6 Estimation of Doses

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6.1 INTRODUCTION

The estimation of local and regional doses resulting from environmental releases from nuclear weapons tests conducted at the main nuclear test sites is discussed in this chapter. Global doses, as estimated by UNSCEAR for all the tests from all nuclear test sites, are also presented.

The main nuclear test sites that are considered are: the Nevada Test Site and the Pacific Grounds for the explosions carried out by the USA, Semipalatinsk and Novaya Zemlya for the former USSR, Lob Nor for China, Mururoa and Fangataufa for France, and Australian sites for the UK.

The status of dose reconstruction at these nuclear test sites is first described in general terms. More technical sections then address specifically:

1. the individual doses from external irradiation;
2. the individual doses from internal irradiation.

The nature and amount of information that are available vary according to the nuclear test site that is considered. Although efforts have been made in this chapter to present similar information for all nuclear test sites, this has not always been possible.

The wartime explosions at Hiroshima and Nagasaki are considered to be beyond the scope of this report.

6.2 NEVADA TEST SITE (USA)

The USA began atmospheric testing of nuclear-weapons-related devices at the Nevada Test Site (NTS) on 27 January 1951. Testing continued intermittently until 5 August 1963 when the USA signed the Limited Test Ban Treaty prohibiting the testing of nuclear weapons in the atmosphere, underwater, or in outer space (US DOE, 1994). During the period of atmospheric testing, 105 tests were conducted above ground surface at the NTS and 14 other tests were

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at depths where containment was not expected (Church *et al.*, 1990). The total energy yield of these explosions was approximately 1 Mt of TNT-equivalent explosive energy. Most of the atmospheric releases of radioactive materials, including about 5 EBq of ^{131}I and 6 PBq of ^{137}Cs, took place in test series conducted in 1951, 1952, 1953, 1955, and 1957.

In addition, approximately 800 tests, conducted underground since 1951, were designed for containment of radioactive debris; 38 of these had releases of radioactive materials that were small in comparison with those of the atmospheric tests, but sufficient to be detected by monitoring equipment located off-site (US DOE, 1994).

6.2.1 Status of dose reconstruction

Public concern began to surface in 1953, when several detonations of the Upshot–Knothole test series led to considerable fallout to the north and east of the test site, and continued to build during the late 1950s and early 1960s (Church *et al.*, 1990). Congressional hearings were held in 1957, 1959, and 1963 to evaluate the impact on the public from fallout of nuclear explosions (US Congress, 1957, 1959, 1963). Although estimated doses to local populations from external irradiation, reported by Dunning in 1959, were low and of little, if any, local concern, the precise magnitude and uncertainty of those exposures were not well established during the 1960s and 1970s. Public action groups were formed to seek Federal Government relief for 'fallout victims', and Congressional Representatives from the States of Utah and Nevada began proposing legislative relief for persons suffering from cancers allegedly caused by radiation. By the late 1970s, hundreds of damage claims had been filed with the US Government alleging that illnesses, primarily cancers, resulted from nuclear testing activities at the NTS. The publication of one particular epidemiological study (Lyon *et al.*, 1979) implied a causal relationship between radioactive fallout deposition and childhood leukemia. Public personalities and some scientists questioned the reliability of exposure estimates provided in 1959, especially as doses from internal irradiation had not been considered. These events and concerns prompted the need for a thorough re-evaluation of radiation exposures to the public from fallout produced by nuclear detonations at the NTS (Church *et al.*, 1990; Whicker *et al.*, 1996). In the 1980s, four major dose-reconstruction studies were undertaken; these studies are now completed.

The four major dose reconstruction studies are known as:

1. the Off-site Radiation Exposure Review Project (ORERP) study of the US Department of Energy (DOE);
2. the Utah leukemia case-control study;
3. the Utah thyroid cohort study;
4. the National Cancer Institute (NCI) fallout study.

The first three studies are concerned with doses received by 'local' populations (less than 800 km from the NTS), whereas the fourth study deals with the estimation of thyroid doses received by populations across the continental USA. In all of these studies, uncertainty estimates were attached to the calculated doses. The second and third studies were conducted in the framework of epidemiological studies (Land, 1996).

6.2.1.1 The ORERP Study of DOE

In 1979, DOE established the Off-site Radiation Exposure Review Project (ORERP) to:

1. collect and organize at one central location all relevant documents and data pertaining to fallout in the off-site area and make these documents available to the public;
2. produce a dosimetric re-evaluation of the off-site area characterized by region, community/locale, and age/occupation (Church *et al.*, 1990).

A methodology was developed by the ORERP to model doses to individuals resulting from specific NTS events. This methodology is based on the establishment of databases containing, for each location of interest, an estimate of the exposure rate at 12 h after each event (H + 12) along with the estimated time of arrival (TOA) of the fallout at that location. Measured and calculated relationships between exposure rate and relative amounts of each fission and activation product for each NTS event as a function of time after the explosion (Hicks, 1981, 1982) were then used to estimate the deposition per unit area of ground (also called deposition density) of each radionuclide. These exposure rates and deposition-density estimates were used both to calculate external doses and to estimate doses from internal irradiation based on environmental transport models.

The first phase of the ORERP, designated as Phase I, was performed at locations within approximately 300 km of the NTS, where ground-monitoring personnel measured gamma exposure rates following nuclear events. These survey-meter readings, along with available fallout patterns, were used to compile the Town Data Base, with 1910 records involving 74 events at 353 locations (Thompson *et al.*, 1994). Each record in the Town Data Base contains the values and estimates of uncertainties for H + 12 exposure rate and fallout arrival time for an event at a given location (Thompson, 1990).

The second phase of the ORERP, designated as Phase II, included the states of Arizona, New Mexico, Nevada, and Utah (excluding areas in the Phase I study region), southeastern California, western Colorado, southern Idaho, southeastern Oregon, and southwestern Wyoming. An analogue of the Town Data Base, the County Data Base (CDB), was developed for the 142 counties and county segments that are part of the Phase II study region (Beck and Anspaugh, 1991). The County Data Base was constructed from ^{137}Cs deposition-density estimates for each of the 142 counties and county segments for each NTS event that deposited significant fallout in that county. The manner in which the TDB and the CDB have been prepared has been described in detail by Beck (1996).

Doses from external irradiation were calculated stochastically using Monte Carlo techniques for nine age/occupation categories for each Phase I location/event combination in the Town Data Base and for each county/event combination in the County Data Base (Henderson and Smale, 1990).

Doses from internal irradiation were estimated using the PATHWAY model (Whicker and Kirchner, 1987). The modelling approach used state-of-the-art dynamic models and site-specific data on agricultural, lifestyle, and environmental transport parameters. Where possible, model predictions were tested against actual, independent data sets prior to use for this analysis. Computations were carried out for 15 565 location/event combinations, 20 radionuclides, four age classes, and 22 organs. Uncertainties in data and model parameters were propagated to dose estimates using Monte Carlo simulation techniques. The shapes and magnitudes of uncertainty distributions of the parameter values that were used in the models were estimated based upon extensive literature searches, the elicitation of expert opinion, and the judgment of the investigators. The radionuclide concentrations in foodstuffs, the human intakes of radionuclides, and the resulting estimated radiation doses were typically best described as lognormal distributions. Therefore, medians or geometric means (GM) and geometric standard deviations (GSD) were used as the descriptors for central tendency and dispersion, respectively, of the radionuclide concentrations in foodstuffs, of the human intakes, and of the estimated doses (Kirchner *et al.*, 1996; Whicker *et al.*, 1996).

6.2.1.2 The Utah Leukemia Case-control Study

The Utah leukemia case-control study, which was funded by the National Cancer Institute, was designed to test earlier observations (Lyon *et al.*, 1979; Machado *et al.*, 1987) that seemed to indicate an excess of childhood leukemia in southern Utah following atmospheric testing of nuclear weapons at the NTS. A subject's inclusion in the leukemia study, either as a case or as a control, was based on the following criteria:

1. a date of birth prior to 1 November 1958, as listed in the records of the Church of Jesus Christ of Latter-Day Saints (LDS);
2. a date of death between 1 January 1952 and 31 December 1981, as indicated on a Utah death certificate (Stevens *et al.*, 1990; Simon *et al.*, 1995).

Cases consisted of all individuals who met these criteria and died of leukemia; 1177 cases were identified. A control population of 5330 subjects was selected randomly from deceased Utah residents and were matched by age, sex, and year of death. Information on the residence of the subjects during the period was made available by the LDS Church from its records exclusively for this analysis. Therefore, a criterion for inclusion in this study was membership in that church.

The tissue of interest for leukemia is the active bone marrow. When all pathways of exposure are considered, external irradiation from radionuclides deposited on the ground present by far the most important dose contribution to the active marrow (Beck and Krey, 1983). Active marrow doses from external irradiation were calculated for all of the 1177 cases and 5330 controls included in the study. The information necessary to perform those calculations includes:

1. the residence history of all individuals considered;
2. the temporal variation of the exposure rates at each location where the cases and controls resided during the exposure period;
3. an age-dependent conversion coefficient from exposure rate to active marrow dose;
4. shielding factors accounting for the fact that people spend most of their time indoors where exposure rates are lower than in the open.

The dosimetry methodology was based on the two ORERP databases (the TDB and the CDB), which provide estimates of exposure rates outdoors at 12 h post-detonation as well as the time of arrival of the fallout cloud at each location, with their associated uncertainties. The variation with time of the exposure rate had also been estimated by Hicks (1982) for each NTS event within the framework of the ORERP. A residence history database was constructed for all individuals considered using mainly the Deceased Membership File and the Church Census Record of the LDS Church, although supplementary information was provided by telephone and city directories (Simon *et al.*, 1995). Conversion coefficients from exposure to active marrow dose and shielding factors were taken from the literature (Simon *et al.*, 1995). The dose assignment for the 6507 subjects in the case-control study is one of the most comprehensive and detailed ever assembled for an investigation of radiation-induced leukemia.

6.2.1.3 The Utah Thyroid Cohort Study

The Utah thyroid cohort study, which was also funded by the National Cancer Institute, was a follow-up to a study conducted in 1965–1970 by the Bureau of Radiological Health, in which children living in Washington County, Utah, and Lincoln County, Nevada, had been examined for the presence of thyroid abnormalities, and children of Graham County, Arizona, had been used as a control group (Rallison *et al.*, 1974). The Utah thyroid cohort study consisted of locating the same cohort of subjects identified in the 1965–1970 study and of re-examining them for the presence of thyroid neoplasms and other thyroid disease. Altogether, doses were assigned for 3545 subjects, of which 3122 were re-examined (Till *et al.*, 1995).

Thyroid doses from NTS fallout are mainly due to the consumption of foodstuffs contaminated with ^{131}I, with other, minor, contributions resulting essentially from the consumption of foodstuffs contaminated with ^{133}I, from external irradiation from fallout activity deposited on the ground, and from inhalation of air contaminated with both ^{131}I and ^{133}I. Because of the smaller mass of their thyroid gland, children receive higher doses than adults for a given intake of ^{131}I. The consumption of fresh cows milk usually accounts for most of the dose because milk is consumed regularly and in large amounts and because of its short shelf life. Other foodstuffs with short shelf life, such as leafy vegetables, may also contribute significantly to the thyroid dose. The information necessary to calculate the thyroid doses received from ingestion by all individuals in the cohort includes:

1. the deposition densities of ^{131}I and ^{133}I;
2. the transfer coefficients from the deposition densities to the radionuclide concentrations in cows milk and other important foodstuffs;
3. the dietary and lifestyle habits of all individuals in the cohort;
4. the thyroid dose coefficients.

The deposition estimates were obtained using the ORERP methodology and the two ORERP deposition databases, supplemented with an additional database, the Other Locations Database, specifically developed for this study. Deposition estimates were ascertained for 5804 locations of subject residences and/or locations of milk producers. The transfer coefficients from the deposition densities to the radionuclide concentrations in cows milk, goats milk, and leafy vegetables were obtained using a suite of models and a survey of dairy management practices (Simon *et al.*, 1990). A diet, lifestyle, and residence history survey was conducted to obtain specific information on the milk consumption rates, the frequency of consumption of leafy vegetables, the source of milk and vegetables, as well as on residence history. Finally, the age-specific thyroid dose coefficients were based on literature data.

6.2.1.4 The NCI Fallout Study

The NCI fallout study consists, in part, of an assessment of the exposure of the American people to ^{131}I in fallout originating from the NTS (Wachholz, 1990). This study is carried out in response to Public Law 97-414, Section 7(a), which sets forth three requirements:

> (1) conduct scientific research and prepare analyses necessary to develop valid and credible assessments of the risks of thyroid cancer that are associated with thyroid doses of Iodine 131;

(2) conduct scientific research and prepare analyses necessary to develop valid and credible methods to estimate the thyroid doses of Iodine 131 that are received by individuals from nuclear bomb fallout;

(3) conduct scientific research and prepare analyses necessary to develop valid and credible assessments of the exposure to Iodine 131 that the American people received from the Nevada atmospheric nuclear bomb tests.

The estimation of the exposure and thyroid doses received by the American people as a result of ^{131}I fallout from the NTS has been completed (NCI, 1997). Following the recommendations of the advisory committee that was established to assist the NCI in addressing these tasks, thyroid doses are estimated for representative individuals in each of the approximately 3100 counties of the contiguous USA for each event at the NTS that resulted in significant fallout. Exposures to ^{131}I in fallout resulted mainly from the pasture–cow–milk foodchain. Other, less important exposure routes (inhalation of ^{131}I-contaminated air, and ingestion of foodstuffs other than fresh cows milk) are also considered, but in a much less detailed manner. In the assessment of the exposures from the pasture–cow–milk foodchain, estimates are made of:

1. the activities of ^{131}I deposited on soil and vegetation;
2. the amount of ^{131}I consumed by dairy cows and the resulting ^{131}I concentrations in cows milk;
3. the ^{131}I ingested by people;
4. the absorbed doses from ^{131}I in the thyroids of people (Bouville *et al.*, 1990).

Conceptually, this study is very similar to the ORERP study (as far as the estimation of thyroid doses from ^{131}I is concerned) and to the dosimetric effort related to the Utah thyroid cohort study. The basic differences between the three studies are that:

1. in the NCI fallout study, the populations across the contiguous USA are considered, whereas the other two studies deal only with people residing in a few states in the vicinity of the Nevada Test Site;
2. thyroid doses in the ORERP study and in the NCI fallout study are assessed for representative, unspecified individuals, whereas thyroid doses to identified individuals are estimated in the Utah thyroid cohort study.

Special efforts were made to reconstruct the deposition of ^{131}I across the USA for each significant event at the Nevada Test Site. EML (Environmental Measurements Laboratory) gummed-film data collected between 1951 and 1958 from the 40 to 95 monitoring sites located throughout the country at that time were used to calculate estimates of daily depositions of ^{131}I at those sites (Beck *et al.*, 1990). Deposition of ^{131}I between monitoring sites was estimated by interpolation using precipitation data and appropriate statistical techniques, especially kriging (Gogolak *et al.*, 1988). For those tests during which the gummed-film network was not in place (i.e. during the Ranger test series in 1951 and for tests carried out after 1958), an atmospheric dispersion and deposition model was developed to provide estimates of ^{131}I during those tests in the areas of the USA where rainfall coincided with the passage of the fallout cloud (Hoecker and Machta, 1990). In addition, the ORERP estimates were used for locations in the vicinity of the Nevada Test Site.

The assessment of the thyroid doses also necessitated information on the pasture practices, milk distribution, and consumption in the continental USA in the 1950s. Special surveys, along with extensive literature searches, were carried out for that purpose (Dreicer *et al.*, 1990).

6.2.2 Local and regional doses from external irradiation

Doses from external irradiation have only been estimated by the ORERP for the populations of the Phase I and Phase II areas. Historical results for the Phase I area have been compiled and analysed by Anspaugh and Church (1986) and by Anspaugh *et al.* (1990) to estimate the cumulative collective and individual exposures by the community in that region. The results are presented in Tables 6.1 and 6.2; the total collective exposure is estimated to be about 80 000 person-R, the most important contributions being due to the test series of 1953 and 1955. Most of the exposures were less than 0.5 R (4.3 mGy) and were essentially due to short-lived radionuclides (with a half-life of less than 100 days).

Thompson *et al.* (1994) used those historical records and the published fallout patterns to prepare the Town Data Base, which provides estimates of exposure rate at H + 12 and of fallout arrival time for 74 nuclear events and 353 locations of interest in the Phase I area. A similar effort was carried out for the Phase II area and resulted in the County Data Base (Beck and Anspaugh, 1991). These two databases, used in conjunction with the radionuclide distributions published by Hicks (1981), allow estimates of the deposition density of all significant radionuclides produced by each NTS event to be made for any location in the Phase I and the Phase II areas.

Using the Town Data Base and taking into account the amount of shielding afforded by structures for nine generic lifestyles, Henderson and Smale (1990), within the framework of the ORERP, derived estimates for:

1. whole-body and skin doses due to gamma rays emitted by the radioactive materials deposited on the ground;
2. skin doses due to beta particles emitted by radioactive products deposited on the skin;
3. skin doses due to beta particles emitted by the radioactive materials deposited on the ground.

Table 6.1 Cumulative collective estimated external exposure by test series and time period (based on Anspaugh *et al.*, 1990).

Test series	Year	Collective exposure (person-R)
Ranger	1951	Small
Buster-Jangle	1951	610
Tumbler-Snapper	1952	4700
Upshot-Knothole	1953	40 000
Teapot	1955	19 000
Plumbbob	1957	11 000
Hardtack II	1958	1500
Several	1961–1963	610
Many	1963–1975	320
Total (rounded)		78 000

Table 6.2 Distribution of individual cumulative exposures during three time periods (Anspaugh *et al.*, 1990).

	Persons within exposure range		
Exposure range (R)	1951 to 1958	1961 to 1963	1963 to 1975
<0.01 to 0.1	61 000	180 000	180 000
0.1 to 0.5	80 000	480	0
0.5 to 1.0	19 000	0	0
1.0 to 5.0	20 000	0	0
5.0 to 10.0	520	0	0
10.0 to 15.0	45	0	0
Total (rounded)	180 000	180 000	180 000

Organ and fetal dose estimates were also calculated. The nine lifestyles considered included four adult lifestyles classified according to the type of occupation: homemaker, employed indoors (school teacher, sales clerk, etc.), employed outdoors (farmer, telephone linesman, etc.), and shepherd (assumed to be full time outdoors). The other five lifestyles were age-dependent: newborn (birth to 4 months), infant (4 months to 1 y), pre-school child (1 to 6 y), elementary student (6 to 12 y), and secondary student (12 to 19 y). The results show, as expected, that the greater whole-body doses from external irradiation are received by people spending all or most of their time outdoors (Henderson and Smale, 1990). For a given place of residence, however, the differences in the whole-body doses received by persons in the nine lifestyle categories are relatively small.

Estimates of bone-marrow doses for the 6507 study subjects of the Utah case-control study were also derived from the Town Data Base and from the County Data Base (Lloyd *et al.*, 1990; Stevens *et al.*, 1990; Simon *et al.*, 1995). In the conversion from exposure to dose, an age-dependent conversion factor

Table 6.3 Utah case-control study: summary of active marrow doses (mGy) for 6507 study subjects (Simon *et al.*, 1995).

	Cases	Controls	Overall
Mean dose	2.9	2.7	2.8
Median dose	3.2	3.1	3.2
Mode	3.4	3.4	3.4
Minimum	0	0	0
Maximum	26	29	29

Table 6.4 Comparison of exposure estimates (R) obtained by various methods (based on Haskell *et al.* (1994) and on Lloyd *et al.* (1990)). The exposures refer to outdoor locations and are integrated from time of arrival of fallout to infinite time.

Location	Soil Cs*	Gummed film†	Survey meter‡	Brick TL§
Ely, NV		1.3	1.7	
Hurricane, UT	4.2		5.0	6.4
Kanab, UT	0.7		2.3	2.9
La Verkin, UT	4.2		5.3	4.7
Las Vegas, NV		0.1	0.3	
Leeds, UT			5.3	2.1
Saint George, UT	3.7		5.3	6.2
Salt Lake City, UT	1.2	1.2		
Washington, UT	2.4		4.7	3.9

* Exposures based on measurements of ^{137}Cs in soil (Beck and Krey, 1983).
† Exposures based on a reappraisal of total beta deposition measured with gummed film (Beck, 1984).
‡ Exposures based on the reanalysis of survey meter readings (Anspaugh and Church, 1986); results were converted to outdoor exposures over infinite time.
§ Exposures derived from measurements of dose to quartz inclusions in bricks (Haskell *et al.*, 1994).

was used, but it was assumed that the amount of shielding afforded by structures was the same for all subjects. Summary results are presented in Table 6.3. The median dose was estimated to be about 3 mGy, both for cases and for controls. The maximum doses were 26 and 29 mGy for cases and for controls, respectively. The minimum doses were zero, as it was assumed that people who lived outside of the domain considered (i.e. part or all of Utah, Nevada, Idaho, Wyoming, Colorado, New Mexico, and Arizona) during the period of intensive fallout (from 1951 to 1958) received no dose from NTS fallout.

For the purposes of validation, brick samples were taken from structures standing since the beginning of the fallout period and were analysed by means of thermoluminescence dosimetry (Haskell *et al.*, 1994). Data shown in Table 6.4 indicate general agreement between the results obtained with this technique and with other methods used to derive the Town Data Base and the County Data Base.

6.2.3 Local and regional doses from internal irradiation

Doses from internal irradiation are mainly due to inhalation of air contaminated with radioactive materials and to ingestion of foodstuffs contaminated with radioactive materials. As far as local fallout is concerned, doses from internal irradiation are, for most organs and tissues, substantially smaller than those from external irradiation. The notable exception is the dose to the thyroid from internal irradiation, which dominates heavily over both the doses from external irradiation and the doses from internal irradiation to other organs and tissues (Whicker *et al.*, 1996).

Only the thyroid doses are considered in this section. As mentioned earlier, the thyroid doses from NTS fallout resulted essentially from the ingestion of milk contaminated with ^{131}I; other, usually less important, pathways of exposure are the consumption of leafy vegetables and eggs.

Thyroid doses from NTS fallout received by the populations of Phases I and II of the ORERP have been studied extensively. Anspaugh *et al.* (1990) compiled the estimates of thyroid doses for an infant living in St George, Utah when the event HARRY occurred on 19 May 1953. St George was one of the more heavily impacted communities and the event HARRY accounted for most of the thyroid doses in that area. The results of Anspaugh *et al.* (1990) are presented in Table 6.5. It is of interest that the historical values, which were derived from meagre information, are relatively close together, and that they compare well with the modern value of Ng *et al.* (1990), calculated for the ORERP, and with the preliminary estimate of the NCI fallout study, which was added to Table 6.5 for comparison purposes.

Estimates of individual thyroid doses for the 3545 subjects considered in the Utah thyroid cohort study are summarized in Table 6.6 (Till *et al.*, 1995). Overall mean thyroid dose for the cohort was 98 mGy, with a median dose of 25 mGy. The maximum calculated thyroid dose for any subject was 4600 mGy. For practical purposes, zero doses were assigned to 135 subjects who did not reside within the domain considered between 1951 and 1958.

The importance of the contribution of the consumption of milk to the thyroid dose is illustrated in Table 6.7. The mean dose among the subjects who did not drink milk was 12 mGy, whereas the mean dose among the subjects who drank milk was 100 mGy. Of particular importance are the 155 subjects who drank goats milk at some point in their childhood. The mean dose among this group was 300 mGy, and the highest dose (4600 mGy) was found for an individual in that group. Five subjects received an absorbed thyroid dose greater than 3000 mGy; all of them drank milk from a family owned goat. These data clearly demonstrate the importance of the goat milk pathway (Till *et al.*, 1995).

Another important feature of the Utah thyroid cohort study is the evaluation of the radioiodine exposure while *in utero*. A total of 480 subjects were

Table 6.5 Historical and current estimates of thyroid dose for an infant living in St George, Utah at the time of the event HARRY (19 May 1953) (Based on Anspaugh *et al.*, 1990).

Authors	Thyroid dose (Gy) Central estimate and range of uncertainty
Mays (1963)	0.68
Reiss (1963)	1 to 7
Pendleton *et al.* (1963)	0.84
Knapp (1963)	1.2 to 4.4
Tamplin and Fisher (1967)	0.78 (0.2 to 1.6)
Perez and Robinson (1967)	0.68
Ng *et al.* (1990)	0.66 (0.2 to 1.9)
NCI (preliminary)	0.5 (0.2 to 1.4)

Table 6.6 Summary of thyroid doses (mGy) from Utah thyroid cohort study (Till *et al.*, 1995).

	Washington County, Utah	Graham County, Arizona	Lincoln County, Nevada	Overall
Number of subjects	1896	1369	280	3545
Mean dose	170	13	50	98
Median dose	72	3.6	28	25
Minimum	0	0	0	0
Maximum	4600	450	840	4600
Mean GSD	2.7	3.0	2.7	2.8

Table 6.7 Comparison of thyroid doses (mGy) between milk drinkers and non-milk drinkers (Till *et al.*, 1995).

	Non-milk drinkers	Milk drinkers	Goats milk drinkers
Number of subjects	120	3337	155
Mean dose	12	100	300
Median dose	0.5	30	39
Maximum dose	25	4600	4600

exposed *in utero* during the fallout period. The average dose to the thyroid of the fetus was 39 mGy; this accounted, on average, for about 20% of each subject's thyroid dose (Till *et al.*, 1995).

The NCI fallout study is the only one in which thyroid doses have been estimated for each county of the USA and for each important nuclear test that was conducted at the NTS. The methodology and the data used to estimate the thyroid doses, along with illustrations of results, are available in hard-

Table 6.8 Comparison of per capita thyroid doses (mGy) summed across all NTS events.

	ORERP	NCI (1997)
St George, UT	245	113
Utah County, UT	125	62
Las Vegas, NV	113	7.8
Salt Lake County, UT	61	40
Weber County, UT	42	42
Bernalillo County, NM	24	23
Los Angeles County, CA	0.67	0.93

copy (NCI, 1997), and the detailed results for each nuclear test, several age groups, and several types of diet have been posted on the Internet (address: http:\\www.nci.nih.gov). Table 6.8 presents a comparison with ORERP's estimates of NCI calculations of per capita thyroid doses summed across all NTS events for localities in Phases I and II. The NCI results are, for most localities, similar to those of ORERP, given the large uncertainties attached to the estimation of doses received about 40 years ago. An important result of the NCI fallout study is that deposition of ^{131}I from NTS fallout occurred at one time or another in every county of the contiguous USA and that it is likely that almost all, if not all, of the people who resided in the contiguous USA between 1951 and 1958 received a thyroid dose from NTS fallout. The collective thyroid dose to the USA population from NTS fallout is estimated to be 4×10^6 person-Gy, corresponding to a per capita thyroid dose of about 20 mGy (NCI, 1997).

6.3 PACIFIC: ENEWETAK AND BIKINI (MARSHALL ISLANDS)

The USA conducted 105 tests in the Pacific Region between 1946 and 1962: 12 at Johnston Island, 42 at Enewetak (Eniwetok), 24 at Bikini (including one shot detonated 100 km west of Bikini), 24 at Christmas Island, and three elsewhere in the Pacific (US DOE, 1994; Simon and Robison, 1997). Explosive yield values are available for all but five of those tests. The total energy yield of the tests with available yields was slightly greater than 151 Mt (Simon and Robison, 1997). From the point of view of radiation doses, the tests conducted at Bikini and Enewetak Atolls in the Marshall Islands were the most important. The 24 tests conducted at Bikini Atoll had a combined yield of about 77 Mt; of special importance among those tests was the shot Bravo, a 15 Mt thermonuclear test conducted in March 1954. The 42 tests detonated at Enewetak Atoll had a combined yield of about 32 Mt (Simon and Robison, 1997).

6.3.1 Status of dose reconstruction

Dose assessments have been made for the populations of the Marshall Islands, essentially for three reasons:

1. the relocation of the 166 inhabitants of Bikini Atoll and of the 145 inhabitants of the Enewetak Atoll to other islands of the Marshall Islands archipelago before the first tests in those atolls (June 1946 at Bikini and April 1948 at Enewetak);
2. the heavy fallout in Rongelap Island and Utirik Atoll resulting from the test Bravo in March 1954;
3. the radiological study covering all atolls in the northern Marshall Islands that was commissioned by the Republic of the Marshall Islands Government in 1989.

Detailed information on events related to atomic weapons testing in the Marshall Islands can be found in Simon (1997).

6.3.1.1 Bikini and Enewetak Atolls

The Bikini Atoll consists of a number of small islands on an elliptical coral reef surrounding a lagoon. The total land area is about 6 km^2. Most of the 23 nuclear tests that took place at Bikini Atoll were conducted on barges anchored in the lagoon or on the reef. All islands were subjected to varying degrees of proximal fallout. Most of the radioactive contamination on Bikini Island was due to the Bravo test of March 1954 (Gudiksen *et al.*, 1976). A few of the individuals of the Bikini community that had been relocated in 1946 returned to live on their native islands in 1970 after a dose assessment determined that rehabitation was acceptable. However, it was later discovered that the lifestyles of the returned residents resulted in greater internal doses than anticipated (Miltenberger *et al.*, 1987). Consequently, the small Bikini community was relocated again in 1978 and, as of 1997, had not returned (Niedenthal, 1997). An extensive database of radionuclide concentrations in the atoll ecosystem has been developed and used to make dose assessments for all exposure pathways for resettlement options at Bikini Atoll (Robison *et al.*, 1996a).

The geographical structure of the Enewetak Atoll is similar to that of the Bikini Atoll. At the time of their relocation in December 1947, the Enewetak people consisted of two groups: the DRI (Displaced Resident Indigenous) Enjebi, who owned the land rights on islands in the northern half of the atoll, and the DRI Enewetak, who owned the land rights on islands in the southern half of the atoll (Robison *et al.*, 1987). An extensive radiological survey of the atoll was carried out in 1972–1973 in order to initiate preparations for the return to the atoll of its owners (US AEC, 1973). The survey results were sufficient to determine that islands in the southern half of the atoll could be resettled because the potential doses were very low; however, the potential doses for the northern half of the atoll were judged to be too high to allow resettlement of the relocated Enjebi people. Resettlement in the southern part of the atoll took place in 1979, following clean-up of the atoll and a series of new environmental radiation measurements (Robison *et al.*, 1987). A new dose assessment for the Enjebi Island was prepared in 1987 on the basis of the analysis of the ^{90}Sr and ^{137}Cs concentrations in many samples of food crops collected between 1979 and 1987 (Robison *et al.*, 1987). To date, the southern half of Enewetak Atoll is inhabited and the northern half of the atoll is only available for food gathering and visitation, and not for unrestricted living (Marelli, 1994).

The dose assessments related to the Bikini and Enewetak Atolls rely essentially on the large number of environmental radiation measurements that have been made in the last four decades. With the exception of the southern half of the Enewetak Atoll, the doses may be delivered only if the populations are resettled. Those potential doses would be primarily due to the ingestion of foodstuffs contaminated by ^{137}Cs. Strontium-90 and the transuranic radionuclides ($^{239+240}Pu$ and ^{241}Am) would contribute relatively little to the internal dose. The external dose from ^{137}Cs deposited on the ground would be the second most important pathway of exposure. Inhalation, drinking water, and marine food pathways would contribute only slightly to the dose (Robison *et al.*, 1996a).

6.3.1.2 Rongelap Island and Utirik Atoll

In the early morning of 1 March 1954, a thermonuclear device named Bravo, with an explosive yield of 15 Mt, was detonated on a tower at Bikini Atoll. An unexpected wind shear condition resulted in heavy fallout eastward rather than over open seas to the north. About 3–6 h after the explosion, the radioactive cloud deposited particulate, ash-like material on 64 inhabitants of Rongelap, located about 200 km eastward of the detonation site, on 18 other Rongelapese who were fishing and gathering copra at the nearby Ailingnae Atoll, and on 23 fishermen on a Japanese vessel, the *5th Lucky Dragon* (Conard, 1980; Lessard *et al.*, 1985; Robbins and Adams, 1989). Slightly further east, 28 American servicemen on Rongerik Atoll were exposed. About 20 h after the explosion, the radioactive cloud reached Utirik, located about 600 km from the detonation site, where 167 people were affected by a much decreased, invisible fallout (Robbins and Adams, 1989; Conard, 1992). Within a few days, the Marshallese were evacuated from Rongelap, Ailingnae, and Utirik Atolls to Kwajalein Atoll for clinical evaluation and treatment (Cronkite *et al.*, 1997). When radiation levels on the residence islands decreased to acceptable levels, the people were allowed to return. The residents of Utirik returned to their atoll in June 1954. The residents of Rongelap Atoll were returned to their homeland in June 1957 with restrictions imposed as to which islands could be visited and which could be used for gathering food. However, in 1985, the Rongelap Community, concerned about the safety of their people, enlisted the assistance of Greenpeace to evacuate them from their islands to an island in the Kwajalein Atoll (Marelli, 1994). Finally, the 23 fishermen of the *5th Lucky Dragon*, their radiation exposure unbeknown to the authorities, returned to their Japanese harbour after 14 days of navigation and were hospitalized in Tokyo (Conard *et al.*, 1980).

Assessments of the doses received before evacuation have been made on the basis of limited personnel monitoring (radiochemical analyses of urine specimens and whole-body gamma spectrographic analyses) combined with the results of radiation measurements on the affected Atolls (Conard *et al.*, 1980). The doses received before evacuation were essentially due to external irradiation from short-lived radionuclides (with radioactive half-lives of up to a few days) present in the radioactive cloud or deposited on the ground, and to internal irradiation caused by the ingestion of short-lived radioiodines deposited on foodstuffs and on cooking utensils (Lessard *et al.*, 1985).

The doses received after the Rongelap and Utirik people returned to live on their home islands are due to radionuclides with relatively long half-lives (principally ^{60}Co, ^{65}Zn, ^{90}Sr, and ^{137}Cs). Those doses were assessed on the basis of a large number of measurements on people and in the environment (Conard *et al.*, 1980). The potential exposures that could be incurred if the Rongelap Atoll were resettled in the future have also been estimated on the basis of extensive radiological surveys (Robison *et al.*, 1994).

6.3.1.3 Other Marshall Islands

Even though several radiological surveys and dose assessments had been sponsored or conducted by the US Government in the most affected islands and atolls, as well as in the northern Marshall Islands, the entire nation of the Marshall Islands had never been evaluated until the Republic of the Marshall Islands (RMI) commissioned in 1989 an independent radiological monitoring programme—the Nationwide Radiological Study—to determine the degree of deposition and the geographical extent of weapons test fallout over its nation, the total land area of which is 180 km^2, divided among 29 atolls and five separate islands, distributed over 6×10^5 km^2 of ocean (Simon and Graham, 1994a,b, 1995; 1996). The Nationwide Radiological Study was completed in 1994. In that Study, all 29 atolls in the Marshall Islands were surveyed. Over 1300 *in situ* gamma spectrometry measurements were made and over 800 soil surface samples were analysed for gamma emitters (^{137}Cs, essentially) and

$^{239+240}Pu$. Native fruits, in particular coconut, were also sampled extensively. External and internal dose assessments were made on the basis of those measurements (Simon and Graham, 1997).

6.3.2 Local and regional doses from external irradiation

6.3.2.1 Bikini and Enewetak Atolls

External exposure calculations related to the eventuality of a resettlement of the Bikini Atoll were made by Robison *et al.* (1996a). These calculations are based on:

1. measurements of exposure rates made on Bikini Island in 1978 and 1993—the values are decay corrected to 1999, date assumed for the resettlement;
2. assumed distributions of time indoors and outdoors, based on observations and on discussions with Marshallese people.

Assuming that:

1. 10 h day^{-1} are spent in the house where the average exposure rate is 1.6 R h^{-1};
2. 9 h day^{-1} are spent around the house and village area where the average exposure rate is 8.5 R h^{-1};
3. 3 h day^{-1} are spent in the interior region of the island where the average exposure rate is 19 R h^{-1};
4. 2 h day^{-1} are spent on the beach or lagoon where the average exposure rate is 0.1 R h^{-1};

the whole-body dose from external irradiation arising from ^{137}Cs released during nuclear weapons testing is estimated to be 0.42 mSv y^{-1} in 1999 (Robison *et al.*, 1996a). Doses for years other than 1999 can be estimated assuming an annual decrease of about 2%. The effective dose accumulated over 70 y would be 15 mSv (Robison *et al.*, 1996a).

Similar calculations were made for Enjebi Island in the northern part of the Enewetak Atoll on the basis of measurements made in 1979 after debris, bunkers, and some soil had been removed (Robison *et al.*, 1987). The average annual whole-body dose from ^{137}Cs was estimated to be 0.22 mSv y^{-1} for 1990 (Robison *et al.*, 1987); the corresponding value for the year 1999 would be 0.18 mSv y^{-1}. The effective dose accumulated over 70 y would be approximately 8 mSv (Robison *et al.*, 1987). A more recent evaluation by Simon and Graham (1995) yielded approximately the same value for the median annual whole-body dose in Enjebi Island, and a value of 0.094 mSv y^{-1} (in 1994) for the entire northern part of the Enewetak Atoll. In comparison, the median value

Table 6.9 Estimated whole-body doses from external irradiation resulting from the Bravo shot. The doses are calculated from the onset of fallout until evacuation time (Lessard *et al.*, 1985).

	Estimated whole-body dose (Gy)	
Location	Sondhaus and Bond, 1955	Lessard *et al.*, 1985
Rongelap	1.75	1.9
Ailingnae	0.69	1.1
Rongerik	0.78	0.81
Utirik	0.14	0.11

for the annual whole-body dose for the entire southern part of the Marshall Islands, which was resettled in 1979, was estimated by Simon and Graham (1995) to be 0.0056 mSv y^{-1} in 1994.

6.3.2.2 Rongelap Island and Utirik Atoll

Dose estimates from external irradiation are available for:

1. the early exposures (before evacuation or before the Japanese fishermen returned
2. dose evaluation made by Lessard *et al.* (1985) on the basis of measurements of the radionuclide composition of fallout and of exposure rates. Results are presented in Table 6.9; the two sets of values are in fairly good agreement. The whole-body doses are estimated to have been of the order of 1 Gy at Rongelap, Ailingnae and Rongerik, and about 0.1 Gy at Utirik.

The 23 Japanese fishermen of the *5th Lucky Dragon* were exposed to heavy fallout that was deposited on the entire boat (deck, cabins, etc.). During the most intensive fallout period, the fishermen could not keep their mouths and eyes open, and fallout deposited on the deck was thick enough to show footprints (Conard *et al.*, 1980). The doses from external irradiation due to radioactive materials deposited on the boat were estimated to range from about 1.7 to 6 Gy, depending on individual behaviour in the boat and the contamination of the cabin. Those doses were received during the 14 days separating the onset of fallout and the return to harbour; half or more of the external doses were received during the first day after the onset of fallout (Conard *et al.*, 1980).

Residual Exposures Whole-body doses from external irradiation that were received up to 1979 by adults who returned to their islands in the 1950s are estimated to amount to about 20 mGy for Rongelap and 30 mGy for Utirik (Conard *et al.*, 1980).

Potential Exposures The whole-body doses from external irradiation that would be incurred if the Rongelap Island, located in the southern part of Rongelap Atoll, was resettled have been estimated by Robison *et al.* (1994) to be essentially due to ^{137}Cs and to amount to 0.11 mGy y^{-1} during the first year of resettlement (assumed to be 1995) and to accumulate to 39 mGy over a 70-y time period. Annual doses for other years of resettlement can be estimated using a decay rate of about 2% per year.

There is a significant difference between the southern half and the northern half of Rongelap Atoll. The concentration of radionuclides in soil and vegetation is about a factor of five lower in the southern half of the atoll. Contamination levels in the northern half of Rongelap are more similar to Bikini Island because the centreline of the fallout pattern crossed the northern half of Rongelap Atoll (Robison *et al.*, 1996b). Resettlement of islands located in the northern part of Rongelap Atoll would result in doses higher than those estimated for Rongelap Island.

6.3.2.3 Other Marshall Islands

The whole-body doses from external irradiation in the remainder of the Marshall Islands were estimated by Simon and Graham (1994a) to be, on average, much smaller than those obtained for Bikini, Enewetak, Rongelap, Rongerik, Ailingnae, and Utirik Atolls. Current average whole-body dose rates are estimated to be less than 0.01 mSv y^{-1} in the remainder of the Marshall Islands.

6.3.3 Local and regional doses from internal irradiation

6.3.3.1 Bikini and Enewetak Atolls

Dose assessments are available for:

1. the people who resettled Bikini between 1971 and 1978, and the southern part of Enewetak Atoll since 1979;
2. the people who could resettle Bikini and the northern part of Enewetak Atoll in the future.

For those populations who were not exposed to early fallout, internal effective doses resulting from nuclear testing in the Marshall Islands contribute about 90% to the total effective dose from external and internal irradiation. These internal doses are mainly due to the consumption of foodstuffs contaminated with ^{137}Cs; their magnitude vary according to the origin of the consumed foodstuffs.

Table 6.10 Estimates of 70-y effective doses for Bikini Island residents for current island conditions when imported foods are available ('mixed diet') and when only local foods are consumed ('local diet') (Robison *et al.*, 1996a).

	70-y effective dose (mSv)	
Mode of exposure	'Mixed diet'	'Local diet'
Internal		
Ingestion		
^{137}Cs	130	530
^{90}Sr	1.5	10
$^{239+240}Pu$	0.051	0.44
^{241}Am	0.075	0.26
Inhalation		
$^{239+240}Pu$	0.23	0.23
^{241}Am	0.15	0.15
External	15	15
Total (rounded)	150	560

Bikini Atoll Greenhouse *et al.* (1980) calculated the total whole-body doses received by the Bikini residents between 1971 and 1978; they estimated that the average whole-body doses, from external and internal irradiation, were 2–3 mSv y^{-1}.

The internal doses that would be delivered to people resettling Bikini Island in 1999 were estimated by Robison *et al.* (1996a), using extensive radionuclide concentration data derived from analysis of food crops, ground water, cistern water, fish and other marine species, animals, air, and soil. Two types of diet were considered: one with local foods only, the other with a mixture of local foods (60% of the diet) and imported foods (40% of the diet). Using the assumption that only local foods would be consumed ('local diet'), the maximum annual effective dose would be about 15 mSv y^{-1}, and the effective dose accumulated over 70 y would be 560 mSv (Robison *et al.*, 1996a). If a mixture of local and imported foods ('mixed diet') is assumed, the estimated doses are lower: the maximum annual effective dose would be about 4.0 mSv y^{-1}, and the effective dose accumulated over 70 y would be 150 mSv. Table 6.10 presents the contributions of inhalation and ingestion and of several radionuclides to the internal 70-y effective doses estimated assuming a 'local' and a 'mixed' diet; doses from external irradiation are added for comparison purposes. It is clear from Table 6.10 that most of the estimated doses arise mainly from ^{137}Cs uptake via the terrestrial food chain, and that ^{90}Sr contributes very little to the effective dose via ingestion; this is in contrast to what is generally observed in continental, silica-based soils, for which the uptakes of ^{90}Sr and of ^{137}Cs are of the same order of magnitude. It is worth noting that a comparison, for the exposed populations of Rongelap and Utirik, of the estimated ^{137}Cs derived from assumed dietary intakes and from measurements by the whole-body counting method show that the two sets of values are in good agreement if it is assumed that the diet includes both local and imported foods (Robison and Casper Sun, 1997).

Enewetak Atoll Similar calculations were made for Enjebi Island in the northern part of the Enewetak Atoll (Robison *et al.*, 1987). Using the assumption that only local foods would be consumed ('local diet'), the maximum annual effective dose would be about 3.2 mSv y^{-1}, and the effective dose accumulated over 70 y would be 115 mSv (Robison *et al.*, 1987). If a 'mixed diet' is assumed, the maximum annual effective dose is estimated to be about 1.5 mSv y^{-1}, while the effective dose accumulated over 70 y would be 54 mSv. Simon and Graham (1995) used different dietary assumptions to estimate effective doses from internal irradiation for the northern and the southern part of Enewetak Atoll; for persons eating a diet of about 18% locally grown foods and 82% imported foods, they estimated median annual effective doses of about 0.2 mSv y^{-1} (in 1994) for the northern part of the Enewetak Atoll, and of about 0.01 mSv y^{-1} (in 1994) for the southern part of the Enewetak Atoll. The corresponding values for persons eating a diet of about 75% locally grown foods and 25% rice with no other imported food would be about 1 and 0.05 mSv y^{-1}, respectively.

6.3.3.2 Rongelap Island and Utirik Atoll

Dose estimates from internal irradiation are available for:

1. the early exposures (before evacuation or before the Japanese fishermen returned to harbour);
2. for the residual exposures received by the people who resettled Rongelap between 1957 and 1985, and Utirik Atoll since June 1954;
3. for the potential exposures that could be incurred if the Rongelap Atoll were resettled in the future.

Early Exposures Because of the evacuation of the most affected populations within a few days after the detonation, the doses from internal irradiation are essentially due to the inhalation and ingestion of short-lived radionuclides. The most important of those are the radioiodines, which concentrate in the thyroid gland, and the radiotelluriums, which decay into radioiodines. A thorough evaluation of the thyroid doses was performed by Lessard *et al.* (1985). That evaluation is based on the measurement of ^{131}I in a pooled sample of urine collected on the 17th day post-detonation from 64 persons evacuated from

Table 6.11 Estimated intakes of radiotelluriums and of radioiodines, in MBq, resulting from the shot Bravo. The intakes are calculated from the onset of fallout until evacuation time (Lessard *et al.*, 1985; Robbins and Adams, 1989).

		Intake* (MBq)		
Radionuclide	Half-life (h)	Rongelap	Ailingnae	Utirik
^{131m}Te	29	1.6–3.0	0.5–0.9	0.3–0.6
^{132}Te	78	10–20	2.7–4.8	2.1–4.1
^{131}I	193	2.0–3.6	0.4–0.7	0.5–0.9
^{132}I	2.3	11–21	2.5–4.4	2.2–4.1
^{133}I	20.8	44–77	11–21	5.9–12
^{134}I	0.8	25–44	16–29	–
^{135}I	6.7	70–130	25–44	2.9–5.2

* The intake varies with age; the lower value is for 1-y olds and the higher is for adults.

Rongelap Island. Complementary measured or derived information include the initial time of arrival of fallout and its duration, the size and radionuclide composition of the fallout, and dietary and living patterns. The intakes of radiotelluriums and of radioiodines, estimated for the atolls of interest from the onset of fallout until evacuation time, are mainly due to the contamination of foodstuffs and of cooking utensils, as the preparation and consumption of food in the open was a common practice among the Marshallese people. Estimated values of intakes are presented in Table 6.11. The intakes of all radioiodines and radiotelluriums are estimated to have been higher at Rongelap than in the other atolls. The intake of ^{131}I, a radionuclide with a relatively long half-life of 8 days, is greater at Utirik than at Ailingnae, but the situation is reversed for all other radionuclides shown in the table, which have a shorter half-life than ^{131}I. This is due to the fact that it took about 20 h longer for the radioactive cloud to reach Utirik than to reach Ailingnae, allowing the short-lived radioiodines to decay substantially during that period of time. The estimated thyroid doses for the evacuated people of the three atolls are presented in Table 6.12; there is a strong variation as a function of age, with maximum values for the infants, who have a smaller thyroid than older children and adults. About half of the thyroid dose was due to the intake of ^{133}I, whereas ^{131}I contributed 10–15% of the thyroid dose at Rongelap and Ailingnae, and about 20% at Utirik (Lessard *et al.*, 1985). The maximum thyroid doses are estimated to have been four times the average (Lessard *et al.*, 1985).

The thyroid doses from ^{131}I that were received by the 23 Japanese fishermen of the *5th Lucky Dragon* were estimated by external counting to range from 0.2 to 1.2 Gy (Conard *et al.*, 1980). In addition to ^{131}I, other short-lived radioiodines contributed to the thyroid dose. Assuming that the fishermen inhaled radioiodines for 5 h after the detonation, the total thyroid dose was estimated to have been about 0.8 to 4.5 Gy (Conard *et al.*, 1980).

Table 6.12 Estimated average thyroid doses* from internal irradiation due to the shot Bravo (Lessard *et al.*, 1985).

Age	Average thyroid doses from internal irradiation (Gy)		
	Rongelap	Ailingnae	Utirik
Adult male	10	2.8	1.5
Adult female	11	2.9	1.6
Fourteen-year old	14	4.1	2.2
Twelve-year old	16	4.5	2.4
Nine-year old	20	5.4	3.0
Six-year old	24	6.4	3.4
One-year old	50	13	6.7
Newborn	2.5	–	0.5
In utero, 3rd trimester	6.8	–	1.0
In utero, 2nd trimester	–	4.9	2.6

* The maximum thyroid doses are estimated to be four times greater than the average thyroid doses.

Residual Exposures Whole-body doses from internal irradiation that were received up to 1979 by adults who returned to their islands in the 1950s are estimated to amount to about 20 mSv for Rongelap and 140 mSv for Utirik (Conard *et al.*, 1980). Most of the whole-body dose at Utirik was contributed by ^{65}Zn, a radionuclide with a radioactive half-life of 245 days. Rongelap was resettled three years after Utirik, allowing time for ^{65}Zn to decay to very low levels before Rongelap was resettled. Consequently, the internal doses received by the people who resettled Utirik are substantially greater than those received by the people who resettled Rongelap, even though the fallout levels at Utirik were lower than at Rongelap.

Potential Exposures The effective doses from internal irradiation that would be incurred if the Rongelap Island had been resettled in 1995 have been estimated by Robison *et al.* (1994) to be essentially due to the ingestion of foodstuffs contaminated with ^{137}Cs (Table 6.13). Using the assumption that only local foods would be consumed ('local diet'), the maximum annual effective dose would be about 0.48 mSv y^{-1}, and the effective dose accumulated over 70 y would be 18 mSv (Robison *et al.*, 1994). If a 'mixed diet' is assumed, the maximum annual effective dose is estimated to be about 0.26 mSv y^{-1}, and the effective dose accumulated over 70 y would be 9.7 mSv. Simon and Graham (1994a,b) used different dietary assumptions to estimate effective doses from internal irradiation: for persons eating a diet of about 18% locally grown foods and 82% imported foods, they estimated median annual effective doses of about 0.3 mSv y^{-1} (in 1994); the corresponding value for persons eating a diet of about 75% locally grown foods and 25% rice with no other imported food would be about 1 mSv y^{-1}.

Table 6.13 Estimates of 70-y effective doses for Rongelap Island residents for current island conditions when imported foods are available ('mixed diet') and when only local foods are consumed ('local diet') (Robison *et al.*, 1994).

	70-y effective dose (mSv)	
Mode of exposure	'Mixed diet'	'Local diet'
Internal		
Ingestion		
^{137}Cs	5.3	13
^{90}Sr	0.15	0.48
$^{239+240}Pu$	0.060	0.23
^{241}Am	0.057	0.10
Inhalation		
$^{239+240}Pu$	0.13	0.13
^{241}Am	0.08	0.08
External	3.9	3.9
Total (rounded)	9.7	18

6.3.3.3 *Other Marshall Islands*

The effective doses from internal irradiation that are currently received in the remainder of the Marshall Islands were estimated by Simon and Graham (1994a) to be, on average, less than 0.1 mSv y^{-1} for persons eating a diet of about 75% locally grown foods and 25% rice with no other imported food. Cumulative effective doses incurred between 1959 and 1994 would be, on average, less than 5 mSv (Simon and Graham, 1994a). Almost all of the effective doses is due to ^{137}Cs.

6.4 SEMIPALATINSK (KAZAKHSTAN)

The Semipalatinsk Test Site (STS) is situated in Kazakhstan, at a distance of about 200 km from the border with the Russian region of Altai. The former USSR began atmospheric tests of nuclear devices at the Semipalatinsk Test Site on 29 August 1949. During the period of nuclear weapons testing, 456 tests of nuclear devices were carried out at that site (Mikhailov, 1997). There were 88 atmospheric tests and 30 surface tests. The last atmospheric test was conducted on 24 December 1962. The first ground thermonuclear test on 12 August 1953 (400 kt) and the high-altitude nuclear test on 22 November 1955 (1.6 Mt) had the greatest yields. The total energy yield of atmospheric nuclear explosions at Semipalatinsk Test Site was about 6.6 Mt (Dubasov *et al.*, 1994).

Following the signing of the Limited Test Ban Treaty (Moscow, 1963), which banned nuclear tests in the atmosphere, open space and under water, exclusively underground tests in galleries and mines in mountain rocks were conducted at the STS. More than 300 devices were exploded underground including four excavation explosions of which two cratering explosions took place on 15 January 1965 (140 kt) and on 14 October 1965 (about 1 kt) (Loborev *et al.*, 1995; Mikhailov, 1997). The last nuclear test conducted at the STS occurred on 19 October 1989.

The main contributions to the local and regional environmental radioactive contamination are attributed to the atmospheric nuclear tests that were conducted on 29 August 1949 (22 kt), 24 September 1951 (38 kt), 12 August 1953 (400 kt), 16 March 1956 (14 kt) and 24 August 1956 (27 kt). These tests are estimated to have contributed more than 95% of the expected collective dose of the exposed population living close to the STS (Dubasov *et al.*, 1994a).

Underground tests, in comparison, have a small environmental and health impact. The radiation impact of underground tests could result from the leakage into the atmosphere of noble radioactive gases from the excavated underground cavities produced by the tests. Due to the mixture with atmospheric air, however, concentrations of radioactive noble gases rapidly decreased with distance and, as a rule, remained undetected with radiation survey instruments beyond the boundaries of the testing grounds of the STS. Those releases of radioactive noble gases resulted in negligible radioactive fallout on the ground surface. Thus, underground nuclear tests produced practically no impact on the environment and on the health status of the population residing close to the STS. An exception must be made for four experimental cratering detonations performed within the scope of a programme on the use of nuclear tests to develop the country's economy on 15 January 1965 (140 kt), 14 October 1965 (1.1 kt), 21 October 1968 (0.24 kt) and 12 November 1968 (0.24 kt) (Andryshin *et al.*, 1996).

6.4.1 Status of dose reconstruction

Usually after the tests, measurements of gamma radiation levels were conducted around the STS. In some cases these measurements extended as far away as 1000 km (Anonymous, 1994). In the former USSR regime, until 1991, results of these measurements were strictly classified and kept in archives of the Ministry of Defense and other State Departments (the State Hydrometeorology Committee, and the Federal Agency of Medical–Biological and Extreme Problems of the Ministry of Public Health). Nevertheless in the population of the regions adjoining the Semipalatinsk Test Site there was an awareness of a potentially negative health impact of the tests that were conducted at the Semipalatinsk Test Site. These feelings became public during the late 1980s, and, more widely, in the early 1990s.

In 1993 a resolution of the Government of the Russian Federation marked the beginning of a Federal programme on the rehabilitation of the population and on social and economic development of settlements of the Altai Region exposed to nuclear tests at the STS. The scope and character of rehabilitative measures applied to certain groups of individuals is specified in regulatory texts and is expressed in terms of effective dose (Gordeev, 1995c). All persons exposed to nuclear tests at the STS are divided into two groups:

1 individuals with a total effective dose greater than 250 mSv, as well as their children and grandchildren;
2 individuals with effective doses lower than 250 mSv but greater than 50 mSv together with their children and grandchildren.

Persons assigned to the first group are entitled to compensation measures whereas members of the second group members benefit from general social measures. Ordinary sanitary and hygienic control of the health status is administered to subjects exposed to doses less than 50 mSv.

A law adopted in Russia in 1995 extended social benefits and compensations to the population exposed due to place of residence when the nuclear detonations were performed. Thus, the problem of dose reconstruction for irradiated individuals primarily originated within the scope of a social problem to identify the groups of residents that were exposed to nuclear tests.

Within the scope of the scientific direction of the Federal programme on rehabilitation of the population and social and economic development of settlements of the Altai Region exposed to nuclear tests, a number of well-known retrospective population dose reconstruction methods were applied: the mathematical modelling of fallout formation and of further migration of radionuclides in the environment (Loborev *et al.*, 1994); use of radiation survey measurements conducted immediately after the tests (Loborev *et al.*, 1994; Gordeev *et al.*, 1994, 1995a); measurements by electron paramagnetic resonance (EPR) of radiation effects in tooth enamel of exposed individuals (EPR dosimetry) and of thermoluminescence (TL) of quartz–ceramic materials (TL dosimetry) (Gordeev *et al.*, 1995b); and measurement of residual activities of long-lived radionuclides, in particular, ^{137}Cs, in the soil (Lagutin *et al.*, 1994).

Presently, there are several groups of Russian experts that are actively involved in the reconstruction of doses received by the populations of the Altai region as a result of nuclear explosions at the Semipalatinsk Test Site. The most important groups are those from the Moscow Institute of Biophysics (IBP) and from the Central Physical–Technical Institute (CPTI) of the Russian Ministry of Defense. Although both groups assess the doses from external and from internal irradiation, the group from the Central Physical–Technical Institute concentrates on the atmospheric transport of radioactive particles and develops mathematical models of atmospheric dispersion of radioactive particles and of their deposition on the ground. The main concern of the group from the Institute of Biophysics is the estimation of internal radiation doses resulting from the deposition of radioactive materials on the ground. Their models simulate the transport of radioactive particles in soil, vegetation and animals, the activity intake by human beings, and, finally the doses from internal irradiation.

6.4.2 Local and regional doses from external irradiation

The essence of mathematical modelling as a method of population dose reconstruction lies in the use of a set of physical and mathematical models that describe all stages of transformation of radioactive products in space from the moment of the explosion to the formation of external individual doses. Such a set, ordinarily, comprises the following mathematical models and methods:

1. a physico-mathematical model of the formation of the isotope content and radioactive characteristics of radioactive particles;
2. a model of a volumetric source of the contamination of the environment, which is a sum of expressions that describe the distribution of radioactive particles by size and space of the cloud when the cloud stabilizes in the atmosphere;
3. a physico-mathematical model of the distribution of radioactive admixtures in the atmosphere;
4. a method of calculation of dose fields above a contaminated area.

The method described was established by a group of scientists from the Central Physical–Technical Institute of the Russian Ministry of Defense (Loborev *et al.*, 1994b). This group proposed a model for the formation of the isotope content of radioactive particles that described processes of the formation of two types of particles.

1. Particles formed due to the intensive heat and mechanical impact of the detonation on the soil covered by the fireball at initial stages of its development. The distribution of the mass of these particles by size is approximated by a logarithmic normal law with parameters that depend upon the nature of the ground surface (granite, clay, sand).
2. The formation of particles conditioned by mechanisms associated with the condensation of soil vapours and vapourized constructional materials of the ammunition and fission products of the nuclear fuel. The distribution of these particles by size in accordance with the available material is also approximated by a logarithmic normal law, with the median diameter of the distribution and the mean squared deviation of the diameter's logarithm being ~ 1.7 mkm and ~ 0.15, respectively.

In the case of ground tests at given heights $-0.3 < \bar{H} = H/q^{1/3} < 0.3$ (H is the absolute height of the test, m; q is the yield of the test, t), in order to represent the formation of particles, an unbalanced molecular–kinetic model is used. The model makes use of a complex approach to the problem under study, the general features of which are described by Freiling *et al.* (1968). A closest analogue of the model was published by Krasilov *et al.* (1971) with its complete description given in a book that was published recently in Russia (Bocharov *et al.*, 1997).

In the case of detonations at given heights $\bar{H} > 0.3$ m $t^{-1/3}$, the calculation of the isotope content is performed on the basis of a half-empirical fractionation scheme, which represents the sum of models known in the literature as models of 'the distribution by radius degrees' (Freiling, 1961) and 'the thermodynamic balance' (Miller, 1953; Izrael, 1973).

The model of a volumetric source of radioactive contamination of the environment is based on results of modelling the development of the cloud from the test using numerical methods and actual data obtained by radiation survey using aeroplanes to monitor clouds from nuclear explosions. In accordance with the data, the distribution of particles in the radioactive cloud and the size of particles is approximated using the following laws:

1. in the horizontal plane by a circular normal law with a height-dependent variation;
2. in the height of the cloud by a normal law with parameters (the vertical variation, the position of the center of the mass) that depend upon the yield and type of the detonation;
3. in the size of particles by a logarithmic normal law with a median value that depends exclusively upon the height (decreases with the height by an exponential law), with constant decrease.

The distribution in the atmosphere and the fallout of radioactive particles under the influence of air currents, atmospheric turbulence and gravity are described by a half-empirical equation of turbulent diffusion. The method applied to solve the problem was a system of equations that represent space and time evolution of the distribution the mass concentration of particles, numerical solutions for different fractionations. The density of radioactive fallout is found by summing all size fractions of particles. A detailed description of the mathematical model of fallout of radioactive particles following a nuclear test is given by Bocharov *et al.* (1997).

Based on the models described above, densities of the contamination of the surface with certain radionuclides and the fallout dispersion content present initial data for calculations of external exposures of an individual and the intake of radionuclides with contaminated air and foodstuffs of local origin. To estimate oral intakes a method of accumulation coefficients described in the literature (Gusev *et al.*, 1991) is applied. Adjustments concerning conditions of major agricultural work and a migration chain of radionuclides characteristic for the area under study are made to the method adopted. The transfer from intakes of radionuclides to internal doses is carried out by means of the dose coefficients recommended by the ICRP.

Specialists from the Central Physical–Technical Institute (CPTI) of the Russian Ministry of Defense (Loborev *et al.*, 1994) and the Moscow Institute of Biophysics (IBP) (Gordeev *et al.*, 1994, 1995a,d) proposed methods of population dose reconstruction based on the radiation survey data. Mathematical models at three levels form the foundation of the methods adopted. Models are intended for the calculation of:

1. radiation situation parameters which determine external and internal exposure (absorbed doses in the air from the radioactive fallout and the cloud, the concentration of radioactive products in the above-ground air, the density of soil contamination with certain radionuclides when fallout stopped);
2. parameters of the radiation and hygiene situation (contamination of the vegetation, meat, milk and other products of local origin);
3. effective doses of external and internal exposures as well as doses in critical human organs.

The methods developed (Gordeev *et al.*, 1994, 1995a,d; Loborev *et al.*, 1994) utilize, on the whole, similar input information. Their main component is the level of gamma radiation measured by the radiation survey above the area of radioactive fallout. The methods differ in ways of determining derived parameters that depend on the detonation's characteristics and yield: the CPTI's method uses the mathematical models described above (Loborev *et al.*, 1994), whereas that of the IBP applies empirical formulae derived by processing experimental data.

The following expressions are proposed for calculations of the density of soil contamination, inhalatory and oral intakes of radioactive products:

$$\sigma_i = \frac{P_\gamma \cdot \delta(\bar{d})}{k \cdot k_\gamma} \cdot r_{i,\mathrm{Cs}}(\bar{d}) \cdot \frac{\lambda_i Y_i}{\lambda_{\mathrm{Cs}} Y_{\mathrm{Cs}}} \cdot \exp\{-\lambda_i(t_1 - t_*)\}, \tag{6.1}$$

$$G_i^{\mathrm{ing}} = \sigma_i V_i \frac{\displaystyle\int_0^\infty a_i^\Sigma(d) k_i^b(d) \alpha_a(d) \frac{f_N(d)}{\beta_0 + W(d)} \delta d}{\displaystyle\int_0^\infty f_N(d) a_i^\Sigma(d) \delta d} \tag{6.2}$$

$$G_{ij} = \sigma_i H_j k_{ij}^0 \frac{\displaystyle\int_0^\infty f_N(d) \beta_j(d) k_i^b(d) a_i^\Sigma(d) \delta d}{\displaystyle\int_0^\infty f_N(d) a_i^\Sigma(d) \delta d} \tag{6.3}$$

where σ_i is the density of soil contamination with the *i*th radionuclide when fallout t_1 stopped; G_i^{ing} is the value of inhalatory intake of the *i*th radionuclide during fallout formation; G_{ij} is the intake of the *i*th radionuclide with the *j*th foodstuff in case of the aerial contamination of agricultural products; P_γ is the yield of gamma radiation from the radioactive cloud above ground at a time t_* after a test; λ_i and Y_i are the constant of nuclear fission and the cumulative output during the fission of an ith radionuclide; λ_{Cs} and Y_{Cs} are analogous values for ^{137}Cs; $\delta(\bar{d})$ is the relative contribution of ^{137}Cs into a total gamma-equivalent of a mixture of fission products which are contained in a particle of a diameter $\bar{d}$; $\bar{d}$ is the median size of particles which formed fallout at the point under study; k_γ is the ionizing gamma-constant of ^{137}Cs (k_γ = 3.242 R m^{-2}/(mCi h^{-1})); k is the stretch coefficient—if $[P_\gamma]$ = R h^{-1}, $[\sigma_i]$ = Ci m^{-2}, $[k_\gamma]$ = R cm^{-2}/(mCi h^{-1}), then $k \approx 3.3$; $r_{i,Cs}(\bar{d})$ is the fractionation coefficient of an ith radionuclide to ^{137}Cs in a particle of size $\bar{d}$; V_l is the rate of human lung ventilation; H_j is the annual consumption of a jth product; k^0_{ij} is the coefficient of the transition of an ith radionuclide from fallout into a jth food product provided its complete biological availability and a maximum retention of particles by the vegetation; β_0 is the rate of a 'dry' precipitation of an imponderable admixture on the surface (β_0 = 0.036 km h^{-1}); $f_N(d)$ is the distribution of radioactive fallout particles in a given area by size; $W(d)$ is the rate of the gravitational precipitation of a particle of diameter d; $a^{\Sigma}_i(d)$ is the content of an ith radionuclide in the volume and on the surface of a particle of diameter d; $k^b_i(d)$ is the coefficient of biological availability of an ith radionuclide—in order to estimate the value of the coefficient it is recommended to apply the following expression

$$k^b_i = \frac{a^s_i(d)}{a^{\Sigma}_i(d)}, \tag{6.4}$$

where $a^s_i(d)$ is the content of an ith radionuclide on the surface of a particle of diameter d; $\beta_j(d)$ is the function that represents an expression of the coefficient of the primary aerial contamination of the vegetation from the size of fallout particles—according to Vlasov *et al.* (1994)

$$\beta_j(d) = \begin{cases} 1, d \le d_0, \\ (d/d_0)^{-n}, d > d_0, \end{cases} \tag{6.5}$$

where n_j is the coefficient dependent upon the type of the vegetation and the stage of its development (n_j = 0.8. . .1.1) and d_0 = 40. . .50 μm; and $\alpha_a(d)$ is the coefficient of aerosol aspirations, with

$$\alpha_a(d) = \begin{cases} 1, d \le 50\ \mu\text{m} \\ 0, d > 50\ \mu\text{m} \end{cases} \tag{6.6}$$

Equation (6.1) reflects a theoretical connection between the yield of gamma radiation above an infinite flat source with an even distribution of the activity and radiation characteristics of the source. Equation (6.2) reflects a connection between the fallout density and the concentration of radioactive products weighted in the near-ground air during the passage of the cloud. Equation (6.3) is the result of the method of coefficients, with adjustments made for the dependency of coefficients of the primary aerial contamination on the size of fallout particles.

Radiation characteristics of particles ($a_{\gamma}^{\Sigma}(d)$, $a_{\gamma}^{i}(d)$, $\delta(d)$) in equations (6.1) to (6.3), coefficients of fractionation of radionuclides ($r_{i,\mathrm{Cs}}(d)$) as well as a characteristic of particle fallout distribution in an area ($f_N(d)$, $\bar{d}$), and the time t_1 of their fallout, are derived with the help of the models described above.

Formulae described below form the basis of the dose reconstruction method (Gordeev *et al.*, 1994, 1995a,d). For the relationship between the surface density of soil contamination, σ, and the level of gamma radiation, P_{γ},

$$\sigma_{\Sigma}(t) = \alpha_{\Sigma} P_{\gamma}(t)$$

is used for the total of fission products and

$$\sigma_i(t = 24) = \alpha_i P_{\gamma}(t = 24)\ X_p^{\beta_i}$$

is used for individual radionuclides, where α_{Σ}, α_i, β_i are empirical coefficients $P_{\gamma}(t = 24)$ is the level of gamma radiation calculated from the moment it was measured to 24 h after the test and X_p is the distance estimated by the formulae

$$X_p = \frac{W_{50} X}{H_{\max} \bar{V}}$$

with X the distance from the centre of a test to the given settlement taken along the route of the radioactive cloud, W_{50} the rate of the gravitational precipitation of aerosol particles with an aerodynamic diameter $d = 50\ \mu$m, $H_{\max}$ the maximum height of the lift off of the radioactive cloud when it stabilized in the atmosphere and $\bar{V}$ the average speed of the wind from maximum altitude to the ground surface.

The distance to the centre function of the proportion of radioactive fallout products on the surface for particles of diameter $d < 50\ \mu$m is determined by

$$\eta_{d<50} = 1 - \left[1 - 0.6(H_{\max}\bar{V})^{-0.9}\right]\exp\left\{-4X_p^3\right\} \qquad (6.9);$$

It is assumed that it is this fraction of radioactive particles that determines contamination of the vegetation in the area of radioactive fallout and the intake of radioactive products in the inhalatory system.

The moment when fallout ceases is determined by

$$t_1 = \frac{X}{\bar{V}} + \Delta t, \tag{6.10}$$

where $\Delta t = 1.5\frac{L_y}{\bar{V}}$ and L_y is the width at distance X from the centre of the test.

External gamma exposure, D_{ext}, is determined by

$$D_{\text{ext}} = 0.87 \cdot P_\gamma(24)\left[\frac{9.44}{t_1^{0.2}}\left(T_0 + \frac{24 - T_0}{k_{\text{tr}}}\right) + \frac{k_r \cdot \Delta t}{k_{\text{cld}} t_1^{1.2}}\right], \tag{6.11}$$

where T_0 is the period during which an individual remained outdoors within 24 h; k_r is a coefficient for which the value depends upon the character of the distribution of radioactive products in the cloud from the test (k_r = 68. . .91); k_{tr} is a coefficient that represents reduction of gamma radiation from fallout through shielding by a building; k_{cld} is a coefficient that represents reduction of gamma radiation from the cloud through shielding by a building. The first item in equation (6.11) conditions the dose obtained from the moment when fallout ceases to a complete fission of radionuclides, and the second conditions the dose over the period of fallout.

To calculate average fallout concentrations of radioactive products in the above-ground air a theoretical expression is used which describes a relationship between the value sought and a dose of radioactive aerosols weighted in the air in approaching their even distribution in space, i.e.

$$\bar{C}_\Sigma = \frac{\bar{k} \cdot D_{\text{cld}}}{\Delta t \cdot \bar{E}_\gamma}, \tag{6.12}$$

where D_{cld} is the dose due to exposure to the cloud of the test; $\bar{E}_\gamma$ is the average yield of gamma radiation of the cloud of the test; and $\bar{k}$ is the sizeable coefficient.

The value of the dose accumulated during the fallout period (the second item in equation (6.11)) is taken as an evaluation for the value D_{cld}.

The value of the inhalation intake of an ith radionuclide in a critical organ is further derived from the expression

$$G_i^{\text{ing}} = \bar{C}_\Sigma \cdot \eta_{d<50}\frac{\sigma_i}{\sigma_\Sigma} V_l \cdot \Delta t \cdot F_{\text{air}} \cdot k_i^b(d < 50)F_{\text{air}}^i, \tag{6.13}$$

where $k_i^b(d < 50)$ is the coefficient of biological availability (solubility) of an ith radionuclide in particles of size $d < 50$ μm; F_{air} is the coefficient for the precipitation of the aerosol in respiratory organs (assumed $F_{\text{air}} = 0.7$); and F_{air}^i

Table 6.14 Estimates of external doses, in mSv, in the open and for two groups of inhabitants of the village Veseloyarsk in the Altai region after the explosion of 29 August 1949 (Barkovski *et al.*, 1995).

Time of dose integration	Out of doors	Farmers	Indoor workers
Dose during the passage of the cloud	7.9	1.8	1.2
Dose for the first day	104	61	21
Dose for the first three days	146	85	28
Total dose	305	189	61

is the proportion of an ith radionuclide from its total detained in respiratory organs which reaches a critical organ, provided there is complete solubility of the radionuclide.

The St Petersburg group (Barkovski *et al.*, 1995) assumed in their external dose assessment that radioactive fallout remained at the ground surface and that the ground surface was a two-dimensional plane (assumption of an infinite plane source). They took into consideration the fraction of time that people spend out of doors, and the fraction of time that people spend in wooden or brick houses, etc. Doses were calculated for 22 tissues and organs of the body. This model was used for instance to estimate doses for inhabitants of the village Veseloyarsk in Rubtsovsk district after the explosion of 29 August 1949 (Table 6.14). Because the outdoor exposure rates are substantially higher than the indoor exposure rates in the same locality, the average external doses received by indoor workers (0.06 Gy) are smaller than those received by farmers (0.2 Gy).

The second approach to estimate the deposition of radioactive materials on the ground, and, subsequently, the doses from external irradiation, is based on the contemporary measurement of long-lived radionuclides such as ^{137}Cs, ^{90}Sr, $^{239,240}Pu$, etc, in the soil. It is supposed that if the radionuclide composition of every test explosion is known, the composition of deposited radionuclides at that time can be determined from the contemporary measurement of a few long-lived radionuclides (Kozmin *et al.*, 1996; Izrael *et al.*, 1998). This method requires very precise measurements of many barely detectable concentrations of radioactive materials in many places and at different depths. This approach, which was used to reconstruct doses from the Nevada Test Site (Beck and Krey, 1983; Beck, 1996), has yet to be applied to the Semipalatinsk Test Site.

In addition, it may be pointed out that a number of dose estimates have been derived from thermoluminescence (TL) and electron spin resonance (ESR) measurements (Gordeev *et al.*, 1995b; Takada *et al.*, 1996; J. Takada, personal communication, 1997). Thermoluminescence measurements of a few samples of bricks collected in 1995 in populated areas near the Semipalatinsk Nuclear Test Site point to whole-body doses of 0.21 Gy in Tchagan, 0.27 Gy in Izvyetska, 0.36 Gy in the city of Semipalatinsk, and 0.89 Gy in Dolon (Takada *et al.*, 1996; J. Takada, personal communication, 1997). The doses in Dolon

Table 6.15 Collective doses of external irradiation resulting from the consequences of nuclear tests by 5-y periods following the beginning of ground and atmospheric tests, for the inhabitants of a number of population centres of the Abay, Beskaragay and Zhanasemey districts and Semipalatinsk city (Tsyb *et al.*, 1990).

District or settlement	Collective dose (person-Sv) 1949–1953	1954–1958	1958–1963	Total
Abay district	602	0.18	–	602.2
Beskaragay district	1330	11	56	1397
Zhanasemey district	0.1	6	–	6.1
Semipalatinsk city	–	607	–	607
Totals (rounded)	1900	620	56	2600

and Tchagan are similar to previously reported values (Tsyb *et al.*, 1990); however, the value for the city of Semipalatinsk, which is much higher than previously reported (0.006 Gy), will have to be confirmed (Takada *et al.*, 1996).

Estimates of collective doses from external irradiation are available. In the vicinity of the Semipalatinsk Test Site, the largest collective doses were received in the Abay and Beskaragay regions of Semipalatinsk Oblast and in Semipalatinsk City (Tsyb *et al.*, 1990). Results are presented in Table 6.15 according to 5-y intervals between 1949 and 1963; according to the results of that Russian study, the total collective dose from external irradiation is estimated to be about 3000 person-Sv for the populations living close to the test site (Tsyb *et al.*, 1990). In Table 6.16, these estimates are compared with those that can be derived from recent publications by scientists from Kazakhstan (B.I. Gusev and N.N. Kurakina, unpublished data, 1996; Kazakhstan, 1997). The dose estimates derived from the Kazakhstan studies are higher than those presented in the Russian study; the reasons for the differences between the two sets of results remain to be explained. Regarding the population of the Altai region, it is estimated (Kiselev *et al.*, 1994) that the collective effective dose received by that population is 42 000 person-Sv, including a contribution of 32 000 person-Sv from the explosion of 29 August 1949 and a contribution of 3000 person-Sv from the explosion of 7 August 1962.

A research group from the Altai State University is actively working on the development of methods of population dose reconstruction using the present value of fallout ^{137}Cs on the ground (Lagutin *et al.*, 1994). The basis of the proposed method of external dose reconstruction is made from mathematical models intended for the description of the formation of particles and assessment of parameters of the dispersion content of radioactive fallout at assigned distances from the test ground.

The model of formation of radioactive particles is similar, in regard to its content, to the one put forward by Izrael (1973). This model is used to estimate activities of nuclei of an ith radionuclide that formed inside ($V_i(t)$) and on the

Table 6.16 Estimates of doses of external irradiation received by the populations of Kazakhstan living in the vicinity of the Semipalatinsk Test Site during the 1949–1962 time period (Gusev and Kurakina, 1996; Kazakhstan, 1997; Tsyb *et al.*, 1990).

District or city	1960 population*	Average external dose† (person-mSv)	Collective dose‡ (person-Sv)	
			Kazakh studies	Tsyb *et al.*, 1990
Abay district:				
Karaul	2335	357.9	836	
Sarzhal	832	1163.3	968	
			1804 (total)	602 (total)
Beskaragay district:				
Budene	325	1679.4	546	
Dolon	906	2174	1967	
Kanonerka	1227	840.9	1032	
Mostik	637	12.7	8	
Tcheremushky	531	153	81	
			3634 (total)	1397 (total)
Zhanasemey district				
Sarapan	187	~400	75	
Znamenka	903	~400	360	
		435 (total)	6.1 (total)	
Semipalatinsk city	163 000	3.7§		607 (total)
Sum of collective doses (person-Sv)			5900	2600

* Gusev and Kurakina (1996).
† Except for Semipalatinsk city, the estimates of average external dose are taken from Kazakhstan (1997).
‡ Values of collective dose were, for the Kazakhstan studies, obtained as the products of the 1960 population and of the average external dose; the values referred to Tsyb *et al.* (1990) are direct quotes from that reference.
§ The estimated average external dose for the Semipalatinsk study was obtained as the quotient of the collective dose reported by Tsyb *et al.* (1990) and of the 1960 population.

surface ($S_i(t)$) of radioactive particles. By the model of aerosol fallout the value of the expression V_i/S_i is estimated, where V_n is the volume of fusion of all radioactive fallout at some distance from the centre of the explosion, and S_n is the surface area of these particles. Further, from derived values of parameters, the density of fallout of an ith radionuclide is calculated:

$$\sigma_i(t) = \sigma_{Cs}(t^*)\frac{V_i(t)k + S_i(t)}{V_{Cs}(t^*)k + S_{Cs}(t^*)}, \qquad (6.14)$$

where $V_{Cs}(t^*)$, $S_{Cs}(t^*)$ are activities of ^{137}Cs in the volume and on the surface of particles at a time $t^* > 20$ min;

$$k = \left(\frac{V_n}{S_n}\right)\left(\frac{V}{S}\right)^{-1} \tag{6.15}$$

with *V*/*S* the relation of a fusion volume to a surface of all particles engaged in the irradiated area; $\sigma_{Cs}(t^*)$ is the density of fallout of ^{137}Cs calculated as

$$\sigma_{Cs}(t^*) = (\sigma_{Cs}(t_u) - \sigma^g_{Cs}(t_u)) \exp\{(t_u - t^*)\lambda_{Cs}\} \tag{6.16}$$

with $\sigma_{Cs}(t_u)$ the density of contamination of soil with ^{137}Cs measured at a time t_u after the test, $\sigma^g_{Cs}(t_u)$ the density of global fallout of ^{137}Cs at a time t_u and λ_{Cs} the radioactive decay constant of ^{137}Cs.

Estimation of effective doses of external exposure is performed with the help of rate dose coefficients (pSv s^{-1})/(Bq m^{-2}) for different gamma irradiation nuclides. Values of the coefficients in question are obtained from published data (Jacob *et al.*, 1988).

In order to make up a list of tests that resulted in fallout on the territory of the Altai Region, trajectories of the transport of air masses from the centre of a test were modelled (Loborev *et al.*, 1995). In addition, an analysis of fallout of beta radiation on meteorological stations and adjacent areas, from 1952 to 1962, was carried out (Gamayunov *et al.*, 1995).

An interesting method of identification of nuclear tests that could have conditioned radioactive fallout in areas with an anomalous content of ^{137}Cs was proposed by Izrael *et al.* (1998). The method is based on the analysis of the content in radioactive particles identified from the radioactive fallout pattern of some long-lived radionuclides—nuclear fuel fission products, soil neutron activity (^{152}Eu, ^{154}Eu, etc.), and the comparison of the ratio of their particle content with similar ratios for other products of a test. Implementation of the proposed method, however, requires precise measurements on the edge of capabilities of modern equipment.

Of other studies related to dose reconstruction methods, noteworthy is the work by Barkovski *et al.* (1994a) that demonstrated the necessity to consider behaviour styles of a population in contaminated areas, and the one by Vlasov (1994) who put forward a probability method of calculation of the structure of radioactive contamination of agricultural products.

For practical application of methods of mathematical modelling in problems on dose reconstruction it is necessary to have detailed information on the structure of air currents when nuclear test explosions were performed. A network of stations for high altitude sounding of the atmosphere in the area of Western Siberia–Kazakhstan was not dense enough to reconstruct the structure of air currents with required precision today. For this reason, methods of full-scale mathematical modelling have not been widely adopted in practical works on reconstruction of doses of Altai Region and Kazakhstan populations due to nuclear tests at the STS.

At present the first results of the Altai population dose assessment have been obtained on the basis of data from measurements of current ^{137}Cs contamination of soil. These results, however, have not been published yet.

More reliable and numerous data on the assessment of doses of Altai and Kazakhstan residents have been obtained with the help of methods based on mathematical processing of archival radiation survey data. In particular, Loborev *et al.* (1994) and Djachenco *et al.* (1998) with use of actual data (Andryshin *et al.*, 1995) conducted reconstruction of external and internal effective doses and thyroid doses of residents of the Altai Region and Kazakhstan due to nuclear explosions on 29 August 1949 and 7 August 1962. This group of specialists estimated doses for the population of a number of settlements in Kazakhstan due to all nuclear explosions at the STS (Loborev *et al.*, 1997). Gordeev *et al.* (1995c) estimated thyroid doses for the Altai Region population due to the nuclear test on 7 August 1949. The results obtained demonstrate the following details.

The nuclear explosion on 29 August 1949 produced the greatest impact on the Altai Region population. In the Uglovski district maximum external dose (ED) values attained ~ 1800 mSv, the length of an area from the centre of the test where doses exceeded 250 mSv was ~ 270 km (Loborev *et al.*, 1994), and the collective dose for the Altai Region population was about 30 000 person-Sv (Djachenco *et al.*, 1998).

The largest area of contamination—practically three-quarters of the Altai Region territory—was the result of the explosion on 7 August 1962 (Loborev *et al.*, 1994). High post-test population exposures are not expected: the highest ED values, formed in the northeastern part of the region, did not exceed 30 mSv, with the collective dose for the regional population being about 3000 person-Sv (Djachenco *et al.*, 1998).

6.4.3 Local and regional doses from internal irradiation

As for doses from external irradiation, doses from internal irradiation are derived from the knowledge of the activities that were deposited on the ground. There are four possible ways for radioactive materials to enter the human body (Gordeev *et al.*, 1994):

1. through food, when people eat foodstuffs polluted by radionuclides;
2. by the inhalation of polluted air;
3. contact, when radioactive materials penetrate through skin;
4. through wounds.

The most important pathways of exposure for the general population are usually ingestion and inhalation.

Internal dose by oral intake of all radionuclides, except radioiodines, is derived on the basis of the method of accumulation coefficients. To estimate intakes of radioiodine with milk an exponential model is applied. The model has the following formula

$$A_i(t) = A_{i\max} \cdot \exp\{-(\lambda_i + \lambda_p)(t - t_{i\max})\} \qquad (6.17)$$

where $A_i(t)$ is the specific contamination of milk with an ith radionuclide at a time t after a test; $A_{i\max}$ is the maximum specific contamination of milk monitored at a time $t_{i\max}$; λ_i is the constant of the fission of an ith iodine; and λ_p is the constant of biological purification of pastures.

The calculation of internal exposure through rates of oral and inhalatory intakes of radionuclides in the organism is performed on the basis of dosimetric models of organs which the authors have developed themselves, and, generally speaking, are different from dosimetric models recommended by the ICRP. Researchers from the Moscow Institute of Biophysics have developed an elaborate model for the assessment of internal doses (Gordeev *et al.*, 1994, 1995a,b). In the model for inhalation, it is assumed that particles with a size exceeding 50 μm are too large to enter the respiratory system through either the nose or the mouth. Another assumption is that radioactive materials enter the human body through unprotected breathing organs only at time $D(t)$, when the radioactive cloud passes the locality considered.

The amount of radioactive materials which can enter into the respiratory tract system and remain there, G_{net}, is calculated as:

$$G_{\text{net}} = F_{\text{air}} \times C \times V \times t \times R$$

where F_{air} is the fraction of inhaled activity that remains in the respiratory system; C is the average concentration of radioactive aerosols near the ground during passage of the radioactive cloud (Ci l^{-1})—it is proportional to the net dose, contained in the cloud, when it passes the location; V is the breathing rate (L h^{-1}); and R is the fraction of activity in the cloud that can be inhaled. A similar expression is recommended for the calculation of the amount of any particular radionuclide in the body. After that it is possible to estimate the distribution of inhaled radioactive materials in different organs of the human body, e.g. nose, lungs, blood and thyroid.

The main source of internal radiation is food. According to Gordeev *et al.* (1995a), food is responsible for 90–95% of the dose from internal irradiation. One of the most important parameters that enters into the calculations is the fraction of fallout activity that is retained by vegetation; Gordeev *et al.* (1994, 1995a,b) estimated the values of this parameter as a function of the distance from the centre of explosion and the density of vegetation. In agricultural areas where cows are kept on pasture, milk is the main pathway of exposure to humans. According to Gordeev *et al.* (1995c), if λ_i is the rate of radioactive decay of radionuclide i, and λ_p is the rate of grass growth, then concentration of a radioisotope in milk at moment t, $A^i(t)$, may be expressed by the following formula:

$$A^i(t) = A^i_{\max} \times \exp[-(\lambda_i + \lambda_p)(t - t_{\max})]$$

where $t_{\max}$ is the time of maximum radioiodine concentration in milk and $A^i_{\max}$ describes the maximum concentration of the radionuclide i in cows milk—it is proportional to daily grass consumption and inverse to excretion of the nuclide.

Although most fission products have a low uptake to blood, some of them, such as I, Cs, and Sr are absorbed effectively by the blood system and accumulate in various tissues and organs of the body. In the model of Gordeev *et al.* (1995a), the distribution between organs and tissues of the most important radionuclides entering the human body with milk is estimated. The net dose for a given organ by the ith radionuclide D^i_{N} as a function of (1) milk consumption V_{m}, measured in litres, (2) the effective energy of beta irradiation of ith radionuclide E_i, and (3) the mass of the considered organ, m, is:

$$D^i_{\mathrm{N}} = \frac{5.12 \times 10^7 g_i f_i E_i}{m\lambda} \frac{1}{\lambda_i + \lambda_p}(1 - \exp[-(\lambda_i + \lambda_p)\vartheta]) + \frac{\exp(-\lambda t)}{\lambda_i - \lambda_p}[1 - \exp(\lambda_i - \lambda_p)\vartheta]$$

where g_i is the amount of the considered radionuclide that enters the body in the first day, it is proportional to V_{m}; f_i is the amount of the nuclide that reaches the considered organ; the last portion of the nuclide enters the body at the moment ϑ; λ is a constant of effective excretion of the nuclide from the body daily; and $\lambda_i + \lambda_p$ is an effective rate of milk purification from the ith radionuclide.

With the help of this model, doses arising from internal irradiation were calculated for inhabitants of the Altai region after the explosions of 7 August 1962 and 15 January 1965. Calculations include estimates of internal thyroid doses for almost every village in the Altai region that was exposed to radiation impact resulting from the nuclear test of 7 August 1962 (Anonymous, 1995). These dose estimates, shown in Table 6.17, were obtained by specialists from the IBP.

Table 6.18 gives obtained doses in different organs of an adult from tests on 29 August 1949 and 7 August 1962 (Loborev *et al.*, 1994; Djachenco *et al.*, 1998). For the test on 29 August 1949 a point is considered ~ 240 km away from the centre of the explosion on the axis of the route of the radioactive cloud (Uglovski district). For the test on 7 August 1962, a point is considered at a maximum fallout area in the northeastern part of the region (Zarinski district).

As seen from Tables 6.17 and 16.18, there is a significant difference in thyroid dose assessment of residents of the Zarinsk district after the explosion on 7 August 1962. Doses calculated by the IBP's methodology (Gordeev *et al.*,

Table 6.17 Internal thyroid doses due to the nuclear test on 7 August 1962, mGy.

	Age group				
Settlement	1 y	5 y	10 y	15 y	20 y
Aleisk	280	140	110	69	61
Baevo	590	280	230	15	120
Barnaul	320	150	120	75	62
Burka	310	150	12	73	61
Alambai*	19 000	9200	7300	4500	3700
Rassypnaya*	20 000	9400	7500	4600	3800
Kalmanka	220	100	83	68	57
Kozikha	220	150	120	73	60
Pospelikha	890	440	360	220	190
Rodino	400	190	150	94	78
Rubtsovsk	580	290	240	140	130
Uglovskoie	420	210	170	110	100

* Settlements of the Zarinsk district located in an area of maximum fallout.

Table 6.18 Estimated doses, mGy, in different organs of a hypothetical adult. For the test explosion on 29 August 1949, the location considered is a point approximately 240 km away from the STS in the Uglovski district; for the test on 7 August 1962, the location considered is a point at a maximum fallout area in the northeastern part of the region (Zarinski district).

	Dose, mGy	
Organ	Test on 29 August 1949	Test on 7 August 1962
Urinary bladder	20	2.5
Stomach	37	4.6
Small intestine	56	7
Upper part of the large intestine	230	29
Lower part of the large intestine	660	84
Kidneys	20	2.5
Liver	21	2.6
Lungs	36	3.4
Skeleton	116	15
Yellow bone marrow	136	19
Red bone marrow	70	9.5
Skin	18	2.4
Spleen	20	2.5
Testes	19	2.4
Thyroid	2800	240
Uterus	21	2.7

Table 6.19 Feed–animal transfer factors from feed to animal products (meat and milk) (Vlasov *et al.*, 1994).

	Feed–meat (Bq kg^{-1})/(Bq day^{-1})		Feed–milk (Bq l^{-1})/(Bq day^{-1})	
Radionuclide	Minimum	Maximum	Minimum	Maximum
Sr	2.0×10^{-4}	6.0×10^{-4}	1.0×10^{-3}	2.0×10^{-3}
Zr	5.0×10^{-7}	1.5×10^{-6}	5.0×10^{-7}	1.5×10^{-6}
Ru	2.0×10^{-3}	4.0×10^{-3}	1.0×10^{-4}	1.8×10^{-4}
I	2.0×10^{-3}	6.0×10^{-3}	5.0×10^{-3}	1.5×10^{-2}
Cs	5.0×10^{-2}	1.1×10^{-1}	5.0×10^{-3}	1.5×10^{-2}
Ba	2.5×10^{-5}	7.5×10^{-5}	3.0×10^{-5}	7.0×10^{-5}
Ce	5.0×10^{-7}	1.5×10^{-6}	5.0×10^{-7}	1.5×10^{-6}
Pu	5.0×10^{-7}	1.5×10^{-6}	5.0×10^{-7}	1.5×10^{-6}

1995d) are nearly a magnitude higher than those derived by the methodology developed by the CPTI (Loborev *et al.*, 1994).

Another model was developed in Obninsk (Vlasov, 1994). The model assesses the contamination of agricultural products, starting from grass to meat, by randomly distributed radionuclides with a given composition. The model takes into account land-use structure, soil conditions, inhomogeneity of contamination of arable land, etc. The model was used to estimate the concentrations of different radionuclides (Sr, Cs, Ce and Pu) in agricultural products of the Altai region after the explosion of 7 August 1949 (Vlasov *et al.*, 1994). The animal–feed transfer factors for radionuclides from fodder to animal products (meat and milk) are shown in Table 6.19.

Estimates of doses from internal irradiation are also available for the populations living in the vicinity of the Semipalatinsk Test Site (Tables 6.20 and 6.21). Internal doses presented in Table 6.20, presumably in terms of effective dose, are about equal to those due to external irradiation (Kazakhstan, 1997). In Table 6.22, collective doses from internal and external irradiation are compared (Tsyb *et al.*, 1990). In Table 6.22, the internal doses are expressed in terms of organ or tissue doses; as expected, the thyroid doses are much greater than the external doses.

6.5 NOVAYA ZEMLYA (RUSSIA)

The first nuclear weapons test at Novaya Zemlya (Northern Test Site) was an underwater shot of 3.5 kt conducted on 21 September 1955, and the last one was an underground test on 24 October 1990 (Andryshin *et al.*, 1996). Novaya Zemlya was the site of the largest nuclear weapons test, a 50 Mt explosion at an altitude of about 3.5 km on 30 October 1961. In all, 130 nuclear tests took place at Novaya Zemlya, with a total explosive yield of 265 Mt (Andryshin *et al.*, 1996).

Table 6.20 Estimated doses of external and internal irradiation received by the populations of Kazakhstan living in the vicinity of the Semipalatinsk Test Site during the 1949–1962 period (Kazakhstan, 1997).

District or city	1960 population*	Average external dose† (mSv)	Average internal dose‡ (mSv)	Average total dose (mSv)
Abay district:				
Karaul	2335	357.9	520	880
Sarzhal	832	1163.3	1300	2460
Beskaragay district:				
Budene	325	1679.4	1800	3480
Dolon	906	2174	2300	4470
Kanonerka	1227	840.9	950	1790
Mostik	637	12.7	9.9	23
Tcheremushky	531	152	110	260
Zhanasemey district:				
Sarapan	187	~400	~400	~800
Znamenka	903	~400	~400	~800

* Grusev and Kurakina (1990)
† Kazakhstan (1997)
‡ Kazakhstan (1997)

Table 6.21 Estimated thyroid and effective doses received by residents of the city of Semipalatinsk, Ust-Kamenogorsk, Kurchatov and the settlement of Chagan, for all tests conducted at the STS (Loborev *et al.*, 1997).

Settlement	Adult thyroid dose, mGy	Effective dose, mSv
Semipalatinsk	28	4
Ust-Kamenogorsk	180	36
Kurchatov	310	58
Chagan	650	230

Table 6.22 Collective doses of external and internal irradiation (Tsyb *et al.*, 1990).

	Collective internal (numerator) and external (denominator) doses (person-Sv)	
District or settlement	Thyroid	Bone marrow
Abay district	1896/602	1956/602
Beskaragay district	2164/1330	54/1330
Zhanasemey district	60/6.1	–/6.1
Semipalatinsk city	6100/607	–/607

6.5.1 Status of dose reconstruction

Even though the nuclear tests conducted on the Novaya Zemlya islands accounted for about half of the total energy yield of all nuclear tests carried out world-wide, there is very little available information on the local and regional doses resulting from those tests. It is likely, however, that the local doses to off-site residents were relatively low for two reasons.

1. most of the atmospheric devices were exploded at high altitudes, so that the expanding fireball did not touch the ground surface. Under these conditions, fallout occurs very slowly and is diluted over very large areas. Only one surface test was conducted, a 32 kt detonation on 7 September 1957. There were also 17 underground tests that vented, resulting in most cases in on-site contamination only (Dubasov *et al.*, 1994).
2. The Novaya Zemlya test site is large and isolated. The two Novaya Zemlya islands together measure about 900 km in length and 81 300 km^2 in area. The nearest village, Amderma, is 280 km away. The much larger population centre of Arkhangelsk is approximately 1000 km away, and three villages lie at intermediate distances (IPPNW, 1991).

An integrated research programme of analysis of the seismic, radiation, sanitary, and ecological situation in the area of the Novaya Zemlya test site has been undertaken (Dubasov *et al.*, 1994b) but results have not been published yet. The available information is mainly related to on-site contamination and to the doses received by reindeer herders, who are the critical population in the lichen–reindeer–human foodchain. High values of ^{137}Cs concentrations, and, to a smaller degree, of ^{90}Sr, have been observed in reindeer meat, which is the staple food of the reindeer herders. These ^{137}Cs concentrations roughly decreased with distance from the test site. Levels of ^{137}Cs in reindeer were high because the lichens, which are an important food for these animals during winter, effectively entrap a substantial fraction of the ^{137}Cs activity falling on to them, and retain it for several years. A comprehensive investigation of this foodchain has been performed for the entire Russian coast of the Arctic Ocean (Ramzaev *et al.*, 1993).

6.5.2 Local and regional doses from external irradiation

Current exposure rates in the Novaya Zemlya islands vary generally from 8 to 12 $\mu R\ h^{-1}$, which is similar to the range observed in adjacent areas and represents essentially natural background radiation (Dubasov *et al.*, 1994b). However, much higher exposure rates can be measured in small areas locally: in zone ‘A’, where the surface nuclear test was detonated on 7 September 1957, the exposure rate does not exceed 1 $mR\ h^{-1}$ in an area less than 10 m^2; in zone ‘B’, which is the site where the underground nuclear test conducted on 2 August

Table 6.23 Measured concentrations of ^{137}Cs (Bq kg^{-1}) in lichen, reindeer, and other environmental materials from the Russian coast of the Arctic Ocean, from 1963 to 1990 (Dubasov *et al.*, 1994).

Type of sample	1963	1969	1970–1978	1980–1988	1988–1990
Moss	222–260	260–370	300–550	220–440	150–180
Lichen	750–1700	1300–1700	750–1500	–	–
Reindeer meat	75–370	80–1100	80–370	80–180	40–75
Fish	2.6–3.7	1.1–1.8	3.0–3.7	2.6–3.7	2.6
Milk	–	0.2	0.56	0.11	0.04
Geese, ducks	–		15–22	11–15	7.5–15

1987 vented, the exposure rate is up to 80 μR h^{-1} in an area of about 100 m^2; and in zone 'C', which was the site of atmospheric explosions, the exposure rate does not exceed 50 μR h^{-1} in an area of about 0.5 km^2 (Dubasov *et al.*, 1994b).

Information on exposure rates or doses from external irradiation in off-site areas has not been found.

6.5.3 Local and regional doses from internal irradiation

Results of measurements of ^{137}Cs in lichen, reindeer, and other environmental materials from the Russian coast of the Arctic Ocean are presented in Table 6.23 (Dubasov *et al.*, 1994b). The ^{137}Cs levels in reindeer meat are much greater than those in milk, fish, geese, or ducks. Therefore, people such as reindeer herders, who use reindeer meat as a staple food, received much higher internal doses than the urban residents, who consume reindeer meat only occasionally. It is estimated that the reindeer breeders have received internal effective dose rates from ^{137}Cs and, to a smaller degree, from ^{90}Sr, of 1 mSv y^{-1} on average since the early 1960s (Ramzaev *et al.*, 1993); the doses to urban residents, in contrast, are estimated to have been about 100 times lower (Ramzaev *et al.*, 1993).

6.6 LOB NOR (CHINA)

China conducted 34 nuclear weapons tests between 1964 and 1988; of these, 22 were atmospheric tests and the others were underground (IPPNW, 1991; De Geer, 1996; Liu Ying and Zhu Changshou, 1996). The total explosive yield of the 22 atmospheric tests was about 20 Mt.

6.6.1 Status of dose reconstruction

Little information is available on dose reconstruction efforts carried out in China. For each test, several surveying methods were used in order to determine the trajectory of the cloud carrying the radioactive debris. Balloons released before the test helped to predict the trajectory of the radioactive cloud. After the test, an aeroplane equipped with sensitive radiation monitoring instruments flew back and forth to determine the position of the cloud and to measure exposure rates. Also, sounding balloons carrying radiation detectors were released below the radioactive cloud in order to measure the vertical profile of radioactivity within the cloud (Zheng Yi *et al.*, 1996). A model of atmospheric transport and deposition was developed in order to predict external exposures up to a distance of 800 km downwind from the test site (Zheng Yi *et al.*, 1994, 1996).

In addition to the early detection system described above, a nationwide monitoring network for environmental radioactivity of 45 stations was set up in the early 1960s by the Ministry of Public Health (Zhu *et al.*, 1994). Monitoring data include the deposition densities of important fallout radionuclides and radionuclide concentrations in air, drinking water and in foodstuffs (China, 1990, 1995). Doses are derived from the measured levels using ICRP and UNSCEAR models (Ye, 1994; Zhu *et al.*, 1994; Liu Ying and Zhu Changshou, 1996).

6.6.2 Local and regional doses from external irradiation

The absorbed doses in air measured outdoors in several population centres located downwind from the test site at distances ranging from 400 to 800 km are presented in Table 6.24 (Zheng *et al.*, 1996). The measured levels, which include exposures resulting from all important Chinese tests, are compared with predicted values obtained using the atmospheric transport and deposition model (Zheng Yi *et al.*, 1996). A reasonable agreement between measured and predicted values is obtained for most cities. The average absorbed dose in outdoor air is 0.18 mGy; assuming that people spend, on average, 80% of their time indoors where the shielding factor to outdoor radiation is 0.2, and that the conversion coefficient from absorbed dose in air to effective dose is 0.7 (UNSCEAR, 1982, 1993), a mean effective dose of 0.044 mSv is estimated for the populations living downwind of the Lob Nor nuclear test site at distances ranging between 400 and 800 km.

6.6.3 Local and regional doses from internal irradiation

The environmental contamination caused by ^{131}I has been reported by Liu Ying and Zhu Changshou (1996). The highest deposition levels measured in the stations of the nationwide monitoring network are presented in Table 6.25, and estimated thyroid doses for adults are shown in Table 6.26. The adult thyroid doses are found to range from 0.06 mGy in Taiyuan to 2.5 mGy in Lanzhou; thyroid doses to infants would be about 10 times higher. The average thyroid dose received by the Chinese population as a result of the tests

Table 6.24 Outdoor air absorbed doses, in mGy, in urban areas located between 400 and 800 km downwind from the Lob Nor test site (Zheng Yi *et al.*, 1996).

City or town	Predicted dose (mGy)	Measured dose (mGy)
Xihu	0.08	0.07
Anxi	0.094	0.064
Tashi	0.065	0.10
Qiaowan	0.51	0.14
Yumenzhen	0.015	0.12
Yumenshi	0.064	0.024
Jinta	0.0045	0.45
Jiayuguan	0.031	0.44
Average	0.108	0.176

Table 6.25 Fallout of ^{131}I, in kBq m^{-2}, in some regions of China (Liu Ying and Zhu Changshou, 1996).

Test number and date	Region	^{131}I deposition (kBq m^{-2})
4 (27 October 1966)	Xi'an	0.33
5 (28 December 1966)	Shenyang	4.8
12 (7 January 1972)	Lanzhou	5.1
15 (17 June 1974)	Lanzhou	10
18 (17 November 1976)	Hohhot	0.22
22 (16 October 1980)	Xining	10

Table 6.26 Thyroid and effective doses to adults resulting from ^{131}I produced in nuclear tests in China (Liu Ying and Zhu Changshou, 1996).

Region	Thyroid dose (mGy)	Effective dose (mSv)
Changchun	0.16	0.0081
Shenyang	2.2	0.11
Taiyuan	0.059	0.003
Xi'an	0.14	0.0072
Hangzhou	0.15	0.0077
Changsha	0.11	0.0054
Nanning	0.097	0.005
Hohhot	0.97	0.05
Xining	2.0	0.1
Lanzhou	2.5	0.13

conducted at Lob Nor is estimated to be about 0.14 mGy (Liu Ying and Zhu Changshou, 1996).

The long-lived fission products ^{90}Sr and ^{137}Cs have been monitored throughout China since the early 1960s. Even though the average deposition density of ^{90}Sr seems to be have been lower in China than in the remainder of the Northern Hemisphere, the internal doses from ^{90}Sr are estimated to be higher in China than in the remainder of the Northern Hemisphere. This apparent discrepancy is explained by the fact that the Chinese diet is not typical of that of the populations of the Northern Hemisphere (Liu Ying and Zhu Changshou, 1996). The average effective dose resulting from the intake of ^{90}Sr is estimated to be 0.27 mSv (Zhu *et al.*, 1994). Most of this effective dose is due to tests that were not conducted on Chinese soil.

6.7 SOUTH PACIFIC: MURUROA AND FANGATAUFA (FRANCE)

The French nuclear tests in the atmosphere were carried out at Hamoudia near Reggane in the Algerian Sahara in 1960 and 1961, and on the uninhabited atolls of Mururoa and Fangataufa in French Polynesia from 1966 to 1974 (Doury and Musa, 1996). Nuclear tests were interrupted in the Sahara in 1961 because of the impending independence of Algeria in 1962. French Polynesia was then selected as a new test site, mainly because only 5000 inhabitants lived within a 1000-km radius of the planned ground zero in Mururoa (IPPNW, 1991). Four atmospheric tests were conducted in the Sahara and 46 in Polynesia (four at Fangataufa and 42 at Mururoa). The total energy yield of the 50 atmospheric tests is equivalent to 10 Mt of TNT (Doury and Musa, 1996). After 5 June 1975, all tests in French Polynesia were conducted underground (IPPNW, 1991).

6.7.1 Status of dose reconstruction

No public information has been found on dose reconstruction efforts related to the tests conducted in the Sahara. Regarding the tests conducted in French Polynesia, annual reports on the radiological situation in populated atolls and islands around Mururoa and Fangataufa are made available to the public and are communicated to the United Nations (see, e.g. RF, 1970, 1984, 1993, 1995, 1996). Because French Polynesia is composed of a very large number of islands scattered over large distances—thousands of kilometres—in the South Pacific, radiological monitoring has been mainly carried out for several islands deemed to be representative of large archipelagos or groups of islands:

1. Tahiti (110 000 inhabitants) for the Society Islands, located at more than 1000 km away from Mururoa and Fangataufa;
2. Tureia atoll (140 inhabitants), the population centre in the Tuamotu archipelago that is the closest (120 km) to the test site;

3. Hao (1100 inhabitants), also in the Tuamotu archipelago;
4. Mangareva (600 inhabitants) for the Gambier Islands;
5. Tubuai (1700 inhabitants) for the Tubuai archipelago;
6. Nuku Hiva (1800 inhabitants) and Hiva Oa (1500 inhabitants) for the Marquise Islands (RF, 1984).

Doses are assessed on the basis of radiation measurements for the selected islands covering the terrestrial and the marine environments. Although occasional venting may have occurred following the underground tests conducted on or after 1975 (IPPNW, 1991), it does not seem to have led to a detectable increase in the exposure rates or in the radionuclide concentrations in foodstuffs (RF, 1984): this implies that annual doses have generally decreased since the mid-1970s.

6.7.2 Local and regional doses from external irradiation

Doses from external irradiation have only been reported since 1982; the effective dose rates ranged between 1 and 10 Sv y^{-1} in 1982 (RF, 1984) and were estimated to be less than 4 Sv y^{-1} in 1995 (RF, 1995).

6.7.3 Local and regional doses from internal irradiation

Doses from internal irradiation have only been reported since 1982; the effective dose rates have been estimated to range from 2 to 32 Sv y^{-1} in 1982 (RF, 1984) and to be lower in the early 1990s (RF, 1993, 1995, 1996). Table 6.27 summarizes the dose estimates for the populations of various atolls and islands of French Polynesia in 1982 (RF, 1984). As in the Marshall Islands, most of the dose is due to the residual presence of ^{137}Cs in the environment. The collective effective dose rate for the populations of French Polynesia is estimated to have been about 1 person-Sv in 1982.

Even though doses were not reported before 1982, estimates can be derived from reported radionuclide concentration measurements in foodstuffs. For example, the thyroid doses due to the contamination of milk by ^{131}I in Tahiti have been calculated by the UNSCEAR Committee for most years during the atmospheric testing period in French Polynesia (UNSCEAR, 1977). Results are presented in Table 6.28; the highest annual thyroid doses to infants are estimated to have been about 7 mGy and to have occurred in 1974.

6.8 EMU, MARALINGA AND MONTEBELLO (AUSTRALIA)

Twelve full-scale tests of nuclear weapons were conducted by Britain in Australia in five series between 1952 and 1957. In October 1952, the only test of

Table 6.27 Estimates of effective doses received in French Polynesia in 1982, as a result of atmospheric tests carried out at Fangataufa and Mururoa from 1966 to 1974 (RF, 1984).

Location	Effective dose rates (Sv y^{-1})				Collective effective dose rate (man Sv y^{-1})
	External irradiation	Inhalation	Ingestion	Total (rounded)	
Tahiti					1.1
Papeete	5	0.06	5.2	10	
Paea	5	0.06	4.2	9	
Hitiaa	5	0.06	5.4	10	
Teahupoo	5	0.06	4.7	10	
Tuamotu					0.035
Tureia	1	0.06	32.3	33	
Hao	1	0.06	2.3	3	
Gambier					0.01
Mangareva	10	0.06	8.8	20	
Marquises					0.04
Nuku-Hiva	3	0.06	2.4	5	
Australes					0.1
Tubuai	5	0.06	15.4	20	

Table 6.28 Concentrations of ^{131}I in milk in Tahiti and corresponding thyroid doses to infants during the atmospheric testing period in French Polynesia (1966–1974) (UNSCEAR, 1977).

Year	Time-integrated milk concentration (Bq day l^{-1})	Estimated thyroid dose to infants (mGy)
1966		
1967	170	0.55
1968	180	0.6
1969		
1970	410	1.3
1971	670	2.1
1972	40	0.12
1973	410	1.3
1974	2200	6.8

the series Hurricane was conducted on a ship near Montebello Island, WA; in October 1953, the two tests of the series Totem were carried out in Emu Field, SA; in May–June 1956, the two tests of the series Mosaic were detonated on Montebello Island, WA; four more tests were conducted in the series Buffalo in September–October 1956 in Maralinga, SA; finally, in September–October 1957, the three tests of the series Antler were detonated in Maralinga, SA. The yield of these tests varied from 1 to 60 kt of TNT-equivalent; the total energy yield of those 12 tests was less than 0.2 Mt of TNT-equivalent (Wise and Moroney, 1985).

6.8.1 Status of dose reconstruction

Rough estimates of dose have been made for local population centres as well as for population centres throughout Australia (Wise and Moroney, 1985).

The main bodies of radiation data and other relevant information available to estimate the doses resulting from those tests include:

1. for the nine nuclear tests comprising Mosaic, Buffalo, and Antler—total beta activities of radionuclides in fallout deposition and in air from Australia-wide monitoring programmes (Butement *et al.*, 1957; Dwyer *et al.*, 1957);
2. for all 12 nuclear tests—trajectories taken by the radioactive clouds across Australia (Gale, 1954; Gale and Crooks, 1954; Peirson, 1955; Butement *et al.*, 1958; Phillpot, 1957, 1959) and meteorological conditions for population centres, including rainfall;
3. for the seven tests of Buffalo and Antler—external dose rate and total beta activity of radionuclides in fallout deposition and in air within the proximal region of fallout (Carter, 1957; Clay, 1957; Cater, 1958);
4. for the two tests of Totem—airborne survey of ground contamination (Cambray and Munnock, 1954);
5. for the three tests of Hurricane and Mosaic—ground contamination of the nearby coastal region of the mainland and of distant population centres (Gale and Crooks, 1954; Matthewman, 1957).

6.8.2 Local and regional doses from external irradiation

External doses from local fallout are not available for the series Hurricane, Totem, and Mosaic of 1952, 1953, and 1956, respectively. External doses for the series Buffalo and Antler of 1956 and 1957 were estimated from the local measurements of exposure rate and fallout deposit, assuming that the external dose rate varied as a function of time, t, as $t^{-1.2}$, and integrating the external dose rate to 1 y. Results are presented in Table 6.29. The whole-body doses from external irradiation are estimated to have been <1 mGy in all local population centres that were monitored.

For distant population centres throughout Australia, the external whole-body doses $D(t)$ for the series Mosaic, Buffalo, and Antler were calculated using the following equation:

Table 6.29 Estimated average external whole-body doses from proximal fallout from nuclear tests of the series Buffalo and Antler (Wise and Moroney, 1985).

Series and test	Population centre	External whole-body dose (mGy)
Buffalo, test 1	Coober Pedy	0.2–0.68
Buffalo, test 1	Ingomar	0.17–0.3
Buffalo, test 1	McDouall Peak	0.03
Buffalo, test 3	Maralinga Village	0.003
Buffalo, test 4	Coober Pedy	0.045
Buffalo, test 4	Ingomar	0.12
Antler, test 1	Emu	0.05–0.37
Antler, test 2	Coober Pedy	0.04
Antler, test 2	Ingomar	0.02
Antler, test 2	Mabel Creek	0.035
Antler, test 3	Bulgannia	0.003
Antler, test 3	Ealbara	0.26–0.27
Antler, test 3	McDouall Peak	0.003
Antler, test 3	Mulgathing	0.1

$$D(t) = 0.17 \times t^{0.775} \times F \times S$$

where D, in mGy, is the external whole-body dose delivered during the first year following the explosion (In fact, Wise and Moroney (1985) express the external dose in terms of effective dose equivalent. The numerical results of the two quantities are similar in the case of external irradiation from fallout.); t, in days, is the time of fallout measurement after the explosion, in the range from 0.1 to 20 days; F, in MBq m^{-2}, is the amount of fallout per unit area of ground; and S is a shielding factor that takes into account the ground roughness and the absorption of gamma radiation by walls (For Australian conditions, the average value of S was estimated to be 0.28 for urban centres and 0.34 for rural communities. The overall average for Australia was taken to be 0.34.).

The number of distant population centres that were monitored was 85 for Buffalo and Antler, and 29 for Mosaic. Estimates of external doses are available for each monitored population centre and for each test of the three series. External doses for the series Hurricane and Totem were estimated by scaling the results from similar nuclear tests of the series Mosaic, Buffalo, and Antler according to the known yields of the explosions. The average doses from external irradiation for the Australian population were found to be quite low: 0.0011 mGy for Mosaic, 0.0041 mGy for Buffalo, and 0.0031 mGy for Antler (Wise and Moroney, 1985).

Table 6.30 Estimates of average individual and collective effective dose equivalent commitments resulting from fallout in the British nuclear tests in Australia, 1952–1957 (Wise and Moroney, 1985).

Series	Test	Average effective dose equivalent (mSv)	Collective effective dose equivalent (person-Sv)
Hurricane	1	0.012	110
Totem	1	0.007	70
Totem	2	0.006	60
Mosaic	1	0.001	10
Mosaic	2	0.0055	52
Buffalo	1	0.0088	83
Buffalo	2	0.0012	11
Buffalo	3	0.0059	56
Buffalo	4	0.011	101
Antler	1	0.0003	3
Antler	2	0.0030	28
Antler	3	0.0125	118
Total (rounded)		0.07	700

6.8.3 Local and regional doses from internal irradiation

Doses from internal irradiation were evaluated for: (1) the ingestion of fallout radionuclides in food, (2) ingestion of fallout radionuclides in drinking water, and (3) inhalation of fallout radionuclides in air. Standard models of environmental transfer from deposition to air, drinking water, and foodstuffs were used (Wise and Moroney, 1985). It was found that internal irradiation accounted, on average, for 83% of the total effective dose equivalent.

Estimates of individual effective dose equivalents, averaged over the entire Australian population, and of collective effective dose equivalents are presented in Table 6.30 for each of the 12 tests. The average individual effective dose equivalent for all tests conducted in Australia is estimated to be 0.07 mSv.

6.9 COLLECTIVE DOSES TO THE WORLD'S POPULATION FROM ALL TESTS

Collective doses to the world's population from all tests have been estimated by the UNSCEAR Committee (UNSCEAR, 1977, 1982, 1993). In order to estimate the full radiation impact of the tests, the UNSCEAR Committee uses the concept of collective dose commitment, which includes the doses delivered in future times, until complete decay or removal from the environment of the radionuclides produced by the nuclear explosions. The collective effective dose

Table 6.31 Collective effective dose commitment to the world's population from atmospheric nuclear testing (UNSCEAR, 1993).

Radionuclide	Half-life	Activity product (Ebq)	Collective effective dose commitment (1000 person-Sv)			
			External	Ingestion	Inhalation	Total
^{14}C	5730 y	0.22		25 800	2.6	25 800
^{137}Cs	30.1 y	0.91	1210	677	1.1	1890
^{90}Sr	28.6 y	0.60		406	29	435
^{95}Zr	64.0 d	143	272		6.1	278
^{106}Ru	372 d	11.8	140		82	222
^{3}H	12.3 y	240		176	13	189
^{54}Mn	312 d	5.2	181		0.4	184
^{144}Ce	285 d	29.6	44		122	165
^{131}I	8.02 d	651	4.4	154	6.3	164
^{95}Nb	35.2 d	–	129		2.6	131
^{125}Sb	2.73 y	0.524	88		0.2	88
^{239}Pu	24 100 y	0.00652		1.8	56	58
^{241}Am	432 y	–		8.7	44	53
^{140}Ba	12.8 d	732	49	0.81	0.66	51
^{103}Ru	39.3 d	238	39		1.8	41
^{240}Pu	6560 y	0.00435		1.3	38	39
^{55}Fe	2.74 y	2		26	0.06	26
^{241}Pu	14.4 y	0.142		0.01	17	17
^{89}Sr	50.6 d	91.4		4.5	6.0	11
^{91}Y	58.5 d	116			8.9	8.9
^{141}Ce	32.5 d	254	3.3		1.4	4.7
Total (rounded)			2160	27 200	440	30 000

commitment to the world's population from all tests is estimated to amount to 3×10^7 person-Sv (UNSCEAR, 1993).

Table 6.31 presents the contributions of the most important radionuclides and exposure routes to the collective effective dose commitment. By far, the most important radionuclide is ^{14}C. Because of its very long half-life (almost 6000 y) and environmental mobility, ^{14}C will keep delivering very small dose rates to the world's population during thousands of years at about the same rate as it does now. It is the accumulation of those very small dose rates for a very long time over a very large population that explains the large contribution of ^{14}C to the collective effective dose commitment from nuclear weapons testing.

The second most important radionuclide with respect to the collective effective dose commitment is ^{137}Cs. The importance of ^{137}Cs has already been noted in doses from local and regional fallout.

Because of its short half-life (about 8 days), ^{131}I is only the ninth contributor to the collective effective dose commitment.

6.10 CONCLUSIONS

Dose estimates resulting from nuclear weapons testing have been reviewed. Emphasis has been placed on the doses from local fallout (within a few hundreds of kilometres from the test site) and from regional fallout (within a few thousands of kilometres from the test site. Because the test sites are isolated and tests can be conducted under favourable meteorological conditions (avoiding the exposure of relatively close residents), doses from local fallout were usually low. It is only when unexpected events occurred (such as those related to the Bravo test) that high radiation exposures were incurred. Extensive dose reconstructions related to local fallout have only been carried out so far for the tests conducted by the USA.

There is little information on the doses from regional fallout. The study related to the Nevada Test Site indicates that high exposures occurred mainly when the passage of the radioactive cloud coincided with rainfall.

Finally, the doses from global fallout have been reviewed extensively by the UNSCEAR Committee and are only briefly discussed in this document.

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