reported (UNSCEAR, 1982) that at least 336 of the early workers died, most due to cancers of their skin and a smaller number due to blood disorders produced by their radiation exposure.

As a result of these injuries and deaths, the attention of scientists turned to setting conditions under which radiation could be used safely. In 1928 the International Congress of Radiology formed the International Commission on Radiological Protection (ICRP). Initially ICRP looked into the possible harmful effects of ionizing radiations, and how those effects could be minimised, when the radiations were used for medical purposes. The early guidelines on radiation protection developed by the Commission were, however, also applied when sources of ionizing radiations were used in scientific research and industry. The occurrence of harmful effects of ionizing radiations on persons decreased as a result of the early work of ICRP.

In the first 10 years or so after the formation of ICRP, an increasing amount of scientific research was undertaken in a number of countries towards a better understanding of how ionizing radiations cause harmful effects in living things and of the levels of radiation which could be tolerated without the effects becoming apparent. The so-called atomic energy era which began in the early 1940s saw a rapid expansion in scientific research in many countries into the possible harmful effects of ionizing radiations on living things and into the relationship between the levels of radiation received and the harmful effects. This scientific research continues today. In the past 40 years, in particular, no potentially harmful environmental agent has been studied in as much detail, or with as much scientific research effort and expenditure of money, as has ionizing radiation.

ICRP has widened its interest in protection against exposure to ionizing radiations to include most of the circumstances which cause radiation doses to persons. The assessments by ICRP of the possible harmful effects of ionizing radiation and its recommendations and guidelines on the safe use of different sources of ionizing radiations have almost universal acceptance by the scientific community, by

competent national authorities in many countries, and by relevant international agencies, such as the World Health Organization, the International Labour Organization, the Food and Agricultural Organization, the International Atomic Energy Agency, and the Nuclear Energy Agency of the Organization for Economic Cooperation and Development. ICRP is a non-governmental body of experts of different scientific disciplines with its members chosen to give an appropriate balance of expertise on the Commission rather than to satisfy national interests. In its work, ICRP is assisted by a number of specialist committees whose members are selected in a manner similar to those of the Commission itself. From time to time the Commission publishes recommendations and guidelines with respect to the basic principles for minimising the possible harmful effects of exposure to ionizing radiations. National authorities and international agencies use the recommendations and guidelines of ICRP to prepare national and international regulations and codes of practice on the safe use of sources of ionizing radiation.

In ICRP Publication 26, the Commission discusses the basis of its current recommendations and points out that decisions on most human activities involve a balancing of their costs and their benefits. The costs to be taken into account are not only measured in financial terms but are also expected to include social costs, for example those on the health and well-being of people and their environment. Furthermore, the benefits may not be readily seen as resulting for the people who appear likely to bear most or all of the social costs. It is for this reason, among others, that in its recommendations in ICRP Publication 26, the Commission sets limits of radiation dose which can be used where the benefits and possible harmful effects of exposure to ionizing radiations may not be received by the same persons. ICRP recommended that:

(1) any practice involving radiation shall be followed only if it produces a positive net benefit;

(2) all exposures to ionizing radiations shall be kept as low as reasonably achievable, economic and social factors being taken into account; and

(3) radiation doses received by persons shall not exceed the limits recommended as appropriate for them by the Commission.

In its recommendations ICRP notes that some uses of sources of ionizing radiations may result in radiation doses in the years to come and stresses the need for ensuring that none of those uses will result in undue exposure of members of the public.

The philosophy of the ICRP and of most of the national and international bodies that issue regulations and codes of practice on the safe use of sources of ionizing radiation is to view the possible harmful effects against the background of the possible contributions that ionizing radiation can make to the health and well-being of people and to the economic development of countries. Such contributions are numerous and expected to increase in developed countries. More and more countries are basing some of their electrical power generation on nuclear reactors. Although in most developing countries full advantage has yet to be taken of the benefits which can arise from the wide variety of applications of sources of iozinzing radiation, their use in medical practice is expanding (see Chapter 7). A number of those countries have started research and development programmes which indicate that benefits in the research, industrial, and commercial fields are anticipated.

As the peaceful uses of nuclear radiation and of X-rays expand in the countries of

the Region, the Technical Group sees a need for each of them to consider the enactment of radiation control legislation. Similar legislation has been adopted by developed countries and some developing countries so as to establish proper standards of radiation protection for workers and members of the public and acceptable levels of radiation dose for persons and the environment. The detailed requirements of such legislation could appropriately be based on the recommendations of the International Commission on Radiological Protection, on codes of practice of other competent international authorities, such as the World Health Organization and the International Atomic Energy Agency, and on the experience gained in this field by other countries.

In arriving at its recommendations and guidelines, ICRP has made use of the large number of published reports which exist on the possible harmful effects of ionizing radiations and on how those effects can be minimised. The reports include publications by individual scientists of many countries and by many national and international bodies. In about the last 30 years, important among the international bodies has been the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). UNSCEAR has prepared eight comprehensive reports to the UN General Assembly: those of the years 1958, 1962, 1964, 1966, 1969, 1972, 1977 and 1982. The reports of UNSCEAR are highly regarded worldwide. Taken together, the publications of the ICRP and the reports of UNSCEAR provide a comprehensive coverage of much of the information required for this Chapter.

4.2 HARMFUL EFFECTS OF IONIZING RADIATION ON LIVING THINGS

The harmful effects produced in living things by exposure to ionizing radiation can be classified into those effects which may occur within the life-time of living things, called somatic effects, and those effects which may appear in the descendants of living things, called hereditary (or genetic) effects. Somatic effects may occur soon after irradiation (early effects) or after some time delay (late effects).

The harmful effects of ionizing radiation occur as a result of the absorption of energy, by living cells, from the ionizing radiation as it is either stopped or partially stopped on its passage through the cells (the radiation dose). For some somatic effects, it has been shown that their severity depends on the size of the radiation dose received. For these effects a threshold or minimum dose is required. These are called non-stochastic effects. The size of the threshold dose is different for different effects and for different living species.

For other effects, particularly late somatic effects, the chances of the effects occurring, rather than their severity, depends on the size of the radiation dose. These are called stochastic effects. For these effects it has not been possible to show whether or not a threshold dose exists. However, so as not to underestimate the chances of such effects occurring, current radiation practice assumes that no threshold exists. In the preparation of this report, the Technical Group assumed no threshold dose in its consideration of possible harmful effects of ionizing radiation.

Our knowledge of the chances of stochastic effects (leukaemia, breast cancer, etc.) occurring has been based on the irradiation of living things (other than humans) and from long term follow-up studies of exposed persons involving, in both cases, high rather than low doses.

The chances of effects observed after high irradiation doses, occurring after low

doses, are calculated by assuming that the chances of the effect occurring are directly related to the size of the irradiation dose, down to the lowest level of dose.

In the above studies on humans, the radiation dose was received in a short time, that is, at a high dose rate. It has been shown that, for most effects, their severity or the chances of their occurrence are less when the same total radiation doses are received over a long time.

When effects of high dose rate studies are extrapolated to what should be the effects at low dose rates, the results may be overestimated.

In considering possible harmful effects of exposure of living things to ionizing radiation, it is important to remember that:

(1) all living things have evolved and developed while exposed to low radiation doses, received at low dose rates, due to natural radiation in the environment, and some live in environments where the natural radiation dose is considerably higher than the world average;
(2) not all living things of the same species exposed to the same radiation doses develop a particular harmful effect;
(3) in assessing the severity and chances of occurrence of particular effects in persons exposed to ionizing radiation, it is often necessary to rely on information obtained from the radiation exposure of lower forms of life, and this introduces uncertainties in the assessments;
(4) while the threshold doses to produce non-stochastic effects are well established, at least for high dose rates, threshold doses for stochastic effects have not been shown to exist, and the assumption of them may result in an underestimate of the chances of the effects occurring at low doses;
(5) the same effects as those which are produced in living things by exposure to ionizing radiations occur naturally because of largely unknown causes, being produced by other physical and chemical agents; and
(6) except in carefully controlled laboratory research, it is impossible to say with certainty that a particular effect in a living thing has occurred because of exposure to ionizing radiation or whether it has occurred naturally or has been caused by some other physical agent or some noxious chemical. With respect to the last point UNSCEAR (1982) notes, for example, that hereditary effects of various levels of importance to the health and well-being of live-born children occur, due to natural causes, in about 10 percent of such children (UNSCEAR, 1982).

It had been suggested that exposure of living things to ionizing radiation results in their premature ageing or in a shortening of their normal life span. UNSCEAR (1982) reviewed this suggestion in detail and concluded: "Although shortening of life span is a real consequence of irradiation, a very large body of evidence in experimental animals indicates that this effect is essentially due, at low to intermediate doses and dose rates, to the induction of specific neoplastic diseases (cancers)." This means that there is no overall effect of ionizing radiation on living things at low doses which specifically reduces the length of their lives. It had also been suggested that exposure to ionizing radiation and to other agents potentially harmful to living things may, in combination, result in an increase in the harmful effects of ionizing radiation. UNSCEAR (1982) noted that, except for the case of tobacco smoke, which works to increase the effect of ionizing radiation in producing cancers of the lungs of persons under some conditions, it was unable to establish for persons any clear interaction between ionizing radiation and other potentially harmful agents which would result in a substantial change in the estimates of the chances of harmful effects of radiation exposure occurring in

significant sections of the population.

For somatic effects of ionizing radiation, a distinction must be made between those which, on the one hand, are harmful because of the damage caused to the way in which an organ or tissue functions and those which are only minor changes in the structure of cells and, as such, may not be harmful. Possible stochastic effects of ionizing radiations include mainly the production, after many years, of cancers of most organs and tissues and the induction of hereditary abnormalities in the first and subsequent generations of the living things. With respect to possible production of these kinds of harmful effects, the radiation doses to be determined for the assessment of the chances of them occurring are, for cancers, the doses to particular organs or tissues and, for hereditary abnormalities, the doses to the gonads (testes and ovaries) of parents-to-be. Because it is assumed that there is no threshold dose for these kinds of harmful effects, it follows that chances of them occurring exist for living things because of the inevitable exposure to natural radiation in the environment. It also follows that the chances will be higher for living things exposed to the levels of natural radiation higher than the world average which occur in many locations.

4.3 POSSIBLE OCCURRENCE OF HARMFUL EFFECTS IN PERSONS EXPOSED TO IONIZING RADIATIONS

The possible harmful effects in persons exposed to ionizing radiations can be considered under two headings. There are those effects for which the severity depends on the size of radiation doses to particular organs or tissues, each effect having a threshold dose below which it will not occur. These effects as a group are called non-stochastic effects. Then there are those for which the chances of their occurrence depend on the size of the radiation dose to a particular organ or tissue and for which it is assumed, in radiation protection practice, no threshold dose for their occurrence exists. These are called stochastic effects.

4.3.1 Non-Stochastic Effects

Non-stochastic effects of exposure to ionizing radiations may occur in many organs and tissues if the threshold doses for the effects are exceeded in those organs and tissues. Examples of harmful non-stochastic effects which are known to follow exposure of persons to ionizing radiations are opacities in the lens of the eye (cataract), non-cancerous effects in organs such as the thyroid, the production of temporary or permanent sterility following radiation doses to the testes of men or to the ovaries of women, and changes in the pattern of development of an embryo exposed to ionizing radiation in the very early stages of a pregnancy. A safe radiation dose for these kinds of harmful effects would be below the threshold doses for their occurrence in persons. Such doses would be given in sievert (see Chapter 3 and the Glossary of Terms).

In addition to the above non-stochastic effects which, for persons, have moderate threshold doses for the different organs and tissues, there are the effects which are known to occur in persons after high radiation doses received in a short time to the whole of their bodies or to a large part of them. The symptoms of these effects are often described as radiation sickness because, if the radiation doses are sufficiently high to the whole body, or to a large part of it, and are received in a short time, nausea, vomiting, diarrhoea and loss of appetite (gastrointestinal symptoms) may occur within a short time after the radiation exposure (a few hours or days). The severity of these symptoms, and the speed with which they appear, depends on the size of the radiation dose. After extremely high doses to the whole body, or to a large part of it, received in a short time, persons may die in a few hours or days due mainly to effects of the radiation exposure on their central

nervous system (brain and spinal cord). When the radiation doses are not so high as to cause almost immediate death, the gastrointestinal symptoms and associated complications may cause death within 1 or 2 weeks. In persons irradiated to this level of dose, and to somewhat lower doses, and who survive the effects of gastrointestinal symptoms for a week or two, other effects appear, particularly those involving the blood cells and blood-forming organs and tissues. These latter effects may cause the death of some of the persons three to six weeks or more after the radiation exposure. At lower doses still, all the exposed persons will survive the early effects produced by the radiation doses they received. They will, however, have increased chances of death occurring, after a number of years, due to cancer of different organs and tissues, and they may develop some of the non-stochastic effects if the threshold doses for them are exceeded. The sizes of the radiation doses in sievert which cause radiation sickness at its various levels of severity in persons are fairly well known from studies of persons exposed to radiation from the atomic bomb explosions (those on two Japanese cities in 1945 and a test at Bikini Atoll in 1954), of the few persons accidentally exposed in their work to such doses, and of patients treated with ionizing radiations for various illnesses. In considering the possible occurrence of radiation sickness at its various levels of severity, it is important to remember that the high radiation doses must be received in a short time. If the same size doses are received as a total over a long time, either continuously at low dose rates or as the result of a number of separate exposures, the radiation sickness symptoms would be most unlikely to occur.

4.3.2 Stochastic Effects

For stochastic effects, for which it is assumed no threshold doses exist, the higher the radiation doses the greater the chances of harmful effects occurring and, conversely, the lower the doses the less the chances of them. For these effects it is accepted in radiation protection practice that the chances of the harmful effects occurring change directly with the size of the radiation doses to particular organs and tissues down to no dose. The effects involved here are cancers in the person exposed to ionizing radiations and hereditary defects in the immediate children, and subsequent generations, born of the exposed persons.

Present scientific knowledge enables risk factors to be calculated for these stochastic effects. These factors give the chance of a particular harmful effect per unit of radiation dose, for example as 1 chance in 100 per sievert of radiation dose to the organ or tissue involved. The chance of an effect occurring in a person under particular radiation exposure circumstances can be obtained by multiplying the appropriate risk factor by the actual radiation dose to the organ or tissue. For example, if a person received a radiation dose of one-thousandth of a sievert to an organ for which the risk factor for radiation-produced cancer was 1 in 100 per sievert, the chance of that person developing cancer of the organ as the result of the radiation exposure would be 1 in 100,000. Taking into account the way in which the risk factors currently used with respect to the radiation exposure of persons have been arrived at, they are likely to over- rather than underestimate the chances of harmful effects in persons when their radiation doses are small and received at low dose rates. This will be the case in most exposures to environmental ionizing radiation. Thus the use of the risk factors gives an upper level of risk of particular harmful stochastic effects in persons.

The above use of the risk factors does not indicate that a particular person exposed to ionizing radiation, after a known dose of environmental radiation, will, because of that dose, develop cancer or be the parent of a child with a hereditary defect. It will simply give the chance of the effect occurring. Risk factors of the type described can also be used to estimate the total number of harmful stochastic

effects which may occur in a large group of persons who have received, or will receive over a period of time, a radiation dose of a particular size. The estimate of the total number of cases of a particular harmful effect in the group of persons can be made by use of an appropriate risk factor and the total radiation dose already received, or to be received, by all persons in the group (the collective radiation dose of the group).

In making use of these risk factors there are other considerations. First, if a threshold dose should exist for one or other of the stochastic effects, no harmful effects will occur unless the threshold dose is exceeded. Second, there is the delay in time for harmful stochastic effects to appear, a delay which, for most of the effects, is measured in years. The chance of a person exposed to ionizing radiation developing a harmful effect in a particular organ or tissue will depend not only on the size of the radiation dose and the relevant risk factor but also on the subsequent length of the natural life of the person. Thus for a given radiation dose to an organ or tissue, cancer, for example, is less likely to result in persons exposed when approaching the end of their normal life span than in persons exposed to the same radiation dose at a younger age. A third consideration in the use of the risk factors is that those in current use have, in most cases, been obtained by using information on persons or living things exposed to high radiation doses received in a short time, that is, at high dose rates. When low radiation doses at low dose rates are received by persons (as is likely to be the case in most exposures of persons to ionizing radiation in their general living environment), the risk factors may considerably overestimate the chances of harmful effects. Further, where risk factors have been calculated on the basis of effects observed only in living things other than persons, there is uncertainty as to the correctness of the use of those risk factors for persons. As a final consideration it is necessary to recall that if harmful stochastic effects are produced by radiation exposure without a threshold dose, the risk factors will apply to radiation doses received by all persons from natural radiation. That exposure will have a chance of producing radiation induced cancers and hereditary abnormalities. If, in a particular location or for particular reasons, persons are exposed to higher than the average natural radiation doses for the world, they will have an increased chance of harmful stochastic effects because of the higher natural radiation doses.

The International Commission on Radiological Protection, the United Nations Scientific Committee on the Effects of Atomic Radiation, a number of national authorities, and various individual scientists have calculated risk factors for harmful stochastic effects of exposure to ionizing radiation. It is the usual practice to give the risk factors as the chances of death occurring in the long term due to cancers caused by radiation doses to particular organs or tissues of persons and as the chances of substantial hereditary defects occurring in live-born descendants of parents exposed to radiation doses.

4.3.3 Dose Limits

ICRP (1977) recommends dose limits for the protection of persons against possible harmful effects of exposure to the various sources of ionizing radiation. Two different sets of dose limits are recommended. One is for persons exposed to ionizing radiation in their work and the other for persons as members of the public. It is only the latter set of dose limits that is considered here.

The dose limits recommended by ICRP for persons as members of the public are based on (1) the Commission's review of present knowledge on possible harmful effects to persons of exposure to ionizing radiation, as discussed earlier in the Chapter, and (2) the appreciation that persons in their everyday lives are exposed to a number of possible harmful effects to their health and well-being from a variety of other

causes, and that exposure to ionizing radiation is another hazard of living which persons could be expected to accept, provided the chances of harmful effects from the exposure are not out of proportion to the other hazards of life which they accept without apparent concern. The ICRP (1977) has pointed out: "Radiation risks are a very minor fraction of the total number of environmental hazards to which members of the public are exposed". The annual dose limits recommended by ICRP for persons as members of the public are (1) those which, if received throughout a lifetime, are small enough to ensure that harmful non-stochastic radiation effects (those which require a threshold dose to be exceeded for their occurrence) will not arise, and (2) those which, if received throughout a lifetime, are small enough to ensure that the chances of harmful stochastic effects (those for which the chances of occurrence change directly with the level of radiation dose and with the assumption of no threshold dose) are not greater than the chances of similar effects occurring due to other causes and being accepted as part of normal living.

For non-stochastic radiation effects for persons as members of the public, ICRP recommends a dose limit of 50 millisievert per year. This limit is one-tenth of the limit for non-stochastic effects recommended by ICRP for persons exposed to ionizing radiation in their work. The lower dose limit for persons as members of the public takes account of the longer time they may be exposed to ionizing radiation throughout their lives when compared with the shorter time persons will be exposed to these radiations in their working lives. Even if persons as members of the public were exposed up to the recommended dose limit each year for the whole of their lives, they would not be expected to develop any of the harmful non-stochastic effects which may occur at low or intermediate radiation doses above the threshold doses. Further, the annual dose limit for non-stochastic effects is so low that, even with a lifetime exposure at that level, radiation sickness and its associated health complications would not occur.

For harmful stochastic radiation effects, the dose limit recommended by ICRP for persons as members of the public is 5 millisievert per year for uniform whole-body exposure. This limit is one-tenth of the dose limit for stochastic effects in persons exposed to ionizing radiation in their work and is about 5 times greater than the effective dose equivalent received each year by persons in the South Pacific Region from natural radiation (see Chapter 5).

Important features of the dose limits recommended by the International Commission on Radiological Protection for persons as members of the public include (1) the dose limits being applied to the total of the doses from external and internal exposure during the year; (2) taking account of exposure to all sources of ionizing radiation except normal natural radiation and exposure to ionizing radiation received by persons as patients; (3) the acceptance of national (and regional) responsibility for ensuring that all the relevant sources of radiation exposure are taken into account in assessing radiation doses to persons as members of the public for comparison with the recommended annual dose limits; and (4) the national (and regional) authorities keeping under review the separate contributions made by the various sources of exposure so that none of them makes an unjustified contribution to the total dose received by persons as members of the public. These features suggest to the Technical Group that, if the recommendation made above in section 4.1 with respect to radiation control legislation, based on the recommendations of the ICRP, is adopted, the legislation should include radiation dose limits for persons as members of the public. In the preparation of such legislation, consideration might be given to setting an upper limit for the contribution which any one source of ionizing radiation might be permitted to make to persons as members of the public. Dose limits adopted in such legislation would provide a basis against which radiation doses to persons in the Region could be monitored and possible harmful effects of the doses assessed.

4.3.4 Fears and Anxieties

In the above discussion of the possible harmful effects on persons exposed to ionizing radiations, no mention was made of the fears and anxieties which often accompany actual or potential exposure to those radiations. More than twenty years ago an Expert Committee on Radiation of the World Health Organization (WHO, 1962) recognized this problem when it wrote: "The spectacular manner in which atomic energy was brought to public notice (the atomic bombing of two Japanese cities), as well as subsequent developments in this field, have resulted in worldwide reactions of fear and anxiety greater than have been associated with any other important technological advance." Whereas the possible consequences to the physical health of persons of known doses of ionizing radiation cannow be estimated with an increasing degree of confidence, the possible consequences to the mental health of persons through their fears and anxieties of exposure to ionizing radiation are much more difficult to assess in terms of identifiable harm.

4.4 REFERENCES

International Commission on Radiological Protection (ICRP), 1977. Recommendations of the International Commission on Radiological Protection. Annals of the ICRP, ICRP-26, Pergamon Press.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1982. Ionizing Radiation: Sources and Biological Effects. Report to the General Assembly, with Annexes, 773 pp.

World Health Organization (WHO), 1962. Radiation Hazards in Perspective. Third Report of the Expert Committee on Radiation, WHO Technical Report Series No. 248, Geneva.

CHAPTER 5

EXPOSURES TO NATURAL IONIZING RADIATION

5.1 INTRODUCTION

Natural sources of ionizing radiation have been present in the environment since the beginning of the earth's history. Living things on earth have evolved while receiving radiation doses from those sources, the doses not changing greatly in that time. Barring a nuclear war or major nuclear reactor accidents, natural sources are likely always to be the main environmental contributor to radiation doses to persons. In this Chapter the doses from natural sources are reviewed for the majority of the world population which lives in what are described as "normal" or "average" natural radiation regions. The review is based, in the main, on the most recent report of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 1982). Changes in natural radiation doses from one region to another and fluctuations in the doses within a region are discussed. Finally, estimates made by the Technical Group of the natural radiation doses to persons in the South Pacific Region are given.

Throughout this Chapter, the emphasis is on radiation doses rather than on concentrations of naturally occurring radionuclides in the environment. However, some information on such concentrations is given to show why differences occur in the natural radiation doses between the average for the world population and for the population in the South Pacific Region.

Estimates of natural radiation doses to which all persons are inevitably exposed throughout their lives are important because they are a valuable measure against which radiation doses to the same persons from man-made (artificial) sources of ionizing radiation can usefully be compared. It is noted here that the differences in the natural radiation doses from one group of persons to another, even in a small population, are often greater than the annual doses they receive from a number of artificial sources of exposure to ionizing radiation. These comparisons help to give a better appreciation of the possible harmful effects of exposure of persons to artificial sources of ionizing radiation. The use of estimates of natural radiation dose in this way is only possible if the risks of many of the potentially harmful effects (specifically, the stochastic effects) of all ionizing radiation are accepted as being directly proportional to the radiation doses persons receive without any threshold (or minimum) dose for the effects to occur. This is the concept accepted by the Technical Group as a basis for the assessment of radiation protection. It is also necessary to understand that at low levels of radiation dose, the different sources of ionizing radiation, whether natural or artificial, have the same potential for causing harmful effects. Although radiation doses to persons from different sources of ionizing radiation can usefully be compared, the same cannot be said of the direct comparison of the concentrations of radionuclides in different environmental materials and in persons, particularly if different radionuclides are involved.

The estimates of radiation doses are given in annual effective dose equivalents. As outlined in Chapter 3, section 3.8, doses estimated in this way take account of the degree of non-uniformity of absorbed radiation doses in the body and the possible difference in the effects on cells and tissues of the different types of ionizing radiation which give rise to the absorbed dose.

Radiation doses to people from natural sources of radiation exposure are received continuously from cosmic rays and from naturally occurring radionuclides. These sources are described in Chapter 3, section 3.10.1.

5.2 COSMIC RAYS

Cosmic rays will continue to be a major source of radiation dose to persons. UNSCEAR (1982) estimates that, on the average, the effective dose equivalent to each person in the world from cosmic rays is about 300 microsievert per year.

The annual effective dose equivalent is not the same throughout the world. There are, now and then during a year, increases in the rate the dose is received on the earth's surface. These increases last for only a short time (hours) and are due to changes in the energy release by the sun (solar flares). The dose rate from cosmic rays also increases with height above sea level and changes with latitude, being lower at the equator and higher at higher latitudes north and south of the equator. The latitude changes are small and the annual effective dose equivalent of 300 microsievert for cosmic rays is a reasonable value to take for all persons irrespective of where they live, except for very high altitudes.

5.3 NATURALLY OCCURRING RADIONUCLIDES

There are two kinds of naturally occurring radionuclides: cosmogenic and primordial radionuclides (Chapter 3, section 3.10.1).

5.3.1 Cosmogenic Radionuclides

Only four of the cosmogenic radionuclides are significant sources of radiation exposure to living things: tritium, beryllium-7, carbon-14, and sodium-22 (UNSCEAR, 1982). Their characteristics are given in Chapter 3, Table 3-1. Radiation doses are received by persons from these radionuclides by internal irradiation through either Pathway 4 or Pathway 5 (Chapter 3, Figure 3-3). The total annual effective dose equivalent to persons throughout the world from these four cosmogenic radionuclides is 15 microsievert (UNSCEAR, 1982), most of the annual dose being from beryllium-7 and carbon-14. The contribution made by any one of them to the annual dose does not vary greatly with location of persons throughout the world.

5.3.1.1 Tritium (hydrogen-3)

About 99 per cent of the tritium produced in the air by cosmic rays becomes water and takes part in the normal water cycle on earth. Because large amounts of tritium have been introduced into the environment in the last forty years by nuclear explosions in the atmosphere, the activity of naturally occurring tritium in the environment must be measured by the use of water sampled prior to nuclear testing. The annual effective dose equivalent for persons from naturally occurring tritium is estimated to be 0.01 microsievert. Any variations in the concentration of natural tritium in water will not have a significant effect on the total annual radiation

doses from the cosmogenic radionuclides.

5.3.1.2 Beryllium-7

The main pathway of beryllium-7 to persons is by leafy vegetables (Pathway 5, Figure 3-3), resulting in an annual intake of about 50 becquerel. The annual effective dose equivalent is 3 microsievert.

5.3.1.3 Carbon-14

This cosmogenic radionuclide quickly combines with oxygen in the air to form carbon dioxide and enters living things. The concentration of natural carbon-14 in the air has decreased slightly in the present century due to the dilution of the carbon dioxide in the air by carbon dioxide produced by the burning of fossil fuels (for example, coal, oil, and natural gas) which do not contain carbon-14. The world inventory of natural carbon-14 is about 8.5×10^{18} becquerel with a production rate of about 1×10^{15} becquerel per year (UNSCEAR, 1977). The annual effective dose equivalent to persons from natural carbon-14 is 12 microsievert, the highest annual contribution from any of the cosmogenic radionuclides. This annual dose does not vary significantly from place to place.

5.3.1.4 Sodium-22

The annual production rate and the air concentration of cosmogenic sodium-22 are very small. Sodium-22 is fairly uniformly distributed through the tissues of persons. The annual effective dose equivalent from natural sodium-22 is 0.2 microsievert.

5.3.2 Primordial Radionuclides

As discussed in Chapter 3, section 3.10.1.3, potassium-40, rubidium-87, and the uranium-238 and thorium-232 decay series are the important primordial radionuclides from the point of view of radiation doses to persons.

5.3.2.1 External irradiation

Potassium-40 and members of the uranium-238 and thorium-232 decay series emit gamma rays and therefore are sources of external radiation to persons. In estimating the annual doses from them it is necessary to take account of the contributions made while persons are out of doors and indoors.

Table 5-1 summarises information on the concentrations in soil of potassium-40, uranium-238, and thorium-232 and on the annual absorbed dose rates in air from them out of doors. UNSCEAR (1982), in its estimate of the contribution these radionuclides make to the external dose to persons living in normal areas, used a value of 3.8×10^{-4} gray per year for the absorbed dose rate in air.

Table 5-1 shows that the measured concentrations of the radionuclides differ widely. These differences in concentration are due to the different types of soil and rock over which the measurements were made. In section 5.4, this type of difference will be discussed further, because it accounts for some reduction in the estimated annual dose from natural radiation to persons living in the South Pacific Region.

To estimate the annual effective dose equivalents to persons from external irradiation by primordial radionuclides, account has to be taken of the effect of the buildings in which they live and work. The absorbed dose rates in buildings made of bricks, concrete and stone are, on the one hand, increased by the gamma

radiation emitted by the primordial radionuclides in the building materials themselves. On the other, the materials shield occupants of the buildings from a part of the gamma radiation coming from the soil and rocks outside. In wooden buildings and in other buildings made of lightweight material this shielding is negligible, but the materials themselves do not contribute significantly to the radiation dose of those in them. UNSCEAR (1982) used a factor of 1.2 by which to increase the outside absorbed dose rate from primordial gamma emitting radionuclides to give, on a world-wide basis, the absorbed dose rate in buildings. There is also a need to take account of the time persons spend each year in and out of doors. For the estimate of the annual effective dose equivalent from natural radiation, it is assumed that worldwide, on the average, persons spend about one-fifth of their time out of doors and four-fifths indoors (UNSCEAR, 1982).

The above factors are clearly not appropriate for many of the people in the South Pacific Region because of the different types of buildings they occupy and of their different living and working habits. These differences were taken into account by the Technical Group in its estimate of the annual effective dose equivalent to persons in the Region from natural radiation (section 5.4).

Using all the parameters discussed above, the annual effective dose equivalent, from external irradiation by primordial radionuclides, to persons in areas of normal natural radiation have been estimated (UNSCEAR, 1982). In total the annual effective dose equivalent from this source of radiation exposure was estimated to be 350 microsievert, with the contributions by potassium-40, the uranium-238 series and the thorium-232 series being respectively 120, 90 and 140 microsievert.

5.3.2.2 Internal irradiation

Primordial radionuclides enter the body of persons, some by ingestion of food and water, some by inhalation, and some by both processes. Once in the body they will be taken up to different extents by different organs and tissues. As a result they cause radiation doses to organs and tissues (Pathways 4 and 5, Figure 3-3).

(a) Potassium-40. Potassium is an essential element in the functioning of cells of all body tissues. Different body tissues have different concentrations of potassium. As the cells of the body tissues use up potassium, it is replaced from dietary intake, and the concentration of the element in different tissues is maintained. The total amount of potassium per unit of body weight is constant. For example, an adult male has about 2 grams of potassium per kilogram of body weight. All potassium contains a small fixed percentage of the primordial radionuclide potassium-40. The annual effective dose equivalent for persons is estimated to be 180 microsievert for potassium-40 (UNSCEAR,1982). Because of the way in which the element potassium is used in the body, the total amount of it in the tissues of persons, and therefore the amount of potassium-40, is not changed by increased intake of the element. Therefore, the above estimate of annual effective dose equivalent will be the same for persons, throughout the world, irrespective of their location or dietary and living habits.

(b) Rubidium-87. Very little is known about how rubidium is used by the tissues of persons. However, the concentration of natural rubidium-87 per unit of body weight is known. The annual effective dose equivalent to persons is estimated to be 6 microsievert for rubidium-87 (UNSCEAR, 1982). As with potassium-40, this value will be the same for all persons throughout the world.

(c) Uranium-238 series. In estimating the contributions made by the various radionuclides in this series (Figure 5-1) to the internal radiation doses of

persons, it is useful to consider five sub-series: uranium-238 to uranium-234, thorium-230, radium-226, radon-222 to polonium-214, and lead-210 to polonium-210.

(i) Uranium-238 sub-series. Uranium-238 is taken into the body through food and inhalation. In areas of normal natural radioactivity, the activity of uranium-238 taken in annually through food is about 5 becquerel. The activity intakes through the drinking water and the breathing of dust are, in normal areas, very much lower. The annual effective dose equivalent from this sub-series to persons living in areas of normal natural radioactivity is about 10 microsievert (UNSCEAR, 1982).

(ii) Thorium-230. The intake of Thorium-230 through inhalation is approximately 0.01 becquerel per year. There is no information on the intake of thorium-230 through food, but even if ingested there would only be a small transfer of it to body tissues because of the low absorption of thorium from the gut. The estimated annual effective dose equivalent to persons in normal areas of natural radioactivity is 7 microsievert (UNSCEAR, 1982).

(iii) Radium 226. Food is the most important route by which radium-226 enters the body, where it is mainly deposited in bone. In areas of normal natural radioactivity, the annual intake of radium-226 through food is about 15 becquerel, whereas the annual intake of the radionuclide with dust and through drinking water drawn from surface water is very much smaller. The concentration of radium-226 in water from some deep wells and in some mineral waters may be much higher than in surface waters. The annual effective dose equivalent from radium-226 to persons living in areas of normal natural radioactivity and where drinking water does not have abnormally high radium-226 concentrations is estimated to be 7 microsievert (UNSCEAR, 1982). In areas where radium-226 in soil and in drinking water is abnormally high, a higher annual effective dose equivalent for persons living there is to be expected. Such areas are discussed in section 5.4.3.

(iv) Radon-222 sub-series. Radon-222 is a radioactive gas with a short half-life. Rocks, soils, and a number of other materials (for example, building materials) contain radium-226 and release radon-222 to the air, where it undergoes radioactive decay to produce its solid daughter products (Figure 5-1). Many measurements have been made of the activity of radon-222 released into the air from land not covered by permanent ice and from the oceans. The releases over the oceans are only about one percent of those from the land. The total activity of radon-222 released to the air is 6.3×10^{19} becquerel per year (Lambert et al., 1982).

As the gaseous radon-222 in the air decays, its radioactive daughter products become attached to the small aerosols there. The half-lives of the successive daughter products (polonium-218 through polonium-214) are sufficiently short for them to reach approximate radioactive equilibrium with the radon-222 in the air. As a result of this equilibrium, and with an annual release of 6.3×10^{19} becquerel of radon-222 into the air from the land and the oceans, a total activity of about 1.9×10^{20} becquerel of the three alpha emitters radon-222, polonium-218, and polonium-214 (Figure 5-1) and a total activity of about 1.3×10^{20} becquerel of the two beta emitters lead-214 and bismuth-214 are introduced into the air each year.

Many measurements have been made of the concentration of radon-222 in the low-level air over continents with values between 2 and 8 becquerel per cubic metre being obtained, a mean value being 5 becquerel per cubic metre (Lambert et al., 1982). However, when the upward movement of low-level air, as controlled by temperature differences, is small, there will be little dilution of the radon-222 in low-level air and concentrations of the radionuclide between 200 and 400 becquerel per cubic metre may be reached over continents for several hours at a time (Servant, 1964). Over the oceans, the lower release of radon-222, the dilution of its concentration by the mixing of lower- and upper-level air without the impediment of temperature-induced effects on the movement of low-level air, and radioactive decay result in much lower concentrations than are found over continents. In the South Pacific Region, the concentration of radon-222 in low-level air is, on average, less than 4×10^{-2} becquerel per cubic metre (Lambert et al., 1982).

Radon-222 and its short-lived daughter products attached to aerosols in the air (the radon-222 sub-series) are inhaled and result in internal exposure of lung tissue (Pathway 4, Figure 3-3). However, in estimating the radiation dose to persons from this sub-series, it is necessary to take into account the higher concentrations of the radionuclides inside buildings, where much of the world's population spends a considerable amount of its time. The higher concentrations inside buildings arise because the air is confined, and concentrations of radon-222 ten times higher than in the outside air are not unusual. The concentrations of radon-222 and of its short lived daughter products inside buildings will clearly be influenced by the effectiveness of the ventilation of the buildings. In this regard it is worth noting that air-conditioning units, particularly those operating as closed-circuit systems, do not effectively ventilate buildings, and therefore, high concentrations of the radionuclides of the radon-222 sub-series are maintained in them. The annual effective dose equivalent for persons living in normal areas of natural radioactivity on continents is estimated to be about 800 microsievert (UNSCEAR, 1982). The lower values for persons who live in the South Pacific Region will be discussed in section 5.4.2.2.

(v) Lead-210 sub-series. The radioactive daughter products in this sub-series have much longer half-lives than those of the radon-222 series. The removal by deposit of the aerosols to which the longer lived daughter radionuclides are attached makes it impossible for radioactive equilibrium to be reached in air between radon-222 and the daughter products lead-210, bismuth-210, and polonium-210.

Many measurements have been made of the concentrations of lead-210 in low-level air over continents, and these are only about 0.01 to 0.02 per cent of the radon-222 concentrations. Over oceans, the relative lead-210 concentrations are higher at about 0.1 per cent of the radon-222 concentration, but the absolute concentrations of lead-210 over the oceans are much lower than over the continents (Lambert et al., 1982). The ratio of bismuth-210 to lead-210 concentrations in most low-level air is about one-half. However the ratio of polonium-210 to lead-210 concentrations is much more variable, ranging from 0.07 to 0.5, a value of 0.1 being most commonly accepted. The polonium-210 to lead-210 ratio is complicated by the natural sources of polonium-210 in the air other than those due directly to the uranium-238 series of radionuclides in the immediate area. Firstly, polonium-210 reaches the

air from the surface of the oceans, where it is concentrated by plankton (Turekian et al., 1974). Secondly, active volcanoes could be responsible for more than half of the polonium-210 in the atmosphere (Lambert et al., 1979; 1982). The ratio of polonium-210 to lead-210 concentration is, on the average, about 0.4 in oceanic regions downwind from active volcanoes. Thus there are many instances where the polonium-210 to lead-210 ratio is higher than expected in terms of the environmental concentrations of lead-210 arising directly from the decay of the radionuclides of the uranium-238 series in the immediate environment.

The radionuclides lead-210, bismuth-210, and polonium-210 enter the body mainly through food, and once there they, to all intents and purposes, reach radioactive equilibrium. The annual effective dose equivalent to persons due to the lead-210 sub-series is estimated to be 130 microsievert (UNSCEAR, 1982). This dose would be higher for cigarette smokers because of an increased intake of lead-210 and polonium-210 by inhalation of tobacco smoke. The additional intake of those radionuclides due to smoking leads to increased concentrations of lead-210 and polonium-210 in various organs, particularly in the lung, where the concentrations exceed, on the average, the levels found in non-smokers by about 1.5 times for lead-210 and three times for polonium-210. Insufficient information is available on smoking habits to enable an estimate to be made now of the additional radiation dose to those who smoke cigarettes. However, recognising the concern expressed about the levels of radiation doses to persons from the various man-made sources of ionizing radiation, it is hoped that further scientific investigations will permit such an estimate so that smokers can assess any additional radiation hazard to their health.

(d) Thorium-232 series. Thorium-232 is the parent of a series of twelve nuclides, of which eleven are radioactive (Figure 5-2). The thorium-232 and the uranium-238 series are similar in that they contain nuclides of the same elements (radium, radon, bismuth, and polonium) and a large proportion of radionuclides which give out alpha radiation in their decay. The main difference is that thorium-232 is the only long-lived radionuclide in its series. Like the uranium-238 series, we estimate the contribution of the radionuclides of the thorium-232 series to the radiation dose. In this case, we consider three sub-series: thorium-232, radium-228 to radium-224, and radon-220 to thallium-208/polonium-212.

(i) Thorium-232. The main source of uptake of thorium-232 into the body is from dust inhalation, the annual intake being about 0.01 becquerel. As in the case of thorium-230, little thorium-232 taken in through food enters body tissues because of the poor absorption of thorium from the gut. The annual effective dose equivalent from thorium-232 to persons living in normal areas of natural radioactivity is estimated to be about 3 microsievert.

(ii) Radium-228 sub-series. The annual intake of radium-228 through food is about 1500 times the annual intake through the inhalation of dust. The sub-series includes the alpha radiation emitters thorium-228 and radium-224, and these radionuclides are the main contributors in this sub-series to the radiation doses to persons. The annual effective dose equivalent from this sub-series is estimated to be 13 microsievert in areas of normal natural radioactivity. There are areas in the world, notably in Kerala, India, and Araxa-Tapira, Brazil, where the annual

intake of radium-228 through food is very much higher than in normal areas. Correspondingly higher annual doses are received by the local populations.

(iii) Radon-220 sub-series. This sub-series is the biggest contributor of the thorium-232 series as a whole to radiation doses to persons living in areas of normal natural radioactivity. However, the activity concentration in air of radon-220, a radioactive gas with an extremely short half-life, is about one-tenth to one-hundredth of the activity concentration of radon-222, a member of the uranium-238 series. As with radon-222 it is the concentration of radon-220 inside buildings which determines the radiation dose to persons from the inhalation of the radioactive gas and its short-lived daughter products. Here again the ventilation of buildings is an important factor to be taken into consideration. It is estimated that the annual effective dose equivalent from the radon-220 sub-series to persons living in normal areas of natural radioactivity is 170 microsievert (UNSCEAR, 1982). This dose is more likely to be received by persons who live on continents. The dose for persons living in the South Pacific Region is likely to be lower for reasons similar to those outlined for the radon-222 sub-series of the uranium-238 series (see section 5.4.2.2).

5.3.3 Summary of Annual Effective Dose Equivalents

Table 5-2 summarizes the estimates of annual effective dose equivalents from natural radiation to the majority of the world population which lives in regions of normal natural radiation levels. The total estimated annual effective dose equivalent is 2000 microsievert.

5.4 EXPOSURES TO NATURAL RADIATION IN THE SOUTH PACIFIC REGION

5.4.1 Average Doses in the Region

In the course of its review of the annual effective dose equivalents summarised in Table 5-2, the Technical Group examined, as well as it could with the information available, factors which might result in the people living in the South Pacific Region receiving doses from natural radiation higher or lower than those for the majority of the world population. As a result of this examination, the Technical Group estimated, in a preliminary way, the annual effective dose equivalent for people living in the Region. There are some uncertainties in the estimate, but the Group is confident that the annual dose from natural radiation for most of the people living in the Region is much lower, about one-half, than that for the majority of the world population living in normal natural radiation areas. As more scientific information is gathered, the estimates which the Group has made may require some revision. The estimates made by the Technical Group are summarised in Table 5-3. In the following paragraphs, explanations are given for the differences between the estimates in Tables 5-2 and 5-3. Reference is made in section 5.4.3 to a few areas in the region where the doses received may be much higher than those given in Table 5-3. These apparent anomalies warrant further scientific investigation.

In Table 5-3, it was necessary to give maximum and minimum estimates of the annual effective dose equivalent for some natural sources of irradiation. This was because of limitations in the scientific information available to the Group. However, in none of these cases is the maximum value higher than that for the corresponding source of irradiation in Table 5-2. With the few exceptions discussed in section

5.4.3, the Technical Group believes that the maximum values given in Table 5-3 do not underestimate the annual effective dose equivalent for the relevant source of irradiation. The minimum estimates in Table 5-3 are much less than the estimates for the corresponding sources of irradiation in Table 5-2. An examination of the two tables shows that, for some sources, the estimates are the same. In this regard the estimate in Table 5-3 for the annual effective dose equivalent for external irradiation by cosmic rays may be slightly overestimated. This dose might have been given a lower value because of the low latitude of many of the countries. However, the Technical Group decided that it would be better to give a single contribution from that source for the whole South Pacific Region and thus err in the direction of an overestimate. The rounded totals for the maximum and minimum annual effective dose equivalents for natural radiation exposure in the region suggest that it would be reasonable to use an estimate of 1000 microsievert (that is, half the total in Table 5-2) as being representative for the region.

5.4.2 Differences Between Doses in the South Pacific Region and the Worldwide Average

5.4.2.1 External irradiation from primordial radionuclides

An examination of Tables 5-2 and 5-3 shows that, while the maximum estimate in Table 5-3 for external irradiation by the different primordial radionuclides is the same as the corresponding estimate in Table 5-2, the minimum estimate is much less. The maximum and minimum estimates given in Table 5-3 for external irradiation from primordial radionuclides took into account a number of measurements of either absorbed dose rates in air or of the concentrations of various primordial radionuclides in soil, from which absorbed dose rates in air can be calculated. In addition it was necessary to take account of the effects of the materials used to construct buildings in the region.

Absorbed dose rates in air due to gamma-emitting radionuclides are clearly influenced by the nature of the islands, whether they are of volcanic or coralline orgin. Table 5-4 gives values of the average absorbed dose rates in air, both outdoors and indoors, in two islands in French Polynesia (Ducousso et al., 1982). It will be seen that at Tahiti, where the island is of volcanic origin, the absorbed dose rates were very much higher than at Hao, a coral atoll. Reasons for the differences in absorbed dose rates given in Table 5-4 can be seen from measurements of the concentrations of potassium-40, thorium-232 and uranium-238 made at Tahiti (volcanic rock) and Hao (coral). For Tahiti, the concentrations were 814, 48 and 48 becquerel per kilogram, respectively, while for Hao the corresponding values were 81, 5 and 15 becquerel per kilogram (Ducousso et al., 1982). It is interesting to note that, whereas the measured concentrations of potassium-40 and thorium-232 in coral at Hao were only about one-tenth of the concentrations of those radionuclides in volcanic rock at Tahiti, indicating that coral has low concentrations of those radionuclides, the concentration of uranium-238 in coral was about one-third of that for the volcanic rock. The presence of uranium in coral-derived soil is due to the fact that living corals accumulate natural uranium from seawater.

Table 5-5 lists the average concentrations of potassium-40, uranium-238 and thorium-232 in the soil in a number of islands and atolls in the South Pacific Region together with the calculated absorbed dose rates in air. For a number of locations the concentrations of one or more of the above radionuclides were not reported. It is assumed that, in those instances, the concentrations were below the level of detection of the measurement methods used. For comparison the concentrations of the same radionuclides in New Zealand soils and corresponding absorbed dose rates are given in Table 5-6. Comparable data are given for world average concentrations in Table 5-1. With a few exceptions, the values in Tables

5-1 and 5-6 are similar. The absence of results for concentrations of potassium-40 for atolls is because coral does not significantly concentrate potassium from sea water. The information provided in Tables 5-4 and 5-5 for islands and atolls in the region justifies the use of the maximum estimates for the annual effective dose equivalent for external irradiation from the various primordial radionuclides. The minimum estimates for the sources of external irradiation take account of the differences between the absorbed dose rates on an island of volcanic origin and for a coral atoll (Table 5-4), of the degree of similarity between absorbed dose rates for some islands in the region and elsewhere, the generally low concentrations of potassium-40 and thorium-232 in coralline soils, and the trend in a number of countries in the Region to construct more buildings with brick, concrete or stone.

5.4.2.2 Internal irradiation from primordial radionuclides

Table 5-3 gives a maximum estimate of the annual effective dose equivalent for internal irradiation from the radon-222 sub-series of the uranium-238 series which is much lower than the corresponding estimate in Table 5-2. The minimum estimate for this sub-series is only about 1 per cent of the estimate in Table 5-2. Both the maximum and minimum estimates in Table 5-3 are based on the knowledge that the concentration of radon-222 over the ocean is very much lower than over the continents and that many of the population of the region spend much of their time out of doors and live in well ventilated buildings made of wood or other lightweight materials. The low maximum and minimum estimates for the radon-220 sub-series of the thorium-232 series result from the consideration of the very low concentrations of radon-220 and its daughter products over the oceans, the low activities of thorium-232 in most of the islands and atolls in the region, and, as with radon-222 and its daughter products, the living habits of many of the population in the region.

5.4.3 Areas with Unusually High Levels of Natural Radioactivity in the South Pacific Region

5.4.3.1 Niue Island

Niue is a small isolated island, presumably a large volcanic cone, completely covered by an unknown thickness of limestone in the form of emerged reefs. Surveys of the radioactivity of New Zealand and South Pacific island soils (Marsden, 1964) showed that samples from Niue gave very high values. Other measurements showed that the alpha activity was due largely to thorium-230 and radium-226 out of equilibrium with the parent uranium-238 (Fieldes et al., 1960). Except on the coral reef which fringes the island, the average absorbed dose rate due to gamma radiation is about 40×10^{-4} gray per year and in some places about 260×10^{-4} gray per year. Corresponding values in some other locations in the region are at 4×10^{-4} gray per year at Samoa, 2×10^{-4} gray per year at Tonga, 2.5×10^{-4} gray per year at Fiji, and 17.5×10^{-4} gray per year at Black Rock, Rarotonga.

Food grown in Niue soil, particularly taro, showed a high uptake of radioactivity. Two varieties gave 23 becquerel per gram of ash of which more than ninety per cent was due to radium-226. It has been estimated that the people in a few villages who get appreciable amounts of food from the particular radioactive areas on the island would take in about 20 becquerel per day of alpha activity and the average person on the island about 4 becquerel per day. These values are large compared with the daily intake of alpha activity in a typical western European diet. Improved roads and housing have reduced both the intake of radionuclides by the inhalation of dust and the indoor radon concentrations. Changes in dietary habits, including the use of New Zealand powdered milk, have also reduced the intake of radionuclides.

The origin of the unusually high amounts of natural radioactivity in the soils of Niue is still unclear. Precipitation of radionuclides from seawater in the geologic past (Fieldes et al., 1960) or supply of radionuclides by hydrothermal transport (Schofield, 1967) have been suggested as possibilities.

5.4.3.2 Guam

A report by Nelson (1979a), from which results of measurements have already been used in compiling Table 5-5, includes data which show a marked difference in the average activity concentrations of uranium-235 (hence, uranium-238) and thorium-232 for northern and southern Guam. No activity concentration for potassium-40 is recorded for either location. The activity concentrations of uranium and thorium in soil suggest that the absorbed dose rate of gamma radiation may be as high as about 135×10^{-4} gray per year at the sampling locations in northern Guam compared with about 4×10^{-4} gray per year in southern Guam. The value for northern Guam is comparable in magnitude to the value measured at Niue. The Technical Group does not know of any action taken to verify the high values in northern Guam, which, except for Niue, is out of character with the known low levels of natural radioactivity in the South Pacific Region. The Technical Group recommends that if follow-up investigations have not been undertaken they should be put into effect at an early date.

TABLE 5-1

AVERAGE CONCENTRATION OF POTASSIUM-40, URANIUM-238 AND THORIUM-232 IN SOIL AND ABSORBED DOSE RATE IN AIR 1 M ABOVE THE GROUND SURFACE

Radionuclide or Decay Series	Average Concentration in Soil (a) (Bq kg^{-1})	Absorbed Dose Rate in Air (a) 10^{-4} Gy y^{-1}
^{40}K	370 (100-700)	1.4 (0.4-2.6)
^{238}U (b)	25 (10-50)	0.9 (0.4-1.9)
^{232}Th (b)	25 (7-50)	1.5 (0.4-2.9)

(a) The typical range is given within brackets.
(b) In radioactive equilibrium with all the decay products.

Source: UNSCEAR (1982)

TABLE 5-2

ESTIMATED ANNUAL EFFECTIVE DOSE EQUIVALENTS TO A PERSON FROM NATURAL SOURCES IN AREAS OF NORMAL BACKGROUND

Source of irradiation	Annual effective dose equivalent (μSv)		
	External irradiation	Internal irradiation	Total
COSMIC RAYS	300		300
COSMOGENIC RADIONUCLIDES		15	15
PRIMORDIAL RADIONUCLIDES			
^{40}K	120	180	300
^{87}Rb		6	6
^{238}u series			
$^{238}u \rightarrow {}^{234}u$	90	10	1044
^{230}Th		7	
^{226}Ra		7	
$^{222}Rn \rightarrow {}^{214}Po$		800	
$^{210}Pb \rightarrow {}^{210}Po$		130	
^{232}Th series			
^{232}Th	140	3	326
$^{228}Ra \rightarrow {}^{224}Ra$		13	
$^{220}Rn \rightarrow {}^{208}Tl$		170	
TOTAL (rounded)	650	1340	2000

Source: UNSCEAR (1982), Annex B, p.102

TABLE 5-3

ESTIMATED ANNUAL EFFECTIVE DOSE EQUIVALENTS
TO A PERSON FROM NATURAL SOURCES IN THE SOUTH PACIFIC REGION

Annual Effective Dose Equivalent (μSv)

Source of Irradiation	External Irradiation		Internal Irradiation		Total	
	Max.	Min.	Max.	Min.	Max.	Min.
Cosmic Rays	300				300	
Cosmogenic Radionuclides	-		15		15	
Primordial Radionuclides						
^{40}K	120	10	180		300	190
^{87}Rb	-	-	6		6	
^{238}U Series						
$^{238}U \rightarrow {}^{234}U$			10			
^{230}Th			7			
^{226}Ra			7			
$^{222}Rn \rightarrow {}^{214}Po$	90	60	100	10	344	224
$^{210}Pb \rightarrow {}^{210}Po$			130			
^{232}Th Series						
^{232}Th			3			
$^{228}Ra \rightarrow {}^{224}Ra$			13			
$^{220}Rn \rightarrow {}^{208}Tl$	140	15	60	0	216	31
Total (Rounded)	650	390	530	380	1180	770

TABLE 5-4

AVERAGE ABSORBED DOSE RATE IN AIR AT 1 M ABOVE GROUND SURFACE DUE TO PRIMORDIAL RADIONUCLIDES

Island/Atoll	Soil Type	Location of Measurement	Average Absorbed Dose Rate in Air (10^{-4} Gy y^{-1})
Tahiti	Volcanic	Outdoors	2.2
		Indoors	2.7
Hao	Coralline	Outdoors	0.5
		Indoors	0.7

Source: Ducousso et al. (1982)

TABLE 5-5

AVERAGE CONCENTRATION OF PRIMORDIAL RADIONUCLIDES IN SOIL IN SOUTH PACIFIC REGION AND CALCULATED ABSORBED DOSE RATE IN AIR 1 M ABOVE GROUND SURFACE

Location	Radionuclide or Decay Series	Average Concentration in Soil ($Bq\ kg^{-1}$)(a)	Absorbed Dose Rate in Air $10^{-4}\ Gy\ y^{-1}$	Remarks
Majuro	^{40}K	26	0.1	Coralline Soil
	^{238}U	27	1.0	Ref. Greenhouse and Miltenberger (1981)
		Total:	1.1	
Ponape	^{40}K	< 8	< 0.03	Volcanic Soil
	^{238}U	22	0.8	Ref. as above
	^{232}Th	37	2.1	
		Total:	2.9	
Truk	^{40}K	< 8	< 0.03	Volcanic Soil
	^{238}U	27	1.0	Ref. as above
	^{232}Th	23	1.3	
		Total:	2.3	
Palau	$^{226}Ra(^{238}U)$	7	0.3	Volcanic Soil
	^{232}Th	16	0.9	Ref. Nelson (1979a).
		Total:	1.2	
Wormej Is. Wotje Atoll	^{238}U	26(10)	1	Coralline Soil Ref. Nelson (1979b)
Wotje Is., Wotje Atoll	^{238}U	27(4)	1	Coralline Soil Ref. as above
Ailuk Is., Ailuk Atoll	^{238}U	27(13)	1	Coralline Soil Ref. as above
Bigen Is. Ailuk Atoll	^{238}U	30(3)	1.1	Coralline Soil Ref. as above
Utirik Atoll	^{238}U	37(6)	1.4	Coralline Soil Ref. as above
Christmas Is.	^{238}U	28(4)	1	Coralline Soil Ref. Nelson (1977)

(a) Number of samples is given in parentheses.

TABLE 5-6

CONCENTRATION OF POTASSIUM-40, URANIUM-238 AND THORIUM-232 IN NEW ZEALAND SOILS AND ABSORBED DOSE RATE IN AIR 1 M ABOVE THE GROUND SURFACE

Radionuclide or Decay Series	Concentration in Soil ($Bq\ kg^{-1}$)		Average Absorbed Dose Rate in Air $10^{-4}\ Gy\ y^{-1}$
	Maximum	Average	
^{40}K	1000	350	1.6
^{238}U (a)	63	23	1.2
^{232}Th (a)	100	30	2.2

(a) In radioactive equilibrium with all the decay products.
Source: National Radiation Laboratory (1974)

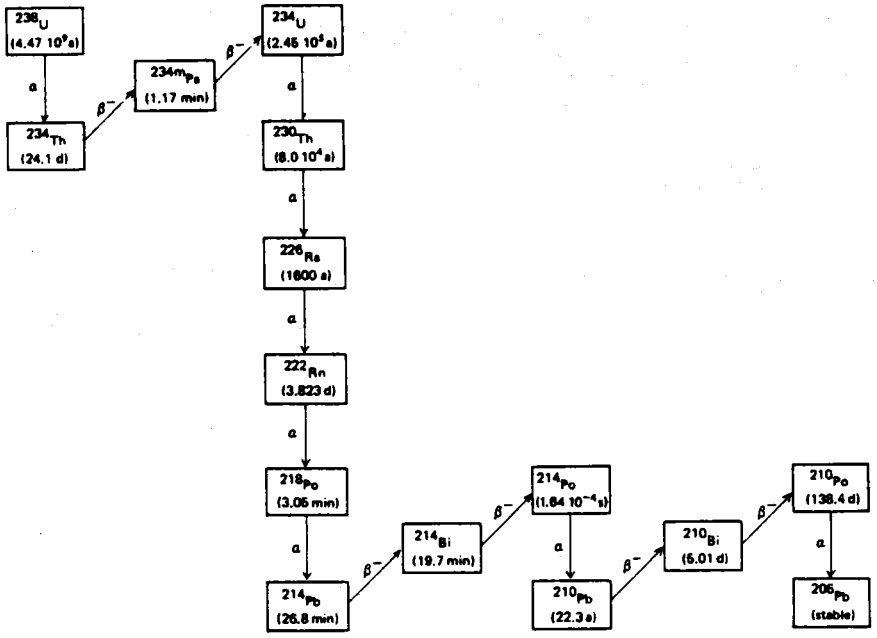


Figure 5-1. Uranium-238 decay series. Radionuclides produced in less than one per cent of the transformations of the parent nuclide are not shown. Source: UNSCEAR (1982), p. 86.

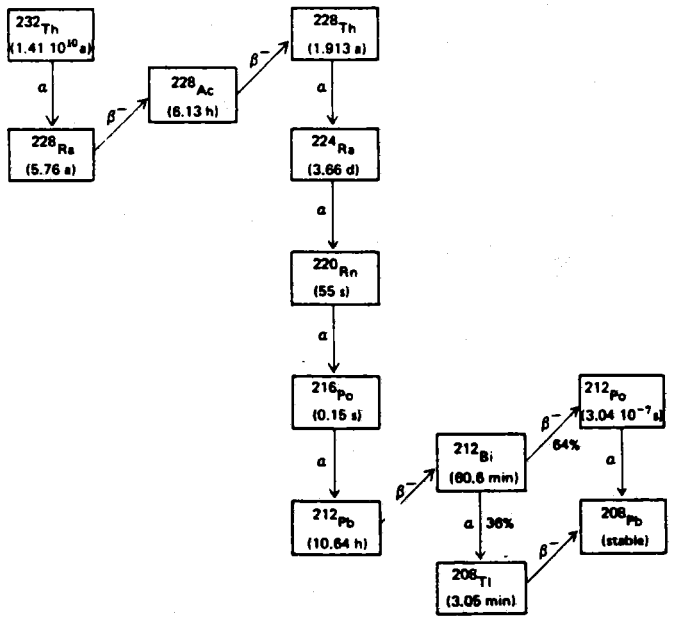


Figure 5-2. Thorium-232 decay series. Source: UNSCEAR (1982), p. 86.

5.5 REFERENCES

Ducousso, R., J.M. Guezengar, J. Boutte and C. Madelmont, 1982. Etude de l'irradiation naturelle externe en Polynésie française. Comparaison entre une île haute (Tahiti) et un atoll (Hao). Rapport C.E.A., R5148.

Fieldes, M., G. Bealing, G.G. Claridge, N. Wells and N.H. Taylor, 1960. Mineralogy and radioactivity of Niue Island soils. N.Z.J. Sci., 3: 658-675.

Greenhouse, N.A. and R.P. Miltenberger, 1981. An intercomparison of natural and technologically enhanced background radiation levels in Micronesia. Second Special Symposium on Natural Radiation Environment, Bombay, India, January 19-23.

Lambert, G., A. Buisson, J. Sanak, and B. Ardouin, 1979. Modification of the atmospheric polonium 210 to lead 210 ratio by volcanic emissions. J. Geophys. Res., 84: 6980-6986.

Lambert, G., G. Polian, J. Sanak, B. Ardouin, A. Buisson, A. Jegou and J.C. Le Roulley, 1982. Cycle du radon et de ses descendants: application à l'étude des échanges troposphère-stratosphère. Ann. Geophys., 38: 497-531.

Marsden, E., 1964. Radioactivity of some rocks, soils, plants and bones. In: The Natural Radiation Environment, J.A.S. Adams and W.M. Lowder (Eds.). Univ. of Chicago Press, pp. 807-824.

National Radiation Laboratory (New Zealand), 1975. Annual Report 1974 F/54.

Nelson, V.A., 1977. Radiological Survey of Plants, Animals and Soil at Christmas Island and Seven Atolls in the Marshall Islands. Report NVO-269-32, Laboratory of Radiation Ecology, University of Washington, Seattle, 69 pp.

Nelson, V.A., 1979a. Radiological Survey of Plants, Animals, and Soil in Micronesia. Report NVO-269-35, Laboratory of Radiation Ecology, University of Washington, Seattle, 28 pp.

Nelson, V.A., 1979b. Radiological Survey of Plants, Animals, and Soil at Five Atolls in the Marshall Islands. Report NVO-269-36, Laboratory of Radiation Ecology, University of Washington, Seattle, 35 pp.

Schofield, J.C., 1967. Origin of radioactivity at Niue Island. N.Z.J. Geol. Geophys., 10: 1362-1371.

Servant, J., 1964. Le radon et ses dérivés à vie courte dans la basse atmosphère. Thèse d'Etat, Université de Paris.

Turekian, K.K., D.P. Kharkar and J. Thomson, 1974. The fates of ^{210}Pb and ^{210}Po in the ocean surface. J. Rech. Atmos., 8: 639-646.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1977. Sources and Effects of Ionizing Radiation. Report to the General Assembly, with Annexes.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1982. Ionizing Radiation: Sources and Biological Effects. Report to the General Assembly, with Annexes, 773 pp.

CHAPTER 6

ENVIRONMENTAL RADIATION FROM NUCLEAR EXPLOSIONS

6.1 PRODUCTION OF ARTIFICIAL RADIONUCLIDES

Of man's activities, the two almost exclusively responsible for the introduction into the environment of artificial radionuclides are atmospheric nuclear explosions and nuclear electric power production. Very little direct information is available about nuclear explosions because of their military nature. Nevertheless, they can be detected at a great distance by the earth tremors, atmospheric pressure waves, and radioactive clouds that they cause. The data published on this subject are uncertain, however. Compilations of data are given in US Weather Bureau (1964), Zander and Araskog (1973), UNSCEAR (1982; see also Table 6-1, this Chapter), and Perkins and Thomas (1980).

With respect to atmospheric explosions only, three main periods are to be considered. Between 1945 and 1960, the USA, USSR, UK and France among them carried out 232 explosions, most of them low- or medium- power, but also including some high-yield thermonuclear (fusion) tests, such as the Mike and Bravo tests conducted by the USA on Enewetak and Bikini. Between August 1961 and December 1962, following a short moratorium obserbed by the USA and USSR, those two countries conducted a total of 127 explosions, including many high yield tests, the frequency of which exceeded all preceding ones. Also, one low-power explosion was made by France during this period. Between 1964 and 1980, sixty-three low- or medium-power explosions were carried out by the Peoples' Republic of China and by France. In addition, numerous underground explosions were effected at the bottom of shafts, which introduced into the atmosphere little or no radioactive material.

All USA, USSR, and Peoples' Republic of China tests were carried out in the Northern Hemisphere. As regards more particularly the atmosphere of the Southern Hemisphere, twelve low-power explosions were carried out by the UK between 1952 and 1957 in Australia; forty-one low-power or medium-power explosions were attributed to France between 1966 and 1974 in the Tuamotus, principally on the atoll of Mururoa. Mention should be made finally of nine British explosions made between 1957 and 1958 and 16 USA explosions made in 1962, mostly of medium power, all at the American test site on the Christmas Islands, which are situated at 2° N in the middle of the Pacific. The clouds from these tests often drifted to the Southern Hemisphere.

Table 6-1 lists the estimated yields of atmospheric nuclear tests from 1945 to 1980. The listing does not include underground nuclear tests, which do not normally release radioactive material to the environment or cause exposure to the public (but see Chapter 9 for further discussion). The production of fission nuclides is proportional to the fission yield of the tests, whereas the production of nuclides formed by neutron activation, such as tritium and carbon-14, can be assumed to be proportional to the fusion yield.

Unlike an explosion, a nuclear reactor is designed to prevent pollution of the environment as much as possible, which explains the fact that nuclear explosions are responsible for almost all the artificial radioactive nuclides that have been introduced into the environment. Chapter 3 explains fission and fusion processes in nuclear reactors and in nuclear and thermonuclear devices. It should also be remembered that, with one or two exceptions, all nuclear reactors are situated in the Northern Hemisphere (see Figure 9-5); it will be seen, however, that their effects cannot be entirely ignored in the Southern Hemisphere.

6.2 ATMOSPHERIC TRANSPORT

Table 3-1 (Chapter 3) gives a non-exhaustive list of the more important nuclides produced by nuclear explosions in the atmosphere. Their subsequent behaviour depends on their physical state at the normal temperature of the atmosphere and on the total power of the nuclear explosion. To understand this, it must be remembered that the atmosphere consists of several successive layers with very different properties (Figure 6-1). Between the surface of the earth and a height of 8 to 20 kilometres (according to latitude and season), there is the troposphere, in which all the phenomena of evaporation, condensation, and precipitation of water or snow occur and where the temperature falls as the altitude rises, making it in general unstable so that vertical mixing occurs very rapidly. Above that there is the stratosphere which goes up to a height of about 40 kilometres; it has a more or less constant temperature and contains almost no water vapour, making it vertically stable. Between the stratosphere and the troposphere, there is a boundary that is usually quite clearly defined, known as the tropopause, the height of which varies from one day to another and from one season to another.

A nuclear explosion produces first of all an extremely hot fireball, in which all matter is vapourized and which cools down slowly as it mixes with the air. Nuclear explosions with a force greater than 1 megaton (that is in fact, those caused by fusion reactions) have enough energy to carry this mixture to the stratosphere. In the cooling process, the naturally gaseous substances mix with the air and may stay for a long time in the atmosphere. Those materials which condense at the temperature of the atmosphere settle, atom by atom or molecule by molecule, on the small aerosols in suspension in the atmosphere.

Nuclear explosions in the kiloton range, when detonated near ground level, release most of their debris into the troposphere, and short-lived radionuclides will predominate in the first fission debris. During the period of French testing in the atmosphere at its testing ground in Polynesia, prevailing winds usually carried debris in an easterly direction so that South America was the first large land mass to receive such fallout. The radioactive cloud would take about three weeks to circle the world, and it would sometimes go around more than once. Because of dispersion, precipitation, and radioactive decay, the danger of any particular area receiving a high level of tropospheric fallout lessens with the progress of the radioactive cloud. Occasionally part of the radioactive cloud would be caught in an anticyclonic eddy and diverted back toward the west. When this happened, slowly diffusing radioactive particles would be carried over islands in the central South Pacific area in a matter of days.

In the troposphere, these aerosols are condensed in the ice crystals of clouds and are quickly precipitated to the ground in the form of rain or snow (humid fallout). Those that reach the ground or vegetation may settle there even without precipitation (dry fallout).

Tropospheric fallout consists of aerosols which deposit with a mean residence time

of up to 30 days. During this period, the debris becomes dispersed non-uniformly in the latitude band of injection, following trajectories governed by wind patterns. From the viewpoint of human exposure, tropospheric fallout is important for nuclides of a few days' to two-months' half-life, such as iodine-131, barium-140 and strontium-89. Stratospheric fallout, which comprises the bulk of the production, is due to those particles which are carried into the stratosphere and later give rise to world-wide fallout, the major part of which remains in the hemisphere of injection. The estimated stratospheric partitioning of nuclear debris is given by UNSCEAR (1982, Annex E, Table 2).

The main features of the mixing processes and air movements in the atmosphere (Figure 6-1) have been determined largely from the measurements of radionuclide concentrations. Aerosols descend gravitationally from the highest altitudes and move with the general air movements at lower levels. Eddy diffusion in the lower stratosphere and upper troposphere causes the irregular migration of air masses in the general directions indicated in Figure 6-1. The circular air flow pattern in the troposphere at lower altitudes is termed Hadley cell circulation. These cells increase or decrease in size and shift latitudinally with season. The mean residence time of aerosols in the lower stratosphere ranges from three to twelve months in the polar regions and from eight to twenty-four months in the equatorial regions. Their re-entry into the troposphere is the result of complex processes of atmospheric dynamics, the effect of which is to transfer air masses intermittently from the stratosphere to the troposphere. Such transfers occur more readily in the local springtime, and in the vicinity of 40° N or 35° S.

Because meridional movements in equatorial regions are very slight, the tropospheric aerosols produced at middle or high latitudes in one hemisphere, or injected into it from the stratosphere at these latitudes, only very exceptionally pass into the other hemisphere, as if there were a kind of "equatorial barrier" stopping them. This is shown in Figure 6-2, where it can be seen that after the resumption of nuclear tests in the Northern Hemisphere in September 1961, gross beta-radioactivity remained unchanged in the Southern Hemisphere, while it increased by twenty times in the Northern Hemisphere.

Gases whose half-lives are sufficiently long may reach a more or less homogeneous concentration in the troposphere.

6.3 MEASUREMENTS AND DATA

It is important to have some understanding of the pathways by which radionuclides contribute to the internal or external radiation dose. Let us consider, as example, the exposure of living things to fallout caesium-137, and consider the exposure pathways shown in Chapter 3, Figure 3-3.

There is first the input of caesium-137 into the atmosphere by a fission or fusion nuclear explosion. The radionuclide becomes more or less unevenly distributed throughout both hemispheres. We can measure the caesium-137 concentration in the atmosphere or in rain or the deposition per unit area of the land surface. The caesium-137 can be inhaled and taken up by man as one pathway (Figure 3-3, Pathway 4). Then again the caesium-137 can be taken in by drinking water or diet and enter body tissues, where it gives an internal radiation dose (Figure 3-3, Pathway 5). Finally, as we will discuss later, the radionuclide, while on the earth's surface or in the atmosphere, can give an external dose of radiation to the body (Figure 3-3, Pathway 2). Transfers between compartments can, in most cases, be easily measured and a relationship established between the amount of a radionuclide released to the environment and the dose received from that nuclide by persons. Many calculations

of such transfers are given by UNSCEAR (1982) or in many other scientific publications.

Every nuclear explosion produces more than 200 kinds of fission products and dozens of activation products, which are far from being all of equal importance. UNSCEAR has compiled data on the distribution of fallout in various compartments.

The great variability of the atmospheric processes of dispersion, of injections of stratospheric air into the troposphere, of precipitation to the ground, and of ingestion of food results in a comparable variability of the doses received by different people. Therefore, there is a need to study what numerical data can describe, in more detail, the exposure of South Pacific populations to fallout radiation. Generally speaking, very little information was available about this situation anywhere in the world before 1958. Since that date several networks or individual stations for taking measurements have been set up. It is the data from those stations that are examined below.

6.3.1 Strontium-90

Strontium-90 is a fission product and a pure beta-emitter (that is, no gamma emission). Its metabolism in the body is similar to that of calcium, which explains its importance in internal irradiation processes. The essential parameters for the ingestion of strontium-90 depend on its rate of deposition on the surface of the earth. Tables 6-2 and 6-3 give the deposit of strontium-90 up to 1980. Table 6-4 shows, station by station, the data available in the South Pacific Region as well as in New York, for purposes of comparison. The injection of stratospheric aerosols in middle latitudes explains why the maximum amounts of deposition of radioactivity per unit of surface are in these latitudes (Table 6-2, Figure 6-3). Table 6-3 shows that the greatest increases in annual deposition occurred in the Southern Hemisphere in the years 1963, 1964, and 1965. They are therefore attributed to the transfer into this hemisphere of that strontium-90 which had been introduced into the stratosphere in 1961 to 1962 as a result of explosions in the Northern Hemisphere. Secondary increases in the years 1969 to 1971 and in 1974 were probably due to French explosions conducted in the Southern Hemisphere. The higher figures observed at Tahiti (Table 6-4) are most likely explained by this.

There are no fallout data available before 1958, but the strontium-90 accumulated in the strata of firn of the Antarctic continent has been measured. It can be seen from Table 6-5 that the deposition per square kilometre was practically the same in the period 1955 to 1963 as it was in the period 1964 to 1968. Before 1955 there were negligible quantities of strontium-90 deposited in Antarctica. The annual deposition of strontium-90 in the Northern and Southern Hemispheres for the period 1958-1980 is shown in Table 6-3, together with the cumulative deposit in each hemisphere and the estimated total injection to January 1981. Since 1971, the annual rate of injection of strontium-90 has been less than the annual rate of decay, and the cumulative deposit has steadily decreased. Total strontium-90 production from nuclear tests was assessed to be 6×10^{17} becquerel to 1980. The global inventory of deposited strontium-90, which is decreasing by radioactive decay, was 4×10^{17} becquerel at the end of 1980.

6.3.2 Caesium-137

Caesium-137 is a fission product, a beta and gamma emitter. Of the fallout radionuclides it is the most important contributor to external irradiation dose. The concentration of caesium-137 in air is most important. Few data from the South Pacific Region exist. Table 6-6 shows some of the available data. Unlike ground deposition, the concentration of caesium-137 in air depends hardly at all upon

precipitation. Therefore, stations situated at the same latitude in a given hemisphere are fairly comparable. In the original tables of values, from which the values given in Table 6-6 were extracted, an important increase in the Northern Hemisphere between February 1970 and July 1971 is noted. It is attributed to the Chinese tests. In the Southern Hemisphere in June 1971, there was a distinct increase at Tahiti (Figure 6-4), where the concentration became 6.88×10^{-15} curie per cubic metre, and rather less distinct at the other stations further away from the French test site. The average level nevertheless remained slightly higher than usual until the end of 1971. It should, however, be noted that the activity of caesium-137 was still much less (between 10 and 2000 times less) than the activity of a natural cosmogenic nuclide like beryllium-7 (Table 6-7).

6.3.3 Short-lived Radionuclides

The observations made in the preceding paragraph clearly show the advantage of detecting the passage of a radioactive cloud, particularly in stations that are relatively near a nuclear test site. This effect is particularly noticeable in the case of short- or very short-lived products. Regular measurements have thus been carried out at Tahiti by the French Atomic Energy Commission (CEA) from 1970 to the present by gamma spectrometry of filters that are changed daily and represent some 72,000 cubic metres of air. Table 6-7 shows, year by year, mean values for months in which activities were sufficient to enable them to be measured. From time to time, considerable levels for nuclides as short-lived as barium-140 (half-life 13 days) were measured. A characteristic example is given in Figure 6-4. The sharp increase observed in the concentration of the short-lived radionuclides in June of 1971 corresponds to the start of the French test program for that year, which lasted until August.

6.3.4 Plutonium-239,240

These two isotopes of plutonium are produced by the action of neutrons on uranium-238, or they constitute residues of unfissioned fissile matter in the nuclear explosive devices. The reason for measuring them is their extreme harmfulness, both radiological and chemical. Generally these two isotopes are not measured separately.

Some data concerning the concentration of plutonium in the air are given in Table 6-8. Owing to the great variability of these results, it was considered preferable to give the extreme values observed each year rather than an average value which would be meaningless. It will be seen that, as is the case for other artificial radionuclides, the highest values are found in the 1960s in the Northern Hemisphere. Data for concentrations in air are not available for Tahiti before 1975. On the other hand, measurements of the plutonium deposition have been made at this station since 1970, and they show generally only very small values (Table 6-9).

6.4 DOSE CALCULATIONS

6.4.1 External Irradiation

6.4.1.1 Fallout radionuclides

Many radionuclides produced in nuclear testing emit gamma rays and contribute to the dose from external irradiation. The most important from this point of view are a number of short-lived radionuclides, particularly zirconium-95 and its daughter niobium-95 and the long-lived caesium-137. In principle, it is possible to calculate external doses from the integrated deposition density of each

radionuclide. In estimating doses received from fallout radionuclides by external irradiation, UNSCEAR (1982) took into account the back-scatter and shielding afforded tissues by other tissues of the body. It also took into account the shielding effect of buildings and the relative proportions of time that people spend indoors and outdoors. The overall factor used to convert absorbed dose in air to absorbed dose in organs was taken to be about 0.3. The effective dose equivalent commitments obtained are presented in Table 6-10. The effective dose equivalent commitment to the world population is estimated to be about 680 microsievert, the combined short-lived radionuclides and caesium-137 each contributing about half of this value.

6.4.1.2 Krypton-85

Krypton-85 is a gaseous fission product. It is almost a pure beta emitter (a gamma emission occurs in only 0.4% of emissions.) Practically the only way to remove krypton-85 from the atmosphere is by radioactive decay (half-life 10.3 years). Substantial stack releases of krypton-85 occur at nuclear fuel reprocessing plants but are not a source of significant exposure in the vicinity of the plant. In 1980 the atmospheric inventory of krypton-85 was estimated at about 3×10^{18} becquerel. The fraction due to atmospheric nuclear explosions is relatively small, about 1.6×10^{17} becquerel (UNSCEAR, 1982).

Almost all of the sources of krypton-85 are located in the Northern Hemisphere, but there is little uptake of krypton-85 by the biosphere or by the ocean. Thus there is a rather uniform distribution of krypton-85 between the two hemispheres.

In the South Pacific Region, where the concentration of radon-222 in the atmosphere is especially low, the activity due to krypton-85 is about two to three times higher than the natural radioactivity in the atmosphere. This is not of great consequence, however, because krypton is not metabolized by living organisms and thus only makes a slight contribution to radiation dose.

6.4.2 Internal Irradiation

Exposure of humans to fallout radioactivity by internal irradiation involves inhalation of activity in surface air and ingestion of contaminated foodstuffs.

6.4.2.1 Strontium 90

Strontium-90 is a beta emitter that decays to yttrium-90, a beta emitter with a half-life of 64 hours. The most important exposure pathway is by ingestion (Chapter 3, Figure 3-3, Pathway 5), and most of the dose is received by bone tissue. The effective dose equivalent commitments calculated by UNSCEAR (1982) for north and south temperate zones and for the world population are given in Table 6-10.

6.4.2.2 Strontium-89

Strontium-89 decays with the emission of beta rays. It is one of the main components of fallout activity in the first few months after a nuclear test. The ratio of activities of strontium-89 to strontium-90 at the time of fission is approximately 150, and the total atmospheric input of strontium-89 is estimated to have been about 90×10^{18} becquerel. Strontium-89 was measured in milk at some sixty-three cities in the US between 1961 and 1965, during which period about 55 percent of the total deposition in the Northern Hemisphere occurred.

Estimates of the effective dose equivalent commitment were made by UNSCEAR(1982), and both inhalation and ingestion pathways were found to be important. The dose commitments weighted for the world population are 1.0 microsievert from ingestion and 1.8 microsievert from inhalation. From measurements of strontium-90, it is estimated that the dose commitments which apply to the population of the south temperate latitudes are a factor of four less than the north temperate zone values and that hemispheric values are about 1.5 times less than the temperate zone values (from data in Table 6-2).

Most of the dose from strontium-89 was delivered in the early 1960s during maximum deposition.

6.4.2.3 Ruthenium-106

Ruthenium-106 is a pure beta emitter. It decays to rhodium-106, a beta emitter that also emits gamma rays. The total stratospheric injection of ruthenium-106, assessed from that of strontium-90 using the activity ratio of 20 at the time of fission, has been estimated at about 12×10^{18} becquerel. Inhalation is the most important pathway, and the effective dose equivalent commitments (Table 6-10) are 49 microsievert (north temperate zone), 11 microsievert (south temperate zone), and 30 microsievert (world).

6.4.2.4 Iodine-131

Iodine-131 is a beta/gamma emitter. The total injection of globally dispersed iodine-131 is estimated to be about 7×10^{20} becquerel. Fresh milk dominates as a source of iodine-131 intake in areas where it is a major dietary component. The short half-life of iodine-131 means that it is not well mixed in the atmosphere before deposition or decay. A rough estimate of total activity deposition density, weighted over the population of the world, has been made by UNSCEAR (1982) from the average ratio of iodine-131/barium-140 measured in deposition. Estimates of the effective dose equivalent commitments (Table 6-10) are 48 microsievert (north temperate zone), 6.9 microsievert (south temperate zone), and 33 microsievert (world).

6.4.2.5 Plutonium and transplutonium elements

The most important plutonium isotopes released during nuclear explosions in the atmosphere are plutonium-239, plutonium-240 and plutonium-241. Since plutonium-239 and plutonium-240 are not usually measured individually, activities reported as plutonium-239 apply generally to a mixture of plutonium-239 and plutonium-240 containing approximately 60 percent of plutonium-239 in terms of activity. The isotope plutonium-241 is a beta emitter with a half-life of 14.4 years, which decays to the alpha emitter americium-241, with a half-life of 433 years. Although it is not produced directly in nuclear explosions, americium-241 activity in the environment is increasing as plutonium-241 decays, and the total ultimate production will amount to 5.5×10^{15} becquerel. Plutonium transfer to human tissue can follow either the pathway of inhalation of airbone plutonium or the ingestion of contaminated food. The most important pathway to man is the inhalation of contaminated air. Estimates of the dose commitments from inhalation of plutonium and americium (Table 6-10) were obtained by UNSCEAR (1982) from the integrated concentrations in air, the committed doses per unit inhaled activity, and an intake rate of air of 20 cubic metres per day. The effective dose equivalent commitments are 1.0 microsievert from plutonium-238, 41 microsievert from plutonium-239,240, 8.8 microsievert for plutonium-241, and 1.7 microsievert from americium-241.

Food samples from the New York area were measured for plutonium-239,240 in 1963,

1964, 1972 and 1974 and for americium-241 in 1974. The dietary intake of plutonium-239,240 was found to be about 10 times higher in 1963 than in 1974, due to the influence of direct deposition. Italian data for the 1975-1978 period were in good agreement with the New York data.

By an approach similar to that used for strontium-90 and caesium-137, a relationship between ingestion in any one year and the deposition rate can be found for the plutonium isotopes. From this relationship an expression for the fallout-to-diet transfer factor can be obtained UNSCEAR (1982). The dose commitments resulting from ingestion of plutonium and americium-241 are given in Table 6-10. With the exception of americium-241, the dose commitments from ingestion are much lower than those from inhalation. The effective dose equivalent commitments weighted for world population from ingestion are 0.0047 microsievert from plutonium-238, 2.7 microsievert from plutonium-239,240, 0.04 microsievert from plutonium-241, and 1.8 microsievert from americium-241.

In addition to the plutonium isotopes released during atmospheric weapons testing, mention should also be made of the significant quantities of plutonium-238 that were released to the environment during the accidental re-entry of a US satellite in 1964 (Hardy et al., 1973). A Transit navigational satellite, launched from Vandenburg Air Force in California, contained as part of its payload a Systems for Nuclear Auxiliary Power generator (SNAP-9A) containing 6.3×10^{14} becquerel (about 1 kilogramme) of plutonium-238. Sampling in the stratosphere indicated that the generator burned up completely during re-entry and turned into small particles at an altitude of about 50 kilometres. Studies of soils collected in 1970-71 showed that over 75 percent of the SNAP-9A deposition occurred in the Southern Hemisphere. On a global basis this event increased the total plutonium-238 deposit by about three times. In the Southern Hemisphere, which received only about 20% of the plutonium-238 fallout from weapons tests, the plutonium-238 deposit was increased by about eight times.

6.4.2.6 Tritium

Tritium, a radioactive isotope of hydrogen, is a pure beta emitter. It occurs naturally, being produced in cosmic ray induced reactions. Man-made tritium has been injected into the stratosphere in substantial amounts by thermonuclear explosions. Most of the tritium exists as tritiated water. Total tritium production is about 2.4×10^{20} becquerel. Twenty percent of this amount has been transferred into or produced in the Southern Hemisphere. The effective dose equivalent commitment is 14 microsievert for a person in the Southern Hemisphere and 51 microsievert for a person in the Northern Hemisphere (Table 6-10).

6.4.2.7 Carbon-14

Carbon-14 is a pure beta emitter with a long half-life of 5730 years. As discussed in Chapter 5 it occurs naturally. It is also formed in large quantities in nuclear explosions, especially in thermonuclear ones.

It may be seen in Figure 6-5 that the carbon-14 activity in atmospheric carbon dioxide increased in the Northern Hemisphere in several successive steps until 1963-1964, when it was double its natural level. Later, the carbon-14 dioxide mixed throughout the atmosphere, the concentrations in both hemispheres becoming very similar by the end of 1967. Since that time, the concentration has decreased quasi-exponentially and was about 30 percent above the natural level in 1980. A simple extrapolation, probably unrealistic, would lead to natural levels by the year 2013. The input of man-made carbon-14 into the atmosphere is estimated at 2.2×10^{17} becquerel. By comparison to natural carbon-14 production and exposure (12

microsievert), a dose commitment of 2600 microsievert has been calculated for bomb carbon-14 (Table 6.10). Carbon-14 is therefore by far responsible for the most important part of the global dose commitment from nuclear explosions, amounting, in fact, to 69 percent.

The dose commitment from carbon-14 is delivered over a very long time period. By the end of the year 2000, only 7 percent of the total commitment will have been delivered (UNSCEAR, 1982). This is in contrast with the case of almost all other artificial radionuclides, whose half-lives are of the order of days, months or years and which will have practically disappeared by that time.

Although there is no doubt of the reality of the value of 2600 microsievert for the total carbon-14 dose commitment, this figure does not allow a correct evaluation of possible harmfulness due to this nuclide.

In effect the proportion of carbon-14 in the carbon atoms of living things in continental areas is practically the same as in the atmosphere, and the carbon-14 atmospheric concentration decreases very rapidly (Figure 6-5). Since this concentration is the same in both hemispheres, such a decrease is mainly due to the carbon dioxide absorption by surface seawater, in which the concentration is steady about 5 to 10 percent above the natural level. It could therefore be expected that the carbon-14 concentration in air would reach a level about 5 to 10 percent above the natural background level. This level might be further modified by subsequent mixing between surface and deep waters. Furthermore, it is known that, as a result of man's activities, some 6×10^9 tons of carbon (that is about 1 percent of the atmospheric content) derived from the combustion of fossil fuels, which are free of carbon-14, are introduced into the atmosphere annually.

It is therefore impossible to predict what will actually be the carbon-14 atmospheric activity beyond the year 2000. It may only be postulated that this activity will differ only a little from its natural level. The Technical Group thus considered that it would be reasonable to limit its assessment to the year 2000. Consequently the effective dose equivalent commitment from carbon-14 to be taken into account in this Report is only 7 percent of that given in Table 6-10, that is, about 200 microsievert instead of 2600 microsievert.

This being so, the actual effective dose equivalent commitments to be borne in mind are those given in Table 6-11, from which it can be seen that, in terms of the dose commitments, the Southern Hemisphere is three times less contaminated by artificial radionuclides than the Northern Hemisphere. This is primarily because most of the atmospheric nuclear explosions were detonated in the Northern Hemisphere, and only a small part of the debris penetrated into the Southern Hemisphere. This is clearly illustrated by Figure 6-6, where the preponderant effect of the explosions carried out in 1961 and 1962 (in the Northern Hemisphere) can be seen.

6.5 SUMMARY OF DOSE COMMITMENTS DUE TO NUCLEAR EXPLOSIONS

Estimates of the dose commitments from nuclear explosions carried out to the end of 1980 are summarized in Table 6-10 (UNSCEAR, 1982). The use of the effective dose equivalent commitments permits a direct comparison of the importance of the various pathways to man and of the importance of the various radionuclides considered. The weighting factors of the ICRP were applied. For the world population, the contribution of ingestion (3000 microsievert) is found to be about four times higher than that of external irradiation (680 microsievert), which in turn is about five times greater than that of inhalation (130 microsievert). The relative importance of ingestion would be very much reduced if an incomplete effective dose equivalent

were calculated up to the end of the year 2000. In that case external irradiation would be the dominant pathway, as carbon-14, which is the major contributor to the ingestion dose, delivers in that time span only a small fraction of its total contribution. The effects of this correction are discussed in section 6.4.2.7. Of the 21 radionuclides considered by UNSCEAR (1982), only seven contribute more than one percent of the effective dose equivalent commitment for the world population. These nuclides are, in decreasing order of importance, carbon-14, caesium-137, zirconium-95 strontium-90, ruthenium-106, cerium-144 and tritium. If the contribution from carbon-14 is only considered through the year 2000, then caesium-137 becomes the most significant radionuclide, and carbon-14 becomes approximately equal in importance to zirconium-95. For zirconium-95, ruthenium-106 and cerium-144, the irradiation to which the world population was committed by nuclear tests to the end of 1980 is already largely completed. For caesium-137, strontium-90 and tritium, a large part of their contribution to the effective dose equivalent commitment will have been delivered by the year 2000. If there is no further nuclear testing in the atmosphere, only carbon-14 will contribute significantly to the dose rate in the third millenium. In the far future, however, the long-lived plutonium isotopes and their decay products may have to be given further consideration.

As regards the artificial sources of radiation, at present consisting almost entirely of nuclear explosions in the atmosphere, the data for the Southern Hemisphere indicate that the radiation doses to which populations are exposed is on average two to three times less than in the case of populations living in the middle latitudes of the Northern Hemisphere. However, the numerical data at present available are not sufficient in the Region, in that numerous nuclides have not been measured and, in respect of many others, the atmospheric measurements have often begun too late. It is therefore possible that certain localised populations may have been exposed, during transient events not documented, to more radiation dose than the average inhabitant of the Region (see also the following section dealing with the Marshall Islands).

However, it does appear that the fraction of the effective dose equivalent received by populations that can be ascribed to artificial sources is still, for the Region as a whole, very small in comparison with the amount from natural sources (Figure 6-6). In particular, it is much less than the extremes of the geographical variations of natural irradiation shown in Chapter 5. In other words, the possible consequences of irradiation from artificial sources might well always be completely masked by the variability of the natural radiation to which populations are exposed.

6.6 AREAS WITH UNUSUALLY HIGH LEVELS OF ARTIFICIAL RADIOACTIVITY IN THE SOUTH PACIFIC REGION

In Chapter 5 it was concluded that the South Pacific Region is, on the whole, an area in which exposure to natural sources of ionizing radiation is low by comparison with the world average; and in this Chapter it has been seen that exposures to artificial sources of ionizing radiation are also low for the region as a whole, because most of the population of the Region lives in the Southern Hemisphere, whereas the greater part of the fallout from atmospheric nuclear weapons tests was delivered in the Northern Hemisphere. It was also pointed out in Chapter 5, however, that certain islands in the Region (Niue and possibly Guam) can be identified as areas having unusually high levels of natural radioactivity. Similarly there are islands in the Region where unusually high levels of artificial radioactivity occur, notably in the Marshall Islands, where large amounts of local fallout from the US atmospheric test series were received.

The United States conducted more than sixty atmospheric nuclear explosions at its Pacific Proving Grounds during the period 1946-1958. In contrast to the more recent French program, in which most of the explosions occurred at high altitudes and led mainly to widely dispersed tropospheric and stratospheric fallout, many of the US detonations occurred at or near ground level. This caused relatively large particles of coralline debris to be sucked upward by the convective forces associated with the rising fireball. The radionuclides associated with the fireball condensed on these large particules and within a few hours led to radioactive fallout close to the point of detonation. Bikini and Enewetak Atolls, where most of the US tests in the Pacific were conducted, became heavily contaminated with debris of this kind.

In addition to the two test sites, other islands and atolls in the Northern Marshalls received significant quantities of local fallout. This more widespread contamination of islands in the area occurred most notably as a result of the 1954 Bravo test, a very high-yield (fifteen-megaton) surface explosion. The trajectory of the fallout cloud from that test was incorrectly forecast, and large quantities of fallout were carried eastward and fell on the inhabited atoll of Rongelap and, in lesser amounts, on Ailinginae, Rongerik, and Utirik before the people living on those atolls were evacuated. In addition, the Japanese fishing vessel Fukuryu Maru, operating east of Bikini, was exposed to the fallout. As a result 239 Marshallese, 28 American servicemen and 23 Japanese fishermen received variably severe exposures to ionizing radiations. Their exposures produced short-term effects and also led to long-term effects that continue to be studied. The most recent review of the effects that occurred in the exposed Marshallese population is given by Conard et al (1980).

A very large amount of scientific research on the radioactive contamination at the Pacific Proving Grounds has been carried out since the 1950s. Recent work has been done for the purpose of establishing whether the people who were displaced from Bikini and Enewetak prior to the testing programs could safely return. The most recent assessments have been carried out by Robison and co-workers at the Lawrence Livermore National Laboratory (LLNL) (Robison et al., 1980; 1982). The survey at Enewetak followed a clean-up operation, in which large quantities of contaminated soil and other debris were disposed of in a crater left by one of the explosions and covered by a concrete cap. In addition to the Bikini and Enewetak assessments, there has also been a recent survey on other islands in the Northern Marshalls, including Rongelap and other locations thought to have received lesser amounts of local fallout (Robison et al., 1981 a,b; 1982; Noshkin et al., 1981).

The LLNL radiological surveys included measurements of external absorbed dose and also large numbers of radionuclide concentration measurements in soil and in plants and animals (including marine organisms) used as food. Doses that would be received by various ingestion pathways were calculated on the basis of different sets of assumptions concerning diet and whether or not imported foods would be eaten extensively. The types of doses calculated were dose equivalents to the whole body and bone-marrow and doses to the lung from inhalation. Maximum annual dose rates were reported, and also calculated were 30-year and 50-year integrated doses (that is, the summed dose equivalents that would be received over those time periods). All the calculated doses are those due to artificial radioactivity only.

The important general observations made from the LLNL radiological assessments, applicable to all the areas studied, are the following: (1) the terrestrial food chain is the most important exposure pathway, contributing more than 50 percent of the total dose, with external gamma exposure being the second most significant pathway and doses received by the marine food chain, drinking water, and inhalation being of much lesser importance; (2) caesium-137 accounts for more than 65 percent

of the total dose, with strontium-90 being the second most significant radionuclide; (3) the transuranic radionuclides contribute a small portion of the predicted lung and bone doses but do present a long-term source of exposure; and (4) the predicted doses depend very heavily on the diet that is assumed. The authors of the reports believe that the predicted doses may be somewhat overestimated.

A summary of the maximum dose rates calculated for the Northern Marshall Islands is given in Table 6-12. Following the year of maximum exposure the dose rates would decline because of radioactive decay. The highest doses are for Bikini Island and are about ten to twenty times (depending on the diet assumed) the average effective dose equivalent estimated for the natural background exposure in the South Pacific Region as a whole (Chapter 5). They are comparable in magnitude to the doses from external irradiation measured at Niue Island, an area of unusually high natural radioactivity (Chapter 5, Section 5.4.1). The doses at Bikini Island exceed the limit of 5,000 microsievert per year for stochastic effects set by the ICRP for exposure of the general public to artificial ionizing radiation (Chapter 3). The Bikinians have not yet permanently resettled their atoll.

At Enewetak the doses are relatively high at Enjebi in the north, where most of the testing was done. In the southern islands, which were recently resettled, the doses are low and within the variability of the natural background exposure. A committee appointed by the U.S. National Academy of Sciences recently evaluated the structure built at Enewetak to contain the radioactive debris from the clean-up operation and concluded that the structure and its contents present no credible health hazard to the people of Enewetak, either now or in the future (NAS/NRC, 1982). The same committee also pointed out, however, that for people who might want to resettle Enjebi in the near future, radiation exposures due to strontium-90 or caesium-137 in locally grown foods may become excessive in relation to current U.S. standards for a general population, especially if food is not imported from other islands of the atoll or from outside.

The results for Rongelap, Rongerik, Ailinginae, and Utirik reflect the residual contamination from the Bravo test. For the other islands in the survey, the doses are quite small compared to natural background fluctuations but presumably are still higher than those which would be received on comparable islands exposed only to worldwide fallout. Robison et al. (1982) estimated that for these islands (Likiep down through Jemo in Table 6-12) approximately 30 percent of the caesium-137 in the soil is from worldwide fallout and not specific to the Marshall Islands. Worldwide fallout accounts for only 7 percent of the caesium-137 at Utirik and only about 2 percent at Rongerik and Rongelap. The other 70, 93, and 98 percent of the caesium-137, respectively, on the islands is due to local and tropospheric fallout.

TABLE 6-1

ESTIMATED YIELDS OF ATMOSPHERIC NUCLEAR TESTS

Year	Country	Number of tests	Estimated yield (Mt)	
			Fission	Total
1945	USA	3	0.05	0.05
1946	USA	2	0.04	0.04
1948	USA	3	0.10	0.10
1949	USSR	1	0.02	0.02
1951	USA	15	0.50	0.50
	USSR	2	0.04	0.04
1952	USA	10	6.6	12.6
	UK	1	0.02	0.02
1953	USA	11	0.25	0.25
	UK	2	0.04	0.04
1954	USA	6	29.6	47.1
	USSR	1	0.5	0.5
1955	USA	13	0.17	0.17
	USSR	4	1.5	3.0
1956	USA	14	9.7	22.7
	USSR	7	2.5	4.8
	UK	6	0.10	0.10
1957	USA	25	0.34	0.34
	USSR	13	4.7	11.3
	UK	7	5.85	9.25
1958	USA	53	8.2	17.6
	USSR	25	16.2	35.2
	UK	5	4.54	7.24
1960	France	3	0.11	0.11
1961	USSR	50	25.4	122.3
	France	1	0.02	0.02
1962	USSR	39	60.05	180.3
	USA	38	16.5	37.1
1964	China	1	0.02	0.02
1965	China	1	0.04	0.04
1966	France	5	0.68	0.68
	China	3	0.62	0.62
1967	France	3	0.20	0.20
	China	2	1.72	3.02

Table 6-1 (Continued)

Year	Country	Number of tests	Estimated yield (Mt)	
			Fission	Total
1968	France	5	4.1	4.9
	China	1	1.2	3.0
1969	China	1	2.0	3.0
1970	France	8	2.55	2.75
	China	1	2.0	3.0
1971	France	5	1.95	1.95
	China	1	0.02	0.02
1972	France	3	0.12	0.12
	China	2	0.12	0.12
1973	France	5	0.05	0.05
	China	1	1.6	2.5
1974	France	7	1.1	1.1
	China	1	0.45	0.60
1976	China	3	2.37	4.12
1977	China	1	0.02	0.02
1978	China	2	0.04	0.04
1980	China	1	0.45	0.6
Summary				
1945-1962	USA	193	72.1	138.6
1949-1962	USSR	142	110.9	357.5
1952-1953	UK	21	10.6	16.7
1960-1974	France	45	10.9	11.9
1964-1980	China	22	12.7	20.7
TOTAL		423	217.2	545.4

Source: UNSCEAR (1982) Annex E, p. 227

TABLE 6-2

LATITUDINAL DISTRIBUTION OF STRONTIUM-90 DEPOSITION[a/]

Latitude band (degrees)	Integrated deposition (10^{16} Bq)	Area of band (10^{12} m^2)	Integrated deposition density (10^3 Bq m^{-2})	Population distribution (%)	Population weighted integrated deposition density (10^3 Bq m^{-2})
NORTHERN HEMISPHERE					
80-90	0.10	3.9	0.26	0	
70-80	0.79	11.6	0.68	0	
60-70	3.29	18.9	1.74	0.4	
50-60	7.39	25.6	2.89	13.7	
40-50	10.16	31.5	3.23	15.5	
30-40	8.53	36.4	2.34	20.4	
20-30	7.12	40.2	1.77	32.7	
10-20	5.09	42.8	1.19	11.0	
0-10	3.57	44.1	0.81	6.3	
Total	46.0			100.0	2.14
SOUTHERN HEMISPHERE					
0-10	2.10	44.1	0.48	54.0	
10-20	1.78	42.8	0.42	16.7	
20-30	2.81	40.2	0.70	14.9	
30-40	2.76	36.4	0.76	13.0	
40-50	2.81	31.5	0.89	0.9	
50-60	1.21	25.6	0.47	0.5	
60-70	0.67	18.9	0.35	0	
70-80	0.25	11.6	0.22	0	
80-90	0.03	3.9	0.08	0	
Total	14.4			100.0	0.54
GLOBAL	60.4			89 (N) 11 (S)	1.96

[a/] Through 1980, including projected deposition of stratospheric burden.

Source: UNSCEAR(1982) Annex E, p. 230

TABLE 6-3

ANNUAL DEPOSITION AND CUMULATIVE DEPOSIT OF STRONTIUM-90

	Annual Deposition (10^{16} Bq)			Cumulative deposit (10^{16} Bq)		
	Northern hemisphere	Southern hemisphere	Global	Northern hemisphere	Southern hemisphere	Global
Pre-1958	6.68 a/	2.37 a/	9.05 a/	6.29	2.22	8.51
1958	2.33	0.95	3.28	8.44	3.11	11.55
1959	3.89	0.68	4.57	12.06	3.70	15.76
1960	0.97	0.62	1.59	12.73	4.22	16.95
1961	1.30	0.64	1.94	13.69	4.77	18.46
1962	5.34	0.98	6.32	18.65	5.59	24.24
1963	9.70	1.14	10.84	27.79	6.59	34.38
1964	6.13	1.56	7.69	33.96	7.99	41.95
1965	2.86	1.32	4.18	35.15	9.10	44.25
1966	1.21	0.77	1.98	35.48	9.62	45.10
1967	0.62	0.41	1.03	35.22	9.81	45.03
1968	0.72	0.38	1.10	35.08	9.92	45.00
1969	0.54	0.52	1.06	34.78	10.21	44.99
1970	0.76	0.47	1.23	34.67	10.43	45.10
1971	0.70	0.56	1.26	34.52	10.73	45.25
1972	0.32	0.35	0.67	33.97	10.80	44.77
1973	0.12	0.11	0.23	33.23	10.66	43.89
1974	0.45	0.14	0.59	32.89	10.55	43.44
1975	0.22	0.13	0.35	32.30	10.40	42.70
1976	0.10	0.08	0.18	31.64	10.25	41.89
1977	0.30	0.08	0.38	31.15	10.06	41.21
1978	0.37	0.07	0.44	30.78	9.88	40.66
1979	0.12	0.04	0.16	30.16	9.70	39.86
1980	0.11	0.04	0.15	29.54	9.51	39.05
Integrated deposition (10^{16} Bq)	45.86	14.41	60.27			
Stratospheric inventory/b (10^{16} Bq)	0.18	< 0.01	0.18			
Total injection through 1980 (10^{16} Bq)	46.0	14.4	60.4			

a/ Estimated from the cumulative deposit.

b/ Measured July 1979 in the northern hemisphere, reduced with a half-time of 10 months to the end of 1980, plus estimated injection in 1980. Estimate only for the southern hemisphere.

Source: UNSCEAR (1982) Annex E, p. 229

TABLE 6-4

STRONTIUM-90 DEPOSITION (10^{-3} CI KM^{-2})

	New York, U.S.A.	Lihue, Hawaii	Wake Is.	Johnston Is.	Clark AB, Philippines	Anderson AFB, Guam	Yap Is.	Truk Is.	Koror Is.	Majuro Is.	Ponape Is.
	40°44N; 74°00W (1)	21°59; 159°21W (1)	19°17N; 166°39E (1)	16°45N; 169°32W (1)	15°11N; 120°33E (1)	13°35N; 144°55E (1)	9°31N; 138°8E (1)	7°28N; 151°51E (1)	7°21N; 134°31E (1)	7°05N; 171°23E (1)	6°58N; 158°13E (1)
4	2.8										
1955	3.6										
6	4.4										
7	4.4										
8	6.2										
9	8.7										
1960	1.6	0.6									
1	2.4	1.3									
2	12.3	9.1									
3	23.8	10.9									
4	15.8	12.3									
1965	5.5	3.1									
6	2.4	1.6									
7	1.6	0.9									
8	1.3	0.7									
9	1.4	0.5									
1970	1.5	0.4									
1	1.4	0.8									
2	0.7	0.4									
3	0.4	0.1									
4	0.9	0.6									
1975	0.7	0.2									
6	0.3	0.1	0.03	0.05	0.02	0.05	0.03	0.08	0.08	0.05	0.10
7	0.8	0.4	0.41	0.14	0.11	0.10	0.17	0.11	0.12	0.12	0.12
8	0.9	0.3	0.17	0.19	0.04	0.22	0.10	0.12	0.19	0.13	0.13
9	0.3	0.04	0.05	0.07	0.01	0.05	0.05	0.04	0.05	0.06	0.03
1980	0.1	0.03	0.03	0.01	0.04	0.05	0.04	0.02	0.02	0.03	0.04
1	0.3	0.08	0.13	0.06	0.02	0.08	0.03	0.03	0.05	0.07	0.09
2											

TABLE 6-4 (Continued)

	Tutuila, American Samoa 14°55S 170°43W (1)	Tahiti, French Polynesia 17°55S 149°30W (3)	Suva, Fiji 18°09S; 178°25E (2)	Rarotonga, Cook Is. 20°30S; 160°W (2)	Easter Is., Chile 27°10S; 109°26W; (1)	Brisbane, Australia 27°28S 153°02E (1)	Hobart, Australia 42°53S 147°20E (1)	New Zealand, - average of 9 stations - ~ 45°S;175°E (2)
4								
1955								
6								
7								
8								
9						1.0	0.7	
1960						0.8	0.5	0.9
1			1.0			1.0	0.8	1.2
2			1.6			1.5	0.7	1.5
3			2.4		0.9	1.7	0.9	1.8
4			2.5		1.8	2.0	1.7	3.5
1965			2.0		1.6	1.8	1.6	3.0
6	1.3		1.2		0.9	1.1	0.9	1.3
7	0.5		0.8	0.9	0.4	0.6	0.4	0.9
8	0.6		1.0	0.6	0.4	0.4	0.3	0.8
9	0.5		1.2	0.7	0.6	0.8	0.5	1.2
1970	0.5	0.3	0.9	0.9	0.4	0.9	0.6	1.0
1	0.8	2.1	1.5	0.3	0.6	1.2	0.7	1.4
2	0.3	0.2	0.9	0.8	0.4	0.7	0.3	0.8
3	0.1	0.3	0.4	0.6	0.07	0.3	0.2	0.3
4	0.3	3.4	0.3	0.3	0.07	0.2	0.1	0.3
1975	0.03	< 0.2	0.2	0.1	0.2	0.2	0.2	0.3
6	0.02	< 0.1	0.1	0.1	0.05	0.09	0.1	0.1
7	0.1	< 0.1	0.08	0.03	0.09	0.02	0.03	0.07
8	0.5	< 0.1	0.08	0.04	0.03	0.06	0.06	0.07
9	0.04	< 0.1	0.07	0.02	0.02	0.03	0.03	0.07
1980	0.3	< 0.1	0.05	0.05	0.04	0.04	0.02	0.06
1	0.03	0.3	0.04	0.2	0.03		0.02	0.05
2		0.4						

Sources: (1) Health and Safety Laboratory, 19; Environmental Measurements Laboratory, 1982.
(2) National Radiation Laboratory, New Zealand, 1981, Annual Report 1980.
(3) Unpublished data, France, DIR-CEN/2029, 22 April 1983.

TABLE 6-5

STRONTIUM-90 ACCUMULATION IN COASTAL ANTARCTICA (10^{-3} CI KM^{-2})
(CALCULATED FROM LAMBERT ET AL., 1983)

Pre-1955	~ 0
1955 - 1963	2.10
1964 - 1968	2.09
1969 - 1971	0.65

TABLE 6-6

CONCENTRATION OF CAESIUM-137 IN AIR
(10^{-15} CI M^{-3})

	New York, USA (1)	Mauna Loa, Hawaii (1)	Easter Is., Chile (1)	Antofagasta, Chile (1)	Puerto Montt, Chile (1)	Tahiti (2)
1963	106	67	-	6.0	3.9	-
4	50	52	-	7.2	3.8	-
5	20.7	23	-	6.1	3.5	-
6	-	-	-	-	-	-
7	-	-	-	-	-	-
8	-	-	-	-	-	-
9	3.7	4.5	1.6	3.3	1.7	-
1970	5.7	6.8	1.6	4.7	1.5	1.45
1	6.3	6.0	1.5	4.2	1.9	2.57
2	1.8	2.4	0.94	2.1	1.3	1.34
3	0.79	1.1	0.44	1.2	0.65	0.88
4	2.6	3.4	0.47	1.1	0.34	1.27
5	1.5	1.9	0.44	1.0	0.49	0.72
6	0.64	0.65	0.23	0.21	0.26	0.23
7	1.9	3.5	0.19	0.10	0.17	0.40
8	2.1	2.4	0.20	0.16	0.16	0.14
9	0.76	1.1	0.13	0.13	0.15	0.21
1980	0.55	0.72	0.25	0.20	0.15	0.16
1	-	-	-	-	-	0.16
2	-	-	-	-	-	0.06

Sources: (1) Environmental Measurements Laboratory, 1981.
(2) Unpublished data, French Atomic Energy Commission.

TABLE 6-7

ACTIVITY OF GAMMA EMITTERS IN AIR AT TAHITI (10^{-15} CI M^{-3})[a/]

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
^{7}Be	63.6	69.3	82.3	84.3	89.9	107	140	117	77.1	75.6	73.4	77.5	83.9
^{95}Zr	68.4 (4)	159 (12)	4.0 (10)	45.4 (4)	89.2 (7)	1.49 (9)	-	0.65 (4)	-	0.56 (1)	0.27 (1)	0.37 (6)	-
^{95}Nb	101 (4)	143 (12)	6.74 (12)	12.4 (7)	61.8 (9)	1.66 (8)	0.13 (1)	0.88 (9)	-	0.09 (1)	0.35 (1)	0.25 (4)	-
^{103}Ru	36.5 (4)	102 (12)	2.20 (9)	100 (4)	110 (6)	0.40 (5)	-	0.17 (1)	-	-	0.37 (1)	0.34 (4)	-
^{106}Rh	10.1 (4)	8.78 (12)	2.72 (12)	5.21 (9)	6.21 (8)	2.50 (5)	1.82 (2)	1.03 (1)	0.49 (2)	1.94 (2)	-	0.55 (1)	0.04 (1)
^{125}Sb	1.11 (3)	0.59 (2)	0.45 (5)	-	1.62 (3)	-	-	-	-	-	-	-	-
^{131}I	-	91.3 (3)	6.09 (1)	199 (2)	98.8 (6)	-	-	-	-	-	-	-	-
^{137}Cs	1.45 (4)	2.57 (12)	1.34 (12)	0.88 (11)	1.27 (9)	0.72 (8)	0.23 (9)	0.40 (10)	0.14 (10)	0.21 (7)	0.16 (8)	0.16 (11)	0.06 (8)
^{140}Ba	30.4 (2)	1063 (5)	16.9 (1)	553 (2)	155 (5)	-	5.86 (2)	-	-	-	-	-	-
^{141}Ce	56.8 (4)	248 (12)	1.60 (9)	125 (4)	166 (6)	0.69 (2)	0.40 (1)	0.81 (1)	-	-	0.36 (1)	0.48 (2)	-
^{144}Ce	29.2 (4)	47.4 (12)	6.56 (12)	5.82 (12)	16.9 (10)	2.81 (9)	0.45 (5)	0.94 (6)	0.47 (7)	0.37 (6)	0.13 (1)	0.28 (9)	0.08 (1)
^{147}Nd	8.48 (2)	565 (4)	3.27 (1)	224 (2)	91.1 (5)	-	-	-	-	-	-	-	-
^{54}Mn	0.63 (6)	0.31 (9)	0.19 (1)	-	0.50 (3)	-	-	0.04 (1)	-	-	-	-	-
^{57}Co	0.72 (4)	0.25 (11)	0.09 (3)	-	2.48 (4)	-	-	-	-	-	-	-	-

Source: Unpublished data, French Atomic Energy Commission

a/ Mean values for months in which activities were high enough to allow reliable measurements. The number of months is indicated in parentheses under each value.

TABLE 6-8

PLUTONIUM 239,240 IN AIR (10^{-18} CI M^{-3})

	New York*, USA (1)	Mauna Loa, Hawaii (1)	Antofagasta, Chile (1)	Easter Is., Chile (1)	Puerto Montt (Chile) (1)	Tahiti (2)
1965	72 - 1300	134	28 - 151	-	-	-
1966	26 - 393	22 - 254	21 - 273	6.5 - 40	12 - 114	-
1967	16 - 155	11 - 85	13 - 142	13 - 29	9 - 34	-
1968	32 - 136	17 - 157	9 - 30	5 - 16	3 - 20	-
1969	17 - 100	18 - 122	10 - 91	5 - 131	8 - 16	-
1970	26 - 125	10 - 155	23 - 126	14 - 32	11 - 27	-
1971	14 - 135	21 - 180	23 - 213	7 - 23	11 - 72	-
1972	5 - 49	14 - 124	14 - 319	5 - 82	7 - 138	-
1973	5 - 21	4 - 37	8 - 62	2 - 12	3 - 34	-
1974	9 - 79	15 - 105	2 - 296	2 - 88	2 - 13	-
1975	4 - 47	2 - 61	13 - 20	2 - 21	2 - 16	2 - 36
1976	3 - 10	7 - 15	2 - 13	2 - 11	1 - 6	2 - 43
1977	7 - 33	13 - 131	-	-	-	2 - 7
1978	8 - 57	10 - 71	-	-	-	1 - 93
1979	3 - 16	6 - 21	-	-	-	1 - 3
1980	-	-	-	-	-	~ 1

* In 1965, the station was at Westwood (New Jersey)

Sources: (1) Environmental Measurements Laboratory, 1981.
(2) Unpublished data, France, DIR CEN/2029, dated 22 April 1983.

TABLE 6-9

MONTHLY DEPOSITION OF PLUTONIUM-239,240 AT TAHITI
(10^{-6} CI KM^{-2})

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
Jan	-	-	0.5	1.1	0	6.0	0.4	0.4	0	0.3	0	0	0
Feb	-	0.4	0.7	0.8	0	0.3	0.9	0.7	0	0.2	0	0.2	0
Mar	-	1.0	0	0.6	0	0.5	0.3	0.4	0	0.4	0	0	0
Apr	-	0	0.3	0.5	0.3	1	25	0	-	0.2	0	0	0
May	-	-	0	0.3	0	0	0	0	0	0	0	0	0
June	-	-	1.9	0	2.9	0	1.6	0.3	0.2	0	0	0	0.3
July	-	-	1.0	0	750	0	0.5	0	0	0	0	0	-
Aug	-	-	0.5	6.0	1.5	1.1	-	0	0	0	0	0	0.3
Sept	-	-	2.0	6.0	2.0	0	0.3	0	0.3	0.3	0	0	0
Oct	7	0.7	0.8	0.3	2.0	1.8	-	0.2	0	0	0	0	0
Nov	24	0.8	0.6	0.2	2.5	0.7	0	0.3	0	0	0	0	-
Dec	-	0.7	1.0	0	1.5	1.9	0	0.4	-	0	0	0.2	0

0 means ≥ 0.2

Source: Unpublished data, France, DIR CEN 2029, dated 22 April 1983.

TABLE 6-10

SUMMARY OF EFFECTIVE DOSE EQUIVALENT COMMITMENTS FROM RADIONUCLIDES PRODUCED IN ATMOSPHERIC TESTS CARRIED OUT TO THE END OF 1980 (MICROSIEVERT)

Radionuclide	North temperate zone				South temperate zone				World population			
	External irradiation	Inhalation	Ingestion	Total	External irradiation	Inhalation	ingestion	Total	External irradiation	Inhalation	Ingestion	Total
^{3}H		4	47	51		1	13	14		3	44	47
^{14}C		0.3	2600	2600		0.3	2600	2600		0.3	2600	2600
^{54}Mn		0.07		0.07		0.004		0.004		0.04		0.04
^{55}Fe			10	10			2	2			9	9
^{85}Kr	0.005			0.005	0.005			0.005	0.005			0.005
^{89}Sr		3	2	5		0.7	0.4	1		2	1	3
^{90}Sr		14	170	180		4	48	52		9	110	120
^{95}Zr	290			290	40			40	200			200
^{103}Ru	25			25	4			4	17			17
^{106}Ru	87	49		140	24	11		35	53	30		83
^{131}I			48	48			7	7			33	33
^{136}Cs			0.1	0.1			0.03	0.03			0.06	0.06
^{137}Cs	600	0.6	280	880	170	0.2	78	250	370	0.4	170	540
^{140}Ba	37	0.3	0.3	38	5	0.04	0.07	5	25	0.2	0.2	25
^{141}Ce	2			2	0.3			0.3	1			1
^{144}Ce	28	60		88	8	17		25	17	37		54
^{238}Pu		2	0.008	2		0.4	0.002	0.4		1	0.005	1
^{239}Pu		40	3	43		11	0.7	12		25	2	27
^{240}Pu		26	2	28		7	0.5	8		16	1	17
^{241}Pu		14	0.07	14		4	0.02	4		9	0.04	9
^{241}Am		3	3	6		0.7	0.7	1		2	2	4
Total (rounded)	1100	220	3200	4500	250	60	2750	3100	680	130	3000	3800

Source: UNSCEAR (1982), Annex E, p. 242.

TABLE 6-11

EFFECTIVE DOSE EQUIVALENT COMMITMENTS (MICROSIEVERT) FROM RADIONUCLIDES PRODUCED IN ATMOSPHERIC TESTS CARRIED OUT TO THE END OF 1980, AFTER CORRECTION OF ^{14}C (SEE TEXT)

North temperate zone	2100
South temperate zone	700
World population	1400

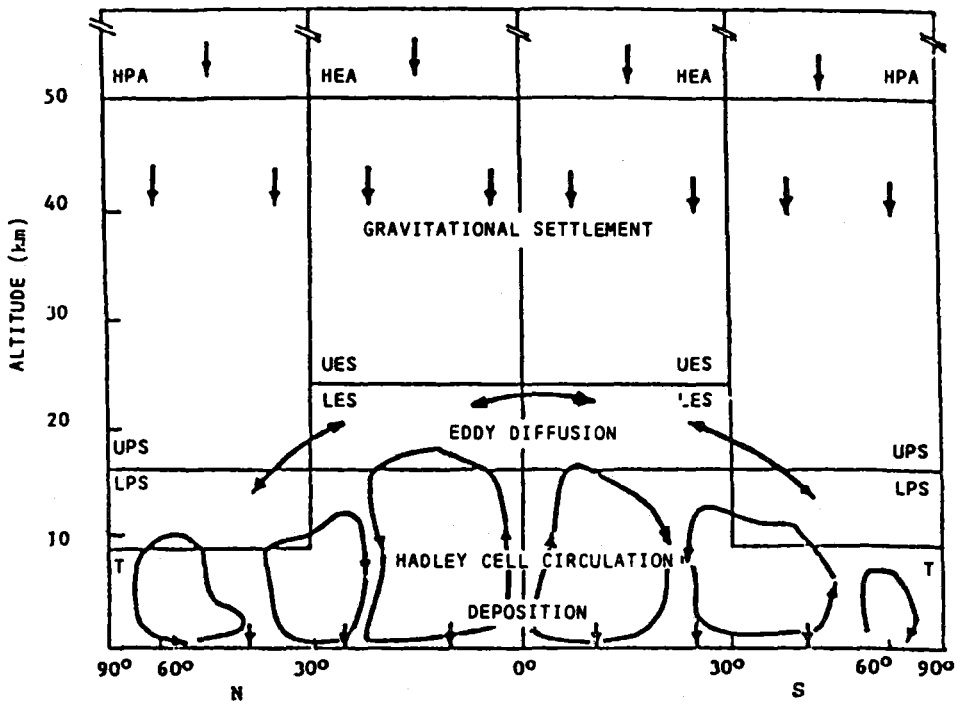
TABLE 6-12

MAXIMUM ANNUAL WHOLE-BODY AND BONE-MARROW DOSE RATES, IN MICROSIEVERT PER YEAR, IN THE NORTHERN MARSHALL ISLANDS FOR DIFFERENT ASSUMED DIET PATTERNS

Location	Whole Body		Bone Marrow	
	With Imports	Without Imports	With Imports	Without Imports
Bikini Atoll				
Bikini Island	10,000	19,000	10,000	19,000
Eneu Island	1,300	2,450	1,360	2,630
Enewetak Atoll				
Enjebi Island	2,770	5,090	2,910	5,540
Southern islands	45	86	51	110

	Whole Body		Bone Marrow	
	MLSC	BNL	MLSC	BNL
Rongelap Atoll				
Northern islands	910-3,250	1,500-4,900	970-3,330	1,350-5,800
Southern islands	350 - 560	550-1,110	390 - 580	900-1,350
Rongerik Atoll	420 - 600	690 - 810	450 - 660	730 - 900
Ailinginae Atoll	130 - 250	200 - 760	140 - 270	250 - 870
Utirik Atoll	110 - 150	220 - 290	120 - 160	240 - 310
Likiep Atoll	32 - 52	130 - 230	34 - 54	140 - 250
Mejit Island	59	310	60	320
Ailuk Atoll	39 - 59	200 - 340	41 - 61	210 - 350
Wotho Atoll	24 - 25	77 - 100	27	87 - 140
Ujelang Atoll	33	57	35	62
Taka Atoll	36 - 48	38 - 61	40 - 53	43 - 70
Bikar Atoll	60 - 61	190 - 230	66 - 100	300 - 690
Jemo Island	42	140	45	160

MLSC: Micronesia Legal Services Corporation dietary survey
BNL: Brookhaven National Laboratory dietary survey
Sources: Bikini - Robison et al. (1982b); Enewetak - Robison et al. (1980); Other Islands - Robison et al. (1982a).



T - troposphere

LPS - lower polar stratosphere
UPS - upper polar stratosphere
HPA - high polar atmosphere
LES - lower equatorial stratosphere
UES - upper equatorial stratosphere
HEA - high equatorial atmosphere

Figure 6-1. Atmospheric regions and the predominant atmospheric transport processes. Source: UNSCEAR (1982), Annex E, p. 213

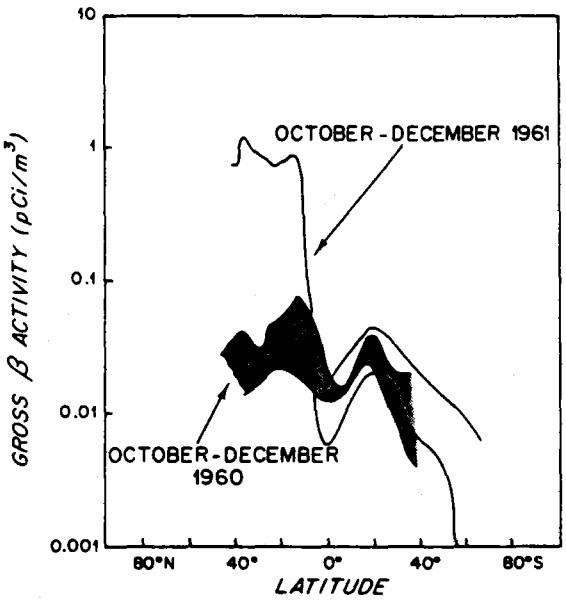


Figure 6-2. Gross beta activity before (shaded region) and after the resumption of nuclear tests in September 1961 following the moratorium (after Labeyrie and Lambert, 1963).

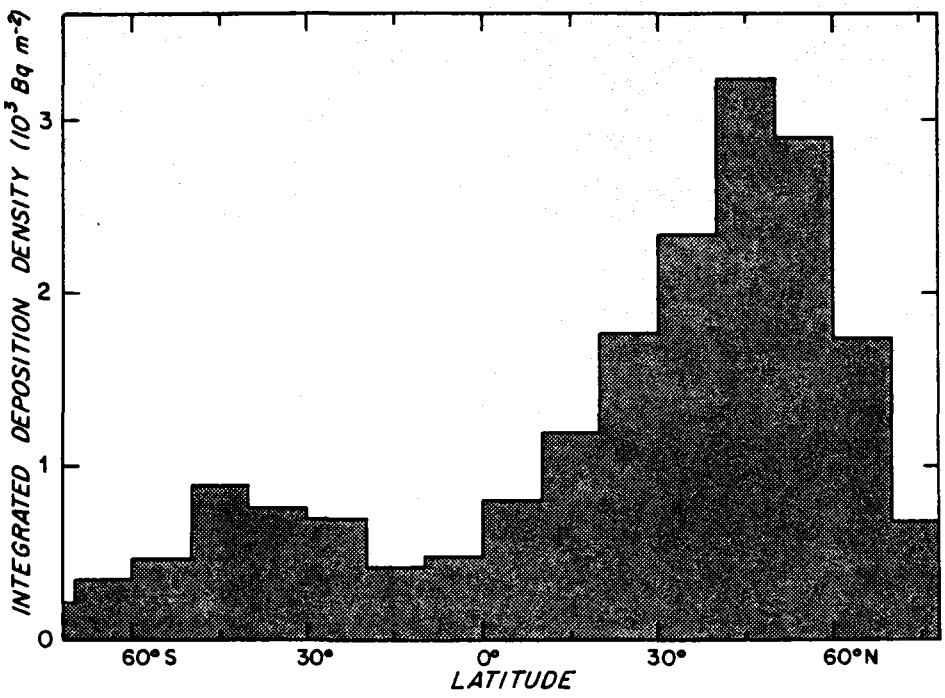


Figure 6-3. Strontium-90 deposition density through 1980 as a function of latitude. Data from Table 6, p. 230; UNSCEAR, 1982.

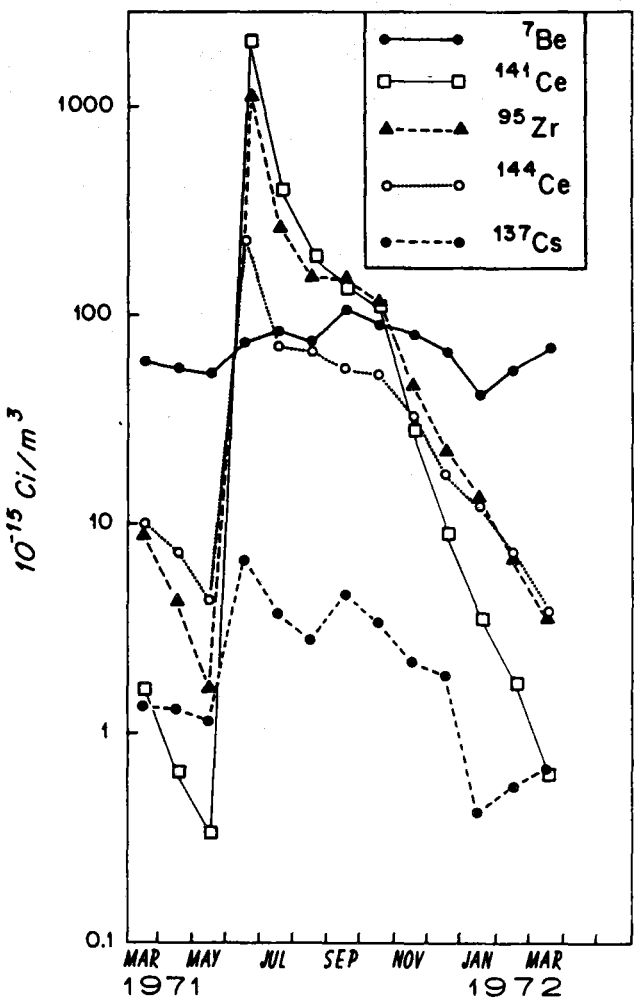


Figure 6-4. Concentrations of gamma emitters in air at Tahiti.
Source: Unpublished data, French Atomic Energy Commission.

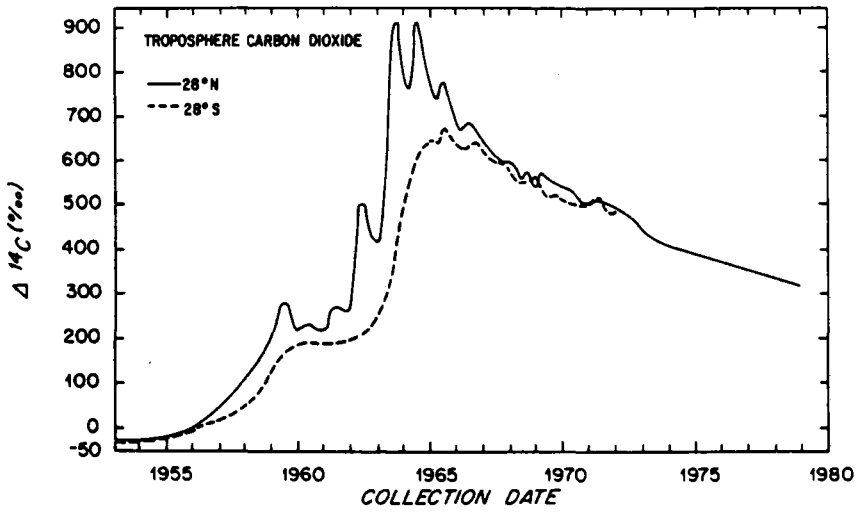


Figure 6-5. Carbon-14 content of atmospheric carbon dioxide as a function of time. Curves are based on data from Rafter and Ferguson (1965), Rafter and O'Brien (1970), Nydal et al. (1979) and Druffel and Suess (1983).

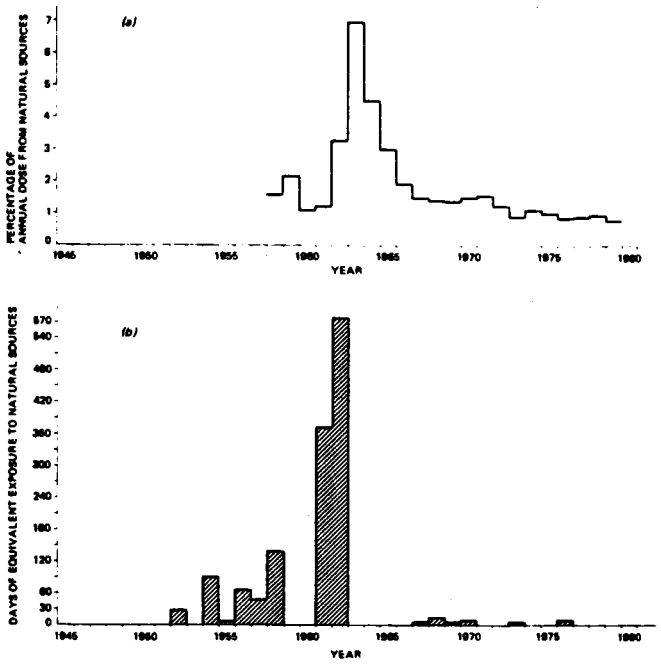


Figure 6-6. Trends with time of collective doses from nuclear explosions in the atmosphere. (a) Average annual collective doses received in 1958-1979; (b) Collective doses committed for the future by explosions carried out between 1945 and 1980.
Source: UNSCEAR (1982), p. 9.

6.7 REFERENCES

Conard, R.A. et al., 1980. Review of Medical Findings in a Marshallese Population Twenty-six Years after Accidental Exposure to Radioactive Fallout. Report BNL 51261, Brookhaven National Laboratory (USA).

Druffel, E. and H.E. Suess, 1983. On the ^{14}C record in banded corals: exchange parameters and net transport of $^{14}CO_2$ between atmosphere and surface ocean. J. Geophys. Res., 88: 1271-1280.

Environmental Measurements Laboratory (USA), 1981. Report EML-395.

Environmental Measurements Laboratory (USA), 1982. Report EML-412.

Hardy, E.P., P.W. Krey and H.L. Volchok, 1973. Global Inventory and Distribution of Fallout Plutonium. Nature, 241: 444-445.

Health and Safety Laboratory (USA), 1977. Report HASL-329.

Labeyrie, J. and G. Lambert, 1963. Sur l'existence d'une barrière de diffusion entre les troposphères des hémisphères nord et sud. C.R. Acad. Sc. t 256, 2664-2667.

Lambert, G., B. Ardouin and Mesbah-Bendezu, 1983. In: Proc. 4th Int. Conf. Scavenging, Santa Monica (USA), Elsevier, 1289-1300.

National Academy of Sciences/National Research Council (NAS/NRC), 1982. Evaluation of Enewetak Radioactivity Containment. National Academy Press, Washington, 42 pp.

National Radiation Laboratory (New Zealand), 1981. Annual Report for 1980.

Noshkin, V. E., R.J. Eagle, K.M. Wong, T.A. Jokela and W.L. Robison, 1981. Radionuclide Concentrations and Dose Assessment of Cistern Water and Groundwater at the Marshall Islands. Lawrence Livermore National Laboratory (USA), Report UCRL-52853 Pt. 2, 34 pp.

Nydal, R., K. Loyseth and S. Gulliksen, 1979. A survey of radiocarbon variations in nature since the Test Ban Treaty. In: Proc. 4th Int. Conf. Radiocarbon Dating, Univ. Calif. Press, Berkeley, 313-323.

Perkins, R.W. and C.W. Thomas, 1980. Worlwide fallout. In: Transuranic Elements in the Environment, W.C. Hanson (Ed.), U.S. Department of Energy Report DoE/TIC-22800, 53-85.

Rafter, T.A. and G.J. Ferguson, 1965. Carbon-14 variations in nature, part 2: increase in ^{14}C activity in the atmosphere of the Southern Hemisphere from the testing of nuclear weapons. N. Z. J. Sci., 8: 472-493.

Rafter, T.A. and B.J. O'Brien, 1970. Exchange rates between the atmosphere and the ocean as shown by recent C-14 measurements in the South Pacific. In: Radiocarbon variations and absolute chronology, I.U. Olsson (Ed.), 355-377.

Robison, W.L., W.A. Phillips, M.E. Mount, B.R. Clegg, and C.L. Conrado. 1980. Reassessment of the Potential Radiological Doses for Residents Resettling Enewetak Atoll. Lawrence Livermore National Laboratory

(USA), Report UCRL-53066, 92 pp.

Robison, W.L., C.L. Conrado, R.J. Eagle, and M.L. Stuart. 1981a. The Northern Marshall Islands Radiological Survey: Sampling and Analysis Summary. Lawrence Livermore National Laboratory (USA), Report UCRL-52853 Pt. 1, 101 pp.

Robison, W.L., V.E. Noshkin, W.A. Phillips, and R.J. Eagle. 1981b. The Northern Marshall Islands Radiological Survey: Radionuclide Concentrations in Fish and Clams and estimated Doses via the Marine Pathway. Lawrence Livermore National Laboratory (USA), Report UCRL-52853 Pt. 3, 33 pp.

Robison, W.L., M.E. Mount, W.A. Phillips, C.A. Conrado, M.L. Stuart, and C.E. Stoker, 1982a. The Northern Marshall Islands Radiological Survey: Terrestrial Food Chain and Total Doses. Lawrence Livermore National Laboratory (USA), Report UCRL-52853 Pt. 4, 60 pp. with Appendices.

Robison, W.L., M.E. Mount, W.A. Phillips, M.L. Stuart, S.E. Thompson, C.L. Conrado and A.C. Stoker, 1982b. An Updated Radiological Dose Assessment of Bikini and Eneu Islands at Bikini Atoll. Lawrence Livermore National Laboratory (USA), Report UCRL-53225, 84 pp.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1982. Ionizing Radiation: Sources and Biological Effects. Report to the General Assembly, with Annexes, 773 pp.

United States Weather Bureau, 1964. Announced nuclear detonations 1945-1962. In: Health and Safety Laboratory Report HASL-142, pp. 218-239.

Zander, I. and R. Araskog, 1973. Nuclear Explosions 1945-1972: Basic Data. Res. Inst. Nat. Def., FOA 4 Rpt. A 4505-A1, Stockholm.

CHAPTER 7

MEDICAL, INDUSTRIAL, RESEARCH, TEACHING AND MISCELLANEOUS USES OF SOURCES OF IONIZING RADIATION

7.1 OUTLINE OF THE PROBLEM

In developed countries, the medical, industrial, research, teaching, and miscellaneous uses of sources of ionizing radiation are known to contribute to different extents and in different ways to the radiation doses received each year by persons in those countries. In medical uses (here taken to include all uses of ionizing radiation on patients for diagnosis and treatment) radiation doses are received by patients who, it can be assumed, are likely to obtain some benefit from their radiation exposure through improvement in their health care. However, during such uses doctors, nurses, technical staff and others involved will also receive some radiation dose. When radionuclides are used for medical purposes there is the added possibility that persons in the general public will receive some radiation dose from the release of radionuclides to the environment during that use or as the result of the disposal of the radioactive wastes.

In the uses of sources of ionizing radiation in industry, research, and teaching, the radiation dose will mainly be received by those working with the sources. However, here again, if radionuclides are used, some applications may involve the release of radionuclides to the environment and the disposal of radioactive wastes, resulting in radiation doses to the general public.

Miscellaneous sources of ionizing radiation involve a wide variety and a large number of materials and everyday items. In most cases, the users of such sources are not aware that they are receiving some radiation exposure from them. In a number of developing countries, increasing use is being made of sources of ionizing radiation. The contribution made by such sources to the radiation dose of the populations of those countries is generally unknown.

It is likely that, with time, the countries in the South Pacific Region will increase their present use of some of these sources (for example, in medical diagnosis) and begin to use others (for example, in industry and student training). There is undoubtedly now quite widespread everyday use in the Region of a number of miscellaneous sources of radiation resulting in exposure of the population.

7.2 MEDICAL USES OF IONIZING RADIATION

7.2.1 General Information

Sources of ionizing radiation are used to some extent in most countries in the world for medical diagnosis and, to a lesser extent, for medical treatment of patients. The sources are X-rays produced when certain electrically operated machines are

switched on, as well as radionuclides which continuously give off ionizing radiation. In a number of developed countries, assessments have been made of the radiation dose to populations from the various uses of ionizing radiation. These assessments show that medical examinations using X-rays make the greatest contribution to the radiation dose, the contribution from the use of radionuclides for medical diagnosis and from all sources for medical treatment being very much smaller. In most developed countries the radiation dose to populations from the medical diagnostic use of ionizing radiation is the largest contributor of all the artificial sources of ionizing radiations. In some of those countries the annual dose from medical diagnostic uses, averaged over the whole population of the country, is about the same as the dose received each year from natural background radiation.

In developed countries and in some developing countries the medical diagnostic uses of ionizing radiation involve large numbers of patients. The radiation doses to individual patients are, in medical diagnosis, most often highly non-uniform throughout their bodies. Although the dose to individual organs and tissues of patients is low for many examinations, the dose is mostly received in a short time, that is, at a high dose rate. The patients include children, sometimes very young children. When the patients are pregnant women, their unborn babies will receive radiation doses which will be higher if the examinations involve the lower abdomen of the women. Studies have shown that unborn children exposed to ionizing radiation undertake risks to their development and future health. For older patients the risks of injury from radiation doses from medical examinations are generally low, although the radiation dose they receive individually may greatly exceed their radiation dose in a year from natural background radiation. Some patients, however, who have had many X-ray examinations of the same parts of their bodies have developed harmful effects from the radiation dose received.

Studies and reports by national and international bodies and by individual scientists show that the radiation dose to individual patients, and hence to the populations of countries, from the medical diagnostic uses of ionizing radiation can be reduced by improved techniques. Improvements that can be effective in reducing risk include the following: (1) more careful selection of patients for X-ray examinations, particularly when young children or women who are, or may be, pregnant are involved; (2) better technical standards in equipment and in procedures used in the examinations; (3) regular inspection and proper maintenance of the equipment used; (4) better training for the medical and technical staff involved; and (5) the use, where appropriate, of other diagnostic procedures, such as ultra-sound, that do not expose patients to ionizing radiation. With such improvements an increase in the number of patients examined each year does not necessarily mean that the radiation doses, averaged over the whole population of a country, will also increase. In addition, the need has been shown for the maintenance of high standards of radiation protection for those who are occupationally exposed during the use of sources of ionizing radiation for medical purposes. When radionuclides are used, careful consideration must be given to their possible environmental release and to the proper management of radioactive wastes which arise. Most countries in which the medical uses of sources of ionizing radiation are widespread rely on the various recommendations and guidelines published by the International Commission on Radiological Protection and on others based on them (for example, those of the World Health Organization) in developing the appropriate practices to be applied.

7.2.2 Impacts in the South Pacific Region

With respect to the use of X-rays for medical diagnosis, in at least some countries in the Region there has been a substantial growth in the number of examinations made

in recent years. For example, at the Apia National Hospital, Western Samoa, the number of X-ray examinations (not including dental X-ray examinations) increased by about 48 per cent between 1970 and 1977 (Western Samoa, Health Department, 1977). In Fiji most of the X-ray examinations are done at three hospitals: the Colonial War Memorial, Lautok and Labasa Hospitals. The number of X-ray examinations (not including dental X-ray examinations) increased by about 19 percent between 1977 and 1980. In 1980 almost 62,000 patients were examined (Fiji, Ministry of Health, 1980; 1982). In New Caledonia between 30,000 and 35,000 patients are examined with X-rays each year. In more recent years the number has decreased because of an increasing use of ultra-sound equipment for medical diagnosis. In Wallis and Futuna Islands, 1080 patients received X-ray diagnostic examinations in 1982. The Technical Group has no information on the use of radionuclides for medical diagnosis in the Region, but such use is probably not widespread. Similarly, the use of sources of ionizing radiations for medical treatment is believed to be small in the Region, though a cobalt-60 unit for the gamma-ray treatment of cancer patients is operated at the Noumea Hospital in New Caledonia (personal communication), and equipment emitting ionizing radiation is probably used in a few other countries in the Region for the treatment of patients. The Technical Group is not aware of any assessment of the radiation dose to the population of any country in the Region from the medical uses of sources of ionizing radiation.

The number of X-ray examinations carried out per 1000 inhabitants per year in developing countries appears to lie between 100 and 200, much less than in developed countries, where the number lies between 300 and 900 (UNSCEAR, 1982). It is reasonable to assume that there will be an increase, and more diversity, in the use of sources of ionizing radiation for medical purposes in the South Pacific Region as health services develop further. In many of the countries, the special facilities necessary for these purposes are becoming more readily available in the major population centres, and it is to be expected that, with time, the facilities will be provided in less densely populated areas. As these developments occur, it will be important for the countries of the Region to ensure that the radiation doses to their populations are minimised. The Technical Group sees value in the development of a regional program through which special technical services to oversee standards with respect to the medical uses of ionizing radiation would be available.

7.3 IONIZING RADIATIONS IN INDUSTRY, RESEARCH, AND TEACHING

7.3.1 General Information

In developed countries, radionuclides and electrically operated equipment which gives off ionizing radiation are used extensively in industry, in industrial and scientific research, and in teaching. In a number of developing countries, the use of sources of ionizing radiation for those purposes is increasing. The radionuclides are either sealed in small source holders or unsealed, for example as liquids or powders.

In industry, sealed radionuclides are used for such purposes as the control of industrial processes, the checking of the effectiveness of welds in metal components, and the killing of bacteria in medical products. The many research uses of unsealed radionuclides include investigation of the mixing of products in industrial processes, the location of leaks in pipelines, the study of the movement of silts and sands in rivers and harbours, and the investigation of physical, chemical and biological phenomena. Electrically operated equipment which gives off X-rays is used in industry and research. Of particular concern are X-ray procedures to analyse industrial products and research materials.

To provide the professional and technical staff to use the various sources of ionizing radiation effectively and safely in industry and research, university and technical students are trained in the use of such sources.

The users of the above sources of ionizing radiation and people in their immediate vicinity will receive some radiation dose. In addition, when radionuclides are used, questions of their possible release to the environment and of the safe disposal of radioactive wastes arise. In countries where these sources are used extensively in industry, research and teaching, national regulations, usually based on the recommendations of the International Commission on Radiological Protection, are the foundation for the effective control of radiation doses, including those to the general public which could arise from environmental releases of radionuclides and the disposal of radioactive wastes.

7.3.2 Possible Impacts in the South Pacific Region

The Technical Group had no information on the use being made in the South Pacific Region of the above sources of ionizing radiation, which are now finding increasing application in a number of developing countries. It is likely that, with time, there will be a need for some of the countries in the South Pacific Region to make use of at least some of those applications. As that occurs it will be important for the countries in the region to develop effective control of the radiation doses to persons, including those doses which arise from environmental release of radionuclides and from the disposal of radioactive wastes.

7.4 MISCELLANEOUS SOURCES OF IONIZING RADIATION

The United Nations Scientific Committee on the Effects of Atomic Radiation in reports to the UN General Assembly (UNSCEAR, 1972; 1977; 1982) drew attention to a variety of products in use by the public (consumer products) which contain radionuclides put into the products to give a particular result. Those reports referred also to some electrical products, components of which operate at high voltages and are possible sources of exposure of persons to X-rays. Most of the users of the above products are unaware that the products are sources of radiation dose to them and to others.

7.4.1 Radionuclides in Consumer Products

UNSCEAR (1977) pointed out that many millions of items of various kinds of consumer products containing radionuclides are used every day by persons around the world. These consumer products were grouped as follows: (1) radioactive luminous products; (2) electronic and electrical devices; (3) antistatic devices; (4) gas and smoke detectors; (5) ceramic ware, glassware and alloys; and (6) other devices and uses, including scientific instruments. Only some of these products are discussed here, the intention being to stress that most users of the products are likely to be unaware that the products are a source of exposure to ionizing radiation.

In radioluminous products radionuclides are included along with a non-radioactive substance so as to cause the latter to give off visible light as a result of the ionizing radiation acting on it. Examples are the dials of some watches and clocks, some compasses and marine navigational instruments, some fishing lights, some exit signs in commercial buildings and aeroplanes, and some mooring buoys and lights. These products contain a variety of radionuclides, most with long radioactive half-lives. The activities of radionuclides vary from one kind of product to another. When radioluminous products were first introduced (particularly for the dials of watches and clocks), naturally occurring radium-226 was used. There is

little doubt that many of the products containing radium-226 are still in use or in the possession of persons. More recently artificially produced radionuclides have been used instead of radium-226, and the radioluminous products with such radionuclides result, in general, in lower radiation doses to the users of the products and to other persons. It is important to realise that not all devices which glow in the dark are radioactive, because some non-radioactive substances give off light by using other non-radioactive agents.

Small amounts of radionuclides are included in some electronic and electrical devices, such as components of fluorescent lamps, electronic valves, sun and germicidal lamps, some lamps for outdoor and industrial lighting, and some high- and low-voltage protective devices. Many of the devices in this group contain artificially produced radionuclides, although, in some of them, naturally occurring radium-226 and thorium are used. Again, not all kinds of the devices mentioned here contain radionuclides.

Some devices designed to eliminate or control static electricity contain radionuclides. Examples of these devices are lightning rods used on large buildings, and brushes and other attachments used to free long playing records and some scientific instruments, of dust attracted to them by static electricity. The radionuclides used in antistatic devices include naturally occurring radium-226 and polonium-210 and some artificially produced radionuclides.

There is increasing use of devices to detect the presence of gas or smoke in buildings. Many devices made at present for these purposes contain either naturally occurring radium-226 and uranium or artificially produced radionuclides including plutonium-238.

Naturally occurring uranium and thorium are used in products such as wall tiles, plates, vases, cups and mugs to give them bright colours. The same naturally occurring radionuclides are used in making special glassware, flints for cigarette lighters, lenses for spectacles, and mantles for gas lamps. Naturally occurring thorium is present in rods used for metal welding.

A number of scientific instruments used in industry and research contain radionuclides (mostly artificially produced) as a means of improving their performance. Artificially produced radionuclides have also been used to identify, against fraud, bank cheques and tokens used in vending machines. A novel use of naturally occurring uranium has been the inclusion of small amounts of it in dental porcelains used to fill teeth and to make false teeth. The uranium makes the tooth fillings and the false teeth look more like natural teeth in both daylight and in artificial light. Because all isotopes of uranium are radioactive, this practice results in radiation doses to the mouth and tongue.

The concern about consumer products which contain radionuclides is not limited to persons who use or work with the products. After a time many of these products are damaged beyond repair, or are no longer effective in operation or are discarded for some other reason. The question of their safe disposal then arises. Even in those developed countries where there are controls on miscellaneous sources of exposure to ionizing radiation, many consumer products containing radionuclides are likely to be disposed of as household or industrial trash without consideration being given to their radioactive content. Such trash is usually dumped on land or burnt and becomes a possible source of radiation exposure to persons other than the original users.

7.4.2 Electrical Products Operated at High Voltages

Some electrical equipment which operates at high voltages (greater than about 10,000 volts) may give off X-rays. Equipment of this kind is used in industry, medicine and research and could result in radiation doses to persons working with it. Colour television receivers, however, are the most common electrically operated product which may cause persons in the general public to be exposed to X-rays. Surveys have shown that, in the 1960s, some colour television receivers gave off X-rays at a level much higher than the limit recommended by the International Commission on Radiological Protection for X-rays at the surface of the receivers. Because of this, in some countries more stringent controls were put on this aspect of colour television receivers. More recently there have been developments in electronics which have removed the main source of X-ray production that existed in the colour television receivers of earlier construction. The X-ray doses to persons from colour television receivers made more recently have been shown to be negligible under conditions of normal operation and proper servicing. The problem which occurred with colour television receivers did not exist with black and white television receivers because of the lower voltages at which their electronic components operated.

7.4.3 Possible Impacts in the South Pacific Region

A report by UNSCEAR (1977) includes the estimate that, on a world-wide basis, consumer products of the kinds discussed above contributed each year a radiation dose equivalent to 3 days' additional exposure of the world population to normal natural radiation. Although this is only a small additional radiation dose, it is the third highest contribution from man's activities, being exceeded only by the medical diagnostic use of ionizing radiation (the highest) and fallout from past nuclear explosions in the atmosphere. The actual contributions to the radiation dose of persons in different countries and regions from consumer products depends on the extent to which the products are used and controlled. The Technical Group did not have available to it any information on the use of these products in the South Pacific Region.

Efforts are being made in more and more countries to control the use of the miscellaneous sources of ionizing radiation discussed above and to minimise the levels of radiation dose persons receive from them. For some of the products (for example, television receivers) international standards have been established. National or regional regulatory procedures along the lines of those recommended in Chapter 4 (section 4.1) would ensure that the radiation dose to persons in the Region from these sources would be limited.

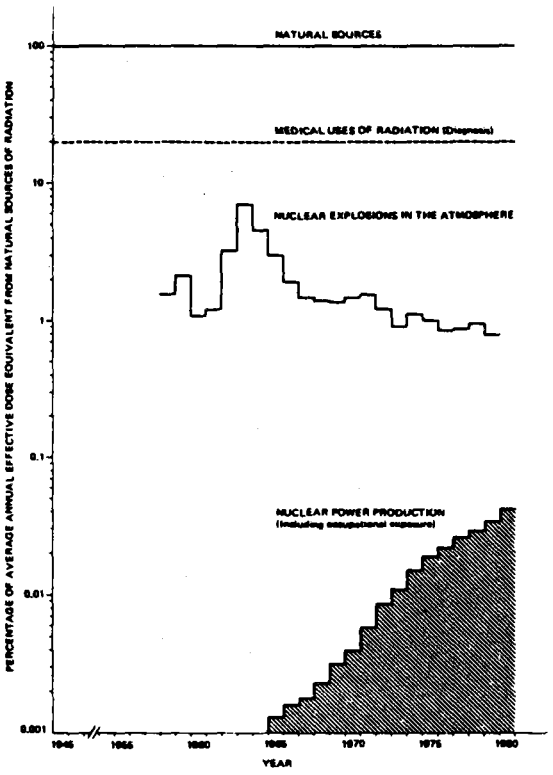
7.5 OTHER SOURCES, NOT AVAILABLE TO THE PUBLIC

UNSCEAR (1972) referred to some miscellaneous sources of ionizing radiation which are not used by persons in the general public but which in the past have resulted in radiation doses to persons and some radioactive contamination of the environment. In particular, the report referred to accidents involving aeroplanes carrying nuclear bombs or components of such bombs, to the loss at sea of nuclear submarines, to the uncontrolled return to earth from outer space of satellite components containing radionuclides (see Chapter 6, section 6.4.2.5), and to the loss, theft, and misuse of radionuclides. Some of these caused limited radioactive contamination of the environment and low radiation dose to groups of people. Others resulted in a higher radiation dose to a few people.

7.6 SUMMARY OF DOSES FROM DIFFERENT SOURCES OF IONIZING RADIATION AND TRENDS WITH TIME

Figure 7.1 shows a comparison of the contributions made by natural sources, medical applications, atmospheric nuclear explosions, and nuclear power production to the radiation exposure received by the world population expressed as a percentage of the average annual effective dose equivalent from natural sources of radiation. Natural sources, with an annual effective dose equivalent of 2000 microsievert (1000 microsievert in the South Pacific Region), make by far the largest contribution (Chapter 5). Among the man-made sources, the largest contribution comes from the medical uses of radiation, particularly for diagnostic purposes. The annual effective dose equivalent from medical uses of radiation throughout the world is taken to be about 400 microsievert (UNSCEAR, 1982), approximately 20 percent of the average annual exposure to natural background. In the South Pacific Region the natural background is lower than the world average, but the average exposure due to medical uses is probably also somewhat lower, so that approximately the same percentage is likely to apply for the Region. The medical uses of ionizing radiation are the area in which countries potentially have the greatest possibility of control over the radiation dose received by their populations.

The contribution made by nuclear explosions has followed a discontinuous trend but has mostly decreased since 1963, with small variations due to more recent explosions. The annual collective effective dose equivalent attributable to the production of electrical energy by nuclear means has been increasing continuously because of the expansion of nuclear power programmes, but its contribution is at a substantially lower order of magnitude.



nual

Figure 7-1. Trends with time of doses from different sources of radiation. Annual effective dose equivalents, expressed as percentage of the average exposure to natural sources.
Source: UNSCEAR (1982), p. 25.

7.7 REFERENCES

Fiji, Ministry of Health, 1980. Report for the year 1978, Parliamentary Paper No. 51 of 1980.

Fiji, Ministry of Health, 1982. Report for the year 1979, Parliamentary Paper No. 49 of 1982.

Western Samoa, Health Department, 1977. Health Statistics for Western Samoa.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1972. Ionizing Radiation:- Levels and Effects. Report to the General Assembly, with Annexes, Volume 1.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1977. Sources and Effects of Ionizing Radiation. Report to the General Assembly, with Annexes.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1982. Ionizing Radiation: Sources and Biological Effects, Report to the General Assembly, with Annexes.

CHAPTER 8

RADIOACTIVITY IN THE PACIFIC OCEAN

8.1 INTRODUCTION

Much of the present concern about radioactivity in the South Pacific Region is due to the possibility of contamination of the marine environment that could result from existing or proposed activities that involve radioactive materials. As background to the discussion of those activities that follow in Chapter 9, this Chapter presents an overview of natural and artificial radioactivity in the Pacific Ocean. It is intended to provide the reader with some appreciation of the levels of radioactivity and of some of the oceanic processes that control the distributions and concentration levels of radionuclides in the ocean. As explained in Chapter 2, the older activity unit, the curie, is retained in this and the following Chapter. Concentrations in seawater are most commonly expressed in picocurie (10^{-12} curie) per litre or kilogram of water. This Chapter contains a number of figures that have been reproduced from the published scientific literature, some of which make use of yet other concentration units. These other units are explained in the figure captions or in the text.

8.2 NATURAL RADIOACTIVITY

Seawater contains virtually all of the radionuclides that occur naturally, though many of them are present at exceedingly low concentrations. This section considers a selection of those natural radionuclides that UNSCEAR (1982) identified as being significant sources of human radiation exposure. Some of the radionuclides to be discussed are also of great importance in considering radiation doses to marine organisms. However, most of the scientific research that has been carried out on natural radionuclides in the oceans has been done because of their importance as tracers for studying how materials are dispersed and transported in the marine environment.

By far the greatest proportion of the data that presently exists on natural radioactivity in the ocean was collected during the Geochemical Ocean Sections Study (GEOSECS), which was part of the International Decade of Ocean Exploration, a multi-nation cooperative study of the world oceans during the period 1970-1980. GEOSECS was a large-scale survey of the chemical properties of the ocean with a major emphasis on the measurement of the radioactive nuclides that could be used as tracers to study circulation and mixing processes in the sea. The Pacific GEOSECS expedition was carried out aboard R/V Melville, a research vessel operated by the Scripps Institution of Oceanography, between August 1973 and June 1974 (Craig and Turekian, 1976). This section of the Report refers largely to GEOSECS data, and a map showing the GEOSECS sampling stations is provided in Figure 8-1.

8.2.1 Cosmogenic Radionuclides

UNSCEAR (1982) identifies only four radionuclides in this category that are significant with regard to human exposure: tritium, beryllium-7, carbon-14, and sodium-22. There have been no measurements of sodium-22 concentrations in seawater, and the natural levels of tritium in the ocean are now insignificant in comparison with the amounts of tritium that have been added from nuclear weapons testing.

8.2.1.1 Beryllium-7

Measurements of beryllium-7 in the Pacific Ocean were reported by Silker (1972). Examples of the vertical distribution of beryllium-7 are shown in Figure 8-2. Concentrations are highest at the surface and in general are relatively uniform in the surface mixed layer, which is rapidly stirred by the winds blowing across the sea surface, but the concentrations drop very sharply in the upper part of the pycnocline (thermocline). The pynocline is the region in the water column where the density of the seawater increases sharply with depth, largely because the water becomes much colder at depth. The strong density gradient across the pycnocline greatly inhibits vertical mixing, and because beryllium-7 has a short half-life (53 days), little of it penetrates through the pycnocline before undergoing radioactive decay. Thus the amounts of beryllium-7 below 100 m in the ocean are usually undetectable. The pycnocline barrier also inhibits the transport to the surface of materials released at depth in the water column or at the seafloor.

8.2.1.2 Natural carbon-14

Carbon-14 exists in the atmosphere in the form of the gas carbon dioxide and enters the ocean by gas exchange at the sea surface. Because of chemical reactions of carbon dioxide with water molecules, the carbon-14 in the ocean occurs largely in the bicarbonate form. Mixing and circulation within the ocean distribute the carbon-14 to all depths. Because the carbon-14 atoms undergo continual radioactive decay while this distribution is going on, it is possible to use measured variations in the carbon-14 content of seawater to estimate the rate of the circulation and mixing processes. This kind of information is fundamental to an understanding of the ocean, and for that reason the carbon-14 distribution in the ocean is of great scientific interest. The measurement of carbon-14 concentrations in seawater was, therefore, an important part of GEOSECS. The Pacific GEOSECS carbon-14 data were published by Ostlund and Stuiver (1980).

Figure 8-3 contains vertical profiles showing the carbon-14 distributions in different oceans. Concentrations of carbon-14 in seawater are always expressed as per mil deviations of the carbon-14/carbon-12 ratio from the ratio that existed in the atmosphere prior to the start of the industrial revolution (that is, prior to about 1850). A Δ C-14 value of -150 per mil, for example, signifies a carbon-14/carbon-12 ratio that is about 150 per mil, or 15 percent, lower than that ratio in the carbon dioxide of the pre-industrial atmosphere. The surface layers of the ocean have been greatly perturbed by the large quantities of carbon-14 produced in the atmosphere by the testing of nuclear weapons, and positive Δ C-14 values, commonly greater than +100 per mil, are now found in ocean surface waters. Thus the near-surface values for natural carbon-14 indicated in Figure 8-3 were re-constructed from measurements made prior to the major inputs of weapons-produced carbon-14 (that is, prior to 1957).

The important features to note in Figure 8-3 are that (1) the highest Δ C-14 values occur at the surface, (2) the largest vertical gradients occur in the main thermocline (pycnocline) region down to 1000 m or so, and (3) the highest deep-water values occur in the North Atlantic, with the lowest occurring in the North Pacific.

The first feature reflects the fact that carbon-14 is added to the ocean only at the sea surface and that the deeper waters are isolated from the atmosphere long enough for significant radioactive decay to occur. As with beryllium-7, the steep gradients illustrate the effect of the thermocline as a barrier that slows down exchange between the surface and deep water masses of the ocean. The very low C-14 values in the deep North Pacific indicate that that water mass has been isolated from contact with the atmosphere longer than any others. The large-scale circulation patterns in the ocean are such that deep waters are derived by sinking of surface waters only in the far North Atlantic and around Antarctica (principally in the Weddell Sea), and there is no deep-water formation in the North Pacific. Figure 8-4 shows a vertical cross-section of the Pacific Ocean illustrating the south-to-north decrease in Δ C-14.

As an approximation it can be considered that the water in the deep Pacific ocean is supplied by an inflow originating in the south, in the Antarctic Circumpolar Current, and leaves by a slow upwelling through the thermocline into the upper layers, where it is exported from the Pacific by a slow southward drift back into the circumpolar region again. The natural carbon-14 measurements made during GEOSECS allow an estimate to be made of the time that this cycle takes. A recent calculation by Stuiver et al. (1983) gave a replacement time of 510 years for water below 1500 metres in the Pacific Ocean. It should be emphasized that this is an average estimate and that some parcels of water may be replaced more or less frequently.

8.2.2 Primordial Radionuclides

8.2.2.1 The very long-lived nuclides

Potassium, rubidium, uranium and thorium are all supplied to the oceans in rivers from weathering of the continents. Recently it has been discovered that significant amounts of potassium and rubidium are also released to the ocean by hydrothermal activity at the crests of the mid-ocean ridges, where seawater percolates through hot, newly-formed rock and leaches out the elements into solution (Edmond et al., 1979). All of the potassium and rubidium delivered to the ocean contain the radioisotopes potassium-40 and rubidium-87 in their natural abundances, and, of course, all the isotopes of natural uranium and thorium are radioactive.

It is an important characteristic of the ocean as a chemical system that everything added to it is also removed from it by deposition in seafloor sediments or by interaction of seawater with hot rock in the hydrothermal circulation mentioned above. For natural substances there is good evidence to indicate that the oceans are at an approximate steady state, at which the input and output rates balance so that there is no change with time in their concentrations in seawater. In other words, it does not appear that the total saltiness of the ocean or the relative proportions of the different elements dissolved in seawater have changed very much, even over long time periods of millions of years. If the input or output rate of an element is compared with the concentration of the element in seawater, then it is possible to define a residence time for that element, which is the average time that an atom of the element spends in the ocean water column before it is removed. For potassium, rubidium and uranium the residence times are very long (10^5-10^7 years) compared with mixing times of the ocean (about 10^3 years), so their radioisotopes have nearly the same concentrations in seawater everywhere: 330 picocurie per litre for potassium-40, 2.9 picocurie per litre for rubidium-87, 1.1 picocurie per litre for uranium-238, 1.3 picocurie per litre for uranium-234 and 0.05 picocurie per litre for uranium-235.

Thorium, unlike potassium, rubidium and uranium, is not very readily mobilized in

natural waters, and most of the thorium transport through the oceans occurs in the solid particulate residues of continental weathering. Thus thorium-232 is rather inhomogeneously distributed in the oceans, and its concentrations are very low.

8.2.2.2 Uranium-series radionuclides

The decay sequence and half-lives of the uranium-series radionuclides are given in Chapter 5, Figure 5-1. It is instructive to compare the relative concentrations of the uranium-series nuclides in seawater. This is done in the graph shown in Figure 8-5, where representative values of surface and deep Pacific waters are used. In any system that is closed to migration of uranium and its decay products for a sufficient time, a type of steady state known as secular equilibrium is reached in which the decay rates, hence the activities, of all members of the decay chain are equal to that of uranium-238 (see Chapter 3). It can be seen (Figure 8-5) that this condition is not found in the oceanic water column, and many examples of disequilibrium are found within the uranium series because of the transport of decay products into and out of the system. The various cases of disequilibrium are of interest because they tell us much about how radionuclides with different chemical properties behave in the ocean.

Uranium has already been mentioned as an element having a long residence time in the ocean, so that its concentration in seawater is uniform everywhere. It can be seen in Figure 8-5 that a slight excess of uranium-234 exists (that is, uranium-234 activity is greater than uranium-238 activity). This arises because of a nuclear recoil effect during radioactive decay such that, in the weathering process, uranium-234 atoms in rocks are somewhat more easily dislodged and taken into solution than are the remaining uranium-238 atoms. Thus rivers have rather large excesses of uranium-234 relative to uranium-238, and the oceans end up with a 15 percent uranium-234 excess.

An important example of radioactive disequilibrium within the uranium series is shown by the thorium isotopes thorium-234 and thorium-230. In surface waters a thorium-234 deficiency is found (thorium-234 activity less than uranium-238 activity). This indicates a process that removes thorium from the surface layer of the ocean. In order to maintain such a deficiency, the removal process must occur at a rate that is comparable to the decay rate of thorium-234. A large number of thorium-234 measurements was made in the North Pacific by Matsumoto (1975), who calculated a residence time of 4-5 months for thorium in the surface layer of the ocean. The removal of thorium is caused by an uptake (adsorption) on the surface of particles in the water which, in the surface layer, are supplied abundantly from the production of plankton. This uptake is followed by a settling out of the particles and transport of the thorium to deeper layers in the water column. The settling can be accelerated by the activity of zooplankton, which ingest fine particulate material and package it into fecal matter that settles more rapidly. This is a good example of the natural stripping processes by which the oceans cleanse themselves of substances added to them. Such processes are part of the basis for statements that the oceans have a certain assimilative capacity for wastes added to them. It should be emphasized that each element and radionuclide behaves differently in the oceans, so the efficiency of the stripping process shows a wide range of variability, depending on the specific chemical properties of the element or radionuclide. For thorium the process is very efficient. For potassium, rubidium and uranium the process is very inefficient, and these elements reside in the oceans for very long periods of time, as mentioned above.

In the deep waters of the ocean, thorium-234 is found to be in equilibrium with uranium-238. This indicates that the stripping, or scavenging, process described above is slower than it is in the surface ocean and slow compared with the decay

rate of thorium-234. The difference between the deep and surface waters is due to the smaller concentrations of particulate matter found in the deep ocean. However, examination of the longer-lived isotope thorium-230 shows that scavenging also continues at depth, and here we have an extreme example of radioactive disequilibrium, with thorium-230 activities almost insignificant compared to those of uranium-234. Although the removal rate of thorium from the deep ocean is slow compared to the decay rate of thorium-234, it is still fast compared with the decay of thorium-230. From the thorium-230/uranium-234 disequilibrium, it can be calculated that the residence time of thorium in the deep ocean is approximately 20-30 years. Thus even though thorium-230 is a long-lived radionuclide (half-life 75,000 years), it does not persist in the oceans for very long. Virtually all of the thorium-230 that would be in equilibrium with uranium-234 in the ocean is found in the bottom sediments, not in the water column.

Because of the efficient removal of thorium-230 from the water column, the remainder of the uranium series decay chain is found largely in the upper sediments on the seafloor. However, a certain amount (about 10 percent) of the radium-226 that is formed there escapes into the bottom water and is dispersed upward. This is an example of a natural release of radioactivity on the seafloor, and it provides a useful analog for considering the possible effects of artificial releases.

A large amount of radium-226 data was collected in the Pacific Ocean during GEOSECS. The data have been published in papers by Chung and Craig (1980) and by Ku et al. (1980). An example of the distributions found is shown in Figure 8-6. Concentrations of radium-226 are higher in the deep water than at the surface, as expected considering the source at the bottom. However, surface concentrations are found to be much too low to be accounted for by physical dispersion models based on the natural carbon-14 distribution, so it has been concluded that there must be processes other than radioactive decay that remove radium-226 from the surface ocean. This occurs by incorporation of radium-226 in the biogenic debris produced at the surface by plankton, much of which dissolves on entering the deep water or on reaching the bottom sediment. Thus a cycle occurs in which dissolved radium-226 is slowly mixed upward to the surface across the thermocline and then carried downward by particles and released at depth. This cycle produces a distribution of radium-226 in the ocean in which the youngest deep water (that is, water which was most recently at the surface) contains the lowest radium-226 concentrations (found in the North Atlantic) and the oldest waters, in the North Pacific, contain the highest concentrations. This is opposite to the trends discussed above for carbon-14, but it is similar to the trends observed for the nutrient elements, especially silicate. Surface waters everywhere contain nearly the same concentration of radium-226 (0.03 - 0.04 picocurie per litre).

Radon-222 and its short-lived daughters are in secular equilibrium with radium-226 throughout most of the oceanic water column. However, near the seafloor excess radon-222 is present (that is, radon-222 activity greater than radium-226 activity) because of input from the bottom sediments. From the distribution of excess radon-222 above the seafloor, it is possible to determine rates of mixing within the bottom layer. A discussion of this, using GEOSECS data from the Pacific and other oceans, is given by Sarmiento et al. (1976). The mixing rate is important in determining the bottom water concentrations that would arise from artificial releases of radioactivity on the seafloor.

At the sea surface a deficiency of radon-222 occurs (radon-222 activity less than radium-226 activity) because of radon loss to the atmosphere. Rates of gas exchange at the interface can be estimated from measurements of the deficiency. However, the ocean is not generally an important source of radon in the atmosphere, most of which comes from the land.

Measurements of lead-210 in seawater show a significant excess (lead-210 activity greater than radon-222 activity) at the surface and a deficiency (lead-210 activity less than radon-222 activity) at depths below the thermocline. The source of the surface excess is the natural fallout of lead-210 from the atmosphere, where it is produced following radioactive decay of radon-222, which derives mainly from the continents. The deficiency in the deep water means that lead-210 is continually being stripped from the ocean as was the case with thorium-230 discussed above.

Figure 8-7 is a map of lead-210 concentrations in surface seawater. Concentrations are seen to be generally higher in the North Pacific than in the South Pacific. This reflects the larger land mass of the Northern Hemisphere, supplying more radon-222 to the atmosphere and hence more lead-210 to the sea surface. It can also be seen (Figure 8-7) that lead-210 concentrations are, in each hemisphere, highest in the central regions of the ocean. This pattern reflects the pattern of biological productivity in the ocean. Like thorium, lead is stripped from the surface waters because of the biologically driven particle formation and settling. The biological activity, hence the stripping process, is most intense around the edges of the ocean and also along the equator. Those waters are most efficiently stripped, so the lead-210 concentrations are lowest.

The vertical distributions of lead-210 in the Pacific Ocean are shown in GEOSECS data published by Nozaki et al. (1980) and by Chung and Craig (in press). Figure 8-8 shows some representative data. Here the results are expressed as the lead-210 minus radium-226 activity difference to show how the magnitude of the disequilibrium changes with depth. The excess lead-210 (positive values) can be seen at the top penetrating downward into the thermocline. Below about 1000 m all the samples show a deficiency (negative values), and the deficiencies are largest near the bottom suggesting that lead-210 removal is fastest near the bottom due to intensified stripping processes occurring near the sediment/water interface.

The final radioactive member of the uranium series is polonium-210. Concentrations of polonium-210 in surface waters from the Pacific ocean were reported by Nozaki et al. (1976). Little of the polonium-210 in the ocean comes from the atmosphere, most of it being produced within the ocean itself by decay of lead-210. It is known that polonium-210 is strongly concentrated by plankton and other marine organisms, and some tissues of marine organisms receive extremely high radiation doses from the polonium-210 deposited within them (Cherry et al., 1982). Because of the uptake by plankton and adsorption on planktonic detritus, polonium-210 is scavenged from the surface ocean, and a polonium-210 deficiency (polonium-210 activity less than lead-210 activity) is found everywhere. This is shown in Figure 8-9, which maps the polonium-210/lead-210 activity ratio in Pacific surface waters. As expected the highest ratios (least amount of scavenging) occur in the central ocean areas of each hemisphere, and the lowest ratios (highest rate of scavenging) are found in those areas where biological productivity is highest.

8.2.2.3 Radionuclides of other decay series

The decay sequence and half-lives of the thorium-series radionuclides are given in Chapter 5, Figure 5-2. Because of the very low solubility of thorium in seawater, and because of the short half-lives of all the thorium-232 decay products, members of the thorium series are ordinarily present at very low concentrations in seawater. However, significant amounts of radium-228 are found around the edges of the ocean and also near the deep seafloor because of its diffusion out of sediments. Like radium-226, radium-228 provides an important analog for considering artificial releases at the seafloor, and thorium-228 measurements provide important information on chemical scavenging (the cleansing or stripping process described above) in the

sea.

The activity level of uranium-235 in nature is less than 5 percent that of uranium-238. UNSCEAR (1982) considers the small contributions to doses received from members of the uranium-235 decay series to be negligible. The concentrations of the uranium-235 decay products in seawater are very low and difficult to measure.

8.3 ARTIFICIAL RADIOACTIVITY

During the period of large-scale atmospheric weapons testing by the U.S. at its Pacific Proving Grounds in the Marshall Islands, several ocean surveys were conducted by Japanese and U.S. scientists to monitor the changes in the radioactivity levels in seawater (Japan Society for the Promotion of Science, 1956; Hines, 1962). Most of the measurement techniques that were employed during those early surveys were not capable of determining the concentrations of individual radionuclides, and the sampling was generally not detailed enough or frequent enough to cope adequately with the high degree of spatial and temporal variability existing at that time. For these reasons, it is difficult from the early work to draw conclusions on the behaviour of artificial radionuclides in the ocean.

As with the natural radionuclides, much of the data that exists on the distributions of individual artificial radionuclides in the Pacific Ocean derives from the Pacific GEOSECS expedition conducted in 1973-1974, some ten years after the large-scale production of nuclear weapons debris from the U.S. and USSR atmospheric tests had stopped. The most important artificial radionuclides measured during GEOSECS were tritium, carbon-14, caesium-137 and plutonium-239,240 (the sum of the two isotopes, which could not be individually measured by the technique that was used). These radionuclides give important information on how materials are moved and dispersed in the ocean, particularly, at this time, in the upper layers of the ocean. Their distributions in the ocean continue to change with time, and for this reason, they belong to a class of substances sometimes referred to as transient tracers. In this respect, they differ from the natural radionuclides, whose distributions remain nearly steady in time.

With the exception of carbon-14, which forms gaseous carbon dioxide in the atmosphere, the radionuclides produced during nuclear explosions in the atmosphere are distributed largely within the hemisphere in which they are produced (Chapter 6). This is true of tritium, which enters the oceans as tritiated water, partly in rain, to a small extent in rivers, but mainly by vapor exchange at the air-sea interface. It is also true of strontium-90, caesium-137 and plutonium-239,240, which are all delivered to the sea surface in rain and also in dry fallout. Carbon-14, as carbon dioxide, has a much longer residence time in the atmosphere and tends to be more evenly distributed between the two hemispheres. In 1973, approximately 50 percent of the total weapons-produced carbon-14 still remained in the atmosphere, whereas only 0.1 percent of the tritium remained (Broecker and Peng, 1982). Thus the atmospheric inventory of carbon-14 continues to be reduced because of its uptake by the oceans (Chapter 6, Figure 6-5).

Tritium and the fallout radionuclides strontium-90, caesium-137 and plutonium-239,240 all reach the sea surface within weeks (for tropospheric injection) or a few years (for stratospheric injection) of the time they are produced in a nuclear explosion. Thus a sharp peak, lagging behind the peak in production by a year or two, is seen when their delivery rates are plotted against time (Figure 8-10). Their behaviour is in contrast to the more gradual removal of carbon-14 from the atmosphere, as discussed in Chapter 6, section 6.4.2.7 and shown in Figure 6-5.

8.3.1 Tritium Distribution in the Pacific Ocean

Figure 8-11a shows one of the tritium sections measured in the Pacific Ocean during GEOSECS. As stated in Chapter 5, the amount of natural (cosmogenic) tritium in the oceans is very small, and virtually all of the tritium now found in the oceans can be considered to be weapons-produced. The asymmetrical distribution of tritium about the equator is striking in these sections. Much higher concentrations are found in the Northern Hemisphere, as expected. The same asymmetry is also evident in the water-column inventories shown in Figure 8-11b. All tritium concentrations are expressed in tritium units (TU). One TU represents one tritium atom for every 10^{18} atoms of hydrogen and is equivalent to 3.2 picocurie per litre of seawater. Thus the highest surface water concentrations shown in Figure 8-11b correspond to about 30 picocurie per litre. In 1973-1974, no tritium could be detected in the Pacific Ocean below about 1000 metres.

8.3.2 Bomb Carbon-14

The amounts of carbon-14 produced during the atmospheric testing of nuclear weapons were large enough to cause a significant increase in the carbon-14 content of the atmosphere and, subsequently, of the surface waters of the ocean. Figure 8-12a shows Δ C-14 values measured in Pacific surface waters during GEOSECS (1973-1974) in comparison with values that were measured earlier before significant inputs of bomb carbon-14 (pre-1958). Figure 8-12b shows the water-column inventories of the artificial component. Comparison with Figure 8-11 shows that, with carbon-14, there is much less asymmetry in the distribution about the equator than there is with tritium. As pointed out above and in Chapter 6, this is because of the long residence time of carbon dioxide in the atmosphere compared to the time required for atmospheric exchange between the Northern and Southern Hemispheres. It is believed that the pronounced carbon-14 minimum at the equator is caused mainly by upwelling, in the equatorial region, of waters that are relatively deficient in carbon-14, and the data provide a means of estimating the upwelling rates (Broecker and Peng, 1982).

8.3.3 The Fallout Radionuclides Strontium-90, Caesium-137 and Plutonium-239,240

A recently published study by Bowen et al (1980), based largely on data from GEOSECS stations, provides the most extensive treatment presently available on fallout radionuclides in the Pacific Ocean. Earlier measurements, most notably by Y. Miyake and co-workers in Japan and by T.R. Folsom and co-workers in the United States, were reviewed by Volchok et al (1971) and Miyake and Sugimura (1974).

The GEOSECS data are shown in vertical sections in Figures 8-13 through 8-16. In general, fallout strontium-90 and caesium-137 are related to each other by a constant ratio (caesium-137/strontium-90 1.45), which is also maintained everywhere in seawater. Thus it would be redundant to present data for both radionuclides, and, in fact, the contours in Figures 8-13 and 8-15 are based on strontium-90 as well as caesium-137 measurements.

The distribution of caesium-137 (and strontium-90) bears a strong resemblance to that of tritium (Section 8.3.1). This similarity reflects the fact that caesium-137 moves largely in true solution in seawater, not being associated significantly with sinking particles. As is the case with tritium, fallout caesium-137 shows a strong asymmetry in its distribution about the equator.

Plutonium-239,240 distributions are in sharp contrast to those of tritium or

Plutonium-239,240 distributions are in sharp contrast to those of tritium or caesium-137. Whereas the tritium and caesium-137 concentratons are generally highest at the sea surface, the highest plutonium concentrations are found, throughout the Pacific, in a sub-surface layer centered at approximately 450-500 metres. The downward penetration of plutonium is more extensive than it is for tritium or caesium-137, and at some of the stations in the North Pacific (Figure 8-14) a plutonium-rich bottom-water layer is found. These distinguishing features of the plutonium-239,240 distribution can be accounted for by an association of plutonium with sinking particles and a subsequent release of plutonium from the particles, either at sub-surface depths in the water column, while the particles are sinking, or at the seafloor, after the particles have reached the bottom.

The GEOSECS data set is extensive enough that water-column inventories of the fallout radionuclides could be calculated. From a comparison of those inventories with the estimated global fallout deliveries, it is evident that over most of the Pacific Ocean represented by the data (mostly north of the equator) there is a substantial excess of both plutonium-239,240 and caesium-137. The excess is most pronouned for plutonium-239,240, especially in the 0-15° N latitude band. Recognizing that there were still gaps in the coverage, Bowen et al. (1980) nevertheless provided estimates of ocean-wide inventories of the fallout radionuclides in the North Pacific. They were, in 1974, as follows: 174×10^3 curies of plutonium-239,240, 5.4×10^6 curies of caesium-137 and 3.72×10^6 curies of strontium-90 (converted from the caesium-137 inventory). Global fallout deliveries to the same area were calculated from worldwide fallout data, to be 69.7×10^3 curies of plutonium-239,240 and 2.68×10^6 curies of strontium-90. Thus the amount of plutonium in the North Pacific is about 2.5 times larger than would be expected from global (stratospheric) fallout alone, and the amounts of caesium-137 (and strontium-90) are about 1.4 times larger. The only obvious source for these large inventory excesses would appear to be close-in and tropospheric fallout clouds from the various nuclear test series conducted in the Pacific. This is consistent with the observations pointed out in Chapter 6 (section 6.6) of unusually high inventories of caesium-137 in soils of the Northern Marshall Islands. Bowen et al (1980) point out that, in order to account for the Pacific Ocean inventory data, the close-in fallout must have had a plutonium-239,240/caesium-137 ratio higher than that found in global fallout and that deep-sea sediments in the vicinity of the US test sites contain unusually high levels of plutonium.

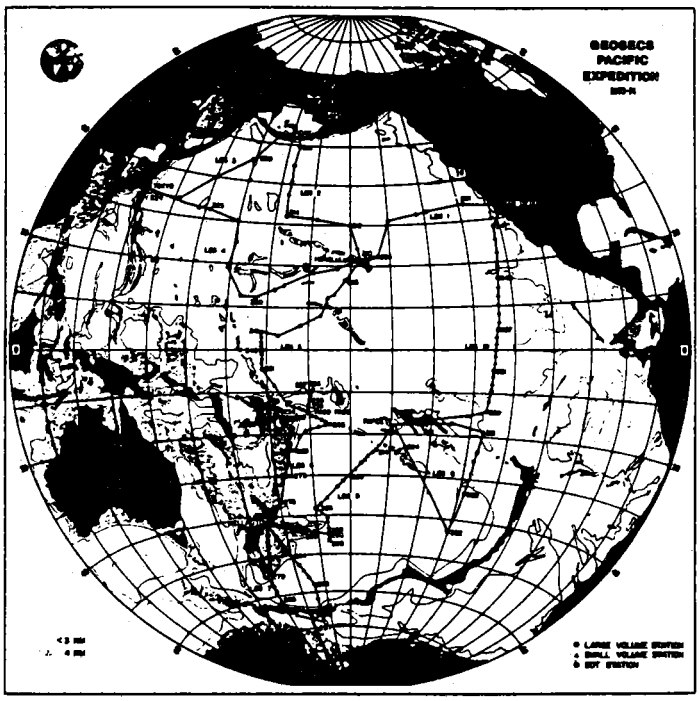


Figure 8-1. GEOSECS Pacific expedition 1973-1974. Thin lines represent the 4-km contour. Shaded area: < 3 km. Source: Craig and Turekian (1976).

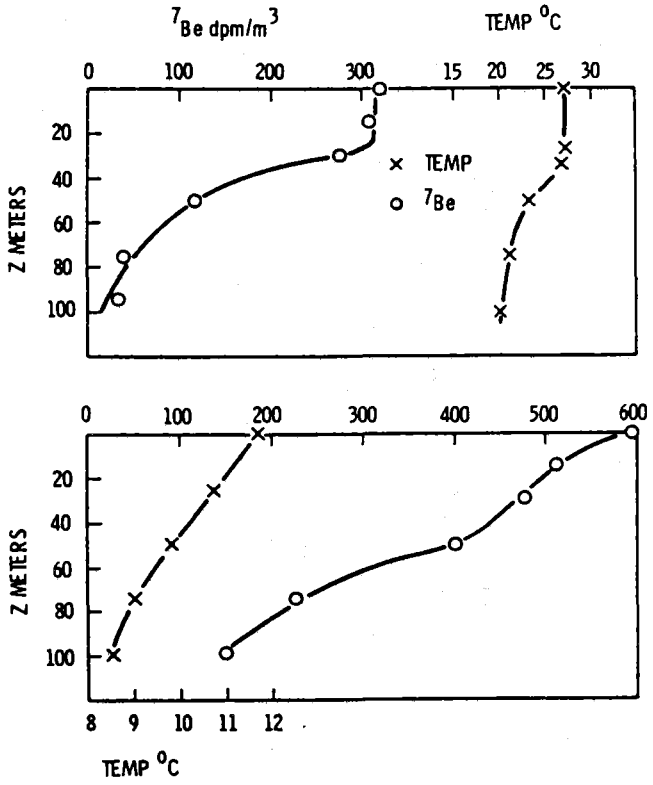


Figure 8-2. Profiles of beryllium-7 concentration and temperature versus depth (Z) measured at two stations in the Pacific Ocean. Upper panel: 30 October 1968; 28°32'N, 160°00'W. Lower panel: 28 April 1968; 44°39'N, 124°53'W. 1 disintegration per minute (dpm)=0.0167 becquerel=0.45 picocurie. Source: Silker (1972).

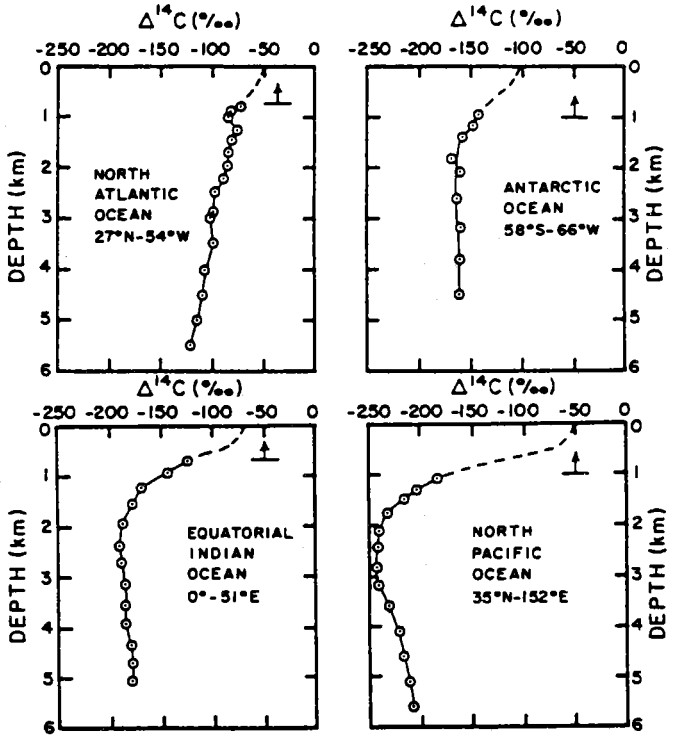


Figure 8-3. Carbon-14/carbon-12 (expressed as Δ C-14) versus water depth at stations in the world's three major oceans and in the Antarctic. The progressive decrease in the values for deep water from Atlantic to Antarctic to Indian to Pacific can be seen. The arrow denotes that portion of the upper water column contaminated with radiocarbon produced by nuclear tests at the times these samples were collected. This depth was determined from the tritium data for these stations. The dashed lines are the prenuclear Δ C-14 trends for this depth zone. Source: Broecker and Peng (1982).

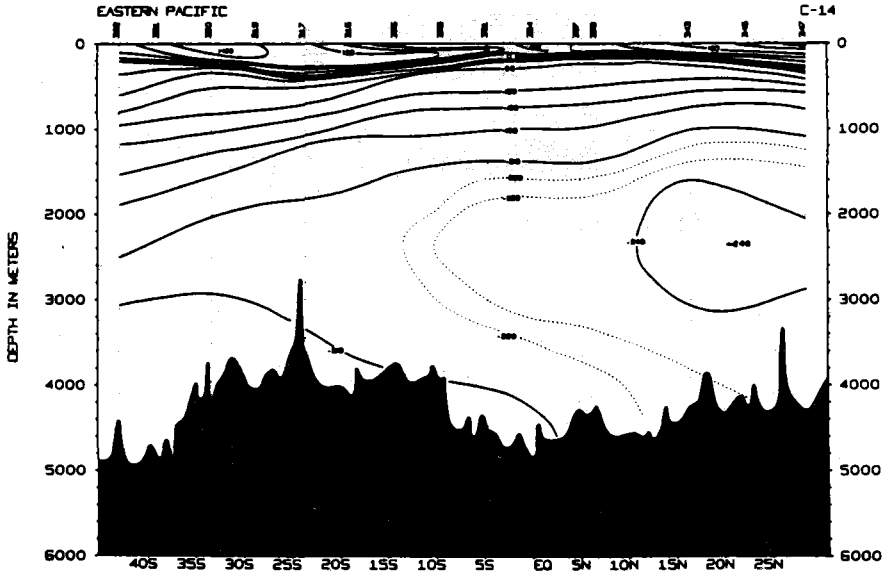


Figure 8-4. Distribution of carbon-14 (expressed as Δ C-14) a north-south transect in the eastern Pacific Ocean. The progressive decrease in the values for deep water from south to north can be seen. Source: Östlund and Stuiver (1980).

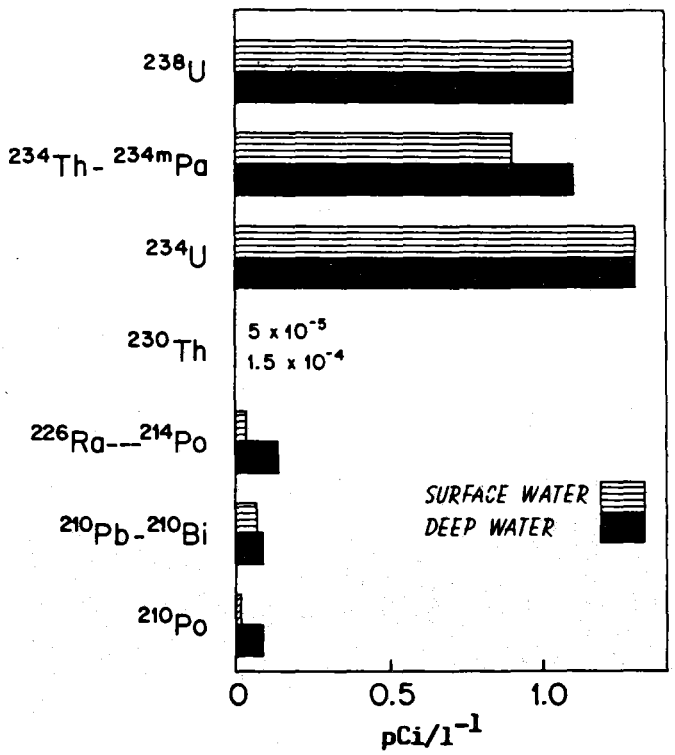


Figure 8-5. Representative concentrations of the uranium-series radionuclides in Pacific Ocean waters. Short-lived nuclides are assumed to be in secular equilibrium with their parents.

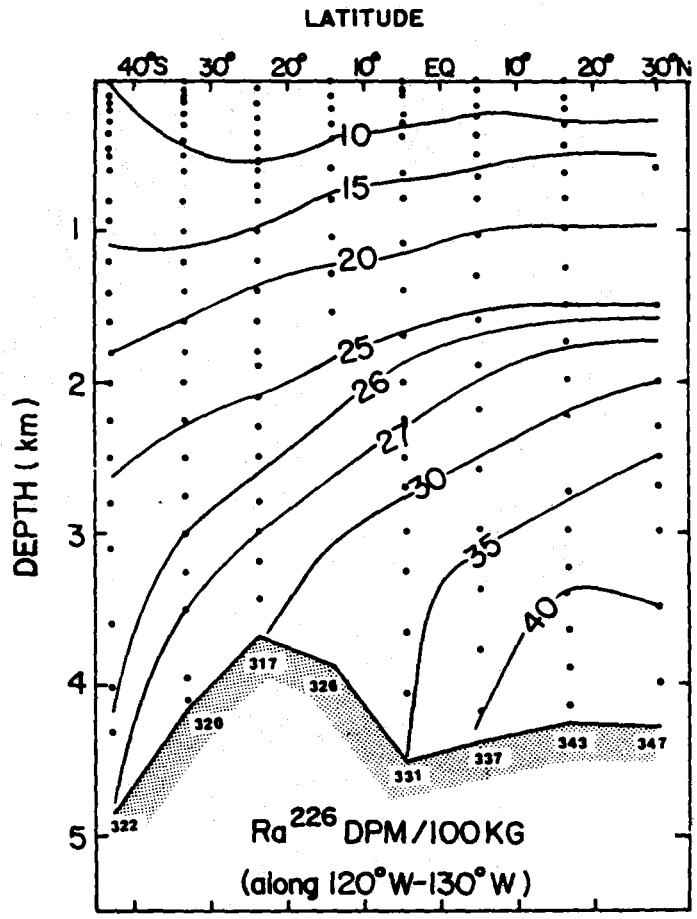


Figure 8-6. Contour diagram of radium-226 concentration in a north-south vertical section in the eastern Pacific. 1 disintegration per minute (dpm)=0.0167 becquerel=0.45 picocurie. Source: Ku et al. (1980).

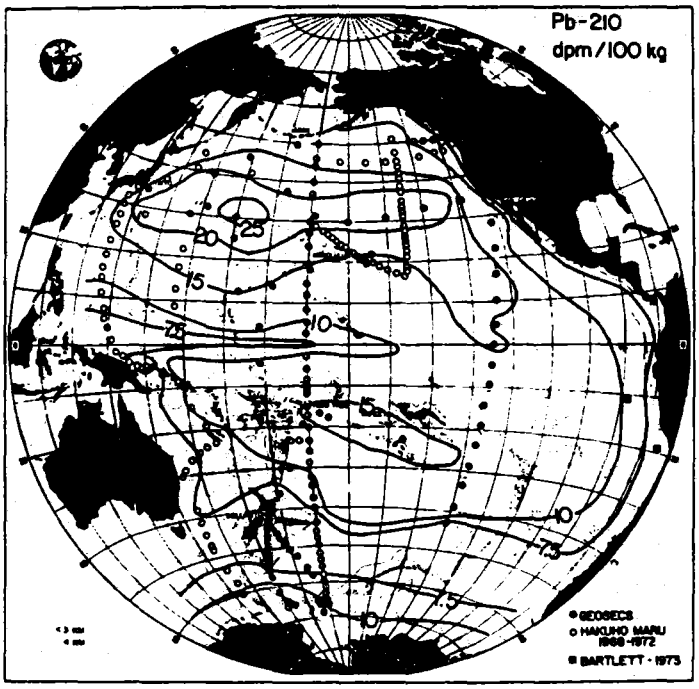


Figure 8-7. Lead-210 distribution in surface waters of the Pacific Ocean. 1 disintegration per minute (dpm)=0.0167 becquerel=0.45 picocurie. Source: Nozaki et al. (1976).

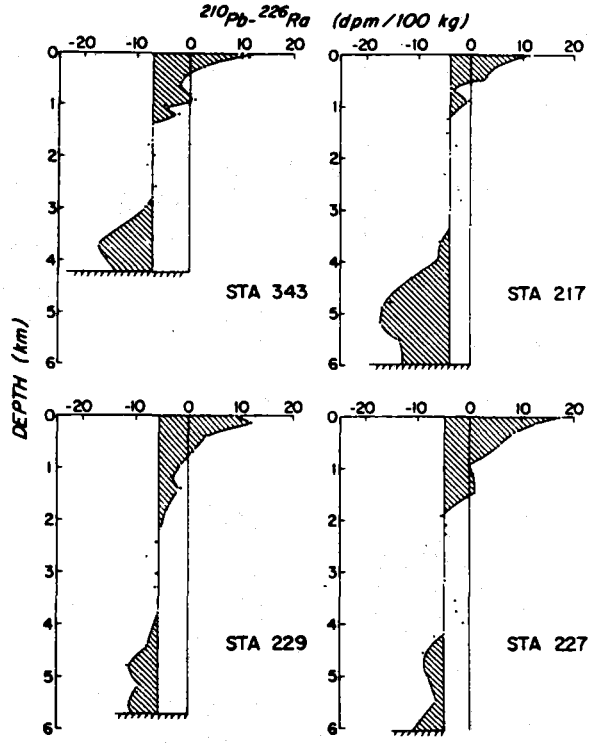


Figure 8-8. Four representative profiles showing lead-210 excess in the upper water column and deficiency in the bottom part of the water column. Shaded areas are the areas of excess and deficiency relative to the mid-depth deficiency as norm. 1 disintegration per minute=0.0167 becquerel=0.45 picocurie. Source: Nozaki et al. (1980).

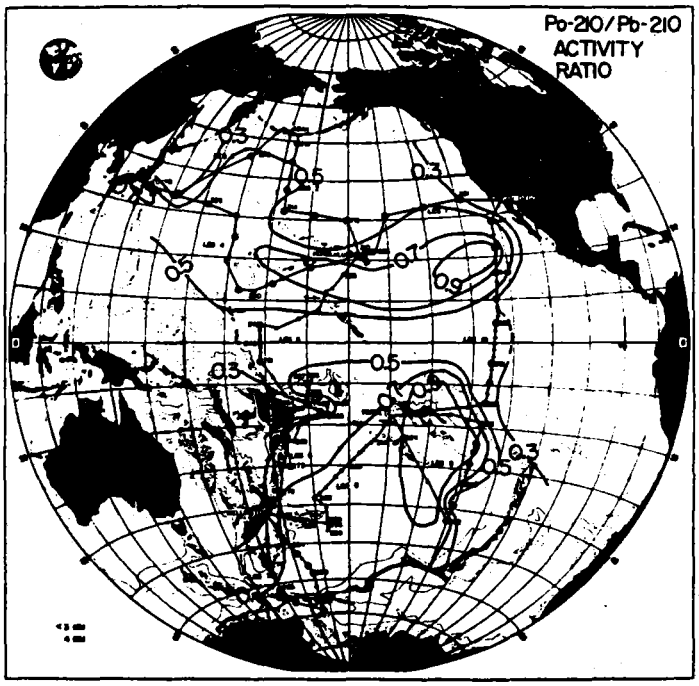


Figure 8-9. The distribution of polonium-210/lead-210 activity ratios in the surface waters of the Pacific Ocean. Source: Nozaki et al. (1976).

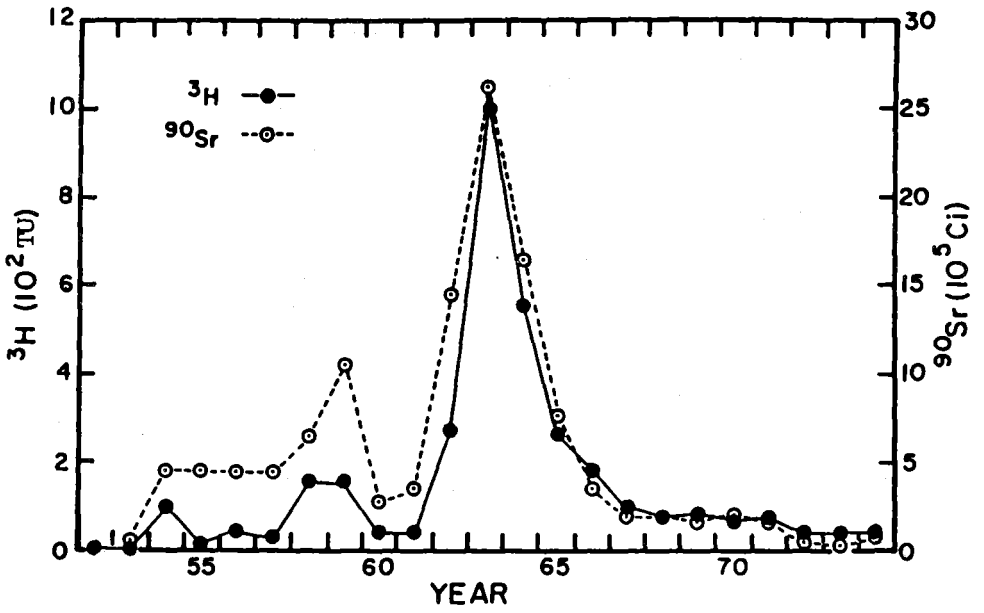


Figure 8-10. Mean tritium content of rain at Valencia, Ireland, from 1952 to 1974. Also given is the total annual Northern Hemisphere strontium-90 deposition. Source: Dreisigacker and Roether (1978), reprinted in Broecker and Peng (1982).

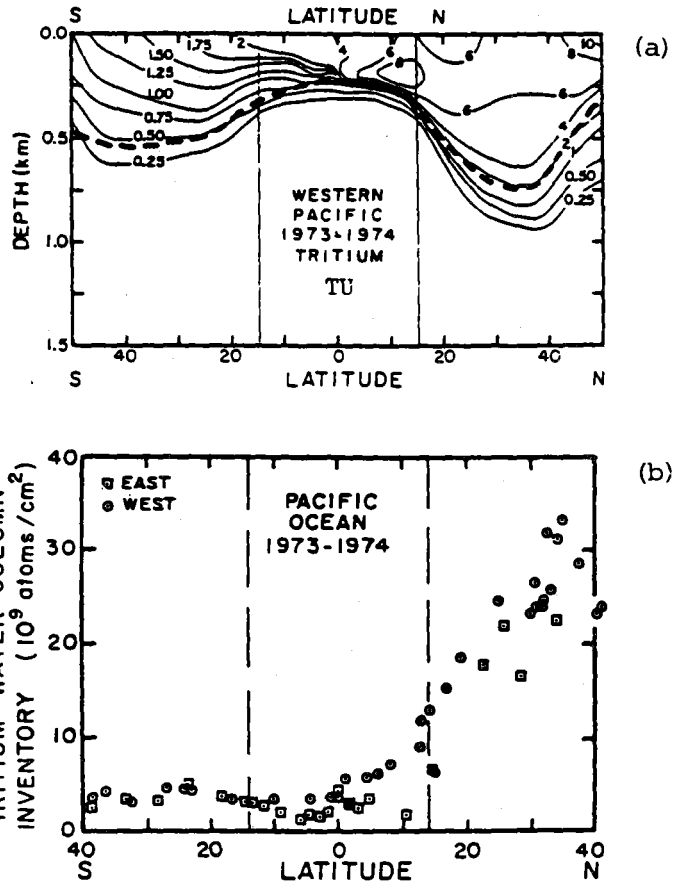


Figure 8-11. (a) Section showing the vertical distribution of tritium along a traverse in the Western Pacific Ocean. The heavy dashed line denotes the depth at which tritium concentration reaches one-quarter the value in the overlying surface water. (b) Water-column inventory of tritium versus latitude in the Pacific Ocean in 1973-1974. Source: Broecker and Peng (1982).

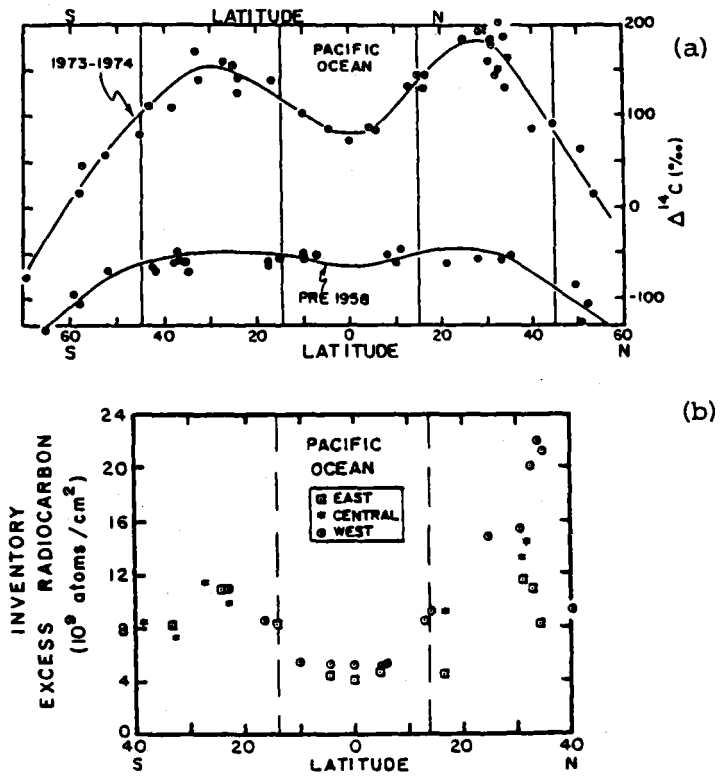


Figure 8-12. (a) Δ C-14 values in surface waters of the Pacific Ocean at the time of GEOSECS (1973-1974) and prior to contamination by bombs C-14 (pre-1958).
(b) Inventories of bomb C-14 versus latitude in the Pacific Ocean in 1973-1974. Source: Broecker and Peng (1982).

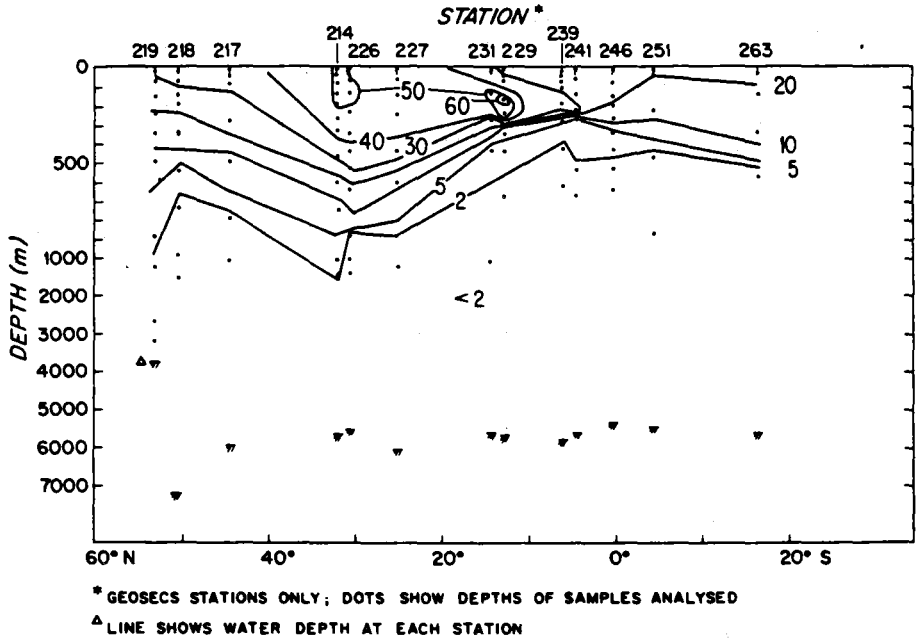


Figure 8-13. Western Pacific, north-south section 170°W-170°E, 1973-74 GEOSECS program: caesium-137 concentrations (dpm/100 kg seawater). 1 disintegration per minute (dpm)=0.0167 becquerel=0.45 picocurie. Source: Bowen et al. (1980).

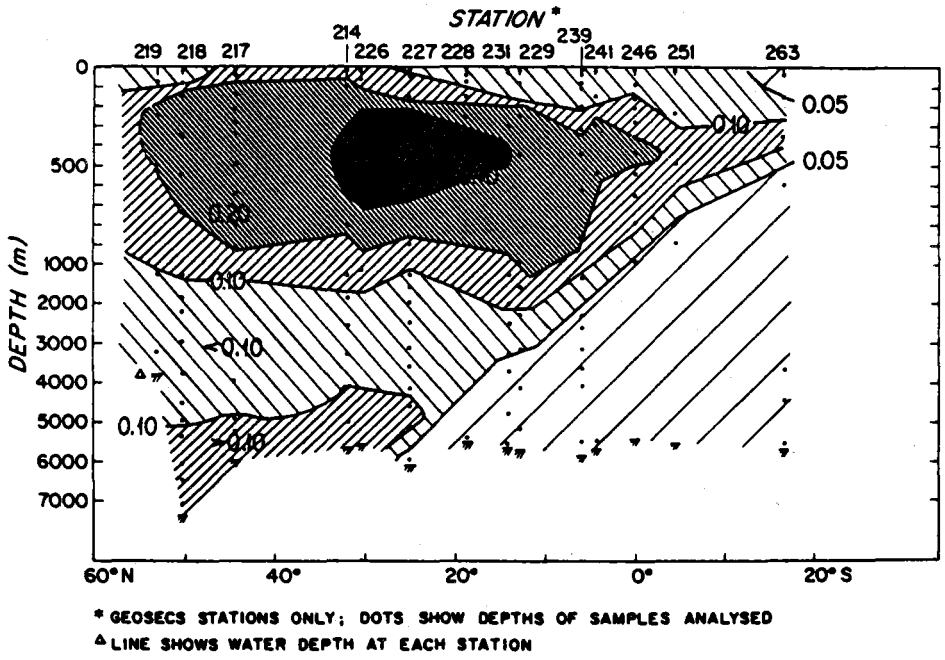


Figure 8-14. Western Pacific, north-south section 170°W-170°E, 1973-74 GEOSECS program: plutonium-239,240 concentrations (dpm/100 kg seawater). 1 disintegration per minute (dpm)=0.0167 becquerel=0.45 picocurie. Source: Bowen et al. (1980).

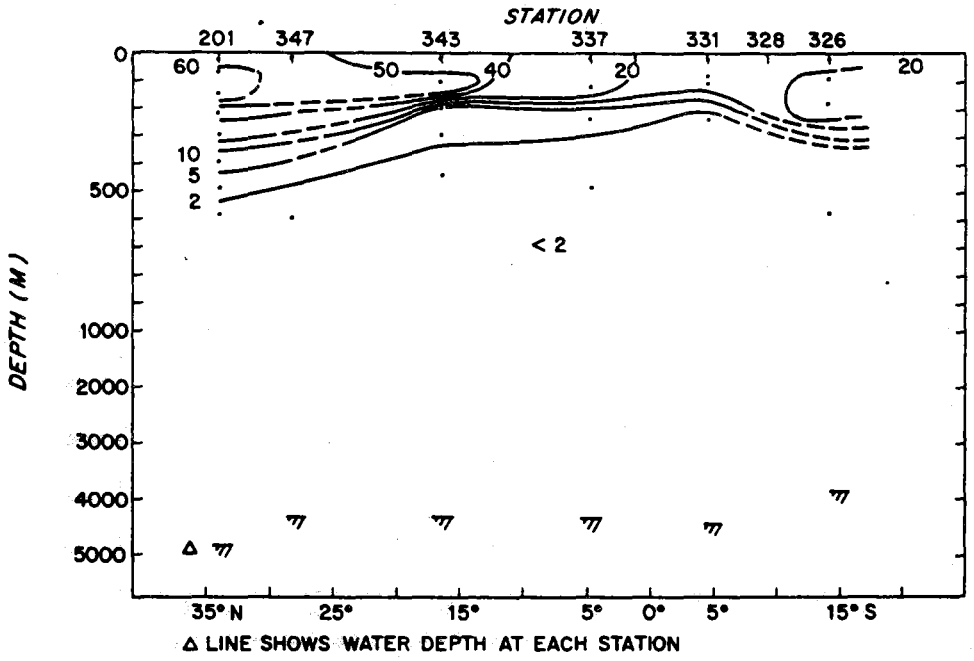


Figure 8-15. Eastern Pacific, north-south section 121-128°W, 1973-74 GEOSECS program: caesium-137 concentrations (dpm/100 kg seawater). 1 disintegration per minute (dpm)=0.0167 becquerel=0.45 picocurie. Source: Bowen et al. (1980).

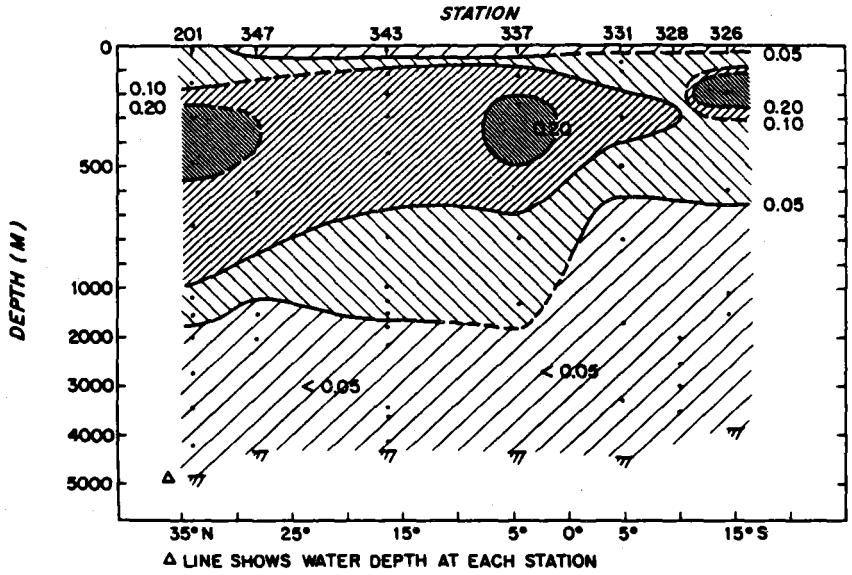


Figure 8-16. Eastern Pacific, north-south section 121-128°W, 1973-74 GEOSECS program: plutonium-239,240 concentrations (dpm/100 kg seawater). 1 disintegration per minute (dpm)=0.0167 becquerel=0.45 picocurie. Source: Bowen et al. (1980).

8.4 REFERENCES

Bowen, V.T., V.E. Noshkin, H.D. Livingston and H.L. Volchok, 1980. Fallout radionuclides in the Pacific Ocean: vertical and horizontal distributions, largely from GEOSECS stations. Earth Planet. Sci. Lett., 49: 411-434.

Broecker, W. S. and T.H. Peng, 1982. Tracers in the Sea. Lamont-Doherty Geological Observatory, Palisades, NY, 690 pp.

Cherry, R. D., and M. Heyraud, 1982. Evidence of high natural radiation doses in certain mid-water oceanic organisms. Science, 218: 54-56.

Chung, Y. and H. Craig, in press. Lead-210 in the Pacific: the GEOSECS measurements of particulate and dissolved concentrations. Earth Planet. Sci. Lett.

Chung, Y. and H. Craig, 1980. Radium-226 in the Pacific ocean. Earth Planet. Sci. Lett., 49: 267-292.

Craig, H. and K. K. Turekian, 1976. The GEOSECS program: 1973-1976. Earth Planet. Sci. Lett., 32: 217-219.

Dreisigacker, E. and W. Roether, 1978. Tritium and ^{90}Sr in North Atlantic surface water. Earth Planet. Sci. Lett., 38: 301-312.

Edmond, J. M., C. Measures, R. E. McDuff, L. H. Chan, R. Collier, B. Grant, L. I. Gordon, and J. B. Corliss, 1979. Ridge crest hydrothermal activity and the balances of the major and minor elements in the ocean: the Galapagos data. Earth Planet. Sci. Lett., 46: 1-18.

Hines, N.O., 1962. Proving Ground: an account of radiobiological studies in the Pacific, 1946-1961. University of Washington Press.

Japan Society for the Promotion of Science, 1956. Research in the effects and influences of the nuclear bomb test explosions.

Ku, T. L., C. A. Huh and P. S. Chen, 1980. Meridional distribution of radium-226 in the eastern Pacific along GEOSECS cruise tracks. Earth Planet. Sci. Lett., 49: 293-308.

Matsumoto, E., 1975. Thorium-234-uranium-238 radioactive disequilibrium in the surface layer of the ocean. Geochim. Cosmochim. Acta, 39: 205-212.

Miyake, Y. and Y. Sugimura, 1976. The plutonium content of Pacific Ocean waters. In: Transuranium Nuclides in the Environment, IAEA, pp. 91-105.

Nozaki, Y., J. Thomson and K. K. Turekian, 1976. The distribution of lead-210 and polonium-210 in the surface waters of the Pacific ocean. Earth Planet. Sci. Lett., 32: 304-312.

Nozaki, Y., K. K. Turekian and K. von Damm, 1980. Lead-210 in GEOSECS water profiles from the North Pacific. Earth Planet. Sci. Lett., 49: 393-400.

Ostlund, H. G. and M. Stuiver, 1980. GEOSECS Pacific radiocarbon. Radiocarbon, 22: 25-53.

Sarmiento, J. L., H. W. Feely, W. S. Moore, A. E. Bainbridge, and W. S. Broecker, 1976. The relationship between vertical eddy diffusion and buoyancy gradient in the deep sea. Earth Planet. Sci. Lett., 32: 357-370.

Silker, W. B., 1972. Horizontal and vertical distributions of radionuclides in the North Pacific Ocean. J. Geophys. Res., 77: 1061-1070.

Stuiver, M., P. D. Quay and H. G. Ostlund, 1983. Abyssal water carbon-14 distribution and the age of the world oceans. Science, 219: 849-851.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1982. Ionizing Radiation: Sources and Biological Effects, Report to the General Assembly, with Annexes, 773 pp.

Volchok, H.L., V.T. Bowen, T.R. Folsom, W.S. Broecker, E.A. Schuert and G.S. Bien, 1971. Oceanic distributions of radionuclides from nuclear explosions. In: Radioactivity in the Marine Environment, National Academy of Sciences, Washington, 42-89.

CHAPTER 9

PRESENT AND PROPOSED ACTIVITIES INVOLVING RADIOACTIVE MATERIALS IN THE SOUTH PACIFIC REGION

9.1 RADIOACTIVE WASTE STORAGE AND DISPOSAL

9.1.1 Low-Level Waste Disposal in the Ocean

9.1.1.1 International requirements

Use of the ocean as a repository for radioactive materials and other hazardous substances is internationally recognized as a matter that requires careful control. Accordingly, a system of principles and practices governing such use has been adopted with the aim of assuring the protection of the marine environment. The most important international agreement governing present waste-disposal practice is the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, which was adopted in London in 1972 and came into force in 1975. This Convention is commonly referred to as the London Dumping Convention (LDC). As of early 1983, the LDC had been signed by some 53 countries (Curtis, 1983), among them being Canada, France, Japan, the Netherlands, Spain, Sweden, USSR, U.K. and U.S.A.

The London Dumping Convention embraces all types of wastes, both radioactive and non-radioactive. Three general categories of waste are recognized (Article IV): (1) extremely hazardous materials, listed in Annex I of the Convention, for which dumping is categorically prohibited; (2) materials requiring special care, listed in Annex II of the Convention, for which a special permit is required; and (3) other materials, for which dumping under a general permit is allowed. Special and general permits are issued by the appropriate national authorities in the countries engaged in dumping (Article VI). Radioactive wastes fall within the first two categories given above. In category (1) are "high-level radio-active wastes or other high-level radio-active matter defined on public health, biological or other grounds, by the competent international body in this field, at present the International Atomic Energy Agency, as unsuitable for dumping at sea" (Annex I, paragraph 6). In category (2) are "radioactive wastes or other radio-active matter not included in Annex I. In the issue of permits for the dumping of this matter, the Contracting Parties should take full account of the recommendations of the competent international body in this field, at present the International Atomic Energy Agency" (Annex II, section D). Thus the International Atomic Energy Agency (IAEA) is charged with the responsibility of defining high-level radioactive waste, for which dumping is prohibited, and of setting recommendations to be followed in the disposal of other radioactive waste, which is permissible under the terms of the LDC.

The IAEA Definition and Recommendations are subject to continual review and may be revised as technological developments and improved scientific knowledge warrant. The present version is given in IAEA (1978a), which defines high-level radioactive

waste as follows:

"For the purposes of Annex I to the Convention, high-level radioactive wastes or other high-level radioactive matter unsuitable for dumping at sea means any waste or other matter with an activity per unit gross mass (in tonnes) exceeding:

(a) 1 Ci/t for α-emitters but limited to 10^{-1} Ci/t for ^{226}Ra and supported ^{210}Po;

(b) 10^{2} Ci/t for β / γ emitters with half-lives of at least 0.5 years (excluding tritium) and β / γ-emitters of unknown half lives; and

(c) 10^{6} Ci/t for tritium and β / γ-emitters with half-lives of less than 0.5 years.

The above activity concentrations shall be averaged over a gross mass not exceeding 1000 tonnes.

The Definition is based on:

(1) An assumed upper limit to the mass dumping rate of 100,000 t per year at a single dumping site; and

(2) Calculated upper limits to activity release rates from all sources (other than natural sources) of

(a) 10^{5} Ci/yr for α-emitters (but limited to 10^{4} Ci/yr for ^{226}Ra and supported ^{210}Po);

(b) 10^{7} Ci/yr for β / γ-emitters with half-lives of at least 0.5 years (excluding tritium) and β / γ-emitters of unknown half lives; and

(c) 10^{11} Ci/yr for tritium and β / γ-emitters with half-lives of less than 0.5 years

at a single dumping site and also in the case of α-emitters when released to an ocean basin of not less than 10^{17} m^{3}."

Radioactive wastes that do not exceed the limits set forth above are included under Annex II and may be dumped under a special permit. The above should be interpreted as upper limits, and the IAEA specifies that permits should not be given which would allow these limits to be approached.

In setting the present limits for radioactive waste disposal in the ocean, the IAEA relied on the advice of two international groups of experts that it convened in 1977. One of those groups reviewed the earlier Provisional Definition and Recommendations, concluded that revisions were necessary, and then went on to consider the oceanographic criteria for setting release limits. The other group of experts considered the radiological criteria. The reports issued by the two groups of experts (IAEA 1978b,c) provide the oceanographic basis and radiological basis for the presently adopted IAEA Definition and Recommendations (IAEA 1978a). Summaries of the IAEA work and accounts of the prior historical development can be found in a number of published sources (Mitchell and Shepherd, 1981; Nishiwaki, 1981; Templeton, 1981a,b). An especially good critical review of the IAEA work is given in a report by Sutton (1982).

The task of the IAEA is one of radiation protection, that is, of assuring that the human exposure to ionizing radiation that would result from dumping stays within specified limits. Thus it is necessary to predict the radiation dose that may be received by people from release of radioactivity on the seafloor. The IAEA experts adopted the critical pathway approach (Foster et al., 1971) in making their predictions. This involves evaluation of sequences of events through which radionuclides released to the environment are diluted, perhaps re-concentrated, and ultimately reach people either in food or in material with which they come in contact. The exposure pathways most likely to result in the highest doses are referred to as critical pathways, and the individuals who will receive those doses are said to belong to critical populations or critical groups.

The steps necessary to predict the radiation dose that may be received by people as a result of radioactive contamination of the marine environment are as follows (Foster et al., 1971):

1. Estimating the concentrations of the contaminants that will exist in seawater.
2. Estimating the relationships between the concentrations in the water and those in seafood, sediments, beaches, fishing gear, and other materials used by people.
3. Estimating rates of consumption of particular seafoods by critical population groups and the extent of exposure (time and distance) to materials that can deliver an external dose.
4. Converting the estimated intakes of radionuclides and the intensity of the deposited contaminants into estimates of internal and external dose.

In order to set release-rate limits, the above steps are taken to predict the dose to critical groups for a hypothetical unit rate of release on the seafloor (for example, 1 curie per year). The permissible release-rate limit is then taken as that number of units which will produce a dose equal to the limit set by some particular standard. In the IAEA work the standard used was the dose limit set by the International Commission on Radiological Protection (ICRP). At present that dose limit for critical populations is 5 millisievert per year over the whole body or doses to individual organs of the body which are estimated to cause equivalent radiation hazard (that is, the effective dose equivalent; see Chapter 3). This is about five times the average dose to people in the South Pacific Region from natural background radiation (Chapter 5).

It is especially important to recognize that the critical groups who could receive the doses estimated by the above procedure consist of those individuals who could receive the largest exposure, not the average exposure, resulting from the release of radioactivity. For example, one of the critical groups used in the IAEA assessment consists of people whose diet would be largely of seafood harvested entirely from that location in the ocean where the highest radionuclide concentrations might conceivably occur. It is unlikely that any such individuals would exist, but even if they did, the release-rate limits are designed to be restrictive enough to protect them. The average individual doses received by entire populations would be many times, probably thousands of times, lower than the maximum doses estimated for the critical groups.

In establishing the oceanographic basis, the IAEA experts recognized that present scientific knowledge does not allow exact predictions to be made of seawater concentrations resulting from radionuclide releases. They also recognized the possibility that some radioactivity could be transferred from the seafloor to human populations by completely unforeseen pathways. Because of these uncertainties, the IAEA experts adopted a conservative approach based on pessimistic assumptions about what might happen in extreme circumstances, not on realistic assumptions about what

would most likely happen. Thus the doses predicted by their calculations are, by intention, most probably overestimated. For this reason the resulting release-rate limits contain built-in safety factors.

The IAEA experts included an additional level of cautiousness in their analysis by recommending that disposal of radioactive waste be limited at the outset to rates not exceeding those which could, if necessary, be continued for very long periods of time -- periods comparable to the half life of plutonium-239. The length of time actually adopted in the calculations was 40,000 years. This is a conservative procedure, particularly for the long-lived wastes, because it would then take thousands of years for their concentrations in the ocean to build up to the maximum levels. They pointed out, however, that there is much concern within the scientific community about the effects of long-lived wastes and the possibility that revisions in the estimates of acceptable levels might become necessary, because it would equally take thousands of years for the long-lived wastes to decay away. The experts therefore recommended adopting a procedure to enforce a slow approach of activity in the environment toward the maximum levels so that time would be allowed for monitoring, assessment, and revision of control procedures should it prove necessary, particularly for the long-lived radionuclides (IAEA, 1978b).

The major task in establishing the oceanographic basis was to estimate radionuclide concentrations throughout the oceanic water column that would result from given rates of release at the seafloor. For any radionuclide released at a constant rate, the concentrations in seawater increases until an equilibrium distribution is eventually built up. When equilibrium is reached, the rate of loss by radioactive decay balances the rate of input, and there are no further increases in concentration. For radionuclides with half-lives much greater than vertical and horizontal mixing times, the equilibrium concentrations are uniform throughout the ocean and are easily calculated. For shorter-lived radionuclides, the concentrations depend also on rates of mixing and are higher near the source and on the ocean bottom than at the surface. For approximate calculations, in which the emphasis was on bottom concentrations, the IAEA experts chose to use the Shepherd dispersion model (Shepherd, 1978). This model considers an ocean of finite size with horizontal circulation and three-dimensional diffusion. The model was acknowledged to be a considerable idealization but was considered adequate for the purpose of defining large-scale, long-term concentrations.

Some examples of results calculated from the Shepherd model are shown in Figure 9-1 for a wide range of radioactive half-lives. For reference purposes the horizontal mixing time of a typical ocean basin can be taken as less than 100 years and the vertical mixing time as in the range of a few hundred to one thousand years. The quantity plotted on the vertical axis of Figure 9-1 is referred to as the specific concentration, which is simply the concentration of radioactivity, in curie per cubic metre, that would result from a unit rate of release (1 curie per second). For any actual rate of release, of course, the result is simply scaled up by multiplication. The volume of the ocean basin is taken to be 10^{17} cubic metres. (The volume of the Pacific Ocean is approximately seven times this value.) Curve H shows the limiting case in which mixing rates are always much faster than decay rates so that concentrations become uniform throughout the ocean. This curve slopes upward to the right, indicating that, for a given release rate, long-lived radionuclides will build up to higher concentrations than short-lived radionuclides provided that constant input is maintained long enough to reach this equilibrium (i.e., for times considerably longer than their half-lives). When mixing rates are comparable to or slower than radioactive decay rates, concentration gradients will occur such that concentrations are higher than average at the bottom of the ocean, near the source (curves C and D), and lower than average at the surface (curves E and F). The differences are large for short half-lives and become small for very

long half-lives. Thus the curves converge toward the upper right-hand part of the diagram. This illustrates how the slowness of vertical mixing in the ocean limits the transport of short-lived radionuclides to the surface. It also shows that the details of the oceanographic model (for example, which value is chosen for the mixing time or the diffusion coefficient) are important for predicting the concentration distributions of the short-lived radionuclides but become unimportant for determining the concentrations of the long-lived radionuclides.

The most obvious pathway for the transfer of radioactivity from the seafloor to human populations is by the dispersion process described above and then by the consumption of fish caught in surface waters. However, in order to allow for the possibility that future pathways might originate at great depths and for the possibility of upwelling from great depths to the surface, the IAEA experts adopted the conservative approach of basing their radiological assessment on the higher bottom concentrations, even for food chains originating in the surface. A vertical dispersion rate corresponding to a 4000-year mixing time was used in their calculations. These assumptions lead to the curve C in Figure 9-1.

The Shepherd model deals only with long-term, large-scale dispersion from a dump site, and leads to estimated average concentrations at the ocean bottom or surface. However, the oceanographic basis considered also the possibility of short-term processes, such as the formation and transport of plumes, that could short-circuit the long-term dispersion process. These are important to consider, because they could lead to higher local concentrations in pathways leading to human populations. The analogy of the smoke-filled room (MAFF, 1980) is helpful: in the long term the build-up of the background concentration is of greatest importance in determining how much smoke will be inhaled by the occupants of the room, but in the short term the actual concentration at a given place, and the amount of smoke inhaled by an individual, may be dominated for a while by a wisp of smoke. The IAEA experts took the possibility of such plume transport and also the possibility of deep convective mixing into account. This is one of the more speculative parts of the report, but calculations based on what were considered to be extreme examples indicated that the specific concentrations arising locally in the short term from a single site might be approximately 10^{-6} curie per cubic metre/curie per second. This value is shown by curve A in Figure 9-1 and was used as a more restrictive limit for single sites, except for the longer-lived nuclides, for which the whole-ocean limit becomes more restrictive.

In carrying out the radiological assessment for all the radionuclides, pathways and critical groups selected, a large number of calculations were necessary, and a simpler one-dimensional model was used, which predicts comparable but somewhat higher concentrations than does the full three-dimensional calculation. The values used are represented by curve B. The oceanographic model finally used for setting the Definition of high-level waste required by the LDC is shown by the highlighted portions of curves A and B in Figure 9-1.

The radiological assessment involved calculations for eighty radionuclides believed most likely to be significant in the marine environment. It postulated twelve representative pathways by which human populations might become exposed to radiation following release of radionuclides on the seafloor (Table 9-1). Release-rate limits were derived by first calculating the dose to critical groups that would be produced by each pathway from a unit release rate. The calculations were based on established radiological methods. For the five pathways involving seafood consumption, empirical concentration factors relating concentrations in marine organisms with concentrations in seawater (from the oceanographic basis) were taken from the scientific literature. Quantities analogous to the concentration factor were introduced for non-ingestion pathways (for example, to estimate the

concentrations of radionuclides in sea-salt aerosols that might be inhaled), and the appropriate maximum permissible annual intakes for ingestion and inhalation pathways were calculated. Finally the release rates which would lead to the ICRP dose limit were derived. The lowest of the release rate limits for the different critical groups was then adopted as the overall release-rate limit for each radionuclide. Table 9-2 gives a listing of the release-rate limits calculated for a finite ocean volume of 10^{17} cubic metres and for a single site. Release-rate limits were derived for each of the individual radionuclides and each of the pathways. However, for administrative convenience and analytical simplicity, the radionuclides were grouped into three main categories according to the basic properties of decay type and half-life. The release-rate limit for the most limiting radionuclide in each group was then adopted as the release-rate limit for that group as a whole. Single-site limits are more restrictive, except for long-lived radionuclides, because of the inclusion of short-term effects in the assessment.

In addition to the Definition of high-level radioactive waste required by Annex I of the LDC, the IAEA also publishes Recommendations concerning disposal of other radioactive wastes as required by Annex II. The current Recommendations are given in IAEA (1978a). They include the recommended basis for issuing special permits for radioactive materials and the recommended detailed basis for operational control of dumping of waste. The former deals with environmental evaluation, monitoring, and assessment. The latter deals with requirements for selection of a dumping site, packaging requirements, approval of the ship and its equipment, escorting officers, record keeping, and international co-operation and observation. The recommendations are quite extensive and detailed. Some of the more important requirements are the following:

a) An environmental assessment by the requesting national authority is required. The purpose of this assessment should be to estimate the likely doses that would actually be received by individuals and populations so that comparisons can be made with alternative methods of disposal or natural background doses. Thus it should differ from the IAEA assessment, which used unlikely maximizing assumptions to assure the protection of even the most highly exposed individuals.
b) There must be compliance with IAEA radiation protection requirements, which are based on ICRP dose limitations. This includes a risk-benefit analysis in comparison with alternative procedures, such as disposal on land. Radiation doses are to be kept as low as is reasonably achievable, economic and social factors being taken into account. Resultant radiation doses to individuals should not exceed ICRP recommended limits, now or in the future.
c) Upper limits to the activity from all sources (other than natural) which may be dumped in an ocean basin must be specified.
d) Minimum requirements for packaging are that packages descend intact to the seafloor and that any inner container remain there during descent. Subsequent release should be minimised to the extent reasonably achievable, but no quantitative requirements for minimum leakage rate are specified. Waste must be either solid, solidified, or absorbed on a solid substrate.
e) Risks to marine life must be considered.
f) Quantities and nature of radioactive waste for dumping must be measured or estimated. Records must be kept and reported to the Inter-governmental Maritime Consultative Organization (IMCO), which is the Secretariat for the LDC. An escorting officer is appointed by the country dumping the waste (and issuing the permit) to supervise the procedure and assure that the conditions of the permit are met.
g) Dump sites must be between latitudes 50°N and 50°S at depths exceeding 4000 metres. They must be clear of continental margins, undersea cables, and potential seabed resources, and they must have areas less than 10,000 square

kilometres.

At present the only active program for ocean dumping of radioactive waste is that conducted by some European nations in the eastern North Atlantic. The operation is conducted within the Multilateral Consultation and Surveillance Mechanism for Sea Dumping of Radioactive Waste, an agreement that was adopted in 1977 by the Organization for Economic Co-operation and Development (OECD/NEA, 1983). The following NEA Member Countries are party to the Mechanism: Belgium, Canada, Denmark, Finland, France, Federal Republic of Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States. Dumping operations are presently limited to a single site of approximately 4000 square-kilometre area centered at 46°00'N and 16°45'W. The site is approximately 700 kilometres from land, and the water depth is approximately 4400 metres. Dumping of radioactive waste is carried out mainly by the UK, but the Netherlands, Belgium and Switzerland have also dumped small amounts in recent years. A review of UK practices is given by Mitchell and Shepherd (1981).

The OECD Mechanism provides a framework for promoting consultation among member states on issues related to the disposal operation. It is designed to provide a means by which each country is assured of the safety of the operations, and it also provides for observation of the dumping operation itself. The Secretariat of the Mechanism is the Nuclear Energy Agency (NEA) of OECD. The NEA is concerned with scientific and technical issues of site selection, packaging, operating procedures, and environmental assessments. Recently the NEA published a review of the suitability of the present North-East Atlantic dump site (OECD/NEA, 1980). The NEA works in close collaboration with the IAEA and has a formal agreement of cooperation with that organization.

Table 9-3 is a summary of recent dumping rates at the North-East Atlantic site and a comparison with the IAEA-recommended release-rate limits. It can be seen that present dumping rates are a very small percentage of the IAEA limits, and it can thus be concluded that maximum individual doses resulting from present operations are likely to be an even smaller percentage of the ICRP-recommended limits (OECD/NEA, 1980).

At the Seventh Consultative Meeting of Contracting Parties to the London Dumping Convention, held in February 1983, a majority of the delegations present voted in favor of a resolution calling for an immediate suspension of any dumping of low-level radioactive wastes, pending presentation of a scientific and technical report on the subject at the Ninth Consultative Meeting, to be held in February 1984 (Curtis, 1983). The resolution is not a legally binding one, and how it will affect the present and planned activities of OECD nations that have existing or proposed programs of ocean disposal remains unclear at this time of writing.

9.1.1.2 Japanese proposal for low-level waste disposal in the North Pacific

Because of its limited land area and geologic instability, Japan has given serious consideration to use of the ocean as part of its strategy for the management of radioactive wastes. Since the early 1960s Japan has participated in international forums considering the sea-disposal option, and since the early 1970s it has conducted research to assess the feasibility of using sites in the western North Pacific for low-level radioactive waste disposal (Ishihara, 1980). Recently a specific proposal has been issued (RWMC, 1980). The Japanese proposal calls for an initial experimental phase to demonstrate operational and environmental safety, followed by a full-scale operation after about two years of monitoring. According to the timetable originally announced, the experimental phase was to have begun in late 1981. However, because of protest against the plan, the operation has been

postponed for an uncertain period of time.

The site chosen for the disposal operation is a 10,000 square-kilometre area centered at 30°N, 147°W, with a water depth of about 6000 metres. It is situated about 900 kilometres southeast of Tokyo and about 1100 kilometres north of the nearest island in the Commonwealth of the Northern Mariana Islands. The conditions required in the site selection were that (1) the main distribution areas of important coastal fisheries should be avoided, (2) deep-sea fisheries should not be affected, (3) bottom current flows and upwellings should be weak, (4) the seafloor should be flat and soft, and (5) seismically active zones should be avoided (STA/NSB, undated, (b)). Site surveys in four candidate areas were carried out, and the proposed site was chosen as best meeting the established criteria. During the experimental phase, approximately 500 curies contained in some 5,000-10,000 200-liter drums would be dumped. The waste would consist almost entirely of beta/gamma-emitters (largely manganese-54, cobalt-60, strontium-90, caesium-137, and cerium-144). Operations would be run by the Radioactive Waste Management Center (RWMC) of Japan under the OECD Mechanism, and there would be monitoring studies carried out after the dumping. Full-scale dumping would then proceed in the same area after about two years, provided that operational and environmental safety had been confirmed. The amount of activity to be involved in the full-scale operation is yet to be determined, but a figure of 100,000 curies per year is used in the environmental assessment and is regarded as an upper limit.

The environmental impact of the proposed Japanese waste-disposal operation has been assessed by the Japanese Nuclear Safety Bureau, Science and Technology Agency. The Technical Group received an undated, draft English translation of the report of that assessment (STA/NSB, undated, (a)) and was informed by representatives of the Japanese Government that a final report was in preparation for submission to NEA for its review under the OECD Mechanism. It is required that this submission be made at least one year before any dumping operations begin.

As in other assessments of radionuclide releases to the marine environment, the impact of the proposed Japan dumping is quantified in terms of the radiation doses that could be received by individuals and populations of people. The calculated doses to critical groups may be compared with limits set by the ICRP or other authorities, or with the natural background exposure, so that a judgement can be made as to whether or not the proposed activity presents an unacceptable hazard. However, the main purpose of the Japanese assessment is, presumably, to obtain realistic estimates of collective doses to populations, or of average individual doses, so that objective comparisons could be made with alternative disposal options. Thus the Japanese assessment does not adopt the high degree of conservatism taken by the IAEA in setting release-rate limits but instead attempts to estimate doses that would be more likely to be received.

The Japanese assessment considers the impact of both the experimental and full-scale phases of the proposed dumping operation. Since the activity involved in the experimental phase (500 Ci) is very small, only the full-scale assessment is considered here. Table 9-4 gives the individual radionuclide dumping rates assumed for the full-scale dumping and shows comparisons with the release rates that formed the IAEA Definition of high-level radioactive wastes (IAEA, 1978a). Most of the activity that would be dumped consists of the four beta/gamma-emitting radionuclides manganese-54, cobalt-60, strontium-90, and caesium-137. The longest-lived of these nuclides is caesium-137, with a half-life of thirty years. The maximum dumping rates of beta/gamma-emitting nuclides would be one percent of the release-rate limits set by the IAEA assessment. For tritium and for radium-226 and the other alpha-emitters, the percentages would be extremely small.

Like the IAEA assessment the Japanese assessment includes an oceanographic model for estimating the radionuclide concentration distributions in the ocean followed by a radiological analysis for calculating the resulting doses. It is assumed that all of the radionuclides are released from the packages immediately upon impact on the seafloor. Thus release rate is taken to equal dumping rate. The design of the waste packages is such that there would be containment of at least some of the nuclides, perhaps for several years or longer, during which time there would be a significant decay of the short-lived nuclides. However, this cannot be quantified, so the worst-case assumption of immediate release is adopted in the assessment.

The oceanographic model considers a box measuring 12,000 kilometres from east to west, 6,000 kilometres from north to south and 5 kilometres in depth, giving a volume of 3.6×10^{17} cubic metres. These are the approximate dimensions of the North Pacific Ocean. The point of release is taken at the seafloor, 1,000 kilometres from the western boundary of the model and 2,000 kilometres from the northern boundary. Released radionuclides are dispersed from that point by horizontal and vertical eddy diffusion (mixing), and after a period of time, a steady-state distribution is reached at which each radionuclide will have built up to its maximum concentration. That concentration then remains steady as long as a constant release rate is maintained.

The aim of the calculations based on the oceanographic model is to estimate the steady-state concentrations that would occur at a depth of 1,000 metres. That depth is chosen in the assessment as the maximum depth to which fishing would be carried out. Most fishing is done at shallower depths, where concentrations would be lower. In the absence of horizontal advection (currents), the maximum concentrations would occur almost directly over the dump site. A steady current would alter the position of the maximum in the horizontal plane but would not significantly affect the maximum concentration level. In the Japanese model, therefore, advection terms are, for simplicity, left out of the transport equation.

The maximum concentration that would be reached at 1000 metres depends on the relative rates of horizontal and vertical diffusion. Increasing the rate at which the material spreads out horizontally reduces the maximum concentration levels that are reached. Increasing the vertical diffusion rate, however, increases the concentration levels that will occur at 1,000 metres by reducing the time available for radioactive decay. In the Japanese assessment a horizontal diffusion coefficient of 10^{7} square centimetres per second was chosen. This is within the range of values considered realistic for describing large-scale dispersion in the deep ocean (Shepherd, 1978). For the vertical diffusion coefficient a value of 200 square centimetres per second was taken. Values of this magnitude may accurately represent mixing near the seafloor in some areas (Sarmiento et al., 1976), but for transport over the entire water column, values closer to 1 square centimetre per second are considered more reasonable (Shepherd, 1978). The higher value used in the Japanese assessment was chosen partly to compensate for the absence of vertical advection (upwelling) in the model and partly as a conservative estimate to cover the possibility of short-term effects.

Table 9-5 gives the results calculated for a depth of 1,000 metres and also for the sea surface and a depth of 3,000 m. For simplicity of calculation, the different radionuclides were grouped according to half-life, and an average half-life for the group was taken. This approximation does not significantly affect the results of the calculations. The concentrations given are for a hypothetical unit rate of release of one curie per year. In the dose assessment that follows, those concentrations are then simply multiplied by the actual release rate of each nuclide. The maximum concentrations (Table 9-5) are those that would be found directly over the release point. They are used in the dose assessment to estimate

maximum individual doses that would be received by critical groups of people. The average concentrations are calculated over a sub-area of 4,000 kilometres by 4,000 kilometres, where most of the activity would occur (not over the entire area of the North Pacific). Those concentrations are used in the later calculations of collective dose. It can be seen from Table 9-5 that, as expected, (1) the concentrations increase with depth, (2) the concentration increase is greatest for the shortest-lived nuclides, and (3) the steady-state concentrations are, for a given release rate, higher for the longer-lived nuclides. In the case of the very long-lived nuclides, the build-up of concentration toward the steady-state value takes so long that there is virtually complete homogenization. Figure 9-2 illustrates the increases in time toward the steady-state maximum values, and Figure 9-3 shows how the steady-state concentrations vary in the horizontal, with the highest concentrations occurring over the point of release.

Following the estimation of the concentrations in seawater, the Japanese assessment proceeds to the estimation of doses. Individual and collective doses are calculated for fishermen working in the disposal area and for the general public. For the individual exposures it is desired to know the maximum doses that would be received by critical groups, that is, those who would be most exposed, so the individual dose calculations are based on the maximum concentrations at 1,000 metres. The purpose of those calculations is to demonstrate whether or not any individuals, even those who are most exposed, would receive unacceptable doses. The collective dose calculations, on the other hand, are an attempt to estimate the impact of the released radioactivity on whole populations. For those calculations the average concentrations at 1,000 metres are used. In the calculation of individual doses, the exposure pathways considered are similar to those used by the IAEA (Table 9-1). It is found that consumption of seafood is the most important pathway, and the collective doses are calculated for that pathway alone. Additional information supplied to the Technical Group by representatives of the Japanese Government indicated that caesium-137 and strontium-90 would be the most important radionuclides contributing to the dose from seafood ingestion.

The calculated individual doses by various exposure pathways are listed in Table 9-6. The maximum individual whole-body dose received by members of the general public is estimated to be about 0.1 microsievert per year, 10,000 times smaller than the average effective dose equivalent in the South Pacific Region from natural radiation (1000 microsievert per year, Chapter 5), and 50,000 times smaller than the ICRP limit (5000 microsievert per year). For fishermen the total exposure is estimated to be about twice as great as for the general public. Collective dose to the general public is estimated to be 4.3 man-sievert per year in Japan and 10 man-sievert per year in other countries. The Japanese report also lists doses to individual organs due to the ingestion of fish. The report concludes that the doses resulting from the proposed dumping operation would be very low.

As pointed out above, the Japanese assessment uses less conservative assumptions than does the IAEA assessment. This can be seen by comparing the radionuclide concentrations used in the two assessments for the entry points into pathways leading to human exposure. The IAEA assessment used bottom-water concentrations, which were kept high by assumption of a slow rate of vertical mixing. This is a conservative approach, because most exposure pathways probably originate in the surface layers, where concentrations would be lower. The Japanese assessment takes the more realistic approach of using the estimated maximum concentrations that would occur at 1,000 metres, though it introduces some conservatism by adopting a rather large value for the vertical diffusion coefficient (200 square centimetres per second). Figure 9-4 compares the specific concentrations that were used in the assessments. For the IAEA assessment concentrations used in both the single-site and finite-ocean calculations are shown. The single-site concentrations are higher,

and the release-rate limits more restrictive, because they include the possibility of short-term, local effects, such as formation of high-concentration plumes in the vicinity of the dumping site. The Japanese assessment also considers the possibility of such events (STA/NSB, undated (a), Appendix II) but concludes that their effects on the long-term average concentrations would be included in the assumed vertical diffusion coefficient.

Compared with the IAEA finite-ocean calculation based on estimated bottom concentrations, the Japanese assessment uses concentrations estimated for 1000 metres depth that range from fifty times lower for half-lives of one year to about three times lower for long-lived nuclides. The difference for the long-lived nuclides is due simply to the difference in ocean-basin volumes assumed in the calculations. Compared with the IAEA single-site calculation, the concentrations used in the Japanese assessment are as much as 1000 times lower for the shortest-lived nuclides. The differences reflect the conservatism in the IAEA assessment, which was aimed at estimating maximum conceivable doses to individuals or critical groups.

For the ingestion pathways leading to internal exposure, the Japanese asssessment uses lower consumption rates than does the IAEA assessment. These rates are compared in Table 9-7. The main reason for the difference appears to be that the IAEA deliberately chose consumption rates sufficiently large that for each pathway it would be unlikely that members of one critical consumption group would also be members of a critical consumption group for another type of seafood (IAEA, 1978c). Thus the release-rate limits are set on the basis of the single most limiting ingestion pathway. In the Japanese assessment, on the other hand, the doses from all the pathways were summed to give the total exposure. For exposure to fishermen the Japanese assessment assumed consumption rates three times the figures given in Table 9-7. These higher figures and the resulting higher doses for fishermen may be more applicable to some Pacific Islanders who depend heavily on seafood in their diets. The concentration factors used in the two assessments to estimate radionuclide concentrations in seafood are very similar. The Japanese assessment also uses less extreme assumptions concerning possible external irradiation from exposure to contaminated sediments than does the IAEA. (Strict application of the IAEA model to the case of the proposed Japan dumping would predict a large contribution to the total dose from cobalt-60 by external irradiation. The Japanese assessment reaches what appears to be the more realistic conclusion that seafood ingestion is the most important exposure pathway.)

It is important to emphasize again the difference in aims between the IAEA and Japan assessments. The IAEA assessment was designed to set upper limits on the permitted rates of release which, in practice, would not be approached. The Japanese assessment, on the other hand, attempts a more or less realistic appraisal of the actual impact of a specific proposed activity, though it too contains some degree of conservatism. Presumably, the purpose of the dose calculations in the Japanese report, particularly the calculations of collective doses, was to provide eventually for a means of comparing sea disposal with other options.

Criticisms of the NSB dumping proposal can be found in a report prepared by Prof. W. Jackson Davis (Davis, 1981), who has also issued other reports dealing with various aspects of ocean dumping of radioactive waste (Davis, 1980; 1982). Prof. Davis's view is that there is insufficient knowledge to guarantee the safety of ocean dumping of radioactive wastes and, for that reason, dumping should not be done. He believes that storage on land is a better alternative. His reports appear to be position papers which advocate that alternative, and it is acknowledged that they are "political not (purely) scientific documents in the conventional sense" (W. J. Davis, personal communication). The reports point out a number of the

uncertainties of present scientific knowledge about the oceans. Unfortunately, however, they do not attempt to quantify the hazards of ocean dumping (except for an erroneous calculation in Davis (1981)), nor do they consider possible hazards of the preferred land-based alternative. The Technical Group considers Davis's reports to be effective statements of the author's position, but it would caution that they are strongly biased and should not be relied upon as objective appraisals of the problem or of the present state of scientific knowledge. Nevertheless, Davis's report on the NSB proposal does raise a number of points that are worthy of consideration by those seeking an understanding of the scientific problems related to ocean dumping. We take some of those points here as a focus for the Technical Group's own comments on the Japanese proposal.

Davis's first criticism is that the proposed Japanese dumping program would violate provisions of the London Dumping Convention. He refers specifically to present fishing activities and the possibility of a future need to exploit seabed mineral deposits in the area (specifically manganese nodules). The LDC requires that these possibly conflicting uses of the ocean be considered, and the Japanese did, in fact, consider them. The proposed dumping site is at a depth of 6,000 metres, greatly below the depths at which fishing is carried out, and only a very small area on the seafloor world be occupied by the dumping site and thus made incompatible with seabed mining activities.

A more fundamental problem in satisfying the provisions of the LDC, and a more difficult one from the scientific standpoint, is the requirement that, in granting permits for dumping at sea, national authorities consider "the practical availability of alternative land-based methods of treatment, disposal or elimination ...". In its Recommendations, the IAEA elaborates on what this requirement means when radioactive materials are concerned (IAEA, 1978a, para.B.1.2):

(1) The operations should be justified by assessing their net benefits, taking into consideration the radiation consequences and possibilities of alternative procedures;

(2) The radiation protection aspects of the operation should be optimized, keeping the resulting collective doses (including their occupational and public components) as low as is reasonably achievable, economic and social factors being taken into account; and,

(3) The doses to individual members of the public should not reach the appropriate dose limits, now or in the future. In estimating the doses, account must be taken of other practices which might expose the same critical population groups.

The above requirements are based on the principles and philosophy established by the ICRP (see Chapter 4).

The requirement for optimization and comparison with alternative disposal options would require, in the final analysis, that predictions of collective doses baed on realistic assumptions be made both for ocean-based and for land-based alternatives. As we have seen in the preceding discussion, however, scientific understanding of oceanic processes and transfer pathways is not sufficient for exact predictions to be made. Davis's reports point to several areas where this is so. If one is only concerned with setting limits, it is possible to overcome these limitations by making very conservative (pessimistic) assumptions about the worst that might happen, as the IAEA has done. This is a very reasonable procedure, and the Technical Group considers the release-rate limits set by IAEA to be based on a very high degree of caution and conservatism.

The dumping rates involved in the proposed Japanese program are far below the IAEA limits, and the proposed site satisfies the general criteria set by the IAEA in its Recommendations. Thus it could easily be argued that the safety of the proposed dumping by Japan is already demonstrated by the IAEA work. The principal aim of the NSB report should be to justify the proposed operation by reference to the IAEA requirements listed above. In this respect, the present draft of the NSB report is inadequate. The dose calculation that are given, particularly for the collective doses, appear to be an approach toward more realistic estimates of doses that might actually be received, but the report contains no comparison with other alternatives.

On the basis, largely, of the work by IAEA discussed in section 9.1.1, it is the view of the Technical Group that the proposed Japanese dumping operation in the North Pacific is not a significant issue from the standpoint of environmental safety (though there may be important legal and political principles involved that are beyond the competence of the Technical Group to assess). The amounts of radioactivity to be disposed of, mostly of short half-life, are small enough that there is insignificant hazard. It is worth noting that the present inventory of, for example, fallout caesium-137 in the North Pacific (about 5×10^6 curies; Bowen et al., 1980) is being reduced at a rate of about 1.2×10^5 curies per year because of radioactive decay. The maximum caesium-137 dumping rate projected for the North Pacific site is , at 3×10^4 curies per year, lower than this. Thus even if dumping were to proceed at the maximum projected rate, the caesium-137 inventory would continue to decline until a steady-state inventory had been reached at about 1.3×10^6 curies. There would also be the difference that the highest concentrations would occur at the bottom of the ocean rather than at the surface, as they do at present.

In his evaluation of an earlier draft of the NSB environmental safety assessment, Davis (1981) arrived at the startling conclusion that the Japanese scientists had based their dose calculations on a total release rate of only one curie per year, rather than the actual dumping rate of 10^5 curies per year, and he asserted that the actual doses that would be received would be 100,000 times larger than they predicted and would exceed legal limits. The Technical Group has carefully examined the present draft translation, and it is quite clear that such an error was not made by the Japanese in their dose calculations. Professor Davis apparently misunderstood the use of one curie per year as a hypothetical unit rate of release that was, later in the calculations, multiplied by the actual rates of release of the individual radionuclides. It should perhaps be explained that this is merely a device used in the calculations to deal conveniently with the fact that each radionuclide must be considered separately and that each is assumed to be released at a different rate.

It does not necessarily follow from the above conclusion regarding the safety of the particular Japan dumping proposal that dumping of radioactive waste in the ocean should be advocated generally as a procedure to be preferred over land-based options. This cannot be clearly decided on the basis of present scientific knowledge alone. Continued objective evaluation of all the alternatives is required. The problem of the management of wastes, both radioactive and non-radioactive, will always exist, and scientific understanding of the environment will continue to be revised. The Technical Group feels it is important that policies and practices remain flexible enough to respond to changed circumstances and improved scientific knowledge. At any moment in time, policy decisions should be based on the best scientific information then available, but there will always be need in the end for the exercise of good judgment and common sense.

9.1.1.3 U.S. proposal to dispose of nuclear submarines

A proposal to use a site on the deep seafloor off the coast of California, U.S.A., for the disposal of decommissioned nuclear submarines is presently being considered, along with other options, by the U.S. Navy. (A second site, in the Atlantic off the Carolinas, is also being considered.) If this option were used, all of the spent fuel would first be removed from the reactors. However, there would still be some radioactivity contained in the reactor pressure vessels of the submarines. The radionuclides present would be due to neutron activation, during reactor operation, of the elements in the steel from which the pressure vessels and other reactor components are made. They would be mainly isotopes of manganese, iron, cobalt and nickel.

The U.S. Navy (1982) recently distributed a draft environmental impact statement in which ocean disposal and land disposal alternatives are evaluated in great detail. Public comment has been invited, and there has been no decision made on which alternative will be used. Dose rates and dose commitments that might result from both alternatives were calculated and compared. For ocean disposal, it was considered that three submarines per year would be disposed of. The total amount of radioactivity contained in each submarine six months after shutdown would be about 6.2×10^4 curies, largely consisting of cobalt-60, nickel-63 and iron-55. Release rates of the radionuclides would be limited by the rate of corrosion of the steel pressure vessel. Initially, and for up to a hundred years after sinking, there would be little or no release expected, because the reactor compartment would be sealed. This would allow for a great reduction of the initial activity by radioactive decay. It is estimated that the maximum release rate in any year from 100 ships on the seafloor would be 39 curies per year, consisting mainly of nickel-63.

Dose commitments were based on oceanographic and radiological calculations. Calculations based on what were considered realistic assumptions gave an average individual whole-body dose of 6×10^{-8} microsievert per year, an altogether trivial value. A worst case calculation, in which it was assumed that a critically exposed person would consume in one year 66 kilograms of seafood all harvested immediately at the deep disposal site, yielded a dose of 20 microsievert per year, also a small value. Seafood consumption would be the most important pathway and nickel-63 the most important contributor to the dose. It can be concluded that the amounts of radioactivity released and the resulting doses received by people would be insignificant by comparison to other radioactivity inputs and radiation doses in the South Pacific Region.

9.1.2 Sub-seabed Emplacement of High-Level Radioactive Waste

High-level radioactive wastes are presently accumulating in a number of countries around the world where nuclear reactors are in operation (Figure 9-5). They result from the nuclear fission process (Chapter 3) and accumulate in the reactor fuel elements. After a reactor has been operating for a period of time, the fuel elements must be replaced. At that point the spent fuel elements may either be disposed of (throwaway fuel cycle) or reprocessed to extract the remaining uranium and plutonium for further use as fuel. Reprocessing also generates high-level wastes consisting mainly of fission products with some residual uranium, plutonium and other transuranic elements (Chapter 3, section 3.11).

The problem of managing high-level radioactive waste is larger by order of magnitude than the corresponding low-level waste problem. One estimate places the accumulated amounts to be disposed of by the year 2000 at 9×10^8 Ci of actinides and 1×10^{14} Ci of fission products from worldwide electric power production (Grimwood and Webb, 1976).

Dispersion of such quantities of radioactivity in the environment is not acceptable, so strategies of isolation must be pursued, unlike the case of low-level waste where it is considered that small releases to the environment may be permissible. It is generally considered that high-level radioactive wastes must be isolated from the biosphere for at least 10^4 years and perhaps as long as 10^6 years, depending on how the potential hazard is quantitatively defined. In the United States a review group appointed by President Carter advised that the responsibility for keeping the wastes isolated should not be left to future generations (Interagency Review Group, 1979). The length of time is simply too long to expect institutional barriers to remain effective. Thus a requirement is that waste repositories be located in sites that are unlikely to be breached, either intentionally or accidentally, by future human activities. This rules out indefinite storage as a long-term waste-management strategy.

Emplacement of high-level radioactive wastes within the sediments of the deep sea is one of several geologic disposal options being considered by the US and other nations. Other geologic media receiving serious attention are basalt, salt, shale, granite, and other types of crystalline rocks. The major effort in the US is directed toward the potential land-based repositories, but since 1973, the Department of Energy has also funded a project to evaluate the feasibility of burial within the deep ocean floor. This project, known as the Subseabed Disposal Program, is coordinated by Sandia National Laboratories. Several accounts of the program are available in the published literature (Anderson et al., 1975; Hollister, 1977, 1981; Hollister et al., 1981; Hinga, 1982; Hinga et al., 1982), and a status report for 1983 is soon to be available (Sandia National Laboratories, 1983). Investigations of the sub-seabed disposal concept are also being carried out in other countries, and an international Seabed Working Group (SWG) has been established under the auspices of the OECD/NEA. The members of the SWG are Canada, the Commission of European Communities, the Federal Republic of Germany, France, Japan, the Netherlands, Switzerland, the United Kingdom and the United States. Through its annual meetings the SWG promotes exchange of information and provides for a continuing review of the sub-seabed disposal option by a large number of scientists.

Consideration of the sub-seabed alternative has focussed on the so-called mid-plate, mid-gyre (MPG) regions of the ocean (Bishop and Hollister, 1974). The plates referred to are the slabs into which the lithosphere (the outer shell of the earth, consisting of brittle rock) is divided (Figure 9-6). At the boundaries between lithospheric plates, violent phenomena such as earthquakes and volcanic eruptions are likely to occur as new oceanic crust is formed (at the mid-ocean ridges) or destroyed (at oceanic trenches), or as the plates slide past each other. Conditions away from the plate boundaries, on the other hand, are relatively quiescent, and the mid-plate regions under the oceans are known to be the most seismically stable (that is, free of earthquakes) areas on earth. Records of the past several million years contained in the sediments of MPG regions show a relative constancy of conditions on the deep-sea floor compared with the situation on land, where drastic changes in climate were felt (Corliss et al., 1982). Additionally, with regard to sedimentation, mid-ocean regions are in general depositional environments, whereas continental areas are generally erosional. These aspects of geological stability and predictability are the main scientific reasons for considering the mid-plate oceanic areas as possible waste repositories. The gyres referred to above are the large-scale systems of ocean circulation. Mid-gyre areas are considered to be potentially the most acceptable sites, because they are where the least biological activity is found. This would add a level of safety, but is probably a less important criterion since the strategy is one of isolation, not dispersion. Other technical criteria that appear to be filled by MPG sites are remoteness from human activities and limitation of exploitable resources compared with other places on earth.

Possible methods of emplacing the wastes beneath the seafloor are illustrated in Figure 9-7. Containment of the waste and isolation from the biosphere are based on the multiple barrier concept illustrated in Figure 9-8. Much of the present research is aimed at determining the time it would take for radionuclides to pass through the multiple barriers and to decide whether that time is long enough for the waste to decay to negligible levels. Present thinking is that emplacement within the unconsolidated sediments, at a depth of some 30 - 100 metres below the seafloor would probably be safer than emplacement within the underlying basement rocks, whose permeability is still not very well known. The sediments themselves are considered to be the principal barrier to migration, because water flows through them very slowly, and migration of radionuclides is retarded by adsorption on the sediment grains.

Survey work in connection with the Subseabed Disposal Program is being conducted in five study regions located in the North Atlantic and North Pacific (Figure 9-9). The purpose of the surveys is to determine whether candidate sites within those regions meet a number of selection criteria related to (1) geological stability, (2) suitability of the sediment to serve as a barrier and (3) avoidance of shipping lanes, communication cables, strong currents, inclement weather and areas with plausible future economic resources.

At present the Subseabed Disposal Program continues to examine the scientific and environmental feasibility of the concept. Some of the important, but as yet unanswered, scientific questions relate to the effects that the heat generated in the waste canisters by radioactive decay would have on (1) the properties of the surrounding sediment, (2) the migration of radionuclides within the interstitial waters of the sediment and (3) the uptake of radionuclides by adsorption on the sediment grains. The question of hole closure, that is, whether or not the hole that is formed during emplacement of a canister will seal itself, thus preserving the barrier, is also among the more important questions remaining to be answered. The feasibility phase of the program is due to run until 1988 (Hinga et al., 1982). If technical feasibility is established by that time, then the engineering development phase is scheduled to follow. It is not known when actual disposal operations might begin, but they would not likely begin until well into the next century, possibly in 25-30 years. In the meantime it would be necessary to establish international agreements and regulatory mechanisms for controlling the operations. Legal and political barriers to implementation of the sub-seabed disposal concept are expected to be quite formidable (Deese, 1977; 1978).

It is too soon yet for anyone to conclude whether or not sub-seabed disposal of high-level radioactive waste would be a safe or practical procedure. Several more years of scientific research are needed before it will be possible to give an informed opinion on that question. It is the view of the Technical Group that scientific research and evaluation of all the competing options for waste management should continue with the aim of finding the best solution, always, of course, subject to review within the scientific community and continued public scrutiny.

9.1.3 Nuclear Waste Storage

In addition to the proposed waste-disposal activities that are now under study and may occur in the South Pacific Region, there is also a recently announced proposal to use Palmyra Island, or possibly other Pacific islands, such as Wake or Midway, as sites for the construction of above-ground, interim storage facilities for high-level nuclear wastes (Van Dyke et al., 1983; Finn, in press (a, b)). According to the proposal, spent nuclear fuel from Japan, Korea and Taiwan would be stored there temporarily while permanent disposal strategies are being developed. The US

and Japan have an agreement to carry out a joint study of the plan.

This proposed activity does not, of course, involve any planned releases of radionuclides to the environment, but one must consider the possibility of accidental releases on the island during the storage period, at sea in case of maritime casualty or in seaports as the result of mishaps during loading or unloading of the waste. The Technical Group has not examined any official or scientific documents relating to the proposed waste storage plan and is thus not able at this time to comment on the hazards that might be associated with it. In view of the large quantities of radioactive material that would be involved, it is essential that a careful study, including quantitative assessments of radiation doses that might be received by people in the event of an accidental release, be carried out.

9.2 NUCLEAR WEAPONS TESTING

At present the US, USSR, France, and Peoples' Republic of China have active programs for the testing of nuclear weapons. In 1963 the US, UK and USSR signed a test-ban treaty which prohibits testing of nuclear weapons in the atmosphere. Since then, tests by those countries have all been conducted underground. France and China were not signatories to the treaty, and both countries conducted a number of explosions above ground after 1963, though not on a large scale compared to the tests conducted by the US and USSR prior to that time. Between 1966 and 1974 France conducted 41 atmospheric tests at its Centre d'Experimentation du Pacifique (CEP) in the Tuamotu Islands (Journal des Forces Armées, 1982). Since 1974 all French testing has been conducted underground, and in recent years only China has conducted nuclear explosions above ground.

The testing of nuclear explosives underground avoids pollution of the atmosphere by radioactive debris and is considered to be a safer procedure, with regard to human health, than is atmospheric testing. This is unquestionably true on the global scale and for the short term, because the radioactive material is contained within the underground cavity rather than being dispersed worldwide. However, one cannot be certain about the long-term effects that might arise in the vicinity of an underground testing site without considering a number of questions that cannot presently be answered. Referring primarily to the US and USSR programs of underground testing, Eisenbud (1973) stated: "Whether the underground accumulations of radioactive debris will in time prove significant as a form of environmental pollution remains to be seen. The quantities of debris so involved are huge, but objective evaluation of potential long-range risks has not been possible because little of the basic data have been made available". The same problem limited the Technical Group's ability to judge the situation in the South Pacific Region. The information available on the subject is limited because of the secrecy that surrounds military activities, especially programs of weapons development.

It is the policy of the French Government not to announce its nuclear weapons tests, and most of the available information regarding them comes from reports made by other countries when the explosions are detected. According to unofficial information given in Journal des Forces Armées (1982), between 1975 and 1982 aproximately 50 tests were carried out underground at CEP, mostly on the atoll of Mururoa.

The Technical Group received information provided by the French Government concerning the procedures used at CEP (DIR CEN 3044, dated 24 June 1982). The underground tests are conducted at the bottom of vertical shafts 1.5 metres in diameter at depths ranging from 500 to 1100 metres, depending on the expected yield

of the explosion (usually between 1 and 100 kilotons). The bottom of the shaft is always below the upper layer of limestone (a highly permeable type of rock) and within the underlying basalt (a dense and less permeable type of rock). Before the explosion, the shaft is sealed with several hundred metres of cement alternating with layers of aggregate, to contain the explosion within the basalt. In the past the shafts were bored on the rim of the atoll, but in the future they are to be bored within the lagoon at distances of more than 1.2 kilometres from the periphery. This change is being made for greater safety.

In order to estimate the amounts of radioactivity produced during the tests, it is necessary to know the fission and fusion yields of the explosions. That information is not available although it is generally considered that explosions of yields less than 100 kt are purely fission explosions, UNSCEAR (1982) estimated the total fission and fusion yields for the 1966-1974 period of atmospheric testing at CEP (Table 6-1). The yields in individual years were highly variable, but the average for the period was about 1 megaton per year each of fission yield and fusion yield. Extrapolation of those averages into the underground testing period, for which actual data are unavailable, allows some approximation to be made of how much radioactivity might be produced in an average year. For one megaton of fission yield, 1×10^5 curie of strontium-90 and 1.6×10^5 curie of caesium-137 are produced (Klement, 1965). In addition the large quantities of neutrons released would yield a variety of activation products in the surrounding rock. Estimates of the amounts of activation products formed by underground explosions were made by Miskel (1964) in connection with the US Plowshare program, which investigated the feasibility of peaceful uses of nuclear explosions. The estimates were for a one-megaton device (99 percent fusion) exploded in basalt. Most of the activation products would be short-lived, with half-lives measured in hours or days, but significant quantities of longer-lived tritium (half-life 12 years) and iron-55 (half-life 2.7 years) would also be produced (1×10^7 curie of tritium and 7.5×10^5 curie of iron-55). The amounts calculated were based on the assumption of a boron absorber surrounding the device, which would reduce the neutron flux by a factor of about 100. In the absence of such an absorber, the amounts of activation products formed would be much larger.

An additional calculation can be carried out to give some perspective on the amounts of artificial radionuclides that might be produced during the French underground testing. During the year 1981, the 261 nuclear power reactors in operation developed a total of 144×10^9 electric watts, which corresponds to a total energy production of about 15×10^{18} joules. On the basis of one megaton per year and 4.55×10^{15} joules per megaton, the French programme of underground tests would contribute approximately 0.03 percent of the total global production of artificial radionuclides.

The above are crude approximations, but it will be seen that although the amounts of radioactivity produced by the underground tests are not especially large by comparison with global production rates, neither can they be regarded as negligible. However, as long as they remain in place within the rock, the radionuclides are harmless to people or any other part of the biosphere. In order to evaluate the possible environmental hazards associated with the underground explosions, what needs to be known is whether or not some of the radionuclides will be released to the ocean as the result of leaching by any seawater that percolates through the rock. This cannot be determined with presently available data. More information is needed on the hydrological situation of the atoll and the permeability and other properties of the rock related to its suitability as a containment medium for the radionuclides that are produced. There have been reports in the news media of possible structural damage to the island and releases of radioactivity to the ocean, but the Technical Group has been unable to obtain any official documentation of these events.

It is the view of the Technical Group that the amounts of radioactivity likely to be produced as the result of the French underground explosions are not large enough to be cause for alarm but that they are large enough to warrant serious concern, especially if the testing program and the accumulation of radionuclides at the underground site are to continue long into the future.

If comparable amounts of radioactive waste were to be produced as the result of a civilian undertaking, and if the wastes were destined for disposal in one of the technologically developed countries in which such an activity was carried out, there would, in most countries, be considerable public concern and a requirement that an environmental impact assessment be conducted, and released for public scrutiny and scientific review, before the undertaking began operation. This was not done in the case of the French military testing program in the Tuamotus. However, it is noted that a scientific mission led by Haroun Tazieff was recently sent by the French Government to investigate the safety of Mururoa and its environment. The report of that group is to be published soon, but it was not available for consideration by the Technical Group.

The Technical Group believes that a careful environmental assessment of the potential long-term effects of underground testing at CEP is needed to evaluate the continued suitability of the site. A carefully designed monitoring of the ocean in the vicinity of the testing site is also needed to determine whether any significant releases of radioactivity are presently occurring. Tritium is likely to be the most sensitive indicator of this, because it is produced in abundance and is the nuclide that, because of its chemical properties, is most likely to escape. In this connection, a survey would need to be designed very carefully to establish regional background levels, because much tritium has already been added to the ocean from the atmosphere. Samples from the 500-1000 metre depth range would be especially important, because they would be expected to contain tritium from any sub-surface releases that might be occurring, and because little of the tritium from the atmosphere has yet penetrated to those depths in the ocean (see Chapter 8). Thus the background tritium concentrations at those depths are very low. It should be emphasized that very careful scientific interpretation of the data obtained in such a survey would be necessary to determine whether any measured tritium is due to a sub-surface release or merely due to the background. Because tritium would probably be the most sensitive indicator of any sub-surface release of radioactivity from the atoll, measurements of other radionuclides would be relatively unimportant unless positive results were obtained from the tritium monitoring.

Further information is also required on the geological and the hydrological properties of the atoll, as possibly modified by the explosions. This information would allow the assessment of the possibility of future releases. If the possible rates of release and depths of release to the ocean were known, then presently available radiological assessment methods, along the lines of those discussed in Section 9.1 above, could be employed to estimate doses that might be received by people and to give an objective evaluation of the environmental impact.

It is the position of the French Government that no release occurs and that there are consequently no doses received by people as the result of underground testing. This may indeed prove to be true for normal operations, but it is not unreasonable to inquire about the effects of possible accidents. It would be desirable to know whether the French Government has considered any worst-case scenarios and, if so, whether it has estimated the doses that might result from them.

The Technical Group urges that any scientific data relating to environmental safety in the vicinity of Mururoa, whether it is presently held by the French Government or

obtained in future surveys, be promptly published and distributed to Governments in the Region.

As an example of the type of scientific data which should be published, reference is made again to the decision by France to conduct future underground nuclear tests at CEP in shafts bored within the lagoon. The Technical Group believes that the decision could only have been taken after a thorough scientific evaluation of the need for the change. The Technical Group urges prompt publication of this scientific evaluation and its distribution to Governments in the Region.

9.3 OTHER ACTIVITIES

A number of additional sources, or potential sources, of artificial radioactivity in the South Pacific Region should be considered. In general the releases of radioactivity from these sources are likely to be small, or, in the case of accidents, unpredictable, and only brief mention of them is made here.

There do not presently appear to be any plans for development of nuclear electric power generating facilities among countries in the South Pacific Region, but such facilities do exist in several countries around the rim of the Pacific, such as the US, Japan, Korea, Taiwan and the Philippines (Figure 9-6). During the production of power by a nuclear reactor, radioactive fission products are formed within the fuel, and neutron activation products are formed within the structural and cladding materials. Radionuclides are found in the coolant water because of activation of impurities in the water itself, because of escape of fission products from the small fraction of the fuel elements with defective cladding, and because of corrosion of the structural and cladding materials. All reactors have treatment systems for the removal of radionuclides from gaseous and liquid wastes, and the low-level releases which occur are monitored and can be controlled at the source. At coastal installations, liquid effluents are discharged to the ocean. The quantities of radionuclides involved are very small and, except at locations very close to the point of discharge, they cannot be detected above levels attributable to worldwide fallout from atmospheric nuclear tests.

Naval propulsion reactors are used on submarines and other warships. Contaminated coolant waters containing small amounts of cobalt-60 and other radionuclides are discharged in harbors, and the demineralizer resins used to decontaminate the coolant are sometimes dumped at sea.

Recently the US and Japan have announced plans to expand existing nuclear reprocessing activities, the US to resume plutonium production at Hanford, Washington, and Japan to scale up commercial spent fuel reprocessing similar to that currently conducted at Tokai Mura (Finn, in press (a,b)). These activities would lead to small coastal discharges that could affect limited areas.

Finally one must consider the possibility of accidental releases of radioactivity to the environment that could conceivably occur during any of the operations in which radioactive materials are handled. The Technical Group has not reviewed this subject in any detail, but notes that it is an important part of the assessments that are being made of possible waste-disposal activities (STA/NSB, undated (a); Sandia National Laboratories, 1983).

TABLE 9-1

PATHWAYS AND MODES OF EXPOSURE CONSIDERED IN IAEA RADIOLOGICAL BASIS

Pathway	Mode of Exposure
Fish consumption	Ingestion
Crustacea consumption	Ingestion
Mollusc consumption	Ingestion
Seaweed consumption	Ingestion
Plankton consumption	Ingestion
Exposure from shore sediments	External irradiation
Exposure from fishermen's gear	External irradiation
Suspension of sediments	Inhalation
Evaporated from sea water	Inhalation
Desalinated water consumption	Ingestion
Sea salt consumption	Ingestion
Swimming	External irradiation

Source: IAEA (1978c)

TABLE 9-2

RECOMMENDED RELEASE RATE LIMITS (CURIES PER YEAR)

	Single Site	Finite Ocean Volume (10^{17} m^3)
Group A ^{226}Ra and very long lived beta-gamma emitters (based on ^{226}Ra)	10^4	10^4
Most alpha emitters and transuranics plus ^{14}C and ^{210}Pb (based on ^{239}Pu)	10^5	10^5
Group C ^{90}Sr, ^{137}Cs and most beta/gamma emitters (based on ^{90}Sr)	10^7	10^8
Group D Tritium and short-lived beta/gamma emitters (based on tritium)	10^{11}	10^{12}

Source: IAEA (1978b)

TABLE 9-3

	Total amounts dumped (assuming no decay took place)	Maximum dumping rate in one year	Average dumping rate	IAEA release rate limits (a)	Percent of IAEA release rate limit
	Ci	Ci/y	Ci/y	Ci/y	Ci/y
Alpha activity	8.3×10^3	1.4×10^3	750	10^5	0.8
Alpha activity (Ra-group)	100 (b)	10 (b)	10 (b)	10^4	0.1
Beta/gamma activity (ex. tritium)	2.5×10^5	4.3×10^4	3.6×10^4 (c)	10^7	0.3
Tritium	2.6×10^5	1×10^5	4.3×10^4 (d)	10^{11}	$<<$ 0.1

(a) IAEA (1978a)
(b) Estimate, no detailed information available over all years
(c) Average over 1975-1979
(d) Average over 1974-1979

Source : OECD/NEA (1980)

TABLE 9-4

RADIONUCLIDE DUMPING RATES ASSUMED AS UPPER LIMITS IN THE JAPANESE ASSESSMENT AND COMPARISON WITH IAEA (1978 a) RELEASE-RATE LIMITS FOR A SINGLE DUMPING SITE

Radionuclide	Percent of Total Activity in Dumped Waste	Assumed Japan Dumping Rate (Ci/yr)	IAEA Rate (Ci/yr)
^{3}H	0.02	20	10^{11}
^{54}Mn	30	3×10^{4}	
^{60}Co	30	3×10^{4}	
^{90}Sr	10	1×10^{4}	
^{106}Ru	0.2	2×10^{2}	
^{137}Cs	30	3×10^{4}	
^{144}Ce	0.1	1×10^{2}	
Total beta/gamma	$\sim$ 100	$\sim 10^{5}$	10^{7}
^{226}Ra	0.00001	1×10^{-2}	10^{4}
^{238}U	0.01	10	
^{239}Pu	0.01	10	
Total alpha (except ^{226}Ra)	0.02	20	10^{5}

TABLE 9-5

CONCENTRATIONS OF RADIONUCLIDES IN A STEADY STATE FOR THE CONTINUAL DISPOSAL OF 1 CI PER YEAR

Unit: (Ci/cm^3)

Radionuclide	Decay constant(1) (1/year)	Maximum concentration (2)			Average concentration (3)		
		Sea surface	Depth 1 km	Depth 3 km	Sea surface	Depth 1 km	Depth 3 km
^{54}Mn ^{65}Zn ^{106}Ru ^{144}Ce	0.7	$7.8x10^{-24}$	$1.9x10^{-23}$	$2.9x10^{-22}$	$5.5x10^{-25}$	1.1x10	$1,3x10^{-23}$
^{55}Fe ^{60}Co	0.2	$9.3x10^{-23}$	$1.5x10^{-22}$	$8.2x10^{-22}$	$1.2x10^{-23}$	1.7x10	$5,1x10^{-23}$
^{3}H	0.06	$3.6x10^{-22}$	$4.7x10^{-22}$	$1.4x10^{-21}$	$8.2x10^{-23}$	9.4x10	$1,6x10^{-22}$
^{90}Sr ^{137}Cs	0.02	$7.6x10^{-22}$	$9.1x10^{-22}$	$2.0x10^{-21}$	$2.2x10^{-22}$	2.8x10	$3,6x10^{-22}$
^{226}Ra ^{239}Pu	$2.8x10^{-5}$				$1.0x10^{-19}$	Homogeneous concentration (4)	

(1) Decay constant = 0.693/half-life.
(2) Maximum concentration of radionuclide in the calculation area (4,000 km x 4,000 km) at the defined depths.
(3) Average radionuclide concentration at the defined depths.
(4) The steady-state equilibrium concentration which, for long-lived radionuclides, is uniform throughout the ocean.

Source: STA/NSB (undated (a)), p. 29

TABLE 9-6

THE RADIATION DOSE TO THE PUBLIC DUE TO SEA DISPOSAL

(Unit: microsievert/year)

Pathway	general public	fishermen
1. Internal Exposure	0.1	0.2
(1) Fish consumption	0.05	0.08
(2) Invertebrate consumption	0.01	0.02
(3) Seaweed consumption	0.04	0.07
(4) Others	0.02	0.04
2. External Exposure	0.005	0.04
Total	0.1	0.2

Source: STA/NSB (undated (a)), p. 50, extracted from Table 4.4

TABLE 9-7

CONSUMPTION RATES OF FISH AND OTHER MARINE PRODUCTS ASSUMED IN JAPANESE (STA/NSB, undated (a)) AND IAEA (1978c) RADIOLOGICAL ASSESSMENTS

Product	Consumption Rate (g/day) Japan	IAEA
Fish	200	600
Invertebrate	20	200[+]
Seaweed	40	300
Plankton	10	30
Desalinated seawater	2000	2000
Sea salt	3	3

[+] Crustacea consumption (100 g/day) plus mollusc consumption (100 g/day)

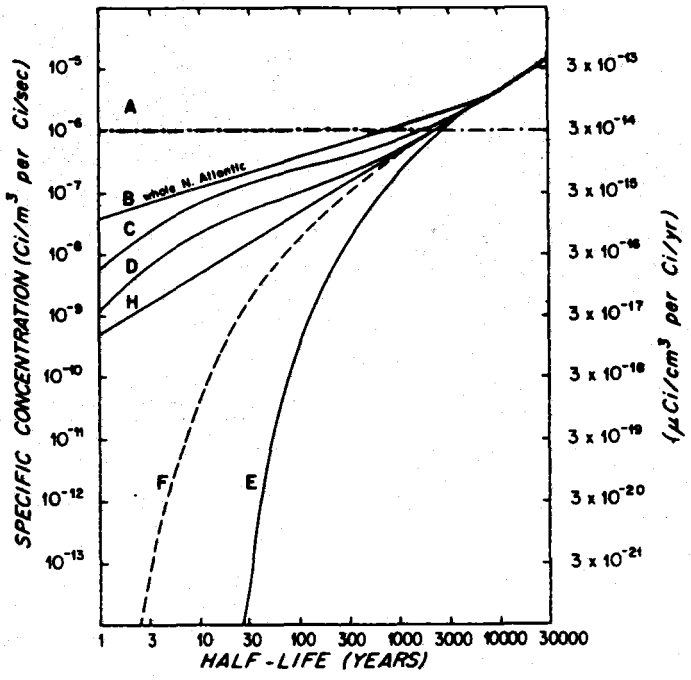


Figure 9-1. Estimates of concentrations of radioactivity in water, per unit rate of release, by various methods, based on an ocean-basin volume of 10^{17} m^3. After IAEA (1978b).

KEY

A Short term processes (strong advection, deep convective mixing) affecting single sites

B Shepherd one-dimensional model, bottom concentration, 5000-yr vertical mixing time

C Shepherd three-dimensional model, bottom concentration, 4000-yr vertical mixing time

D Shepherd three-dimensional model, bottom concentration, 400-yr vertical mixing time

E Shepherd three-dimensional model, surface concentration, 4000-yr vertical mixing time

F Shepherd three-dimensional model, surface concentration, 400-yr vertical mixing time

H Well mixed average

Source: Shepherd, (1978).

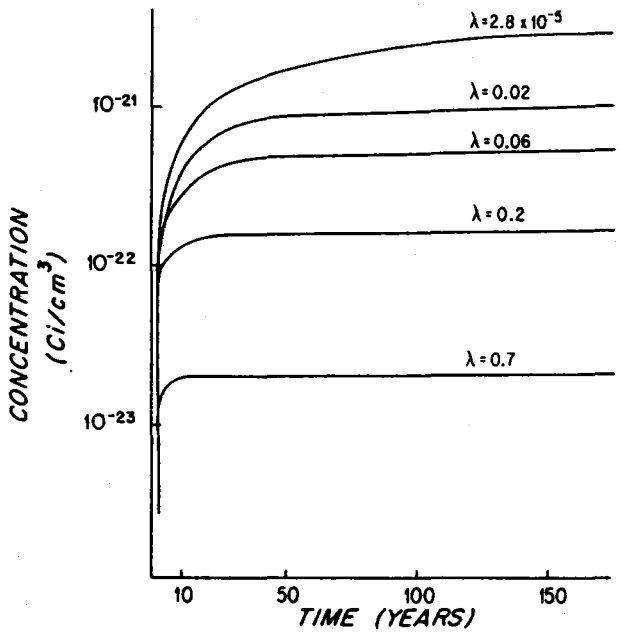


Figure 9-2. Yearly changes of the radionuclide concentrations at 1 km depth for the continual disposal of 1 Ci per year, calculated from the Japanese oceanographic model. Horizontal and vertical eddy diffusion coefficients were taken to be 10^7 and 200 cm^2/sec, respectively. Decay constant (λ) 0.693/half-life. Source: STA/NSB (undated (a)), p. 32.

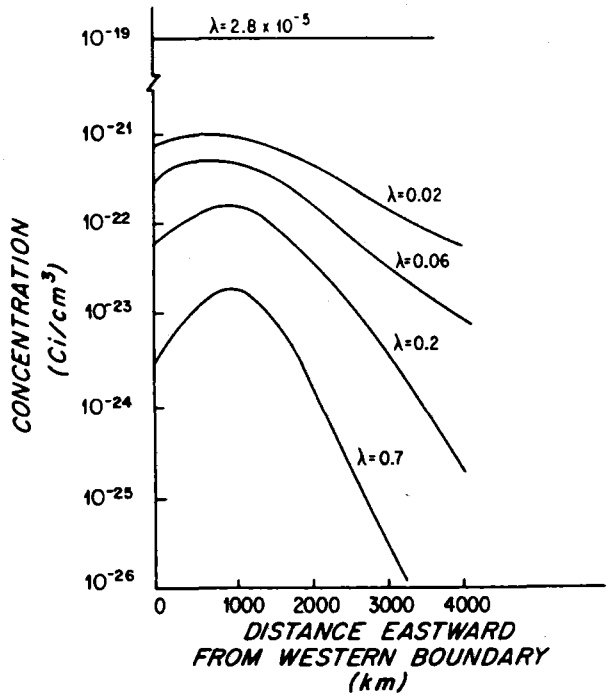


Figure 9-3. Horizontal distribution of radionuclide concentrations at 1 km depth in a steady state for continual disposal at 1 km depth in a steady state for continual disposal of 1 Ci per year, calculated from the Japanese oceanographic model. Horizontal and vertical eddy diffusion coefficients were taken to be 10^7 and 200 cm^2/sec, respectively. Decay constant (λ) 0.693/half-life. Source: STA/NSB (undated (a)), p. 33.

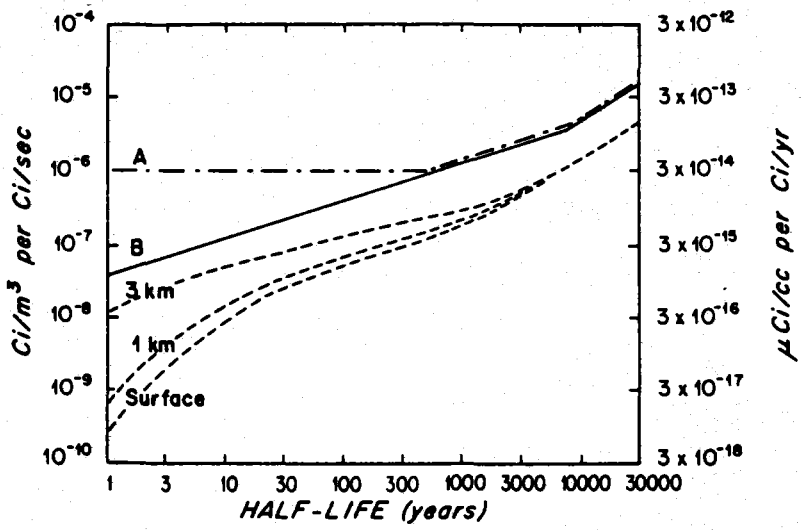
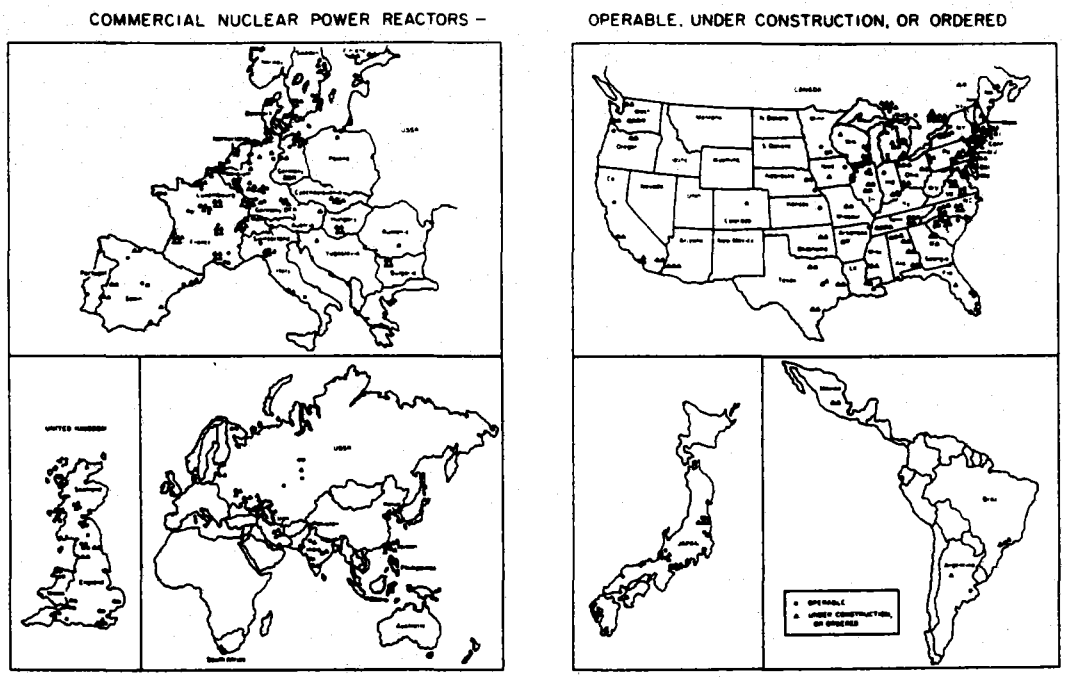


Figure 9-4. Comparison of seawater concentrations of radionuclides used in IAEA basis (curves A and B; cf. Figure 9-1) and maximum concentrations calculated from Japanese oceanographic model (lower dashed curves, sketched from information in Table 9-5).



Adopted from data supplied
by Nuclear News, September 1976,
and from U.S. ERDA.

Figure 9-5. Source: Deese (1977), pp. 56-57.

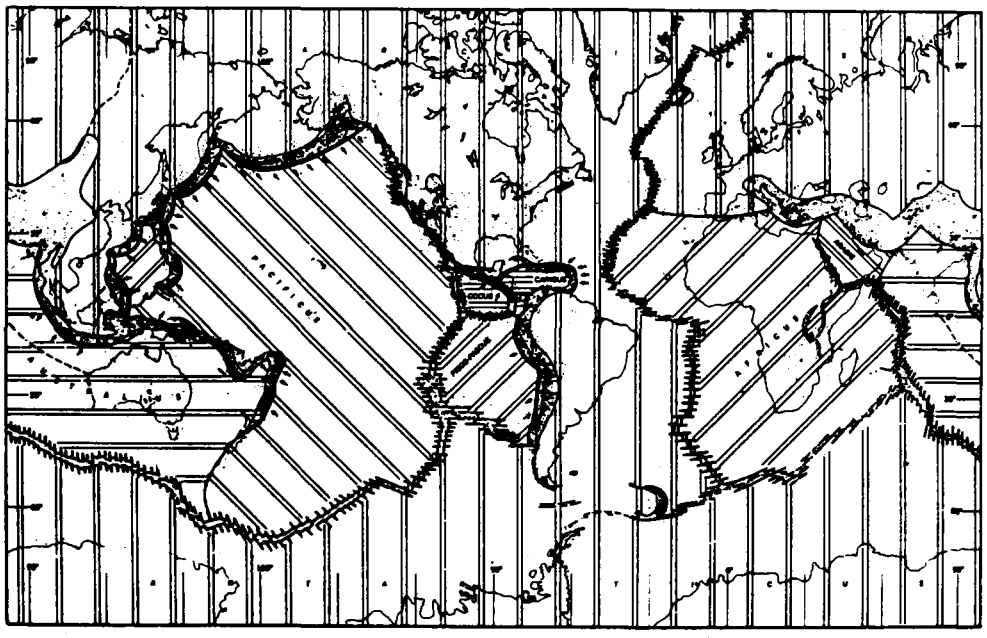


Figure 9-6. Plate tectonic map of the world. The plates of the world are in motion relative to one another. They are either slowly moving apart, with the creation of new crust, moving together with the destruction of old crust, or moving past one another. Source: Heezen and Hollister (1971).

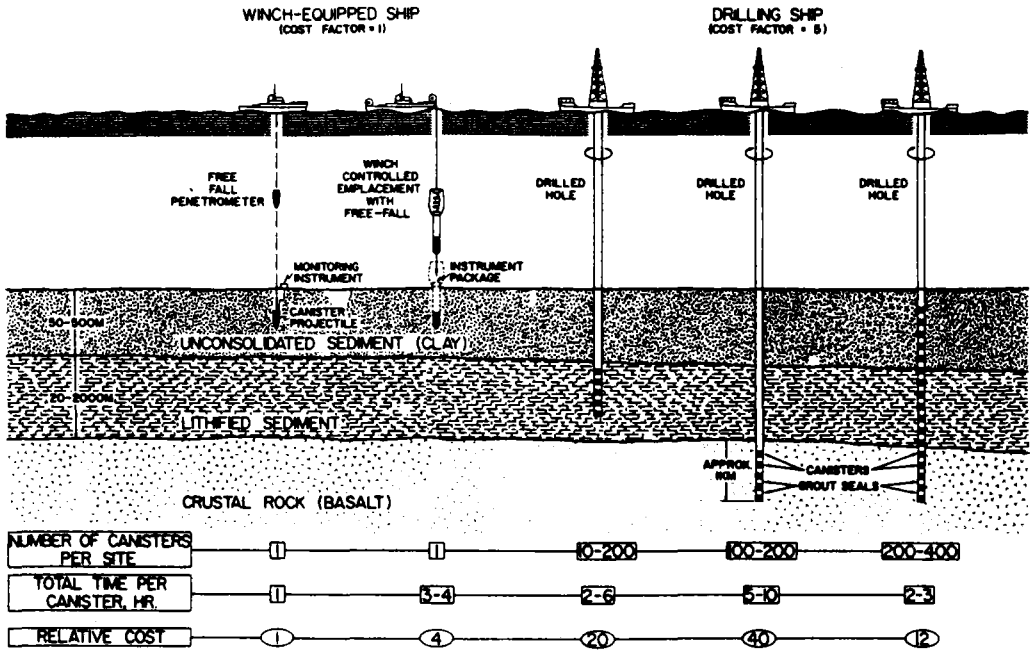


Figure 9-7. Engineering concepts for emplacement of radioactive waste canisters in the seabed. Source: Silva (1977).

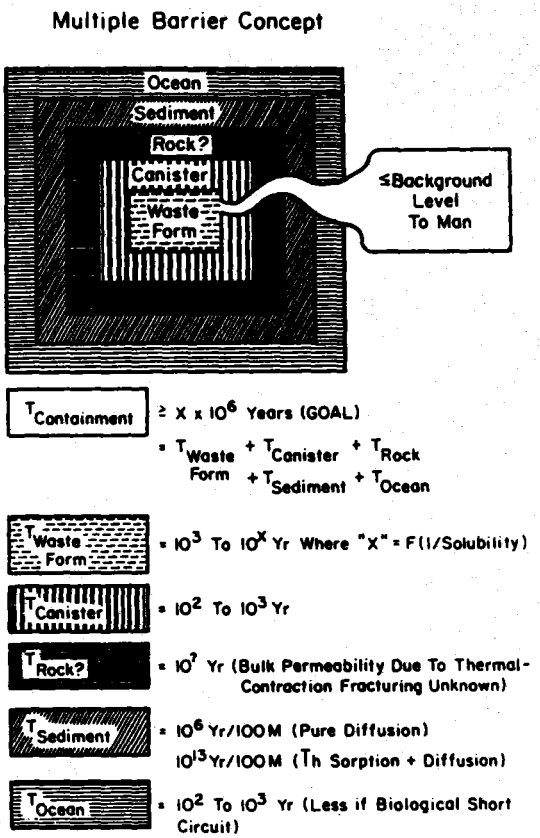


Figure 9-8. Diagram of the seabed containment model. Note that the sediment barrier appears to be the most promising with respect to breakthrough time. Source: Hollister (1977).

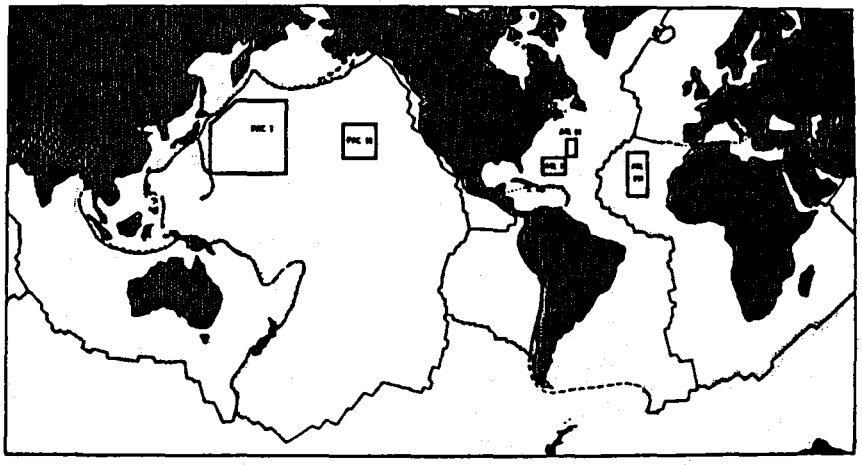


Figure 9-9. Study regions, Subseabed Disposal Program. Source: Sandia National Laboratories (1983)

9.4 REFERENCES

Anderson, D. R., W. P. Bishop, V. T. Bowen et al., 1975. Release pathways for deep seabed disposal of radioactive wastes. In: Impacts of Nuclear Releases into the Aquatic Environment, IAEA, 483-504.

Bishop, W.P. and C.D. Hollister, 1974. Seabed disposal - where to look. Nuclear Technology, 24: 425-443.

Bowen, V.T., V.E. Noshkin, H.D. Livingston and H.L. Volchok, 1980. Fallout radionuclides in the Pacific Ocean: vertical and horizontal distributions, largely from GEOSECS stations. Earth Planet. Sci. Lett., 49: 411-434.

Corliss, B.H., C.D. Hollister et al., 1982. A palaeoenvironmental model for cenozoic sedimentation in the central North Pacific. In: The Ocean Floor, R.A. Scrutton and M. Talwani (Eds.), Wiley, 277-304.

Curtis, C. E., 1983. Ocean dumping nations vote radwaste suspension. Oceanus, 26: 76-78.

Davis, W. J., 1980. Radioactive Dumpsites in U.S. Coastal Waters. September 15, 52 pp.

Davis, W. J., 1981. The Proposed Japanese Oceanic Nuclear Waste Disposal Program: a Scientific Analysis. May 1, 64 pp.

Davis, W. J., 1982. Evaluation of Oceanic Radioactive Dumping Programs. Draft Report, July, 167 pp.

Deese, D. A., 1977. Seabed emplacement and political reality. Oceanus, 20: 47-63.

Deese, D. A., 1978. Nuclear Power and Radioactive Waste: A Subseabed Disposal Option. Lexington Books, 106 pp.

Eisenbud, M., 1973. Environmental Radioactivity, 2nd edition. Academic Press, New York, 542 pp.

Finn, D. P., in press(a). Nuclear waste management activities in the Pacific Basin and regional cooperation on the nuclear fuel cycle. Ocean Development and International Law, 13.

Finn, D. P., in press(b). Radioactive waste disposal in the Pacific Basin and international cooperation on nuclear waste management. In: The Emerging Marine Economy of the Pacific, C. Gopalakrishnan (Ed.), Ann Arbor Science.

Foster, R. F., I. L. Ophel and A. Preston, 1971. Evaluation of human radiation exposure. In: Radioactivity in the Marine Environment, National Academy of Sciences (USA), 240-260.

Grimwood, P. D. and G. A. M. Webb, 1976. Assessment of the Radiological Protection Aspects of Disposal of High Level Waste on the Ocean Floor. National Radiological Protection Board (UK) Report NRPB-R48, Harwell, 117 pp.

Heezen, B.C. and C.D. Hollister, 1971. The Face of the Deep. Oxford University

Press.

Hinga, K. R., 1982. Ocean research conducted for the subseabed disposal program, EOS Trans. Am. Geophys. Un., October 5, 63: 802-803.

Hinga, K. R., G. R. Heath, D. R. Anderson and C. D. Hollister, 1982. Disposal of high-level radioactive wastes by burial in the sea floor. Env. Sci. Tech., 16: 28A-37A.

Hollister, C. D., 1977. The seabed option. Oceanus, 20: 8-25.

Hollister, C. D., 1981. A review of current science and technology for disposal of high-level radioactive wastes within geological formations of the deep seabed. In: Nuclear Waste Management: the Ocean Alternative, T. C. Jackson (Ed.), Pergamon Press, New York, 56-69.

Hollister, C. D., D. R. Anderson and G. R. Heath, 1981. Subseabed disposal of nuclear wastes. Science, 213: 1321-1326.

Interagency Review Group on Nuclear Waste Management, 1979. Report to the President, TID-29442, Washington (cited in Hinga et al., 1982).

International Atomic Energy Agency (IAEA), 1978a. Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter: the Definition Required by Annex I, Paragraph 6 to the Convention, and the Recommendations required by Annex II, section D. IAEA Information Circular INFCIRC/205/Add. 1/Rev. 1.

International Atomic Energy Agency (IAEA), 1978b. The Oceanographic Basis of the IAEA Revised Definition and Recommendations Concerning High-level Radioactive Waste Unsuitable for Dumping at Sea. IAEA Technical Document IAEA-210, Vienna, 59 pp.

International Atomic Energy Agency (IAEA), 1978c. The Radiological Basis of the IAEA Revised Definition and Recommendations Concerning High-level Radioactive Waste Unsuitable for Dumping at Sea. IAEA Technical Document IAEA-211, Vienna, 58 pp.

Ishihara, T., 1980. Low-level radioactive waste management. Atoms in Japan, August, 24: 11-17.

Journal des Forces Armées, 1982. Terre-Air-Mer, December 17.

Klement, A. W., 1965. Radioactive fallout phenomena and mechanisms. Health Phys., 11: 1265 (cited in Eisenbud, 1973).

Ministry of Agriculture, Fisheries and Food (MAFF), 1980. Report of Ad Hoc Working Group Meeting on Co-ordination of Research Related to the Control of Deep Sea Disposal of Low-level Radioactive Waste. MAFF Directorate of Fisheries Research, Lowestoft, UK, Internal Report No. 7, 24 pp.

Miskel, J. A., 1964. Charateristics of radioactivity produced by nuclear explosives. Proc. 3rd Plowshare Symp. Eng. Nucl. Explosives, 1964 (cited in Eisenbud, 1973).

Mitchell, N. T. and J. G. Shepherd, 1981. The UK disposal of solid radioactive waste into the Atlantic Ocean and its environmental impact. In:

Environmental Impact of Nuclear Power, BNES, London, 119-154.

Nishiwaki, Y., 1981. Some historical background to the IAEA Definition and Recommendations concerning high-level radioactive wastes or other high-level radioactive matter unsuitable for dumping at sea. In: Impacts of Radionuclide Releases into the Marine Environment, IAEA, Vienna, 163-200.

Organisation for Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA), 1980. Review of the Continued Suitability of the Dumping Site for Radioactive Waste in the North-East Atlantic. April, Paris.

Organisation for Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA), 1983. Decision of the OECD Council of the 22nd of July 1977 Establishing a Multilateral Consultation and Surveillance Mechanism for Sea Dumping of Radioactive Waste. Paris, 29 pp.

Radioactive Waste Management Center (RWMC), 1980. Low-level Radioactive Wastes: Dumping at the Pacific. RWMC Japan, 14 pp.

Sandia National Laboratories, 1983. The Subseabed Disposal Program: 1983 Status Report. Rough draft.

Sarmiento, J.L., H.W. Feely, W.S. Moore, A.E. Bainbridge and W.S. Broecker, 1976. The relationship between vertical eddy diffusion and buoyancy gradient in the deep sea. Earth Planet. Sci. Lett., 32: 357-370.

Science and Technology Agency/Nuclear Safety Bureau (STA/NSB), undated, (a). Environmental Safety Assessment on Sea Disposal of Low-level Radioactive Wastes in the Northwest Pacific. 112 pp.

Science and Technology Agency/Nuclear Safety Bureau (STA/NSB), undated, (b). Sea Disposal of Low-level Radioactive Wastes in Japan. 12 pp.

Shepherd, J. G., 1978. A simple model for the dispersion of radioactive wastes dumped on the deep-sea bed. Mar. Sci. Comm., 4: 293-327; originally issued as Technical Report 29, Ministry of Agriculture, Fisheries and Food (UK), Lowestoft, 1976.

Silva, A.J., 1977. Physical processes in deep-sea clays. Oceanus, 20: 31-40.

Sutton, H. C., 1982. Requirements of the London Convention for Dumping Radioactive Waste at Sea. Institute of Nuclear Sciences Report INS-R-312, D.S.I.R. (New Zealand), Lower Hutt, 41 pp.

Templeton, W. L., 1981a. The basis of the revised International Atomic Energy Agency Definition as related to the dumping of low-level radioactive wastes in the deep ocean. In: Nuclear Waste Management: the Ocean Alternative, T. C. Jackson (Ed.), Pergamon Press, New York, 17-29.

Templeton, W. L., 1981b. Dumping of low-level radioactive waste in the deep ocean. In: Impacts of Radionuclide Releases into the Marine Environment, IAEA, Vienna, 451-464.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1982. Ionizing Radiation: Sources and Biological Effects. Report to the General Assembly, with Annexes, New York, 773 pp.

United States Department of the Navy, 1982. Draft Environmental Impact Statement on the Disposal of Decommissioned, Defueled Naval Submarine Reactor Plants.

Van Dyke, J., K. R. Smith and S. Siwatibau, 1983. Nuclear activities and the Pacific Islanders. Paper presented at Nuclear Electric Power Conference, Resource Systems Institute, East-West Center, Honolulu.

Appendix 1

GLOSSARY OF TERMS

The definition of many of the terms listed in this short glossary have been taken from the report of The Australian Ionising Radiation Advisory Council AIRAC No. 6 June 1979.

absorbed dose — When ionizing radiation passes through a material, some of its energy is imparted to the material. The amount of energy retained per unit mass of the material is called the absorbed dose. The unit of absorbed dose is the Gray: 1 Gy = 1 J/kg = 100 rad

activation — The process of making a material radioactive by exposing the material to neutrons, protons, or other nuclear particles. Activation is also referred to as radioactivation.

activity — A measure of the rate at which a material is emitting nuclear radiation. Activity is usually measured in terms of the number of nuclear disintegrations which occur from a quantity of the material over a period of time. The standard unit is the becquerel which represents one disintegration per second. A former unit was the Curie (C_i), which is equal to 3.7×10^{10} disintegrations per second, i.e. 37 billion disintegrations per second.

alpha particle — A positively charged particle emitted by certain radioactive materials. It is made up of two neutrons and two protons bound together, which means it has an electrical charge of +2, and it is identical to the nucleus of helium-4 (He-4) atoms. It is the least penetrating of the three common types of ionizing radiation (alpha, beta, and gamma) emitted by radioactive materials and can be stopped by a sheet of paper.

artificial radioactivity — Man-made radioactivity produced by the capture of neutrons by atoms, by the irradiation of atoms by high energy particles or electromagnetic radiation or radionuclides produced in nuclear fission or fusion.

atom — The smallest amount of an element which has the chemical properties of that element. An atom cannot be sub-divided by chemical means. It has a central nucleus which carries a positive electric charge. Negatively charged electrons move in orbits around the nucleus. Each nucleus is made up of a number of protons and a number of neutrons, except in the case of the

simplest hydrogen atom which has only one proton in its nucleus. The number of protons in the nuclei of atoms of an element is the atomic number of that element and determines its chemical properties. The number of protons in a nucleus of an atom and the number of electrons in its orbits are equal and being of equal but opposite electric charge result in atoms having no nett electric charge (that is being electrically neutral). The sum of the number of protons and neutrons in the nuclei of the atoms of an element determine the mass number of the element. The number of neutrons in the nuclei of atoms of a given element can vary giving atoms which have the same atomic number but different mass numbers. These different forms of the same element are called isotopes of the element and each is identified by its different mass number, for example uranium-233, uranium-235 and uranium-238 are isotopes of the element uranium (atomic number 92). The different isotopes of an element have the same chemical properties but different physical properties.

atomic number — The number of protons in the nucleus of an atom of an element. All atoms of the same element have the same number of protons, whether radioactive or stable.

atomic weight — The average weight of an atom of an element which is usually expressed relative to one atom of the carbon isotope 12 which is taken to have a standard atomic weight of 12.

background radiation — Radiation coming from outer space (cosmic) and from radioactive materials found on earth. Also called natural radiation.

beta particle — A charged particle emitted by certain radioactive materials. It has a unit electrical charge and a mass which is equal to 1/1837 of a proton. A negatively charged beta particle is identical to an electron and is the more common form of beta activity. A positively charged beta particle is called a positron and is less common. Exposure to large levels of beta particles may cause skin burns, and materials that emit beta particles are harmful if they enter the body. Most beta particles are stopped by a few millimetres of lead or steel.

biota — Plant and animal life.

collective dose — (Collective-dose equivalent). The sum of the radiation doses to an organ or tissue received by all the individuals in a population group exposed to a source of radiation. In simple terms, a collective dose to an organ or tissue is the product of the number of persons in the population group and the average dose to that organ or tissue of the members of the group. The unit of collective dose is person sievert (Synonym man-sievert).

collective dose equivalent commitment — The sum over an infinite period of time, or over a limited period, of the annual collective doses received by the organs or tissues of a population group as the result of a given practice which gives rise to radiation exposure. This time may be extended over several generations

as in the case of the release of a long-lived nuclide ^{14}C. The population group may be as small as desired (for example, a local, regional, or national population) or as large as the global population. The unit of collective dose commitment is person sievert (synonym man-sievert).

committed dose-equivalent — A special type of dose equivalent commitment to express the dose equivalent received by an organ or tissue of a particular individual during his or her working life as a result of a single intake of radioactive material into the body. The dose will be delivered over a period of time depending of the half-life of the radionuclide and on its retention and rate of elimination from the body. The unit of committed dose equivalent is the sievert.

concentration — The activity of a radioactive material (radionuclide) per unit volume of air, water or other substance or per unit mass of non-radioactive (stable) material. Typical units of concentration are:
becquerels per millilitre (Bq/ml) of water
becquerels per gram (Bq/g) of solid matter

containment — An enclosure to prevent or minimise the release to the environment of radioactive materials (radionuclides) from a nuclear reactor or radioactive wastes.

contamination — Radioactive material (radionuclide) in unsealed, gaseous, liquid or particulate form released to the environment in air, water or other substance or present on a surface.

cosmic ray — A stream of ionizing radiation of extraterrestrial origin, chiefly of protons, alpha particles, and other atomic nuclei but including some high energy photons and electrons. A "natural" source of radiation.

cumulative dose — (Cumulative Dose-Equivalent). Total dose equivalent to an organ or tissue resulting from a continuous or repeated exposure to radiation. The unit of cumulative dose is the sievert (see Dose-Equivalent).

daughter product — A nuclide formed in the decay of a radionuclide (called the parent). Some daughter products are also radioactive and others are non-radioactive (stable) nuclides.

decay, radioactive — The process of spontaneous transformation of a radioactive nuclide to a different nuclide or different energy state of the same nuclide. Radioactive decay involves the emission of alpha particles, or beta or gamma rays from the nuclei of the atoms. If a radioactive nuclide is transformed to a stable nuclide, the process results in a decrease of the number of original radioactive atoms. Radioactive decay is also referred to as radioactive disintegration.

disintegration — Any process in which a nucleus of a nuclide emits one or more particles or photons of radiation energy, either spontaneously in the case of a radionuclide or as the result of a nuclear reaction.

disposal (of radioactive wastes.) Either the planned release of radioactive wastes to the environment as airborne or liquid effluent or their permanent placement with the intention of them not being retrievable.

dose A general term which denotes the quantity of radiation or the radiation energy absorbed; usually expressed in gray for doses to man.

dose equivalent commitment This is a measure of the average dose commitment, per individual, to a group of exposed people, summed over infinite time and possible over several generations. It may be defined as the sum over an infinite period of time, or if desired over a limited period, of the annual radiation doses to an organ or tissue, which will be received by the average member of a population group as a result of a practice which gives rise to radiation exposure. The "average" member receives a dose which is the average of that received by the group. The population group may be as large as the global population or as small as desired (for example, a local, regional, or national population). The unit of dose equivalent commitment is sievert.

dose equivalent The quantity which expresses absorbed dose on a common scale for the purpose of assessing protection against possible deleterious biological consequences of the absorbed dose. In this Report, unless qualified the term 'dose' means dose equivalent, is the product of the absorbed dose and a quality factor, the value of which depends on the type and energy of the radiation which gave rise to the absorbed dose. For radiation protection purposes, the ICRP recommends the following quality factors:

X-rays, gamma rays, beta rays	1
Thermal neutrons	2.3
Fast neutrons	10
Alpha rays	20

The unit of dose equivalent, the sievert (Sv), is numerically equal to the absorbed dose in gray multiplied by the appropriate quality factor.

dose rate The amount of radiation dose delivered in a unit amount of time, for example, in sievert per year.

electron A negatively charged particle with a mass which is equal to 1/1837 of a proton.

electron volt (eV). A small unit of energy numerically equal to the energy gained by an electron when accelerated by an electrical potential difference of one volt. One eV equals 1.6×10^{-19} joule (J). Multiple units of the electron volt are frequently used.

1 kilo-electron volt (keV) 10^3 (1000) eV
1 mega-electron volt (MeV) 10^6 (1 000 000) eV.

element — A substance that cannot be divided into simpler substances by chemical means. A substance whose atoms all have the same atomic number.

exposure — A measure of the ionisation produced in air by radiation; a general term used to describe any process which will result in an absorbed dose of radiation being imparted to a material or in a dose-equivalent of radiation being received by an organ or tissue of a person.

exposure, external — The subjecting of the outside of the body of an organism to ionizing radiation.

exposure, internal — The subjecting of the inside of the body of an organism to ionizing radiation.

fallout — Airborne radioactive fission or fusion debris which descends to the surface of the earth. Created by above-ground nuclear explosions.

fast neutrons — Neutrons, resulting from fission, which have lost relatively little of their energy by collision with atoms. Compared with thermal neutrons they travel at much higher speeds (see also Thermal Neutrons).

fissile — A material whose nucleus is capable of being split (fissioned) by neutrons of variable energies.

fission — The splitting of a heavy nucleus into approximately equal parts which is accompanied by the release of a relatively large amount of energy and generally one or more neutrons.

fission products — Isotopes of elements resulting from fission. These isotopes are predominantly radioactive.

fusion — A process by which heavier nuclei are formed by the combination (or fusion) of lighter ones (such as those of hydrogen). The formation of the heavier nuclei is accompanied by the release of energy.

gamma ray — High-energy, short wavelength electromagnetic radiation. Gamma radiation frequently accompanies beta particle emissions. Gamma rays are very penetrating and are stopped most effectively by dense materials such as lead or uranium. They are essentially similar to X-rays but are usually more energetic and originate from the nucleus. Cobalt-60 is an example of a radionuclide that emits gamma rays.

half-life, biological — The time required for a biological system, such as an organ or tissue in an organism, to clear by natural (nonradioactive) processes, half the amount of a substance that has entered it.

half-life, radioactive — (of a radionuclide): The time required for the activity of a radionuclide to decay to half its initial value. During that time half the radioactive atoms present initially will have disintegrated. Each radionuclide has a unique

half-life. The half-lives of the different radionuclides range from small fractions of a second to millions of years. The half-life of a radionuclide cannot be changed by physical or chemical processes.

high-level Pertaining to the intensity of a radioactive waste with medium to long half-life radionuclides.

ion An atomic particle, atom or chemical component carrying an electric charge, either positive or negative.

ionization The process of adding or removing electrons so as to form ions. Ionization can be caused by high temperatures, electrical discharges, or nuclear radiation.

ionizing radiation Any radiation which displaces electrons from atoms or molecules, thereby producing ions. Examples include alpha, beta, and gamma radiation. Exposure to ionizing radiation may produce skin or tissue damage.

irradiation The exposure of a material to radiation.

irradiated Having been exposed to or treated with radiation.

isotope One of two or more nuclides which have the same number of protons but have different numbers of neutrons in their nuclei. Therefore, the isotopes of an element have the same atomic number but different atomic weights. Isotopes usually have very nearly the same chemical properties but somewhat different physical properties.

low-level Refers to radioactivity of low intensity.

metabolism Chemical processes in general which occur within an organism, or part of one.

molecule A cluster of two or more atoms bonded together chemically. The atoms may be of the same element to give a molecule of that element or of different elements to give a molecule of a chemical compound. For example, uranium dioxide is an aggregate of atoms of the elements uranium and oxygen.

monitoring The systematic collection and assessment of information to determine the adequacy of protection against radiation exposure. For example, absorbed doses due to external radiation exposure or the concentration of radionuclides in air or water may be monitored.

multiples and sub-multiples The following prefixes are used with units of quantities to denote multiples or sub-multiples of these units. The multiple or sub-multiple may be expressed as the power of ten to which it is equal.

Prefix	Multiple	Sub-multiple
kilo (or k)	thousand = 10^3	
mega (or M)	million = 10^6	

giga (or G)	billion = 10^9	
milli (or m)	thousandth	10^{-3}
micro (or μ)	millionth	10^{-6}
nano (or n)	billionth	10^{-9}
pico (or p)	billion billionth	10^{-12}

natural radioactivity — Radioactivity of naturally occurring radionuclides.

neutron — An uncharged nuclear particle with a mass slightly greater than that of a proton, found in the nucleus of every atom heavier than hydrogen. Neutrons sustain the fission chain reaction in a nuclear reactor. Outside a nuclear of an atom, a neutron is radioactive, decaying with a half-life of about 12 minutes to produce a proton and an electron.

nuclear — Involving a nucleus specifically, or relating to nuclear energy generally.

nuclear reactor — A plant in which a fission chain reaction is maintained and controlled. It usually contains nuclear fuel, a coolant, a moderator, control rods and safety devices and is most often enclosed in a concrete biological shield to absorb neutron and gamma radiations.

nucleus — The positively charged central region of an atom which is composed of protons and neutrons and contains almost all of the mass of an atom.

nuclide — An atomic form of an element which is distinguished by its atomic number, atomic weight, and the energy state of its nucleus. These factors determine the other properties of the element, including its radioactivity.

organism — Any living plant or animal.

photon — An indivisible unit of energy generally regarded as a discrete particle which has zero mass and no electrical charge.

plankton — The generally microscropic plant and animal organisms that float or weakly swim in a body of water.

proton — A stable, positively charged particle in the nucleus of an atom.

rad — The earlier used unit of absorbed dose. 1 rad equals 0.01 joule per kilogram (J/kg).

radiation — The emission and propagation of energy through matter or space by means of electromagnetic disturbances which display both wave-like and particle-like behaviour. In this context, the "particles" are known as photons. The term has been extended to include streams of fast-moving particles such as alpha and beta particles, free neutrons, and cosmic radiations. Nuclear radiation is that which is emitted from atomic nuclei in various nuclear reactions and includes alpha, beta, and gamma radiation and neutrons.

radiation risk	The chance of deleterious biological consequences occurring in a person following a radiation dose.
radiation therapy	Any form of disease treatment that uses radiation; commonly known as radiotherapy.
radiation threshold	The level of exposure below which it is assumed that no damage takes place. Doctors and scientists have challenged the assumption that such a threshold exists.
radioactive	Possessing or pertaining to radioactivity.
radioactive equilibrium	The situation existing when the local activity of a radionuclide equals that of its parent. "Disequilibrium" refers to perturbation in this state produced by geochemical processes.
radioactive series	A series of radionuclide, each except the first being the daughter product of the previous one in the series; for example the Uranium series and the Thorium series in which the end product of each series is a stable isotope of lead.
radioactivity	The process of spontaneous decay or disintegration of an unstable nucleus of an atom; usually accompanied by the emission of ionizing radiation.
radioisotope	An unstable isotope of an element that decays or disintegrates spontaneously and emits radiation. More than 1300 natural and artificial radioisotopes have been identified.
radionuclide	A radioactive nuclide.
rays	Alpha-Helium nuclei (He-4) emitted in alpha-decay. Beta-Electrons emitted in beta-decay. Gamma rays - high energy photons of electro-magnetic energy and X-rays photons of electromagnetic energy at lower energy levels than those of gamma rays.
relative risk assessment	An assessment of the radiation risks of a radiation dose to persons made by comparing that dose with another dose received by the persons, for example from natural background radiation.
rem	The earlier used unit of dose-equivalent, dose commitment and committed dose.
reprocessing	A chemical process used to recover residual fissile material from spent nuclear fuel (for example unused fissile uranium-235 and fissile plutonium-239 bred in uranium based nuclear fuel). Reprocessing results in gaseous and liquid radioactive effluents, low and intermediate level solid radioactive wastes and high level liquid radioactive wastes.
risk coefficient	A factor by which the dose to an organ or tissue of persons may be multiplied to assess their chance of developing deleterious biological consequences as a result of that dose. Risk

coefficients from radiation exposure are discussed in detail in AIRAC No. 3.

short-lived radioactivity — Radioactive nuclides which decay rapidly, therefore, having short half-lives. In this statement, it refers to those radionuclides with half-lives that are short in comparison to the expected time required for penetrating their containment; therefore, the following radionuclides as considered short-lived: Sulfur-35, Scandium-46, Chromium-51, Manganese-54, Iron-55, Cobalt-58, Iron-59, Cobalt-60, Zirconium-95, and Hafnium-181. Nickel-63 is considered an intermediate between short-lived and long-lived radioactivity.

threshold hypothesis — An assumption that no deleterious biological consequences will occur below a specified (threshold) level of radiation dose.

transmutation — Any process in which a nuclide is transformed into a different nuclide or more specifically into a different element by a nuclear reaction.

transuranic elements — Artificially produced elements of atomic number 93 and higher. Transuranic elements are produced in uranium based nuclear fuel as the result of neutron capture by the nuclei of atoms of uranium-235 and uranium-238 present in the fuel and subsequent radioactive decay and neutron capture by a chain of nuclides formed. Transuranic elements include radioisotopes of plutonium, neptunium, americium and curium. Transuranic elements predominantly undergo alpha-decay.

X-rays — Photons of electromagnetic energy of lower energy levels than those of gamma rays. They are emitted in the decay of some radionuclides but they are most frequently produced in practice in electrically operated X-ray tubes.

PUBLICATIONS IN THE UNEP REGIONAL SEAS REPORTS AND STUDIES SERIES

No. 1 UNEP: Achievements and planned development of UNEP's Regional Seas Programme and comparable programmes sponsored by other bodies. (1982)

No. 2 UNIDO/UNEP: Survey of marine pollutants from industrial sources in the West and Central African region. (1982)

No. 3 UNESCO/UNEP: River inputs to the West and Central African marine environment. (1982)

No. 4 IMCO/UNEP: The status of oil pollution and oil pollution control in the West and Central African region. (1982)

No. 5 IAEA/UNEP: Survey of tar, oil, chlorinated hydrocarbons and trace metal pollution in coastal waters of the Sultanate of Oman. (1982)

No. 6 UN/UNESCO/UNEP: Marine and coastal area development in the East African region. (1982)

No. 7 UNIDO/UNEP: Industrial sources of marine and coastal pollution in the East African region. (1982)

No. 8 FAO/UNEP: Marine pollution in the East African region. (1982)

No. 9 WHO/UNEP: Public health problems in the coastal zone of the East African region. (1982)

No. 10 IMO/UNEP: Oil pollution control in the East African region. (1982)

No. 11 IUCN/UNEP:Conservation of coastal and marine ecosystems and living resources of the East African region. (1982)

No. 12 UNEP: Environmental problems of the East African region. (1982)

No. 13 UNEP: Pollution and the marine environment in the Indian Ocean. (1982)

No. 14 UNEP/CEPAL: Development and environment in the Wider Caribbean region: A Synthesis. (1982)

No. 15 UNEP: Guidelines and principles for the preparation and implementation of comprehensive action plans for the protection and development of marine and coastal areas of regional seas. (1982)

No. 16 GESAMP: The health of the oceans. (1982)

No. 17 UNEP: Regional Seas Programme: Legislative authority. (1985)

No. 18 UNEP: Regional Seas Programme: Workplan. (1982)

No. 19 Rev. 2. UNEP: UNEP Oceans Programme: Compendium of projects. (1985)

No. 20 CPPS/UNEP: Action Plan for the protection of the marine environment and coastal areas of the South East Pacific. (1983)

No. 21 CPPS/UNEP:Sources, levels and effects of marine pollution in the South-East Pacific. (1983) (In Spanish only)

No. 22 Rev. 2. UNEP: Regional Seas Programme in Latin America and Wider Caribbean. (1985)

No. 23 FAO/UNESCO/IOC/WHO/WMO/IAEA/UNEP: Co-ordinated Mediterranean Pollution Monitoring and Research Programme (MED POL) - Phase I: Programme Description. (1983)

No. 24 UNEP: Action Plan for the protection and development of the marine and coastal areas of the East Asian region. (1983)

No. 25 UNEP: Marine pollution. (1983)

No. 26 UNEP: Action Plan for the Caribbean environment programme. (1983)

No. 27 UNEP: Action Plan for the protection and development of the marine environment and coastal areas of the West and Central African region. (1983)

No. 28 UNEP: Long-term programme for pollution monitoring and research in the Mediterranean (MED POL) - Phase II. (1983)

No. 29 SPC/SPEC/ESCAP/UNEP: Action Plan for managing the natural resources and environment of the South Pacific region. (1983)

No. 30 UNDIESA/UNEP: Ocean energy potential of the West and Central African region. (1983)

No. 31 A. L. DAHL and I. L. BAUMGART: The state of the environment in the South Pacific. (1983)

No. 32 UNEP/ECE/UNIDO/FAO/UNESCO/WHO/IAEA: Pollutants from land-based sources in the Mediterranean. (1984)

No. 33 UNDIESA/UNEP: Onshore impact of offshore oil and natural gas development in the West and Central African region. (1984)

No. 34 UNEP: Action Plan for the protection of the Mediterranean. (1984)

No. 35 UNEP: Action Plan for the protection of the marine environment and the coastal areas of Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates. (1983)

No. 36 UNEP/ECLAC: The state of marine pollution in the Wider Caribbean region. (1984)

No. 37 UNDIESA/UNEP: Environmental management problems in resource utilization and survey of resources in the West and Central African region. (1984)

No. 38 FAO/UNEP: Legal aspects of protecting and managing the marine and coastal environment of the East African region. (1983)

No. 39 IUCN/UNEP: Marine and coastal conservation in the East African region. (1984)

No. 40 SPC/SPEC/ESCAP/UNEP: Radioactivity in the South Pacific. (1984)

No. 41 UNEP: Socio-economic activities that may have an impact on the marine and coastal environment of the East African region. (1984)

No. 42 GESAMP: Principles for developing coastal water quality criteria. (1984)

No. 43 CPPS/UNEP: Contingency plan to combat oil pollution in the South-East Pacific in cases of emergency. (1984)

No. 44 IMO/ROPME/UNEP: Combating oil pollution in the Kuwait Action Plan region. (1984)

No. 45 GESAMP: Thermal discharges in the marine environment. (1984)

No. 46 UNEP: The marine and coastal environment of the West and Central African region and its state of pollution. (1984)

No. 47 UNEP: Prospects for global ocean pollution monitoring. (1984)

No. 48 SPC/SPEC/ESCAP/UNEP: Hazardous waste storage and disposal in the South Pacific. (1984)

No. 48/ Appendices SPC/SPEC/ESCAP/UNEP: Hazardous waste storage and disposal in the South Pacific. (1984)

No. 49 FAO/UNEP: Legal aspects of protecting and managing the marine and coastal environment of the East African region: National Reports. (1984)

No. 50 IUCN/UNEP: Marine and coastal conservation in the East African region: National Reports. (1984)

No. 51 UNEP: Socio-economic activities that may have an impact on the marine and coastal environment of the East African region: National Reports. (1984)

No. 52 UNEP: Arab co-operation for the protection and development of the marine environment and coastal areas resources of the Mediterranean. (1984)

No. 53 UNEP: UNEP Regional Seas Programme: the Eastern African Experience. (1984)

No. 54 UNIDO/UNEP: Contingency planning for emergencies associated with industrial installations in the West and Central African region. (1985)

No. 55 FAO/UNEP: Marine mammals: global plan of action. (1985)

No. 55/ Annex FAO/IUCN/IWC/UNEP: Marine mammals: global plan of action. (1985)

No. 56 GESAMP: Cadmium, lead and tin in the marine environment. (1985)

No. 57 IMO/UNEP: Oil spills and shoreline clean-up on the coasts of the Eastern African region. (1985)

No. 58 UNEP: Co-operative programmes sponsored by UNEP for the protection of the marine and coastal environment in the wider Indian Ocean region. (1985)

No. 59 UNEP: Environmental problems of the marine and coastal area of India: National Report. (1985)

No. 60 IUCN/UNEP: Management and conservation of renewable marine resources in the Indian Ocean region: Overview. (1985)

No. 61 UNEP: Action Plan for the protection, management and development of the marine and coastal environment of the Eastern African region. (1985)

No. 62 IUCN/UNEP: Management and conservation of renewable marine resources in the South Asian Seas region. (1985)

No. 63 IUCN/UNEP: Management and conservation of renewable marine resources in the Kuwait Action Plan region. (1985)

No. 64 IUCN/UNEP: Management and conservation of renewable marine resources in the Red Sea and Gulf of Aden region. (1985)

No. 65 IUCN/UNEP: Management and conservation of renewable marine resources in the East Asian Seas region. (1985)

No. 66 IUCN/UNEP: Management and conservation of renewable marine resources in the Eastern African region. (1985)

No. 67 UN/UNEP: Coastal erosion in West and Central Africa. (1985)

No. 68 GESAMP: Atmospheric transport of contaminants into the Mediterranean region. (1985)

No. 69 UNEP: Environment and resources in the Pacific. (1985)

No. 70 UNESCO/ROPME/UPM/UNEP: Proceedings of the Symposium/Workshop on oceanographic modelling of the Kuwait Action Plan (KAP) region. (1985)

No. 71 IUCN/ROPME/UNEP: An ecological study of the rocky shores on the southern coast of Oman. (1985)

No. 72 IUCN/ROPME/UNEP: An ecological study of sites on the coast of Bahrain. (1985)

No. 73 SPC/SPEC/ESCAP/UNEP: Ecological interactions between tropical coastal ecosystems. (1985)