Dose assessment methods used to evaluate the radiation exposures from nuclear testing in the atmosphere, with emphasis on the tests conducted in French Polynesia

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When a nuclear weapon is tested in the atmosphere, the large amount of radioactive debris produced in the explosion is freely released into the environment. The radioactive debris, consisting of gases and particulate radionuclides with radioactive half-lives ranging from fractions of a second to thousands of years, disperses with atmospheric circulation and is transported and deposited throughout the world. People everywhere are then exposed to external irradiation from radionuclides in air, in water and on the ground, and are also exposed to internal irradiation from radionuclides that enter the body by inhalation of air and by ingestion of foods and water.

Tests of nuclear weapons in the atmosphere were conducted by five countries during the period 1945-1980. The most active test period was between 1952 and 1962, when many tests were conducted by the United States and the former Soviet Union and a limited testing program was carried out by the United Kingdom. Atmospheric testing by France occurred from 1960 through 1974 (including 41 tests conducted from 1966 to 1974 at two atolls, Mururoa and Fangataufa, in French Polynesia), and by China (22 tests) from 1964 through 1980. No further atmospheric tests have taken place since 1980. Altogether, there were 541 atmospheric tests of total explosive yield 440 Megatons of TNT.

In addition to the atmospheric tests, there were more than 1800 nuclear weapons that were conducted underground. In the underground tests, the radioactive debris is confined by design to the underground cavity. If the underground test has been conducted properly, there is no release or venting of gases in the atmosphere and no radiation exposure of the population. Therefore, underground tests are not considered in this report.

The purpose of this report is to review the methods used to estimate the radiation exposures resulting from the U.S., Russian, and French tests that were conducted in the atmosphere.

Following a description of the types and characteristics of dose assessment, the technical details of the methods used for a range of atmospheric tests will be presented: first, the general method used in the U.S. and Russian studies, and, second, a more detailed presentation of the methodologies used in the studies related to the tests that were conducted in French Polynesia.

Types and characteristics of dose assessment

Information on average doses to large groups of people

Many radiation measurements were made throughout the world during the period of atmospheric testing. These radiation measurements were essentially made to verify that the populations were not submitted to excessive levels of exposure. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) was established in 1955 to compile and assemble the national reports and to evaluate them. UNSCEAR published its reviews of radioactive fallout and resulting doses from atmospheric nuclear weapons tests within a few years' intervals from 1958 until 2000 (UNSCEAR, 1958, 1962, 1966, 1969, 1972, 1977, 1982, 1993, 2000). The principal aims of the UNSCEAR reports was to estimate the average deposition densities of the most important radionuclides according to 10^{o} latitude bands and the population-weighted doses over the entire populations of the northern and southern hemispheres, and of the entire world. As shown in Figure 1, the radioactive cloud produced by the explosion can be widely dispersed at the continental scale within a few days. The part of the radioactive cloud that is contained in the troposphere will circle the world, roughly in the same latitude band, in 20 to 30 days, while the part of the radioactive cloud that reaches the stratosphere will remain there during a year or two before descending to the ground.

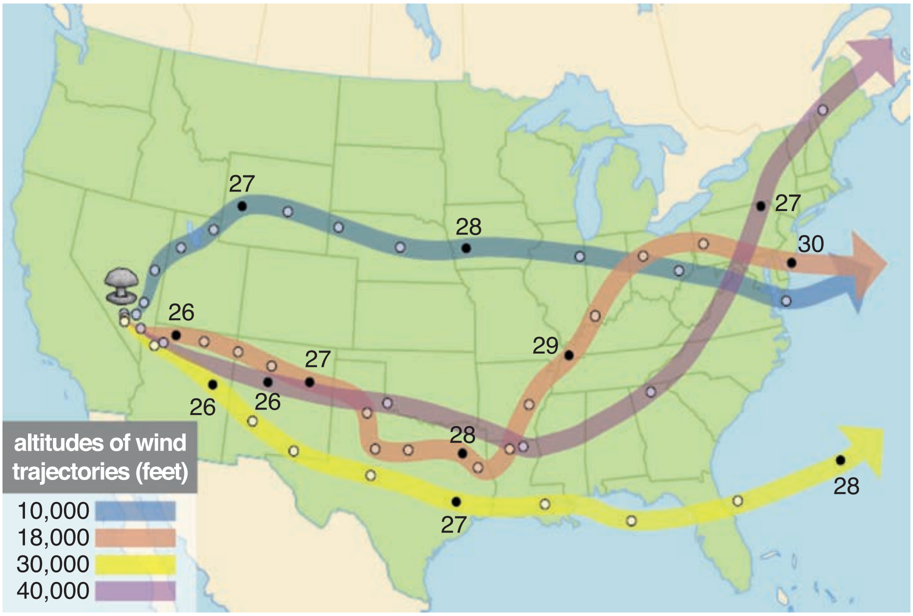

Figure 1: Dispersion of the radioactive cloud produced by an atmospheric nuclear weapons test

In the UNSCEAR as well as in all other dose assessments, a distinction is made between the external and the internal doses, which have very different characteristics:

- External dose:

– Dose approximately uniform over all organs and tissues

– Dose delivered only during exposure

– No monitoring (except for workers)

- Internal dose:

– Dose usually not uniform over all organs and tissues

– Protracted with time

– Monitoring possible via bioassay measurements

– Possible mixture of high-LET[140] and low-LET components

UNSCEAR is mainly concerned with the collective effective dose commitment for the world population. An example of results presented in UNSCEAR Reports is shown on Table 1. A summary of the temporal variation of the doses can be found in (Bouville *et al.*, 2002).

140. LET: Linear energy transfer.

Table 1: Collective effective dose to the world population committed from atmospheric nuclear testing (based on UNSCEAR, 1993)

Radionuclide	Half-life	Collective effective dose (1000 man Sv)			
		External	Ingestion	Inhalation	Total
^{14}C	5730 y		25800	2.6	25800
^{137}Cs	30 y	1210	677	1.1	1890
^{90}Sr	28.6 y		406	29	435
^{95}Zr	64 d	272		6.1	278
^{106}Ru	372 d	140		82	222
^{3}H	12.3 y		176	13	189
^{54}Mn	312 d	181		0.4	181
^{144}Ce	285 d	44		122	166
^{131}I	8.02 d	4.4	154	6.3	165
^{95}Nb	35 d	129		2.6	132
^{125}Sb	2.73 y	88		0.2	88
^{239}Pu	24100 y		1.8	56	58
^{241}Am	432 y		8.7	44	53
^{140}Ba	12.8 d	49	0.81	0.66	50
^{103}Ru	39 d	39		1.8	41
^{240}Pu	6560 y		1.3	38	39
^{55}Fe	2.74 y		26	0.06	26
^{241}Pu	14.4 y		0.01	17	17
^{89}Sr	51 d		4.5	6.0	11
^{91}Y	58.5 d			8.9	8.9
^{141}Ce	35 d	3.3		1.4	4.7
^{238}Pu	86 y		0.003	2.3	2.3
Total		2160	27200	440	30000

Estimation of doses to critical groups

A range of human exposure pathways is possible as a result of an atmospheric nuclear weapons test (see Figure 2). The radiation measurements carried out in the local area (which typically extends to 200-300 km from the site of the explosion) are in part used to make sure that local populations were not subjected to excessive levels of radiation or that the maximally exposed critical groups received doses below the regulatory limits. These dose assessments are carried out using conservative assumptions and are not, as a rule, available in the open literature, although there are exceptions (see, for example, *Ministère de la Défense*, 2006 and Royal Commission into British Nuclear Tests in Australia, 1985). A review of the available information on the radiation doses to local populations near nuclear weapons test sites worldwide was published by Simon and Bouville (2002).

Input data for use in epidemiologic studies of risk projection

Beginning in the late 1970s, a push was made by the U.S. Government to obtain more detailed and realistic information on the radiation doses

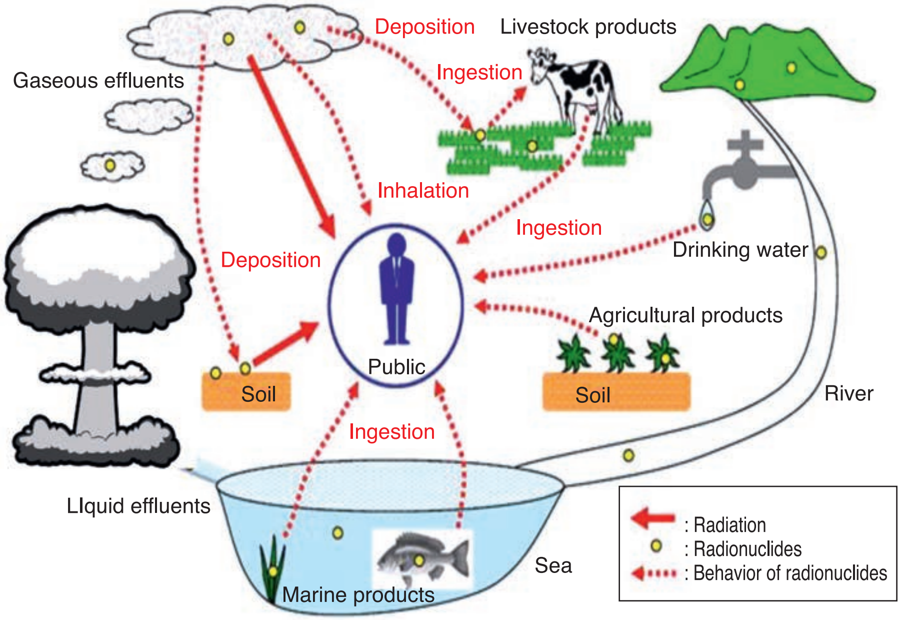

Figure 2: Illustration of pathways of human exposure resulting from an atmospheric nuclear weapons test

received by the populations residing in the proximity of the Nevada Test Site (NTS). In 1979, the U.S. Department of Energy established the Off-site Radiation Exposure Review Project (ORERP) to: (1) collect and organize at a central location all relevant documents and data pertaining to fallout in the off-site area and make these documents available to the public, and (2) produce a dosimetric re-evaluation of the off-site area characterized by region, community/locale, and age/occupation (Church *et al.*, 1990). The methodology of dose assessment that was developed by ORERP (Anspaugh and Church, 1986; Hicks, 1982; Whicker and Kirchner, 1987), as well as the data that were collected and processed, form the basis upon which the epidemiologic studies on fallout from nuclear weapons studies conducted in the U.S., either completed or ongoing, relies upon. In the area of risk projection, these studies, which were mandated by the U.S. Congress, include: (1) a National Cancer Institute (NCI) study of thyroid doses from ^{131}I intakes, and resulting thyroid cancer, received by populations across the continental USA (NCI, 1997), (2) a study jointly conducted by Centers for Disease Control and Prevention (CDC) and NCI on the feasibility to reliably estimate the health consequences to the American population from nuclear weapons tests conducted by the U.S. and other nations (DHHS, 2005), (3) a study of radiation doses and cancer risks in the Marshall Islands from U.S.

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nuclear weapons tests (Simon *et al.*, 2010a), and (4) a study to estimate radiation doses and cancer risks from radioactive fallout from the Trinity nuclear test (NCI, 2008). The doses calculated in these studies are as unbiased as possible and are for representative individuals with typical dietary, residential, and lifestyle habits. The dose values are then applied to the population groups corresponding to the representative individuals. An example of results obtained in this manner is shown in Table 2.

Table 2: Best estimates of cumulative acute internal and chronic internal doses (mGy) for four organs and of external dose (at all organs) to adults of four representative population groups (based on Simon *et al.,* 2010a)

Organ / Mode of exposure	Population groups			
	Majuro residents	Kwajalein residents	Utrik Community	Rongelap Community
Thyroid				
Acute internal	22	66	740	7600
Chronic internal	0.76	1.3	25	14
RBM[a]				
Acute internal	0.11	0.25	2.3	25
Chronic internal	0.98	1.7	33	17
Stomach wall				
Acute internal	0.32	1.1	16	530
Chronic internal	0.75	1.3	24	14
Colon				
Acute internal	4.4	12	180	2800
Chronic internal	0.99	1.7	32	17
Whole-body external	9.8	22	130	1600

[a] RBM: Red bone marrow.

Input data for use in analytical epidemiologic studies

The ORERP methodology and data were also used in the framework of analytical epidemiologic studies (case-control or cohort), in which individual doses to all study subjects need to be estimated: (1) the Utah leukemia case-control study, related to radiation exposures resulting from NTS atmospheric tests (Simon *et al.*, 1995), (2) the Utah thyroid cohort study, also related to the NTS tests (Till *et al.*, 1995), (3) the Semipalatinsk cohort study, conducted jointly by U.S. and Russian investigators (Gordeev *et al.*, 2006 a and b), and (4) the French Polynesia thyroid case-control study (Drozdovitch *et al.*, 2008, 2019, 2020a, 2020b). In the analytical epidemiologic studies, information, as complete and reliable as possible, needs to be obtained on the residential, dietary, and lifestyle habits of all study subjects, generally through the use of a combination of individual interviews, focus groups, and available records. Because the individual dose estimates for analytical epidemiologic studies must be as unbiased as possible, it is necessary to use as many radiation measurements (exposure rates, radionuclide concentrations in air, water, foodstuffs, etc.) as possible. Fortunately, as will be seen later, large numbers of such measurements were made in French Polynesia at the time of the atmospheric tests (Coulon *et al.*, 2009).

An example of dosimetry results obtained in an analytical epidemiologic study is shown in Table 3.

Table 3: Summary of active marrow doses (mGy) for the 6507 study subjects of the Utah leukemia case-control study (based on Simon *et al.,* 1995)

	Cases	Controls	Overall
Mean	2.9	2.7	2.8
Median	3.2	3.1	3.2
Mode	3.4	3.4	3.4
Minimum	0.0	0.0	0.0
Maximum	26.0	29.0	29.0
Variance	0.64	0.48	0.51

Validation of the dose estimates

The validation of the dose estimates is the process used to ensure that the dose estimates are as accurate as possible and do not reflect systematic biases. Whenever feasible, it is important to perform as many validation tests as possible and to consider making adjustments to the dose estimation process as a result of those validation tests.

The ideal approach is to estimate the dose for a suitable proportion of the targeted subjects using a biologically-related measure that correlates highly with dose and to compare the measurements made by the primary approach with estimates of doses made by other means. There are biodosimetric techniques, notably fluorescence in situ hybridization (FISH) and electron paramagnetic resonance (EPR), for validation of the external doses. The EPR technique was used to validate the external doses related to the tests conducted at Semipalatinsk (Sholom *et al.*, 2007), but it does not seem to have been applied to any other fallout study related to nuclear weapons tests. In the NTS study conducted by NCI (1997), the ^{131}I concentrations measured in urine were used to indirectly validate the thyroid doses.

Unfortunately, because of the overall uncertainties in the dose estimates as well as in the validation measurements, the validation process usually provides only an indication of substantial flaws in the primary measurement methods or parameter values (when models are used) used for dose estimation.

Uncertainties in the dose estimates

There are many sources of dosimetric uncertainty in the environmental radiation measurements, the mathematical models and parameter values used to supplement the gaps in the radiation measurements, lifestyle data based on personal interviews, and, in the case of internal irradiation, uncertainties in the metabolic and anatomic attributes of each person or representative individual.

A single ideal approach to evaluate and account for all dosimetric uncertainties is not available but is an area of active research (NCRP, 2009). Until recent years, the evaluation of the uncertainties consisted of numerical simulations in which variability and lack-of-knowledge uncertainties were combined in Monte-Carlo simulations. In that method, probability density distributions are assigned to the parameter values that are deemed to have a substantial influence on the dose estimate and multiple realizations of individual doses are estimated (NCRP, 1996). The primary limitation of many such simulations is that shared errors and intra-individual correlations are not accounted for. A more sophisticated method, the two-dimensional Monte-Carlo procedure, was used in the Semipalatinsk study to separate and distinguish between the shared and the unshared components (Land *et al.*, 2015; Simon *et al.*, 2015). In most studies, uncertainties were evaluated in a subjective manner, if at all.

Methods of dose assessment used for the U.S. and Russian tests

The methods described in this section are related to dose assessments carried out for the purpose of risk analysis or for use in analytical epidemiologic studies. They have been, in part, developed jointly with Russian scientists and applied to both U.S. and Russian tests.

Estimation of external doses

External doses from nuclear weapons tests are essentially due to the γ rays emitted by the radionuclides produced during and after the explosion. Under most circumstances, almost the entire external dose arises from the radionuclides deposited on the ground.

The estimation of the doses from external irradiation resulting from the activity deposited on the ground generally consist of 3 steps: (1) estimation of the outdoor exposure rates normalized to a fixed time after the test, (2) estimation of the total exposure over the time period when the populations under consideration were exposed, and (3) estimation of the organ and tissue doses received by the populations considered.

Estimation of the normalized outdoor exposure rates

Measurements of outdoor exposure rate were systematically conducted after the U.S. and Russian nuclear weapons tests to determine the pattern of fallout deposition on the ground, and, in turn, to estimate in a rough manner the external dose that would be received by people residing in the contaminated areas.

It was important to make sure that the outdoor exposure-rate measurements were made at a sufficient number of locations after the time of arrival of fallout, usually abbreviated as TOA, and that they were normalized to a given time after the explosion (for example, H + 12 h). The value of TOA at specific locations could also be estimated from meteorological considerations or other radiation measurements. The normalization of the outdoor exposure to H + 12 was derived from the function representing the variation with time of the exposure rate.

The temporal variation of the exposure rate cannot be represented by a simple equation that is valid at all times, but it can be approximated as $t^{-1.2}$ for times between 30 minutes to 200 days after the explosion (Glasstone and Dolan, 1977). This is the equation that was typically used for the dose assessments related to the Russian tests (Gordeev *et al.*, 2006a). In the United States, the temporal variation of the exposure rates was established for all important tests as a 10-component multi-exponential function, which is rather complex but can be applied to any time after the explosion. For a given degree of fractionation between refractory and volatile radionuclides (R/V fractionation ratio), there is little variation from one test to another (see Figure 3).

Estimation of the total exposure

The total exposure is calculated as the product of the outdoor exposure rate at H + 12 h and of the integral over time of the normalized outdoor exposure rate, shown in Figure 3, taking the fractionation ratio R/V into account. The fractionation ratio reflects the fact that particles of all sizes are in the radioactive cloud. The large particles, with sizes > 50 µm, are enriched with refractory radionuclides, whereas the small particles, with sizes < 50 µm, are enriched with volatile radionuclides. Because the large particles deposit more

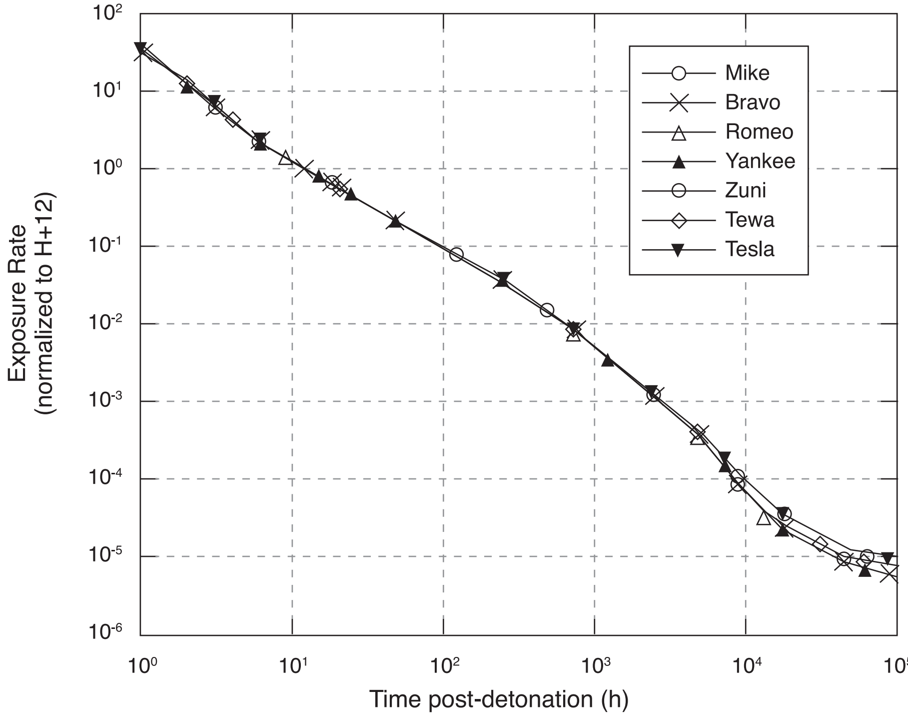

Figure 3: Variation of the exposure rate with time for several atmospheric tests for a fractionation ratio (R/V) of 0.5 (Bouville *et al.,* 2010)

quickly than the small particles, meaning that they reach the ground at smaller distances from the site of the explosion, the value of R/V decreases as the distance from the site of the explosion increases. The value of R/V, which usually is in the range from 0.5 to 3.0, is estimated to vary as a function of TOA/T_{cr}, where the critical time T_{cr} is the length of time since detonation for all particles > 50 µm to be deposited (Beck *et al.*, 2010). For locations where $TOA > T_{cr}$, all deposited particles are smaller than 50 µm and R/V = 0.5.

In the calculation of the total exposure, the lower bound is TOA and the upper bound is the time until which the dose is to be calculated, usually 1 or 50 years. The exposure rate is usually expressed in mR h^{-1} and the total exposure in Roentgen (R). Because most radionuclides produced by a nuclear test have very short half-lives, the exposure rate decreases rapidly with time (see Figure 3), so that almost the totality of the exposure is obtained during the first year after the detonation.

Estimation of the organ and tissue doses

In order to calculate the organ and tissue dose from the outdoor exposure values, one must first convert exposure to dose in air using a factor of 8.75 10^{-3} Gy R^{-1}. Then, a factor of 0.75 Gy Gy^{-1} is typically used to convert from dose in air to dose in tissue or organ of an adult (UNSCEAR, 1993). This factor varies with the energy of the gamma ray and with the orientation with respect to radiation incidence, as well as with the organ or tissue that is considered and with the anthropomorphic characteristics of the person. Because there is little difference between the values of the conversion factor from an organ to another for gamma rays of a few hundred keV that are typical for fission products, the same value can be used for adults for all organs and tissues usually considered in fallout studies. However, calculations using anthropomorphic phantoms of different ages indicate that slightly higher values are obtained for younger ages (Jacob *et al.*, 1990). Based on those calculations, the conversion factors for younger (< 3 y, including in utero) and older (3 through 14 y) children were derived in the Marshall Islands study by multiplying the adult conversion factors by 1.3 and 1.2, respectively (Bouville *et al.*, 2010). Finally, the calculation of the outdoor dose must take the fraction of time spent outdoors into account. If it is assumed to be 0.2 (UNSCEAR, 1993), the overall conversion factor from outdoor exposure to tissue dose is 8.75 10^{-3} (Gy R^{-1}) × 0.75 (Gy Gy^{-1}) × 0.2 = 1.3 10^{-3} Gy R^{-1} for representative adults. For specific individuals, the value of the fraction of time spent out of doors must be obtained from individual interviews or derived from focus groups or interviews of experts.

The calculation of the external tissue dose received indoors due to exposure outdoors is carried out in a similar manner, the only differences being that the fraction of time spent being exposed is different (1 – 0.2 = 0.8 for the example given above) and that the shielding provided by the building structure must be taken into account. If the shielding factor is assumed to be 0.2 (UNSCEAR, 1993), the overall conversion factor from indoor exposure to tissue dose is 8.75×10^{-3} (Gy R^{-1}) × 0.75 (Gy Gy^{-1}) × 0.8 × 0.2 = 1.05×10^{-3} Gy R^{-1} for representative adults. For specific individuals, the value of the fraction of time spent indoors must be obtained from individual interviews or derived from focus groups or interviews of experts; the value of the shielding factor is ideally obtained from measurements. In the absence of measurements, literature values (for example, Glasstone and Dolan, 1977) are used.

The total tissue dose from external irradiation from radionuclides deposited on the ground is obtained as the sum of the two components (outdoors and indoors).

Estimation of internal doses

Internal doses from nuclear weapons tests are essentially due to inhalation of contaminated air and ingestion of contaminated water and foodstuffs. The method used to estimate the internal doses depends on the environmental and human radiation data that are available. The bioassay measurements performed on exposed persons are the data of choice: they are the foundation of the dose estimates for the Marshall Islands study (Simon *et al.*, 2010b), as the doses from acute intakes of radionuclides are derived from historical measurements of ^{131}I in pooled samples of urine collected from adults about 2 weeks after the Bravo test (Harris *et al.*, 2010) and the doses from intakes of long-lived radionuclides are based on measurements of whole-body activity of ^{137}Cs, ^{60}Co, and ^{65}Zn (Lessard *et al.*, 1984). For the other U.S. tests and for the Russian tests, bioassay data are either non-existent or limited to a small of persons (see, for example NCI, 1997). This is true as well for environmental radiation data. In most cases, the assessment of internal doses related to U.S. and Russian tests is based on models of environmental transfer from the activity deposited on the ground to the radionuclide concentrations in air, water, and foodstuffs; it generally consists of 5 steps: (1) estimation of the ground deposition densities (Bq m^{-2}), (2) estimation of radionuclide concentrations in the vegetation and in soil (Bq kg^{-1}), (3) estimation of radionuclide concentrations in air (Bq m^{-3}), water (Bq L^{-1}), milk (Bq L^{-1}), plants, animals and animal products (Bq kg^{-1}), (4) estimation of internal doses from inhalation (Gy), and (5) estimation of internal doses from ingestion (Gy).

Estimation of the ground deposition densities of each radionuclide

The data reported by Hicks (1981) provide not only the variation of the exposure rate with time after the detonation for values of R/V of 1.0 and 0.5, but also the corresponding ground deposition densities of a large range of radionuclides. Beck *et al.* (2010) extended these calculations to other values of R/V appropriate to fallout near the site of the explosion.

Estimation of vegetation and soil radionuclide concentrations

The fraction of the ground deposition density that is retained by the vegetation is a key factor in the estimation of the internal doses. Both dry and wet processes are considered in the estimation

With regard to dry processes, it is assumed that only the particles < 50 µm can be retained by vegetation. The fraction f_{dry} of the β activity attached to particles < 50 µm that is initially retained by vegetation as a result from deposition via dry processes is calculated as:

$$f_{dry} = M(1 - \exp(-\alpha Y)),$$

where M is the maximum interception (unitless), α is the foliar interception constant (m^2 kg^{-1} (dry mass)), and Y is the standing crop biomass (kg (dry mass) m^{-2}). The values of Y may vary according to the ecozone and the type of vegetation, while the values of α and M may vary according to the type of vegetation (Thiessen and Hoffman, 2018).

With respect to wet processes, the fraction f_{wet} of the β activity attached to particles of all sizes that is initially retained by vegetation as a result from deposition, among other factors, on the amount of rainfall, R in mm, that occurred during the passage of the radioactive cloud at location under consideration. In case rainfall occurs during the passage of the radioactive cloud, f_{wet} could be calculated (Thiessen and Hoffman, 2018) as:

$$f_{wet} = min(1; LAI \times k \times S/R \times [1 - exp(-R \times ln(2)/c \times k \times S)]$$

where LAI is the leaf area index, a dimensionless quantity that characterizes plant canopies (unitless); k is a unitless constant that quantifies the ability of an element to be attached to the vegetation; S is the water storage capacity of the plant (mm); R is the total amount of rain during a single event (mm), and c is a unitless constant dependent on the type of plant and ambient conditions (e.g., rainfall intensity and wind speed).

The activity deposited on soil is obtained by subtracting the activity deposited on vegetation from the ground deposition density.

Estimation of radionuclide concentrations in air, water, and foodstuffs

The estimation of radionuclide concentrations in air (Bq m^{-3}), water (Bq L^{-1}), milk (Bq L^{-1}), plants, animals and animal products (Bq kg^{-1}) is conducted using a range of models well described in the literature (e.g., NCI, 1997; Thiessen and Hoffman, 2018; Whicker and Kirchner, 1987).

Estimation of internal doses from inhalation

The internal doses (age-dependent organ-specific doses) from inhalation include those occurring during the passage of the radioactive cloud and those occurring after the passage of the cloud due to resuspension in the air of part of the activity deposited on the ground. The inhalation doses are derived from the time-integrated radionuclide concentrations in ground-level air, taking into consideration the breathing rates of the study subjects and the dose coefficients from inhalation intake to absorbed doses in the organs and tissues under consideration.

For example, in a NTS study, the relationship between the deposited activity on the ground, A_{gd}, of radionuclide Z at location L, and the time-integrated concentration of the respirable-sized particles in air during the passage of the radioactive cloud, $IC_{air,\ cloud}$, was estimated by Simon *et al.* (1990) to be:

$$IC_{air,\ cloud}(Z,L) = A_{gd}(Z,L,R/V,TOA) \times f_{or}(TOA) / 2.41\ 10^{-2}$$

with $f_{or}(TOA) = 0.086 \times (TOA)^{0.61}$

where TOA is expressed in hours.

The inhalation dose due to resuspension has not been included in any U.S. or Russian study, but there are plans to include it in the Trinity study (NCI, 2007). The calculation of the time-integrated concentrations in air due to resuspension $IC_{air,res}(Z,L)$ in Bq d m^{-3}, would be derived from measured values of the resuspension factor $S_f(t)$, which is the ratio of the air concentration and of the deposited activity (Anspaugh *et al.*, 2002; Maxwell and Anspaugh, 2011):

$$IC_{air,res}(Z,L) = \int A_{gd}(Z,L,\tfrac{R}{V},t)\ S_f(t)\ dt$$

where the resuspension factor $S_f(t)$, in m, is expressed as:

$$S_f(t) = 10^{-5}\ e^{-0.07\,t} + 7\ 10^{-9}\ e^{-0.002\,t} + 10^{-9}$$

where the time *t* after deposition at TOA is expressed in days.

Estimation of internal doses from ingestion

The internal doses (age-dependent organ-specific doses) from ingestion are derived from the estimated time-integrated radionuclide concentrations in water and foodstuffs, taking into consideration the commercial distribution of the considered foodstuffs, the consumption rates of the study subjects, the reduction in activity due to processing and culinary factors, and the dose coefficients from ingestion intake to absorbed doses in the organs and tissues under consideration (NCI, 1997; Ng *et al.*, 1990). For specific individuals, the food consumption rates of the study subjects must be obtained from individual interviews or derived from focus groups or interviews of experts (Schwerin *et al.*, 2010; Drozdovitch *et al.*, 2011).

Methods used for the tests conducted in French Polynesia

France conducted forty-one atmospheric nuclear weapons tests (and five safety tests) in French Polynesia in 1966-1974 (UNSCEAR, 2000; Bataille and Revol, 2002). The nuclear test sites were two atolls, Muruora and

Fangataufa, located in the southeastern part of Tuamotu-Gambier archipelago at about 1150 km from Tahiti, the most populated island in French Polynesia.

The network of environmental surveillance included different islands representative of the five French Polynesian archipelagoes. In selecting these islands, environmental and ecological diversity, heterogeneous demography, and predominant winds that potentially affected the consequences of nuclear tests were taken into account. Radiological monitoring on land was supplemented with measurements on buoys, ships, and aircraft (Coulon *et al.*, 2009; IAEA, 2009-2010). In addition, 25 campaigns of anthropogammametry measurements were conducted among the populations of the islands close to the nuclear sites; unfortunately, the results, expressed in terms of triage index, cannot be used for dose assessment purposes as no additional information is available.

The methodologies used by the French authorities (*Ministère de la Défense*, 2006; DSND, 2006a, 2006b) and by Inserm in a study of thyroid cancer in French Polynesia (Drozdovitch *et al.*, 2008, 2019, 2020a, 2020b) are presented in turn.

Dose assessment by the French authorities

The French authorities reported doses, in terms of effective doses and of thyroid doses, for the most important tests and for two age categories (1-2 year old and adults) in the most exposed populations (*Ministère de la Défense*, 2006). The main purpose of the dose assessments was to make sure that the dose levels were below the regulatory limits.

The exposure pathways that were taken into consideration are:

- external exposure from immersion during the passage of the radioactive cloud,
- external exposure from fallout deposition on the ground following the passage of the radioactive cloud,
- internal exposure from inhalation of radioactive materials,
- internal exposure from ingestion of water, milk, and foodstuffs.

Assessment of the external doses

- ***Immersion dose during the passage of the radioactive cloud***

The method used by the French authorities to calculate the immersion doses was based on the measured global β activity of the ground deposition density, expressed in Bq m^{-2}. The activity of each of the approximately 70 radionuclides contributing substantially to the global β activity, as well as their variation with time after detonation, were derived from the JEFF database[141] (AEN, 2005). The time-integrated concentration in air, expressed in Bq s m^{-3}, was then obtained using a deposition velocity, the value of which varied according to estimated TOA at the location considered and the occurrence, or not, of rain. Deposition velocities ranging from 10^{-3} to 10^{-1} m s^{-1} were used for TOAs shorter than one day. The final step of the calculation of the immersion dose consisted in applying an appropriate effective dose coefficient, expressed in Sv per Bq s m^{-3}, to each radionuclide (Eckerman and Ryman, 1993) and in summing the results over the 70 radionuclides. The reduction of the dose due to shielding while indoors was taken into account, using a protection factor of 0.5 if the radioactive cloud arrived during the night or while the population was sheltered. The dependence of the dose with age was not taken into account.

- ***External dose resulting from ground deposition of fallout***

In the method used by the French authorities, the ground deposition density of each of the approximately 70 radionuclides contributing substantially to the external dose is calculated in the same manner as is done in the calculation of the immersion dose. The effective dose rate, expressed in Sv h^{-1}, for each radionuclide is then calculated using an appropriate effective dose rate coefficient (Eckerman and Ryman, 1993). Integrating over the time of exposure, taking radioactive decay into account, yields the external effective dose due to the radionuclide under consideration. Summation over the approximately 70 radionuclides leads to the total external effective dose due to the ground deposited activity. Modifying factors were applied to this result: (1) a reduction factor of 2/3 based on the assumption that people spent part of their time in the contaminated area, and (2) when the radioactive cloud arrived during the night, it was assumed that the populations, being indoors, were not exposed during the first 6 hours after TOA.

It is worth noting that, although exposure rates were measured at various locations after each test, the measured values do not appear to have been preferentially used in the calculation of the external doses by the French authorities, which used the measured global β activity of the ground deposition density as the starting point of the dose calculation. This is in sharp contrast with the method used in the U.S. studies, in which the ground deposition density did not have to be measured in order to calculate the external dose, although it should be recognized that if the measurements of

141. JEFF: Joint Evaluated Fission and Fusion nuclear data library (Nuclear Energy Agency).

the outdoor exposure rates were missing or insufficient, the exposure rates were derived from the ground deposited activity, measured for example using gummed film (Beck *et al.*, 1990; Bouville and Beck, 2000).

- ***Internal dose resulting from inhalation of radioactive materials***

The internal dose from inhalation of aerosols in ground-level air during the passage of the radioactive cloud was also based on the deposition density. For a given radionuclide, the time-integrated concentration in outdoor air (Bq s m^{-3}) was obtained as the ratio of the ground deposition density (Bq m^{-2}) of that radionuclide and of a value of the deposition velocity (s m^{-1}) ranging from 10^{-3} to 10^{-1} m s^{-1}, according to the TOA and of the occurrence of rain, as indicated in section "Immersion dose during the passage of the radioactive cloud" on the immersion dose. It was usually assumed that people were out of doors during the passage of the radioactive cloud. However, if the passage of the radioactive cloud occurred at night, when people were indoors, or in shelters, the air concentration was divided by a factor of 2 for people indoors at night or by a factor of 10 for people in shelters. The inhalation dose was then calculated as the sum of the products of the time-integrated air concentration and of the appropriate dose coefficient for the age of the person, the chemical form of the radionuclide, and the type of dose that was considered (effective or thyroid). Radioactive isotopes of noble gases were not considered as their resulting doses from inhalation are extremely small. Also, the dose due to resuspension of radioactive aerosols was not considered as their contribution to the inhalation of dose is generally very small.

It is worth noting that the ground deposition density appears to have been systematically used as the starting point of the calculation of the inhalation dose, even though direct measurements of air concentrations were available in many cases.

- ***Internal dose resulting from ingestion of water, milk, and foodstuffs***

Calculation of doses by ingestion was done in the early tests (in the late 1960s) using the total β activities in consumed foodstuffs of local origin. In later tests (from 1971 through 1974), measurements of a few specific radionuclides were also available. In the absence of information on the environmental transfer from the ground deposition density to the concentration in foodstuffs, the activity distribution in foodstuffs was assumed to be identical to the activity distribution of the various radionuclides in the ground deposition density, calculated using a variation with time according to a power function of $t^{-1.2}$. Following the calculation of the radionuclides in foodstuffs, either from measurements or from a relationship between the ground deposition density and the concentration in the considered foodstuff, the ingestion dose was then calculated as the sum of the products of the time-integrated concentration in the foodstuff (Bq d kg^{-1}), the consumption rate of the foodstuff (kg d^{-1}) and the appropriate dose coefficient dose (Sv or Gy Bq^{-1}) for the age of the person, the chemical form of the radionuclide, and the type of dose that was considered (effective or thyroid).

The consumption rates of the foodstuffs for representative adults of the five archipelagoes of French Polynesia were established on the basis of dietary surveys conducted in 1965 and 1985 (Lederman, 1965; Grouzelle *et al.*, 1985). Only locally produced foodstuffs were considered. The consumption rates of children were derived from the consumption rates of adults.

The effective dose coefficients and the thyroid dose coefficients were taken from ICRP publications (ICRP, 1995, 1996a, 1996b).

- ***Dose estimates***

Radioactive fallout from the atmospheric tests conducted in French Polynesia was extremely small when the actual meteorological conditions were consistent with those that were predicted. However, this was not the case for several tests (including Aldebaran (2 July 1966), Rigel (24 September 1966), Arcturus (2 July 1967), Encelade (12 June 1971), Phoebé (8 August 1971), and Centaure (17 July 1974)). Relatively important fallout from those tests occurred either on Tureia (the closest atoll to the test sites, located at about 110 km), the Gambier Islands (450 km from the test sites), or Tahiti (including Pirae, Hitiaa, and Taravao), located 1150 km away from the test sites. The estimates of the thyroid doses for 1-2 y old children (mGy) and of the effective doses (mSv) for adults are presented in Tables 4 and 5 at the most exposed locations for each of the exposure pathways taken into consideration.

Tables 4 and 5 show that the consumption of water and seafood were important exposure pathways in the atolls and islands close to the test sites, where the populations were small and the diet was limited to a few staples. In Tahiti, where more than half of the total French Polynesian population resided, there was a large variety of food products, including cow's milk, and the consumption of water played a relatively minor role.

Table 4: Estimated thyroid doses to 1-2 y old children (mGy), calculated by the French authorities for the 6 tests with significant fallout (based on *Ministère de la Défense,* 2006)

Test Name	Dose location	Ext. cloud	Ext, dep.	Inhalation	Ingestion food	Ingestion water	Total	Major pathway
Aldebaran	Gambier	0.02-0.2	2.9	3-30	1.3-42	0-6	7.2-81	Inhalation, water
Rigel	Tureia	Small	0.05	0.03	0.06-1.15	0.55-0.88	0.65-2	Water
Rigel	Gambier	Small	0.019	0.011	0.15-0.51	4.4-7.3	4.6-7.8	Water
Arcturus	Tureia	Small	0.7	0.2-1.4	0.7-34.8	1.24	2.2-38	Seafood
Encelade	Tureia	Small	1.1	0.14-0.8	0.71-4.6	3.0-21.1	4.9-28	Water
Phoebé	Gambier	Small	0.11	0.01-0.04	0.52-9.6	4.3-88.2	4.8-98	Water
Centaure	Pirae	0.002	0.053	0.57	13	0.6	14	Milk, seafood, plants
Centaure	Hitiaa	0.025	1.2	6.4	41	1.3	50	Milk, seafood, plants
Centaure	Taravao	0.09	1.1	24	15.4	0.22	40	Inhalation, milk, seafood, plants

Table 5: Estimated effective doses to adults (mSv), calculated by the French authorities for the 6 tests with significant fallout (based on *Ministère de la Défense,* 2006)

Test name	Dose location	Ext. cloud	Ext, dep.	Inhalation	Ingestion food	Ingestion water	Total	Major pathway
Aldebaran	Gambier	0.02-0.2	2.9	0.1-1.2	0.09-2.2	0-0.12	3.1-6.6	External
Rigel	Tureia	Small	0.05	0.002	0.002-0.07	0.01-0.02	0.06-0.1	External
Rigel	Gambier	Small	0.019	Small	0.01-0.04	0.1-0.17	0.1-0.2	Water
Arcturus	Tureia	Small	0.7	0.01-0.07	0.04-2.4	0.03	0.8-3.2	Seafood
Encelade	Tureia	Small	1.1	0.01	0.06-0.31	0.06-0.5	1.2-1.9	External
Phoebé	Gambier	Small	0.11	Small	0.03-0.66	0.1-1.8	0.2-2.6	Water
Centaure	Pirae	0.002	0.053	0.046	0.34	0.016	0.5	Food
Centaure	Hitiaa	0.025	1.2	0.52	0.82	0.03	2.6	External
Centaure	Taravao	0.09	1.1	1.9	0.46	0.0045	3.6	External

Dose assessment for the Inserm study of thyroid cancer in French Polynesia[142]

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 consisted of two phases. Phase I included

142. This part has been updated after the meeting with the experts group of Inserm collective expertise. This part is based on 3 studies recently published:
Drozdovitch V, Bouville A, Tetuanui T, *et al.* Behavior and food consumption pattern of the French Polynesian population in the 1960s-1970s. *Asian Pac J Cancer Prev* 2019; 20: 3667-77.
Drozdovitch V, de Vathaire F, Bouville A. Ground deposition of radionuclides in French Polynesia resulting from atmospheric nuclear weapons tests in Mururoa and Fangataufa atolls. *J Environ Radioact* 2020a; 214-215: 1061762.
Drozdovitch V, Bouville A, Tetuanui T, *et al.* Thyroid doses to French Polynesians resulting from atmospheric nuclear weapons tests: Estimates based on radiation measurements and population lifestyle data. *Health Phys* 2020b (in press).

all alive cases of thyroid cancer developed between 1985 and 2003 in persons who were children, adolescents, and young adults at the time of atmospheric nuclear testing. Epidemiological aspects of Phase I and estimates of risk of thyroid cancer were published by de Vathaire *et al.* (2010). Overall, 602 subjects, both cases and controls, were included in the risk analysis, which was performed using thyroid doses calculated in 2008 by means of the "Thyroid Dosimetry 2008 system" (TD08) (Drozdovitch *et al.*, 2008). In 2014-2017, Inserm undertook Phase II of the epidemiological study, including 348 additional subjects, thus resulting in a total of 950 subjects. Because of deficiencies in TD08, mainly related to limitations in the input data, the dosimetry system was improved for the assessment of thyroid doses for all subjects of the epidemiologic study. Unit 605 of Inserm (currently Unit 1018) coordinated the case-control study.

The methodology of the dose assessment and the dose estimates for Phase I of the study were published by Drozdovitch *et al.* (2008). The radiation dose to the thyroid gland had to be evaluated for each study subject. However, the following limitations of TD08 were recognized:

• One of the major deficiencies was the limited information on lifestyle in French Polynesia in the 1960s-1970s that was available for TD08. Individual data for each study subject had been collected by means of personal interviews on (i) places of residence in 1966-1974; (ii) consumption rates of various foodstuffs at age 15; (iii) source of drinking water, i.e. individual cistern, communal cistern, other; and (iv) type of residence, i.e. apartment or house. However, important information, needed for precise dose estimation, was missing in the questionnaire; this included: (i) the type of construction materials used to build the residences; (ii) the time spent indoors at different ages and locations; (iii) the consumption rates of foodstuffs by the subjects during infancy and childhood; (iv) the consumption rates of foodstuffs by women (mothers of the study subjects) who were pregnant or lactating during the period of atmospheric testing. To overcome these limitations, a special study was conducted in French Polynesia in 2016-2017 to collect historical behavior and dietary habits of the French Polynesia population in the 1960s-1970s using focus-group discussions and key-informant interviews. Detailed description and results of the focus-group study can be found elsewhere (Drozdovitch *et al.*, 2019).

• Another limitation of TD08 was related to the paucity of radiation measurements that were available for the estimation of the radionuclide deposition densities, and, in turn, of the thyroid doses in TD08. The radiation data for TD08 included mainly the results of measurements of (i) total-beta activity in filtered air, (ii) ^{131}I and ^{137}Cs concentrations in cow's milk produced in Tahiti, and (iii) total gamma activity in foodstuffs. These radiation data had been taken from annual reports on radiation monitoring in French Polynesia, which had been sent to the United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR) Secretariat (Republic of France, 1967, 1969, 1971-1975) by the French Government after each series of tests. However, the results of radiation monitoring were reported only for 9 islands and atolls after some tests.

To overcome these limitations, improve the thyroid dose estimates for the case-control study, and reduce uncertainties in doses, two special studies were conducted in 2016-2019 on: (i) collection of historical data on lifestyle of French Polynesians at the time of nuclear tests, and (ii) evaluation of ground deposition of radionuclides in French Polynesia resulting from atmospheric nuclear weapons tests using a large number of original internal reports on the radiation measurements made in French Polynesia, which were declassified by the French Ministry of Defense in 2013.

Results of these studies were used to update TD08 and create the "Thyroid Dosimetry 2019 system" (named TD19 here and below), which was used to process the input data on population lifestyle and radiation fallout and to estimate the individual thyroid doses received by all study subjects of Phase I and Phase II of Inserm case-control study of thyroid cancer in French Polynesia. The description of these studies will be presented in brief in this document; it will be followed by a detailed description of the methodology of dose reconstruction and by a presentation of the improved thyroid dose estimates.

Behavior and food consumption pattern of the French Polynesian population in the 1960s-1970s

Because four to five decades had elapsed since the nuclear tests were conducted, the focus group discussion and key informant interview methodology was chosen to overcome normal memory recall limitations (McLafferty, 2004). The focus group discussions and key informant interviews are retrospective data collection strategies that provide more reliable recall than individual subject interviews. Low validity and reproducibility of data on recalled individual diet are typically characterized for recollections exceeding 10 years (Willett, 1998) and recall of diet in distant past is strongly influenced by present dietary habits (Rohan and Potter, 1984). Focus group discussion helps to stimulate recall about lifestyle questions and overcome low reproducibility in providing information. Interaction of focus group participants is a unique and compelling feature where participants share their experiences to provide "true" group consensus data as well as the reasons for differences among participants (Kitzinger, 1995). However, we observed during the study that individual opinion may be inflected or influenced by group consensus; this may be a limitation of focus group strategy. The focus-group methodology was successfully used to collect quantitative and qualitative data on lifestyle and occupational habits for the purposes of retrospective dose reconstruction for radiation epidemiology studies of population exposed in 1949-1962 to fallout from Semipalatinsk nuclear test site in Kazakhstan population (Drozdovitch *et al.*, 2011; Schwerin *et al.*, 2010) and nuclear medicine technologists who diagnostic radioisotope procedures in the 1950s-mid 1970s (Drozdovitch *et al.*, 2014).

Many of the study subjects were too young at the time of exposure to recall their consumption habits; therefore, mothers and caretakers of children were considered to be a more reliable source of those data. Women, whose children were less than 21-year old during the period of atmospheric testing in 1966-1974, were selected to participate in focus groups to provide information about their children's behavior.

Focus groups

The focus groups field study was conducted in three phases in August-September 2016, in February, and in May-June 2017 in seven islands and atolls, namely Gambier, Hiva Oa, Manihi, Raiatea, Rangiroa, Rurutu and Tahiti, that represent all archipelagoes of French Polynesia. The focus group locations covered the places of residence for 75% of the 950 subjects included in the study. In each island or atoll, two focus-group meetings (except Tahiti where 7 focus-group meetings were conducted) with up to eight women (mothers and caregivers of children living on the island or atoll at the time of the nuclear tests) were conducted. In total, 108 women participated in the focus-group meetings. The age of the women who participated in the focus groups ranged from 57 to 95, with a mean and median age of 71. The focus-group participants were selected from the population of residents of the fallout-affected islands/atolls at the time of the tests. The women were identified and contacted by the staff of the town halls of the local municipalities.

The topics for discussion in the focus groups were intended to reflect the social practices at the time of the nuclear tests. Women mainly took care of children and, therefore, were a reliable source of information on diet and activity patterns of children. The focus-group participants provided information about the time children spent outdoors daily and about children's consumption patterns at different ages (0-12 mo, 1-3 y, 4-6 y, 7-14 y, and

15-21 y). We found that only a few participants of the focus groups had children aged 15-21 at the time of the testing, therefore women were asked about their own consumption habits at age 15-21 as surrogate data. Data obtained from the mothers for age 15-21 were combined with data reported for the children of the same age group. According to the study participants, the diet remained constant between 1966 (and even 10 or 15 years earlier) and 1974; newer foods were not introduced into the diets until the late 1970s. Therefore, behavior and dietary information collected from the focus groups reflects the situation during the years of exposure. To capture the variability of lifestyle patterns, at least two groups per archipelago were conducted.

Participants of the focus groups were also asked about their own food consumption rates during pregnancy and breast feeding. This information is important for the dose reconstruction as 96 study subjects (10.1% of the total) were exposed while in utero and 131 study subjects (13.8% of the total) were breastfed in 1966-1974.

During the focus group meeting, to stimulate participant memory, the moderator asked open-ended questions for each topic of discussion. The answers from the participants were written down on data collection sheets. Table 6 shows, as example of data collected during the focus groups, daily consumption by children of different ages in mid 1960s – mid 1970s of fresh cow's milk, leafy vegetables and fâfâ that were the major sources of ^{131}I intake with food.

Table 6: Daily consumption[a,b] (g(mL) d^{-1}) of foodstuffs by children of different ages in mid 1960s – mid 1970s (Drozdovitch *et al.*, 2019)

Foodstuff	Archipelago / Island	Age, y				
		< 1	1-3	4-6	7-14	15-21
Fresh cow's milk	Tahiti	–	371±70	321±53	213±25	314±62
Leafy vegetables	Tahiti	–	31±3.7	36±3.2	61±7.9	79±14
	Society	109±34	147±27	*210*[c]	*7*	121±55
	Tuamotu	–	–	*30*	110±32	96±27
	Gambier	–	*60*	76±5.6	62±14	93±40
	Marquises	–	5.2±1.4	88±14	*260*	92±31
	Australes	–	48±7.3	73±17	110±44	86±15
Fâfâ	Tahiti	–	*2.9*	38±12	54±8.0	61±8.2
	Society	12±1.8	18±1.2	11±1.6	69±18	77±8.8
	Gambier	–	–	21±5.9	7.8±1.4	14±3.1
	Marquises	–	8.5±2.9	*2.7*	–	61±30
	Australes	104±25	107±13	100±27	130±19	160±32

[a] Arithmetic mean ± standard error of mean among children for whom consumption of cow's milk, leafy vegetables and fâfâ was reported.
[b] Locally produced food unless otherwise indicated.
[c] For values printed in italic, all focus group participants reported the same consumption rates for their children.

Key informant interviews

To collect information about supplemental factors that are also required for environmental dose reconstruction, individual interviews were conducted with "key informants" in addition to the focus group meetings. Eighteen persons with extensive experience and knowledge of different aspects of daily life in the study area at the period of atmospheric nuclear weapons testing were interviewed in 2016-2017. The age of the 8 female and 10 male key informants ranged from 58 to 83, with a median age of 72. During 1966-1974, these individuals worked as teachers (n = 7), politicians and local authorities (n = 5), owners of business (n = 2), fishermen (n = 2), agriculture workers (n = 1), and military personnel (n = 1).

The key informants provided information on lifestyle and dietary practices in the mid-1960s – mid-1970s, including: (1) consumption of fresh cow's milk and milk products in Tahiti; (2) consumption of "exotic" food on different archipelagoes; (3) the fraction of the families that lived in different types of residences (e.g. family house, multistore house, straw house) and construction materials of residences; (4) culinary practices for leafy vegetables; (5) attendance of schools by children and construction materials of schools; (6) peculiarities of diet for pregnant women and women during breast feeding; and (7) sources of drinking water for residents as well as cisterns' size and area of rain water collection for family and communal cisterns. The oral responses of the key informants were documented on paper forms by the interviewer.

Detailed description of the results of the study on behavior and food consumption pattern of the French Polynesian population in the 1960s-1970s can be found in Drozdovitch *et al.* (2019).

Reconstruction of ground deposition of radionuclides in French Polynesia resulting from atmospheric nuclear weapons tests at Mururoa and Fangataufa atolls

The French Ministry of Defense in 2013 de-classified 148 original reports from the Joint Radiological Safety Service (Service Mixte de Sécurité Radiologique, SMSR) and from the Joint Biological Control Service (Service Mixte de Contrôle Biologique, SMCB), which include detailed results of radiation monitoring of terrestrial and marine environment, foodstuffs and drinking water. Data from these reports were used to reconstruct the ground deposition of radionuclides in French Polynesia.

Radiation monitoring

Radiation monitoring during the 1966-1974 time period of atmospheric nuclear weapons tests in French Polynesia was conducted by two organizations: SMSR, which was in charge of the radiation measurements in the physical environment (exposure rates, concentrations in air and water, and deposition on the ground), and SMCB, which was in charge of the radiation measurements performed in the biological environment (plants, vegetables, fruit, milk, milk products, animals from the terrestrial and aquatic environments) (Coulon *et al.*, 2009; *Ministère de la Défense*, 2006).

The SMSR network included Radiological Control Stations (PCR, Postes de Contrôle Radiologique), Radiological Surveillance Posts (PSR, Postes de Surveillance Radiologique), and Telemetry Measurements stations (TLM). PCRs and PSRs were responsible for the measurements of exposure rate in air, total beta-concentration in air and deposition density on the ground surface, a substantial difference between the two types of stations being that the PCRs were manned by radiation protection technicians, whereas the PSRs could be operated by non-specialized personnel. The TLM stations, in which measurements of exposure rate were conducted, were located on small low-populated and uninhabited islands and atolls in the southeastern part of Polynesia close to the test sites of Mururoa and Fangataufa. All results of the SMSR network were relevant to the purposes of reconstruction of ground deposition of radionuclides. Figure 4 shows the locations of PCRs, PSRs and TLMs in French Polynesia during the time period of the atmospheric nuclear tests. It should be noted that the numbers of PCR and PSR varied from year to year. In addition, measurements of total beta- concentration in air were performed in 1966 in Moorea, Raiatea (Society Islands) and in Anaa, Makemo, Hikueri, Takaroa (Tuamotu); however, these locations were not included in the SMSR network in later years and are not shown on Figure 4. In addition to the SMSR reports, meteorological information, namely daily precipitation and wind speed and direction, was available from Météo France; the location of the 23 meteorological stations is also shown on Figure 4.

The SMCB network was responsible for the measurements of radioactivity in biological samples, i.e. fresh cow's milk produced on Tahiti, other foodstuffs, plants, lagoon and ocean fish, mollusks, etc. Only results of measurements of ^{131}I in fresh cow's milk from SMCB reports (SMCB, 1970, 1972, 1973) were considered.

More results of measurements were available in the declassified SMSR (SMSR, 1966-1975) reports in comparison with those available in UNSCEAR reports: 7,526 vs 439 for total beta-concentration in filtered air, 251

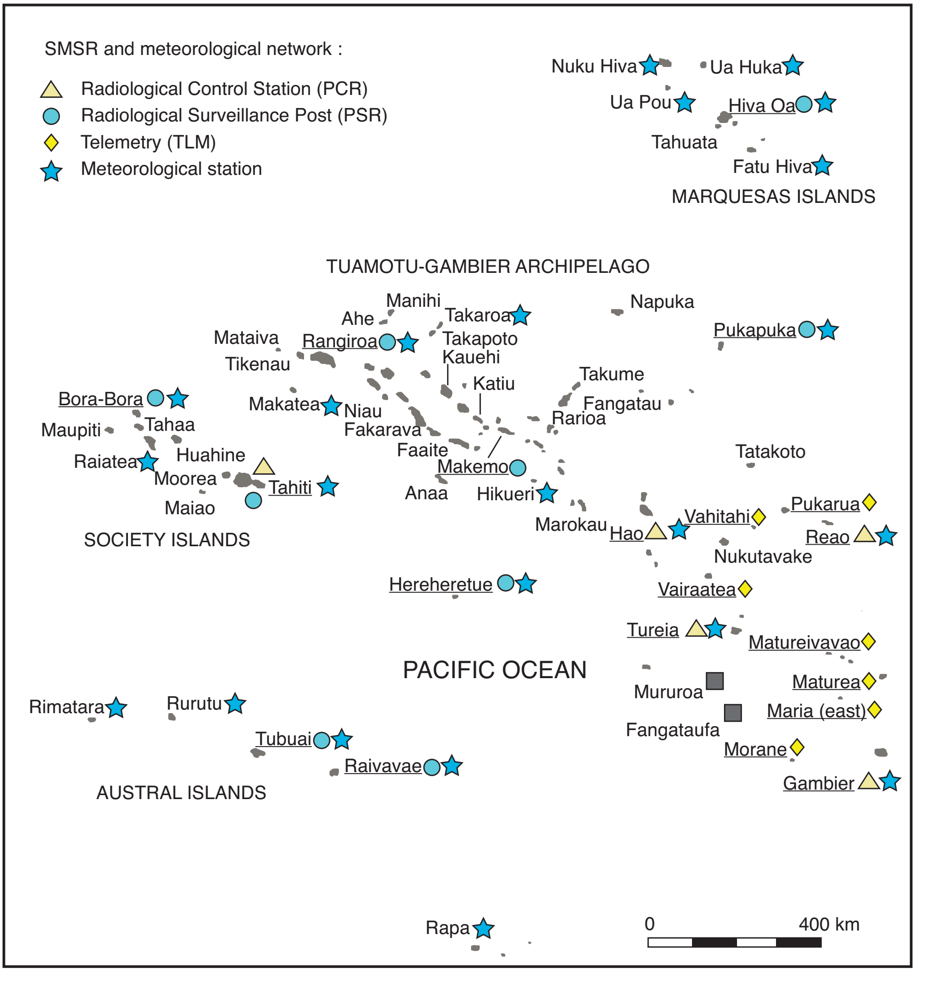

Figure 4: Locations of SMSR network (underlined names of islands and atolls) and meteorological stations in French Polynesia in 1966-1974 (Drozdovitch *et al.,* 2020a)

vs 0 for ground deposition density, 339 vs 2 for exposure rate, respectively. The numbers of measurements of ^{131}I activity concentration in cow's milk were found to be similar in the SMCB reports (SMCB, 1970, 1972, 1973) and in the reports to UNSCEAR.

Estimation of the time of arrival of fallout (TOA)

The radioactive clouds produced by the nuclear explosions usually extended vertically to the highest levels of the troposphere. They were then transported by the local winds, which generally blew from East to West, and were affected by high-pressure systems located to the North and to the South. The bulk of the radioactive cloud, giving rise to what is called "direct fallout", consequently flew in the general direction from East or West, but parts of them, under the influence of the high-pressure systems, were extracted from the main cloud, changed direction, and in some cases, led to "secondary fallout" in areas west of the nuclear test sites, where most of the atolls and islands of French Polynesia are located. In addition, the cloud circled the earth in the same latitude band in a matter of 2 to 4 weeks and resulted in some cases in another component of "secondary fallout".

For the tests conducted in French Polynesia and for the 49 islands and atolls of interest, the values of TOA were preferably taken from the SMSR reports (SMSR, 1966-1975), the reports to UNSCEAR (Republic of France, 1967, 1969, 1971-1975), or the report from the *Ministère de la Défense* (2006). When the TOA values were not available in those reports, they were estimated from the results of measurements of daily total beta-concentration in air. Because of the horizontal and vertical wind shear, the radioactive clouds produced by the nuclear weapons tests usually followed different trajectories during the atmospheric transport over the large territory of French Polynesia; and there were many cases where "secondary fallout" extended over several days and where there were not one, but several waves of ground deposition. Figure 5 shows, for example, the variation with time of the daily total beta-concentration in air measured in Gambier Islands after the tests conducted in 1966: one part of the radioactive cloud from test Aldébaran (conducted on 2 July 1966) led according to data from SMSR (1966a) to direct fallout that reached Gambier at TOA = H+10h45 ("H" denotes time of detonation). Secondary fallout after test Aldébaran started at Gambier at H+9 d, and maximal concentration of total beta-concentration in air was reached on days 13 and 14 after the test. TOA for secondary fallout was taken to occur during the time of maximal concentration and to be H+13 d. The same considerations were applied for TOA after test Rigel (conducted on 24 September 1966): TOA for direct fallout was taken as H+12 h according to SMSR (1966b) and TOA of H+4 d for secondary fallout was derived from the temporal variation of the results of measurements of daily total beta-concentration in air (Figure 5).

Estimation of the ground deposition density

More than 100 of the fission products that are produced in nuclear explosions contribute to radioactive fallout. Additionally, more than 10 radionuclides are produced by activation of the fuel, bomb construction and other surrounding materials. These radionuclides, notably ^{140}Ba+^{140}La, ^{132}Te+^{132}I,

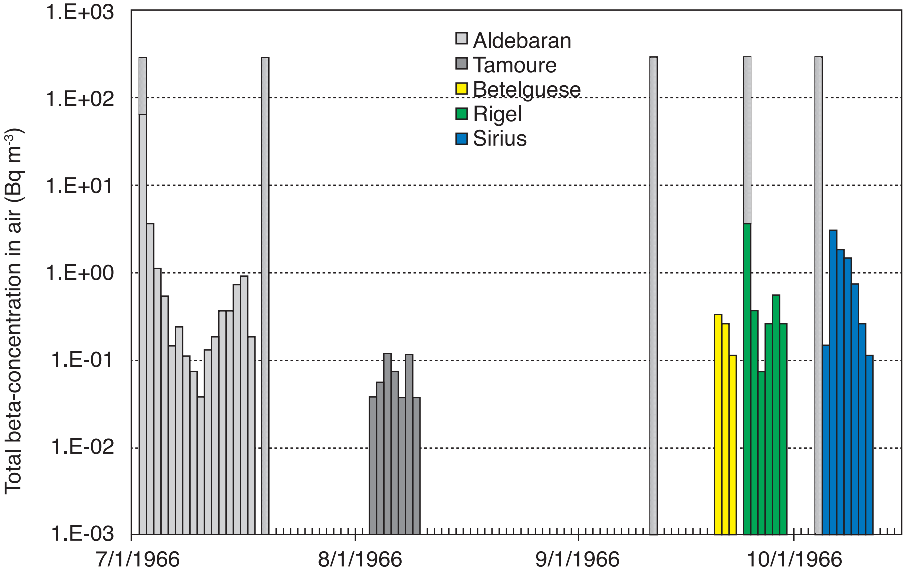

Figure 5: Variation with time of daily total beta-concentration in air measured in Gambier Islands after the tests conducted in 1966. Bar with pattern fill shows date of the test (Drozdovitch *et al.,* 2020a)

$^{95}Zr+^{95}Nb$, ^{103}Ru, ^{131}I, and ^{239}Np, deposited on the ground and other surfaces were the source of external irradiation of the thyroid. However, relatively few radionuclides, mainly ^{131}I, ^{132}I, ^{133}I, ^{135}I and ^{132}Te, contributed substantially to the internal thyroid doses received by the population.

With a few exceptions, measurements of radionuclide composition in air or in fallout were not available to us for the atmospheric tests conducted in French Polynesia. To estimate the activities of specific radionuclides deposited on the ground, the results obtained for the atmospheric nuclear weapons tests conducted in the 1950s at the Nevada Test Site (NTS) in the USA were used. For these tests, Hicks (1981) calculated the deposition densities of radionuclides, normalized to an exposure rate of 1 mR h^{-1} at 12 hours post-detonation (H+12h), for different types and platforms of nuclear weapons tests and for different times of arrival of fallout (TOA). Hicks (1981) data indicate that although the variability of the normalized deposition density for specific radionuclides from test to test may be substantial, there is little difference in the total deposition densities. Using data from 33 representative tests conducted at the NTS, deposition densities were calculated for fractionation values (ratios of refractory and of volatile radionuclides, R/V) equal to 0.5 (15 tests) for tower tests and equal to 1.0 (18 tests) for balloon tests. Use of the mixture of R/V values reflects conditions at

French Polynesia where direct fallout occurred in islands close to the test sites (R/V = 1.0) as well as secondary fallout in distant locations with TOA up to H+20 d (R/V = 0.5). Table 7 shows the medians of the normalized total deposition densities and deposition densities of important radionuclides at different TOAs derived from reports of Hicks (1981). These tabulated values were used to reconstruct fallout from tests conducted in French Polynesia.

Table 7: Calculated median deposition densities of selected radionuclides at different TOAs normalized to an exposure rate of 1 mR h^{-1} at 12 hours post-detonation (H+12h) (estimated from Hicks, 1981)

Radio-nuclide	Half-life[a]	Normalized deposition density (Bq m^{-2} per mR h^{-1} at H+12h) at TOA							
		H+6h	H+9h	H+12h	H+1d	H+2d	H+5d	H+10d	H+20d
^{54}Mn	312.3 d	1.4	1.4	1.4	1.4	1.4	1.4	1.3	1.3
^{89}Sr	50.53 d	4.7×10^3	4.7×10^3	4.7×10^3	3.7×10^3	3.7×10^3	3.5×10^3	3.3×10^3	2.9×10^3
^{90}Sr	28.79 y	25	25	25	25	25	25	25	25
^{90}Y	64.1 h	–	–	–	5.8	10	18	24	25
^{91}Sr	9.63 h	4.1×10^5	3.3×10^5	2.7×10^5	1.1×10^5	2.0×10^4	1.2×10^2	–	–
^{91m}Y	49.71 m	2.7×10^5	2.2×10^5	1.8×10^5	7.4×10^4	1.3×10^4	76	–	–
^{91}Y	58.51 d	1.4×10^3	1.9×10^3	2.4×10^3	3.5×10^3	4.1×10^3	4.1×10^3	3.9×10^3	3.5×10^3
^{93}Y	10.18 h	3.6×10^5	2.9×10^5	2.4×10^5	1.0×10^5	2.0×10^4	1.5×10^2	–	-
^{95}Zr	64.03 d	4.4×10^3	4.4×10^3	4.4×10^3	4.1×10^3	4.1×10^3	4.0×10^3	3.7×10^3	3.4×10^3
^{95}Nb	34.99 d	20	31	41	80	1.6×10^2	3.8×10^2	7.0×10^2	1.2×10^3
^{97}Zr	16.744 h	3.0×10^5	2.7×10^5	2.4×10^5	1.5×10^5	5.5×10^4	2.9×10^3	22	–
^{97m}Nb	60 s[b]	2.9×10^5	2.6×10^5	2.3×10^5	1.4×10^5	5.3×10^4	2.8×10^3	21	–
^{97}Nb	72.1 m	3.1×10^5	2.8×10^5	2.5×10^5	1.5×10^5	5.5×10^4	2.9×10^3	22	–
^{99}Mo	65.94 h	9.7×10^4	9.4×10^4	9.1×10^4	8.1×10^4	6.3×10^4	3.0×10^4	8.7×10^3	7.0×10^2
^{99m}Tc	6.015 h	4.4×10^4	5.5×10^4	6.2×10^4	7.1×10^4	6.0×10^4	2.9×10^4	8.3×10^3	6.7×10^2
^{103}Ru	39.26 d	6.9×10^3	6.9×10^3	6.9×10^3	6.8×10^3	6.6×10^3	6.4×10^3	5.8×10^3	4.9×10^3
^{106}Ru	373.59 d	3.7×10^2	3.7×10^2	3.7×10^2	3.7×10^2	3.7×10^2	3.7×10^2	3.6×10^2	3.6×10^2
^{125}Sb	2.76 y	4.7	4.7	4.8	5.0	5.5	6.7	8.3	10
^{131}I	8.02 d	2.9×10^4	2.9×10^4	2.8×10^4	2.7×10^4	2.5×10^4	2.0×10^4	1.3×10^4	5.6×10^3
^{132}Te	3.204 d	8.2×10^4	8.0×10^4	7.8×10^4	7.0×10^4	5.7×10^4	3.0×10^4	1.0×10^4	1.2×10^3
^{132}I	2.30 h	8.5×10^4	8.2×10^4	8.0×10^4	7.2×10^4	5.8×10^4	3.1×10^4	1.1×10^4	1.3×10^3
^{133}I	20.8 h	3.9×10^5	3.6×10^5	3.2×10^5	2.0×10^4	9.1×10^4	8.4×10^3	1.6×10^2	–
^{135}I	6.57 h	6.4×10^5	4.7×10^5	3.4×10^5	1.0×10^5	8.3×10^3	4.8	–	–
^{136}Cs	13.16 d	2.8×10^2	2.8×10^2	2.8×10^2	2.7×10^2	2.5×10^2	2.2×10^2	1.7×10^2	98
^{137}Cs	30.17 y	34	34	34	34	34	34	34	34
^{140}Ba	12.75 d	2.4×10^4	2.4×10^4	2.4×10^4	2.3×10^4	2.2×10^4	1.8×10^4	1.4×10^4	8.1×10^3
^{140}La	1.68 d	2.4×10^3	3.4×10^3	4.4×10^3	7.9×10^3	1.3×10^4	1.8×10^4	1.6×10^4	9.4×10^3
^{141}Ce	32.51 d	5.2×10^3	6.5×10^3	7.2×10^3	8.6×10^3	8.5×10^3	8.0×10^3	7.2×10^3	5.8×10^3
^{143}Ce	30.039 h	1.6×10^5	1.5×10^5	1.4×10^5	1.1×10^5	6.6×10^4	1.4×10^4	1.2×10^3	7.5
^{143}Pr	13.57 d	2.0×10^3	3.0×10^3	3.9×10^3	7.0×10^3	1.1×10^4	1.4×10^4	1.2×10^4	7.3×10^3
^{144}Ce	284.91 d	7.1×10^2	7.0×10^2	7.0×10^2	7.0×10^2	7.0×10^2	7.0×10^2	6.9×10^2	6.7×10^2
^{147}Nd	10.98 d	1.0×10^4	9.9×10^3	9.8×10^3	8.8×10^3	8.3×10^3	7.2×10^3	5.0×10^3	2.7×10^3
^{239}Np	2.357 d	5.0×10^5	4.8×10^5	4.6×10^5	4.0×10^5	3.0×10^5	1.3×10^5	2.8×10^4	1.5×10^3
Total		5.0×10^6	3.6×10^6	3.1×10^6	1.9×10^6	1.0×10^6	3.8×10^5	1.5×10^5	6.1×10^4
Exposure rate (mR h^{-1})		2.3	1.4	1.0	0.44	0.19	0.063	0.027	0.012

[a] ICRP (2008).
[b] (Eckerman and Ryman, 1993).

For some tests, measurements of total deposition density on the ground surface from direct fallout were available for some atolls and islands. In such instances, the deposition density of a given radionuclide was estimated by normalizing the total deposition density at TOA (Hicks, 1981) to the measured total deposition. If measurement of total deposition on the ground surface was not available, the following approaches were used to determine the deposition densities of the various radionuclides, 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+12h 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.

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 1.76×10^{-2} m·s^{-1} in case of dry deposition and of light rainfall (R < 1 mm d^{-1}), and of 6.2×10^{-2} m s^{-1} for rainfall greater than, or equal to, 1 mm d^{-1}.

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.

When radiation measurements were not available for the considered islands or atolls, the deposition densities of the various radionuclides were estimated from values of total beta-activity in filtered air obtained for given island or atoll by interpolation on distance between or from nearest location with available measurements (see Drozdovitch *et al.* (2020a) for detail).

As a result, ground deposition densities of 33 radionuclides were reconstructed for each of the 41 atmospheric tests in the 49 islands and atolls in French Polynesia where the study subjects resided during the atmospheric test period. Table 8 shows the total and the ^{131}I deposition densities estimated for these 49 islands and atolls and indicate the test that contributed the most to the fallout that occurred in each location. The tests that contributed the most to the radioactive fallout in each archipelago of French Polynesia were:

– For Society Islands: test Centaure (17/07/1974);

– For Tuamotu-Gambier: tests Aldébaran (2/07/1966), Sirius (4/10/1966), Altaïr (5/06/1967), Arcturus (2/07/1967), and Centaure (17/07/1974);

– For Marquesas Islands: test Sirius (4/10/1966); and

– For Austral Islands: test Pallas (18/08/1973).

Table 9 gives examples of radiation data available for Tahiti and of reconstructed deposition densities. As mentioned above, test Centaure (17/07/1974) resulted in the highest radioactive contamination of the most populated island in French Polynesia. Tests Sirius (4/10/1966) and Arcturus (2/07/1967) also resulted in substantial deposition in Tahiti. All other tests contributed less than 6% to the total deposition from all tests. Regarding ^{131}I, tests Centaure, Sirius and Arcturus contributed around 85% of the ^{131}I deposition in Tahiti.

For several tests and locations, the deposition densities obtained in this study using different approaches could be compared with the deposition densities reported by SMSR and Bourges (1997) (Table 10). The ratios of the deposition densities estimated in this study by different approaches to the deposition densities reported by SMSR and Bourges (1997) are characterized by an arithmetic mean ± standard deviation of 0.9±0.4, a geometric mean of 0.8 and range from 0.2 to 1.5 for approach #1 (13 deposition events); the corresponding values for approach #2 (8 deposition events) are 1.2±1.2 for the arithmetic mean, 0.9 for the geometric mean, and 0.4-4.0 for the range; for approach #3 (3 deposition events), the obtained values are 0.6±0.4 for the arithmetic mean, 0.6 for the geometric mean, and 0.4-1.1 for the range. For most deposition events (19 from 24, 79.2% of the total) a good agreement (within a factor of 2) was observed between the deposition densities estimated in this study and those reported in the literature.

A detailed description of the results of the study on reconstruction of ground deposition of radionuclides in French Polynesia resulting from atmospheric nuclear weapons tests at Mururoa and Fangataufa atolls can be found in Drozdovitch *et al.* (2020a).

Table 8: Total and ^{131}I deposition densities from atmospheric nuclear weapons tests conducted in French Polynesia for the 49 islands and atolls where the study subjects resided in 1966-1974 (Drozdovitch *et al.*, 2020a)

Archi-pelago	Island	Deposition density from all tests (Bq m^{-2})		Most important contributor	Date of test (dd/mm/yyyy)	TOA	Deposition density from the most important test (Bq m^{-2})	
		Total	^{131}I				Total	^{131}I
Society	Tahiti	4.3×10^{6}	1.3×10^{5}	Centaure	17/07/1974	H+56h	3.4×10^{6}	9.5×10^{4}
	Bora-Bora	1.1×10^{6}	4.4×10^{4}	Centaure	17/07/1974	H+2.5d	8.8×10^{5}	2.6×10^{4}
	Huahine	1.1×10^{6}	4.3×10^{4}	Centaure	17/07/1974	H+2.5d	7.5×10^{5}	2.2×10^{4}
	Maiao	3.8×10^{6}	1.2×10^{5}	Centaure	17/07/1974	H+2.5d	3.3×10^{6}	1.0×10^{5}
	Maupiti	1.1×10^{6}	4.4×10^{4}	Centaure	17/07/1974	H+2.5d	8.8×10^{5}	2.6×10^{4}
	Moorea	1.2×10^{6}	4.4×10^{4}	Centaure	17/07/1974	H+58h	1.0×10^{6}	3.0×10^{4}
	Raiatea	1.1×10^{6}	4.1×10^{4}	Centaure	17/07/1974	H+2.5d	7.5×10^{5}	2.2×10^{4}
	Tahaa	1.1×10^{6}	4.1×10^{4}	Centaure	17/07/1974	H+2.5d	7.5×10^{5}	2.2×10^{4}
Tuamotu-Gambier	Ahe	4.9×10^{5}	3.3×10^{4}	Sirius	04/10/1966	H+5d	1.3×10^{5}	6.9×10^{3}
	Anaa	5.9×10^{6}	1.7×10^{5}	Centaure	17/07/1974	H+2d	4.1×10^{6}	1.0×10^{5}
	Apataki	5.7×10^{5}	3.7×10^{4}	Sirius	04/10/1966	H+6d	1.3×10^{5}	8.1×10^{3}
	Arutua	5.7×10^{5}	3.7×10^{4}	Sirius	04/10/1966	H+6d	1.3×10^{5}	8.1×10^{3}
	Faaite	1.4×10^{6}	7.3×10^{4}	Arcturus	02/07/1967	H+3d	5.8×10^{5}	2.0×10^{4}
	Fakarava	1.2×10^{6}	6.8×10^{4}	Arcturus	02/07/1967	H+3d	4.6×10^{5}	1.6×10^{4}
	Fangatau	6.2×10^{5}	4.1×10^{4}	Arcturus	02/07/1967	H+3d	1.5×10^{5}	5.2×10^{3}
	Gambier	7.2×10^{7}	7.6×10^{5}	Aldébaran [a]	02/07/1966	H+10h45/ H+13d	6.1×10^{7}/ 1.6×10^{4}	5.4×10^{5}/ 1.5×10^{3}
	Hao	1.4×10^{6}	3.9×10^{4}	Arcturus	02/07/1967	H+33h	9.2×10^{5}	1.6×10^{4}
	Katiu	1.7×10^{6}	8.9×10^{4}	Arcturus	02/07/1967	H+3d	6.7×10^{5}	2.3×10^{4}
	Kauehi	1.5×10^{6}	7.8×10^{4}	Arcturus	02/07/1967	H+3d	5.7×10^{5}	2.0×10^{4}
	Kaukura	5.8×10^{5}	3.8×10^{4}	Sirius	04/10/1966	H+6d	1.3×10^{5}	8.1×10^{3}
	Makatea	1.7×10^{6}	5.5×10^{4}	Centaure	17/07/1974	H+3d	1.4×10^{6}	3.4×10^{4}
	Makemo	1.8×10^{6}	9.6×10^{4}	Arcturus	02/07/1967	H+3d	6.7×10^{5}	2.3×10^{4}
	Manihi	4.9×10^{5}	3.3×10^{4}	Sirius	04/10/1966	H+5d	1.3×10^{5}	6.9×10^{3}
	Marokau	1.1×10^{6}	3.5×10^{4}	Arcturus	02/07/1967	H+36h	7.3×10^{5}	1.4×10^{4}
	Mataiva	2.5×10^{5}	1.8×10^{4}	Altaïr	05/06/1967	H+11d	3.5×10^{4}	3.3×10^{3}
	Napuka	6.2×10^{5}	4.1×10^{4}	Arcturus	02/07/1967	H+3d	1.4×10^{5}	5.2×10^{3}
	Niau	1.2×10^{6}	6.8×10^{4}	Arcturus	02/07/1967	H+3d	4.6×10^{5}	1.6×10^{4}
	Nukutavake	5.3×10^{5}	3.2×10^{4}	Sirius	04/10/1966	H+5d	1.2×10^{5}	6.2×10^{3}
	Pukarua	1.2×10^{7}	2.5×10^{5}	Arcturus	02/07/1967	H+38h	1.1×10^{7}	2.1×10^{5}
	Rangiroa	2.4×10^{5}	1.7×10^{4}	Altaïr	05/06/1967	H+11d	3.5×10^{4}	3.3×10^{3}
	Raroia	6.2×10^{5}	4.1×10^{4}	Arcturus	02/07/1967	H+3d	1.5×10^{5}	5.2×10^{3}
	Reao	1.2×10^{7}	2.6×10^{5}	Arcturus	02/07/1967	H+36h	1.1×10^{7}	2.1×10^{5}
	Taenga	1.8×10^{6}	9.6×10^{4}	Arcturus	02/07/1967	H+3d	6.7×10^{5}	2.3×10^{4}
	Takapoto	4.9×10^{5}	3.3×10^{4}	Sirius	04/10/1966	H+5d	1.3×10^{5}	6.9×10^{3}
	Takume	6.2×10^{5}	4.1×10^{4}	Arcturus	02/07/1967	H+3d	1.5×10^{5}	5.2×10^{3}
	Tatakoto	1.2×10^{7}	2.5×10^{5}	Arcturus	02/07/1967	H+40h	1.1×10^{7}	2.1×10^{5}
	Tikehau	2.5×10^{5}	1.8×10^{4}	Altaïr	05/06/1967	H+11d	3.6×10^{4}	3.3×10^{3}
	Tureia	4.0×10^{7}	3.9×10^{5}	Arcturus	02/07/1967	H+11h40	1.6×10^{7}	1.5×10^{5}
Marquesas	Fatu Hiva	2.9×10^{5}	2.1×10^{4}	Sirius	04/10/1966	H+6d	8.2×10^{4}	5.0×10^{3}
	Hiva Oa	5.2×10^{5}	3.5×10^{4}	Sirius	04/10/1966	H+6d	2.9×10^{5}	1.8×10^{4}
	Nuku Hiva	1.9×10^{5}	1.3×10^{4}	Sirius	04/10/1966	H+6d	8.2×10^{4}	5.0×10^{3}
	Tahuata	5.2×10^{5}	3.5×10^{4}	Sirius	04/10/1966	H+6d	2.9×10^{5}	1.8×10^{4}
	Ua Huka	2.0×10^{5}	1.4×10^{4}	Sirius	04/10/1966	H+6d	8.2×10^{4}	5.0×10^{3}
	Ua Pou	2.0×10^{5}	1.3×10^{4}	Sirius	04/10/1966	H+6d	8.2×10^{4}	5.0×10^{3}
Austral	Raivavae	5.1×10^{5}	1.9×10^{4}	Pallas	18/08/1973	H+3d	3.8×10^{5}	1.3×10^{4}
	Rapa	4.1×10^{5}	2.2×10^{4}	Pallas	18/08/1973	H+5d	3.2×10^{5}	1.7×10^{4}
	Rimatara	5.1×10^{5}	1.9×10^{4}	Pallas	18/08/1973	H+3d	3.8×10^{5}	1.3×10^{4}
	Rurutu	5.1×10^{5}	1.9×10^{4}	Pallas	18/08/1973	H+3d	3.8×10^{5}	1.3×10^{4}
	Tubuai	5.2×10^{5}	1.9×10^{4}	Pallas	18/08/1973	H+3d	3.8×10^{5}	1.3×10^{4}

[a] Direct fallout / secondary fallout.

Table 9: Reconstructed deposition densities on Tahiti island from the atmospheric nuclear weapons tests conducted in French Polynesia (Drozdovitch *et al.,* 2020a)

Name of test	Date of test	TOA	Time-integrated beta-concentration in air (Bq s m^{-3})	Precipi-tation (mm)	Deposition density (Bq m^{-2})	
					Total	^{131}I
Aldébaran	02/07/1966	H+10d	2.7×10^5	0	4.7×10^3	4.1×10^2
Tamouré	19/07/1966	H+8d	1.1×10^5	308	7.0×10^3	5.2×10^2
Bételgeuse	11/09/1966	H+10d	4.1×10^5	0	7.1×10^3	6.2×10^2
Rigel	24/09/1966	H+4d	7.0×10^4	0	1.2×10^3	54
Sirius [a]	04/10/1966	H+18h / H+7d	6.4×10^6 / 2.3×10^6	151 / 0	4.0×10^5 / 4.0×10^4	4.5×10^3 / 2.7×10^3
Altaïr	05/06/1967	H+13d	3.8×10^5	0	6.7×10^3	6.5×10^2
Antarès	27/06/1967	H+4d	2.7×10^5	0	4.7×10^3	2.1×10^2
Arcturus	02/07/1967	H+4d	6.4×10^6	0	1.1×10^5	4.9×10^3
Capella	07/07/1968	H+7d	2.4×10^5	0	4.1×10^3	2.8×10^2
Castor	15/07/1968	H+14d	1.8×10^5	0	3.2×10^3	3.1×10^2
Pollux	03/08/1968	H+12d	6.3×10^5	0	1.1×10^4	1.1×10^3
Canopus	24/08/1968	H+6d	2.2×10^5	86	1.4×10^4	8.3×10^2
Procyon	08/09/1968	H+20d	1.2×10^5	0	2.1×10^3	2.0×10^2
Andromède	15/05/1970	H+16d	7.1×10^4	0	1.2×10^3	1.2×10^2
Cassiopée	22/05/1970	H+12d	4.5×10^4	0	7.9×10^2	75
Dragon	30/05/1970	H+4d	1.6×10^4	0	2.7×10^2	12
Eridan	24/06/1970	H+15d	2.3×10^4	0	4.0×10^2	39
Licorne	03/07/1970	H+10d	1.5×10^5	8	9.6×10^3	8.4×10^2
Pégase	27/07/1970	H+10d	1.6×10^5	3	9.9×10^3	8.7×10^2
Orion	02/08/1970	H+14d	1.9×10^5	1	1.2×10^4	1.1×10^3
Toucan	06/08/1970	H+4d	4.1×10^5	1	2.6×10^4	1.1×10^3
Dioné	05/06/1971	H+10d	5.9×10^4	2	3.7×10^3	3.2×10^2
Encelade	12/06/1971	H+11d	1.4×10^6	0	2.3×10^4	2.1×10^3
Japet	04/07/1971	H+8d	2.1×10^5	0	3.7×10^3	2.8×10^2
Phoebé	08/08/1971	H+6d	4.0×10^4	0	7.0×10^2	43
Rhéa	14/08/1971	H+15d	9.5×10^4	2	5.9×10^3	5.8×10^2
Umbriel [b]	25/06/1972	H+2d	–	0	4.7×10^3	1.2×10^2
Titania	30/06/1972	H+10d	5.9×10^4	0	1.0×10^3	91
Obéron	27/07/1972	H+17d	1.0×10^5	45	6.5×10^3	6.3×10^2
Euterpe	21/07/1973	H+21d	1.4×10^4	16	8.5×10^2	76
Melpomène	28/07/1973	–	–	–	–	–
Pallas [c]	18/08/1973	H+3d	–	5	4.7×10^4	1.6×10^3
Parthénope [c]	24/08/1973	H+7d	–	31	1.2×10^4	8.3×10^2
Tamara	28/08/1973	H+2d	–	2	1.3×10^4	3.1×10^2
Capricorne	16/06/1974	H+5d	1.0×10^5	4	6.3×10^3	3.4×10^2
Gémeaux	07/07/1974	H+8d	2.0×10^4	0	3.5×10^2	22
Centaure	17/07/1974	H+56h	5.5×10^7	1	3.4×10^6	9.5×10^4
Maquis	25/07/1974	H+5d	1.0×10^5	0	1.8×10^3	96
Scorpion	15/08/1974	H+2d	2.9×10^4	0	5.2×10^2	13
Taureau	24/08/1974	H+6d	4.7×10^4	0	8.3×10^2	50
Verseau	14/10/1974	H+6d	7.0×10^4	0	1.2×10^3	75

[a] Direct / secondary fallout.
[b] Using approach #3.
[c] Reconstructed using measured total deposition.

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Table 10: Deposition densities at TOA reconstructed in this study using different approaches and measured (Bourges, 1997; SMSR, 1966b, 1967b, 1968-1969, 1970c, 1971a, 1973b, 1974a, b, 1975)

Name of test	Date of test	Archipelago	Island (atoll)	TOA	Deposition density (Bq m^{-2})			
					Reconstructed using approach			Measured[a]
					#1	#2	#3	
Aldébaran	02/07/1966	Gambier	Gambier	H+10h45	–	6.1×10^7	–	6.0×10^7 [b]
Rigel	24/09/1966	Tuamotu	Tureia	H+12h30	2.0×10^5	–	–	5.0×10^5
Arcturus	02/07/1967	Tuamotu	Hao	H+33h	8.0×10^5	–	–	9.2×10^5
Arcturus	02/07/1967	Tuamotu	Tureia	H+11h40	–	1.5×10^7	–	1.6×10^7
Canopus	24/08/1968	Tuamotu	Reao	H+24h	5.5×10^3	–	–	8.9×10^3
Andromède	15/05/1970	Society	Tahiti	H+16d	1.2×10^3	–	7.9×10^2	–
Dragon	30/05/1970	Tuamotu	Tureia	H+31h	–	2.1×10^5	–	2.4×10^5
Dragon	30/05/1970	Austral	Rapa	H+56h	2.9×10^3	–	–	3.4×10^3
Orion	02/08/1970	Society	Tahiti	H+14d	1.2×10^4	–	1.4×10^4	–
Dioné	05/06/1971	Society	Tahiti	H+10d	3.7×10^3	–	8.9×10^3	–
Encelade	12/06/1971	Society	Tahiti	H+11d	2.3×10^3	–	3.4×10^3	–
Encelade	12/06/1971	Tuamotu	Tureia	H+12h	–	1.2×10^7	–	1.3×10^7 [b]
Phoebé	08/08/1971	Gambier	Gambier	H+11h15	1.0×10^7	9.2×10^6	–	–
Umbriel	25/06/1972	Society	Tahiti	H+2d	3.2×10^3	–	4.7×10^3	–
Pallas	18/08/1973	Austral	Raivavae	H+3d	3.8×10^5	1.6×10^5	–	–
Pallas	18/08/1973	Austral	Tubuai	H+3d	3.8×10^5	1.5×10^5	–	–
Parthénope	24/08/1973	Society	Tahiti	H+7d	1.6×10^4	–	5.8×10^3	1.2×10^4
Tamara	28/08/1973	Society	Tahiti	H+2d	1.6×10^4	–	1.4×10^4	1.3×10^4
Tamara	28/08/1973	Tuamotu	Hao	H+24h	5.8×10^4	–	–	5.3×10^4
Tamara	28/08/1973	Tuamotu	Reao	H+2d	6.1×10^3	–	–	1.5×10^4
Centaure[c]	17/07/1974	Society	Tahiti	H+56h	3.4×10^6	2.0×10^6	1.3×10^6	3.4×10^6
Centaure	17/07/1974	Tuamotu	Tureia	H+56h	3.9×10^4	2.0×10^4	–	4.5×10^4
Scorpion	15/08/1974	Tuamotu	Reao	H+12h	–	9.3×10^3	–	2.3×10^3
Taureau	24/08/1974	Tuamotu	Gambier	H+18h	1.3×10^4	3.4×10^4	–	5.7×10^4
Taureau	24/08/1974	Tuamotu	Reao	H+5d	2.2×10^4	–	–	1.5×10^4
Taureau	24/08/1974	Tuamotu	Tureia	H+5d	4.9×10^3	–	–	5.4×10^3

[a] Declassified report of Joint Radiological Safety Service (SMSR, 1966b, 1967b, 1968-1969, 1970c, 1971a, 1973b, 1974a, b, 1975), unless otherwise indicated.
[b] Bourges (1997).
[c] Measured deposition density is given for Mahina.

Thyroid doses to French Polynesians resulting from atmospheric nuclear weapons tests: estimates based on radiation measurements and population lifestyle data

Individual thyroid doses were estimated for the study subjects for the time period from 2 July 1966 (date of first test Aldébaran) through 31 December 1974 (last day of the last year of atmospheric testing). The reconstruction of doses was performed blindly regarding the case or control status of the study subject. The following pathways of exposure were considered:

- Inhalation of ^{131}I and of short-lived radioiodine isotopes (^{132}I, ^{133}I and ^{135}I) and radiotellurium (^{132}Te) with contaminated air;
- Ingestion of ^{131}I and of short-lived ^{132}I, ^{133}I, ^{135}I and ^{132}Te with fresh cow's milk (only in Tahiti), leafy vegetables and drinking water;

- External irradiation from radionuclides deposited on the ground and other materials;
- Ingestion of ^{137}Cs with foodstuffs and drinking water.

Essentially the same methodology was used to calculate thyroid doses in TD08 (Drozdovitch *et al.*, 2008) and TD19 (Drozdovitch *et al.*, 2020b). As it was indicated above, new radiation measurements available from declassified reports and population lifestyle and consumption data collected during the focus group study were used in TD19.

Assessment of the internal doses resulting from inhalation

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

$$D_k^{inh} = V_k^{air} \cdot RF^{air} \cdot \sum_i TIA_i^{air} \cdot DC_{i,k}^{inh} \qquad (1)$$

where V_k^{air} is the age-dependent breathing rate of the study subject (m^3 s^{-1}) (ICRP 2002); RF^{air} is the reduction factor associated with indoor occupancy (unitless). As buildings in French Polynesia are very open for outdoor air circulation, $RF^{air} = 1$ was applied in the calculations; TIA_i^{air} is the time-integrated concentration of radionuclide i in air (Bq s m^{-3}); $DC_{i,k}^{inh}$ is the age-dependent inhalation dose coefficient for the thyroid, i.e. the thyroid dose due to inhalation of unit activity of radionuclide i by a study subject of age k (mGy Bq^{-1}) (ICRP, 1995).

Values of total time-integrated concentration in air were taken from SMSR reports or estimated as described by Drozdovitch *et al.* (2020a). The value of the time-integrated concentration in air of specific radionuclide i was derived from the radionuclide mix at time of arrival of fallout (TOA) calculated by Hicks (1981) assuming that the radionuclide composition in filtered air was the same as that in the activity deposited on the ground. If the total deposition density was measured, an estimate of the time-integrated concentration of radionuclide i in air was obtained from the deposition density and the effective deposition velocity of radionuclide onto the ground surface:

$$TIA_i^{air} = \sigma_i / v, \qquad (2)$$

where σ_i is the deposition density of radionuclide i at TOA (Bq m^{-2}); $v = 1.76 \times 10^{-2}$ or 6.2×10^{-2} m s^{-1} is the effective deposition velocity of radionuclides onto the ground surface in case of dry deposition or of light rain (R < 1 mm d^{-1}) (UNSCEAR, 1993) or wet deposition (Drozdovitch *et al.*, 2008), respectively. The assumption was made that the radionuclide distribution in the deposited activity was not influenced by the type of deposition, i.e. wet *vs* dry.

Thyroid dose due to ingestion of radioiodine isotopes and ^{132}Te

The thyroid dose to a study subject of age k arising from ingestion of radioiodine isotopes (^{131}I, ^{132}I, ^{133}I, ^{135}I) and ^{132}Te with fresh cow's milk (in Tahiti), leafy vegetables, and drinking water, D_k^{ing} (mGy), was calculated as:

$$D_k^{ing} = \sum_i DC_{i,k}^{ing} \cdot \sum_m V_{m,k} \cdot PF_{i,m} \cdot TIA_{i,m}^{food}, \quad (3)$$

where $DC_{i,k}^{ing}$ is the age-dependent ingestion dose coefficient for the thyroid, i.e. the age-dependent internal thyroid dose due to intake via ingestion of unit activity of radionuclide i by a study subject of age k (mGy Bq^{-1}) (ICRP, 1993, 1996a); $V_{m,k}$ is the consumption rate of foodstuff m and drinking water by the subject of age k (kg (L) d^{-1}); $PF_{i,m}$ is the processing factor, i.e., the fraction of radionuclide i remaining in foodstuff m after washing, culinary preparation and time delay between production and consumption (unitless); $TIA_{i,m}^{food}$ is the time-integrated concentration of radionuclide i in foodstuff or drinking water m (Bq d kg^{-1} (L^{-1})).

- ***Estimation of consumption rates at age k from the consumption rates reported for age 15***

As mentioned above, daily consumption rates of foodstuffs for age 15 were reported by the study subjects during their personal interviews. To estimate the consumption rates at age k during childhood, the following equation was used:

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

where $V_{m,k}$ is the consumption rate of foodstuff m by a study subject at age k (kg (L) d^{-1}); $V_{m,15}$ is the consumption rate of foodstuff m at age 15 that was reported by the study subject during her or his personal interview (kg (L) d^{-1}); $SF_{m,k}$ is the scaling factor to adjust the consumption rate of foodstuff m at age 15 to that at age k (unitless). Table 11 shows, as example, values of the scaling factor, $SF_{m,k}$, that were derived for Tahiti and Tuamotu archipelago (except Gambier Islands) from a focus-group survey of dietary patterns in French Polynesia (Drozdovitch *et al.*, 2020b).

Table 11: Scaling factors, $SF_{m,k}$, for age-dependent consumption rates of foodstuffs for Tahiti and Tuamotu archipelago (except Gambier Islands) (Drozdovitch *et al.*, 2020b)

Foodstuff	Tahiti					Tuamotu archipelago (except Gambier Islands)				
	0-12 mo	1-3.9 y	4-6.9 y	7-14.9 y	15-21 y	0-12 mo	1-3.9 y	4-6.9 y	7-14.9 y	15-21 y
Fresh cow's milk	-[a]	0.34	0.39	1.03	1.00	-	-	-	-	-
Leafy vegetables[b]	-[a]	0.05	0.22	0.77	1.00	-[a]	-[a]	0.14	1.20	1.00
Fâfâ[c]	-[a]	0.05	0.15	0.56	1.00	-	-	-	-	-
Coco milk	0.02	0.22	0.53	0.50	1.00	0.27	0.33	0.57	0.86	1.00
Coco copra	0.03	0.13	0.82	0.80	1.00	-[a]	0.21	1.00	1.00	1.00
Uru	-[a]	0.03	0.32	0.59	1.00	-[a]	0.03	0.23	0.42	1.00
Banana	0.03	0.32	0.64	0.77	1.00	-[a]	0.06	0.52	0.97	1.00
Mango	0.06	0.38	0.52	0.79	1.00	-[d]	-[d]	-[d]	-[d]	-[d]
Papaya	0.25	0.38	0.42	0.43	1.00	-[a]	0.25	0.35	0.67	1.00
Manioc	-[a]	0.26	0.53	0.68	1.00	-[a]	-[d]	-[d]	-[d]	-[d]
Taro	-[a]	0.26	0.67	0.76	1.00	-[a]	-[d]	-[d]	-[d]	-[d]
Sweet potatoes	-[a]	0.31	0.70	0.81	1.00	-[a]	-[d]	-[d]	-[d]	-[d]
Poultry	-[a]	0.14	0.63	0.74	1.00	-[a]	0.08	0.39	1.13	1.00
Beef	-[a]	0.13	0.81	0.96	1.00	-[a]	-[d]	-[d]	-[d]	-[d]
Pork	-[a]	0.00	0.67	0.90	1.00	-[a]	-[a]	0.23	0.46	1.00
Benitier	-[a]	0.04	0.12	0.58	1.00	-[a]	-[a]	0.22	0.41	1.00
Fish[e]	0.01	0.19	0.39	0.73	1.00	-[a]	0.06	0.27	0.63	1.00

[a] Did not consume this foodstuff at this age.
[b] Including pota, watercress, spinach, lettuce.
[c] Leaves of taro.
[d] Did consume this foodstuff, but it was not locally produced.
[e] Either from sea or from lagoon.

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

The time-integrated concentration of radionuclide i in fresh cow's milk locally produced in Tahiti, $TIA_{i,milk}$, was obtained as the integral over time from TOA to infinity of the concentration at time t (Müller and Pröhl, 1993; NCI, 1997):

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

where $A_{i,milk}(t)$ is the concentration of radionuclide i in milk at time t (Bq L^{-1}); F_i^* is the mass-interception coefficient of radionuclide i by grass, i.e. the fraction of radionuclide initially retained by unit mass of grass or of leafy vegetable: 0.7 m^2 kg^{-1} (fresh weight) for iodine and tellurium for dry deposition, and 0.1 m^2 kg^{-1} for iodine and 0.2 m^2 kg^{-1} for tellurium for wet deposition (Gavrilin *et al.*, 2004); I_g = 40 kg d^{-1} is the daily intake of grass by cows, fresh weight; TF_i is the 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); λ_i^m is biological transfer rate in cow's milk: 0.99 and 0.69 d^{-1} for stable iodine and tellurium, respectively (Müller and Pröhl, 1993); λ_i^w is the elimination rate of radionuclide i from grass due to processes of weathering and growth dilution: 0.069 and 0.047 d^{-1} for stable iodine and tellurium, respectively (Miller and Hoffman, 1983; Müller and Pröhl, 1993); λ_i^r is the radioactive decay constant of radionuclide i (d^{-1}).

When calculating the thyroid dose arising from ingestion of radionuclides with fresh cow's milk using eqn (3), the values of the processing factors, $PF_{i,milk}$, for radioiodine isotopes and ^{132}Te were equal to 1.0.

The measured concentration of ^{131}I in milk produced in Tahiti after the test Centaure (Republic of France, 1975) provided the opportunity to validate the ^{131}I concentration obtained using this method. The measured (Republic of France, 1975) and the calculated ^{131}I concentration in cow's milk are compared in Figure 6. There is good agreement between the two sets of values.

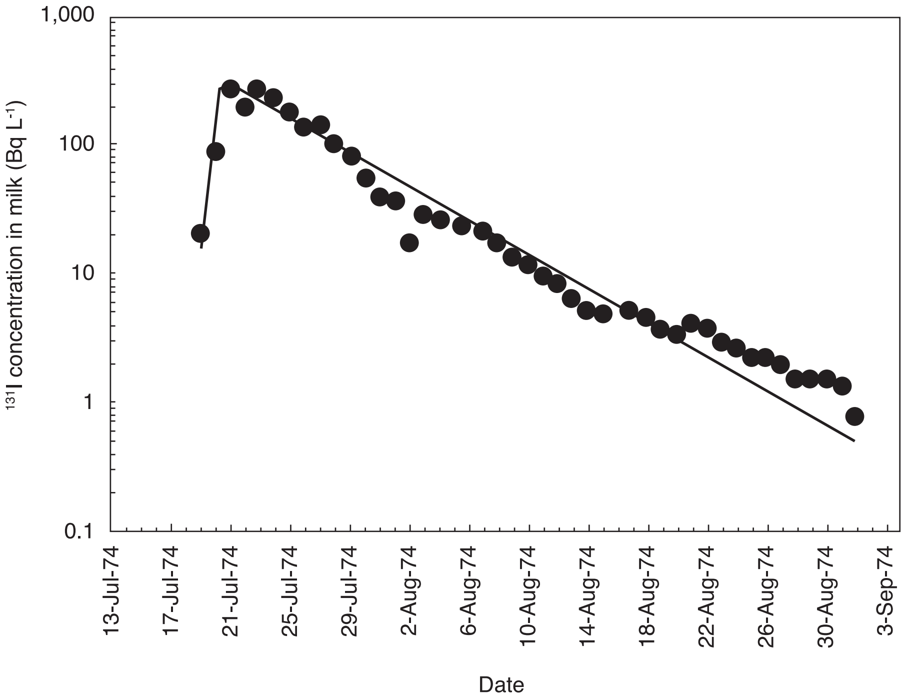

Figure 6: ^{131}I activity in cow's milk produced in Tahiti after the test Centaure: calculation (curve) and measurements (open circles) (Drozdovitch *et al.,* 2008)

- ***Estimation of the time-integrated concentration in leafy vegetables***

Leafy vegetables consumed in French Polynesia include fâfâ, pota, watercress and spinach. The time-integrated concentration of radionuclide *i* in leafy vegetables, $TIA_{i,LV}$, was obtained as the integral over time from TOA to infinity of the concentration at time *t*, $A_{i,LV}(t)$:

$$A_{i,LV}(t) = \sigma_i \cdot F_i^* \cdot e^{-(\lambda_i^w+\lambda_i^r)\cdot t}. \qquad (6)$$

To calculate the thyroid dose arising from ingestion of radionuclides with leafy vegetables using eqn. (3), the values of the processing factors, $PF_{i,LV}$, for radioiodine isotopes were taken to be equal to 0.5 for watercress (washing) and 0.7 for fâfâ, pota and spinach (washing and boiling) (IAEA, 1997). For ^{132}Te, the values of the processing factors were taken to be equal to 1.0 for watercress (washing) and 0.9 for fâfâ, pota and spinach (washing and boiling).

Results of measurements of total gamma-activity in leafy vegetables were available only as averages during a trimester (Republic of France, 1967, 1969, 1971-1975). Figure 7 compares the total gamma concentrations in leafy vegetables measured in Tahiti after test Centaure and calculated using this method. In general, the model provides estimates that are in reasonable agreement with the measurements.

- ***Estimation of the time-integrated concentration in drinking water***

Rainwater collected in a cistern was the only source of drinking water for all study subjects who resided in Tuamotu Archipelago and for some of the subjects who resided in other archipelagos. Typically, there was a family cistern that belonged to a single household and a communal cistern that could be used by the entire village. The variation with time of the concentration of radionuclide *i* in drinking water in a cistern was calculated as:

$$A_{i,water}(t) = \frac{1}{W(t)}\left[A_{i,water}(t-1)\cdot\left(W(t-1)\cdot e^{-\lambda_i^r\cdot\Delta t} - W_{cons}\right) + \sigma_i(t)\cdot S_{coll}\cdot SL\right], \qquad (7)$$

where $A_{i,water}(t)$ is the water concentration of radionuclide *i* in the cistern at time *t* (Bq L^{-1}); $W(t)$ is the amount of water in the cistern at time *t* (L); $A_{i,water}(t-1)$ is the water concentration of radionuclide *i* in the cistern at time *t*-1 day (Bq L^{-1}); $W(t-1)$ is the amount of water in the cistern at time *t*-1 day (L); Δt = 1 d is the calculation step; W_{cons} is the amount of cistern water consumed daily (L); S_{coll} is the area of rainwater collection for the cistern (m^2); *SL* is the solubility of radioisotopes in rainwater (unitless). The solubility of radioiodine isotopes and ^{132}Te in rainwater was taken to be 0.2 (Lessard *et al.*, 1973) for direct fallout with TOA of H+24h or less. For TOA

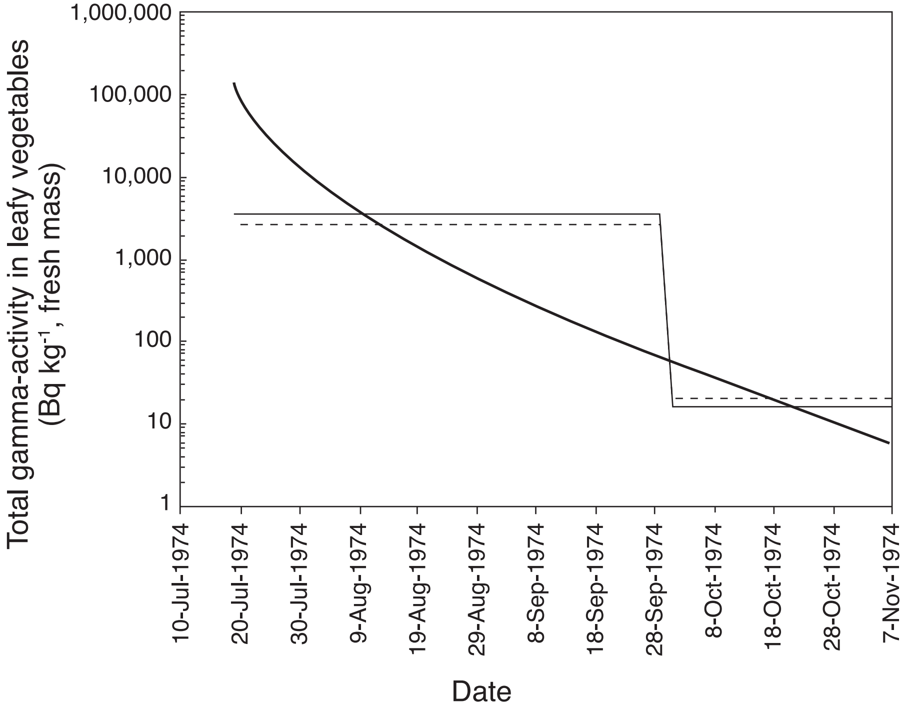

Figure 7: Total gamma-activity in leafy vegetables in Tahiti after the test Centaure: calculation (curve) and average measurements during a trimester in lettuce (thin line) and fâfâ (broken line) (Drozdovitch *et al.,* 2008)

greater than one day, the solubility of radioiodine isotopes was taken to be equal to 1.

The amount of rainwater in a cistern was calculated as:

$$W(t) = \left\{ \begin{array}{c} 0,\ if\ W(t) \leq 0 \\ W(t-1) - W_{cons} + R(t) \cdot S_{coll},\ if\ 0 < W(t) < W_{cistern} \\ W_{cistern},\ if\ W(t) \geq W_{cistern} \end{array} \right\} \quad (8)$$

where *R(t)* is the precipitation on day t (Météo France, 2005) (mm); $W_{cistern}$ is the volume of the cistern equals to 15,000 and 90,000 L for family and communal cisterns, respectively (HCRFP, 1977).

The deposition density of radionuclide *i*, $\sigma_t(t)$, was defined as:

$$\sigma_i(t) = \left\{ \begin{array}{c} \sigma_i,\ if\ t = TOA\ and\ R(t) \neq 0 \\ 0,\ if\ t \neq TOA \end{array} \right\} \quad (9)$$

The daily consumptions of water from the cistern were 200 and 2000 L for family and communal cisterns, respectively, and the areas of rainwater collection for the cisterns were 30 and 200 m^2, respectively (Drozdovitch *et al.*, 2019). The amount of water in the cisterns was calculated for each year of atmospheric testing for the time period starting 2 weeks before the first nuclear weapons test and ending 5 weeks after the last test of the year. The initial content of rainwater in the cistern was assumed to be 1/4 of its volume. The model considers that the daily consumption of drinking water varied from 0.25 L for 0-12 mo to 2.0 L for adults.

Thyroid dose due to external irradiation from radionuclides deposited on the ground

The thyroid dose for a study subject of age k due to external irradiation from radionuclides deposited on the ground, D_k^{ext} (mGy), was calculated as:

$$D_k^{ext} = BF_k \cdot \sum_i DC_{i,k}^{ext} \cdot \int_{t_1}^{t_2} \sigma^i(t)\ \mathrm{d}t \tag{10}$$

where BF_k is the behavioral factor that takes into account the fraction of time spent indoors by the subject of age k and the shielding properties of residential building (unitless); $DC_{i,k}^{ext}$ is the thyroid dose rate coefficient for radionuclide i, that is, the absorbed dose rate in the thyroid (mGy d^{-1}) per unit deposition (Bq m^{-2}) of radionuclide i in a plane source covered by 3 mm of soil representing ground roughness (Bellamy *et al.*, 2019); t_1 and t_2 are the times of beginning and end of residence at a given location (d).

The variation with time of the deposition density, $\sigma_i(t)$, of ^{95}Nb, ^{97}Nb, ^{132}I, and ^{140}La was estimated from the deposition density of their precursors, i.e., ^{95}Zr, ^{97}Zr, ^{132}Te, and ^{140}Ba, respectively. Radionuclides ^{91m}Y, ^{99m}Tc, ^{103m}Rh, ^{106}Rh, ^{137m}Ba and ^{144}Pr, with half-lives on the order of hours or less, were taken to be in radioactive equilibrium with their precursor, and the contributions from both nuclides were considered in a single conversion factor. It should be noted that the migration to deeper layers of soil, which occurs at time since deposition increases, was not considered, even for long-lived radionuclides, such as ^{137}Cs, ^{106}Ru, ^{144}Ce, as doses were calculated over the relatively short time from TOA until 31 December of the year when the test was conducted. This seems to be a reasonable simplification as, for example, dose due to external irradiation in 1969 from long-lived radionuclides deposited after the tests conducted in 1968 was, typically, around a few µGy.

The behavioral factor, BF_k, was calculated using the following equation:

$$BF_k = \frac{1}{24} \cdot [SF \cdot T_{indoors,k} + LF \cdot (24 - T_{indoors,k})], \tag{11}$$

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where *SF* is the shielding factor, which is related to the attenuation of the gamma rays emitted outdoors by the building material of the dwellings (unitless). It was 0.1 for concrete, 0.3 for wood and 0.7 for straw and bamboo (Drozdovitch *et al.*, 2008); $T_{indoors,k}$ is the time spent indoors in a day by a subject of age *k*, which depends for schoolchildren aged 7-14.9 y on the time of year: school days or school vacation (from 15 June to 15 August) (h). Age-, archipelago- and season-specific values of time spent indoors for the Polynesian population was collected by Drozdovitch *et al.* (2019); *LF* is the location factor for outdoor conditions that depends on the type of environment (unitless). It was taken to be 0.5 for a typical urban environment and 0.7 for a rural environment (Drozdovitch *et al.*, 2008).

Table 12 provides the values for BF_k, calculated using eqn (11), that were used in this study. If the study subject reported during the personal interview the type and construction material of residence, the value of the behavioral factor corresponding to age *k* of the study subject and to her/his archipelago and type of residence was used in the dose calculation. If the study subject did not recall the type and construction material for her/his residence, the behavioral factor was estimated using the archipelago-specific distribution of types and construction materials of residences that were reported by the focus groups to be typical in the 1960s-1970s (Drozdovitch *et al.*, 2019).

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

The thyroid dose arising from ingestion of ^{137}Cs, D_k^{Cs} (mGy), was calculated as:

$$D_k^{Cs} = N \cdot D_k^{Cs} \cdot \sum_m V_{m,k} \cdot PF_m^{Cs} \cdot A_m^{Cs} \quad (12)$$

where *N* is the number of days of residence in a given archipelago during which the contaminated foodstuffs were consumed (d) in the year under consideration; D_k^{Cs} is the age-dependent thyroid dose coefficient for ^{137}Cs ingestion (ICRP, 1993) (mGy Bq^{-1}); $V_{m,k}$ is the consumption rate of foodstuff *m* by the subject of age *k* (see Table 2 for the list of foodstuffs) (kg (L) d^{-1}); PF_m^{Cs} is the processing factor that reflects the change in activity concentration of ^{137}Cs resulting from the culinary preparation of the raw product (unitless); A_m^{Cs} is the average annual concentration of ^{137}Cs in foodstuff *m* for each year from 1966 to 1974 (Bq kg^{-1}(L^{-1})).

Archipelago-specific average annual concentrations of ^{137}Cs in foodstuffs were derived from the results of measurements of ^{137}Cs in foodstuffs provided in reports to UNSCEAR (Republic of France, 1967, 1969, 1971-1975) and in de-classified reports (SMSR, 1970; SMCB, 1975a,b, 1976a,b, 1978a,b).

Table 12: Archipelago-specific values of the behavioral factor, BF_k (Drozdovitch *et al.*, 2020b)

Age	Type of residence	Tahiti	Society Islands	Tuamotu archipelago	Gambier Islands	Marquesas Islands	Austral Islands
0-12 mo	Concrete house	0.30	0.31	0.35	0.30	0.30	0.31
	Wooden (*pinex*) house	0.50	0.51	0.55	0.50	0.50	0.51
	Bamboo house	0.70	0.70	0.70	0.70	0.70	0.70
	Concrete apartment	0.10	0.12[a]	-	-	-	-
	Unknown[b]	0.50	0.59	0.63	0.47	0.52	0.31
1-3.9 y	Concrete house	0.33	0.32	0.34	0.33	0.36	0.34
	Wooden (*pinex*) house	0.53	0.52	0.54	0.53	0.56	0.54
	Bamboo house	0.70	0.70	0.70	0.70	0.70	0.70
	Concrete apartment	0.16	0.14[a]	-	-	-	-
	Unknown	0.53	0.60	0.63	0.50	0.57	0.34
4-6.9 y	Concrete house	0.36	0.33	0.36	0.34	0.36	0.38
	Wooden (*pinex*) house	0.56	0.53	0.56	0.54	0.56	0.58
	Bamboo house	0.70	0.70	0.70	0.70	0.70	0.70
	Concrete apartment	0.23	0.16[a]	-	-	-	-
	Unknown	0.55	0.61	0.64	0.51	0.53	0.38
7-14.9 y[c]	Concrete house	0.33	0.33	0.34	0.33	0.33	0.31
	Wooden (*pinex*) house	0.53	0.53	0.54	0.53	0.53	0.51
	Bamboo house	0.70	0.70	0.70	0.70	0.70	0.70
	Concrete apartment	0.15	0.15[a]	-	-	-	-
	Unknown	0.52	0.60	0.63	0.50	0.50	0.31
7-14.9 y[d]	Concrete house	0.34	0.37	0.38	0.37	0.37	0.38
	Wooden (*pinex*) house	0.54	0.57	0.58	0.57	0.57	0.58
	Bamboo house	0.70	0.70	0.70	0.70	0.70	0.70
	Concrete apartment	0.18	0.23[a]	-	-	-	-
	Unknown	0.54	0.63	0.65	0.54	0.53	0.38
15-21 y	Concrete house	0.33	0.35	0.38	0.37	0.33	0.38
	Wooden (*pinex*) house	0.53	0.55	0.58	0.57	0.53	0.58
	Bamboo house	0.70	0.70	0.70	0.70	0.70	0.70
	Concrete apartment	0.17	0.19[a]	-	-	-	-
	Unknown	0.53	0.62	0.65	0.54	0.50	0.54

[a] Only in Raiatea.
[b] For unknown type of residence, behavior factor was estimated using archipelago-specific combination of type and construction material of residences according to Drozdovitch *et al.* (2019).
[c] During school days.
[d] During school vacation from 15 June to 15 August.

To calculate the thyroid dose arising from ingestion of ^{137}Cs using eqn. (12), the values of the processing factor were equal to 0.6 for root vegetables, 0.7 for fâfâ and pota, 0.8 for meat, 0.9 for leafy vegetables (except fâfâ and pota), fish, and uru (IAEA, 1997). For foodstuffs other than those listed above, the value of the processing factor was 1.0.

Study subjects exposed in utero

Fetal doses to the thyroid gland due to intakes of radioiodine isotopes (^{131}I, ^{132}I, ^{133}I, ^{135}I) and ^{132}Te by the mothers of the study subjects were calculated for inhalation of contaminated air and for ingestion of contaminated fresh cow's milk in Tahiti, and of leafy vegetables and drinking water in all atolls and islands of interest.

The thyroid dose to a fetus arising from inhalation of contaminated air by the mother, D_{fetus}^{inh} (mGy), was calculated as:

$$D_{fetus}^{inh} = V_{adult}^{air} \cdot RF^{air} \cdot \sum_i TIA_i^{air} \cdot DC_{fetus}^{inh,i}(t_g), \quad (13)$$

where V_{adult}^{air} is the breathing rate of the mother of the study subject ($m^3\ s^{-1}$) (ICRP, 2002); $DC_{fetus}^{inh,i}(t_g)$ is the thyroid dose coefficient to a fetus of gestational age t_g at time TOA of the test under consideration, per unit of acute inhalation intake of radioiodine or tellurium isotopes by the mother (ICRP, 2001) ($mGy\ Bq^{-1}$).

The thyroid dose to a fetus arising from ingestion by the mother of radionuclide-contaminated foodstuffs and drinking water, D_{fetus}^{ing} (mGy), was calculated as:

$$D_{fetus}^{ing} = \sum_{g=n}^{l} \sum_i DC_{fetus}^{ing,i}(t_g) \cdot \sum_m V_{m,preg}^{*} \cdot PF_{i,m} \cdot TIA_{i,m}^{food}, \quad (14)$$

where $D_{fetus}^{ing,i}(t_g)$ is the thyroid dose coefficient to fetus of gestation age t_g due to acute ingestion intake of radioiodine or tellurium isotopes by the mother of the subject (ICRP 2001) ($mGy\ Bq^{-1}$); n is the gestational age at time TOA of the test under consideration (wk); l is the gestational age two months after TOA of the test under consideration (wk); $V_{m,preg}^{*}$ is the consumption rate of foodstuff m or drinking water by the pregnant mother of the subject (kg (L) d^{-1}).

Archipelago-specific values of consumers' fractions and of consumption rates of locally-produced foodstuffs by pregnant women, which were obtained during the focus-group study (Drozdovitch *et al.*, 2019), are given in Table 13. The consumption rate of foodstuff m by pregnant women used in this study, $V_{m,preg}^{*}$, was calculated from the focus-group data as:

$$V_{m,preg}^{*} = P_{cons,preg} \cdot V_{m,preg}, \quad (15)$$

where $P_{cons,preg}$ is the fraction of consumers of foodstuff m among pregnant women (unitless); $V_{m,preg}$ is the consumption rate of foodstuff m by pregnant women who reported non-zero consumption of the foodstuff during the focus-group study (kg (L) d^{-1}).

Breastfed study subjects

Doses to the thyroid gland of breastfed children due to intakes of radioiodine isotopes (^{131}I, ^{132}I, ^{133}I, ^{135}I) and ^{132}Te by the mothers of the study subjects were calculated for inhalation of contaminated air and for ingestion of contaminated fresh cow's milk in Tahiti and of leafy vegetables and drinking water in all atolls and islands of interest.

Table 13: Archipelago-specific fractions of consumers ($P_{cons,preg}$) and consumption rates[a] of locally produced foodstuffs, $V_{m,preg}$ (kg (L) d^{-1}), by pregnant women (Drozdovitch *et al.*, 2020b)

Foodstuff	Tahiti		Society Islands		Tuamotu archipelago		Gambier Islands		Marquesas Islands		Austral Islands	
	P_{cons}	V_m	P_{cons}	V_m	P_{cons}	V_m	P_{cons}	V_m	P_{cons}	V_m	P_{cons}	V_m
Fresh cow's milk	0.30	0.15	0.30	0.15	-	-	-	-	-	-	-	-
Leafy vegetables[b]	0.72	0.10	0.83	0.070	0.40	0.065	1.0	0.070	0.44	0.093	0.89	0.14
Fâfâ	0.66	0.074	0.50	0.060	-	-	0.43	0.14	-	-	0.89	0.20
Coco milk	0.74	0.29	0.67	0.19	1.0	0.36	1.0	0.31	0.56	0.11	0.78	0.16
Coco copra	0.85	0.077	0.75	0.060	0.93	0.10	0.71	0.056	1.0	0.31	0.78	0.11
Uru	0.77	0.20	0.83	0.090	0.93	0.47	1.0	0.21	1.0	0.090	0.78	0.18
Banana	0.89	0.23	0.67	0.16	0.93	0.18	1.0	0.44	0.89	0.45	1.0	0.36
Mango	0.91	0.41	0.75	0.56	-[c]	-[c]	1.0	0.33	0.89	0.61	0.67	0.58
Papaya	0.79	0.24	0.67	0.23	1.0	0.38	0.71	0.31	0.89	0.44	0.78	0.30
Manioc	0.60	0.10	0.83	0.074	-[c]	-[c]	1.0	0.13	0.78	0.10	0.89	0.20
Taro	0.91	0.13	0.83	0.078	-[c]	-[c]	-[c]	-[c]	0.56	0.036	1.0	0.35
Sweet potatoes	0.6	0.063	0.83	0.078	-[c]	-[c]	0.86	0.10	-[c]	-[c]	0.78	0.15
Poultry	0.74	0.070	0.75	0.064	0.87	0.068	1.0	0.15	0.78	0.19	0.78	0.074
Beef	0.51	0.036	0.58	0.031	-[c]	-[c]	0.57	0.044	0.78	0.055	0.33	0.041
Pork	0.38	0.049	0.42	0.050	0.87	0.052	0.71	0.069	0.78	0.16	0.56	0.045
Goat	-	-	-	-	-	-	-	-	0.78	0.065	-	-
Benitier	0.51	0.045	0.42	0.047	0.93	0.053	0.57	0.031	0.67	0.028	0.22	0.058
Fish (sea, lagoon)	0.98	0.23	0.83	0.27	1.0	0.50	1.0	0.24	0.67	0.22	1.0	0.29

[a] Consumption rates are provided for consumers only.
[b] Leafy vegetables including pota, watercress, spinach, lettuce.
[c] Foodstuff consumed but not locally produced.

The internal thyroid dose to a breastfed child arising from inhalation of contaminated air by the mother, D_{brfed}^{inh} (mGy), was calculated as:

$$D_{brfed}^{inh} = V_{adult}^{air} \cdot RF^{air} \cdot \sum_i TIA_i^{air} \cdot DC_{brfed}^{inh,i}, \tag{16}$$

where $DC_{brfed}^{inh,i}$ is the thyroid dose coefficient to a breastfed child due to inhalation of a specific radioiodine or tellurium isotope by the mother (ICRP, 2004) (mGy Bq^{-1}).

The thyroid dose to a breastfed child arising from ingestion of radioiodine isotopes and ^{132}Te by mother with foodstuffs and drinking water, D_{brfed}^{ing} (mGy), was calculated as:

$$D_{brfed}^{ing} = \sum_i DC_{brfed}^{ing,i} \cdot \sum_m V_{m,lact}^{*} \cdot PF_{i,m} \cdot TIA_{i,m}^{food}, \tag{17}$$

where $DC_{brfed}^{ing,i}$ is the thyroid dose coefficient for the breastfed child due to ingestion of a specific radioiodine or tellurium isotope by the mother (ICRP, 2004) (mGy Bq^{-1}); $V_{m,lact}^{*}$ is the consumption rate of foodstuff m or drinking water by the lactating woman (kg (L) d^{-1}).

Archipelago-specific values of consumers' fractions and consumption rates of foodstuffs by lactating women, which were obtained during the focus-group study (Drozdovitch *et al.*, 2019), are given in Table 14. By analogy

Table 14: Archipelago-specific fractions of consumers ($P_{cons,lact}$) and consumption rates[a] of locally produced foodstuffs, $V_{m,lact}$ (kg (L) d^{-1}), by lactating women (Drozdovitch *et al.*, 2019)

Foodstuff	Tahiti		Society Islands		Tuamotu archipelago		Gambier Islands		Marquesas Islands		Austral Islands	
	P_{cons}	V_m	P_{cons}	V_m	P_{cons}	V_m	P_{cons}	V_m	P_{cons}	V_m	P_{cons}	V_m
Fresh cow's milk	0.30	0.17	0.30	0.15	-	-	-	-	-	-	-	-
Leafy vegetables[b]	0.70	0.10	0.75	0.068	0.40	0.065	1.0	0.070	0.44	0.093	0.89	0.14
Fâfâ	0.66	0.074	0.67	0.055	-	-	0.43	0.14	-	-	0.89	0.20
Coco milk	0.72	0.24	0.58	0.11	0.93	0.36	1.0	0.31	0.56	0.11	0.78	0.16
Coco copra	0.83	0.068	0.83	0.056	0.87	0.11	0.71	0.056	1.0	0.30	0.78	0.11
Uru	0.72	0.20	0.83	0.093	0.93	0.46	1.0	0.21	1.0	0.066	0.78	0.18
Banana	0.83	0.22	0.75	0.17	0.87	0.18	1.0	0.44	0.89	0.37	1.0	0.36
Mango	0.87	0.40	0.75	0.46	-[c]	-[c]	1.0	0.33	0.78	0.59	0.67	0.58
Papaya	0.77	0.23	0.75	0.28	1.0	0.38	0.71	0.31	0.89	0.38	0.78	0.30
Manioc	0.64	0.066	0.83	0.074	-[c]	-[c]	1.0	0.13	0.78	0.10	0.89	0.20
Taro	0.96	0.12	0.83	0.074	-[c]	-[c]	-[c]	-[c]	0.56	0.036	1.0	0.35
Sweet potatoes	0.62	0.061	0.83	0.074	-[c]	-[c]	0.86	0.10	-[c]	-[c]	0.78	0.15
Poultry	0.72	0.072	0.75	0.067	0.93	0.071	1.0	0.15	0.78	0.19	0.78	0.074
Beef	0.51	0.036	0.58	0.027	-[c]	-[c]	0.57	0.044	0.78	0.055	0.33	0.041
Pork	0.38	0.049	0.42	0.050	0.80	0.056	0.71	0.069	0.78	0.16	0.56	0.045
Goat	-	-	-	-	-	-	-	-	0.78	0.065	-	-
Benitier	0.49	0.039	0.42	0.051	0.87	0.054	0.57	0.031	0.67	0.028	0.22	0.058
Fish (sea, lagoon)	1.0	0.25	0.83	0.30	1.0	0.50	1.0	0.24	0.67	0.22	1.0	0.29

[a] Consumption rates are provided for consumers only.
[b] Leafy vegetables including pota, watercress, spinach, lettuce.
[c] Foodstuff consumed but not locally produced.

with pregnant women, the consumption of foodstuff *m* by lactating women used in this study, $V^*_{m,lact}$, was calculated from the focus-group data as:

$$V^*_{m,lact} = P_{cons,lact} \cdot V_{m,lact}, \quad (18)$$

where $P_{cons,lact}$ is the fraction of consumers of foodstuff *m* among lactating women (unitless); $V_{m,lact}$ is the consumption rate of foodstuff *m* by lactating women who reported non-zero consumption of the foodstuff during the focus-group study (kg (L) d^{-1}).

Individual thyroid dose estimates

The assessment of individual thyroid doses in TD19 took into account: (1) the residential history and dietary habits of the subjects, which were obtained by means of personal interviews, and historical lifestyle and consumption data collected during the focus-group study; 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 about the case or control status of the study subjects.

The contributions of the different exposure pathways to the thyroid dose estimates are summarized in Table 15. The average thyroid dose due to all

Table 15: Thyroid doses reconstructed for the study subjects from different exposure pathways (Drozdovitch *et al.,* 2020b)

Exposure pathway	Thyroid dose (mGy)		
	Min	Mean	Max
Intake of ^{131}I	0.002	3.5	27
Intake of short-lived ^{132}I, ^{133}I, ^{135}I, and ^{132}Te	0.001	0.75	14
External exposure	0.005	0.41	5.8
^{134,137}Cs ingestion	3.4×10^{-5}	0.08	0.94
All exposure pathways	0.014	4.7	36

exposure pathways combined was estimated to be 4.7 mGy (range: 0.014 mGy to 36 mGy), including: (1) 3.5 mGy (range: 0.002 mGy to 27 mGy) due to intake of ^{131}I, (2) 0.75 mGy (range: 0.001 mGy to 14 mGy) due to intake of short-lived iodine isotopes (^{132}I, ^{133}I, ^{135}I) and ^{132}Te, (3) 0.41 mGy (range: 0.005 mGy to 5.8 mGy) from external irradiation, and (4) 0.08 mGy (range: ~0 mGy to 0.94 mGy) from ingestion of ^{137}Cs.

Intake of ^{131}I via inhalation and ingestion was estimated to be the main pathway of thyroid exposure accounting for 72% of the total dose. The mean 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, 12% for external exposure, and around 2% 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. With respect to external exposure, the main contributors to thyroid dose were ^{140}Ba+^{140}La, ^{132}Te+^{132}I, ^{95}Zr+^{95}Nb, ^{103}Ru, ^{131}I, and ^{239}Np and, in addition, ^{97}Zr+^{97}Nb, ^{133}I, ^{135}I, ^{99}Mo and ^{143}Ce, if the deposition was due to direct fallout occurring within 24 hours after the test.

Figure 8 compares the contributions of each exposure pathway to the total thyroid dose of the study subjects by archipelago: intake of ^{131}I and short-lived radioiodine isotopes (^{132}I, ^{133}I, ^{135}I) and ^{132}Te with (i) inhaled air, (ii) cow's milk, (iii) leafy vegetables, and (iv) drinking water, in addition to (v) external irradiation, and (vi) ingestion of ^{137}Cs with foodstuffs. The residents of the Society Islands received thyroid doses, mainly, from consumption of leafy vegetables and fresh cow's milk with minor contributions from other pathways. The large contribution to the thyroid dose from the consumption of leafy vegetables was found for the study subjects who resided in the Marquesas Islands and, especially, in the Austral Islands. For the Austral Islands, the relatively high consumption rates of leafy vegetables were reported both by the study subjects during their personal interview and during the focus-group study (Drozdovitch *et al.*, 2019). For the study subjects who resided in Tuamotu archipelago, drinking of rainwater followed by consumption of leafy

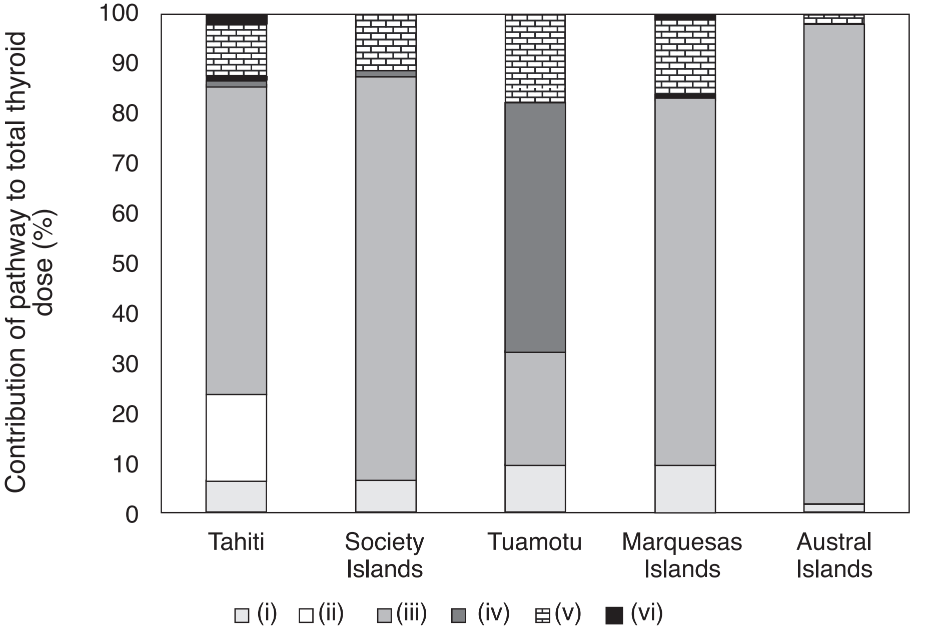

Figure 8: Contribution (%) of the exposure pathways to the total thyroid dose for the study subjects in each archipelago: intake of ^{131}I, ^{132}I, ^{133}I, ^{135}I and ^{132}Te with (i) inhaled air, (ii) cow's milk, (iii) leafy vegetables, and (iv) drinking water; also (v) external irradiation from the activity deposited on the ground, and (vi) ingestion of ^{137}Cs with foodstuffs (Drozdovitch *et al.*, 2020b)

vegetables and external irradiation were found to be the major contributors to the thyroid dose.

Table 16 presents the annual thyroid doses received by the study subjects during the period of atmospheric testing in French Polynesia (1966-1974). The lowest thyroid doses were received in 1968, 1970 and 1972. Atmospheric tests were not conducted in 1969, but exposure to fallout occurred due to ingestion of ^{137}Cs with locally produced food. The highest thyroid dose of 30 mGy is estimated to have resulted from the test Aldébaran in 1966 by a study subject who resided in the Gambier Islands. In 1967, thyroid doses of up to 6-7 mGy were received by study subjects who resided in Tahiti, Reao, and Takakoto (Tuamotu), but fallout was deposited rather uniformly throughout French Polynesia. In 1973, the maximal thyroid dose of 23 mGy was received after test Pallas by a study subject who resided in Rapa (Austral Islands). The major exposure in 1974 occurred after test Centaure in Tahiti and other Society Islands with a maximal thyroid dose among the study subjects of 21 mGy.

Table 16: Thyroid doses received by the study subjects[a] in each year of the atmospheric testing period in French Polynesia (1966-1974) (Drozdovitch *et al.,* 2020b)

Year	Thyroid dose (mGy)		
	Min	Mean	Max
1966	0.006	0.62	30
1967	0.018	1.0	7.2
1968	0.004	0.29	1.7
1969 [b]	1.1×10^{-4}	0.011	0.079
1970	0.007	0.15	1.0
1971	0.002	0.37	4.2
1972	2.6×10^{-4}	0.058	0.41
1973	0.001	0.33	23
1974	5.4×10^{-4}	2.5	21
All years	0.014	4.7	36

[a] Only individuals who resided at given year in French Polynesia and were exposed to fallout.
[b] Exposure due to ingestion of ^{137}Cs in locally-produced foodstuffs.

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Table 17 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 17. The highest individual dose was estimated for a subject who resided in Tahiti after the test Centaure in 1974.

The doses that have been estimated using the methodology described in Drozdovitch *et al.* (2008, 2020b) 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 by Drozdovitch *et al.* (2008). Table 18 compares the dose estimates published by UNSCEAR (1977) and by Bourges (1997) with the average doses reconstructed based on input data and methodology of Drozdovitch *et al.* (2008). In general, the agreement between the dose estimates obtained in the different studies is reasonable. Results of measurements of ^{131}I concentration in cow's milk were used for dose reconstruction in all 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

Table 17: Estimated thyroid doses[a,b] received by the study subjects from each of the 41 atmospheric nuclear tests (Drozdovitch *et al.*, 2020b)

Test	Date of test (dd/mm/yyyy)	Thyroid dose (mGy)		
		Min	Mean	Max
Aldébaran	02/07/1966	0.002	0.22	30
Tamouré	19/07/1966	4.8×10^{-4}	0.018	0.19
Bételgeuse	11/09/1966	0.002	0.089	0.55
Rigel	24/09/1966	3.5×10^{-4}	0.012	0.29
Sirius	04/10/1966	0.006	0.27	3.1
Altaïr	05/06/1967	0.002	0.11	0.68
Antarès	27/06/1967	7.4×10^{-4}	0.035	0.24
Arcturus	02/07/1967	0.014	0.84	6.7
Capella	07/07/1968	1.8×10^{-4}	0.035	0.26
Castor	15/07/1968	0.001	0.051	0.29
Pollux	03/08/1968	0.004	0.15	0.92
Canopus	24/08/1968	9.8×10^{-4}	0.026	0.28
Procyon	08/09/1968	5.8×10^{-4}	0.025	0.17
Andromède	15/05/1970	1.8×10^{-4}	0.016	0.13
Cassiopée	22/05/1970	3.6×10^{-4}	0.011	0.081
Dragon	30/05/1970	6.5×10^{-5}	0.004	0.19
Eridan	24/06/1970	2.2×10^{-4}	0.008	0.16
Licorne	03/07/1970	0.001	0.030	0.35
Pégase	27/07/1970	3.7×10^{-4}	0.022	0.14
Orion	02/08/1970	0.001	0.027	0.18
Toucan	06/08/1970	7.4×10^{-4}	0.031	0.46
Dioné	05/06/1971	8.6×10^{-4}	0.012	0.34
Encelade	12/06/1971	0.003	0.28	2.3
Japet	04/07/1971	3.7×10^{-4}	0.040	0.47
Phoebé	08/08/1971	8.3×10^{-5}	0.023	3.6
Rhéa	14/08/1971	8.2×10^{-5}	0.014	0.32
Umbriel	25/06/1972	6.8×10^{-4}	0.021	0.19
Titania	30/06/1972	3.7×10^{-4}	0.014	0.24
Obéron	27/07/1972	1.4×10^{-4}	0.016	0.11
Euterpe	21/07/1973	2.7×10^{-4}	0.002	0.045
Melpomène	28/07/1973	4.9×10^{-4}	0.002	0.005
Pallas	18/08/1973	8.6×10^{-4}	0.30	23
Parthénope	24/08/1973	5.1×10^{-4}	0.029	0.37
Tamara	28/08/1973	0.001	0.011	0.12
Capricorne	16/06/1974	5.9×10^{-4}	0.009	0.064
Gémeaux	07/07/1974	1.0×10^{-4}	0.003	0.045
Centaure	17/07/1974	4.1×10^{-4}	2.4	20
Maquis	25/07/1974	2.5×10^{-4}	0.015	0.11
Scorpion	15/08/1974	5.3×10^{-5}	0.060	0.51
Taureau	24/08/1974	2.7×10^{-4}	0.095	0.85
Verseau	14/10/1974	1.3×10^{-4}	0.012	0.13

[a] Only individuals who were exposed to fallout from given test.
[b] Do not include thyroid dose due to ^{137}Cs ingestion as ^{137}Cs activity in foodstuffs cannot be attributed to specific tests.

shared by all subjects to whom it applies. Other uncertainties could be independent and, therefore, unshared by subjects. The major sources of uncertainty include:

• The uncertainties attached to the estimation of deposition densities of specific radionuclides. When measurements of total beta-activity in air were

Table 18: Comparison of dose estimates: UNSCEAR (1977), Bourges (1997), and Drozdovitch *et al.* (2008)

Test	Date	Location	Exposure pathway or ingestion of	Thyroid dose for 1-year infants (UNSCEAR, 1977) (mGy)	Effective dose for adults (Bourges, 1997) (mSv)	Drozdovitch *et al.* (2008) (mGy, 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
Aldébaran	02/07/66	Gambier	External	-	3.4	3.9
Arcturus	02/07/67	Tureia	External	-	0.7	0.4
Encelade	12/06/71	Tureia	External	-	0.9	1.0
Phoebé	08/08/71	Gambier	External	-	0.9	0.4
Centaure	17/07/74	Tahiti	External	-	0.6	0.4
Aldébaran	02/07/66	Gambier	Inhalation	-	0.2	0.4
Arcturus	02/07/67	Tureia	Inhalation	-	0.023	0.035
Encelade	12/06/71	Tureia	Inhalation	-	0.003	0.03
Phoebé	08/08/71	Gambier	Inhalation	-	0.002	0.04
Centaure	17/07/74	Tahiti	Inhalation	-	0.08	0.01
Aldébaran	02/07/66	Gambier	Leafy vegetables	-	1.2	1.9
Phoebé	08/08/71	Gambier	Leafy vegetables	-	0.2	0.3
Centaure	17/07/74	Tahiti	Leafy vegetables	-	0.04	0.08
Aldébaran	02/07/66	Gambier	Drinking water	-	0.14	0.13
Phoebé	08/08/71	Gambier	Drinking water	-	0.035	0.013
Centaure	17/07/74	Tahiti	Milk	-	0.3[a]	0.4

[a] Effective dose for 1-y old infants.

available, the deposition density of the main contributors to the thyroid dose, such as $^{95}Zr+^{95}Nb$, ^{103}Ru, ^{131}I, $^{132}Te+^{132}I$, ^{133}I, ^{135}I, $^{140}Ba+^{140}La$ (radionuclides listed according to increasing mass number, not according to their importance) was generally estimated with an uncertainty factor of up to 2 (Drozdovitch *et al.*, 2020a). For islands and atolls where measurements were not performed, procedures of interpolation and extrapolation resulted in uncertainties in the estimated deposition densities within a factor of 2 to 3 around the best estimate. In addition, the results obtained for atmospheric nuclear weapons tests conducted at the Nevada test site in the USA were used to estimate the deposition densities of specific radionuclides (Hicks, 1981) because the corresponding data for the tests conducted in French Polynesia were not found in the open literature.

- The uncertainties attached to the values of the thyroid mass. It is challenging to estimate the degree of iodine deficiency and the values of the thyroid mass around the time of tests in the 1960s-1970s because data for that period of time are not available. The only data on thyroid mass-values in French Polynesians available to us were the results of thyroid volume measurements in a group of 83 individuals aged 12 to 17 conducted in 2007 (F. de Vathaire, personal communication, Paris, France, 2018). The mean thyroid mass-value in this group was found to be 9.2 g, which is consistent (within 30%) with the ICRP (2002) reference thyroid-mass value of 12 g for the same age group (15 years, according to the ICRP definition). We used in this study a thyroidal uptake of 30% and the age-dependent values of the thyroid mass recommended by ICRP (ICRP, 2002).

- The uncertainties attached to the information obtained in 2001-2004 (for Phase I) and in 2014-2017 (for Phase II) during personal interviews regarding relocation history and individual diet. Recall of diet during childhood in distant past is strongly influenced by current diet (Dwyer *et al.*, 1989) and is characterized by low reproducibility and validity if recollections exceeding 10 years (Maruti *et al.*, 2005). For example, as information on the locations of the schools attended by the study subjects aged 7 to 14 was not available, it was assumed that the schools were in the islands / atolls of residence.

The uncertainties in the doses that were estimated for the Inserm study were not evaluated in a quantitative manner because of the complexity of the model and multiple events of exposure that occurred in 1966-1974. However, based on the extensive assessment of uncertainties in thyroid doses performed for populations exposed to radioactive fallout from atmospheric nuclear weapons tests conducted at the Semipalatinsk Nuclear Test Site from 1949 to 1962 (Land *et al.*, 2015), it was subjectively estimated that the overall uncertainties of the thyroid doses in this study are characterized, on average, by a geometric standard deviation of 2.5 to 3.0.

Conclusions

This report presents a general description of the dose assessment methods used to evaluate the radiation exposures from nuclear weapons testing in the atmosphere, with emphasis on the tests conducted in French Polynesia. The report provides a detailed methodology of reconstruction of thyroid doses for an Inserm case-control study of thyroid cancer in French Polynesia. The limitations of the previous dose assessment, TD08, were overcome by conducting two special studies in 2016-2019 on: (i) collection of historical data on lifestyle of French Polynesians at the time of nuclear tests, and (ii) evaluation of ground deposition of radionuclides in French Polynesia resulting from atmospheric nuclear weapons tests using a large number of original internal reports on the radiation measurements, which were declassified by the French Ministry of Defense in 2013.

Using focus-group sessions and key informant interviews, information on lifestyle and consumption of various foodstuffs in mid-1960s-mid-1970s was collected from residents of islands and atolls. This information on several key aspects of daily life on French Polynesian archipelagoes about 50 years ago, which was collected in such detail for the first time in history, was used to correct biases from previous assumptions and to obtain more appropriate values for parameters important for radiation dose estimation.

The availability of the reports on radiation monitoring of environment that were de-classified by the French Ministry of Defense in 2013 made it possible to conduct a comprehensive estimation of the ground deposition density of radionuclides in French Polynesia resulting from the 41 atmospheric nuclear weapons tests that were conducted between 1966 and 1974 at Mururoa and Fangataufa atolls. For each test, the deposition density at the time of arrival of fallout was estimated for 33 radionuclides either from measurements of total ground deposition or from measurements of total beta-concentration in air or of exposure rate at different locations in French Polynesia. However, uncertainties in estimates of the ground deposition density of radionuclides are relatively high because of simplifying assumptions, interpolation procedures applied for locations without measurements, and conversion from total beta-concentration in air and in deposition to radionuclide concentrations.

The information on population lifestyle and radiation fallout that was obtained in the two special studies conducted in 2016-2019 allowed us to improve the TD08 system and to create the “Thyroid Dosimetry 2019 system”, which was used to estimate the individual thyroid doses received by all study subjects of Phase I and Phase II of the Inserm case-control study of thyroid cancer in French Polynesia. Individual thyroid doses due to intake of ^{131}I and of short-lived radioiodine isotopes (^{132}I, ^{133}I, ^{135}I) and ^{132}Te, external irradiation from gamma-emitted radionuclides deposited on the ground, and ingestion of long-lived ^{137}Cs were reconstructed. Thyroid doses were found to be low, the mean thyroid dose among the study subjects being around 5 mGy, while the highest dose was estimated to be around 36 mGy. Intake of ^{131}I via inhalation and ingestion was estimated to be the main pathway of thyroid exposure accounting for 72% of the total dose. The mean 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, 12% for external exposure, and around 2% for ^{137}Cs ingestion. The residents of the Society Islands received thyroid doses from consumption of leafy vegetables and fresh cow’s milk, for the most part, with minor contributions from other pathways. For the study subjects who resided in the Marquesas Islands and in the Austral Islands, the larger contribution to the thyroid dose arose from the consumption of leafy vegetables. For the residents of Tuamotu archipelago, drinking of rainwater followed by consumption of leafy vegetables and external irradiation were found to be the major contributors to the thyroid dose. Although the uncertainties in the dose estimates were not evaluated in a quantitative manner, they were subjectively assessed to be relatively high and to be characterized, on average, by a geometric standard deviation around 2.5-3.0.

The results presented in this report are being used to evaluate the risk of thyroid cancer among subjects of an Inserm case-control study of thyroid cancer in French Polynesians exposed as children and adolescents to fallout from atmospheric nuclear weapons tests.

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