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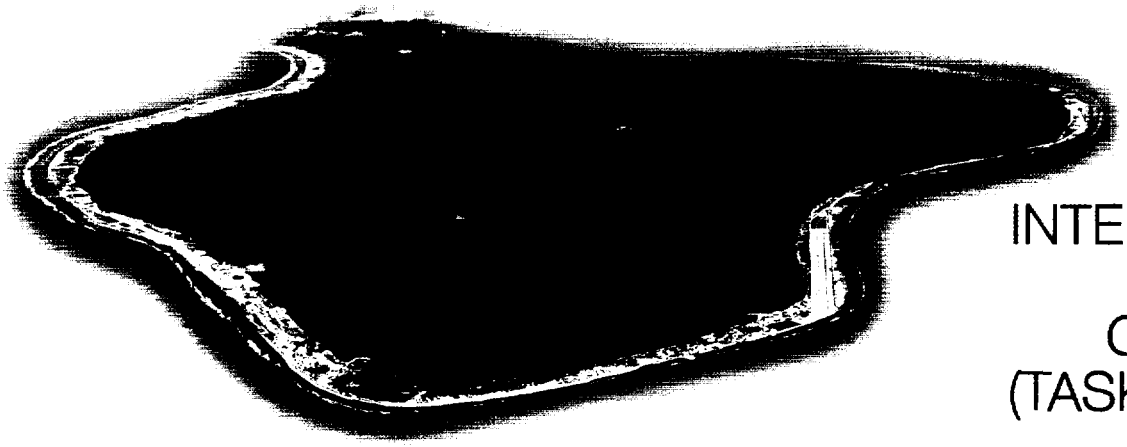
TECHNICAL REPORT



REPORT BY AN INTERNATIONAL ADVISORY COMMITTEE (TASK GROUP A)

THE RADIOLOGICAL SITUATION AT THE ATOLLS OF MURUROA AND FANGATAUFA

DOSES DUE TO RADIOACTIVE MATERIALS PRESENT IN THE ENVIRONMENT OR RELEASED FROM THE ATOLLS

Vol. 6

THE RADIOLOGICAL SITUATION AT THE ATOLLS OF MURUROA AND FANGATAUFA

TECHNICAL REPORT

In six volumes

VOLUME 6

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Report by an
International Advisory Committee
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VOLUME 6:
DOSES DUE TO RADIOACTIVE MATERIALS PRESENT IN THE ENVIRONMENT OR RELEASED FROM THE ATOLLS
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FOREWORD

At the present time there are various locations around the world affected by radioactive residues. Some of these residues are the result of past peaceful activities, others result from military activities, including residues from the testing of nuclear weapons. Stimulated by concern about the state of the environment, the steps taken towards nuclear disarmament, and improved opportunities for international co-operation, attention in many countries has turned to assessing and, where necessary, remediating areas affected by radioactive residues.

Some of these residues are located in countries where there is an absence of the infrastructures and expertise necessary for evaluating the significance of the radiation risks posed by the residues and for making decisions on remediation. In such cases, governments have felt it necessary to obtain outside help. In other cases, it has been considered to be socially and politically desirable to have independent expert opinions on the radiological situation caused by the residues. As a result, the International Atomic Energy Agency (IAEA) has been requested by the governments of a number of Member States to provide assistance in this context. The assistance has been provided by the IAEA in relation to its statutory obligation "to establish...standards of safety for protection of health...and to provide for the application of these standards...at the request of a State".

On 22 September 1995, a resolution of the General Conference of the IAEA called on all States concerned "to fulfil their responsibilities to ensure that sites where nuclear tests have been conducted are monitored scrupulously and to take appropriate steps to avoid adverse impacts on health, safety and the environment as a consequence of such nuclear testing".

The Study reported upon here was requested by the Government of France, which asked the IAEA to assess the radiological situation at the atolls of Mururoa and Fangataufa in French Polynesia, where France had conducted a nuclear weapon testing programme between 1966 and 1996. The IAEA convened an International Advisory Committee (IAC), under the chairmanship of Dr. E. Gail de Planque of the United States of America, to supervise the Study.

The IAC, which was given the tasks of providing scientific guidance and direction to the IAEA in the conduct of the Study, and of reporting on the Study's findings, conclusions and recommendations, met formally for the first time on 13–14 April 1996; this signalled the start of the Study of the Radiological Situation at the Atolls of Mururoa and Fangataufa. The Study has now been completed and a number of documents have been prepared. These documents are: the Main Report (which includes the Executive Summary); a Summary Report; and a Technical Report in six volumes.

I am pleased to have received these reports, which are being made available through the IAEA to a wider audience.

Mohamed ElBaradei

Director General
International Atomic Energy Agency

The Government of France covered most of the direct costs of the Study and provided invaluable logistic assistance throughout. Significant in-kind contributions were made by Argentina, Australia, Austria, Belarus, Belgium, Cuba, Denmark, Fiji, Germany, Indonesia, Japan, the Republic of Korea, New Zealand, Norway, the Russian Federation, Slovenia, Spain, Sweden, Switzerland, the United Kingdom, the United States of America, the European Commission, the South Pacific Forum, the South Pacific Regional Environment Programme, the Office of the Sub-Regional Representative for the Pacific of the Food and Agriculture Organization of the United Nations, the World Health Organization and the United Nations Scientific Committee on the Effects of Atomic Radiation.

In addition, significant in-kind contributions were made by the laboratories and other institutions involved in the Study, whose activities were co-ordinated by the Agency's Laboratories at Seibersdorf, Austria, and the IAEA Marine Environment Laboratory, Monaco. The laboratories and other institutions were: the Australian Nuclear Science and Technology Organisation (ANSTO), Sydney, and the Australian Radiation Laboratory, Melbourne, Australia; the Institute for Inorganic Chemistry and the Federal Institute for Food Control and Research, Vienna, Austria; the Institute of Radiobiology, Minsk, Belarus; the Centro de Isótopos, Havana, Cuba; the Risø National Laboratory, Roskilde, Denmark; the Physikalisch-Technische Bundesanstalt, Braunschweig, and the Federal Fisheries Research Centre, Hamburg, Germany; the National Radiation Laboratory, Christchurch, and the Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand; the Norwegian Radiation Protection Authority, Østerås, Norway; the Jožef Stefan Institute, Ljubljana, Slovenia; the Instituto del Medio Ambiente, CIEMAT, Madrid, Spain; the Radiochemistry Group, Central Veterinary Laboratory, Addlestone, Surrey, and the Centre for Environment, Fisheries and Aquaculture Science, Lowestoft, Suffolk, United Kingdom; and the Environmental Measurements Laboratory, US Department of Energy, New York, N.Y., and Lawrence Livermore National Laboratory, Livermore, California, United States of America.

The IAEA wishes to thank the large number of people who were involved in different ways in the Study. They are all acknowledged in the various reports of the IAC.

EDITORIAL NOTE

PREFACE

Between 1966 and 1996, France conducted 193 'expériences nucléaires' (nuclear experiments — a term used by the French authorities to include the full testing of nuclear weapons and the conduct of certain safety trials) above and beneath the atolls of Mururoa and Fangataufa in the Tuamotu Archipelago of French Polynesia. All French testing ceased on 27 January 1996. Before the completion of the last series of tests the Government of France requested the International Atomic Energy Agency (IAEA) to conduct a study to assess the radiological impact of the tests.

The IAEA agreed to carry out a study — the Study of the Radiological Situation at the Atolls of Mururoa and Fangataufa — for the purpose of ascertaining whether, as a consequence of the tests, radiological hazards exist now or will exist in the future, and making recommendations on the form, scale and duration of any monitoring, remedial action or follow-up action that might be required. An International Advisory Committee (IAC) was convened by the Director General of the IAEA to provide scientific direction and guidance to the IAEA in the conduct of the Study and to prepare a report on the Study's findings, conclusions and recommendations.

The IAC's first formal meeting took place in Vienna on 13–14 April 1996 and its final one, also in Vienna, on 3–5 February 1998. This publication constitutes one of several reports of the IAC to the Director General describing the conduct of the Study and its findings, conclusions and recommendations.

The terms of reference of the Study called for an evaluation of the radiological situation at the atolls (and in other involved areas). It is important to emphasize that it is the radiological situation at the atolls, both as it is at present and as it might develop in the long term, including its consequences for human health, that the Study was required to address, and not any past radiological consequences of the French nuclear testing programme. This had two implications for the Study.

First, it was not within the terms of reference of the Study to attempt to assess retrospectively doses received by inhabitants of the region as a result of the atmospheric nuclear tests at the time when those tests were carried out. Those doses were due in part to short lived fallout — for example, radioactive iodine (especially ^{131}I, which has a half-life of eight days). However, the Secretariat of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) did provide the IAC with the results of a review of such doses that had been received by people in the South Pacific region in the past. The IAC believes that readers will be interested in these results, and it has therefore included them in an annex to the Main Report on the Study. The results are accepted by the IAC as providing an objective and balanced view of the situation.

Second, the IAC felt that the most informative indicator of the radiological situation at the atolls would be the present and future individual annual effective doses that people (real and hypothetical) at the atolls and in other involved areas might receive as a consequence both of the radioactive material that is now in the accessible environment and of that which might be released into the accessible environment over time from underground. It should be noted that while UNSCEAR has invoked other dosimetric quantities — the 'effective dose commitment' and the 'collective effective dose commitment' — in assessing the global impact of nuclear weapon testing, the IAC did not consider it appropriate to use these quantities in any reports of the Study for the reasons discussed in Section 1 of the Main Report.

The French Government provided much of the information used in the Study. This information was independently evaluated by Study participants and, where practicable, validated. For example, to provide a basis for the evaluation of French environmental monitoring data, the IAEA carried out an environmental sampling and surveillance campaign to measure independently contemporary levels of radioactive material present in the environment of the atolls. Also, with the co-operation of French scientists, samples of underground water were collected by Study participants from two test cavity–chimneys beneath the rim of Mururoa, and from deep in the carbonate layer beneath the two lagoons. These samples were analysed for a number of radionuclides, and the results provided an independent check on the validity of assumptions made in some of the Study's calculations, for example of radionuclide concentrations in the cavity–chimney of each test. The French Government allowed complete access to the atolls for these surveys and provided the necessary logistic support.

In addition to the information provided by the French Government, a small amount of information had been published in the open literature on measured levels of certain radionuclides (^{60}Co, ^{90}Sr, ^{137}Cs and $^{239+240}Pu$) in the environment of the atolls, and reports of three scientific missions to the atolls — the Tazieff Mission of June 1982, the Atkinson Mission of October 1983 and the Cousteau Mission of June 1987 — were in the public domain. Issues raised by these missions guided the IAC in the choice of certain topics to be addressed in the Study.

It is not possible to place reliable quantitative limits on the errors associated with the dose assessments carried out by the Study. The estimated upper limits to contemporary doses can be accepted with confidence as they are based on measurements of the concentrations of residual radioactive material at present in the environment of the atolls. However, considerable uncertainty is possible in the estimation of future doses because of the complexities of the physical processes involved in releases from underground sources and the limitations of the geological migration models used. Therefore, in the absence of definitive information, conservative assumptions have been made and the estimated future doses can be regarded as upper limit values. In any event, they are so small that large errors in the assumptions made would not affect the IAC's basic finding that possible radiation doses to people now, and potential doses at any time in the future, arising from the conditions at the atolls are a very small fraction of the doses people already receive from natural radiation sources.

The Main Report (which includes the Executive Summary) is a distillation of the large amount of scientific work carried out in the course of the Study, which is described in detail in the accompanying six volume Technical Report. The Summary Report presents a comprehensive summary of the Main Report, including its findings, conclusions and recommendations.

ACKNOWLEDGEMENTS

The Main Report and the Technical Report, compiled essentially between September 1997 and March 1998, represent an enormous effort by many people. All Study participants contributed, but the major load was borne by the Task Group Chairmen (A. McEwan and D.M. Levins) and the Working Group Chairmen (F. Schönhofer, D. Woodhead, L.-E. De Geer, C. Fairhurst and E. Mittelstaedt). The members of the IAEA management team, particularly A.J. González and R.M. Fry, also worked tirelessly. The Summary Report was compiled by D. Delves of the IAEA. The IAC wishes to acknowledge their dedication and that of all other participants, and also to thank the many IAEA staff members without whose efforts the Study would not have been possible. In addition, the co-operation of the French Government and the efforts of members of the French Liaison Office — G. Goutière and P. Delcourt and, in the past year, J.-F. Sornein and G. Corion — must be commended.

The IAC thanks those laboratories — all listed in the Main Report and the Technical Report — which were involved in the analysis of samples collected during the sampling and surveillance campaign, and the underground water sampling exercise, at the atolls and commends the efforts of the staff of the Agency's Laboratories at Seibersdorf, Austria, and the IAEA Marine Environment Laboratory, Monaco, who helped to co-ordinate, manage and conduct those campaigns.

The IAC expresses its appreciation for the support and encouragement of the former Director General of the IAEA, H. Blix, and the current Director General, M. ElBaradei, and for their willingness to provide the IAEA resources necessary for carrying out the Study.

The Chairman further wishes to thank all the members of the IAC for their thoughtful and competent guidance throughout the course of the Study.

E. Gail de Planque

Chairman
International Advisory Committee

NOTE FROM THE TASK GROUP CHAIRMEN

The Study of the Radiological Situation of the Atolls of Mururoa and Fangataufa, scientific details of which are presented in this Technical Report, was carried out under the scientific direction and guidance of an International Advisory Committee convened by the IAEA. It involved the efforts of a large number of scientists with expertise in many disciplines. The assessments were carried out in teams organized into two Task Groups and five Working Groups.

Task Group A evaluated the present levels of residual radioactive material in the environment of the atolls and their surrounding waters, and assessed the present and future radiation doses to people and the present radiation doses to aquatic biota attributable to this material. The Group was supported by two Working Groups dealing with Terrestrial Environmental Contamination (Working Group 1) and Aquatic Environmental Contamination (Working Group 2).

Task Group B estimated the rate at which the residual radioactive material, at present underground, might migrate through the geosphere and be released into the surrounding ocean, thereby providing the basis for the assessment of long term doses attributable to this material. The Group was supported by three Working Groups dealing, in turn, with the underground radionuclide inventory, called the Source Term (Working Group 3), Geosphere Radionuclide Transport (Working Group 4) and Marine Modelling (Working Group 5).

Each of the Working Groups produced a detailed report, which was drawn upon in the preparation of the Main Report of the Study. In addition, a sixth volume was written dealing with the estimation and assessment of radiation doses based on information provided by the Working Groups. The titles of these six volumes, which form the Technical Report of the Study, are:

Volume 1: *Radionuclide Concentrations Measured in the Terrestrial Environment of the Atolls,* A report by Working Group 1;

Volume 2: *Radionuclide Concentrations Measured in the Aquatic Environment of the Atolls,* A report by Working Group 2;

Volume 3: *Inventory of Radionuclides Underground at the Atolls,* A report by Working Group 3;

Volume 4: *Releases to the Biosphere of Radionuclides from Underground Nuclear Weapon Tests at the Atolls,* A report by Working Group 4;

Volume 5: *Transport of Radioactive Material within the Marine Environment,* A report by Working Group 5;

Volume 6: *Doses due to Radioactive Materials Present in the Environment or Released from the Atolls,* A report by Task Group A.

This document, Volume 6 of the Technical Report, is divided into two parts. Part A provides details of the dose and risk assessments to humans described in Section 9 of the Main Report. Doses that would be received, now and in the long term, by people living on Tureia, and by hypothetical groups occupying the atolls, and living elsewhere within the South Pacific region, are assessed. Contemporary doses are based on measured concentrations of relevant radionuclides now in the environment, and future doses are based on predictions of the way contemporary concentrations will decline with time and on the estimates, provided by Working Group 5, of concentrations of relevant radionuclides at various places and at various times in the ocean due to release of radioactive material from the atolls. The calculations of dose to a variety of marine organisms inhabiting a number of different ecological niches are presented in Part B, which supplements Section 10 of the Main Report.

Andrew McEwan

Chairman
Task Group A

Des Levins

Chairman
Task Group B

ACKNOWLEDGEMENTS

Part A of this volume, dealing with the estimation of doses and radiological risk to humans, was prepared by A. McEwan, Chairman of Task Group A, with assistance from J. Cooper, a member of Task Group B, and C. Robinson. Part B, on doses to biota, was written by D. Woodhead, Chairman of the Aquatic Working Group.

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PART A. DOSES TO HUMANS

PART B. DOSES TO BIOTA

Part A

DOSES TO HUMANS

1. INTRODUCTION

In the previous volumes of this Report the concentrations of residual radioactivity in the environment of Mururoa and Fangataufa atolls have been described, and assessments made of the releases to the environment in the future. The further step in radiological assessment is the derivation of radiation doses that arise to actually or potentially exposed populations, from these concentrations and releases. These doses are estimated in this report. The existence of a hypothetical population resident on Mururoa is postulated as the group which would be most exposed. Doses to this group are estimated together with doses to maximally exposed residents on nearby South Pacific islands, and further afield.

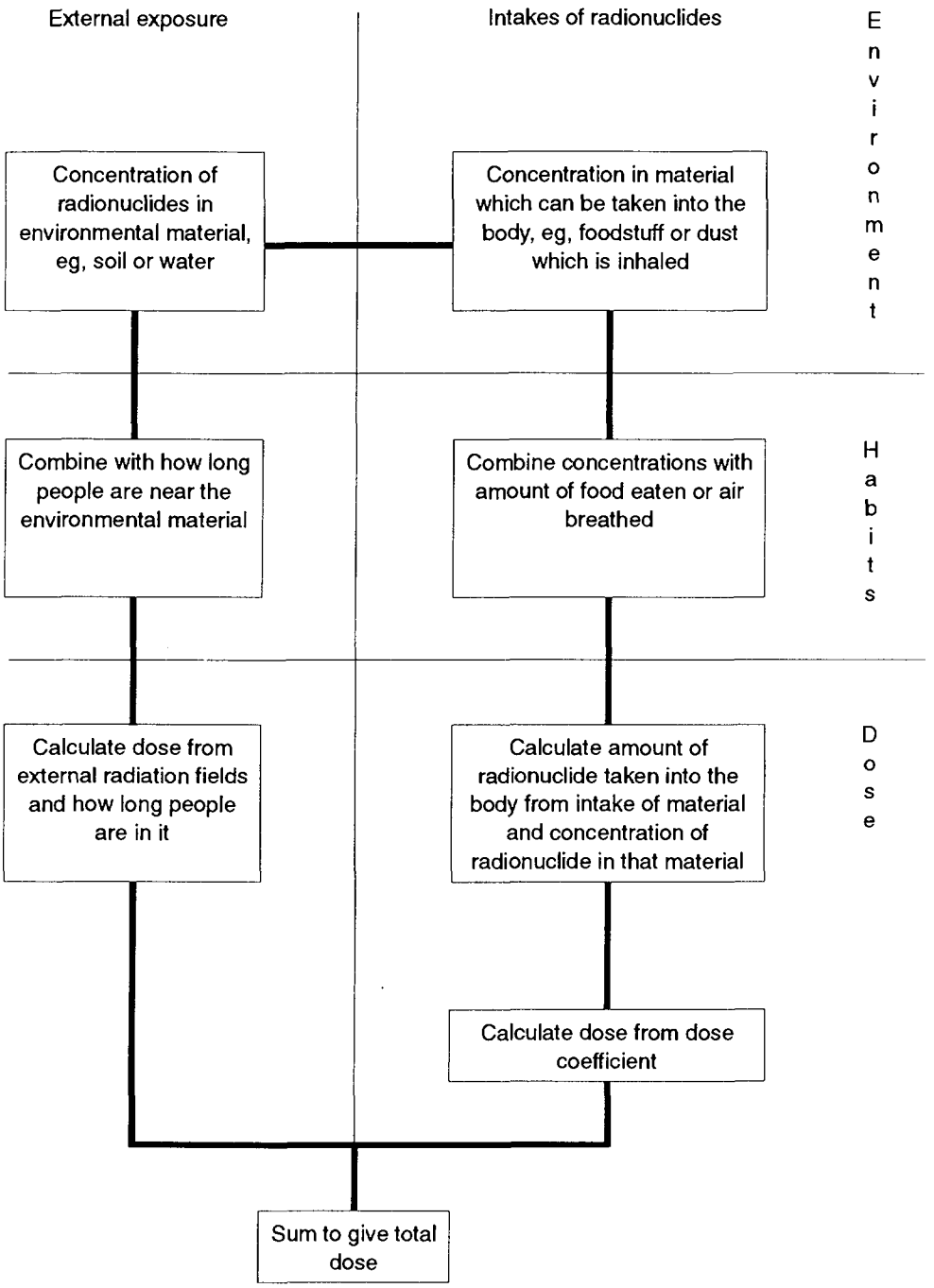

FIG. 1. Scheme for dose calculation.

1.1.GENERAL METHOLOGY FOR CALCULATING DOSES

People receive radiation doses in several different ways. Radionuclides emitting penetrating radiations, most commonly gamma radiation, can give rise to a radiation dose while outside the body (external dose). However, radionuclides in the air, in foods or on the ground, may also be taken into the body by inhalation, ingestion or through cuts and wounds. Once within the body, emitted radiation interacts with cells of organs where the radionuclides are stored, and those of neighbouring organs, giving a dose (internal dose). The approach used to calculate radiation doses is outlined briefly below.

Assessing doses is a three stage process, as demonstrated in Fig. 1. The first stage is to gather information about the environment, specifically the concentrations of radionuclides in environmental materials. For external doses, either the concentrations in soil or water or direct measurements are needed. For internal doses it is necessary to know concentrations in foods or aerosols which may be taken into the body. The activity concentrations and measured data used in this assessment are described in earlier volumes of this report. The second stage of the process is to combine concentrations with habit and dietary information. For external doses the amount of time spent in different radiation fields is needed, while for internal exposures information on the amount of food eaten or air breathed is required. The final stage is to use coefficients which either relate concentrations in soil to external dose rates (external doses), or which convert a unit of intake into dose (internal doses). These latter coefficients are estimated using complex mathematical models of radionuclide behaviour and radiation absorption in the body. Internationally agreed values for a large number of radionuclides have been derived by the ICRP and are published in the International Basic Safety Standards (IAEA, 1996). These values have been used in this assessment.

2. DOSES TO ATOLL RESIDENTS

2.1. THE REFERENCE GROUP POPULATION

Mururoa and Fangataufa were uninhabited atolls when developed by France as a testing site; either the natural resources or locations of these atolls, or both, are such as to discourage human habitation. There is therefore little recent history of human habitation on the atolls on which to base assumptions about possible future living patterns for an assumed resident population group. To support habitation, atolls generally must have adequate rainfall to provide fresh water for drinking and household purposes, and be of sufficient size to support the growth of a variety of tree and other fruits. Traditionally atoll dwellers have engaged in little cultivation of crops but have depended on the availability of adequate local fish supplies and atoll soil staples such as coconut (both milk and flesh) and arrowroot. There is a growing dependence also on imported foods (and drinks), and entirely traditional diets are now rare throughout the Pacific region, with conversion to staples of rice and noodles in locations well served by transport services.

For atolls in relatively close proximity, such as Mururoa and Fangataufa, a common residential pattern would be for one or more villages to be established on the larger islands of the larger atoll, and for the smaller atoll to be visited periodically for food gathering expeditions. Habitation is unlikely to be established in the future unless there are sufficient mature coconut groves, provision of some village infrastructure, including rain water collection and treatment, and transport links. If a hypothetical population group were to occupy Mururoa it could be expected that a village at the widest eastern end of the atoll (Anemone) would be established. Maintenance of the air strip would be considered important to maintain links with other parts of French Polynesia. The establishment of a resident population is also necessarily dependent on economic resources, and clearly the maintenance

of transport links would be a significant cost. Some revenue might be generated by copra production but the opportunities for significant revenues would seem limited. It is beyond the scope of this analysis to assess whether the establishment of a resident population would be an economic possibility.

Atolls can be divided into three areas of use to residents. The village area(s) is the most heavily utilised as this is where people live. It comprises houses, public buildings, roadways and useful plants. Coconut trees tend to be in a minority in villages but other useful plants and trees, such as breadfruit, are found in greater abundance. The second area of the atoll consists of the land area outside the village. This may be used mainly for copra production, although only land areas that are both sufficiently large and reasonably accessible are likely to be developed for this purpose. Residence islands of atolls are commonly the largest islands and may comprise a large fraction of the useable land area. The third area of atolls of importance for residents is the lagoon, from which reef fish and other marine species that contribute to diet are collected. The lagoon is also used to travel to other villages.

For radiological assessment purposes it is assumed that a population becomes established in a village at Anemone. It is further assumed that the supply of imported foods is restricted so that local marine and atoll sources dominate dietary intake and that there are no restrictions on fishing or gathering of land grown produce. It is to be noted that such assumptions could be valid only for a population of at most a few hundred persons. A larger resident population would require greater dependence on imported food.

The Mururoa hypothetical resident population would be the most exposed, and therefore the 'critical' or reference group, both for the near future (up to 100 years) and for periods of hundreds of years.

2.2. EXPOSURE PATHWAYS

The identifiable actual or potential exposure pathways for the hypothetical Mururoa resident population making use of locally available or potentially available foods are:

(a) external radiation from radionuclides deposited in soil
(b) inhalation of radionuclides resuspended from soil
(c) ingestion of foodstuffs grown on the atolls
(d) ingestion of fish and other marine environment species
(e) incorporation of plutonium containing particles in a wound
(f) ingestion of soil by young children (pica)
(g) external radiation from beaches and fishing gear.

2.3 EXPOSURE RATES FROM ARTIFICIAL RADIONUCLIDES CURRENTLY IN THE ENVIRONMENT

Doses to the hypothetical resident population on Mururoa arising from the different routes of exposure are considered in turn.

2.3.1. External radiation from radionuclides deposited in soil

Residual radioactivity from atmospheric tests contributes up to a few tens of μSv/a in part of the Kilo-Empereur region of Fangataufa, and lesser to negligible values in other areas of the two atolls. For the Anemone area, the terrestrial sampling results confirmed ^{137}Cs soil concentrations of the order of 1 Bq/kg or less, with the *in situ* monitoring showing areal concentrations of less than 100 Bq/m^2 and very low concentrations of other gamma emitters (see Technical Report, Vol. 1).

Measurements reported by Simon and Graham (1995) indicate that for coral soils an areal deposition of 100 Bq/m^2 of ^{137}Cs gives rise to an external effective dose rate of about 0.25 μSv/a. The external exposure rate in the Anemone area is therefore much less than 1 μSv/a. External photon radiation from plutonium and americium in the Colette region could give effective doses of the order of 100 μSv/a for continuous exposure in that region (see Technical Report, Vol. 1).

If visits were made to the Colette area from Anemone as frequently as 1 day in 20, and on average 4 hours were spent there per visit (see discussion in 2.3.4.3), the annual dose from external radiation due to artificial radionuclides would be about 1 μSv/a.

2.3.2. Inhalation of radionuclides resuspended from soil

Of the radionuclides present, those of greatest potential significance for the inhalation exposure pathway are $^{239+240}$Pu and ^{241}Am incorporated in surface soil particles which can be resuspended by wind and vehicle action. Detailed studies of coral soils in the northern Marshall Islands have found that the average resuspension of surface soil is very low, with resuspension factors ranging from 10^{-11}– 10^{-10}/m (IAEA, 1997). Similarly low resuspension factors have been found in the Palomares region of Spain, where explosive dispersal of fissile material occurred (Garcia–Olivares and Iranzo, 1997). These low values imply that even for the higher surface soil concentrations in the Colette and air strip regions inhalation doses are likely to be very low. The SMSRB measured mean air concentrations of $^{239+240}$Pu in 1994 in the Anemone region of 7.5 × 10^{-8} Bq/m^3 (French Liaison Office, Document No. 3) give rise to resident adult doses of about 0.03 μSv/a for a 'moderate' (M) clearance rate (IAEA, 1996), and about 0.01 μSv/a for 'slow' (S) clearance, with somewhat lower values for children. Mean air concentrations measured by the IAEA team over a limited sampling period in 1996 were, for Anemone, very similar to the 1994 SMSRB value, and for the Airport region 2 × 10^{-6} Bq/m^3, which was about an order of magnitude higher than the French value for the Kathie region. If the lower range of resuspension factors for the northern Marshall Islands were applicable to the higher surface concentrations of $^{239+240}$Pu on Colette (assuming an average of 3 × 10^6 Bq/m^2, and taking account of the fact that less than 2% of the activity is associated with particles of below 250 μm, and therefore within the respirable range (Technical Report, Vol. 1) continuous occupation in that area would incur a dose from resuspension of the order of less than 3 μSv/a for M clearance, or 1 μSv/a for S clearance.

If visits were made from Anemone on the same basis as postulated in (a) above, total annual doses from inhalation would be less than 0.1 μSv/a.

2.3.3. Ingestion of foodstuffs grown on the atolls, and of fish and other marine environment species

Doses incurred via the ingestion route are dependent on assumptions made about the types and amounts of foodstuffs in the diet of the reference population.

The atoll environment generally provides coconut and fish in abundance all year round, together with breadfruit, pandanus, bananas and other seasonal tree fruits. Chicken, pigs and, in French Polynesia, dogs, are also local sources of food. Total dependence on local foods no longer occurs, and imports of bread, rice and noodles have tended to replace traditional staples. Atoll geography and rainfall affect soil quality and productivity. Actual diets vary regionally and with atoll group and local characteristics, such as income level and regularity and nature of transport from regional centres, but a comparison of diets from areas as separated as the Marshall Islands and Tureia shows general similarities. Dietary survey data obtained by two independent surveys for "outer atoll" groups in the Marshalls are shown in Tables I (Robison et al., 1995) and II (Dignan et al., 1994).

TABLE I. LLNL* DIET MODEL FOR ADULTS ON BIKINI ISLAND (Robison et al., 1995)

Local Food	Imported foods diet g/d	Local foods only diet g/d
Reef fish	24.2	86.8
Tuna	13.9	72
Mahi Mahi	3.56	21.4
Marine crabs	1.68	19.5
Lobster	3.88	35.2
Clams	4.56	58.1
Trochus	0.10	0.24
Tridacna	1.67	11.4
Jedrul	3.08	19.4
Coconut crabs	3.13	24.9
Octopus	4.51	49.0
Turtle	4.34	17.8
Chicken muscle	8.36	31.2
Chicken liver	4.5	17.7
Chicken gizzard	1.66	3.32
Pork muscle	5.67	13.9
Pork liver	2.60	6.70
Pork heart	0.31	0.62
Bird muscle	2.71	26.4
Bird eggs	1.54	22.8
Chicken eggs	7.25	41.2
Turtle eggs	9.36	235
Pandanus fruit	8.66	63.0
Pandanus nuts	0.50	2.00
Breadfruit	27.2	186
Coconut juice	99.1	333
Coconut milk	51.9	122
Drinking coco flesh	31.7	181
Copra meat	12.2	71.3
Sprout. coco	7.79	122
Papaya	6.59	27
Pumpkin	1.24	5.44
Banana	0.02	0.58
Arrowroot	3.93	94.9
Citrus	0.10	0.2
Total Kcal/d	*547*	*2783*

* Lawrence Livermore National Laboratory.

Both show the effect of constraining importations of foods and maximising dependence on local foods. The "imported foods available" diets are fairly typical of current actual diets of Marshall Island "outer atoll" residents. Tables I and II may be compared with dietary information for Tureia, shown in Table III, as used by the Institut de Protection et de Surete Nucleaire (IPSN, 1995) for estimation of radiation doses from dietary intakes. The Tureia diet can be considered a reasonable approximation to the likely diet of a resident population at Mururoa under conditions of some constraints on imported foods. Tureia Atoll, however, is a closed atoll and noted for its production of clams. Clam consumption for a Mururoa population is therefore likely to be lower than that for Tureia. Atoll groups in French Polynesia with greater populations and with good links to regional

TABLE II. RONGELAP DIET ASSUMED FOR NWRS* (Dignan et al., 1994)

	Adult male diet of 18% local food + rice + imports (g/d)	Adult male diet of 75% local food + rice only (g/d)
Bird, KALO, roasted	14.0	59.7
Coconut cream (solid)	64.2	274.3
Coconut milk	16.1	68.8
Coconut, drinking	24.3	103.7
Coconut embryo	1.5	6.3
Coconut hard (waini)	5.3	22.8
Coconut soft (mede)	5.3	22.6
Coconut crab	1.3	5.4
Jekeru	83.5	357.1
Jemanin	3.7	15.8
Pandanus fruit, raw	12.7	54.5
Pandanus fruit, cooked	6.1	26.1
Papaya	6.9	29.4
Pork	2.7	11.4
Pumpkin	1.5	6.3
Reef fish	35.8	153.3
Ocean fish	20.1	86.2
Rice	500	500
Imported foods	~990	0
Total Kcal/d	*2484*	*2484*

*Nationwide Radiological Study [3].

TABLE III. SMSRB DIET FOR ADULT TUREIA POPULATION (IPSN 1995)

		Tureia derived g/d	Imported g/d
Beverages	Drinking water	2000	
	Coconut milk	144	
	Coco cola, soft drinks		0.27
	Imported fresh milk		0.52
	Beer		108
Meat	Dog	20	
	Pork	2.1	
	Chicken	5.4	33.0
	Eggs		24.8
	Beef		31.0
Fish	Reef fish	395	
Sea foods	Clam	40	
	Lobster	6.4	
	Octopus	26.7	
	Turban	1.6	
Fruit	Banana	7.7	
	Coconut flesh	104	
	Papaya	15	
	Breadfruit	7.2	
Miscellaneous	Bread		190
	Pasta		4.1
	Rice		85.5

TABLE IV. DOSES FROM INGESTION FOR A HYPOTHETICAL RESIDENT POPULATION AT ANEMONE (TUREIA DIET)

		Adult intake kg/a	Cs ratio to surf.soil	^{137}Cs Bq/kg	^{90}Sr Bq/kg	$^{239+240}Pu$ Bq/kg	^{241}Am Bq/kg	^{60}Co Bq/kg	^{238}Pu Bq/kg	^{137}Cs intake	^{90}Sr intake	$^{239+240}Pu$ intake	^{241}Am intake	^{60}Co intake	^{238}Pu intake	
Beverages	Drinking water	730	0	0	0	0	0	0	0	0	0	0	0	0	0	
	Coconut fluid	52.6	0.42	0.2	0.02	0	0	0	0	10.52	1.052	0	0	0	0	
										0	0	0	0	0	0	
Meat	Dog	7.26	3.2	1.5	0	0	0		0	10.89	0	0	0	0	0	
	Pork	0.77	3.2	1.5	0	0	0		0	1.155	0	0	0	0	0	
	Chicken	1.97	0.065	0.03	0	0	0		0	0.0591	0	0	0	0	0	
										0	0	0	0	0	0	
Fish	Reef fish	144.2		0.21	0.004	0.01	0.00013	0.3	0.002	30.282	0.5768	1.442	0.018746	0	0.2884	
										0	0	0	0	0	0	
Sea foods	Clam	14.6		0.063	0.002	0.75	0.05	3.1	0.15	0.9198	0.0292	10.95	0.73	0.438	2.19	
	Lobster	2.34		0.063	0.004	0.075	0.0013	0.03	0.015	0.14742	0.00936	0.1755	0.003042	0.234	0.0351	
	Octopus	9.75		0.063	0.004	0.075	0.0013	0.1	0.015	0.61425	0.039	0.73125	0.012675	0.2925	0.14625	
	Turban	0.58		0.063	0.002	0.75	0.05	0.03	0.15	0.03654	0.00116	0.435	0.029	0	0.087	
										0	0	0	0	0	0	
Fruit	Banana	2.81	0.065	0.03	0	0	0	0	0	0.0843	0	0	0	0	0	
	Coconut flesh	37.8	2.3	1.1	0.02	0	0	0	0	41.58	0.756	0	0	0	0	
	Papaya	5.48	0.36	0.2	0.02	0	0	0	0	1.096	0.1096	0	0	0	0	
	Breadfruit	2.63	0.13	0.06	0	0	0	0	0	0.1578	0	0	0	0	0	
								Total intake		97.5	2.57312	13.7	0.79	0.96	2.74675	Bq
								Dose coefficient		1.30E-08	2.80E-08	2.50E-07	2.00E-07	3.40E-09	2.30E-07	Sv/Bq
								Effective dose		1.27E-06	7.2E-08	3.43E-06	1.59E-07	3.28E-09	6.32E-07	Sv
										Total effective dose from ingestion of foods					5.57E-06	Sv

centres such as Tahiti have a greater proportion and variety of imported foods than the Tureia diet. The IPSN data for 1995 (IPSN, 1996) gives evidence of a resurvey of dietary components for Tureia residents indicating a shift towards greater reliance on imports. The 1994 diet is retained here for dose calculational purposes to provide more conservative, i.e. higher, dose estimates.

Comparison of doses assessed for the different atoll diets provides a degree of sensitivity analysis for dietary variations.

Using the IAEA measurements and SMSRB data on concentrations of radionuclides in marine and plant foodstuffs, committed effective doses have been calculated for each of the diets indicated in Tables I–III. Mururoa has only a limited number of coconuts to indicate concentrations in food crops which might be grown on the atoll and plant to surface soil ratios based on data for Bikini (Robison et al., 1995) have been employed to estimate expected plant and animal concentrations. These ratios are indicated in Table IV, which provides details of the dose calculation for the Tureia diet.

The water concentrations of radionuclides and concentration factors proposed in the Technical Report, Vol. 2 and Section 4 of the Main Report have been used to estimate concentrations in marine dietary components. These values are shown in Table V.

TABLE V. ASSESSED CONCENTRATION FACTORS (CF) AND CURRENT CONCENTRATIONS IN MARINE SPECIES IN MURUROA LAGOON

Nuclide	Water concentration Bq/m^3	CF for Fish	Bq/kg in Fish	CF in Molluscs	Bq/kg in Molluscs	CF in Crustacea	Bq/kg in Crustacea
^{90}Sr	2.0	2	0.004	1	0.002	2	0.004
^{137}Cs	2.1	100	0.21	30	0.063	30	0.063
$^{239+240}$Pu	0.25	40	0.01	3000	0.75	300	0.075
^{238}Pu	0.05	40	0.002	3000	0.15	300	0.015
^{241}Am	0.0025	50	0.00013	20000	0.050	500	0.0013

Annual doses to residents on Anemone from ingestion of local foodstuffs are 9.7, 3.1 and 5.6 μSv/a, respectively, for the diets of Tables I–III. It is to be noted that the imported food component (for foods shown in Table III as imported from Tahiti and outside French Polynesia) contributes a further 0.35 μSv/a, based on SMSRB data (IPSN, 1995).

The differences in annual doses between the three diets is very largely attributable to the differences in the amounts of molluscs, particularly clams, in the diets. The Marshalls Nationwide Radiological Survey (NWRS) diet does not have any clam in the diet, and this reflects the current living conditions of the Rongelap population living on Mejatto island of Kwajelein Atoll. For the Tureia diet, actinides in clams account for 54% of the annual dose.

The ingestion doses to residents on Anemone from ingestion of local foodstuffs (based on the Tureia diet) in Table IV are calculated taking account of all local dietary intake. This intake necessarily includes a contribution from global fallout, and the lagoon and ocean measurements of radionuclide concentrations indicate that almost all the lagoon water ^{137}Cs derives from global fallout. For the Tureia diet the marine ingestion pathway contributes about 0.4 μSv/a from ^{137}Cs in lagoon water. Local sources of radionuclides resulting from tests at Mururoa therefore contribute slightly less than the 5.6 μSv/a calculated for the Tureia diet. The distribution of dose contributions with radionuclide and foodstuff type is summarized in Table VI.

TABLE VI. SUMMARY OF INGESTION EFFECTIVE DOSE CONTRIBUTIONS FOR MURUROA RESIDENTS (μSv/a)

Radionuclide	^{90}Sr	^{60}Co	^{137}Cs	^{238}Pu	$^{239+240}Pu$	^{241}Am	All
Seafood	0.02	0.00	0.41	0.63	3.43	0.16	4.65
Other	0.05	0.00	0.86	0.00	0.00	0.00	0.91
Total diet	0.07	0.00	1.17	0.63	3.43	0.16	5.56

2.3.4. Incorporation of plutonium in a wound

2.3.4.1. Introduction

One potential hazard to future residents at Mururoa is incorporation of particles containing significant activities of $^{239+240}Pu$ and ^{241}Am in a wound as a result of an accident. The SMSRB (French Liaison Office, Document No. 2, 1996) has reported that particles with activities up to the order of 100 000 Bq of plutonium exist in the sand bank on the lagoon side of the Colette motu, and that these are fairly uniformly distributed in the sand thickness. This sand bank is covered by a few metres of water but the possibility of persons involved in activities (such as fishing or recreational diving being) in the area and suffering some injury has been considered. It is, perhaps more likely that an accident may occur, giving rise to incorporation of some soil, on the Colette, Ariel or Vesta Motus which also had plutonium dispersed on them as a consequence of the safety trials. These areas have been subject to several clean-up operations with average surface concentrations reported (French Liaison Office, Document No. 2) as now complying with a guidance clean-up level of 10^6 Bq/m^2 — averaged over 20 × 20 m^2. The IAEA monitoring team measurements indicate somewhat higher current peak levels by a factor of around 2 to 6, as discussed in the Technical Report, Vol. 1 and Section 4 of the Main Report. Comparable deposition levels occur also in parts of the area affected by explosive dispersal of plutonium following the accident in the Palomares region of Spain (Garcia-Olivares and Iranzo, 1997). It is to be noted that the emergent motus are largely coral 'bedrock' with little soil or sand over a large proportion of the area, that parts are below normal high tide levels, and that occasional storms wash over the entire area.

2.3.4.2. Doses from activity incorporated in a wound

Doses arising from accidents in which coral soil or particles are incorporated in grazes or wounds are not easily determined. Large masses of material would not normally remain incorporated but would be removed by normal wound treatment. Medical opinion was sought on the likely size of material which could be incorporated at the site of a wound and remain embedded over an extended period of time. The invariable response was that the volume of material would be 'very small' as a consequence of wound treatment and normal wound repair processes, but quantification was difficult. The volume of particles subcutaneously embedded during forestry and gorse clearing operations in a gorse infested area was used to provide representative information. Gorse is a prickly shrub whose spicules can readily penetrate the skin. Most commonly these cause irritation, or the site becomes infected and the spicule is removed. A small number may remain indefinitely. Most likely body sites for long term retention are hands and knees. Volumes of particles embedded were estimated from direct measurement of darkly coloured spicules visible in the skin. The estimates are necessarily subject to uncertainties of up to about 30%, but have been made conservatively in that over- rather than under-estimates have been made.

Particle sizes ranged from less than 0.02 to 0.4 mm^3, although smaller particles may have been present and less readily visible. Variates in biological systems are commonly distributed log-normally and a log-normal distribution fitted to the observed distribution had a mean of about 0.1 mm^3 and a standard deviation which gave a 99.9th percentile (3 standard deviation) volume of 2.1 mm^3.

There is inevitably some uncertainty as to how well gorse spicules might simulate the size distribution of incorporated coral particles or fragments. The very sharp nature of gorse spicules implies they penetrate skin very readily, but the particles also tend to be easily visible, as well as irritating, which aids their removal. To provide a conservative estimate of the likely distribution of incorporated coral material the mean of the observed gorse spicule distribution has been increased by a factor of 2, to give a mean of 0.2 mm^3 and a 99.9th percentile volume of 4.2 mm^3, i.e. the distribution

$$y = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(\log V - \log 0.2)^2}{2\sigma^2}}$$

where $\sigma = 0.4407$.

If a density of 2.4 g/cm^3 for solid coral, an average depth of distribution of Pu equal to 0.3 g/cm^2 is assumed (from information given in Vol. 1 of the Technical Report), and the average in the more contaminated area is 3×10^6 Bq/m^2, then the maximum average concentration at Colette is about 1000 Bq/g, and a practical upper limit to the mass of soil which might be retained as a result of a severe graze to a limb is about 0.01 g. If the plutonium distribution were entirely uniform the maximum incorporated in a wound would be about 10 Bq.

Consideration of committed effective doses from material incorporated subcutaneously has been given by Harrison et al. (1993) in studies carried out by the UK National Radiological Protection board (NRPB), of active particles from Maralinga incorporated in rats (appropriate values are given in Table VII). Doses incurred are dependent on rates of activity clearance from the wound site. Contaminated dust aerodynamically separated from soil had an initial dissolution (up to 1 month) with no evidence of continued clearance. Some particles studied which may be more representative of those at Colette, had a more extended dissolution and may be better approximated by the 10^{-3}/a clearance rate as an upper bound to calculated doses.

TABLE VII. DOSE PER UNIT OF ACTIVITY IMPLANTED SUBCUTANEOUSLY[1]

Nuclide	Fractional clearance from implant	Effective dose equivalent to age 70 a (Sv/Bq)			
		Child (1a)	Child (10 a)	Adult (20 a)	Adult (40 a)
^{238}Pu	10^{-2} acute	2.0×10^{-5}	1.2×10^{-5}	9.5×10^{-6}	6.6×10^{-6}
^{241}Am		2.1×10^{-5}	1.2×10^{-5}	9.8×10^{-6}	6.9×10^{-6}
^{239}Pu	10^{-3}/a	1.5×10^{-5}	1.0×10^{-5}	8.9×10^{-6}	5.9×10^{-6}
^{241}Am		1.6×10^{-5}	1.1×10^{-5}	9.2×10^{-6}	6.1×10^{-6}
^{239}Pu	10^{-4} acute	2.0×10^{-7}	1.2×10^{-7}	9.5×10^{-8}	6.6×10^{-8}
^{241}Am		2.1×10^{-7}	1.2×10^{-7}	9.8×10^{-8}	6.9×10^{-8}

[1] Based on information from Harrison et al. (1993).

For insoluble material in oxide form estimated committed doses to a 20 year old adult human could then be of the order of up to 9×10^{-6} Sv/Bq, implying a dose of up to about 100 μSv for a 10 Bq intake. Clearly, incorporation of a very active small particle could result in considerably larger doses than those estimated on the basis of average soil activity.

Subsequent analysis of active particles collected at Colette at NRPB (Pellow et al., 1998) confirmed that the dissolution characteristics of the particles were similar to those obtained from Maralinga. The NRPB study found that not more than 0.1% of particle activity would be dissolved and contribute to systemic body exposure over a 28 day period. Over longer periods the rate of dissolution could be expected to reduce both through decreasing availability through chemical changes and particle size reduction, and nodule formation at the site. The extreme scenario of continued dissolution at the initial rate could give rise to a committed effective dose to an adult over 50 years of about 190 μSv for a 10 kBq particle. This is a similar magnitude to that found in the more detailed study of Maralinga particles, for similar dissolution assumptions. Systemic doses of about 9 μSv/Bq of particle activity have therefore been assumed in the risk estimates made here. The assumption that no localized wound treatment occurs represents a worst case and could be considered to lead to an upper limit estimate of risk.

2.3.4.3. Radiological risks from activity incorporation in a wound

A number of probabilities need to be taken into account in the estimation of overall radiological risk.

a) The probability of residence on the atoll.
The likelihood of the establishment of a resident population in the longer term is not known. For the purpose of dose estimation the existence of a resident population in the Anemone region of Mururoa and having a fairly traditional atoll lifestyle is assumed.

b) The probability of visiting the Colette area from Anemone.
Reasons for visits would be almost entirely associated with food gathering activities. Access to the area by land is limited, with about half the area of the Colette motus being routinely subject to tidal inundation, and the ground, being largely coral rock, is unlikely to support food crop trees in the near future. Visits might, however, take place to fish along the lagoon side, although the relative remoteness of the area and the distance and difficulty of access have to be recognised. For current conditions a visit more frequently than 1 in 60 days is unlikely: for future conditions and for the purposes of dose estimation a visit by some adult persons for an average of 4 h/d on 1 day in 20 was assumed.

c) The probability of accident while in the area.
Accidents and incidents resulting in cuts from coral are not uncommon for atoll populations. These present opportunities for incorporation of soil or coral particles and fragments within the body. For the purposes of risk estimation it was assumed that an average younger (and more adventurous) person in an environment such as at Colette, may suffer a cut or wound with a frequency of 1 day in every 50, where the risk per day is equally spread over an 8 hour active period. (b) and (c) together imply an average annual individual risk of accident in the Colette region of about 0.2.

d) The probability of having a significant activity incorporated and retained in a wound.
This has two components.

   i) Estimation of the mass of soil or coral that might be incorporated. This is not easily estimated and in any particular event would be a value lying between zero and the maximum feasible quantity (estimated above as 0.01 g, or volume 0.004 ml).

ii) Estimation of the activity of $^{239+240}$Pu and ^{241}Am in the incorporated mass of soil. The distribution of "hot spots" of americium in a 10 × 10 m^2 area was systematically determined by the IAEA sampling team. If the assumption is made that each detected spot above the threshold of detection represents a single "hot particle", then for the plot sampled, the number of particles (above about 2500 Bq $^{239+240}$Pu equivalent) is 124, and these contribute around 5% of the total activity (see Technical Report, Vol. 1). A question arises as to how representative of the total Colette area the sampled plot is. A higher proportion of total activity was found in hot particles in loose coral soil, although this material was collected on a less systematic basis and half the very active particles came from a single sample. Apart from the two discrete large particles, the range of particle sizes found in the systematic sampling included that found from examination of loose soil.

e) The probability, having incorporated and retained a particle of a certain activity, of the consequent dose (reckoned at 9 μSv/a per Bq) leading to a late fatality due to cancer (reckoned at 5×10^{-2} fatalities per Sv).

At a meeting in May 1997 the French Liaison Office provided further information on the sampling conducted on Colette and neighbouring motus in 1986 prior to the final clean-up operation. Areas between 20 × 20 m gridlines were divided into 4 quadrants which were each carefully surveyed by detectors responding to ^{241}Am 60 keV photon emissions. Assuming total activities greater than 100 MBq/quadrant (as assessed by the French scientists) were cleaned up and those below were not, (and therefore should represent the current situation), there are 21 quadrants listed in a transect of Colette which had activities falling below 100 MBq. These had a mean number of hot particles and spots of 186, with a range of 12–362. The IAEA survey team result of 124 hot spots is well within this range, although there were undoubtedly some differences in measurement sensitivity between the types of instrumentation used. The French Liaison Office also provided data on the individual readings obtained for each hot spot or particle identified in one of the grid areas (G4) (see Technical Report, Vol. 1). For the G44 quadrant, which is the only one of the G4 grid not to have been cleaned up, as the total estimated activity was less than 1×10^8 Bq $^{239+240}$Pu, the total of the product of each (^{241}Am) activity reading and the number with that reading was 28170. The number of identified particles and spots was 278, and the given total $^{239+240}$Pu activity was 71.5 MBq, or a factor of about 2500 greater than the total reading. The activity readings on the G4 sheet are not therefore actual ^{241}Am activities, but assuming a plutonium/americium ratio of 50, about 1/50 of the americium activity. The tail on the particle activity distribution extends out to higher activities than the IAEA survey team found, but the general shape is similar. The distribution is shown in Fig. 2. The recorded readings show some evidence of bias in recording, with even and major scale figures being noted more frequently.

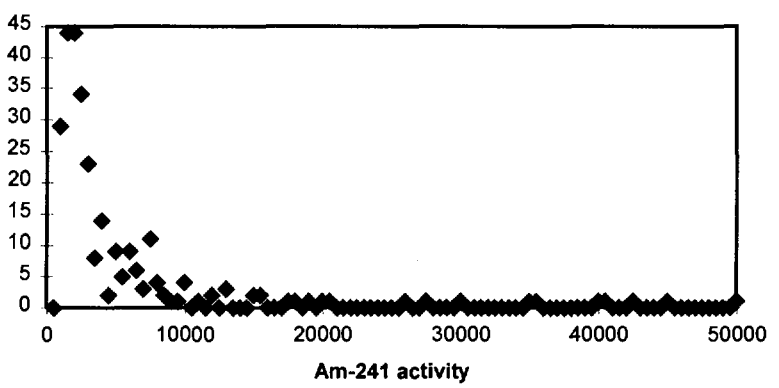

FIG. 2. Activity distribution of active particles found in quadrant G44.

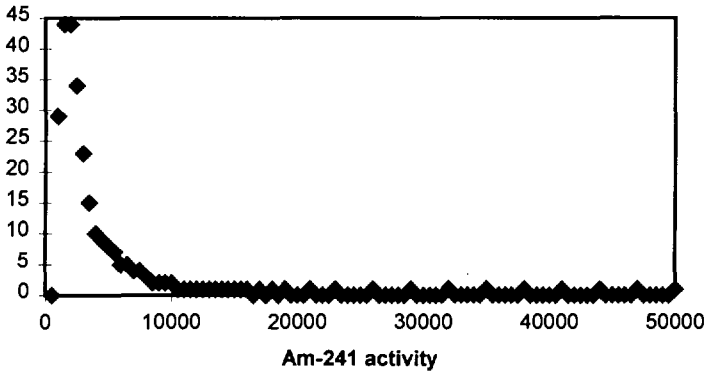

FIG. 3. Smoothed activity distribution of active particles found in quadrant G44.

The French Liaison Office supplied more complete information on the survey work on the affected motus in September 1997 (Ministère de la défense, 1997). This explained in detail the calibration procedure which was used to convert the count rate of the X-ray detector employed in the monitoring to $^{239+240}$Pu activity. The additional data also demonstrated that the number of active particles per 10 × 10 m^2 area for the G44 quadrant was representative of an above average activity per unit area for the Colette and Ariel motus and generally above levels found on the Vesta Motu.

As a basis for assessing risks from residual plutonium, it was assumed that the Colette area has a uniform "background" level of 120 MBq/100 m^2 and that active particles (individual activities > 2500 Bq) contribute a further 71.5 MBq/100 m^2 with a distribution shown in Fig. 3, obtained by smoothing the distribution above found by systematic sampling of the 10 × 10 m G44 plot. The average areal activity being assumed is therefore 191.5 MBq/100 m^2, and the number of active particles is 278/100 m^2. A "background" level of 120 MBq/100 m^2 corresponds to a surface concentration of about 400 Bq/g.

Some comparisons can be made with measurements carried out at the safety trials test site of Taranaki at Maralinga (Burns et al., 1986). There, for locations close to the firing pads, active particles per 100 m^2 numbered a few hundred and made up 10–30% of the total activity. The peak activity concentration found was about 200 Bq/g of plutonium.

The probability distribution for activity incorporated in a wound can be obtained from (i) and (ii) by Monte Carlo methods.

The activity in an incorporated volume of soil from the "background" level is 400Vρ or 960V Bq, where V is the volume in ml, and ρ is the density of coral. Sampling the distribution of retained incorporated particles determined above in sub-section 2.3.4.2, therefore provides an estimate of the distribution of activity incorporated from the relatively uniform distribution of small particles.

A volume V may, however, contain additionally a higher activity particle, activity A Bq, where A is sampled from the distribution in the figure above, and the probability one particle out of 278/100 m^2 is found in V is $278V\rho/(0.3 \times 10^6) = 0.00222V$. This assumes particles are small in relation to V. In reality the French activity data includes spots which have some lateral spread in addition to point sources of activity, with the points contributing 80% of the total activity, and inclusion of all identified particles and spots slightly overestimates activity incorporation. An additional factor to be considered, however, is that if the activity A is very large and the sampled volume, V, is small, it may not be physically possible for the active particle of activity A to fit in V. The mass of plutonium (assumed pure metal) in a volume 5 ml is $V\rho_p$, where ρ_p is the density of plutonium (16.5 g/ml). Metallic ^{239}Pu has an activity of 2.3×10^9 Bq/g so the limiting activity, A_L, in V is $2.3 \times 10^9 V\rho_p$.

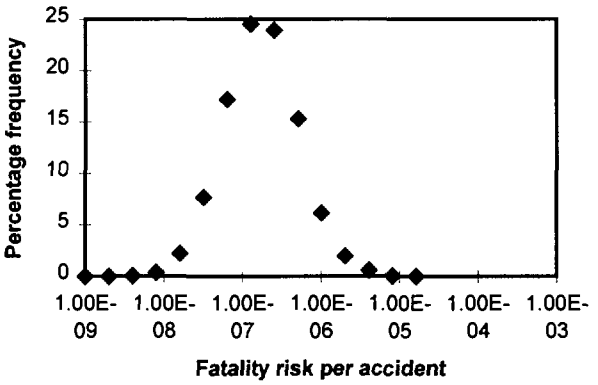

FIG. 4. Frequency distribution of fatality risk per accident.

The risk consequent upon an accident in the Colette area is then

$(960\ V + 0.00222\ VA)\ Bq \times 9 \times 10^{-6}\ Sv/Bq \times 5 \times 10^{-2}$ late fatalities/Sv, for $A < A_L$,
$= (960 + 2.22 \times 10^{-3} A)\ V \times 4.5 \times 10^{-7}$.

Inclusion of the probabilities (b) and (c) introduces a further factor of 0.2.

The overall annual risk distribution derived from a Monte Carlo analysis (10 000 cycles) is shown in Fig. 4. For log-normal distributions a 95th percentile value has sometimes been adopted as the effective upper limit for exposure or risk. For the risk assessment carried out here the 99.9th percentile is 3.7×10^{-6}/a. Taking account of the assumed probabilities of visiting the Colette area from Anemone and of the probability of an accident occurring while there, the 99.9th percentile of risk is 7.4×10^{-7}/a.

2.3.4.4. Conclusions

The IAEA survey measurements and subsequent extensive analyses, coupled with additional data provided by the French Liaison Office have provided sufficient information on the numbers and distribution of hot particles in the relatively remote Colette region to allow an upper estimate of the risk of a late fatality (due to cancer) to a resident population at Mururoa to be made. An examination of the risk distribution shows that the presence of active particles gives rise to a tail extending to larger values, the shape of the distribution being governed by the frequency distribution for the size of particle which could be incorporated at a wound site. There are recognised uncertainties in the form of this distribution although the parameters chosen would appear to provide a conservative estimate of risk. The 99th percentile of risk is likely to be less than 1×10^{-6}/a, and much less than a risk criterion for intervention in the situation of chronic potential exposure (See Section 11 in the Main Report of this Study (IAEA (1998)). The mean risk is comparable to that from inhalation.

2.3.5. Soil ingestion

There is evidence from some parts of the world of a tendency known as pica where individuals, primarily young children, ingest non-food items such as soil in significant quantities. Such behaviour tends to be intermittent and not to be sustained over an extended period, but amounts of 0.1–1 kg could be consumed over the course of a year.

The mean surface soil activity in the Anemone region is about 4 Bq/kg. Using the effective dose per Bq ingested conversion factor for 1–2 year old children $^{239+240}$Pu, in the Basic Safety Standards (IAEA, 1996), of 4.2×10^{-7}, implies maximum likely doses from this route of about 2

μSv/a. This may be an overestimate because the plutonium in soil may be less available (i.e. have a lower gut transfer factor) than that in usual dietary sources.

2.3.6. External radiation from beaches and fishing gear

For assumed occupancies of 2 h/d for both beach use and fishing (730 h/a), the annual doses to residents from external radiation from radionuclides present in lagoon water are several orders of magnitude below those from ingestion. The primary contributor to external exposure is ^{137}Cs. Fuller details are given in Section 3, below.

2.3.7. Summary of current exposures from artificial radionuclides already in the environment

Based on assessments using study measurements and concentration data provided by the French Liaison Office, the doses to a hypothetical population living in the Anemone region of Mururoa are as shown in Table VIII. Periodic excursions by residents to other parts of the atoll have been taken into account in the assessment.

TABLE VIII. SUMMARY OF EFFECTIVE DOSES TO ADULT MURUROA RESIDENTS (μSv/a)

Source	Mururoa - Anemone
Artificial	
External radiation, excluding natural	~1.1
Inhalation	<0.1
Ingestion	5.6
Total artificial	~7
Natural	
External radiation, natural	270
K-40 (internal)	180*
Po-210 + Pb-210	~940
Total natural	~1390
Total	~1390

* IPSN 1995

For comparison, Table VIII also gives estimated doses that would be received by the Anemone residents from naturally occurring sources of exposure. Concentrations of ^{210}Po in marine foodstuffs are derived from mean values obtained in an international (MARDOS) study (Aarkrog et al., 1997), where global concentrations of 2.4 Bq/kg wet weight (w.w.) in fish, 15 Bq/kg w.w. in molluscs, and 6 Bq/kg w.w. in crustacea were reported. However, the mean concentration of ^{210}Po in the flesh of reef fish from lagoons of coral atolls in the equatorial Pacific may be considerably higher than the mean level encountered in other species of fish from continental shelf and colder areas. A study by Jeffree et al. (1997) found enhanced uptake of ^{210}Po on zooplankton in French Polynesia. The concentrations of ^{210}Po in fish species found by Noshkin et al. (1994), in the Marshall Is are about 2–5 times greater than the mean values found in the MARDOS study. If similar concentrations applied at Mururoa,

doses from naturally occurring sources could reach 3 mSv/a. However, the assumption of a Tureia diet for Mururoa may distort the estimate of doses arising from natural sources somewhat, because of the high intake of clam flesh at Tureia, and the high natural concentration of ^{210}Po in clams.

Current annual doses to a hypothetical population resident at Anemone on Mururoa, and to residents of Tureia (the closest inhabited island) are compared in Table IX. The radionuclide content of all terrestrial and marine food items will contain some component due to global fallout. The contribution to terrestrial food items from global fallout is indeterminate, but in sea food it can be calculated, because the concentration of global fallout radionuclides in the open ocean is known. The contribution to the marine ingestion dose is estimated to be about 0.4 μSv/a for the Tureia diet. For Tureia residents the terrestrial foodstuffs ingestion route is more important because of the relatively higher ^{137}Cs concentrations in soil partly due to global fallout. However, the marine foodstuffs ingestion contribution is very small. The global fallout contribution to the marine foodstuffs ingestion doses of about 0.4 μSv/a, and ingestion doses arising from consumption of imported foods, have not been included for both groups in Table IX.

TABLE IX. EFFECTIVE DOSES TO ADULT RESIDENTS FROM NUCLEAR TESTS (μSv/a)

Source	Mururoa - Anemone	Tureia
External radiation, excluding natural	~1	<1
Inhalation	<0.1	-
Ingestion - terrestrial	0.9*	4*
Ingestion - marine	4.3#	0.01#
Total	~6	~5

* Some contribution from global fallout included.

The contribution to the marine ingestion dose of 0.4 μSv/a arising from global fallout is not included in these dose estimates.

The total annual dose rate from artificial radionuclides in the environment arising from the French nuclear tests is clearly a very small fraction of that due to natural sources, and trivial in relation to the uncertainty associated with the estimation of doses incurred from polonium in marine foodstuffs. It may be noted that the dose estimates are in close agreement with French estimates for both Mururoa (Bourlat, Millies–LaCroix and Martin, 1996) and Tureia (IPSN, 1995, 1996).

While the existence of a resident population on Fangataufa is considered impractical, the dose to a very small group on the area of Kilo of highest residual activity has been estimated for comparison purposes. The French measurements show peak soil concentrations of ^{137}Cs up to 200 Bq/kg (French Liaison Office Document No. 2), about an order of magnitude higher than the less extensive survey sampling results (see Technical Report, Vol. 1). French Liaison Office Document No. 2 also notes that the activity ratio of ^{137}Cs and other radionuclides to plutonium activity is relatively constant. The $^{239+240}$Pu concentration isopleths show a 3 km strip of the Kilo-Empereur region, largely on the lagoon side of the strip, with plutonium concentrations above about 100 Bq/kg. A much smaller area of about 5 ha has levels in the range 500–5000 Bq/kg implying a similar area of ^{137}Cs deposition in the range 20–200 Bq/kg. Sampling of coconuts in one of these pockets of higher concentration (located approximately 800 m from the southern end of the airstrip) showed coconut flesh concentrations of 170–190 Bq/kg. Based on these limited measurements in the higher soil concentration area, and assuming a coconut flesh ^{137}Cs concentration of 200 Bq/kg, the ingestion dose to a family or very small group deriving all plant foodstuffs from the immediate locality (not more than 1–2 ha) would be about 160 μSv/a. To this is to be added a contribution from external exposure

of up to about 60 μSv/a, based on French measurements (French Liaison Office, Document No. 3) and assuming full time occupancy within the peak exposure area.

2.4. DOSE TRENDS WITH TIME FROM RADIONUCLIDES CURRENTLY IN THE ENVIRONMENT

The current low levels of ^{90}Sr and ^{137}Cs in the terrestrial and marine environments arising from the atmospheric tests will decline at least as fast as the about 30 year half-life of the two nuclides. Natural removal processes will increase the rate of decline in concentrations, particularly in the marine environment, where decline with an effective half life of less than 20 years can be expected (Technical Report, Vol. 2).

Actinides in lagoon sediments can be expected to make a small contribution to resident population doses over a long time. The effect of a small net sedimentation rate coupled with sediment discharge from the lagoon, will be to dilute the concentrations in surface layers of sediment over a long time span. Assuming a small net sedimentation gain, and allowing for periodic turbulent mixing as a result of cyclones, the concentration of actinides in surface sediments could be expected to have declined to about one tenth or less of current levels after 1000 years. Concentrations in molluscs, as the main dietary contributor to doses from actinides, could be expected also to decline to at least a similar extent over this time span. In practice the observed rate of decline in plutonium concentration in filtered water has been particularly rapid with a significant decline over the last decade (Technical Report, Vol. 2).

Estimated future annual effective doses arising from the declining levels of artificial radionuclides currently in the environment and from predicted future releases from underground sources are estimated in the next section.

2.5. DOSES TO ATOLL RESIDENTS FROM FUTURE RELEASES

Section 8.4.1 of the Main Report (IAEA, 1998) provides estimates of the way the concentrations of ^{90}Sr, ^{137}Cs and plutonium in the lagoons will vary with time. The predicted concentrations of ^{90}Sr and ^{137}Cs decrease with time, while for plutonium the level declines initially with a half-time of about 10 years, but after about 100 years contributions from underground sources begin to appear, and the modelling predicts a new peak concentration, somewhat below the present day levels, in about 6000 years (see Fig. 109 in the Main Report of this Study (IAEA, 1998)).

TABLE X. VARIATION IN ANNUAL EFFECTIVE DOSES (μSv) TO MURUROA RESIDENTS WITH TIME FOR PREDICTED FUTURE ENVIRONMENTAL CONCENTRATIONS OF RADIONUCLIDES

Years from 1995	0	20	50	100	200	500	1000	2000	5000	10 000
External radiation	1.1	1.1	1.0	1.0	0.9	0.9	0.9	0.9	0.9	0.9
Ingestion-terrestrial	0.9	0.5	0.2	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Ingestion-marine	4.3	0.9	0.3	0.2	0.1	0.2	0.4	0.6	3.4	2.2
TOTAL	6.3	2.5	1.5	1.2	1.0	1.1	1.3	1.5	4.3	3.1

Based on these predicted concentrations in Mururoa lagoon, doses arising from ingestion of marine foods to Mururoa residents at future times have been calculated and are shown in Table X. Future doses arising from ^{137}Cs and ^{90}Sr in food from terrestrial sources were calculated assuming a 25 year half-time for decline in contemporary concentrations of these nuclides in the terrestrial environment. The assumption was also made that residents' diets and habits would be unchanged throughout the entire period.

Doses in the far future are dominated by the long term release rate of plutonium to the lagoons, but are very small fractions of doses arising from natural sources.

3. DOSES TO OTHER SOUTH PACIFIC RESIDENTS

The release of radionuclides from either current or future discharges from Mururoa and Fangataufa atolls can contribute to radiation exposures of persons elsewhere in the South pacific only by ocean transport, and primarily via the seafood ingestion route. Other, minor, pathways are external radiation from radionuclides in beach sediments, and doses to fishermen from handling fishing gear with adhering radioactive particulates. The nearest inhabited atolls are those of Tureia to the north-east, and Tematangi to the west, both supporting small populations. The estimation of concentrations at South Pacific locations is described in Vol. 5 of the Technical Report (and in Section 8 of the Main Report of this Study (IAEA, 1998)) for different postulated releases and release rates.

Doses to high seafood consumers resident in the South Pacific have been estimated from the dietary intake for such consumers proposed in the IAEA Safety Series No. 7– 8 (IAEA, 1986). This diet comprises a daily intake of 300 g of fish, and 100 g each of molluscs, crustacea and seaweeds, and can be considered to provide a basis for comparing indicator upper limit doses rather than estimating actual doses to residents. Generic concentration factors (i.e. the ratio of the concentration in each type of seafood to that in sea water) for different elements have been published by the IAEA (IAEA, 1985). These data, together with the above ingestion rates and internationally agreed dose conversion factors (IAEA, 1996), have been used to derive a dose per unit sea water concentration conversion factor for a number of significant radionuclides. These data are presented in Table XI.

TABLE XI. ANNUAL DOSES TO 'HIGH SEAFOOD CONSUMERS' FOR A SEA WATER CONCENTRATION OF 1 Bq/m^3

Nuclide	Annual dose (μSv/a per Bq/m^3)
^{60}Co	2.9
^{90}Sr	0.014
^{129}I	0.52
^{137}Cs	0.20
^{237}Np	2.3
$^{239+240}Pu$	49.5
^{241}Am	208

The Equidistant-Grid Compartmental model as described in Vol. 5 of the Technical Report has been used to provide estimates of surface water concentrations at various Pacific islands at various times in the future. These concentrations have been calculated using the time dependent predicted releases of ^{90}Sr, ^{137}Cs and plutonium from the atolls discussed in Section 8.4.2, and shown in Fig. 114, of the Main Report. Doses currently (calculated for 1995) arising to high seafood consumers, as defined above, are shown in Table XII, where the dominant contributions to doses are from actinides. Over time, the dose to high seafood consumers in the South Pacific will track the release rate from the atolls, so that in about 6000 years hence, annual doses are predicted to rise again as shown in Fig. 5, to be about one third the current low levels. It may be noted from Vol. 5 of the Technical Report that the Equidistant-Grid Compartment model for ocean dispersion provides somewhat higher estimates of maximum concentrations than the MELPAC and South Pacific Compartment models. The assumption has also been made that all releases are into surface waters, whereas some releases directly to the ocean (i.e. not via the lagoons) could be into waters deeper than 450 m.

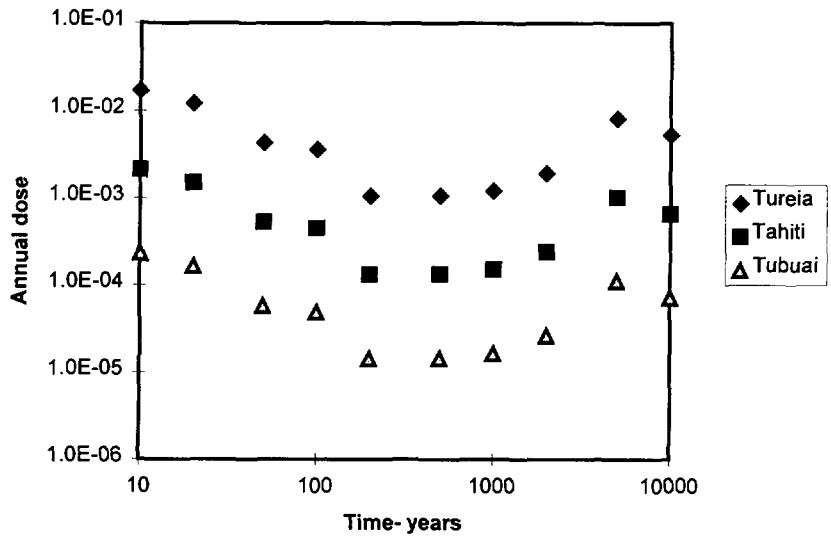

FIG. 5. Summary of doses (μSv/a) to "high sea food" consumers from releases from Mururoa and Fangataufa.

In Table XII and Fig. 5 the contribution from ^{238}Pu has been included assuming a concentration of 0.2 that of $^{239+240}Pu$ initially, and taking account of ^{238}Pu radioactive decay. Over 90% of the doses are contributed by plutonium isotopes.

TABLE XII. CURRENT ANNUAL EFFECTIVE DOSES TO 'HIGH SEAFOOD CONSUMERS' ON FRENCH POLYNESIAN ISLANDS ARISING FROM RELEASES FROM MURUROA AND FANGATAUFA

Island	Tureia	Hao	Tahiti	Temetangi	Mangareva	Tubuai
Annual dose (μSv/a)	0.026	0.0064	0.0032	0.018	0.0046	0.00035

3.1. EXPOSURES FROM OCEAN–BORNE SEDIMENTS

Estimates of conversion factors to convert concentrations in unfiltered sea water to effective doses from external exposures from beach sediments and fishing gear are shown in Table XIII (Cooper, 1997). A suspended sediment load of 10^{-7} t/m^3 is assumed, appropriate to the mid ocean region. The external dose rates over beach sediments were calculated using an external dose model (Simmonds et al., 1995) which estimates the dose rate one metre above an infinite area with activity well mixed down to a depth of 0.3 m. The concentration in beach materials is assumed to be the same as that in suspended sediment. The external dose rates from handling fishing gear are estimated by scaling the dose rates over beach sediments on the basis of a model described by Hunt (1984). Sediment K_ds are from IAEA Technical Report 247 (IAEA, 1985).

Some measurements carried out by the National Radiological Protection Board suggested that concentrations in sandy beaches are around an order of magnitude lower than the calculated value for suspended sediment (Cooper, 1997). The rates from beach sediments in Table XIII have been reduced by a factor of 10 to take this into account.

TABLE XIII. EXTERNAL EXPOSURE RATES FROM BEACH SEDIMENTS AND FISHING GEAR FROM ACTIVITY IN SUSPENDED SEDIMENTS

Nuclide	Beach sediments (Sv/h)/(Bq/m^3)	Fishing gear (Sv/h)/(Bq/m^3)
^{90}Sr	1.4×10^{-18}	1.4×10^{-20}
^{137}Cs	2.9×10^{-10}	2.9×10^{-12}
^{238}Pu	2.8×10^{-13}	2.8×10^{-15}
$^{239+240}$Pu	6.3×10^{-13}	6.3×10^{-15}

For assumed islander occupancies of 2 h/d for both beach use and fishing (730 h/a), the annual doses to islander residents from external radiation from radionuclides released from Mururoa and Fangataufa are 3–4 orders of magnitude below those from ingestion. The primary contributor to external exposure is ^{137}Cs.

3. 2. DOSES FROM RELEASES IN PERSPECTIVE

As a comparison of the magnitude of the doses arising from releases, it may be noted that for Tureia, for which the highest annual doses are calculated, the current annual doses are equivalent to the doses received from about 5 min exposure to average natural radiation sources. Doses at other locations and times are all lower. For islands in the Cook's group and further west, doses to high sea food consumers are unlikely to exceed 0.001 μSv/a either now or at any future time.

4. DOSES FROM POSSIBLE DISRUPTIVE OR CLIMATE CHANGE EVENTS

Section 7 of the Main Report evaluated a range of hypothetical disruptive and climate change events which could affect the atolls over the long term. Of these, two were assessed as possibly having implications for modifying releases from the atolls and therefore perhaps having some implications for human exposure. The radiation dose implications are evaluated here.

4.1. SLIDE OF CARBONATE ROCK IN THE NORTHERN REGION OF MURUROA

In Section 7 of the Main Report a major slide of carbonate rock is assumed to occur in the near future on the northern flank of Mururoa in an area which included a number of CRTV tests, and all of the underground safety trials. It is assumed that this slide intersects the chimney of one of the CRTV tests (with a yield of 5 kt) and the cavity of one safety trial containing 3.7 kg of plutonium. It is further assumed that all of the plutonium from the safety trial and the radioactive material in the cavity chimney of the CRTV test is released instantaneously into the ocean. The assumed releases are ^{3}H, 1000 TBq; ^{90}Sr, 10 TBq; ^{137}Cs, 30 TBq; and $^{239+240}Pu$, 10 TBq, as shown in Table XLIX of the Main Report. Both the Equidistant-Grid Compartmental model and the MELPAC model evaluate instantaneous release situations and the resulting time variation of radionuclide concentrations at regional locations. The models show that, if the release occurs above a depth of about 400 m, the peak concentrations at the nearest island of Tureia occur within the first few months; while for locations further away, such as Tahiti and Hao, the peak concentrations are lower and at times of 2–3 years. The average concentration in the 0–450 m column predicted by the two models can be compared for the predicted magnitude and depth of release. The models give values which are generally within a factor of three of each other, with the equidistant grid model giving the higher values. If the releases were to occur at depths greater than the thermocline, higher concentrations at depth in sea water could occur at some islands, but there would be little impact on food sources consumed so that lower doses would result.

The time variation of ingestion doses to high intake sea food consumers at Tureia and Tahiti is shown in Table XIV, calculated for the concentrations predicted by the Equidistant-Grid Compartmental model. For high sea-food intake residents on Tureia, the maximum dose, which would be received during the first year following the release, is about 7 μSv declining to 3 μSv in the second year. Even though the doses assessed are very low, the pessimistic nature of the assumptions underlying these dose estimates should be recognised. Most of the dose is contributed by the plutonium postulated to be involved in the slide and assumed all to go into solution. In reality this is unlikely to occur.

TABLE XIV. MAXIMUM DOSES TO HIGH SEA FOOD CONSUMERS IN THE YEARS FOLLOWING A POSTULATED INSTANTANEOUS RELEASE RESULTING FROM A ROCK SLIDE (ANNUAL DOSES IN THE INDICATED YEAR IN MICROSIEVERTS)

Year	1	2	3	5	10	20
Tureia	6.6	2.8	1.2	0.42	0.09	0.004
Hao	0.39	0.93	0.53	0.25	0.08	0.003
Tahiti	0.006	0.21	0.41	0.18	0.04	0.002

4.2. GLACIATION

An ice age, after a postulated 50 000 years (see Section 7 of the Main Report), would result in drainage of the lagoon and the potential for a resident population to be exposed via the inhalation pathway to residual plutonium in lagoon sediments. Sediment production and exchange processes

currently result in a loss from the lagoon of about 5.4 GBq/a, or about 0.03%/a of the total inventory in sediments. Over recent years, however, the rate of loss has been declining, so that removal by solution and sediment transfer may be of less significance in the future. Even if not all the material was as available for removal as that currently being removed, a net increase in sediment thickness of about 2 mm/a would result in a very great reduction in surface concentrations over a period as long as that being considered. The effect of sedimentation, coupled with periodic surface layer mixing as a result of storms and bioturbation, is to continuously dilute the concentration of radionuclides in the surface layer. Assuming only radioactive decay, and a net sedimentation increase of only 0.07 mm/a (the lowest rate estimate), the present mean surface concentration of less than 200 Bq/kg could be expected to reduce to well below 5 Bq/kg, over the next 25 000 years, with at least a similar proportionate reduction in concentration over the following 25 000 years. The dose from resuspension and inhalation for a surface concentration of 5 Bq/kg, for moderately dusty conditions (100 $\mu g/m^3$ with an enhancement factor of 3 (Shinn et al., 1997)) is about 0.6 μSv/a. The inhalation dose from residual plutonium can be considered trivial should the lagoon bed be dry and inhabited in 50 000 years.

The glaciation scenario discussed in 7.3.2 also postulated the formation of a fresh water lens which might extend to the region of the cavities of the safety trials in the carbonates. Three of the seven underground safety trials went critical forming a lava of the basalt sand and cuttings used for packing, in which much of the residual plutonium would be trapped. The plutonium left after the non-critical trials would be free to dissolve in the water saturating the carbonate formations. The analysis, based on the unlikely assumption of total retention of the plutonium released from the four cavities in the carbonates, led to an average concentration in the water of about 3 Bq/m^3. If such water were used untreated for drinking, based on a daily intake of 1.7 L (ICRP 23), annual doses of about 0.5 μSv/a would be received.

The possibility was also considered of high concentration plutonium plumes existing in the immediate vicinity of each of the four non-critical safety trial sites (see Technical Report, Vol. 4, Sec. 3.4.1). A plume volume of about 200 m^3 of porous rock, implying a high concentration water volume of about 70 m^3 for a 30% porosity, was estimated, and the possibility considered of a bore being drilled into such a region. The concentration of plutonium in the water of these plumes is assumed to be at the solubility limit which Working Group 4 has recommended, in these circumstances, to be 10^{-8} molar or 6×10^3 Bq/L (Technical Report, Vol. 4, Sec. 4.3.1). The continuous drinking of water at this concentration would lead to a dose rate of about 1 Sv/a which would constitute a serious health risk. It is, however, not conceivable that water of the above concentration would be brought to the surface without dilution — a dilution of only 100 would reduce potential doses to about the IAEA suggested generic guideline for intervention of 10 mSv/a. In addition, the probability that such exposures will occur must be extremely small. Taking account of the depth of the safety trials (at least 280 m), and that fresh water extraction would more likely occur at shallower depths and towards the centre of the island rather than at the rim near the sea where the safety trials were located, the probability of direct extraction of high concentration plume water is less than $70 \times 4/(6 \times 10^9) \cong 5 \times 10^{-8}$, where the number of non-critical safety trials in the carbonates is 4 and the estimated fresh water volume of the lens is 6×10^9 m^3.

Any analysis based on events in the far future must involve conjecture. Thus, in this assessment, it has been assumed, for example, that the safety trial cavities will be in the fresh water lens, that underground bores would be the source of fresh water rather than alternative technologies (such as desalination), that the water would not be analysed or treated before drinking, and that risk factors for ingestion of radionuclides would not have been reduced by advances in medical science. The risk associated with such a remote occurrence was considered to be so low that it was not explored further.

5. SUMMARY AND CONCLUSIONS ON DOSES TO POPULATIONS IN THE SOUTH PACIFIC REGION

Current and future doses to a hypothetical population resident on Mururoa from existing environmental concentrations and future releases, and to high sea food consumers on some French Polynesian islands from potential future releases from Mururoa and Fangataufa are summarised in Table XV. The doses to high seafood consumers do not include the currently larger contributions due to global fallout of radionuclides in the terrestrial and marine environments arising from all atmospheric nuclear testing.

TABLE XV. SUMMARY OF ANNUAL EFFECTIVE DOSES FROM RESIDUAL RADIOACTIVITY AT MURUROA AND FANGATAUFA

	Annual doses (μSv) at various times in the future (a)									
	1	20	50	100	200	500	1000	2000	5000	10000
Mururoa residents	6	3	2	1	1	1	1	1	4	3
High sea-food consumers										
Tureia	0.03	0.01	0.004	0.004	0.001	0.001	0.001	0.002	0.008	0.005
Tahiti	0.003	0.002	0.0005	0.0005	0.0001	0.0001	0.0002	0.0002	0.001	0.001
Tubuai	0.0004	0.0002	0.00006	0.00005	0.00001	0.00001	0.00002	0.00003	0.00001	0.00007

The calculated annual doses from dispersion of radionuclides from the weapons testing programme at Mururoa and Fangataufa are all very small when compared with annual doses from other common sources and in particular are a very small fraction of the doses from naturally occurring radiation sources. The health impact must be a similarly insignificant fraction of whatever health impact may be associated with normal natural background radiation.

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Part B

DOSES TO BIOTA

1. INTRODUCTION

An assessment of the potential environmental impact of the residual contaminant radionuclides from the nuclear weapons testing at Mururoa and Fangataufa requires estimates of the incremental dose rates to a variety of marine organisms inhabiting a number of different ecological niches. These estimated dose rates provide the only secure basis for an assessment of the potential radiation effects in the organisms. The approach adopted for this assessment is that employed in a number of recent studies (IAEA, 1988, 1992; NCRP, 1991) and adapts the dosimetry models for the particular organisms of interest in the atoll environment.

2. DOSIMETRY MODELS

2.1. FOR DISPERSED RADIONUCLIDES

The organisms that may be considered in the assessment are dictated by the availability of data on radionuclide concentrations in both their tissues and their external environment. Each the organisms has been represented by a simplified geometry and the models are summarized in Table I. The following is a brief account of the dosimetry models and fuller information is given in (IAEA, 1979, 1988; NCRP,1991).

TABLE I. DOSIMETRY MODELS ADOPTED FOR THE ESTIMATION OF DOSE RATES TO MARINE ORGANISMS FROM BETA AND GAMMA RADIATION

Organism	Geometry	Mass	Major axes cm	Comments
Zooplankton	Flat ellipsoid	16 mg	0.63 × 0.31 × 0.16	
Shrimp	Flat ellipsoid	2 g	3.1 × 1.6 × 0.76	
Pearl oyster	Flat ellipsoid	100 g	12 × 5.8 × 2.9	Soft tissue only
Troca	Sphere	500 g	9.8 cm diameter	Soft tissue only
Lobster	Thick ellipsoid	300 g	12 × 8.6 × 5.8	
Small fish	Elongated ellipsoid	1 kg	45 × 8.7 × 4.9	
Large fish	Elongated ellipsoid	10 kg	97 × 19 × 10	

In the absence of more detailed information, it has had to be assumed that the measured radionuclide concentrations in the organisms are uniformly distributed throughout the soft tissues of the whole body. For α-radiation with short ranges (a few 10s of μm) in tissue, this will lead to underestimates of the dose rates to specific tissues if there is preferential accumulation of the relevant radionuclides in particular organs. The short range of these radiations also means that essentially the only source of exposure is internal contamination, and that the dose rate is the equilibrium value in an effectively infinite source (IAEA, 1979), i.e.

$$D_\alpha(\infty) = 0.576\ C\ E_\alpha\ n_\alpha \text{ nGy/h}$$

where

C is the radionuclide concentration in Bq/kg;
E_α is the α-particle energy in MeV; and
n_α is the emission proportion of α-particles with energy E_α Mev.

The corollary is that there is essentially no contribution to the dose rate from α-particle sources outside the bodies of the organisms.

For β-radiation, the dimensions of the models for the zooplankton and the shrimp are sufficiently small that the dose rate at the centre of the organism can be less than $D_\beta(\infty)$ for the higher β-energies (see pp. 44–45 of (IAEA,1988), and Fig. 1 (for β-particles) and Fig. 2 (for mono-energetic electrons)). The dose rate from high energy β-emitters in the water and sediment can also be estimated using the data in Fig. 1. For the larger organisms, the β-radiation dose rate at the centre from internal sources is effectively $D_\beta(\infty)$, and that from external sources effectively zero.

The range of γ-radiation in tissue is such that a significant proportion of the γ-ray energy emitted by internal contamination is dissipated outside the bodies of all the organisms considered here. The absorbed fractions for the differing geometries have been taken directly, or extrapolated, from the data tabulated by Brownell et al. (1968) (see Fig. 3).

The estimated dose rates from a variety of radionuclides detected in the atoll environments are given in Table II and, in summary form, in Table III. Estimated dose rates from the natural radionuclide, ^{40}K, are included for comparison; these values are based on data for the ^{40}K content of the coral sand in the Mururoa and Fangtaufa lagoons available from the present study, and the reasonable assumptions that the ^{40}K contents of both seawater (only varies with salinity) and the organisms (under homeostatic control) would be the same as those given previously (IAEA, 1976).

Text cont. on p. 39.

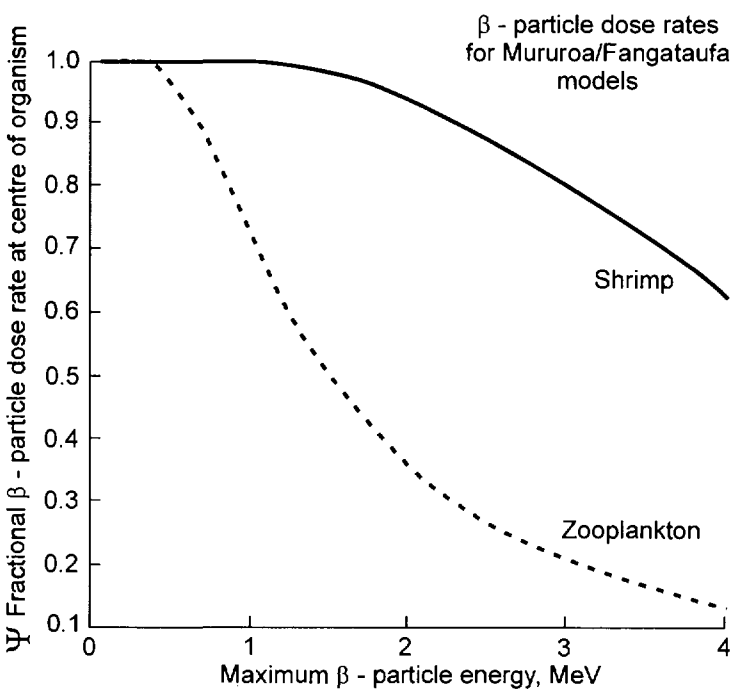

FIG. 1. β-particle absorbed dose rate at the centre of the organisms as a fraction of the corresponding $D_\beta(\infty)$. A uniform distribution of the radionuclides in the body of the organisms has been assumed.

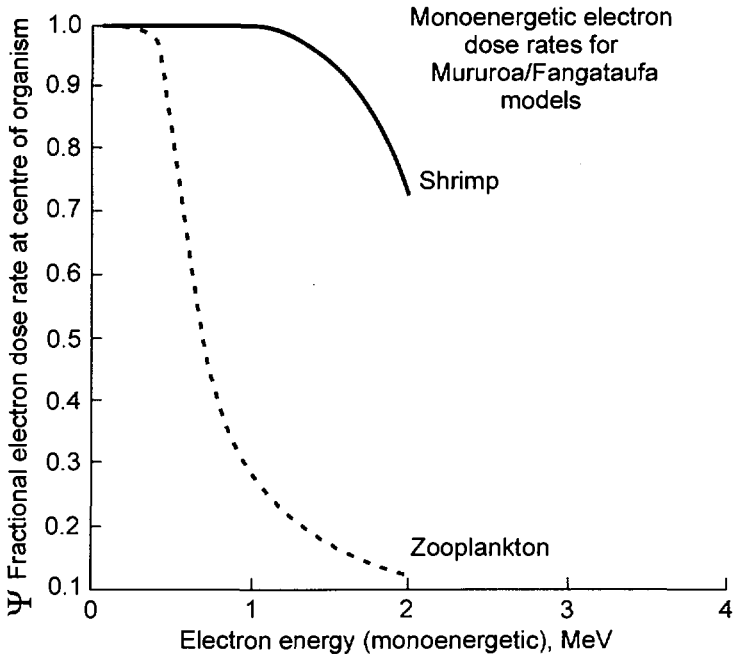

FIG. 2. *Absorbed dose rate from mono-energetic electrons at the centre of the organisms as a fraction of the corresponding $D_e(\infty)$. A uniform distribution of the radionuclides in the body of the organisms has been assumed.*

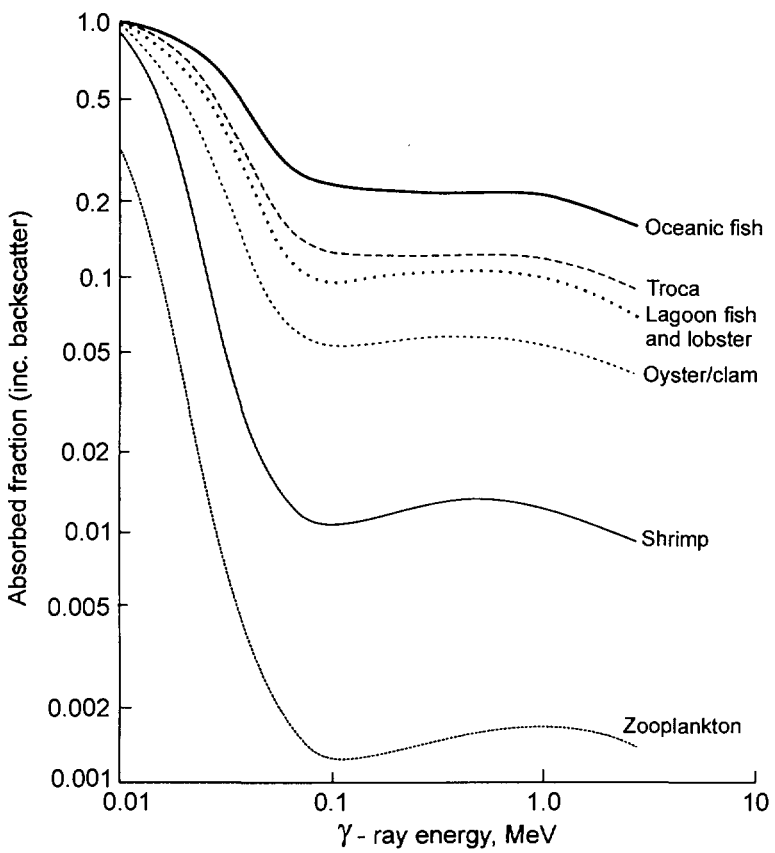

FIG. 3. *The γ-ray absorbed fractions (including backscatter) for a uniform distribution of the radionuclides in the body of the organisms.*

TABLE II. ESTIMATED DOSE RATES TO MARINE ORGANISMS FROM DISPERSED RADIONUCLIDES, nGy/h

Source	Nuclide	Lagoon zooplankton		Small benthic crustacean		Pearl oyster	
		Low LET radiation	High LET radiation	Low LET radiation	High LET radiation	Low LET radiation	High LET radiation
Contaminants in							
Water	^{90}Sr-^{90}Y	6.7×10^{-4} to 1.8×10^{-3}	NA	3.4×10^{-4} to 9.0×10^{-4}	NA	ND	NA
	^{137}Cs	5.9×10^{-4} to 1.4×10^{-3}	NA	2.9×10^{-4} to 6.9×10^{-4}	NA	2.6×10^{-4} to 6.1×10^{-4}	NA
	^{99}Tc	2.3×10^{-8} to 3.5×10^{-8}	NA	1.2×10^{-8} to 1.8×10^{-8}	NA	NA	NA
	^{241}Am	4.3×10^{-8} to 1.4×10^{-7}	NA	2.1×10^{-8} to 6.9×10^{-8}	NA	1.6×10^{-8} to 5.5×10^{-8}	NA
Tissue	^{3}H	3.0×10^{-4} to 2.2×10^{-3}	NA	3.0×10^{-4} to 2.2×10^{-3}	NA	3.0×10^{-4} to 2.2×10^{-3}	NA
	^{90}Sr-^{90}Y	ND	NA	ND	NA	5.9×10^{-3}	NA
	^{137}Cs	1.8×10^{-3} to 4.8×10^{-3}	NA	1.8×10^{-3} to 4.8×10^{-3}	NA	6.4×10^{-3}	NA
	^{60}Co	1.1×10^{-2} to 6.8×10^{-2}	NA	1.1×10^{-2} to 6.8×10^{-2}	NA	1.2×10^{0}	NA
	^{155}Eu	3.2×10^{-2}	NA	3.2×10^{-2}	NA	9.8×10^{-3} to 4.2×10^{-2}	NA
	$^{239+240}Pu$	NA	9.0×10^{0} to 1.6×10^{2}	NA	9.0×10^{0} to 1.6×10^{2}	NA	7.7×10^{0} to 1.0×10^{1}
	^{238}Pu	NA	1.1×10^{0} to 4.0×10^{1}	NA	1.1×10^{0} to 4.0×10^{1}	NA	2.6×10^{0} to 4.2×10^{0}
	^{241}Am	5.6×10^{-4}	6.5×10^{0}	5.6×10^{-4}	6.5×10^{0}	1.1×10^{-3} to 1.4×10^{-3}	8.4×10^{-1} to 1.1×10^{0}
Sediment	^{137}Cs	NA	NA	1.4×10^{-1} to 2.5×10^{2}	NA	1.1×10^{-1} to 2.2×10^{2}	NA
	^{60}Co	NA	NA	4.6×10^{1} to 6.3×10^{2}	NA	4.4×10^{1} to 6.0×10^{2}	NA
	^{155}Eu	NA	NA	2.3×10^{-2} to 2.8×10^{1}	NA	1.9×10^{-2} to 2.3×10^{1}	NA
	^{241}Am	NA	NA	1.3×10^{-3} to 1.9×10^{2}	NA	1.0×10^{-3} to 1.5×10^{2}	NA
Total dose rate		1.4×10^{-2} to 1.1×10^{-1}	1.0×10^{1} to 2.0×10^{2}	4.6×10^{1} to 1.1×10^{3}	1.0×10^{1} to 2.0×10^{2}	4.4×10^{1} to 1.0×10^{3}	1.1×10^{1} to 1.6×10^{1}
Background							
Water	^{40}K	3.2×10^{0}	NA	1.5×10^{0}	1.5×10^{0} NA	5.1×10^{-1}	5.1×10^{-1} NA
Tissue	^{40}K	1.2×10^{1}	NA	1.2×10^{1}	1.2×10^{1} NA	3.3×10^{1}	3.3×10^{1} NA
Sediment	^{40}K *	NA	NA	1.4×10^{0} to 4.7×10^{0}	NA	4.6×10^{-1} to 1.5×10^{0}	NA
Total dose rate		1.5×10^{1}		1.5×10^{1} to 1.8×10^{1}		3.4×10^{1} to 3.5×10^{1}	

ND = no data NA = not applicable * ^{40}K data were obtained for the coral sand samples

TABLE II. (CONTINUED)

Source	Nuclide	Troca		Small lagoon fish		Large lagoon fish	
		Low LET radiation	High LET radiation	Low LET radiation	High LET radiation Low	LET radiation High	LET radiation
Contaminants in							
Water	^{90}Sr-^{90}Y	NA	NA	NA	NA	NA	NA
	^{137}Cs	2.4×10^{-4} to 5.7×10^{-4}	NA	5.0×10^{-4} to 1.2×10^{-3}	NA	4.4×10^{-4} to 1.0×10^{-3}	NA
	^{99}Tc	NA	NA	NA	NA	NA	NA
	^{241}Am	2.8×10^{-8} to 9.0×10^{-8}	NA	3.0×10^{-8} to 9.7×10^{-8}	NA	2.3×10^{-8} to 7.4×10^{-8}	NA
Tissue	^{3}H	3.0×10^{-4} to 2.2×10^{-3}	NA	3.0×10^{-4} to 2.2×10^{-3}	NA	3.0×10^{-4} to 2.2×10^{-3}	NA
	^{90}Sr-^{90}Y	2.6×10^{-2}	NA	3.9×10^{-2}	NA	2.0×10^{-2}	NA
	^{137}Cs	2.9×10^{-3} to 6.9×10^{-3}	NA	2.7×10^{-2} to 5.3×10^{-2}	NA	1.4×10^{-1} to 1.1×10^{0}	NA
	^{60}Co	1.8×10^{-1} to 1.1×10^{0}	NA	8.4×10^{-3} to 1.2×10^{-1}	NA	1.8×10^{-2} to 1.5×10^{-1}	NA
	^{155}Eu	1.5×10^{-3} to 5.6×10^{-3}	NA		NA	3.0×10^{-3}	NA
	$^{239+240}Pu$		3.3×10^{0} to 1.4×10^{1}	NA	8.4×10^{-3} to 1.8×10^{0}	NA	1.4×10^{-2} to 3.9×10^{-2}
	^{238}Pu		6.0×10^{-1} to 6.1×10^{0}	NA	6.4×10^{-4} to 6.8×10^{-2}	NA	8.7×10^{-4} to 2.6×10^{-2}
	^{241}Am	1.5×10^{-4} to 7.4×10^{-4}	7.1×10^{-2} to 3.5×10^{-1}	8.2×10^{-7} to 2.0×10^{-4}	4.5×10^{-4} to 1.1×10^{-1}	2.6×10^{-8} to 1.8×10^{-5}	9.3×10^{-4} to 6.4×10^{-3}
Sediment	^{137}Cs	NA	NA	NA	NA	NA	NA
	^{60}Co	NA	NA	NA	NA	NA	NA
	^{155}Eu	NA	NA	NA	NA	NA	NA
	^{241}Am	NA	NA	NA	NA	NA	NA
Total dose rate		1.8×10^{-1} to 1.2×10^{0}	4.0×10^{0} to 2.0×10^{1}	3.6×10^{-2} to 2.1×10^{-1}	9.5×10^{-3} to 1.9×10^{0}	1.6×10^{-1} to 1.2×10^{0}	1.5×10^{-2} to 7.1×10^{-2}
Background							
Water	^{40}K	4.8×10^{-1}	NA	9.8×10^{-1}	NA	8.8×10^{-1}	NA
Tissue	^{40}K	3.3×10^{1}	NA	2.9×10^{1}	NA	2.9×10^{1}	NA
Sediment	^{40}K	NA	NA	NA	NA	NA	NA
Total dose rate		3.4×10^{1}		3.0×10^{1}		3.0×10^{1}	

ND = no data NA = not applicable * ^{40}K data were obtained for the coral sand samples

TABLE II. (CONTINUED)

Source	Nuclide	Oceanic zooplankton		Oceanic shrimps		Lobster (Open ocean)	
		Low LET radiation	High LET radiation	Low LET radiation	High LET radiation Low	LET radiation High	LET radiation
Contaminants in							
Water	^{90}Sr-^{90}Y	4.9×10^{-4} to 5.1×10^{-4}	NA	6.1×10^{-5}	NA	ND	NA
	^{137}Cs	6.0×10^{-4} to 6.8×10^{-4}	NA	4.0×10^{-4}	NA	2.5×10^{-4} to 2.8×10^{-4}	NA
	^{99}Tc	ND	NA	ND	NA	ND	NA
	^{241}Am	ND	NA	ND	NA	ND	NA
Tissue	^{3}H	1.7×10^{-5} to 3.2×10^{-4}	NA	1.1×10^{-2} to 1.6×10^{-2}	NA	1.7×10^{-5} to 3.2×10^{-4}	NA
	^{90}Sr-^{90}Y	ND	NA	ND	NA	1.1×10^{-2}	NA
	^{137}Cs	3.1×10^{-3} to 3.4×10^{-3}	NA	2.6×10^{-3} to 6.0×10^{-3}	NA	1.8×10^{-2}	NA
	^{60}Co	4.4×10^{-3} to 6.1×10^{-3}	NA	4.9×10^{-3} to 1.2×10^{-2}	NA	1.9×10^{-2}	NA
	^{155}Eu	2.7×10^{-3}	NA	4.7×10^{-3}	NA	ND	NA
	$^{239+240}Pu$	NA	3.0×10^{-1}	NA	3.7×10^{-2} to 3.2×10^{-1}	NA	1.2×10^{-2}
	^{238}Pu	NA	3.5×10^{-2}	NA	8.9×10^{-3} to 4.1×10^{-2}	NA	2.6×10^{-2}
	^{241}Am	2.1×10^{-6}	2.5×10^{-2}	3.8×10^{-6} to 1.9×10^{-5}	7.1×10^{-3} to 3.6×10^{-2}	2.4×10^{-5}	1.3×10^{-2}
Sediment	^{137}Cs	NA	NA	NA	NA	NA	NA
	^{60}Co	NA	NA	NA	NA	NA	NA
	^{155}Eu	NA	NA	NA	NA	NA	NA
	^{241}Am	NA	NA	NA	NA	NA	NA
Total dose rate		8.6×10^{-3} to 1.4×10^{-2}	3.6×10^{-1}	1.9×10^{-2} to 3.9×10^{-2}	5.2×10^{-2} to 4.0×10^{-1}	2.7×10^{-4} to 4.8×10^{-2}	5.1×10^{-2}
Background							
Water	^{40}K	3.2×10^{0}	NA	6.1×10^{-1}	NA	4.9×10^{-1}	NA
Tissue	^{40}K	1.2×10^{1}	NA	2.7×10^{1}	NA	2.9×10^{1}	NA
Sediment	^{40}K	NA	NA	NA	NA	NA	NA
Total dose rate		1.5×10^{1}		2.7×10^{1}		2.9×10^{1}	

ND = no data NA = not applicable * ^{40}K data were obtained for the coral sand samples

TABLE II. (CONTINUED)

Source	Nuclide	Oceanic reef fish				Open ocean fish			
		Low LET radiation		High LET radiation		Low LET radiation		High LET radiation	
Contaminants in									
Water	^{90}Sr-^{90}Y	NA		NA		NA		NA	
	^{137}Cs	4.5×10^{-4}	to 5.0×10^{-4}	NA		4.5×10^{-4}	to 5.0×10^{-4}	NA	
	^{99}Tc	NA		NA		NA		NA	
	^{241}Am	ND		NA		ND		NA	
Tissue	^{3}H	1.7×10^{-5}	to 3.2×10^{-4}	NA		1.7×10^{-5}	to 3.2×10^{-4}	NA	
	^{90}Sr-^{90}Y		1.3×10^{-2}	NA			7.8×10^{-3}	NA	
	^{137}Cs	2.4×10^{-2}	to 1.0×10^{-1}	NA		3.9×10^{-2}	to 4.8×10^{-2}	NA	
	^{60}Co	9.1×10^{-3}	to 3.1×10^{-2}	NA			1.0×10^{-2}	NA	
	^{155}Eu		1.4×10^{-2}	NA			2.5×10^{-3}	NA	
	$^{239+240}Pu$			9.0×10^{-4}	to 1.6×10^{-2}			2.4×10^{-3}	to 5.1×10^{-3}
	^{238}Pu			1.6×10^{-4}	to 3.3×10^{-3}			9.7×10^{-4}	to 1.9×10^{-3}
	^{241}Am		2.7×10^{-7}		9.6×10^{-5}		5.3×10^{-7}		1.9×10^{-4}
Sediment	^{137}Cs	NA		NA		NA		NA	
	^{60}Co	NA		NA		NA		NA	
	^{155}Eu	NA		NA		NA		NA	
	^{241}Am	NA		NA		NA		NA	
Total dose rate		3.4×10^{-2}	to 1.6×10^{-1}	1.1×10^{-3}	to 2.0×10^{-2}	4.0×10^{-2}	to 6.9×10^{-2}	3.4×10^{-3}	to 7.2×10^{-3}
Background									
Water	^{40}K		9.8×10^{-1}	NA			9.8×10^{-1}	NA	
Internal	^{40}K		2.9×10^{1}	NA			2.9×10^{1}	NA	
Sediment	^{40}K	NA		NA		NA		NA	
Total dose rate			3.0×10^{1}				3.0×10^{1}		

ND = no data NA = not applicable * ^{40}K data were obtained for the coral sand samples

TABLE III. SUMMARY OF DOSE RATES TO MARINE ORGANISMS FROM DISPERSED RADIONUCLIDES, nGy/h

Organism	Contaminant radionuclides		Natural ^{40}K
	Low LET radiation	High LET radiation	Low LET radiation
Lagoon zooplankton	1.4×10^{-2} to 1.1×10^{-1}	1.0×10^{1} to 2.0×10^{2}	1.5×10^{1}
Small benthic crustacean	4.6×10^{1} to 1.1×10^{3}	1.0×10^{1} to 2.0×10^{2}	1.5×10^{1} to 1.8×10^{1}
Pearl oyster	4.4×10^{1} to 1.0×10^{3}	1.1×10^{1} to 1.6×10^{1}	3.4×10^{1} to 3.5×10^{1}
Troca	1.8×10^{-1} to 1.2×10^{0}	4.0×10^{0} to 2.0×10^{1}	3.4×10^{1}
Small lagoon fish	3.6×10^{-2} to 2.1×10^{-1}	9.5×10^{-3} to 1.9×10^{0}	3.0×10^{1}
Large lagoon fish	1.6×10^{-1} to 1.2×10^{0}	1.5×10^{-2} to 7.2×10^{-2}	3.0×10^{1}
Oceanic zooplankton	8.6×10^{-3} to 1.4×10^{-2}	3.6×10^{-1}	1.5×10^{1}
Oceanic shrimp	1.9×10^{-2} to 3.9×10^{-2}	5.2×10^{-2} to 4.0×10^{-1}	2.7×10^{1}
Lobsters (open ocean)	2.7×10^{-4} to 4.8×10^{-2}	5.1×10^{-2}	2.9×10^{1}
Oceanic reef fish	3.4×10^{-2} to 1.6×10^{-1}	1.1×10^{-3} to 2.0×10^{-2}	3.0×10^{1}
Open ocean fish	4.0×10^{-2} to 6.9×10^{-2}	3.4×10^{-3} to 7.2×10^{-3}	3.0×10^{1}

Data for the concentrations of other natural radionuclides in the tropical organisms of interest in this study are scarce and, as it is known that they can be very variable (IAEA, 1976), no attempt has been made to estimate the dose rates from these additional sources.

2. 2. FOR ACTIVE PARTICLES ("HOT PARTICLES")

A particular problem of dosimetry arises in respect of the contamination of the Colette sand bank with particularly active small particles, so called "hot particles", from the safety tests conducted on the adjacent motus. The plutonium content of the sediments can be very high (up to 1.07×10^6

TABLE IV. OBSERVED HOT PARTICLE ACTIVITIES AND SIZES FOR TWO SEDIMENT SAMPLES FROM THE COLETTE SANDBANK

Sample 204301			
Particle code	Activity detected	Estimated total particle activity, corrected for solid angle and self-absorption,	Estimated apparent radius of hot particle
	Bq	Bq	μm
204301-A	0.66	9.1	50-60
204301-B	0.51	6.3	50-70
204301-C	0.96	23.0	20-25
204301-D	1.00	16.0	30-45
204301-E	3.00	49.0	20-40
204301-F	2.00	29.0	20
204301-G	0.60	15.0	15-25
204301-H	0.50	6.0	25-40
204301-I	0.75	2.8	25-50
204301-J	1.90	91.0	15
Estimated total activity in particles		247.2	
204302-A	5.30	70.0	20
204302-B	3.30	46.0	10-20
204302-C	7.00	110.0	15-20
204302-D	6.20	100.0	20
204302-E	130.00	1800.0	35 × 300
204302-F	35.00	530.0	15-25
204302-G	2.00	29.0	25-35
204302-H	0.82	11.0	10-15
204302-I	1.20	20.0	10-15
204302-J	1.30	15.0	10-30
204302-K	2.30	39.0	60 × 150
204302-L	2.10	26.0	35
204302-M	1.10	13.0	35
Estimated total activity in particles		2809.0	

TABLE V. ESTIMATED ACTIVITY DISTRIBUTION OF HOT PARTICLES IN SEDIMENT SAMPLES FROM THE COLETTE SANDBANK

Interval (particle activity)	Geometric mid -x X(i)	Sediment sample 204301			Sediment sample 204302		
		Number of	%	n(i) x X(i)	Number of	%	n(i) x X(i)
Bq	Bq	particles, n(i)/kg		Bq/kg	particles, n(i)/kg		Bq/kg
0.25							
	0.35	1	0.0	1.90×10^{-1}	2	0.1	7.68×10^{-1}
0.5							
	0.71	12	0.0	8.50×10^{0}	9	0.3	6.70×10^{0}
1							
	1.41	146	0.6	2.07×10^{2}	33	0.9	4.71×10^{1}
2							
	2.83	970	3.9	2.74×10^{3}	94	2.6	2.66×10^{2}
4							
	5.66	3503	14.1	1.98×10^{4}	214	5.8	1.21×10^{3}
8							
	11.31	6883	27.8	7.79×10^{4}	390	10.6	4.42×10^{3}
16							
	22.63	7365	29.7	1.67×10^{5}	574	15.6	1.30×10^{4}
32							
	45.25	4290	17.3	1.94×10^{5}	679	18.5	3.07×10^{4}
64							
	90.51	1361	5.5	1.23×10^{5}	646	17.6	5.85×10^{4}
128							
	181.0	235	0.9	4.25×10^{4}	495	13.4	8.95×10^{4}
256							
	362.0	22	0.1	8.00×10^{3}	305	8.3	1.10×10^{5}
512							
	724.1	1	0.0	8.19×10^{2}	151	4.1	1.09×10^{5}
1024							
	1448.2	0	0.0	4.56×10^{1}	60	1.6	8.71×10^{4}
2048							
	2896.3	0	0.0	1.38×10^{0}	19	0.5	5.58×10^{4}
4096							
	5792.6	0	0.0	2.29×10^{-2}	5	0.1	2.88×10^{4}
8192							
	Totals	24790	100	6.36×10^{5}	3677	100	5.89×10^{5}

Bq/kg dry weight) and this would be expected to lead to high dose rates to the in-fauna. The fact that the activity is present as α-emitting hot particles means, however, that the dose rate is extremely inhomogeneous in both space and time. In principle, the exposure of the organisms can be both internal, from the passage of ingested particles through the gut, and external. Both of these potential sources of exposure have been considered for two typical organisms inhabiting the sediment: a small worm and a (larger) burrowing shrimp. First, however, it is necessary to define the magnitude of the source, i.e. the number and size distribution of the populations of hot particles in the sediment.

Two of the sediment samples from the Colette sandbank (IAEA Nos 204301 and 204302) have been examined for hot particles using the CR-39 plastic track etch detection technique (see Technical Report Vol. 2). The activities (corrected for the effects of solid angle and self-absorption) are given in Table IV. For these two samples, it has been assumed that the observed particles are random representatives of lognormal populations with the same geometric mean and standard deviation (see Table IV). On this basis, the total number of particles in defined activity intervals, normalised for the total plutonium activity per kilogram of dried sediment, have been estimated (see Table V). The two sediment samples are from the 0–1 and 1–3 cm horizons of the core, so that the in-fauna could be exposed to both particle activity distributions. To cover both possibilities, dose rates have been assessed for representative particles from the two distributions i.e. particle activities of 7.1, 17.3, 54.6 and 241.5 Bq (being antilog (m/s), antilog (m) for 204301 and antilog (m) and antilog (m × s) for 204302, respectively). On the assumption that the particles are spheres of pure plutonium, the particle diameters would be 7.1, 9.6, 14 and 23 μm respectively.

Using the α-particle point source dose distribution function (IAEA, 1979), the dose rates in tissue, at different distances in wet sediment from these idealised sources, have been calculated (Table VI) (note that the discontinuous nature of the wet sediment on the scale of the α-particle range has been discounted and it has been assumed to have a uniform composition equivalent to the average down to the smallest scale). The dose rates do not scale in direct proportion with the hot particle activity due to the effects of α-particle self-absorption in the source, and vary from about 1 Gy/h at the end of the α-particle range for the smallest particle considered to about 310 Gy/h close to the surface of the largest particle.

To assess the potential α-radiation dose rate to the organisms, it is necessary to estimate the probabilities that they will ingest a hot particle or pass within 18 μm (the range of a plutonium α-particle in the wet sediment) of a hot particle. In this context, it is useful to have information on the inactive sediment particle size distribution. Both sediment samples were relatively coarse coral sand with a maximum particle size of the order of 2 mm diameter. The sediment particle size distribution has been approximated by a lognormal distribution with log m ± log s ≡ 2.24 ± 0.32 truncated at a maximum particle radius of 1.024 mm. Table VII gives the number size distribution (in intervals of particle radius) normalised to 1 kg of dry sediment assuming that the density of the coral is 2.71gm/cm^3. There are approaching 10^7 particles/kg and this means that there is one hot particle in 400 and 2700, in samples 204301 and 204302 respectively.

TABLE VI. ESTIMATED ABSORBED DOSE RATES IN TISSUE FROM IDEALIZED HOT PARTICLES IN WET SEDIMENT, Gy/h

Particle activity	Radius of hot particle as pure ^{239}Pu	Distance of the point of interest in wet sediment from the surface of the hot particle, μm				
Bq	μm	2	4	7.5	12.5	17.5
		Estimated absorbed dose rate in tissue at the point of interest, Gy/h				
7.1	3.6	1.2×10^2	8.1×10^1	5.2×10^1	1.7×10^1	1.1
17.3	4.8	1.9×10^2	1.5×10^2	7.5×10^1	2.5×10^1	1.7
54.6	7.0	2.8×10^2	1.9×10^2	1.0×10^2	3.9×10^1	2.9
241.5	11.5	3.1×10^2	2.4×10^2	1.5×10^2	6.1×10^1	4.9

TABLE VII. ESTIMATED CORAL SAND PARTICLE SIZE DISTRIBUTION ON THE COLETTE SANDBANK

Interval (particle radius) μm	Geometric mid-x X(i) μm	no of particles n(i)	%	Mass of particles g
2.5				
	3.2	9.2×10^{-1}	0.0	8.4×10^{-11}
4.0				
	5.0	2.3×10^{1}	0.0	8.4×10^{-9}
6.3				
	8.0	3.9×10^{2}	0.0	5.6×10^{-7}
10.1				
	12.7	4.4×10^{3}	0.0	2.6×10^{-5}
16.0				
	20.2	3.4×10^{4}	0.3	7.8×10^{-4}
25.4				
	32.0	1.7×10^{5}	1.8	1.6×10^{-2}
40.3				
	50.8	6.1×10^{5}	6.2	2.3×10^{-1}
64.0				
	80.6	1.4×10^{6}	14.5	2.1×10^{0}
101.6				
	128.0	2.3×10^{6}	23.0	1.4×10^{1}
161.3				
	203.2	2.4×10^{6}	24.7	5.8×10^{1}
256.0				
	322.5	1.8×10^{6}	17.9	1.7×10^{2}
406.4				
	512.0	8.6×10^{5}	8.7	3.3×10^{2}
645.1				
	812.7	2.8×10^{5}	2.9	4.3×10^{2}
1024.0				
	Totals	9.9×10^{6}	100	1×10^{3}

The generalised model (Woodhead, unpublished) adopted for the small worm was originally derived to represent a small vegetarian polychaete, *Ophryotrocha diadema*. It consists of a cylinder 0.325 cm long by 0.03 cm diameter with hemispherical end caps, and a concentric cylindrical gut 0.004 cm diameter. The bilateral gonads lie between the gut and the body wall and are separated from both by 0.002 cm of tissue, i.e. the shortest distance of gonad tissue from α-emitters in the gut contents or the external environment is 0.002 cm. Given the size distribution of the sand on the Colette bank, it is unlikely that the organisms would routinely ingest the sand to extract food particles (as is commonly the case in fine muds); the worms are likely to be much more discriminating in food choice and either actively select detrital particles of plant or animal origin, or be carnivorous. Although, in theory, all of the plutonium particles considered above could be ingested and deliver dose rates at the low end of the ranges given in Table VI (<~100Gy/h) to a proportion of the gonad tissue while in transit through the gut, the observed particle sizes (see Table IV) and their apparent association with inactive material render it unlikely that ingestion would be a real possibility.

Alpha-irradiation from an external particle can only occur if it is less than 18 μm from the body surface, i.e. there is a hot particle in a sediment volume of 6.4×10^{-5} cm^3. As there are approximately 50 and 7 hot particles per cm^3 of wet sediment in samples 204301 and 204302, respectively, the worm would have to move either 330x or 2230x its own body length through the sediment to encounter, on average, one hot particle. If worms were moving through the sediment at these rates in the 30 day lifetime, then the encounter time with the hot particle would be either two hours or twenty minutes during which time the α-radiation dose rate would be in the range 1–300 Gy/h. In fact, the worms are likely to be more active and move, perhaps, 4×10^4 body lengths in the 30 days; this will reduce the encounter time with individual particles, but increase the number of encounters. Thus, the total dose received in the lifetime would remain in the same general range but would be accumulated in more, and smaller, increments.

There is no existing model for the burrowing shrimp. As was the case for the small worm, there is no reason to expect deliberate ingestion of sediment particles, hot or otherwise, but with a larger alimentary tract, accidental ingestion of a hot particle remains a possibility. In this case the duration of the exposure (the gut transit time) might be of the order of a few hours, but the potential α-dose received by the gut lining and adjacent tissues would depend on the exposure time of any particular segment as the particle passed by and the dose rate (1–300 Gy/h from Table VI). If the transit speed is assumed to be 5 cm in 5 h (or 10^4 μm/h) and the particle irradiates an anterior-posterior band of tissue 100 μm wide, then the exposure time is 10^{-2} h and the maximum dose received by any piece of tissue would be less than 3 Gy.

The degree of external exposure again depends on the likelihood of a particle being within 18 μm of the body surface. A shrimp with a body length of 5 cm could, with due account being taken of appendages etc., have a surface area of 20 cm^2, and be exposed to the hot particles in 0.036 cm^3 of sediment. With 7–50 hot particles/cm^3 in samples 204301 and 204302, this means that the body surface of the shrimp is, on average, always exposed to one hot particle. Consequently, a tissue volume up to 1.5×10^{-7} cm^3 (perhaps 25 cells) is exposed at dose rates up to 300 Gy/h (probably less if account is taken of the acellular chitin exoskeleton). The total dose received by any given group of cells will, however, depend on the rate at which the shrimp moves through the sediment.

3. DISCUSSION

From the data presented in Table II, it can be seen that contaminant radionuclides in seawater are not an important source of exposure; the lagoon zooplankton experience the highest dose rate, but at about 3.2×10^{-3} nGy/h it is three orders of magnitude less than that from the natural ^{40}K in seawater.

The dose rates from the contaminant radionuclides in tissue have been broken into two components: low LET radiation (β-particles and γ-rays) and high LET radiation (α-particles). It is to be expected that the latter would be more effective than the former, per unit absorbed dose rate, in producing damage in biological systems. At present, and in contrast to the human radiation protection situation, there is no accepted method of combining the low and high LET components of dose rate to non-human organisms to obtain an estimate of the total biologically effective dose rate. For the human situation a weighting factor of 20 is applied to high LET radiation exposures, and it has been suggested that a lower weighting factor of 5 might be appropriate for the exposure of non-human organisms in the natural environment (UNSCEAR, 1996). The highest dose rates from low LET radiation from internal source are of the order of 1–1.2 nGy/h and are from ^{60}Co in the pearl oyster and the Troca and from ^{137}Cs in the large lagoon fish. These dose rates are at least a factor of 20 less

than the dose rate from ^{40}K in the body tissue. The absorbed dose rates from internal sources of high LET α-radiation, at about 200 nGy/h, are significantly higher in the lagoon zooplankton and the benthic crustacean than in any of the other organisms considered (maximum of 20 nGy/h in the Troca). Although higher than the absorbed dose rate (12 nGy/h) from the low LET radiation from the internal ^{40}K source these values are, nevertheless, lower than the estimated absorbed dose rate of 4000 nGy/h to the testes of a small mid-water oceanic shrimp from the accumulated natural α-emitting radionuclide, ^{210}Po (UNSCEAR,1996). The absorbed dose rate to benthic organisms from contamination in the coral sand can reach about 900 nGy/h from ^{60}Co and ^{137}Cs in an area of about 1 km^2 at Dindon, and perhaps 200 nGy/h from ^{241}Am in another small area (on the Colette sandbank); the highest dose rate from the contamination is about 200 times that from the ^{40}K in the sediment. Coral sand is, however, relatively deficient in ^{40}K and the radionuclides of the ^{238}U and ^{232}Th series; previous estimates of the γ-radiation exposure of benthic organisms from a wider range of sediment types have ranged up to 160 nGy/h (UNSCEAR,1996).

The hot particles in the sediments of the Colette sandbank are clearly a more significant source of potential radiation exposure with absorbed dose rates in the immediate vicinity (within 18 μm) of the particle surfaces up to 300 Gy/h (in the assessment of potential impact, no account has been taken of the expected higher biological effectiveness of the high LET α-radiation). The actual exposure of the in-fauna does, however, require that the hot particles and animal tissue do come this close together. Some plausible situations have been considered and it appears possible that total doses of α-radiation sufficient to produce deterministic effects in small volumes of tissue could be accumulated. The consequences of this for the individual animals are unknown as there have been no relevant experimental studies. It should be noted, however, that this situation only exists in a limited area of the lagoon and that it is, therefore, unlikely that there would be any deleterious effects at the population level.

4. CONCLUSIONS

Overall, therefore, it appears that the dose rates to the great majority of the native marine organisms from the dispersed contaminant radionuclides in the atoll environments are less than, or of the same order as, the natural background. In fairly restricted areas, the exposure of benthic organisms from sediment contamination may be as much as 5 times higher than the highest previous estimates of the natural γ-radiation background on the seabed. Additional exceptions to the general situation are the sediment in-fauna that are potentially exposed to α-radiation from hot particles in the Colette sandbank. Here, absorbed dose rates up to 300 Gy/h and total absorbed doses of several Gy to small tissue volumes are a possibility.

Earlier studies (IAEA, 1976, 1988; UNSCEAR, 1996) have concluded that there is no convincing evidence that chronic absorbed dose rates less than 4×10^5 nGy/h to the most highly exposed members of populations of aquatic organisms would have any detrimental impact on the populations. Aside from the particular situation on the Colette sand bank, the highest dose rates estimated for the marine organisms in the vicinity of the Mururoa and Fangataufa atolls, even allowing for a five-fold enhancement of the high LET component of the exposure, are at least a factor of 200 lower than this value. It is unlikely, therefore, that the incremental radiation exposure from the widely dispersed contaminant radionuclides would induce any significant damage in the native marine fauna. On the Colette sandbank, however, it appears entirely possible that the sediment in-fauna could receive absorbed doses of high LET α-radiation from hot particles that would be sufficient to produce deterministic effects in small volumes of tissue. The consequences of this for the individuals are unknown, but it is unlikely that there would be any deleterious impact on the wider populations of the whole lagoon.

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