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RECONSTRUCTION OF INDIVIDUAL RADIATION DOSES FOR A CASE-CONTROL STUDY OF THYROID CANCER IN FRENCH POLYNESIA

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Abstract

Forty-one atmospheric nuclear weapons tests (plus five safety tests) were conducted in French Polynesia between 1966 and 1974. To evaluate the potential role of atmospheric nuclear weapons testing on a high incidence of thyroid cancer observed since 1985 in French Polynesia, a population-based case-control study was performed. The study included 602 subjects, either cases or controls, all aged less than 40 y at the end of nuclear weapons testing in 1974. Radiation doses to the thyroids of the study subjects were assessed based on the available historical results of radiation measurements. These were mainly found in the annual reports on the radiological situation in French Polynesia that had been sent to the UNSCEAR Secretariat. For each atmospheric nuclear weapons test that contributed substantially to the local deposition of radionuclides, the radiation dose to the thyroid from ¹³¹I intake was estimated. In addition, thyroid doses from the intake of short-lived radioiodines (¹³²I, ¹³³I, ¹³⁵I) and ¹³²Te, external exposure from gamma-emitted radionuclides deposited on the ground, and ingestion of long-lived ¹³⁷Cs were reconstructed. The mean thyroid dose among the study subjects was found to be around 3 mGy while the highest dose was estimated to be around 40 mGy. Doses from short-lived iodine and tellurium isotopes ranged up to 10 mGy. Thyroid doses from external exposure ranged up to 3 mGy, while those from internal exposure due to cesium ingestion did not exceed 1 mGy. The dose estimates that have been obtained are based on a rather limited number of radiation measurements performed on a limited number of islands and are highly uncertain. A thorough compilation of the results of all radiation monitoring that was performed in French Polynesia in 1966–1974 would be likely to greatly improve the reliability and the precision of the dose estimates.

INTRODUCTION

Atmospheric nuclear weapons tests conducted from 1945 through 1980 resulted in exposure from fallout of radioactive debris, especially to the population that resided close to nuclear test sites (UNSCEAR 2000). To evaluate the health impact of nuclear testing to members of the public, epidemiological studies including reconstruction of radiation doses to the

exposed populations have been carried out in the United States (Ng et al. 1990; Thompson 1990; Simon et al. 2006), in Kazakhstan (Gordeev et al. 2002), and in other countries (Simon and Bouville 2002).

France conducted forty-one atmospheric nuclear weapons tests (and five safety tests) in French Polynesia between 1966 and 1974 (Table 1) (UNSCEAR 2000; Bataille and Revol 2002). The nuclear test sites were two atolls, Mururoa and Fangataufa, located in the southeastern part of Tuamotu-Gambier Archipelago at about 1,150 km from Tahiti, the most populated island in French Polynesia.

To evaluate the potential role of atmospheric nuclear weapons testing on a high incidence of thyroid cancer observed since 1985 in French Polynesia (de Vathaire et al. 2000), a population-based case-control study of thyroid cancer was performed. The study included 602 subjects aged less than 40 y at the end of the nuclear weapons testing program in 1974. Unit 605 of the National Institute for Health and Medical Research (INSERM) coordinated the case-control study.

Under normal conditions, the radioactive debris produced by a nuclear weapons test was carried out to the east of the test site over uninhabited regions of the Pacific. However, some of the radioactive debris was caught in the troposphere in anticyclones eddies and was transferred back to the central South Pacific area within a few days. Radioactive clouds with these types of trajectories resulted in local deposition of radionuclides on the ground of inhabited islands of French Polynesia.

The radiation dose to the thyroid gland had to be evaluated for each study subject. Rather limited information on measurements of radiation in environmental samples was available for the purposes of thyroid dose reconstruction. These included annual reports on radiation monitoring in French Polynesia that had been sent by the French Government to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) Secretariat (RF 1967, 1969, 1971–1975). These reports contain results of total beta activity in filtered air measured in selected locations in French Polynesia as well as measurements of ^{131}I and ^{137}Cs concentrations in cow's milk produced in Tahiti and measurements of total gamma activity in foodstuffs produced on selected islands.

The assessment of thyroid doses included the following pathways of exposure:

- * Internal irradiation resulting from intakes of ^{131}I via inhalation and ingestion;
- * Internal irradiation resulting from intakes of short-lived ^{132}I , ^{133}I , ^{135}I , and ^{132}Te ;
- * External irradiation resulting from the deposition of radionuclides on the ground; and
- * Internal irradiation resulting from intakes of long-lived radionuclides such as ^{137}Cs .

It was expected that intake of ^{131}I would be the main pathway of thyroid exposure for the population of French Polynesia, but that other pathways could be relatively important for persons with little or no milk consumption.

The purpose of this paper is to estimate the individual thyroid doses to the study subjects resulting from radioactive fallout from the atmospheric nuclear weapons tests conducted in French Polynesia.

MATERIAL AND METHODS

Geographical and age distribution of the study subjects

The study included 602 subjects aged less than 40 y at the end of atmospheric nuclear weapons testing in 1974. During the atmospheric nuclear weapons testing period, the study subjects resided in 46 islands and atolls (Fig. 1). Among them, the majority (more than 80%) lived in the most populated Societe Islands, particularly in Tahiti.

Fig. 2 shows the distribution of the study subjects according to year of birth. Almost 20% of study subjects were aged 7 y or less at the time of the nuclear weapons tests. There were 38 persons among the study subjects who resided outside the study area during the testing period ($n = 11$) or who were born after July 1975 ($n = 27$). These persons were not considered in the dose reconstruction.

Available information on measurements of radiation in environmental samples and on meteorology

Rather limited information on radiation measurements in environmental samples was available for the purposes of dose reconstruction. These included seven reports on radiation monitoring in French Polynesia that had been sent by the French Government to the UNSCEAR Secretariat (RF 1967, 1969, 1971–1975). The ground deposition of specific radionuclides in selected locations of French Polynesia was derived from the activities in filtered air presented in these reports. Radiation monitoring results also included concentrations of ^{131}I and ^{137}Cs in fresh cow's milk in Tahiti. In addition, the reports contain results of measurements of total gamma activity in foodstuffs produced on the archipelagos in French Polynesia. Table 2 shows the number of measurements available. A few results of measurements of exposure rates and deposition densities in Gambier (tests Aldebaran and Phoebe), in Tureia (tests Arcturus and Encelade), and in Tahiti (test Centaure) were also available (Bourges 1997).

The meteorological information that is available includes the wind speed and direction, measured 8 times a day at 11 locations, and the daily precipitation at 21 locations.

Reconstruction of fallout from the nuclear weapons tests

More than 100 of the fission products and their decay products with relatively long half-lives that are produced in nuclear explosions contribute to radioactive fallout. Tens of other radionuclides are produced by activation of the fuel, bomb construction, and other surrounding materials. However, relatively few radionuclides contribute substantially to the thyroid doses received by the population.

Measurements of radionuclide composition in air or in fallout were not available to us for the tests conducted in French Polynesia. To estimate the activities of specific radionuclides deposited on the ground, the results obtained after atmospheric nuclear weapons tests conducted at the Nevada Test Site (NTS) in the U.S. were used. For these tests, Hicks (1981) calculated the deposition densities of a large number of radionuclides, normalized to an exposure rate of 1 mR h^{-1} at 12 h post-detonation ($H + 12 \text{ h}$), for different nuclear weapons tests and different times of arrival of fallout (TOA). Table 3 shows the medians of the normalized deposition densities of important radionuclides at different TOAs for 34 tests conducted at the NTS. These tabulated values were used to reconstruct fallout from tests conducted in French Polynesia. For all tests conducted in French Polynesia and for the 46 islands and atolls of interest, the values of TOA were preferably taken from the literature (RF 1967, 1969, 1971–1975; Bourges 1997) when available or were roughly estimated from the meteorological data on wind speeds and directions (MF 2005).

For the purpose of determining the deposition densities of the various radionuclides, the following approaches were used depending on the type of data available for the locations of interest.

Approach #1. An exposure rate measurement was available

Step 1. The measured exposure rate was corrected to time H+12 h using the assumption that the exposure rate varied with time after detonation, t in hours, according to $t^{-1.2}$ during the first week after the test (Dunning 1958).

Step 2. The deposition density of a particular radionuclide was estimated by multiplication of the corrected exposure rate (obtained in step 1) by the normalized deposition density at TOA calculated by Hicks (1981).

Approach #2. Measurements of ^{131}I concentration in milk were available

Step 1. The ^{131}I deposition density was derived from the measured activity of ^{131}I in cow's milk as described in a later Section on "Estimation of the time-integrated concentrations in local cow's milk in Tahiti."

Step 2. The deposition density of any radionuclide other than ^{131}I was estimated using the ratio of ^{131}I deposition density at TOA (Hicks 1981) to that obtained in step 1 as a scale.

Approach #3. A measurement of total beta activity in filtered air was available

Step 1. The total deposition density was calculated from the measured time-integrated activity in air, using deposition velocity values of $1.76 \times 10^{-2} \text{ m s}^{-1}$ in case of dry deposition and of light rainfall ($R < 1 \text{ mm d}^{-1}$), and $6.2 \times 10^{-2} \text{ m s}^{-1}$ for rainfalls greater than, or equal to, 1 mm d^{-1} (see Section on "Internal dose due to inhalation" for details).

Step 2. The deposition density of a particular radionuclide was estimated by normalizing the total deposition density at TOA (Hicks 1981) to that obtained in step 1.

Deposition densities of radionuclides were reconstructed for each location where study subjects resided during the atmospheric test period. Table 4 gives examples of available radiation data and deposition densities reconstructed using approach #3 or approach #2 for tests that contributed substantially to local fallout in Tahiti.

For a few tests and locations, reconstructed deposition densities could be compared with reconstructed deposition densities reported by Bourges (1997) (Table 5). In most cases, a rather good agreement (within a factor of 2) was observed between reconstructed and measured deposition densities as well as between estimates of deposition density reconstructed according to different methods.

Thyroid dose reconstruction

The following pathways of thyroid exposure were considered:

- * Inhalation of contaminated air during the cloud passage;
- * Ingestion of ^{131}I and of short-lived radioiodines (^{132}I , ^{133}I and ^{135}I) and radiotellurium (^{132}Te) with foodstuffs and drinking water;
- * External irradiation from radionuclides deposited onto ground and other materials; and
- * Ingestion of ^{137}Cs with foodstuffs and drinking water.

External irradiation due to submersion to the radioactive cloud during its passage was estimated to be on the order of a few tens of μGy for the worst case of exposure in the Gambier Islands after test Aldebaran. Exposure from this pathway for other locations and tests was expected to be negligible (on the order of a few μGy or less) and, therefore, was not considered.

For the purposes of dose reconstruction, we took advantage of personal interviews that were conducted in 2000–2004 with each study subject, and in which the following information was requested: (1) age; (2) residential history; (3) type of building in each residence; (4) diet at the age of 15; (5) source of drinking water; and (6) duration of breast feeding. Dose reconstruction was performed without knowledge of the health status of the subject, i.e., case or control.

Internal dose due to inhalation

Internal thyroid dose for a person of age k arising from inhalation of contaminated air, D_{kinh} , was calculated as:

$$D_k^{\text{inh}} = V_k^{\text{air}} \times RF^{\text{air}} \times \sum TIA_i^{\text{air}} \times DF_{i,k}^{\text{inh}}, \quad (1)$$

where:

V_k^{air} = breathing rate for a person of age k (ICRP 2002), $\text{m}^3 \text{s}^{-1}$;

RF^{air} = reduction factor associated with indoor occupancy, unitless. As buildings in French Polynesia are very open, $RF^{\text{air}} = 1$ was applied in the calculations;

$DF_{i,k}^{\text{inh}}$ = inhalation dose coefficient for the thyroid, i.e., internal thyroid dose due to inhalation of unit activity of radionuclide i for a person of age k (ICRP 1995), mGy kBq^{-1} ; and

TIA_i^{air} = time-integrated concentration of radionuclide i in air, kBq s m^{-3} .

When measured total beta activities in air were available, TIA_i^{air} was derived from the radionuclide mix at TOA calculated by Hicks (1981). It was assumed that the radionuclide mix in filtered air was the same as that in the activity deposited on the ground. In the absence of measurements in filtered air, a crude estimate of time-integrated concentration of radionuclide i in air was obtained from the reconstructed deposition density using approaches #1 or #2 and the effective deposition velocity of radionuclide onto the ground surface:

$$TIA_i^{\text{air}} = \frac{\sigma_i}{v_i}, \quad (2)$$

where:

$[\text{final sigma}]_i$ = deposition density of radionuclide i at TOA, kBq m^{-2} ; and

$[\text{nu}]_i$ = effective deposition velocity of radionuclide i onto the ground surface, m s^{-1} .

The same value of effective deposition velocity was applied for all radionuclides. Such approach gives a rough estimate of the time-integrated concentration of radionuclide i in air, as the effective deposition velocity varies with the precipitation rate and with the chemical and physical forms of the radionuclides. UNSCEAR used an average value of effective deposition velocity of $[\text{nu}]_i = 1.76 \times 10^{-2} \text{ m s}^{-1}$ that was derived from long-term observations of the relationship between fallout in the air and on the ground in New York City (UNSCEAR 1993). This value was used in the calculations in case of dry deposition or of light rain ($R < 1 \text{ mm d}^{-1}$). For wet deposition with heavier rainfall, a value of $[\text{nu}]_i = 6.2$

$\times 10^{-2} \text{ m s}^{-1}$ was derived from measurements of time-integrated concentration in air and deposition density in Tahiti after test Centaure (precipitation $R = 2 \text{ mm d}^{-1}$).

Internal dose due to ingestion of radioiodines and ^{132}Te

The thyroid dose for a person of age k arising from ingestion of radionuclides with foodstuffs and drinking water, D_k^{ing} , was calculated as:

$$\sum_i DF_{k,i}^{\text{ing}} \times \sum_m V_{k,m} \times PF_{i,m} \times TIA_{i,m}, \quad (3)$$

where:

$DF_{k,i}^{\text{ing}}$ = ingestion dose coefficient for thyroid, i.e., internal thyroid dose due to intake via ingestion of unit activity of radionuclide i for a person of age k (ICRP 1993, 1996a), mGy kBq^{-1} ;

$V_{k,m}$ = consumption rate of foodstuffs or drinking water, m , by a person of age k , kg(L) d^{-1} ;

$PF_{i,m}$ = processing factor, i.e., the fraction of radionuclide i remaining in foodstuff m after washing, culinary preparation and due to time delay between production and consumption, unitless; and

$TIA_{i,m}$ = time-integrated concentration of radionuclide i in foodstuffs or drinking water, m , kBq d kg(L)^{-1} .

The consumption rates of fresh cow's milk and leafy vegetables, as well as drinking water, reported by the study subjects during the personal interviews were considered to be sources of intake of radioiodines (^{131}I , ^{132}I , ^{133}I , ^{135}I) and ^{132}Te .

The individual consumption rates of foodstuffs or drinking water, m , by a person of age k were estimated by scaling the information obtained from personal interviews for age 15 y:

$$V_{k,m} = V_{15y,m} \times SF_{k,m}, \quad (4)$$

where:

$V_{15y,m}$ = consumption rate of foodstuff or drinking water, m , by a person at age 15 y, reported during the personal interview, kg(L) d^{-1} ; and

$SF_{k,m}$ = scaling factor for consumption rate of foodstuffs m at age k and at age 15 y, unitless.

The scaling factors, $SF_{k,m}$, were derived from Grouzelle et al. (1985) to be 0.5, 0.65, 0.9, 1.0, and 1.05 for persons aged 2–4, 4–8, 8–13, and 13–20 y old, and for adults older than 20 y, respectively, for all foodstuffs except leafy vegetables. For leafy vegetables, scaling factors were estimated to be 0.65, 0.7, 0.95, 1.0, and 1.2 for the same age groups. For the children aged 1 to 2 y old and less than 1 y old, the diet was assumed to be 80% and 40%, respectively, as that for 2–4 y old. For infants less than 1 y old, the information on breastfeeding that was reported in the questionnaires was used.

Another potential source of activity intake was the distribution of one glass of milk per day to children aged 4 to 14 in schools in Tahiti.^{††} However, the fraction of fresh cow's milk to the total amount of milk consumed in Tahiti at that time was rather small, up to 20%.^{‡‡} Therefore, it was assumed that the fraction of fresh cows' milk distributed in schools was 20% in the communes in Presqu'île where milk farms are located, 10% in other communes in Tahiti, and 0% on other islands or atolls.

Estimation of the time-integrated concentrations in local cow's milk in Tahiti

The time-integrated concentration of radionuclides in local cow's milk in Tahiti was obtained as the integral over time from TOA to infinity of the milk concentration at time t (Müller and Pröhl 1993; NCI 1997):

$$A_{i,\text{milk}}(t) = \sigma_i \times F_i^* \times I_g \times T F_i \times \frac{\lambda_i^m}{\lambda_i^m - \lambda_i^w} \times (e^{-(\lambda_i^w + \lambda_i^r) \cdot t} - e^{-(\lambda_i^m + \lambda_i^r) \cdot t}), \quad (5)$$

where:

$A_{i,\text{milk}}(t)$ = concentration of radionuclide i in milk at time t , kBq L⁻¹;

F_i = mass-interception coefficient of radionuclide i by grass, i.e., the fraction of radionuclide initially retained by unit mass of grass or of leafy vegetables; it was taken to be 0.7 m² kg⁻¹ (fresh weight) for iodine and tellurium for dry deposition, and 0.1 m² kg⁻¹ for iodine and 0.2 m² kg⁻¹ for tellurium for wet deposition (Gavrilin et al. 2004);

I_g = 10 kg d⁻¹, the daily intake of grass by cows, dry mass;

$T F_i$ = cow's intake-to-milk transfer coefficient of radionuclide i , d L⁻¹. It was taken to be 3×10^{-3} and 5×10^{-4} d L⁻¹ for stable iodine and tellurium, respectively (Müller and Pröhl 1993);

$[\lambda]_i^m$ = biological transfer rate in milk, d⁻¹. It was taken to be 0.99 and 0.69 d⁻¹ for stable iodine and tellurium, respectively (Müller and Pröhl 1993);

$[\lambda]_i^w$ = elimination rate of radionuclide i from grass due to processes of weathering and growth dilution, d⁻¹. It was taken to be 0.069 and 0.047 d⁻¹ for stable iodine and tellurium, respectively (Miller and Hoffman 1983; Müller and Pröhl 1993); and

$[\lambda]_i^r$ = radioactive decay constant of radionuclide i , d⁻¹.

The measured concentration of ¹³¹I in milk produced in Tahiti after the test Centaure (RF 1975) provided the opportunity to validate the ¹³¹I concentration obtained using eqn (5). The measured (RF 1975) and the calculated ¹³¹I concentration in cow's milk are compared in Fig. 3. There is good agreement between the two sets of values.

When calculating the thyroid dose arising from ingestion of radionuclides with milk using eqn (3), the values of the processing factor for radioiodines and ¹³²Te were taken to be equal to 1.0.

As indicated previously, eqn (5) was also used to derive the deposition density of ¹³¹I when measured concentrations of ¹³¹I in milk were available.

Estimation of the time-integrated concentrations in leafy vegetables

Leafy vegetables consumed in French Polynesia include lettuce, fafa (very similar to spinach) and Chinese cabbage. The time-integrated concentration of radionuclide i in leafy vegetables was obtained as the integral over time from TOA to infinity of the concentration at time t :

$$A_{i,\text{veg}}(t) = \sigma_i \times F_i^* \times e^{-(\lambda_i^w + \lambda_i^r) \cdot t}, \quad (6)$$

where $A_{i,\text{veg}}(t)$ is the concentration of radionuclide i in leafy vegetables at time t , kBq kg⁻¹.

Results of measurements of total gamma activity in leafy vegetables were available only as averages during a trimester (RF 1967, 1969, 1971–1975). Fig. 4 compares the total gamma concentrations in leafy vegetables measured in Tahiti after test Centaure and calculated using eqn (6). In general, the model provides estimates that are in reasonable agreement with the measurements.

To calculate the thyroid dose arising from ingestion of radionuclides with leafy vegetables using eqn (3), the values of the processing factor for radioiodines were taken to be equal to 0.64 for leafy vegetables (one-third of lettuce and two-thirds of fava) and 0.5 for Chinese cabbage (IAEA 1997). For ^{132}Te , the values of the processing factors were taken to be equal to 0.96 for leafy vegetables and 1.0 for Chinese cabbage.

Estimation of the time-integrated concentrations in drinking water

Rainwater collected in a cistern was the main source of drinking water for population of Tuamotu Archipelago. Typically, there was an individual cistern that belonged to the family and a communal cistern that could be used by the entire village. Fifty-seven and 20 study subjects reported that they drank rainwater from individual and communal cisterns, respectively. The variation with time of the concentration of radionuclide i in rainwater in cistern was calculated as:

$$A_{i,\text{water}}(t) = \frac{1}{V(t)} \times \left[A_{i,\text{water}}(t-1) \times (V(t-1) \times e^{-\lambda_i} - V_{\text{cons}}) + \sigma_i(t) \times S_{\text{cistern}} \times SL \right], \quad (7)$$

where:

$A_{i,\text{water}}(t)$ = concentration of radionuclide i in rainwater in cistern at time t , kBq L^{-1} ;

$V(t)$ = amount of rainwater in cistern at time t , L;

$A_{i,\text{water}}(t-1)$ = concentration of radionuclide i in rainwater in cistern at time $t-1$ d, kBq L^{-1} ;

$V(t-1)$ = amount of rainwater in cistern at time $t-1$ d, L;

V_{cons} = amount of water daily consumed from cistern, L. It was taken to be equal to 100 and 600 (L) for the individual and the communal cisterns, respectively;

$[\text{final sigma}]_i(t)$ = deposition density of radionuclide i , kBq m^{-2} ;

S_{cistern} = area of rainwater collection for the cistern, m^2 . It was taken to be equal to the area of the roof over the individual or the communal cistern, 15 and 60 m^2 , respectively (HCRFP 1977); and

SL = solubility of radioiodines in rainwater, unitless.

The amount of rainwater in cistern was calculated as:

$$V(t) = \begin{cases} 0 & \text{if } V(t) \leq 0 \\ V(t-1) - V_{\text{cons}} + R(t) \times S_{\text{cistern}} & \text{if } 0 < V(t) < V_{\text{cistern}} \\ V_{\text{cistern}} & \text{if } V(t) \geq V_{\text{cistern}} \end{cases} \quad (8)$$

where $R(t)$ = daily precipitation (MF 2005), mm; and V_{cistern} = volume of cistern, L. It was taken to be equal to 15,000 and 90,000 L for the individual and communal cisterns, respectively (HCRFP 1977).

The deposition density of radionuclide i , $[\text{final sigma}]_i(t)$, was defined as:

$$\sigma_i(t) = \begin{cases} \sigma_i & \text{if } t = TOA \text{ and } R(t) < 0 \\ 0 & \text{if } t > TOA \end{cases} \quad (9)$$

The solubility of radioiodine in rainwater was taken to be 0.2 (Lessard et al. 1973) for direct deposition that occurred shortly after the test and on islands located rather close to the detonation site (Tureia, Gambier). For indirect deposition from radioactive clouds caused by anticyclone eddies at further distances, the solubility of radioiodine was taken to be 1.

The amount of rainwater in the cisterns was calculated for the time period starting from 2 wk before the first nuclear weapons test to 5 wk after the last test for each year of testing. The initial content of rainwater in the cistern was assumed to be one-third of its volume. To evaluate how the initial content of rainwater in the cistern may influence the thyroid dose estimates, a sensitivity study was conducted for the individuals who reported consumption of rainwater. It was found that the individual thyroid dose is not very sensitive (within a factor of 1.5) to the initial content of rainwater in the cistern.

External irradiation from radionuclides deposited onto ground

The thyroid dose for a person of age k due to external irradiation from radionuclides deposited on the ground, $D_{k\text{ext}}$, was calculated as:

$$D_k^{\text{ext}} = BF \times MF_k \times \sum_i CF_i^{\text{ext}} \times \int_{t_1}^{t_2} \sigma_i(t) dt, \quad (10)$$

where:

BF = behavioral factor that takes into account the fraction of time spent indoors and the shielding provided by the environment, unitless;

MF_k = modifying factor that takes into account the age dependence of the conversion factor, unitless;

CF_i^{ext} = conversion factor for radionuclide i from the plane source on ground surface to absorbed dose rate in the thyroid gland of adults, mGy d⁻¹ per kBq m⁻²; and

t_1, t_2 = times of beginning and end of residence at a given location, d.

The variation with time of the deposition density, $[\text{final } \sigma]_i(t)$, of ⁹⁵Nb, ⁹⁷Nb, ¹³²I, and ¹⁴⁰La was estimated taking into account the deposition of their precursors, i.e., ⁹⁵Zr, ⁹⁷Zr, ¹³²Te, and ¹⁴⁰Ba, respectively.

The values of the conversion coefficients from a uniform plane source on the ground surface to absorbed dose rate in thyroid gland of an adult person were taken from Eckerman and Ryman (1993) for dry deposition. If deposition occurred with precipitation, a reduction factor of 0.7 was used to take into account the penetration of radionuclides in the soil (Beck 1980).

Radionuclides ^{91m}Y, ^{97m}Nb, ^{99m}Tc, ^{103m}Rh, ¹⁰⁶Rh, and ¹⁴⁴Pr, with half-lives on the order of hours or less, were considered to be in radioactive equilibrium with their precursor, and the contributions from both nuclides were taken into account in a single conversion factor.

The age-dependent modifying factors, MF_k , were derived from the International Commission on Radiological Protection (ICRP 1996b) to be 1.2, 1.15, 1.11, 1.06, and 1.02 for newborns, 1, 5, 10, and 15-y-old children, respectively.

The behavior factors, BF, were estimated to be 0.37, 0.43, and 0.70 for persons who lived in apartments, individual houses, and straw houses, respectively. These values were evaluated based on information on the behavior of the Polynesian population:§§

- * An individual house is a one-floor building of light construction (depth of concrete walls around 10 cm) with open windows and doors;
- * Polynesians spend on average one-third of their daily time indoors; location factors (that depend on the type of dwelling material) are taken to be 0.1 for apartments, 0.3 for individual houses, and 0.7 for straw houses; and
- * For outdoor activities the location factors (that depend on the type of environment) are taken to be 0.5 for typical settlements with individual houses and 0.7 for locations with straw houses.

Ingestion of long-lived ^{137}Cs with foodstuffs

Although it was expected that the thyroid dose due to ingestion of ^{137}Cs in general was negligible, this pathway of exposure was considered in the dose reconstruction. The thyroid dose arising from ingestion of ^{137}Cs at age k , $D_{k,\text{ing,Cs}}$, was calculated as:

$$D_{k,\text{ing,Cs}} = N \times DF_{k,\text{ing,Cs}} \times \sum_m V_{k,m} \times PF_m^{\text{Cs}} \times A_m^{\text{Cs}}, \quad (11)$$

where:

$D_{k,\text{ing,Cs}}$ = thyroid dose coefficient for ^{137}Cs for ingestion i for a person of age k (ICRP 1993), mGy kBq^{-1} ;

N = number of days during which contaminated foodstuffs were consumed during the year under consideration, d ;

$V_{k,m}$ = consumption rate of foodstuff m , kg d^{-1} ;

PF_m^{Cs} = processing factor that reflects the change in activity concentration resulting from culinary preparation, unitless; and

A_m^{Cs} = average annual concentration of ^{137}Cs in foodstuff m for each year from 1966 to 1974, kBq kg^{-1} .

Seventeen different foodstuffs were considered in the reconstruction of the thyroid dose due to ^{137}Cs ingestion, including local cow's milk, coco milk, coco copra, fruits (bread tree, banana, papaya) and vegetables (manioc, taro, potatoes, leafy vegetables, cabbage), meat (poultry, beef, pork), fish (lagoon and sea) and mollusks. Archipelago-specific average annual concentrations of ^{137}Cs in foodstuffs were derived from reported results of measurements (RF 1967, 1969, 1971–1975).

To calculate the thyroid dose arising from ingestion of ^{137}Cs using eqn (11), the values of the processing factor were taken to be equal to 0.6 for potatoes, 0.7 for Chinese cabbage, 0.8 for meat, and 0.9 for leafy vegetables, fish, and bread tree (IAEA 1997). For other foodstuffs from listed above, the value of the processing factor was taken to be equal to 1.0.

RESULTS AND DISCUSSION

Individual thyroid dose estimates

The assessment of individual thyroid doses took into account: (1) the residential history and dietary habits of the subjects, which were obtained by means of personal interviews; and (2) the deposition densities of radionuclides reconstructed for each island where a subject

resided during the testing period. Reconstruction of doses was performed blindly with regard to the case or control status of the study subjects.

The thyroid doses received by the study subjects were low (Table 6). The mean dose from all exposure pathways was found to be around 3 mGy, while the highest reconstructed thyroid dose was around 40 mGy. Thyroid doses from short-lived iodine and tellurium isotopes ranged up to 10 mGy. Doses from external exposure ranged up to 3 mGy, while those from internal exposure due to cesium ingestion did not exceed 1 mGy.

Intake of ^{131}I was estimated to be the main pathway for thyroid exposure. The median contribution to the total thyroid dose from sources of exposure other than ^{131}I intake was found to be 14% for intake of short-lived iodine and tellurium isotopes, 14% for external exposure, and around 5% for ^{137}Cs ingestion. However, for individuals who did not consume locally produced foodstuffs, external exposure was the main pathway followed by internal exposure due to inhalation.

Table 7 compares the mean thyroid doses among study subjects received after different atmospheric nuclear tests that contributed substantially to the local deposition in French Polynesia. The highest mean dose among the study subjects was observed after the test Centaure in 1974. The highest thyroid doses after different atmospheric nuclear tests are also compared in Table 7. The highest individual dose was estimated for a subject who resided in Tahiti after the test Centaure in 1974.

As mentioned above, a large number of fission products are produced in a nuclear explosion. However, only a few of them contribute substantially to the thyroid dose. Internal thyroid dose from inhalation and ingestion is mainly due to intakes of ^{131}I , ^{133}I , and $^{132}\text{Te} + ^{132}\text{I}$. With respect to external exposure, the main contributors to thyroid dose are $^{140}\text{Ba} + ^{140}\text{La}$, $^{132}\text{Te} + ^{132}\text{I}$, $^{95}\text{Zr} + ^{95}\text{Nb}$, ^{103}Ru , ^{131}I , and ^{239}Np .

Comparison with results of other studies

The doses that have been estimated in this study were compared with results obtained earlier (UNSCEAR 1977; Bourges 1997). The consumption rates of milk (0.7 L d^{-1}), leafy vegetables (0.1 kg d^{-1}), and drinking water (2 L d^{-1}) that were used by UNSCEAR (1977) and by Bourges (1997) were also applied in this study. Table 8 compares the dose estimates published by UNSCEAR (1977) and by Bourges (1997) with the average doses reconstructed based on input data and methodology of this study. In general, the agreement between the dose estimates obtained in different studies is reasonable. It should be noted that the input data used for dose reconstruction by UNSCEAR (1977) and in this study are rather similar. Results of measurements of ^{131}I concentration in cow's milk were used for dose reconstruction in the two studies; the differences in the dose estimates may be due to differences in data processing or in the values of the parameters used in the models.

Uncertainties in thyroid dose estimates

Uncertainties in the thyroid dose estimates arise from different sources. Some of the dosimetry model parameter values were the same for certain groups of subjects implying that any error made on these parameter values was shared by all subjects to whom it applies. Other uncertainties could be considered to be independent and, therefore, unshared by subjects. The major sources of uncertainty include:

1. The uncertainties attached to the dosimetry models. There are fluctuations in the concentrations of radionuclides in foodstuffs produced at a given location, as well as variability in the thyroid mass and metabolic parameters between individuals. These sources of shared and unshared errors are important as the study considers

the individual doses. It should be noted that the level of iodine deficiency has not been taken into account in the calculations, as an increase in the thyroid mass due to iodine deficiency would likely be compensated by an increase in the thyroid uptake (Zvonova 1989);

2. The uncertainties attached to the reconstruction of deposition densities of radionuclides. Reconstruction was based on a rather limited number of radiation measurements performed on a limited number of islands. Procedures of interpolation and extrapolation were applied to estimate the deposition densities on islands where measurements were not performed. In addition, there is variability in the deposition density within the same island. It should be noted that to estimate the deposition densities of specific radionuclides, the results obtained for atmospheric nuclear weapons tests conducted at the NTS in the U.S. were used, as the corresponding data for the tests conducted in French Polynesia were not found in the open literature; and
3. The uncertainties attached to the information obtained during personal interviews regarding individual diet and habits of more than 25 years ago. It is obvious that the reliability of personal information on consumption rates, residence history, etc. is rather low. The extrapolation of dietary data from age 15 y to another age is also fraught with uncertainties. In addition, the exact age at which the diet was requested might have been misinterpreted; hence, if the subject reported diet at 10 y of age instead of 15, the dose estimates would be slightly different. This source of unshared errors is important for individual dose estimates.

Despite the numerous sources of uncertainty and the paucity of published environmental radiation data, it is remarkable that reasonable agreements are found between the measured and calculated deposition densities, the measured and calculated ^{131}I concentrations in milk, and the measured and calculated total gamma activities in leafy vegetables. On that basis, the overall uncertainties in the individual thyroid dose estimates are subjectively assessed to be a factor of 3 (one geometric standard deviation assuming lognormal distribution) around the central values for most individuals.

CONCLUSION

Forty-one atmospheric nuclear weapons tests (plus five safety tests) were conducted in French Polynesia between 1966 and 1974. To evaluate the potential role of atmospheric nuclear weapons testing on the high incidence of thyroid cancer observed since 1985, a case-control study of thyroid cancer was performed in French Polynesia.

Thyroid doses for individuals included in the study were assessed based on the available historical results of radiometric measurements and meteorological data. These included annual reports on the radiological situation in French Polynesia that had been sent to the UNSCEAR Secretariat. Results of measurements of exposure rate and of total activity in filtered air were used to evaluate the ground depositions of specific radionuclides. Radiation monitoring also included measurements of ^{131}I and ^{137}Cs in cow's milk produced in Tahiti and measurements of radioactivity in foodstuffs produced on selected islands.

For each atmospheric nuclear weapons test that contributed substantially to the local deposition of radionuclides, the radiation dose to the thyroid from ^{131}I intakes via inhalation and ingestion was estimated. In addition, thyroid doses from the intake of short-lived radioiodines (^{132}I , ^{133}I , ^{135}I) and ^{132}Te , external exposure from gamma-emitting radionuclides deposited on the ground, and ingestion of long-lived ^{137}Cs were reconstructed. The assessment of individual thyroid doses took into account: (1) the residential history and dietary habits of the subjects, which were obtained by means of personal interviews; and (2)

the deposition densities of radionuclides reconstructed for each island where a subject resided during the testing period.

The mean thyroid dose among study subjects was found to be around 3 mGy. Estimated individual thyroid doses ranged up to 40 mGy. The intake of ^{131}I was estimated to be the main pathway for thyroid exposure. Doses from short-lived iodine and tellurium isotopes ranged up to 10 mGy. Thyroid doses from external exposure ranged up to 3 mGy, while those from internal exposure due to cesium ingestion did not exceed 1 mGy.

The reconstructed doses are associated with high uncertainties arising from (1) the assumptions made and variability of parameters of dosimetric models; (2) the procedures of interpolation and extrapolation applied to reconstruct the environmental radiation field in locations where measurements were not performed; and (3) uncertainties attached to the personal information from questionnaires.

The dose estimates that have been obtained are based on a rather limited number of radiological measurements performed on a limited number of islands. A thorough compilation of the results of all radiological monitoring that was performed in French Polynesia in 1966–1974, if it were made available to the public, would be likely to greatly improve the reliability and the precision of the dose estimates.

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REFERENCES

- Bataille, C.; Revol, H. Report on the environmental and health impact of nuclear tests performed by France between 1960 and 1996 and of comparison with tests from other nuclear sites. Paris: National Assemblée, Office for Evaluation of Science and Technology, N 3571; 2002. (in French)
- Beck, HL. Exposure rate conversion factors for radionuclides deposited on the ground. Springfield, VA: U.S. Department of Energy; 1980. Report EML-378
- Bourges, G. Study of the radiological situation at the Atolls of Mururoa and Fangataufa. Paris: CEA/DAM/DRIF/DASE; 1997. Radiological consequences of the atmospheric tests on the islands of French Polynesia from 1966 to 1974.
- de Vathaire F, Le Vu B, Vathaire CC. Thyroid cancer in French Polynesia between 1985 and 1995: influence of atmospheric nuclear bomb tests performed at Mururoa and Fangataufa between 1966 and 1974. *Cancer Causes Control*. 2000; 11:59–63. [PubMed: 10680730]
- Dunning GM. Radiation exposure from nuclear tests at the Nevada Test Site. *Health Phys*. 1958; 1:255–267. [PubMed: 13620167]
- Eckerman, KF.; Ryman, JC. External exposures to radionuclides in air, water, and soil. Washington, DC: U.S. Environmental Protection Agency; 1993. Federal Guidance Report No 12
- Gavrilin Y, Khrouch V, Shinkarev S, Drozdovitch V, Minenko V, Shemiakhina E, Ulanovsky A, Bouville A, Anspaugh L, Voilleque P, Luckyanov N. Individual thyroid dose estimation for a case-control study of Chernobyl-related thyroid cancer among children of Belarus. Part 1: ^{131}I , short-lived radioiodines (^{132}I , ^{133}I , ^{135}I), and short-lived radiotelluriums ($^{131\text{m}}\text{Te}$ and ^{132}Te). *Health Phys*. 2004; 86:565–585. [PubMed: 15167120]

- Gordeev K, Vasilenko I, Lebedev A, Bouville A, Luckyanov N, Simon SL, Stepanov Y, Shinkarev S, Anspaugh L. Fallout from nuclear tests: dosimetry in Kazakhstan. *Radiat Environ Biophys*. 2002; 41:61–67. [PubMed: 12014413]
- Grouzelle, C.; Dominique, M.; Lafay, F.; Ducousso, R. Fontenay-aux-Roses. France: Commissariat on Atomic Energy; Report CEA-R-5304; 1985. Results of survey of foodstuffs consumption rates performed in Tahiti from 1980 through 1982. (in French)
- Height Commissariat of Republic of French Polynesia. Aquatic installations in Tuamotu-Gambier Archipelago. Papeete, French Polynesia: HCRFP; 1977. (in French)
- Hicks, HG. Results of calculations of external radiation exposure rates from fallout and the related radionuclides composition. Vol. Parts 3–4. Livermore, CA: Lawrence Livermore National Laboratory; LLNL Report UCRL-53152; 1981. p. 6-8.
- International Atomic Energy Agency. Generic assessment procedures for determining protective actions during a reactor accident. Vienna: International Atomic Energy Agency; IAEA-TECDOC-955; 1997.
- International Commission on Radiological Protection. Ingestion dose coefficients. Vol. 23. New York: Elsevier Science; ICRP Publication 67; 1993. Agedependent doses to members of the public from intake of radionuclides: Part 2. *Ann ICRP*
- International Commission on Radiological Protection. Inhalation dose coefficients. Vol. 25. New York: Elsevier Science; ICRP Publication 71; 1995. Agedependent doses to members of the public from intake of radionuclides: Part 4. *Ann ICRP*
- International Commission on Radiological Protection. Compilation of ingestion and inhalation dose coefficients. Vol. 26. New York: Elsevier Science; ICRP Publication 72; 1996a. Agedependent doses to members of the public from intake of radionuclides: Part 5. *Ann ICRP*
- International Commission on Radiological Protection. Conversion coefficient for use in radiological protection against external irradiation. Vol. 26. New York: Elsevier Science; ICRP Publication 74; 1996b. *Ann ICRP*
- International Commission on Radiological Protection. Basic anatomical and physiological data for use in radiological protection: reference values. Vol. 32. New York: Elsevier Science; ICRP Publication 89; 2002. *Ann ICRP*
- Lessard, ET.; Miltenberger, RP.; Conard, RA.; Musolino, SV.; Naidu, JR.; Moorthy, A.; Schopfer, CJ. Thyroid absorbed dose for people at Rongelap, Utirik, and Sifo on March 1, 1954. New York: Brookhaven National Laboratory; 1973. BNL Report No. 51882
- Meteo France. Paris: Meteo France; 2005. Precipitations, speed and direction of wind in French Polynesia from 1966 through 1974. (in French)
- Miller CW, Hoffman FO. An examination of the environmental half-time for radionuclides deposited on vegetation. *Health Phys*. 1983; 45:731–744. [PubMed: 6885479]
- Müller H, Pröhl G. ECOSYS-87: a dynamic model for assessing the radiological consequences of nuclear accidents. *Health Phys*. 1993; 64:232–252. [PubMed: 8432643]
- National Cancer Institute. Estimated exposures and thyroid doses received by the American people from iodine-131 in fallout following Nevada atmospheric nuclear bomb tests. Bethesda, MD: National Cancer Institute; 1997.
- Ng YC, Anspaugh LR, Cederwall RT. ORERP (Off-Site Radiation Exposure Review Project) internal dose estimates for individuals. *Health Phys*. 1990; 59:693–713. [PubMed: 2211124]
- Republic of France. Information submitted by France to UNSCEAR. New York: United Nations; UNSCEAR Report A/AC. 82/G/L. 1146; 1967. Radioactive fallout after the nuclear explosions in Polynesia, June–December 1966. (in French)
- Republic of France. Information submitted by France to UNSCEAR. New York: United Nations; UNSCEAR Report A/AC. 82/G/L. 1276; 1969. Radioactive fallout after the nuclear explosions in Polynesia, 1967 and 1968. (in French)
- Republic of France. Information submitted by France to UNSCEAR. New York: United Nations; UNSCEAR Report A/AC. 82/G/L. 1381; 1971. Radioactive fallout after the nuclear explosions in Polynesia, May–December 1970. (in French)

- Republic of France. Radioactive fallout after the nuclear explosions in Polynesia, June–October 1971. Information submitted by France to UNSCEAR. New York: United Nations; UNSCEAR Report A/AC. 82/G/L. 1407; 1972. (in French)
- Republic of France. Monitoring of radioactivity in 1972. Information submitted by France to UNSCEAR. New York: United Nations; UNSCEAR Report A/AC. 82/G/L. 1444; 1973. (in French)
- Republic of France. Monitoring of radioactivity in 1973. Information submitted by France to UNSCEAR. New York: United Nations; UNSCEAR Report A/AC. 82/G/L. 1485; 1974. (in French)
- Republic of France. Monitoring of radioactivity in 1974. Information submitted by France to UNSCEAR. New York: United Nations; UNSCEAR Report A/AC. 82/G/L. 1521; 1975. (in French)
- Simon SL, Bouville A. Radiation doses to local populations near nuclear weapons testing sites worldwide. *Health Phys.* 2002; 82:706–725. [PubMed: 12003020]
- Simon SL, Anspaugh LR, Hoffman FO, Scholl AE, Stone MB, Thomas BA, Lyon JL. 2004 update of dosimetry for the Utah Thyroid Cohort Study. *Radiat Res.* 2006; 165:208–222. [PubMed: 16435919]
- Thompson CB. Estimates of exposure rates and fallout arrival times near the Nevada Test Site. *Health Phys.* 1990; 59:555–563. [PubMed: 2211115]
- United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation. New York: United Nations; 1977. 1997 Report; Sales No. E. 77.IX. 1
- United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation. New York: United Nations; 1993. 1993 Report; Sales No. E. 94.IX. 2
- United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation. New York: United Nations; 2000. 2000 Report; Sales No. E. 00.IX. 4
- Zvonova IA. Dietary intake of stable I and some aspects of radioiodine dosimetry. *Health Phys.* 1989; 57:471–475. [PubMed: 2777553]

Fig. 1.
Map of French Polynesia. The numbers of study subjects who resided on each island or atoll are given within parentheses.

Fig. 2.
Distribution of the study subjects according to year of birth.

Fig. 3.
 ^{131}I activity in cow's milk produced in Tahiti after the test Centaure: calculation (curve) and measurements (circles).

Fig. 4. Total gamma activity in leafy vegetables in Tahiti after the test Centaure: calculation (curve) and average measurements during a trimester in lettuce (thin line) and fafa (broken line).

Table 1

Atmospheric nuclear weapons tests conducted in French Polynesia in 1966–1974^a (UNSCEAR 2000; Bataille and Revol 2002).

Name	Date	Time (UT ^b)	Type	Height (m)	Yield (kt) ^c			Partitioned fission yield (kt)		
					Fission	Fusion	Total	Local and regional	Troposphere	Stratosphere
Aldebaran	02/07/1966	15h34	Barge	0	28 ^d	0	28	14	14	—
Tamoure	19/07/1966	15h05	Air drop	1,000	50 ^d	0	50	—	49	1
Betelgeuse	11/09/1966	17h00	Balloon	470	110 ^d	0	110	—	—	110
Rigel ^e	24/09/1966	17h00	Barge	3	125 ^d	0	125	62.5	59.5	3
Sirius	04/10/1966	21h00	Barge	10	205 ^d	0	205	102.5	92.1	10.4
Altair	05/06/1967	19h00	Balloon	295	15 ^d	0	15	—	15	—
Antares	27/06/1967	18h30	Balloon	340	120 ^d	0	120	—	—	120
Arcturus	02/07/1967	17h30	Barge	0	22 ^d	0	22	11	11	—
Capella	07/07/1968	22h00	Balloon	463	115 ^d	0	115	—	—	115
Castor	15/07/1968	19h00	Balloon	650	450 ^d	0	450	—	—	450
Pollux	03/08/1968	21h00	Balloon	490	150 ^d	0	150	—	—	150
Canopus ^e	24/08/1968	18h30	Balloon	520	1,300	1,300	2,600	—	—	1,300
Procyon	08/09/1968	19h00	Balloon	700	640	640	1280	—	—	640
Andromede	15/05/1970	18h00	Balloon	220	13 ^d	0	13	—	13	—
Cassiopee	22/05/1970	18h30	Balloon	500	150	74	224	—	—	150
Dragon ^e	30/05/1970	18h00	Balloon	500	472.5	472.5	945	—	—	472.5
Eridan	24/06/1970	18h30	Balloon	220	12 ^d	0	12	—	12	—
Licorne	03/07/1970	18h30	Balloon	500	457	457	914	—	—	457
Pegase	27/07/1970	19h00	Balloon	220	0.05 ^d	0	0.05	—	0.05	—
Orion ^e	02/08/1970	19h00	Balloon	400	72 ^d	0	72	—	70	2
Toucan	06/08/1970	19h00	Balloon	500	297	297	594	—	—	297
Dione	05/06/1971	19h15	Balloon	275	34 ^d	0	34	—	34	—
Enclade	12/06/1971	19h15	Balloon	450	290	150	440	—	—	290

Name	Date	Time (UT) ^b	Type	Height (m)	Yield (kt) ^c			Partitioned fission yield (kt)		
					Fission	Fusion	Total	Local and regional	Troposphere	Stratosphere
Japet	04/07/1971	21h30	Balloon	230	9 ^d	0	9	—	9	—
Phoebe	08/08/1971	18h30	Balloon	230	4 ^d	0	4	—	4	—
Rhea	14/08/1971	19h00	Balloon	480	478	477	955	—	—	478
Umbriel	25/06/1972	19h00	Balloon	230	0.5 ^d	0	0.5	—	0.5	—
Titania	30/06/1972	18h30	Balloon	220	4 ^d	0	4	—	4	—
Oberon	27/07/1972	18h40	Balloon	220	6 ^d	0	6	—	6	—
Euterpe	21/07/1973	18h00	Balloon	220	11 ^d	0	11	—	11	—
Melpomene	28/07/1973	23h00	Balloon	270	0.05 ^d	0	0.05	—	0.05	—
Pallas	18/08/1973	18h15	Balloon	270	4 ^d	0	4	—	4	—
Parthenope	24/08/1973	18h00	Balloon	220	0.2 ^d	0	0.2	—	0.2	—
Tamara	28/08/1973	18h30	Air drop	—	6 ^d	0	6	—	6	—
Capricorne	16/06/1974	17h30	Balloon	220	4	0	4	—	4	—
Gemeaux	07/07/1974	23h15	Balloon	312	100	50	150	—	—	100
Centaure	17/07/1974	17h00	Balloon	270	4	0	4	—	4	—
Maquis	25/07/1974	17h30	Air drop	250	8	0	8	—	8	—
Scorpion	15/08/1974	00h30	Balloon	312	96	0	96	—	93	3
Taureau	24/08/1974	23h45	Balloon	270	14	0	14	—	14	—
Verseau	14/10/1974	23h30	Balloon	433	221	111	332	—	—	221

^aExcluding five safety tests.

^bUniversal time. Universal time coordinated (local time) in Tahiti: UTC = UT — 10h.

^cEstimated fission and fusion yields unless otherwise indicated; reported total yields.

^dReported fission or fusion yield.

^eThis test was conducted on Fangataufa Atoll, others — on Mururoa Atoll.

Table 2

Number of results of measurements available (RF 1967, 1969, 1971–1975).

Archipelago	Year	Total activity in filtered air	Number of results of measurements		
			¹³¹ I in cow's milk	Total gamma activity in cow's milk and leafy vegetables ^a	Total gamma activity in other foodstuffs ^a
Societe	1966	41	—	—	3 (—)
	1967	22	64	13 (11)	36 (17)
	1968	29	77	13 (10)	151 (65)
	1970	44	93	21 (11)	176 (89)
	1971	38	89	15 (11)	342 (49)
	1972	36	13	43 (26)	359 (137)
	1973	36	47	56 (41)	582 (154)
	1974	33	115	28 (21)	558 (112)
	1966	32	—	—	—
	1967	—	—	—	27 (13)
Tuamotu-Gambier	1968	18	—	—	60 (26)
	1970	—	—	1 (—)	53 (25)
	1971	—	—	—	108 (40)
	1972	—	—	—	148 (59)
	1973	—	—	—	154 (62)
	1974	—	—	—	105 (56)
	1966	14	—	—	—
	1967	—	—	1 (1)	11 (5)
	1968	—	—	3 (3)	44 (14)
	1970	11	—	1 (1)	10 (2)
Marquises	1971	11	—	3 (—)	32 (18)
	1972	—	—	3 (3)	28 (18)
	1973	—	—	3 (2)	51 (20)
	1974	—	—	4 (2)	41 (23)
	1966	21	—	—	—
	1967	—	—	1 (1)	20 (5)
Australes	1966	21	—	—	—
	1967	—	—	1 (1)	20 (5)
	1968	—	—	3 (3)	44 (14)
	1970	11	—	1 (1)	10 (2)
	1971	11	—	3 (—)	32 (18)
	1972	—	—	3 (3)	28 (18)
	1973	—	—	3 (2)	51 (20)
	1974	—	—	4 (2)	41 (23)
	1966	21	—	—	—
	1967	—	—	1 (1)	20 (5)

		Number of results of measurements			
Archipelago	Year	Total activity in filtered air	¹³¹ I in cow's milk	Total gamma activity in cow's milk and leafy vegetables ^a	Total gamma activity in other foodstuffs ^a
	1968	17	—	—	54 (18)
	1970	16	—	2 (1)	30 (12)
	1971	20	—	4 (2)	57 (21)
	1972	—	—	2 (2)	36 (14)
	1973	—	—	6 (—)	59 (21)
	1974	—	—	8 (4)	73 (31)
Total		439	498	231 (153)	3,409 (1,126)

^aNumber of measurements of only ¹³⁷Cs is given in parentheses.

Table 3

Calculated median deposition densities of selected radionuclides at different TOA normalized to an exposure rate of 1 mR h⁻¹ at 12 h post-detonation (H + 12h) [derived from Hicks (1981)].

Radionuclide	Normalized deposition density (kBq m ⁻² per mR h ⁻¹ at H + 12h) at TOA							
	H + 12h	H + 1d	H + 2d	H + 5d	H + 10d	H + 20d		
⁸⁹ Sr	4.7	3.7	3.7	3.5	3.3	2.9		
⁹⁰ Sr	2.5 × 10 ⁻²	2.5 × 10 ⁻²	2.5 × 10 ⁻²	2.5 × 10 ⁻²	2.5 × 10 ⁻²	2.5 × 10 ⁻²		
⁹⁰ Y	—	5.8 × 10 ⁻³	1.0 × 10 ⁻²	1.8 × 10 ⁻²	2.4 × 10 ⁻²	2.5 × 10 ⁻³		
⁹¹ Sr	2.7 × 10 ²	1.1 × 10 ²	20	0.12	2.7 × 10 ⁻⁵	—		
^{91m} Y	1.8 × 10 ²	74	13	7.6 × 10 ⁻²	1.4 × 10 ⁻⁵	—		
⁹¹ Y	2.4	3.5	4.1	4.1	3.9	3.5		
⁹³ Y	2.4 × 10 ²	1.0 × 10 ²	20	0.15	4.4 × 10 ⁻⁵	—		
⁹⁵ Zr	4.4	4.1	4.1	4.0	3.7	3.4		
⁹⁵ Nb	4.1 × 10 ⁻²	8.0 × 10 ⁻²	0.16	0.38	0.7	1.2		
⁹⁷ Zr	2.4 × 10 ²	1.5 × 10 ²	55	2.9	2.2 × 10 ⁻²	—		
^{97m} Nb	2.3 × 10 ²	1.4 × 10 ²	53	2.8	2.1 × 10 ⁻²	—		
⁹⁷ Nb	2.5 × 10 ²	1.5 × 10 ²	55	2.9	2.2 × 10 ⁻²	—		
⁹⁹ Mo	91	81	63	30	8.7	0.7		
^{99m} Tc	62	71	60	29	8.3	0.67		
¹⁰³ Ru	6.9	6.8	6.6	6.4	5.8	4.9		
¹⁰⁶ Ru	0.37	0.37	0.37	0.37	0.36	0.36		
¹²⁵ Sb	4.8 × 10 ⁻³	5.0 × 10 ⁻³	5.5 × 10 ⁻³	6.7 × 10 ⁻³	8.3 × 10 ⁻³	1.0 × 10 ⁻²		
¹³¹ I	28	27	25	20	13	5.6		
¹³² Te	78	70	57	30	10	1.2		
¹³² I	80	72	58	31	11	1.3		
¹³³ I	3.2 × 10 ²	2.0 × 10 ²	91	8.4	0.16	5.4 × 10 ⁻⁵		
¹³⁵ I	3.4 × 10 ²	1.0 × 10 ²	8.3	4.8 × 10 ⁻³	—	—		
¹³⁶ Cs	0.28	0.27	0.25	0.22	0.17	9.8 × 10 ⁻²		
¹³⁷ Cs	3.4 × 10 ⁻²	3.4 × 10 ⁻²	3.4 × 10 ⁻²	3.4 × 10 ⁻²	3.4 × 10 ⁻²	3.4 × 10 ⁻²		
¹⁴⁰ Ba	24	23	22	18	14	8.1		

Radionuclide	Normalized deposition density (kBq m ⁻² per mR h ⁻¹ at H + 12h) at TOA					
	H + 12h	H + 1d	H + 2d	H + 5d	H + 10d	H + 20d
¹⁴⁰ La	4.4	7.9	13	18	16	9.4
¹⁴¹ Ce	7.2	8.6	8.5	8.0	7.2	5.8
¹⁴³ Ce	1.4 × 10 ²	1.1 × 10 ²	66	14	1.2	7.5 × 10 ⁻³
¹⁴³ Pr	3.9	7.0	11	14	12	7.3
¹⁴⁴ Ce	0.7	0.7	0.7	0.7	0.69	0.67
¹⁴⁷ Nd	9.8	8.8	8.3	7.2	5.0	2.7
²³⁹ Np	4.6 × 10 ²	4.0 × 10 ²	3.0 × 10 ²	1.3 × 10 ²	28	1.5

Available radiation data and reconstructed deposition densities for tests that contributed substantially to the local deposition of radionuclides on Tahiti.

Table 4

Name of test	Date of test	TOA	Time-integrated activity in air (kBq s m ⁻³)	Precipitation (mm)	Deposition density ^a (kBq m ⁻²)	
					Total	¹³¹ I
Aldebaran	02/07/1966	H + 10d	1.1 × 10 ²	0	1.9	0.2
Tanoure	19/07/1966	H + 4d	30	11	1.9	8 × 10 ⁻²
Betelgeuse	11/09/1966	H + 9d	4.2	17	0.3	2 × 10 ⁻²
Rigel	24/09/1966	H + 4d	92	0	1.6	7 × 10 ⁻²
Sirius	04/10/1966	H + 7d	7.6 × 10 ²	0	13	0.9
Altair	05/06/1967	H + 10d	1.4 × 10 ²	0	2.5	0.2
Antares	27/06/1967	H + 3d	37	0	0.6	2 × 10 ⁻²
Arcturus	02/07/1967	H + 2d	2.4 × 10 ²	47	15	0.4
Capella	07/07/1968	H + 8d	1.4 × 10 ²	0	2.4	0.2
Castor	15/07/1968	H + 14d	1.5 × 10 ²	0	2.7	0.3
Pollux	03/08/1968	H + 12d	1.5 × 10 ²	0	2.6	0.25
Canopus	24/08/1968	H + 6d	4.1 × 10 ²	0	7.3	0.45
Andromede	15/05/1970	H + 16d	71	0	0.8 ^b	8 × 10 ^{-2b}
Eridan	24/06/1970	H + 10d	30	0	0.5	5 × 10 ⁻²
Licorne	03/07/1970	H + 17d	1.1 × 10 ²	0	1.9	0.2
Orion	02/08/1970	H + 8d	4.2 × 10 ²	1	11 ^b	0.85 ^b
Toucan	06/08/1970	H + 9d	32	0	0.6	5 × 10 ⁻²
Dione	05/06/1971	H + 16d	7.0 × 10 ²	0	8.9 ^b	0.9 ^b
Enclade	12/06/1971	H + 7d	1.3 × 10 ²	0	3.4 ^b	0.2 ^b
Japet	04/07/1971	H + 6d	1.0 × 10 ²	0	1.8	0.1
Rhea	14/08/1971	H + 14d	43	0	1.0 ^b	0.1 ^b
Pallas	18/08/1973	H + 5d	2.5 × 10 ²	17	40 ^b	2.1 ^b
Parthenope	24/08/1973	H + 8d	1.2 × 10 ²	0	5.8 ^b	0.4 ^b
Tamara	28/08/1973	H + 12d	32	0	3.6 ^b	0.35 ^b

Name of test	Date of test	TOA	Time-integrated activity in air (kBq s m ⁻³)	Precipitation (mm)	Deposition density ^a (kBq m ⁻²)	
					Total	¹³¹ I
Capricorne	16/06/1974	H + 5d	1.0 × 10 ²	4	6.4	0.35
Centaure	17/07/1974	H + 2d	4.6 × 10 ⁴	2	2.8 × 10 ^{3c}	69 ^c

^aReconstructed from measurements of total beta activity in air (approach #3) unless otherwise indicated.

^bReconstructed from ¹³¹I measurements in milk (approach #2).

^cReconstructed from the measured exposure rate (approach #1).

Table 5

Deposition densities at TOA reconstructed in this study and measured (Bourges 1997).

Name of test	Date of test	Archipelago	Island (atoll)	Deposition density (kBq m ⁻²)			
				Reconstructed using approach			Measured (Bourges 1997)
				#1	#2	#3	
Aldebaran	02/07/1966	Gambier	Gambier	6.1×10^4	—	—	6.0×10^4
Arcturus	02/07/1967	Tuamotu	Tureia	3.2×10^3	—	—	3.3×10^3
Andromede	15/05/1970	Societe	Tahiti	—	0.8	1.2	—
Orion	02/08/1970	Societe	Tahiti	—	11	7.3	—
Dione	05/06/1971	Societe	Tahiti	—	8.9	12	—
Encelade	12/06/1971	Societe	Tahiti	—	3.4	2.4	—
Encelade	12/06/1971	Tuamotu	Tureia	1.1×10^4	—	—	1.3×10^4
Phoebe	08/08/1971	Gambier	Gambier	3.3×10^3	—	—	1.1×10^3
Rhea	14/08/1971	Societe	Tahiti	—	1.0	0.6	—
Centaure	17/07/1974	Societe	Tahiti	2.8×10^3	1.3×10^3	8.0×10^2	2.0×10^3

Table 6

Thyroid doses reconstructed for the study subjects from different exposure pathways.

Exposure pathway	Thyroid dose (mGy)		
	Min	Mean	Max
Intake of ^{131}I	0.003	2.0	28
Intake of short-lived ^{132}I , ^{133}I , ^{135}I , and ^{132}Te	0.0008	0.4	10
External exposure	0.004	0.2	2.6
^{137}Cs ingestion	0.0006	0.1	0.8
All exposure pathways	0.03	2.7	37

Table 7

Estimated mean and highest thyroid doses received by the study subjects from different tests.

Name of test	Date of test	Thyroid dose (mGy)	
		Mean among study subjects	Highest individual
Aldebaran	02/07/1966	0.09	16.1
Tamoure	19/07/1966	0.004	0.05
Betelgeuse	11/09/1966	0.002	0.09
Rigel	24/09/1966	0.01	0.2
Sirius	04/10/1966	0.18	8.0
Altair	05/06/1967	0.03	0.57
Antares	27/06/1967	0.003	0.07
Arcturus	02/07/1967	0.01	0.18
Capella	07/07/1968	0.03	0.42
Castor	15/07/1968	0.04	0.59
Pollux	03/08/1968	0.04	0.55
Canopus	24/08/1968	0.06	0.90
Andromede	15/05/1970	0.01	0.21
Eridan	24/06/1970	0.008	0.12
Licorne	03/07/1970	0.03	0.49
Orion	02/08/1970	0.03	0.45
Toucan	06/08/1970	0.008	0.13
Dione	05/06/1971	0.12	2.6
Encelade	12/06/1971	0.04	0.7
Japet	04/07/1971	0.02	0.34
Rhea	14/08/1971	0.01	0.28
Pallas	18/08/1973	0.09	4.6
Parthenope	24/08/1973	0.05	1.2
Tamara	28/08/1973	0.04	0.9
Capricorne	16/06/1974	0.01	0.13
Centaure	17/07/1974	2.0	34.0

Table 8

Comparison of dose estimates: UNSCEAR (1977); Bourges (1997); and this study.

Test	Date	Location	Exposure pathway or ingestion of	Thyroid dose for 1-y-old infants (UNSCEAR 1977)	Effective dose for adults (Bourges 1997)		This study (mGy, mSv)
				(mGy)	(mSv)	(mSv)	
	1967	Tahiti	Milk	0.6	—	—	0.5
	1968	Tahiti	Milk	0.6	—	—	0.5
	1970	Tahiti	Milk	1.3	—	—	1.5
	1971	Tahiti	Milk	2.1	—	—	1.7
	1972	Tahiti	Milk	0.12	—	—	0.11
	1973	Tahiti	Milk	1.3	—	—	1.3
	1974	Tahiti	Milk	6.8	—	—	6.8
Aldebaran	02/07/1966	Gambier	External	—	3.4	3.9	3.9
Arcturus	02/07/1967	Tureia	External	—	0.7	0.4	0.4
Encelade	12/06/1971	Tureia	External	—	0.9	1.0	1.0
Phoebe	08/08/1971	Gambier	External	—	0.9	0.4	0.4
Centaure	17/07/1974	Tahiti	External	—	0.6	0.4	0.4
Aldebaran	02/07/1966	Gambier	Inhalation	—	0.2	0.4	0.4
Arcturus	02/07/1967	Tureia	Inhalation	—	0.023	0.035	0.035
Encelade	12/06/1971	Tureia	Inhalation	—	0.003	0.03	0.03
Phoebe	08/08/1971	Gambier	Inhalation	—	0.002	0.04	0.04
Centaure	17/07/1974	Tahiti	Inhalation	—	0.08	0.01	0.01
Aldebaran	02/07/1966	Gambier	Leafy vegetables	—	1.2	1.9	1.9
Phoebe	08/08/1971	Gambier	Leafy vegetables	—	0.2	0.3	0.3
Centaure	17/07/1974	Tahiti	Leafy vegetables	—	0.04	0.08	0.08
Aldebaran	02/07/1966	Gambier	Drinking water	—	0.14	0.13	0.13
Phoebe	08/08/1971	Gambier	Drinking water	—	0.035	0.013	0.013
Centaure	17/07/1974	Tahiti	Milk	—	0.3 ^a	0.4	0.4

^a Effective dose for 1-y-old infants.