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An environmental radiation survey of Christmas Island, Kiribati

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AN ENVIRONMENTAL RADIATION SURVEY OF CHRISTMAS ISLAND, KIRIBATI

by

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SUMMARY

An environmental radiation survey of Christmas Island has been carried out by the National Radiation Laboratory, Christchurch, New Zealand. Particular attention was given to sites of former known radioactive contamination. Radioactivity concentrations in soil were found to be consistent with global fallout levels for a low rainfall equatorial area and external radiation dose rates were almost entirely attributable to cosmic radiation. Committed dose equivalents from drinking-water and locally produced foodstuffs for a postulated Gilbertese diet were estimated to be of the order of 0.01 mSv per year. No site on the island was found to present a risk to the health of the resident population from radioactive contamination or to require any restriction on land use.

AN ENVIRONMENTAL RADIATION SURVEY OF CHRISTMAS ISLAND, KIRIBATI

1. INTRODUCTION

Christmas Island in the Line Islands group of the Republic of Kiribati (formerly the Gilbert Islands) was used both by British and United States forces as a base for nuclear weapon testing during 1957-58 (British) and 1962 (US). The Kiribati Government, which became independent from the United Kingdom in 1978, had, as a result of radiation survey and clean-up measures in 1964, been given an assurance by the UK Government that Christmas Island was safe for re-settlement and continued habitation. The Kiribati Government however more recently sought independent confirmation of environmental radiation levels, and a request was formally made by the UK Government to utilise the services of the New Zealand National Radiation Laboratory (NRL) to undertake a study of residual radiation at Christmas Island. Funding for the survey was provided by the UK Overseas Development Administration (ODA).

The ODA terms of reference for the study were:

" (i) To determine external radiation levels on Christmas Island and radionuclide concentrations in environmental samples and particularly in foodstuffs.

(ii) To derive effective dose equivalents to island residents taking account of dietary intakes of foodstuffs and water, external radiation levels and possible inhalation of resuspended particulate material.

(iii) To provide an assessment of possible current fallout radiation levels.

(iv) To confirm or otherwise that radiation levels throughout the island are sufficiently low as not to present a hazard to the health of persons resident there indefinitely. "

On the basis of information on the relative activities of long-lived radionuclides produced in nuclear detonations and making some assumptions about initial deposition patterns, upper limits to present day deposition levels and exposure rates can be estimated. Such an estimate was made and this suggested that present day external radiation exposure rates contributed by deposited fission products were unlikely to exceed 0.1 nGy h^{-1} (0.01 μR h^{-1}) or ^{137}Cs soil concentrations to be greater than about 5 Bq kg^{-1}. A British report on the final radiological survey and decontamination operations at Christmas Island prior to the closing down of the base in 1964 was made available to NRL to provide background information for the present survey. This report gave details of sites of particular interest where radioactive materials had been

handled or where contaminated areas or equipment had been designated prior to the clean-up operations. The report indicated that there were no areas presenting significant radiation or radioactivity hazards to human occupation at the end of 1964.

1.1 Geography

Christmas Island is situated in the mid-Pacific about 2° north of the equator and 2000 km south of Honolulu. It is the largest coral atoll in the world with a maximum length of about 60 km from north-west to south-east, and it varies in width from about 30 km at its broadest point to under 6 km in the south-east. Of its total area of about 900 square kilometres enclosed by its coast-line more than 600 square kilometres are lagoons. The island is fringed by a reef of from 50 to 150 metres from the shore, and beyond the reef the sea bed drops steeply into deep water. The ground is flat and the maximum height above sea level does not exceed about 12 metres. There is little top soil and vegetation consists of sporadic coarse grass, evergreen bushes (principally *Scaevola taccada* and *Messerschmidia argentea*) and a number of coconut plantations. The plantations and a number of other government operations, principally fish exporting, provide employment for the local Gilbertese population, numbering about 1300, resident in three villages. With a maritime equatorial climate, temperature varies little throughout the year. Day temperatures reach about 30°C with a drop of about 5°C at night and constant high humidity. Rainfall is unpredictable and has ranged from zero to 4800 mm in a year, with an average of about 750 mm.

The staple dietary component of the resident Gilbertese population is imported rice. Fish and coconuts are the only important local dietary contributors although land crabs are eaten in varying amounts. Apart from the coconuts, the infertile soil and low and erratic rainfall does not allow the cultivation of other traditional fruits and vegetables. Both rain and fresh ground water are used for drinking.

2. SURVEY CONCEPT

The procedures to be followed involved a survey of radiation exposure rates and collection of representative environmental samples in a pattern covering the entire island, and a reassessment of levels of possible residual contamination in former sites of particular interest. The environmental samples were to be brought to NRL for gamma spectrometrical and radiochemical analysis.

Gamma radiation exposure rates were to be measured, to the extent possible

without surveyor assistance, at identifiable locations. Gamma radiation from deposited fallout nuclides is accompanied by beta radiation, the ratio of intensities being relatively constant for long-lived material. Because of this, and the smaller contribution of external beta radiation to total effective dose equivalent, and also the expected magnitude of the exposure rates, it was not considered necessary to make separate measurements for external beta radiation.

Samples of foodstuffs, particularly coconuts and fish, and drinking-water supplies, were required to enable dietary radioactivity intakes to be assessed. Samples of non-edible plants could be used to provide an indication of concentrations in possible food-producing species in areas where these were not grown. Radioactivity concentrations in soils could also be used to provide such an indication. Concentration profiles with soil depth may be related to external gamma exposure rates, and also provide estimates of air concentrations from resuspension of material. Similarly lagoon water samples would provide an indication of possible concentrations in lagoon fish.

The derivation of environmental sample reference concentrations, to which measured concentrations may be compared, is discussed in the Appendix. These derived concentrations are those which for more pessimistic assumptions regarding dietary intakes, would give rise to committed dose equivalents of one-tenth the dose limits for occupationally exposed persons recommended by the International Commission on Radiological Protection (ICRP, 1977).

A programme was drawn up to carry out gamma measurements and to obtain an adequate and representative number of samples of the above types without incurring too formidable an analytical burden, but with flexibility to take account of any areas of elevated readings and with increased attention to sites of particular interest in the past. Scheduled air services to the island operated only weekly and a 2-week period was proposed in which to carry out the survey. It was subsequently found that the outlined programme could be completed by the survey team within one week. The field survey was carried out in the period 18-24 March 1981.

3. MONITORING AND SAMPLING PROCEDURES

3.1 Gamma monitoring

All roads and major tracks on the island were followed and measurements carried out every 2 miles (3.2 km) at a distance of approximately 50 m from the road in an area of undisturbed soil. The measurements were performed using an

Eberline PRM-5N count-rate meter with 25 x 25 mm NaI (Tl) EIC SPA-2 probe mounted on a tripod so that the detector was aligned vertically downwards at a height of 1 m above the ground. A counter-timer attachment to the count-rate meter, constructed at NRL, allowed counts to be integrated for periods of up to 5 minutes. Count-rates recorded at all survey points were derived from 5-minute integrated counts.

Three count-rate meters were taken on the survey and each was calibrated against ^{137}Cs using a 30% window setting. For this setting a count-rate of 30 cpm corresponded to a ^{137}Cs gamma dose rate of about 10 nGy h^{-1} (1 μrad h^{-1}) to air. Regular checks for stability were carried out using a low activity ^{137}Cs check source. Because environmental ^{137}Cs concentrations were found to be very low the survey meters were subsequently intercompared with a high pressure ionization chamber (calibrated in μR h^{-1} against radium) in locations around Christchurch, New Zealand, where the instruments were exposed to cosmic radiation and varying amounts of terrestrial radiation (principally naturally-occurring ^{40}K and radium and thorium series). This intercomparison demonstrated that the energy window setting of the survey meters, while readily detecting terrestrial radiation, largely discriminated against cosmic radiation. Using this calibration observed count-rates have been converted to total dose rates to air(from both cosmic and terrestrial radiation) expressed in nGy h^{-1}.

3.2 Soil samples

Soil samples were taken at approximately every third gamma monitoring site, and core samples at every third soil site. The soil samples were obtained by bulking 8 individual samples taken from the top 10 cm layer from 4 points each distributed at a radius of 0.5 m and 4 points at a radius of 1 m from the survey meter detector position. After mixing, a composite sample of about 500 g was sealed in a plastic bag. Soil profile samples were obtained in 10 cm depth steps down to 0.5 m using a 50 mm diameter soil corer, or, where this was not possible, using a shovel.

3.3 Plant samples

Coconuts are the sole plant species grown on the island that are consumed in any quantity. Samples of fresh and dried copra, and coconut milk were obtained. In addition, samples of widespread non-edible species, saltbush (*Scaevola taccada*), *Sida fallax* and *Messerschmidia argentea* were collected from different areas. *Sida fallax* was collected from the airport area and *Fimbristylis cymosa* from the Balloon Site. Approximately 1 kg samples of cuttings of leaves and

stems were taken. For comparative purposes a copra sample was also obtained from Manuae in the Cook Islands (almost due south of Christmas Island).

3.4 Fresh water

A rainwater sample (hotel drinking water) and samples of pumped groundwater supplies for each of the villages of London, Banana and Poland were obtained. The samples were collected in 10-litre plastic containers (to which a small volume of Cs and Sr carrier solution had been added) and passed through a filter (Whatman GFA) and ion exchange column containing 90 ml of Amberlite IR-120 resin (standard grade purified by passing 7 bed volumes of 6 M HCl and converted to ammonium form after washing). It had not been possible to obtain ^{242}Pu tracer solution prior to departure for Christmas Island but a 2-litre sample of potable groundwater was taken for assessment of ^{239}Pu concentration. Subsequently arrangements were made to obtain further groundwater samples in containers to which ^{242}Pu tracer had been added.

3.5 Fish

Whole fish samples representing lagoon and reef species were supplied through the courtesy of the Fisheries Officer. One specimen was taken of each of Milk-fish (*Chanos chanos*), Bonefish (*Albula vulpes*), Parrotfish (*Scarus* spp.), Red snapper (*Lutjanus gibbus*), and Yellow snapper (*Lutjanus fulvus*).

3.6 Lagoon waters (salt)

The ^{137}Cs concentration of lagoon waters was investigated by pumping water, using a specially developed pumping system, through columns containing 10 g of copper ferrocyanide (CuFC) to concentrate caesium isotopes (Folsam and Sreekumaran, 1970). Tests performed at NRL had established that CuFC gave >95% retention of caesium, even in salt water. Flow rates of 0.5 - 1.0 l min^{-1} were obtainable allowing sampling of up to about 50 l in an hour. Total flows were metered.

3.7 Land crabs

Two whole land crabs were collected (from near Banana village) for analysis.

All decomposable samples were preserved in formalin after weighing and sealed in plastic bags for return to NRL.

4. SAMPLE ANALYSIS AND COUNTING

All samples were analysed initially by gamma spectrometry and a proportion of

these were subsequently analysed radiochemically for ^{90}Sr and ^{239}Pu. Techniques are described below and results are given in Section 5.

4.1 Gamma counting

Concentrations of gamma emitters were assessed using a lithium-drifted germanium detector (Canberra type 7229) coupled to a 4096 channel pulse height analyser (Canberra 8180). Counting times of between 8 and 55 hours were used. Samples were counted in a 400 ml Marinelli beaker. Soils were dried at 100°C and large coral fragments were removed before counting; plant and coconut samples were counted without drying, 200-400 g (fresh weight) being packed into the beaker; whole fish and crab bodies were minced (skeleton, flesh, viscera all included) without drying and 150-300 g were packed into the beaker. Ion exchange resins and filters were counted in large petri fishes. The lower limit of detection for ^{137}Cs was approximately 40 mBq per sample.

4.2 ^{90}Sr analysis

All coconut, fish, crab and plant samples and selected soil samples were analysed for ^{90}Sr by ashing at 600°C, recovering added strontium carrier (from 100 g of soil ash or 2 - 5 g of ashes of other samples) by nitric acid and ion exchange separations, and counting the ^{90}Y daughter in a low-background beta scintillation counter after ingrowth. The method has been described fully elsewhere (Gregory, 1970).

4.3 ^{239}Pu analysis

Samples of ash (approximately 1 g for fish, crabs and plants, and up to 5 g for soils) were analysed for ^{239}Pu by the method of Talvitie (1971, 1972) involving ion exchange purification of Pu and electrodeposition on polished stainless steel discs followed by alpha spectrometry using surface barrier detectors (Ortec type BA-030-450-100) coupled to a 1024 channel pulse height analyser (Inotech 5300).

5. MEASUREMENT RESULTS

5.1 Gamma monitoring

Sites (other than locations at which more detailed surveys were carried out) where gamma radiation measurements were obtained, are indicated in Figure 1. At only one site (41) did the dose rate to air exceed 35 nGy h^{-1}, and since the cosmic ray dose rate to air at sea level in this equatorial region is about 0.25 mGy per year (NCRP, 1976; UNSCEAR, 1977) or about 30 nGy h^{-1}, it is apparent that the natural radiation background dose rate was almost entirely

attributable to cosmic rays and that there was very little contribution from terrestrial radioactivity, either natural or introduced. At site 41, which was on the shore of an enclosed salty lagoon, the dose rate was about 45 nGy h^{-1} and decreased to about 40 nGy h^{-1} at a distance of 40 m from the water's edge. High concentrations of crystallised salts were evident in the surface soil, particularly near the water's edge. A soil sample demonstrated that the slight elevation in dose rate at this site was due to radium salts: the ^{226}Ra concentration in surface soil at site 41 was 230 Bq kg^{-1}. At a distance of 100 m from the water's edge it had decreased to 100 Bq kg^{-1}.

Many additional gamma measurements, including extensive surveys with hand-held instruments, were obtained in the following areas (with their 1957-62 designations)"

Airfield runways and standings

AWRE Decontamination Area

- Radioactive soakaway areas
- Sites of buildings DB17, DB14, DB31 and DB32
- Aircraft washdown area

AWRE W.A. Area

- Site of building WB10

AWRE J.O.C. Area

- Sites of buildings JB2, JB2.1 and JB24.2

BW Area, S.E. point

Although all buildings were in an advanced stage of demolition and encroached on by vegetation, all sites were readily identifiable. There appeared to have been very little windborne surface soil movement so that bulldozed bunkers and the sand heaped over the washdown pad remained intact.

Residual radioactivity was detectable at a few specific locations within these sites, but in no case did dose rates exceed about 60 nGy h^{-1}. Elevated readings were obtained over a urinal drain hole in building DB32, in the former balance room of JB2.1, over a urinal outlet in JB2 (this urinal was destroyed and an active sample removed for analysis: the activity proved to be naturally-occurring thorium), and over the anchorage shackels and surrounding ashphalt at the centre of the balloon site. The latter were attributed to residual neutron-induced activity, and concentrations of 2.4 Bq kg^{-1} of ^{152}Eu and 0.2 Bq kg^{-1} of ^{60}Co were measured in a surface soil sample taken at the edge of ashphalted area west of the central anchorage mounts.

No other locations were detected showing significant increases above the average background rate over the island of about 30 nGy h^{-1}. This value may be compared with the outdoors background rate over undisturbed soil in Christchurch, New Zealand, of about 80 nGy h^{-1}, about 50 nGy h^{-1} of which is contributed by natural terrestrial radioactivity.

5.2 Laboratory analysis

This survey was primarily concerned with artificial radionuclides in the Christmas Island environment and although naturally-occurring radionuclides - viz. ^{40}K, ^{226}Ra and U isotopes - were detected in many samples, their concentrations are not tabulated or generally discussed in this report. Where a radionuclide concentration was below the lower limit of detection this limit is shown in the tables, while positive results are expressed with 95% confidence levels.

5.2.1 Soils (Tables 1 and 2)

^{137}Cs concentrations in the surface (0-10 cm) layer ranged up to 2.4 Bq kg^{-1}. The profile studies (Table 2) have shown that 45-70% of the ^{137}Cs is retained in this layer; little, if any, penetrating below 40 cm.

Apart from in the BW Area referred to in 5.1, other artificial gamma-emitters were not detected in any surface soil samples. Concentrations appeared to vary with soil texture and organic content: differences between surface and 0-10 cm profile samples could be attributed to positional and small depth variations in sample collection.

^{90}Sr concentrations ranged up to 2.76 Bq kg^{-1}, while ^{239}Pu concentrations ranged from <0.07 to 1.13 Bq kg^{-1}.

5.2.2 Water samples (Table 3)

^{137}Cs was the only artificial gamma-emitter detected in lagoon waters, with concentrations ranging from 0.028 to 0.052 Bq l^{-1}. Of the groundwater supplies, ^{137}Cs was detected only in water collected at the hotel. ^{90}Sr and ^{239}Pu were not detected in groundwaters, the limit of detection for ^{239}Pu analysis being of the order of 0.0003 Bq l^{-1}.

5.2.3 Vegetation (Tables 4 and 5)

^{137}Cs was the only artificial gamma-emitter detected in vegetation samples, with concentrations in the range 0.2 to 8.1 Bq kg^{-1}. ^{90}Sr concentrations ranged from 0.03 to 3.26 Bq kg^{-1}. Highest levels of both ^{137}Cs and ^{90}Sr were found in the *Sida fallax* sample collected from beside the washdown pad. ^{239}Pu was detected only in this *Sida fallax* sample, with a concentration of approximately 0.052 Bq kg^{-1}.

^{137}Cs was detected in coconut samples (Table 5), with undried coconut (including shell) having a concentration of 7.8 Bq kg^{-1}, while in copra ^{137}Cs concentrations of 1.5 to 1.9 Bq kg^{-1} were found. The copra sample obtained from the Cook Islands for comparison contained 27 Bq kg^{-1}. This higher value may be attributed to the differences in latitude, rainfall and soil type.

^{239}Pu and ^{90}Sr were below the limits of detection in the coconut and copra samples analysed.

5.2.4 Fish and Crabs (Table 6)

No artificial gamma-emitters were detected in any fish sample.

^{90}Sr was detected in Yellow snapper and Parrotfish, with the highest level (0.11 Bq kg^{-1}) being in the former.

^{137}Cs and ^{90}Sr were detected in the crab samples with concentrations of 3-4 and 2 Bq kg^{-1} respectively.

^{239}Pu was not detected in any of the fish or crab samples.

6. DISCUSSION

In common with other coral atolls (USAEC, 1973), and as evidenced by the gamma radiation survey, Christmas Island has very low concentrations of naturally-occurring radionuclides in its soil. The concentrations of ^{137}Cs in soils throughout the island were found to be uniformly low and consistent with levels that might be expected from global fallout in a low rainfall equatorial region. As a consequence, the measured external radiation levels of about 30 nGy h^{-1}, giving rise to dose equivalents of about 0.25 mSv (25 mrem) per year, arise almost entirely from cosmic radiation and are amongst the lowest over land of any region of the world.

Residual radioactive contamination, neutron-induced radioactivity and natural radioactive deposits are detectable in a few localised areas, but these represent trivial perturbations of the external radiation environment.

Consistent with the low soil concentrations, radionuclide concentrations in groundwater drinking supplies are low and imply annual dose equivalents to the resident population of not greater than about 0.2 μSv (0.02 mrem) from water intake.

Measured radionuclide concentrations in fish were consistently at or below limits of detection (Table 6). ^{137}Cs concentrations in coconuts, the other

major local component of diet, were somewhat variable, although concentration ranges of about an order of magnitude for a constant soil concentration have been found in other surveys (USAEC, 1973, p.550). A statistical correlation between concentrations in soil and coconut meat was however found in the USAEC Enewetak survey. If this relationship is extrapolated to the mean ^{137}Cs soil concentration determined on Christmas Island in this study of 0.87 Bq kg^{-1} (dry), a mean concentration in coconut meat of about 4 Bq kg^{-1} (wet) is predicted. While the extrapolation may not be entirely valid, the predicted value is not inconsistent with the measured concentrations listed in Table 5. Concentrations in coconut milk and meat have been found to be similar (USAEC, 1973, p.546), as indicated in Table 5.

The postulated diet for the Enewetak population (USAEC, 1973, p.496) would appear to provide a reasonable upper limit basis for assessing effective dose equivalents arising from locally obtained foodstuffs in the Christmas Island Gilbertese diet. These dose equivalents, derived from data in the Appendix and for the assumed mean daily intakes, are as follows:

Foodstuff	Daily intake (g)	Effective dose equivalent (mSv y^{-1})
Fish	600	<0.0007
Domestic meat (hens, pigs)	60	0.001
Coconut	100	0.007
Coconut milk	300	
Land crabs	25	0.001
		0.010

In the case of land crabs allowance has been made for the contribution of the measurable ^{90}Sr concentration. For domestic meat it has been assumed that the ^{137}Cs transfer coefficient from diet (assumed to have a concentration equivalent to vegetation) to muscle is about 1 (USAEC, 1973, p.578). Since strontium accumulates in bone rather than soft tissues, the contribution of ^{90}Sr to the effective dose equivalent from ingestion of locally produced meat is much smaller than that of ^{137}Cs.

In the immediate vicinity of the former washdown pad concentrations in vegetation are marginally elevated by factors of 2-10. If this area were ever to be planted with coconuts, nuts from a few trees at this site would have marginally raised concentrations but the small numbers involved and the minor variation in concentrations would ensure that the mean dose equivalent arising from ingestion would not be affected.

It is probable that imported foodstuffs would contribute an effective dose equivalent of the order of at least 0.005 mSv in addition to that of the 0.01 mSv arising from locally obtained dietary components. These values may be compared with estimated mean dose equivalents from ^{90}Sr and ^{137}Cs dietary intake in New Zealand in 1980. Based on the mean concentrations in milk for all collecting stations of 0.20 Bq/gCa for ^{90}Sr and 0.80 Bq/gK for ^{137}Cs (National Radiation Laboratory, 1981), and assuming concentrations in milk are representative of total diet, the resulting committed dose equivalents for intake in 1980 are 0.004 mSv and 0.012 mSv for ^{90}Sr and ^{137}Cs, respectively.

The principal components of natural radiation and fallout radionuclide radiation exposure of the Gilbertese population on Christmas Island may be summarised as follows (dose equivalents in mSv):

External	
Cosmic rays (and natural terrestrial)	0.25†
^{137}Cs in soil	∿0.0004
Internal	
Primordial and cosmogenic radionuclides (principally ^{40}K)	∿0.20†
^{137}Cs + ^{90}Sr	0.01*

* excluding the contribution from imported foodstuffs

† UNSCEAR (1977)

7. CONCLUSION

External radiation levels on Christmas Island are low in relation to world averages owing to low soil concentrations of both natural and fallout radionuclides. Committed dose equivalents from dietary intake of local foodstuffs would appear to be similar in magnitude to those for populations in southern hemisphere mid-latitude zones.

While traces of residual contamination from the nuclear weapon test era were detectable in a few localised sites, in all cases concentrations in soil and vegetation remained several orders of magnitude below derived reference level concentrations. No radioactive contamination was detected which would present a hazard to resident islanders.

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APPENDIX

REFERENCE CONCENTRATIONS IN ENVIRONMENTAL SAMPLES

The significance of radioactivity concentrations in foodstuffs and water may be assessed in relation to reference concentrations derived from the annual limits of intake (ALI) for radiation workers recommended by the ICRP. In general an ALI for a particular radionuclide will result in an annual committed effective dose equivalent of 50 mSv (5 rem). For individuals who are not classified as radiation workers the ICRP has recommended annual dose equivalent limits of 1/10 those for occupationally exposed persons. The corresponding limiting intakes for ingestion for radionuclides of interest (from ICRP Publication 30) are as follows (in Bq):

^{60}Co	^{90}Sr	^{137}Cs	$^{239+240}Pu$
7×10^5	1×10^5	4×10^5	2×10^4

Reference-man intakes (ICRP Publication 23) may not be strictly applicable to Pacific island population groups or to children, but are adequate for the purpose of estimating reference concentrations. Intake values are:

daily fluid intake	2000 ml
daily food intake	1000 g
light activity respiration rate	9600 l per 8 h

Apart from direct measurement of radioactivity concentrations in drinking water and foodstuffs, less direct measures of radioactivity intake could be derived from soil and lagoon water sampling and determination of concentrations in non-edible plant materials. From a knowledge of concentration ratios or transfer rates of radioactivity to dietary components, derived reference concentrations have been estimated for these materials also.

Reference concentrations in drinking water

On the basis of annual fluid intakes of about 730 l, the reference concentrations for the nuclides listed above are:

	^{60}Co	^{90}Sr	^{137}Cs	$^{239+240}Pu$
Bq cm^{-3}	0.96	0.14	0.55	0.027
(pCi cm^{-3})	(26)	(3.7)	(15)	(0.74)

Reference concentrations in foodstuffs

A conservative or pessimistic approach is to apply the same concentration limit

to all foodstuffs (e.g., plant materials and fish) as if each type were the sole component of diet.

For an annual dietary intake of 365 kg, reference concentrations are then:

	^{60}Co	^{90}Sr	^{137}Cs	$^{239+240}Pu$
Bq g^{-1}	1.9	0.27	1.1	0.055
(pCi g^{-1})	(52)	(7.4)	(30)	(1.5)

Reference concentrations in soil

A: derived from plant uptakes

Some published values of concentration factors ($\frac{\text{Bq g}^{-1}\text{ wet weight of plant}}{\text{Bq g}^{-1}\text{ dry weight of soil}}$) are listed for different plant materials as follows. There appears to be a considerable variation between species (and soil types) in plant uptake factors.

Plant	^{60}Co	^{90}Sr	^{137}Cs	^{239}Pu	Reference
Grass			3×10^{-2}		1
Box elder leaves				$(0.008-0.52\times10^{-3})$	2
Grass	5×10^{-3} - 1×10^{-2}		5×10^{-3} - 1×10^{-2}		3
Rye grass		0.06 - 0.22	2×10^{-2}		4
Various tropical		0.2	1	5×10^{-3}	5
Adopted factors	0.1	0.2	1	5×10^{-3}	

Applying the adopted more conservative concentration factors to edible plants, the corresponding derived reference concentrations in soil are:

	^{60}Co	^{90}Sr	^{137}Cs	$^{239+240}Pu$
Bq g^{-1}	19	1.4	1.1	11
(pCi g^{-1})	(520)	(37)	(30)	(300)

B: derived from inhalation of resuspended material

ICRP (Publication 30) derived air concentrations (DAC) are based on light activity for 8 h d^{-1}. Adopting conservative inhalation limits for non-occupationally exposed persons of 1/30 DAC for 24 h d^{-1} inhalation, and a soil resuspension average concentration in air of 50 μg m^{-3} (which may be compared with a measured mean value of 21 μg m^{-3} over undisturbed soil at Bikini Atoll[6]), the reference air concentrations and derived soil concentrations are:

	^{60}Co	^{90}Sr	^{137}Cs	$293 + 240Pu$
Reference air concentration ($Bq\ m^{-3}$)	17	2	67	0.007
Derived soil concentration ($Bq\ g^{-1}$)	3.3×10^5	4×10^4	1.3×10^6	1.3×10^2

For ^{60}Co, ^{90}Sr and ^{137}Cs the reference concentrations in soil derived from plant uptakes are clearly much more limiting than from inhalation of resuspended soil.

Reference concentrations in lagoon waters

Published values of concentration factors for fish flesh ($Bq\ g^{-1}$ in fish flesh/ $Bq\ g^{-1}$ in sea water) include the following:

^{60}Co	^{90}Sr	^{137}Cs	$239 + 240Pu$	Reference
10	0.1	15	3	7
			10	8

Applying the conservative reference concentrations determined above for foodstuffs to fish flesh, derived reference concentrations for sea water are:

	^{60}Co	^{90}Sr	^{137}Cs	$239 + 240Pu$
$Bq\ l^{-1}$	190	2700	75	5.5
($pCi\ l^{-1}$)	5.2×10^3	7.4×10^4	2.0×10^3	1.5×10^2

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TABLE 1 - ^{137}Cs, ^{90}Sr and ^{239}Pu concentrations in surface soils (Bq kg^{-1} dry)

Site No	^{137}Cs	^{90}Sr	^{239}Pu
3	0.56 ± 0.16	1.30 ± 0.10	<0.07
7	0.44 ± 0.10	N.D.	N.D.
12	0.44 ± 0.16	N.D.	N.D.
14	2.44 ± 0.52	2.76 ± 0.10	1.13 ± 0.46
28	0.48 ± 0.10	N.D.	<0.33
36	1.89 ± 0.22	1.19 ± 0.06	0.17 ± 0.09
41	<0.10	N.D.	N.D.
45	0.56 ± 0.12	N.D.	N.D.
48	0.93 ± 0.14	N.D.	N.D.
Over Washdown Pad	0.74 ± 0.14	0.96 ± 0.07	0.10 ± 0.10
Centre BW Area (near edge of ashphalt)	0.60 ± 0.06	1.25 ± 0.08	0.16 ± 0.13

N.D. = Not Determined

TABLE 2 - ^{137}Cs soil concentration profiles (Bq kg^{-1} dry)

	Depth (cm)				
Site	0-10	10-20	20-30	30-40	40-50
3	0.56 ± 0.16	<0.08	0.07	<0.08	<0.08
4	<0.11	<0.11	<0.10	0.56 ± 0.20	<0.24
25	--- 1.30 ± 0.20 ---		0.89 ± 0.16	0.44 ± 0.08	0.22 ± 0.08
36	1.89 ± 0.22	0.78 ± 0.08	0.59 ± 0.08		
Over Washdown Pad	--- 0.19 ± 0.08 ---		<0.14	0.26 ± 0.08	<0.14
W. side of DB32	1.33 ± 0.08	0.59 ± 0.14	<0.18	<0.18	
Centre, BW Area (near edge of ashphalt)	0.89 ± 0.08	0.15 ± 0.08			

TABLE 3 - ^{137}Cs and ^{90}Sr concentrations in lagoon and ground waters (Bq l^{-1})

	^{137}Cs	^{90}Sr
Lagoons:		
Manulu lagoon Site 12	0.028 ± 0.004	N.D.
Lagoon Site 16	0.052 ± 0.008	N.D.
Lagoon Site 41	0.046 ± 0.006	N.D.
Groundwaters:		
London	<0.002	<0.0006
Poland	<0.002	<0.0004
Banana	<0.002	<0.0005
Hotel	0.024 ± 0.004	<0.0005
Rainwater	<0.002	N.D.

N.D. = Not Determined

TABLE 4 - ^{137}Cs, ^{90}Sr and ^{239}Pu concentrations in vegetation (Bq kg^{-1} wet)

Site	^{137}Cs	^{90}Sr	^{239}Pu
Site 36			
Scaevola	1.10 ± 0.34	<0.050	<0.009
Washdown pad			
Scaevola	2.60 ± 0.38	0.10 ± 0.028	<0.006
Messerschmidia	7.04 ± 0.60	0.71 ± 0.036	<0.012
Sida	8.15 ± 1.00	3.26 ± 0.14	0.052 ± 0.022
Near DB32			
Scaevola	<0.18	N.D.	N.D.
Near WB10			
Messerschmidia	<0.20	0.089 ± 0.084	<0.012
BW Area			
Scaevola	0.74 ± 0.20	0.031 ± 0.030	<0.009
Fimbristylis	<0.56	N.D.	N.D.

N.D. = Not Determined

TABLE 5 - ^{137}Cs, ^{90}Sr and ^{239}Pu concentrations in coconuts (Bq kg^{-1})

Sample	^{137}Cs	^{90}Sr	^{239}Pu
Undried, Banana	7.78 ± 1.06	<0.051	<0.011
Dried, Banana	1.85 ± 0.40	N.D.	N.D.
Dried, Poland	1.48 ± 0.34	<0.046	<0.006
Milk, Banana	1.11 ± 0.28	N.D.	N.D.
Dried, Cook Islands	27.00 ± 0.96	N.D.	<0.008

N.D. = Not Determined

TABLE 6 - ^{137}Cs, ^{90}Sr and ^{239}Pu concentrations in fish and land crabs (Bq kg^{-1} wet)

	^{137}Cs	^{90}Sr	^{239}Pu
Bonefish	<0.25	<0.026	<0.021
Milkfish	<0.23	<0.021	<0.015
Red snapper	<0.18	<0.040	<0.025
Yellow snapper	<0.30	0.11 ± 0.08	<0.048
Parrotfish	<0.15	0.028 ± 0.028	<0.024
Land crab	4.08 ± 0.32	2.17 ± 0.20	<0.092
Land crab	3.00 ± 0.36	2.03 ± 0.34	<0.099

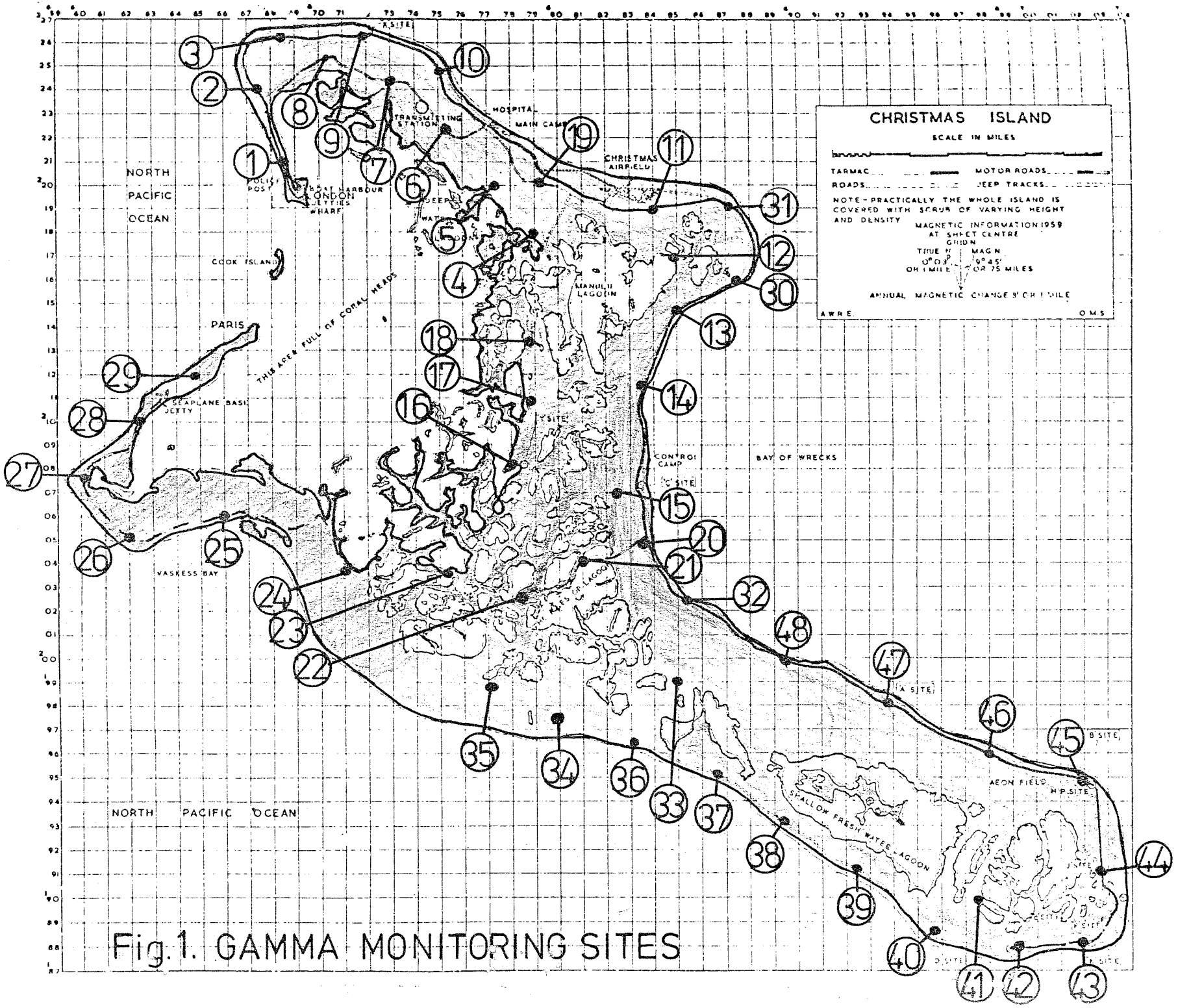

Fig. 1. GAMMA MONITORING SITES