7 Health Effects

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7.1 INTRODUCTION

In the early 1960s, global fallout from nuclear testing and its possible effect on human health became a major public concern. This concern and reduced international rivalry led in August 1963 to a limited ban on atmospheric testing (UNSCEAR, 1993). Atmospheric tests by countries developing nuclear arms went on until October 1980, albeit at a much lower frequency. At the end of atmospheric testing, a total explosive yield of 545 Mt TNT-equivalent had been released. Longer-lived radioactivity totalled about 2300 EBq (1 Ebq = 10^{18} Bq) originating from fission of ^{239}Pu, ^{235}U and ^{238}U (total fission yield about 155 Mt); much of that yield came from the third stage of the large bombs based on the fission–fusion–fission process. In addition, fusion reactions resulted in the production of large amounts of ^{3}H and ^{14}C, 240 EBq and 0.22 EBq, respectively. International assessments (UNSCEAR, 1982) of the ensuing total effective dose commitment to the world population were derived by the summing up of exposures from external radiation, inhalation, and ingestion on the basis of population-weighted fallout deposition, and resulted in an estimate of 3.7 mSv for a theoretical immortal human being living through the whole testing period in the Northern Hemisphere. Seventy per cent of the dose commitment is delivered by ^{14}C at a very low dose rate, i.e. only 10% until the year 2200. The next-ranking radionuclides are ^{137}Cs (13% contribution), ^{90}Sr (3%), ^{95}Zr (2.4%), ^{106}Ru (1.9%), ^{54}Mn (1.5%), ^{144}Ce (1.4%) and ^{131}I (1.4%). The relatively unimportant ^{239}Pu causes only 18 μSv or 0.5% of the total dose. The collective committed effective dose to the world population amounts to about 3×10^{7} person-Sv (UNSCEAR, 1993).

As far as possible health effects are concerned, the radiological burden from global fallout contributed only a small fraction to the detriment caused by natural and anthropogenic exposures to ionizing radiation. Therefore, noticeable increases in cancer, genetic, or teratogenic effects, are not to be expected. However, in those instances, where atmospheric bomb testing led to

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considerable local contaminations, exposures of the populations in the vicinity of test sites might have been far higher than the global mean value. For example, external exposures exceeded 1 Gy on several occasions, and thyroid doses from ^{131}I ranged up to 200 Gy in one instance. Exposures at this level pose a considerable health risk and might have led, or may still lead, to significant changes in morbidity and mortality. At a time when formerly classified information is increasingly accessible, careful assessments of local exposures and health effects are becoming possible. Although doses decreased rapidly with time after the explosion, a careful reconstruction is needed as a prerequisite for the proper evaluation of present and future health risks to the affected populations.

7.2 RADIATION AND HEALTH

7.2.1 Biological effects of radiation

An understanding of radiation-induced health effects has to be built from basic concepts of radiobiology as given in this introductory section. Biological effects of ionizing radiation result from the modification and destruction of cellular components. The large energies released in fission reactions or radioactive decay are in the range of MeV per decay (1.6×10^{-13} J). In comparison, the binding energy of typical chemical bonds in organic molecules amounts to only 300 kJ mol^{-1}, i.e. about 3 eV or 5×10^{-19} J per single bond. An electron of 1 MeV energy produces about 30 000 ionizations in an aqueous solution and a still larger number of excitations over the short distance it travels. Biological response to such highly localized energy depositions is complex, and depends on many different parameters. Radiation quality, i.e. ionization density along particle tracks, is important. In view of the fact that the exposures considered here are made up almost exclusively of gamma and beta radiation, i.e. sparsely ionizing low LET (linear energy transfer) radiation, the following considerations of basic principles of radiation biology are restricted to this radiation quality.

1. About 70% of biological damage from low LET radiation is due to the indirect action of free radicals, and 30% to the direct action on the target molecule. The indirect radiation component can be strongly modified by the presence of oxygen, radioprotectors, and radiosensitizers.
2. Cells from different tissues vary markedly in radiosensitivity. At doses up to about 2 Gy, low LET radiations are relatively inefficient in killing the majority of the stem cells of a tissue. The survival curve shows a steeper downward slope at higher doses.
3. The radiosensitivity of cells varies according to their stage in the cell cycle, the G2 phase prior to mitosis being most sensitive. In general, the

sensitivity of mammalian cells to ionizing radiation is directly proportional to their rate of cell division, and inversely proportional to their degree of cellular differentiation. Therefore, the cellular kinetics of tissues is important in terms of response to radiation, embryo/foetus and newborn being more sensitive than adults.

Radicals, formed mainly by interaction of radiation with water molecules in the cell, may react with critical structures, such as the DNA of the cell nucleus, the carrier of the genetic information. The amount of primary radiation damage in biological structures per unit dose is modified by many physical and chemical agents. The most significant chemical modifier is molecular oxygen, because, by combining with primary free radicals formed from water, it can yield more damaging agents, such as the peroxyl radical. Many constituents of the cell can scavenge radiogenic free radicals before they attack critical structures. Radioprotector molecules containing sulfhydryl groups, such as glutathione or cysteamine, are most important in the aqueous environment of the cells; other molecules, such as hydroquinones (vitamins E and K) also protect from free radicals in lipid compartments. At a later stage, electron and hydrogen donors may restore the native chemical structures through the breaking up of labile bonds of radicals with cellular macromolecules. For an in-depth treatment of molecular radiation biology, the reader is referred to the excellent monographs devoted to this field (see e.g. Hall, 1994).

7.2.2 Health effects

Non-repaired or incorrectly repaired modifications of radiation-induced DNA damage can affect cellular and organ functions and consequently the health of the organism. Table 7.1 shows how distinct radiation effects at the cellular level are linked to clinical endpoints. Some of these health effects emerge only at higher dose rates. Many deterministic effects are due to loss of proliferative capability and result only when a high proportion of the stem cells of a functional unit are affected; hence, they exhibit a steep dose–effect relationship, usually with a threshold in the range of a few sieverts. In general, deterministic effects show up soon after exposure. Local skin burns, epilation (hair loss), or thyroid dysfunction are typical examples of deterministic effects found in the most highly exposed victims of atmospheric tests.

More subtle changes in the genome may lead to stochastic effects such as cancer or germline mutations, which may even express themselves decades or generations later. For this class of damage, theory predicts that loss or modification of genetic information in one single stem cell may cause functional inabilities, deregulation of cellular growth and later on, cancer.

Loss or alteration of crucial genetic information in gonadal cells can result in an elevated risk of hereditary diseases in subsequent generations.

Table 7.1 Classification of cellular damage caused by ionizing radiation, and the resulting effects on the organism.

Cellular change	Effects on organism	Existence of threshold	Dose > Sv
Cell death	Acute loss of body functions, death due to CNS (central nervous system) syndrome, vascular collapse	Yes	50
	$LD_{50/30}$ in humans		3–5
Loss of proliferative capacity	Loss of immune and barrier functions, death within weeks from breakdown of the immune system, intestinal linings	(Yes)	1–2
Disruption of organ formation	Developmental defects during embryogenesis	?	0.1
Cell transformation (oncogene activation, tumour suppressor inactivation)	Tumours, cancer after a latency period ranging from years to decades	(No)	
Cell mutation	Changes in the DNA of germ cells increasing the potential of genetically caused defects in offspring	No	

The following clinical endpoints need to be considered as potential results of exposures from atmospheric bomb tests.

1. *Acute effects* (deterministic effects) typically have threshold doses and include skin burns, epilation, teratogenic effects, wasting syndrome, thyroid gland dysfunction and autoimmunodisease. Substantial organ doses in the range of 1 Sv or more are needed for the induction of such acute effects. Thus, only relatively small numbers of people, such as a ship crew and Pacific islanders after the Bravo test (see section 7.3.3), and villagers in the nearfield of the Semipalatinsk Test Site (see section 7.3.2), are known to have incurred acute effects such as radiation sickness, skin burns and thyroid malfunction. Deterministic effects may be the result of external whole-body irradiation (wasting, spontaneous abortion), of skin and hair contamination with local fallout (epilation, skin burns), or of ingestion or inhalation (thyroid dysfunction).
2. *Teratogenic effects* from exposure to ionizing radiation in early pregnancy are of special concern. During brain formation in weeks 8 to 11 (and less so until week 21) fetal cells were shown to be especially sensitive to irradiation (UNSCEAR, 1993). In the absence of definitive data, a relatively low threshold dose of 100 to 200 mSv has been assumed.

3. *Late somatic effects*, especially *cancers*, are regarded the most critical stochastic effects of radiation, and the linear non-threshold model is applied to assess the risk of cancers at low-dose radiation. The reason for this is based mainly on two sets of considerations. One is an analysis of radiation effects in which biologically harmful damage, such as DNA double strand break, is induced by even a single track of radiation. Secondly, epidemiological studies indicate that the incidence of solid tumours among atomic bomb survivors increases linearly with dose to as low as 0.2 Sv. However, molecular biological analysis suggests that the process of carcinogenesis involves many genetic and epigenetic steps in the same cell lineage, which should lead to highly non-linear dose–effect relationships. In addition, detailed analyses indicate that biological responses differ qualitatively and quantitatively between different cells, tissue and organisms. In view of these uncertainties, the probability of induction in a single individual is prudently assumed to be about 5×10^{-5} mSv^{-1} effective dose for mortality from all malignancies. The following malignancies are of special concern:
   (a) *Leukemia*, a malignant growth of transformed precursors of white blood cells may develop in only a few years after radiation exposure. An increase in the incidence rate of this disease is generally relatively easy to detect because leukaemia normally is a rare disease. Thus, leukemia is often taken as a direct and early indicator for the quantitatively more important but protracted risk of solid tumours, such as lung, colon and breast cancer.
   (b) *Thyroid tumours* and carcinomas are of great concern because fission radionuclides of iodine are produced with a high yield, are mobile in the foodchain and are actively concentrated in the human thyroid gland. Consequently, thyroid doses may be orders of magnitude higher than whole-body doses. Fresh milk supply from contaminated meadows that may reach small children is a critical exposure pathway. In addition, recent findings in the aftermath of the Chernobyl accident suggest that the infant thyroid gland is more sensitive to ionizing radiation than has formerly been inferred from a large data base on the carcinogenic effect of therapeutic doses of ^{131}I in adults. Excess nodularity and thyroid carcinomas did occur among children in the Marshall Islands who were exposed to fallout from a thermonuclear bomb test in 1954, but the specific contribution of ^{131}I to this excess cannot be isolated from contributions from other radioiodine isotopes and external gamma rays from other radionuclides (UNSCEAR, 1994). A recently published analysis of five different studies (Ron *et al.*, 1995) yielded a pooled estimate of Express Radiation Rate (ERR) = 7.7 Gy^{-1} with 95% confidence limits of 2.1, to 28.7 for exposure before 15 y of age. There was a marked decrease in ERR with

Table 7.2 Site-specific lifetime risks for solid tumours and leukaemia following a whole-body acute exposure of 1 Sv [UNSCEAR 1994].

	Risk of exposure-induced death (REID) (%)		
Site of cancer	Males	Females	Both
Leukaemia*	1.3	0.9	1.1
Oesophagus	0.3	0.7	0.5
Stomach	0.9	2.0	1.4
Colon	0.5	0.6	0.6
Liver	2.2	0.3	1.2
Bladder	0.4	0.2	0.3
Lung	1.8	3.1	2.5
Breast	–	2.0	1.0
Ovary	–	0.5	0.3
Other	4.3	2.0	3.1
Total (except leukaemia)†	10.4	11.4	10.9
Total	11.7	12.3	12.0

* Leukaemia risks were computed using the excess absolute risk model.
† Solid tumour risks were computed using linear dose–response models with age-at-exposure and sex-specific relative risks and a 10-y latency period.

increasing age at exposure, from about 9.6 (for exposure at 0–4 y of age) to 4.8 (at 5–9 y) and 1.9 (at 10–14 y).

(c) *Other solid cancers* make up the bulk of radiation-induced malignancies in adults. Critical, i.e. radiosensitive organs include: lung, liver, female breast, stomach, and colon (Table 7.2). For a review of the most recent risk estimates the reader is referred to Annex A, *Epidemiological Studies of Radiation Carcinogenesis* of the UNSCEAR (1994) Report.

4. *Genetic effects* could not be identified in radioepidemiological studies such as those conducted in the offspring of atomic bomb survivors of Hiroshima or Nagasaki, because their normal incidence is high compared with the relatively low rate by which they are induced by radiation. This auspicious finding may be explained by the fact that the genotoxic effect of radiation is generally due to gross lesions such as translocations and deletions, which kill affected germ cells with no consequent transmission of damage to future generations. Since there exists no human data base on genetic effects from ionizing radiation, risk coefficients derived from rodents need to be used to predict the potential effects in affected populations. The detriment from genetic effects is estimated to be considerably smaller, about one-fifth, than that from radiation-induced cancer.

Based on this biomedical knowledge, possible health effects resulting from local exposures from atmospheric tests may be inferred from a careful

assessment of doses. For many early atomic bomb tests, no direct measurements of external doses and exposures from inhalation and from ingestion of contaminated foodstuff are available. For this reason, reconstruction of exposures is needed (see Chapter 6). These calculations must be based on theoretical considerations such as fission yield, release height, weather conditions, lifestyles and monitoring data on residual long-lived radionuclides in the environment. Although such calculations usually are fraught with considerable errors, the exercise is still important for the identification of potentially affected populations. These assessments allow the concentration of health care resources and professional activities on those in need of treatment or counselling.

In line with the generally short half-lives of radionuclides from fallout the remaining, present-day exposures are generally very low, i.e. a fraction of natural exposures. Thus, regulations concerning agricultural practices or lifestyle are not needed at this time; potential long-range transfer of ^{3}H ($^{3}H_2O$) in underground aquifers, or ^{239}Pu in the topsoil of arid environments and some tropical islands near ground zero locations are exceptions to this statement.

Since radiogenic cancers are indistinguishable from spontaneous cases, a direct assessment of health effects must rely on complete health records, and registers of cancer incidence and birth defects. Disease and death rates would have to be compared for study periods from the onset of tests to the end of the lifespan of the populations possibly affected, and appropriate controls would have to be established. In general, no prospective studies and registers are available that fulfil this condition. Possible radiation-induced diseases must, therefore, be assessed retrospectively. Often the populations have lifestyles and disease rates that may deviate substantially from international averages. In such instances it is a generally accepted approach to estimate past and future health impacts from local fallout by multiplying collective dose estimates with risk coefficients for radiation-induced diseases, such as cancer. The risk coefficients are predominantly based on radioepidemiological findings and on the radiobiological knowledge of the effects of ionizing radiations that has been gained in molecular, cellular, and animal studies.

7.2.3 Radioepidemiology

Radioepidemiological studies assess health risks in irradiated populations and correlate excess morbidity or mortality with radiation exposures. In the case of atmospheric bomb testing, retrospective and prospective cohort studies were initiated in all areas which have encountered local fallout. However, some of these studies only started recently and are still hampered by secrecy on the part of the source term, i.e. the released radioactivity, and poor health records. Psychosocial stress not directly linked to radiation dose, feelings about being abused again for scientific purposes not well understood by the local population, and compensation issues are important problems to be addressed.

Doses and dose rates from local fallout have in most instances been of a magnitude where biological response has not resulted in deterministic effects and only stochastic effects are possible. However, thyroid and skin doses, and in a few cases whole-body doses, in some cohorts reached levels which cause deterministic effects. In two cases, following the Bravo test in the Pacific and from the first test in Semipalatinsk, such effects were reported. Lens opacification may also be a deterministic endpoint to be taken into consideration under these conditions.

Quantitative estimates of cancer risks from ionizing radiation in humans are mainly derived from studies on highly exposed persons (UNSCEAR, 1994). The survivors of Hiroshima and Nagasaki are the most important cohort for this information, due to the relatively good estimates of doses, the wide range of doses experienced, the broad age distribution and highly organized and detailed medical follow up. The lifetime mortality risk from leukemias and solid tumours in this group is estimated at about 10 to 12% Sv^{-1} of acute (high dose rate) irradiation (see also Table 7.2). To account for the presumed lower biological effectiveness of protracted exposures, the generally employed risk coefficient for stochastic effects from low doses of ionizing radiation or from higher doses delivered at a low dose rate (< 200 mSv day^{-1}) is 0.05 Sv^{-1} effective dose. In view of the relatively large contributions from short-lived radionuclides in atmospheric tests, some of the exposures might have been so acute that the use of a reduction factor (DDREF: dose and dose rate efficiency factor) in the estimation of risk becomes questionable. However, even in such extreme circumstances, the dose rate is still much lower than in the case of Hiroshima or Nagasaki, where practically the whole exposure was delivered in a few seconds after detonation of the bomb. In that case, the considerable height above ground of the explosions prevented major local fallout.

Interaction of ionizing radiation with biological structures induces various changes that are sufficiently stable to serve as indicators of exposure. Indicators of exposure are important for the reconstruction of doses in situations where some or all exposure pathways are poorly documented. Indicators of individual risk are emerging from the rapidly expanding knowledge on the mechanisms of carcinogenesis and on genetic susceptibility. If cell clones are present that have already undergone crucial transformations towards malignant growth or if there are genomic features, such as heterogeneity for functional tumour suppressor genes, they are to be seen as determinants of health risks in the remaining lifespan or in subsequent generations.

There is little data available from dosimetric measurements relating to the short-lived radionuclides from fallout, thus retrospective assessments of past exposures are subject to considerable uncertainties and errors. Indicators of exposure in human tissue or blood are, therefore, of considerable interest as a means to assess the reliability of dose estimates and to reduce the uncertainty inherent in purely computational dose reconstruction. However, the

quantification of stable radiation-induced changes in exposed persons demands considerable resources and expertise, and it is, consequently, restricted to specialized laboratories. A further constraint is the need for biological materials, sometimes difficult to obtain for large-scale screening of cohorts affected by atmospheric bomb tests. Peripheral lymphocytes, in particular, display rare but radiation-specific lesions such as dicentric chromosomes. In the absence of physical dosimetry these lesions are particularly suited to estimate doses. Unfortunately, dicentric aberrations are unstable, so that this particular signal fades rapidly with time after exposure. There are, however, two recently introduced techniques that are based on stable signals: the FISH (fluorescent *in situ* hybridization) method visualizes stable chromosome translocations which are not associated with changed numbers of centromeres per chromosome, and the EPR (electron paramagnetic resonance) method which measures radiation-induced persistent changes in tooth enamel and dentin. Eye dosimetry based on a quantitative determination of ocult cataracts is another promising method for retrospective individual dosimetry.

Because of limited resources for radiation-effects research, the study of the exposed cohorts needs to be justified by providing health benefits to those who were affected by the atmospheric bomb tests as well as providing new knowledge about radiation effects. The development and implementation of methods to quantify risk to individuals is important, because it can contribute towards the identification of persons or critical groups who may profit from enhanced medical surveillance. There have been important recent advances in the determination of specific changes in the genome of an individual that may reflect an increased likelihood of developing a specific cancer. The information to be obtained from individual genetic testing may turn out to be helpful for early diagnoses and in increased survival rates in those who develop radiation related cancers.

7.2.4 Learning from the atmospheric bomb tests

A variety of summary reports on high exposures from bomb fallout in the Pacific and in the vicinity of the Semipalatinsk Test Site suggest that epidemiology may not only help in estimating present and future local risks from such exposures, but may also accrue additional knowledge on radiation risk factors from these experiences. Whether the in-depth recording and study of health effects from atmospheric bomb tests will broaden our understanding of radiation-induced health effects is dependent on many factors. Some of the necessary prerequisites may be difficult or impossible to achieve. Accurate dose estimates for a majority of affected persons and reliable health records kept in consistent format over long time periods need to be produced. The benefits could be considerable. A full assessment of the health effects from high thyroid doses produced by short-lived radioiodines from bomb fallout might have

enabled predictions to be made on the early onset of thyroid carcinoma risk in Belarus children after Chernobyl.

The significant political and economic changes of the last few years in the former USSR clearly imperil on-going studies and the initiation of new investigations in this area (see chart, Burkart, 1996). For these reasons as well as for ethical reasons, epidemiological activities need to be linked closely to mitigation activities which benefit members of the cohorts directly. Improved medical care and counselling of possibly affected persons are needed to relieve widespread fears and anger about practices of the past, but also to help secure a stable base for epidemiological work.

7.3 MAJOR AFFECTED POPULATIONS: CRITICAL EXPOSURES AND HEALTH EFFECTS

7.3.1 Nevada and Utah, USA

Between 1951 and 1962, about 100 atmospheric tests were conducted at the Nevada Test Site (NTS); some resulted in exposure to nearby populations. The combined fission yield was approximately 1 Mt. Exposure estimates for the near-field are available from dose reconstruction efforts. The local population that was considered in these studies amounts to about 180 000 persons, who received an effective dose of about 500 person-Sv from external exposure. Thyroid doses in children may well have ranged up to 1 Gy.

There have been several health effect studies of cancer risk among residents of areas downwind from the NTS. These studies were of varying quality, but at least two were major undertakings involving individualized radiation dosimetry. Some innovative and sophisticated approaches were used, but the overall conclusions of the studies were limited, because the radiation doses were too low to present much of a possibility of learning anything new about risk. The sole exception was thyroid cancer risk from childhood exposure to ^{131}I.

The geographic pattern of exposure was complex (see Chapter 6), but the highest levels of exposure to any sizeable population occurred in the southwestern corner of Utah and in adjacent areas of Nevada and Arizona. Over the years, a number of epidemiological investigations have been carried out to study possible relationships between radiation dose from fallout and disease occurrence in the affected populations, especially among residents of Utah, Nevada, and Arizona.

7.3.1.1 Review of Public Health Service Documents

An important source of information on early studies of fallout exposure and possible radiation-related health effects among residents of areas downwind from the NTS was the 1979 report of a panel of experts appointed by the

director of the National Institutes of Health (NIH). This group was to review archived Public Health Service (PHS) documents related to the exposure issue. A network of medical liaison officers was established by the PHS in 1956; shortly after that it assumed responsibility for monitoring possible adverse health effects of fallout exposures. This was a consultant service for local practitioners who might see patients suspected of having radiation-related disease, and it was also considered to be a surveillance system. The Utah–Nevada–Arizona Population Study was developed in the 1960s with the participation of the Division of Radiological Health (DRH) and Centers for Disease Control (CDC) of the PHS, the health departments of the three states, and the University of Utah. Its purpose was to link and coordinate several studies, either contemplated or ongoing at the time, including vital statistics studies in Utah, a CDC investigation of leukemia clusters in Utah and Arizona, and a thyroid nodule survey in exposed communities in Utah, Nevada, and a control community in Arizona.

Weiss (1967) reported on a surveillance of thyroid surgery in Utah and Nevada during 1948–1962 in persons below age 30. An increase over time was observed in rates of surgery for thyroid cancer in women. Later that rate was found to be statistically significant in an independent analysis, but no changes were observed in surgery rates for thyroid adenoma or for non-toxic nodular goiter. Weiss pointed out that there was a strong likelihood of bias due to complex and changing histological criteria and due to the impact that publicity may have had on the frequency with which surgeons in Utah and Nevada decided to operate on the thyroid glands of their patients. These authors also concluded that later follow-up studies might be more revealing in view of the long latency period of radiation-induced thyroid cancer.

Screening began in 1965 by the PHS for a study of thyroid disease prevalence among several thousand junior and senior high school students, all of whom were 2–3 years of age at the time of the major fallout event in southwestern Utah, which occurred in 1953. About half (2298 students) were located in the vicinity of St George, Utah, and another 381 in adjacent areas of Nevada; 2123 presumably non-exposed controls were selected from Graham County, Arizona. Prevalence of all thyroid disease including nodules was the same among those assumed as exposed and the controls (Weiss, 1971), including immigrants to St George from other parts of the country. There were just two cases of thyroid cancer, both in the non-exposed group. Reactivation of the study was considered in subsequent years by the Bureau of Radiological Health (BRH), but was not attempted. In the view of the NIH-appointed panel of experts, this cohort study was the only scientifically satisfactory study in the PHS archive for determining whether fallout from the weapons tests had caused an increased incidence of thyroid disease.

According to documents in the PHS archive, investigations by the CDC, the Utah State Health Department, and the BRH involved seven leukemia clusters

identified between 1961 and 1972. The first cluster, investigated by Weiss *et al.* of the BRH, was suggested by 11 out of a total of 25 leukemia deaths in Washington and Iron counties, Utah, during the 15-y period (1950–64) having had onsets in the 3-y period 1958–60. A manuscript of this investigation was prepared, but was not submitted for publication because of severe uncertainties, including the possibility of bias, incongruity with current knowledge of radiation-related leukemia risk, and uncertainties about the inferential basis for asserting that a true cluster had occurred. For example, five of the 11 deaths, including two cases of chronic lymphocytic leukemia (CLL), occurred after age 30. Normally a radiation-related excess would be expected to be dominated by childhood leukemias and not involve CLL.

In addition, four cases of leukemia in Fredonia, Arizona (50 miles east of St George, Utah, and 7 miles south of Kanab, Utah) were diagnosed during 1960–65, two of them in 1960 (ages 48 and 36) and two in 1964 (ages 43 and 14). The latter two were next-door neighbours. No cases were observed in Kanab, a much larger town only 7 miles away. One question raised by the NIH panel of experts was whether the two communities should have been treated as one, as were the towns of Parowan and Paragonah, Utah, a location less than 100 miles north of St George, with a combined population of 1966 in 1960. These latter two towns experienced two cases of acute myelogenous leukemia (AML) in Parowan in 1967, one in a teenager and one in an adult who moved there in 1958, and two cases of ALL in Paragonah in 1969–70, both in teenagers.

Monticello, Utah, with a population of 1845 in 1960, had four childhood cases of acute lymphocytic leukemia (ALL) between 1956 and 1965. A uranium processing plant operated in the town during 1949–60 and a stream contaminated by radioactive isotopes ran through the mill property, but there was no evidence of unusual exposure of the cases. There was no dosimetric information to try and relate a causal relationship with fallout exposure.

Pleasant Grove, Utah, a small town 40 miles south of Salt Lake City, experienced four leukemia deaths in 2 y (1965–67), three of them in children under the age of 7, i.e. born in 1958 or later. On the basis of birth dates, the cluster was unlikely to have been related to fallout exposure.

Three cases of acute leukemia were observed in a residential neighbourhood of South Salt Lake City, a 16-y-old girl and a 10-y-old girl diagnosed in 1968 and another 16-y-old girl diagnosed in 1971. There was no evidence to suggest any specific causal factor.

Eight cases of leukemia observed in Flagstaff, Arizona during 1960–71 did not represent an unusual frequency given the size of the population, as judged by Connecticut Tumour Registry rates, and showed no clustering by time or neighbourhood. It was concluded that these cases did not constitute a cluster.

No publications resulted from the seven cluster investigations. The NIH expert panel report mentions that Clark Heath, who at that time headed the

Leukemia Unit, Epidemiology Branch, CDC, and who directed the investigations of all but the first potential clusters, wrote to an American Medical Association official in 1971. In that communication he explained that the findings were not submitted for publication because they were inconclusive and in his opinion did not suggest that the clusters might be due to fallout exposure.

7.3.1.2 Geographical Studies

One of the last documents mentioned in the NIH expert panel report was a handout from a talk given by Lynn Lyon of the University of Utah at the June 1978 meeting of the Society for Epidemiological Research. The subject was an analysis (published the subsequent year) of death certificates from the Utah State Register of Vital Statistics in relation to county population stratified by age, sex, and year and compared leukemia mortality among children (< 15 y of age) according to place of residence.

In this study, information on residential histories prior to leukemia diagnosis or to age 15 was not obtained because this would have required a far more expensive study; instead, it was assumed that any child resident in a given county at a given time had the exposure history of someone who had lived there up to that time. The years 1951–1958 were considered to be the period of substantial fallout exposure in Utah. Children born before 1959 were considered to have been exposed to some level of fallout in 1951 or later, but to have been free from prior exposures, during 1945–1950. Children born in 1959 or later were assumed to be non-exposed. Age-specific comparisons within geographical areas were made of mortality among children exposed by a given age and children of the same age who were non-exposed. Exposure status was estimated by dividing the state into northern (low fallout) counties and southern (high fallout) counties. Standardized mortality ratios for exposed versus non-exposed age-year groups were computed for the northern, low fallout region and the southern, high fallout region, and the two ratios were compared. Standardized childhood leukemia mortality rates reported by Lyon *et al.* were 2.1 and 3.84 for southern and northern Utah, respectively, for non-exposed children during the pre-testing period 1944–1950, 4.4 and 4.2 for exposed children, and 2.0 and 3.3 through to 1975 for non-exposed children born after 1958. Lyon's conclusion was that the exposed/non-exposed mortality ratio was significantly higher in the high fallout region than in the low fallout region. Furthermore, it was concluded that a normal low rate of childhood leukemia mortality prevailed in southern Utah prior to 1951 and equally among children born too late to experience fallout from the NTS, but that there were increases among exposed children following the initiation of above-ground test explosions at the NTS. The explanation preferred by the authors was that exposure to fallout had temporarily increased childhood leukemia mortality in southern Utah.

An accompanying editorial (Land, 1979) urged caution in drawing firm conclusions, pointing out that not enough was known about other factors that might have influenced the comparison. In support of that view, a similar analysis was presented but based on mortality data for childhood cancers other than leukemia. This second analysis indicated a quite different interrelation between region and possible effect. The later analysis was equal in size and statistical significance but opposite in direction to that observed for leukemia, thus casting doubt on fallout exposure as a causal factor. Later, Land *et al.* (1984) published an analysis of county mortality data for 1950–1978 obtained from the National Center for Health Statistics (NCHS). That analysis failed to confirm the leukemia findings of Lyon *et al.* even though similar analytical methods were used. Leukemia mortality rates among exposed children were 4.1 and 4.3 per 100 000 for southern and northern Utah, respectively. The low control value of 2.8 in both regions for non-exposed children, yielded exposed/non-exposed mortality ratios of 1.5 for both regions. Ratios of 1.8, 1.2, and 1.35, similarly calculated, were obtained for eastern Oregon, Iowa, and the USA as a whole, and appeared to reflect a general declining trend in childhood leukemia mortality rates over the period 1950–1978. However, data for 1944–49, which were not available from the NCHS and had to be deduced from data presented by Lyon *et al.*, indicated that only three childhood leukemia deaths occurred in southern Utah compared with 38 in northern Utah, a remarkable difference given the approximately fourfold difference in population size at that time. Thus, the different findings of the two studies could be ascribed to an anomalously low mortality rate for childhood leukemia in southern Utah during 1944–49. The low rate might have been due to underdiagnosis of leukemia or to an identification of leukemia mortality with associated causes of death.

The preceding year, Beck and Krey had pointed out that, although Washington County did get more fallout than the rest of the state, the mean population dose was higher in northern Utah than in the southern part of the state as a whole.

Johnson (1984) published an analysis of cancer incidence data in 4125 Mormon families (Members of the Church of the Latter Day Saints) in SW Utah during the period 1951 through to 1962, who were identified from telephone books in St George, Parowan, Paragonah, and Kanab, Utah; Fredonia, Arizona; and Bunkerville, Nevada. Family included all persons related by blood or marriage, and the survey, by trained volunteers from the surveyed towns, was filled out jointly by the surveyor and the head of the family. Response items included church membership, effects felt immediately after fallout, such as skin burns, eye burns, hair loss, change in hair colour, nausea, and diarrhoea, and diagnoses of cancer among family members. Respondents reported a total of 288 cancers among 4125 family members for the combined periods 1958–66 (chosen to detect leukemia) and 1972–80 (chosen to detect

solid cancers). These rates were 60% higher than the 179 expected according to published cancer incidence rates for all Utah Mormons and were comparable to that observed in Hiroshima and Nagasaki survivors who received more than 1 Gy. Rate ratios were extremely high for certain cancers: fivefold for leukemia, eightfold for thyroid cancer, twofold for breast and brain cancer, threefold for melanoma, and 11-fold for bone cancer. Among those who were reported to have suffered from acute fallout effects, the rate ratios were 45 for leukemia, 11 for breast cancer, and five for all cancers, numbers considerably higher than those calculated for A-bomb survivors with near-lethal doses exceeding 4 Gy.

Leukemia clusters had already been reported in all of these communities except for Kanab and Bunkerville. Excess risks are, of course, likely if communities are selected because rates are known to be high and are then compared with other communities or with the state as a whole. This explanation alone would, however, not explain the extremely high ratios reported for leukemia, or the high rate ratios for other cancers. A critical issue was the scientific rigour of the data gathering process and the possible lack of attention paid to problems of bias, which could have affected the accuracy of reporting of cancer cases and the inclusion of family members in the enumeration. Reported cancer cases were not confirmed with the state tumour registry, an important omission. Many other aspects of the study, such as the inclusion of an acute effects subgroup, also appear questionable.

While the scientific community tends over the long term to separate valid from invalid findings, poorly conducted studies can result in considerable confusion. This was the case from the Johnson (1984) article, partly because it was published in the most widely circulated medical journal in the USA. A partial replication of the Johnson (1984) study was carried out by Machado *et al.* using Utah county mortality statistics for 1950–80; their rationale was that increases in cancer incidence of the magnitudes reported would have to be reflected in cancer death rates. The Utah communities surveyed by Johnson (1984) were located in Washington, Iron, and Kane counties in the southwestern corner of the state, and contributed about half the population of these counties. Fredonia, Arizona, and Bunkerville, Nevada, were not included in the Machado study because they contributed less than 2% of the populations of their respective counties, which are large in area and had very non-uniform distributions of fallout. Migration into the three Utah counties was estimated, and site-specific mortality ratios relative to the rest of the state were estimated on the basis of the Johnson (1984) findings and with the assumption that immigrants and the remainder of the population have the same rates.

The observed mortality ratios were grossly inconsistent with Johnson's (1984) incidence estimates. A significant *deficit* of cancer mortality relative to the rest of the state was observed in the three southwestern counties and there was no evidence of excess risk for any solid cancer site. There was a significant excess for leukemia mortality (Table 7.3), however, it was far smaller than that

Table 7.3 Leukemia mortality risk, SW Utah vs. the remainder of Utah, 1955–80, by age at death (Machado, Land, and McKay, *American Journal of Epidemiology*, 1987).

Age at death	Standardized rate per 10^5 per year (number of cases)		Odds ratio	90% confidence interval
	SW Utah	Rest of Utah		
All ages	10.30 (62)	6.68 (1219)	1.45	1.18–1.79
0–14	8.20 (9)	3.69 (110)	2.84	1.65–4.90
15–29	2.87 (4)	2.21 (122)	1.12	0.48–2.58
30–49	3.45 (5)	2.58 (135)	1.39	0.66–2.94
50+	25.80 (44)	17.87 (852)	1.36	1.06–1.75

predicted according to the Johnson (1984) estimate. The leukemia finding was generally consistent with what one might expect to find in an irradiated population. There was no evidence of excess risk in 1950–54, whereas in 1955–80—two or more years after the greatest amount of fallout—there was a statistically significant excess. It appeared to be largest for childhood leukemia, but this result was based on only nine leukemia deaths in the three counties. This was the first statistical evidence of a leukemia excess possibly related to fallout, for which no obvious explanation unrelated to radiation has so far been provided. Still it must be noted that it is not necessarily surprising to find a leukemia excess among residents of an area in which leukemia clusters had been reported previously. That Washington county had the highest fallout levels in the state is no proof of radiation causation. The Machado *et al.* study and the two previous mortality studies, which were based on geographic contrasts, differed in one main aspect, namely in the geographic comparisons that were made. Presumably, the leukemia excess would have been found earlier, if the high fallout area had been restricted to the southwestern corner of the state.

One of the major limitations of geographical comparisons is that higher disease rates in a high-dose region is not satisfactory proof of a relation between the exposure and the disease. A case-control approach, as used in an NCI sponsored study of leukemia mortality by the University of Utah, could resolve the uncertainty by basing the inference on individual dosimetry. Subjects for the study were born before 1 November 1958, and died as residents of Utah in the period 1952–1981; each subject was required to have a resident's death certificate on file with the state of Utah, and to be recorded in the deceased membership file (DMF) of the Mormon church, which was made available for the study. The DMF was used to determine residential history during the period of fallout exposure. Leukemia cases were identified from death certificates and verified through hospital and physicians' records; the 1177 cases thus obtained were classified as acute or chronic, and as lymphocytic

or non-lymphocytic leukemia, yielding a fourfold classification (ALL, ANL, CLL, or CNL). Controls (n = 5330), individually matched to cases by year of death, age, and sex, were selected from the DMF and cross-checked with the Utah death certificate files. Controls could have died from any condition other than leukemia. Inferences were based on the relative dose distributions among the cases and the matched controls. Simon *et al.* have described the process by which bone marrow doses were estimated for individual study members, based mainly on their residential histories. Figure 7.1 gives average dose estimates for different counties, obtained for subjects who remained within a single county from 1952 to 1958.

The main results of the study are given in Table 7.4. There was a non-significant association (one-tailed p = 0.08 for trend) between estimated radiation dose and leukemia mortality for all types, excluding CLL which is not thought to be caused by ionizing radiation exposure. It is somewhat surprising that the same level of association was observed for CLL, although with even less statistical significance. As also observed in the Machado *et al.* study, these findings were based on small numbers. More pronounced associations with dose were found for certain subsets, in particular, for leukemia mortality before 20 y of age (p = 0.02), at any age during 1952–57 (p = 0.04), and from ALL, the most common leukemia type among children (p = 0.01). These are selected comparisons, of course, and they are interrelated, but if there were a dose response in this population, it might be expected to be stronger in these comparisons than in some others.

The estimated number of attributable leukemia deaths in the highest dose group (6 to 30 mSv) of this subset of Utah residents was 6.2, or 36% of 17 non-CLL deaths. This is nearly twice as high as the number (3.2, or 19%) predicted according to the leukemia model developed by the 1990 BEIR (Biological Effects of Ionising Radiation) V Committee, but is nevertheless consistent with it, given the wide confidence bounds on the case-control study estimate. The number of leukemia deaths estimated to be attributable to radiation in all dose groups was 62.2 (6.6% of 939 non-CLL deaths), compared with 30.2 (3.2%) based on the BEIR V model.

7.3.1.3 A Cohort Study of Thyroid Disease

Almost concurrently with the leukemia case-control study and under the same NCI contract, the PHS thyroid disease prevalence study of school children in St George, Utah and adjacent Nevada areas was reactivated by the University of Utah; a control population was chosen in Arizona. About half (2473) of the original cohort were included in the analysis, which was based on re-examination of the subjects' thyroid glands, interviews with subjects' parents about milk and vegetable consumption during the fallout period, and a complex dosimetry system (see Chapter 6).

Figure 7.1 Map of Utah counties, as divided by Lyon *et al.* (*New England Journal of Medicine*, 1979; **300**, 397–402) into northern, 'low fallout' counties and southern, 'high fallout' counties, which are separated by the heavy line. The entries below the name of each county give the average bone marrow doses in the later case-control study (Stevens *et al.*, *Journal of the American Medical Association*, 1990; **264**, 585–591), estimated for subjects who remained in a single county during the entire period of fallout (1952 to 1958). The absorbed dose estimates are based on an assumed shielding factor of 0.5.

Estimated thyroid doses from ^{131}I ranged from low averages of 13 mGy among subjects exposed in Graham County, Arizona, 50 mGy in Lincoln County, Nevada, and 170 mGy (maximum 4600 mGy) in Washington County, Utah. Approximately 73% of the dose was attributed to milk consumption and the dose estimates varied according to the source of milk and the amount reported to have been consumed. Thirty-eight of the subjects had non-neoplastic thyroid nodules at some time during the period 1965–1986, 11 had benign neoplasms including eight with follicular adenomas; eight had papillary carcinomas, including one subject with both a non-neoplastic nodule and a carcinoma. Interestingly, the thyroid cancer rate was nearly twice as high in Arizona as in Utah, with four cases among eligible subjects in each state, although age-adjusted thyroid cancer rates are about the same in the two states.

As summarized in Table 7.5, trend tests for dose response were suggestive for carcinomas (excess relative risk at 1 Gy = 7.9), with a negative 95% lower confidence limit (one-tailed $p = 0.096$); statistically significant for benign and malignant neoplasms combined (ERR = 7.0, with lower limit = 0.74 and $p =$

Table 7.4 Odds ratios and 95% confidence intervals by estimated bone marrow dose (Stevens *et al.*, *Journal of American Medical Association*, 1990; **264**, 585–591).

Cause of death	Dose intervals			p value for trend (2-tailed test)
	0–2.9 mGy	3.0–5.9 mGy	6.0–30.0 mGy	
All leukemia	1.00	1.08 (0.91–1.27)	1.69 (1.01–2.84)	0.068
Chronic lymphocytic leukemia	1.00	1.06 (0.76–1.50)	1.70 (0.61–4.73)	>0.10
All leukemia except CLL	1.00	1.08 (0.89–1.30)	1.72 (0.94–3.12)	0.094

0.019), and non-significant for the group of non-neoplastic nodules, benign neoplasms, and carcinomas combined (ERR = 1.2, with negative lower limit and $p = 0.16$). The analyses were adjusted for state, age, and sex, implying that different zero-dose intercepts were estimated for each subset corresponding to specific values or ranges of values for each of these variables. Therefore, the estimated regression coefficients were case-weighted averages of subset-specific coefficients. Thus, for example, the value ERR = 7.9 for carcinomas reflects case-weighted, estimated dose response coefficients within Arizona and within Utah (Nevada did not contribute, having no cases), rather than a contrast between higher-dose Utah and lower-dose Arizona. The results of an analysis that was not stratified by state would have been somewhat different. For example, the estimated ERR for carcinomas probably would have been substantially lower than 7.9. This is not a criticism of the analysis that was done but rather an indication of the fragility of these data and the tenuous character of any conclusion relating the thyroid cancer risk from fallout exposure. No separate analyses were reported for non-neoplastic nodules or benign neoplasms but it was stated that the regression coefficient for the eight carcinomas was slightly higher than the one computed for the eight follicular adenomas considered separately. The point estimate of ERR = 7.9 for carcinoma corresponds to about 2.7 cases attributable to radiation, 0.4 of 4 in Arizona, and 2.3 of 4 in Utah. For all thyroid neoplasms, the corresponding numbers were 0.24 of 5 in Arizona and 7.6 of 14 in Utah.

7.3.1.4 Nationwide Estimates on Health Effects

A recent report by the US National Cancer Institute (NCI) reassessed thyroid doses from the NTS for every county in the continental USA and projected cancer risks for the US population. The overall average dose to the approximately 160 million people in the USA in the 1950s was estimated to be 20 mGy, with cumulative average doses of 90 to 160 mGy to individuals living in counties of western states located east and north of the Nevada Test Site.

Table 7.5 Period prevalence of thyroid nodules, benign and malignant neoplasms combined, and cancers, 1965–86 (Kerber *et al.*, *Journal of American Medical Association*, 1993; **270**, 2076–2082).

		Thyroid nodules, including neoplasms		Thyroid neoplasms, including cancers		Thyroid cancers	
Dose (mGy)	Subjects	Number	Relative Risk	Number	Relative Risk	Number	Relative Risk
0–49	1418	29	1.0	7	1.0	5	1.0
50–249	646	12	0.9	3	0.8	0	0.0
250–399	240	8	1.9	5	2.8	2	3.8
400+	169	7	2.3	4	3.4	1	1.7
Regression analysis:		$ERR_{1Gy} = 1.2$, $p = 0.16$, negative lower 95% confidence bound		$ERR_{1Gy} = 7.0$, $p = 0.019$, lower 95% confidence bound = 0.74		$ERR_{1Gy} = 7.9$, $p = 0.096$, negative lower 95% confidence bound	

7.3.1.5 Summary

In retrospect, the various investigations of cancer and thyroid disease in areas downwind of the NTS, and widespread concern among residents of these areas about possible health effects from fallout, appear to have led inevitably to the two recent studies carried out by the University of Utah. Despite a large effort, little new knowledge was gained about radiation related risk. These studies are a good example of the many difficulties that have to be addressed in order to quantify the small risk associated with low radiation doses by studying the exposed populations.

In spite of its limitations, the definitive study in Utah, may with its unique case ascertainment and dose reconstruction, serve as a model for epidemiological studies in areas more heavily affected by atmospheric bomb tests. Its strength included a statewide tumour registry that met the exacting standards of the National Cancer Institute's Surveillance, Epidemiology, and End Results (SEER) Program, residential histories obtainable through the DMF and census records maintained by the Mormon Church which included most Utah residents among its members, the County Database and Town Database of the US Department of Energy for estimates of fallout deposition by locality and date, and individualized dosimetry and uncertainty estimates.

Given that the dosimetry work will not need to be redone, it may be feasible to update the thyroid study once or twice during the coming decades. However, thyroid cancer incidence rates do not increase markedly after about age 35, and because thyroid cancer is normally an indolent disease, the screening process may have identified cases that ordinarily would not have been diagnosed or

would have been diagnosed much later. According to SEER statistics, about 10 lifetime thyroid cancers would, in the absence of radiation exposure, be expected in a population of 2473 persons with roughly equal numbers of men and women.

7.3.2 Semipalatinsk and Altai, former USSR*

The Semipalatinsk Test Site in Kazakhstan was used from 1949 onwards (see Figure 7.2). About 122 atmospheric tests were detonated with a total yield of 6.6 Mt. Near-ground, ground-surface or shallow underground nuclear explosions, i.e. with considerable local fallout, contributed about 550 kt, of which 72% (400 kt) relate to the explosion conducted on 12 August 1953. Shallow underground explosions were undertaken to test the feasibility of large earth movements. In a first assessment, collective effective dose from external radiation to the local population is estimated at 2600 person-Sv, ingestion led to 2000 person-Sv. Collective thyroid doses for the same population are estimated at 10 000 person-Sv. Several recent publications address exposures and health risks also in the more distant, but more densely populated Altai area in the Russian Federation, east of the test site. Maximum effective doses received within the population from the atmospheric bomb test on 29 August 1949 were of the order of 2 Sv (Loborev *et al.*, 1994). Estimates of the size of cohorts exposed to an effective dose of 50–250 mSv and to more than 250 mSv amount to 270 000 and 40 000 persons, respectively. A test on 7 August 1962 is assumed to have resulted in very high thyroid doses from ingested and inhaled short-lived radioactive iodine isotopes. Maximum organ doses as high as 20 Sv were reconstructed (Rosenson *et al.*, 1996).

7.3.2.1 Semipalatinsk Region

There are few published research data on the health effects of the nuclear tests on the population around the STS in Kazakhstan. This is because throughout the entire period of nuclear testing from 1949 to 1989, only military experts were allowed to carry out limited radiation measurements such as exposure doses on the ground. From 1957 to 1960, the Kazakhstan National Academy of Sciences and the Kazakhstan Ministry of Health sent a research team to the Semipalatinsk region to investigate the health effect of nuclear tests. No epidemiological methods for comparative studies were applied. Although they found higher prevalence in the surrounding villages than in control villages for

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* The sole responsibility for this section remains with Drs Shoikhet, Kiselev and Tsukatani who provided most of the data discussed. Due to formerly restricted access to classified information on the radiological impact of the Semipalatinsk tests, independent validation is not yet available. Although some of the provisional dosimetric and health data reported below are strongy disputed, there is enough direct and circumstantial evidence indicating considerable acute and chronic local health impact, especially from the first explosion in 1949.

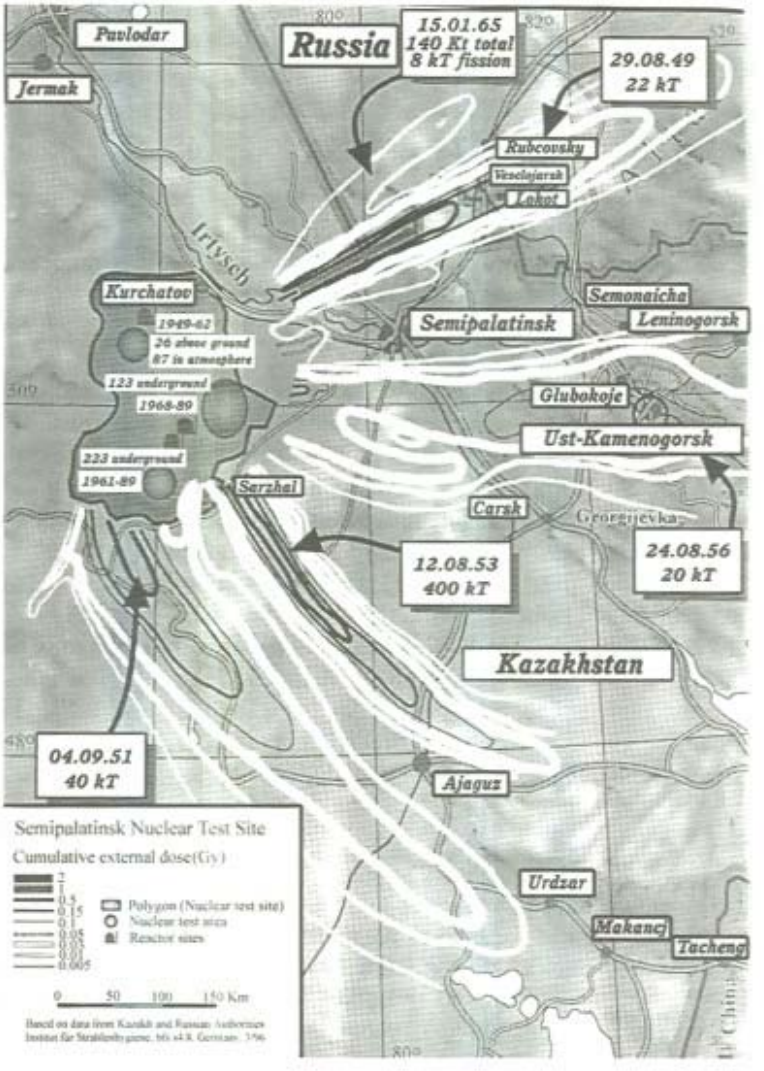

Figure 7.2 Provisional map of fallout trails from atmospheric and ground tests on the Polygon test site near Semipalatinsk. Isodose lines give estimated cumulative unshielded external doses on the ground. Based on data from Kazakhstan and Russian ministries. Boxes give date and bomb yield in kt TNT.

symptoms such as bronchial haemorrhage, conjunctive haemorrhage from mouth and genitals, dystrophia mucosa, asthenia universalis and vegetative neurosis syndrome, peripheral blood state alteration, juvenile cataract, etc., their relation with radioactivity was rejected at a general meeting on the research team results held in 1961 in Moscow. Since then no further research by Kazakhstan institutions had been allowed until the independence of the Republic. The report submitted in Moscow in 1958 described interim results of the team and was reprinted both in Russian and Japanese in Nagasaki in 1997.

The Kazakhstan Scientific Research Institute for Radiation Medicine and Ecology started an epidemiological study on cancer incidence around the STS. Interim results were reported at the Second Hiroshima International Symposium in 1996 (Gusev *et al.*, 1996). The initial premise was based on the belief that the main contribution to the formation of the cumulative effective radiation dose derived from the nuclear tests of 1949 through to 1956. It was during this period that the population around the STS received about 70% of the total effective dose. Cumulative external doses included contributions from radioactive clouds and from ground contamination. The internal dose was estimated from ingestion and inhalation. The calculated effective equivalent irradiation dose for the exposed group (Main Group) ranged from 0.87 to 4.47 Sv, with an average of about 2.0 Sv. Note that the summary effective equivalent irradiation dose for the Control Group was about 0.07 Sv.

The bulk of the Main Group was made up of the populace from nine towns and villages of Kazakhstan around the STS. The Control Group was formed from the populace of the Kokpekty district, which is located near the mouth of Lake Zaisan about 300 km SE of STS. Both groups were formed of approximately 10 000 people, in which the number of men and women was roughly equal. Individuals of European and Asian descent were represented equally. The age representation remained practically the same. The '0-to-19' y age group was the most representative, it comprised half of all those included; individuals aged 20 to 39 y made up 25 to 28%; and people of 40 y and older comprised 19 to 24%.

The temporal development of cancer incidence in the Main and Control Groups was analysed from 1956 through to 1994 at 5-y intervals. The group aged 40 y and older that is critical for cancer was replenished annually by individuals of 20 to 39 y of age, and it gradually started being replenished by individuals from the starting '0-to-19' y age group. Noting that the '0-to-19' y age group in 1990–1994 consisted of those who were born after 1971, it is certain that some individuals in the Main Group did not receive a radiation dose large enough to allow for statistically conclusive findings, despite the random variation in numbers. Numbers of the population samples fluctuated for reasons of death and birth rates and natural migration. While those who arrived from other regions were excluded in the Main Group, arrivals from other areas were included into statistics in the Control Group. Of vital

consideration is the number in the Main Group from the village of Dolon, which had shrunk from 1300 in 1960 to 100–150 by 1985. This group was replenished by people from another village that is 125 km distant from Dolon but received a dose of no less than 3 Sv from the first test of 29 August 1949.

At the initial stage of 1956, the official cancer incidence index in the Main and Control Groups was as low as 61.7 and 63.6 cases per 100 000 population respectively, indicating considerable underreporting of cancer deaths. Beginning in 1960 to 1970, the oncological incidence in both groups kept increasing. In the Main Group, after the initial level was exceeded in 1960 by 1.5 times (from 7 to 11; see Table 7.6), a rapid fourfold increase occurred by 1965, followed by the climax of 36 incidences by 1970. In the Control Group, the oncological incidence by 1970 had grown by a substantially lower rate. In the next 5 y, the incidence rate in the Main Group dramatically plummeted from 395 to 208 cases per 100 000 population (see Table 7.7). In the Control Group, the incidence rate remained practically the same and did not differ statistically from the Main Group rate. Beginning in 1975, the oncological incidence in the Main Group again starts to grow and, in 1990, it reached its second climax of 354 cases per 100 000 population. The relative risk compared to the Control Group was 2.35 ($p = 0.005$). Beginning again in 1990, the oncological incidence in the Main Group takes another dive to reach 215 cases per 100 000 population. For the Control Group, the level of cancer incidence during the same period did not change significantly. The tumours localized in the gastroenteric tract dominated the structure of the oncological incidence; the carcinoma of the oesophagus was the leading ailment in this structure, although there was a substantial change in the structure of oncological morbidity during the study period. According to the Kazakhstan national statistics, cancer of the oesophagus among the populace of the Semipalatinsk Region is a local pathology, and its spontaneous level exceeded three- or fourfold that of the national average. By 1970 (14 y after 1956), it climaxed with 186 cases per 100 000 population. Among the participants in the Control Group the cancer of the oesophagus incidence grew at a slower pace. Since 1975, a considerable decrease has been steadfastly observed in the incidence of oesophagus cancer among the Main Group, whose rate statistically equalled that of the Control Group.

During the atmospheric nuclear tests an average of 344 000 residents, primarily of the Semipalatinsk Region, were exposed to irradiation. An average of 28 000 people received doses of more than 1 Sv from the passing radioactive clouds and radioactive fallout on the ground (Table 7.8). After 1962, it was this exposed population only that became the subject of all-round research of early and delayed effects of irradiation. An average of 37 200 residents of the Semipalatinsk Region could have received doses of 0.35 to 1.00 Sv. The majority of the population, that is some 280 000 people, received doses from 0.07 to 0.35 Sv.

Naturally, any medical research and examination of health effect will have to be conducted in such a way as to differentiate population groups with real

Table 7.6 Tumour incidence among exposed and control populations (1956–1994).

		Year									
	Study groups	1956	1960	1965	1970	1975	1980	1985	1990	1994	Total
Population	Exposed		9900	9650	9125	9620	9510	9630	9320	10250	
	Control		10125	10000	11325	11265	10950	11130	11270	10950	
All sites	Exposed	7	11	29	36	20	27	28	33	22	213
	Control	6	10	14	16	17	16	17	17	17	130
Oesophagus	Exposed	5	7	16	17	10	12	11	10	7	95
	Control	4	6	6	9	9	7	6	7	6	60
Stomach	Exposed	2	1	5	7	3	4	4	6	3	35
	Control	2	1	4	4	2	3	3	3	4	26
Lung	Exposed		1	2	3	1	3	2	4	2	18
	Control		1	1	1	1	1	2	2	1	10
Leukemia	Exposed		2	4	4	2	5	3	3	2	25
	Control		2	2	2	1	3	0	2	1	13
Others	Exposed		0	2	5	4	3	8	10	8	40
	Control		0	1	0	4	2	6	3	5	21

Table 7.7 Tumour incidence rate* and relative risk§.

		Year								
	Study groups	1956	1960	1965	1970	1975	1980	1985	1990	1994
All sites	Exposed	62	111	301	395	208	284	291	354	215
	Control	65	99	140	141	151	146	153	151	155
	Relative risk	0.97	1.13	2.15†	2.79‡	1.38	1.94†	1.90†	2.35†	1.38
Oesophagus	Exposed	44	71	166	186	104	126	114	107	68
	Control	42	59	60	79	80	64	54	62	55
	Relative risk	1.04	1.19	2.76†	2.34	1.30	1.97	2.12	1.73	1.25

* Incidence rate is in cases per 100 000 persons and not adjusted by age and sex distribution.
†, ‡ Significance level of the relative risk: † < 0.05; ‡ < 0.01.
§ Incidence rate and relative risk are corrected using Table 7.6.

Table 7.8 Population around Semipalatinsk nuclear test site.

Dose equivalent (mSv)	Year									Population (10^3)	Age distribution	
	1949	1951	1953	1955	1956	1957	1958	1960	1962		0–19 y	20 y
> 1000	14.5	–	14.5	–	12.5	–	–	–	–	28.0	14 560	13 440
350–999	10.0	5.6	27.5	–	19.5	2.1	2.1	–	–	37.2	17 856	19 344
70–349	21.0	27.5	11.5	5.6	136.5†	5.7	6.1	–	–	157.0	81 640	75 360
< 70	125.0*	41.3	97.3	12.5	97.5	56.5	42.3	76.0‡	76.0‡	222.0	113 220	108 780
Total	167.5	84.4	150.8	18.1	156.0	64.3	50.5	76.0	76.0	344.0	161 120	182 880

* Including the population of the Altai Region, Russia.
† Including the population of east Kazakhstan Oblast.
‡ Including the population of Pavlodar Oblast.

but different irradiation doses from those with the same rate of disease and disorders but in the absence of radiation. From this point of view, the above comparative groups would be suitable for further cohort study. It is desirable for such a study to make a careful and objective dose-reconstruction for the non-uniform nature of exposure caused by nuclear explosion. It has to be remarked also that there should be no retroactive alterations, deletions or additions to the input data. There is a possibility in this type of study that newly added cohorts could affect the health results in such a way as to decrease the incidence in the latter half of the study period.

A cross-sectional study, an epidemiological survey in Semipalatinsk Region, by Belozerov and Dzhasybaeva from the Almaty Medical Institute of Kazakhstan, also showed an interesting result. Prevalence of general diseases in 1990 was compared between eight districts (rayons). These eight districts are rural, and consist of almost the entire Semipalatinsk Region. Equivalent radiation doses were around 0.5 Gy in three districts, 0.5–1.0 Gy in two districts, and 1.5–2.0 Gy in four districts. Kokpekty district was again chosen as a control.

From the Primary Health Documents, prevalence rates were analysed for each of the eight districts and control districts for infection and parasitosis, endocrinopathy, skin and subcutaneous tissue diseases, diseases of the blood circulation system, urinary and genital diseases, respiratory diseases, digestive disease, blood and haematogenous tissue disease, congenital malformation, mental disease, etc. The prevalence rate of each disease was summed using a weighting system for each district. The scores correlated well with the level of radiation doses, in which the higher ones are from those districts where dose levels range from 1.5 to 2.0 Gy.

The joint agreement of the governments of Russia and UK on co-operation in the fields of medicine and public health produced in 1994 a comparative study of childhood cancer incidence in four regions around STS by Zaridze *et al.* (1994). Cancer records were gathered for children aged up to 14 y diagnosed in hospitals in the Pavlodar, Karaganda, Semipalatinsk and east Kazakhstan regions. For each case, details recorded were the site of tumour, sex of the patient, resident state (urban or rural), nationality, and district of residence. The main aim for this study was the association between risk of childhood cancers and distance of residence from the STS. Fifty-five districts in all were classified into four groups with respect to the distance of residence: 400 km or more, 300–399 km, 200–299 km, and 200 km or less. For common cancers (acute leukemia, lymphomas, brain tumours, bone sarcoma and kidney cancer), data were analysed using Poisson regression, with incident cases offset by population estimates, in order to assess the extent and significance of the effect of distance from STS.

Statistically significant differences between regions were noted with respect to rates of acute leukemia, brain tumours and all sites combined. The highest rates of leukemia were in Semipalatinsk Region. Results with respect to distance

showed that there was a significant trend of increasing relative risk (1.00, 1.52, 1.65, and 2.02) with increasing proximity to STS for all sites combined. While acute leukemia makes up 36% of all cancers, it showed a modest relative risk of 1.76 associated with living less than 200 km from the STS, compared with living more than 400 km away. Factors other than distance from the STS had an effect on cancer risk. Rural residential status is associated with considerably lower risk of acute leukemia, non-Hodgkin's lymphoma and brain tumours.

7.3.2.2 Health Effects of the Nuclear Tests Conducted at the Semipalatinsk Test Site for the Population of the Altai Region

The Altai Region is an administrative unit of the Russian Federation located to the northeast of the Semipalatinsk Test Site (STS). Atmospheric nuclear tests were conducted at the STS from 1949 till 1962. Weather conditions in this region resulted in most fission products being transported towards the Altai Region (Loborev *et al.*, 1994). Over a long time the medical and demographic situation in the Altai Region has been under stress, as shown by high mortality rates, in particular, from tumours, respiratory, infectious and parasitic diseases (Shoikhet *et al.*, 1994).

To assess the impact and effects of the nuclear detonations the Government of the Russian Federation set up the 'Semipalatinsk Test Site—Altai' Federal Programme (Shoikhet *et al.*, 1994).

Fallout from 48 out of 133 atmospheric nuclear tests is presently known to have affected the Altai Region, with the greatest contribution being from the first nuclear test carried out at the STS on 29 August 1949. As a result of the fallout from this test, effective doses in certain settlements in the southwest of the Altai Region exceeded 2.5 Sv (Loborev *et al.*, 1994), with the collective dose being 32 000 person-Sv (Algazin *et al.*, 1995). Exposure was mostly acute: up to 70% of the entire external dose was accumulated within the first month after fallout, and approximately 50% effective external dose occurred within the first 4 days. The internal dose accumulated more slowly: during the first month, > 40%, during the following 3 y, > 75%.

A register of the irradiated population was compiled within the framework of the 'Semipalatinsk Test Site—Altai' Programme and now lists 40 235 exposed individuals.

Since 1992, the programme has been carrying out studies on health effects of the nuclear test conducted at the STS on 29 August 1949 for residents of affected settlements.

Risk of Mortality from Different Fallout-related Diseases Currently a vast amount of data on mortality and causes of death for 44 y after exposure among individuals exposed to the nuclear test on 29 August 1949 has been collected. On analysis, special attention is paid to the assessment of actual risks

found among irradiated individuals in comparison with risk values estimated using different projection models.

Estimations of risks of mortality from malignant tumours derived using the methodology of the latest modification of the BEIR V model (NAS, 1991) for risk analysis (BARD), which has been developed within the framework of the 'Semipalatinsk Test Site—Altai' Programme (Belyaev *et al.*, 1994), indicate that about a half of excess deaths from radiation-induced cancer due to the test of interest had occurred prior to 1994, with the other half to be expected after 1994. Time–mortality distributions for various types of radiation-induced cancer differ: excess mortality from leukemia and thyroid cancer began relatively early, to reach maximum values 10–15 y after exposure, with a maximum of cancer in respiratory organs after 15–20 y; the peak of annual mortality for other cancer types was expected much later: within 30–35 y for the female breast and within 45–55 y for other cancer types.

In order to study mortality among men affected by the detonation on 29 August 1949, permanent residents of exposed settlements were selected. The study did not include individuals who had moved out from the affected areas. Residents of 36 settlements from five Altai districts were enrolled in the study cohort. In accordance with values of mathematical expectations of probable ED (Effective Dose v. Glossary) without relation to their dispersions, four dose groups were made up. The first dose group comprised individuals with ED 0.010–0.179 Sv, the second group comprised individuals with ED 0.180–0.349 Sv, the third group comprised individuals with ED 0.350–0.999 Sv, and the fourth group comprised individuals with ED > 1 Sv. Mean ED values in groups were estimated to be 0.088, 0.244, 0.468, and 1.525 Sv, respectively.

The cohort comprised a total of 4595 individuals with the total of years at risk being 146751.89 PY (person years).

Two groups made up the control cohort. The first group comprised 1433 male residents of areas unaffected by the test of interest (three control districts). The second group included 2489 individuals who had moved to the irradiated areas after the exposure period (immigrants). The total years at risk in the control cohort was 132780.89 PY.

In order to study causes of death, copies were made from death certificates available at the Altai Region registration office issued for residents of the above settlements from 29 August 1949 till 31 December 1993. Further coding of causes of death was performed under the 'International Statistical Classification of Diseases and Health Related Problems, ninth revision' (ICD-9). The analysis covered death certificates of irradiated residents who had died in the same settlements (the main cohort), immigrants and residents of three settlements located in control districts.

The retrospective mortality study revealed no differences in mortality rates from all causes of death, between the exposed and the control cohort for the period 1949–1993. An age-at-exposure analysis showed that individuals with

Table 7.9 Assessment of risk coefficients (confidence intervals (95%) in parentheses) of mortality from non-malignant diseases among men exposed to the nuclear test on 29 August 1949 (1949–1993).

Age at exposure (Y)	Dose group			
	1	2	3	4
0–19	0.98 (0.76–1.24)	0.97 (0.74–1.18)	0.98 (0.80–1.19)	0.97 (0.59–1.49)
20–49	0.92 (0.97–1.07)	0.94 (0.84–1.10)	0.89 (0.79–1.09)	0.96 (0.85–1.19)
≥ 50	1.46* (1.21–1.75)	1.37* (1.18–1.58)	1.38* (1.19–1.59)	1.15 (0.85–1.52)
All ages	0.99 (0.89–1.10)	0.98 (0.90–1.07)	0.97 (0.89–1.05)	0.96 (0.81–1.11)

* $p < 0.05$.

age ≥ 20 y at exposure have a statistically significant increase of mortality from all causes of death. For men aged ≥ 50 y at exposure, the relative risk (RR) was 1.35 (1.25–1.45) and elevated in all time intervals. For the group aged 20–49 y at exposure, the risk of mortality from all causes of death in the main group was higher during first 24 y since exposure, with RR being 1.19 (1.08–1.81), but during last 20 y is lower than in the control cohort.

Regarding non-malignant diseases, in general, in individuals aged < 50 y at exposure, mortality rates in all dose groups did not differ from those in the control cohort. However, for persons aged ≥ 50 y at exposure, the relative risk of mortality from non-malignant diseases was significantly higher than in the control cohort practically in all dose groups and ranged from 1.15 to 1.46 (Table 7.9).

The relative risk of mortality from solid cancers of all sites for 44 y was 0.96 (0.76–1.20) for the group with mean ED of 0.088 Sv, 1.04 (0.87–1.23) for the group with mean ED of 0.244 Sv, 1.16 (0.99–1.36) for the group with mean ED 0.468 Sv, and 1.38 (1.04–1.79) for the group with mean ED > 100 cSv;. With a minimum 10-y latent period excluded from the analysis of deaths from malignant tumours that occurred earlier, elevated relative risks were observed in the third and the fourth groups of 1.23 (1.03–1.45) and 1.43 (1.04–1.91), respectively (with a minimum 10 y latent period excluded from the analysis of deaths).

The highest relative risk value was registered during first 10–29 y following the exposure, namely 1.32 (0.94–1.70) in the first group, 1.31 (1.01–1.70) for the second group, 1.52 (1.21–1.90) for the third group, and 1.84 (1.18–2.72) for the fourth group. A particularly substantial increase of this value was detected 20–29 y after exposure, when it was estimated as 1.69 (1.21–2.30) in the group with mean ED of 0.468 Sv and 2.52 (1.34–4.31) for the group with mean ED of 1.152 Sv.

Table 7.10 Assessment of risk coefficients (confidence intervals (95%) in parentheses) of mortality from all malignant neoplasms among men exposed to the nuclear test on 29 August 1949 (1949–1993).

Age at exposure (Y)	Dose group			
	1	2	3	4
0–19	0.95 (0.55–1.52)	0.57 (0.32–0.92)	1.13 (0.74–1.65)	1.03 (0.33–2.40)
20–49	0.93 (0.69–1.23)	0.95 (0.75–1.19)	1.24 (1.03–1.49)	1.56 (1.04–2.08)
≥ 50	1.17 (0.66–1.89)	1.42 (1.01–1.93)	1.00 (0.67–1.44)	1.65 (0.90–2.77)
10–59	1.01 (0.80–1.28)	0.93 (0.77–1.12)	1.26 (1.07–1.47)	1.65 (1.22–2.18)
30–49	0.95 (0.64–1.36)	0.94 (0.69–1.22)	1.45 (1.15–1.81)	1.80 (1.19–2.61)
40–59	1.14 (0.17–1.72)	1.25 (0.91–1.67)	1.55 (1.15–2.05)	2.05 (1.29–3.08)

An age–effect analysis indicated that among persons aged 20–49 at exposure, the mortality risk was significantly elevated in the third and fourth dose groups, with RR being 1.24 (1.03–1.49) and 1.50 (1.04–1.08), respectively. Relative risks of cancer mortality were estimated for the stratum 30–49 y at exposure to be 1.45 (1.15–1.81) for the group with mean ED of 0.468 Sv and 1.80 (1.19–2.81) for the group with mean ED of 1.525 Sv (Table 7.10).

Digestive and respiratory cancer were major contributors among malignant tumours. Collected data for malignant neoplasms of digestive organs demonstrate that 10–29 y following the test, there were already reliable values of the relative risk in the second, third and fourth groups, i.e. with mean ED > 0.244 Sv.

Malignant tumours of respiratory organs ranked second among rates of other cancer sites. In the first dose group they made up 30.9%, in the second group, 26.9%, in the third group, 37.7% and in the fourth group, 37.5%, i.e. they were noted more frequently in groups with higher ED. For 44 y the relative risk of mortality from respiratory cancer was derived to be 0.91 (0.51–1.34) in the dose group with ED 0.088 Sv, 0.78 (0.54–1.08) in the dose group with ED 0.244 Sv, 1.37 (1.06–1.75) in the dose group with ED 0.468 Sv, and 1.77 (1.09–2.71) in the dose group with ED > 1 Sv. Similar data were obtained when excluding the first 10 y of the latent period. In 10–29 y after the test the relative risk of mortality was significantly elevated for dose groups with ED 0.468 Sv and 1.525 Sv, being 1.71 (1.15–2.41) and 2.81 (1.45–4.92), respectively. The highest estimates were derived for the interval 20–29 y after the detonation, when it was 2.09 and 3.96 in the dose groups with ED 0.468 Sv and 1.525 Sv, respectively.

Thus, during the first 24 y men aged > 20 y at exposure had an elevated risk of overall mortality: the relative risk of mortality was 1.16 (1.05–1.27) for the cohort 20–49 y at exposure and 1.34 (1.23–1.45) for the cohort $\geq$ 50 y at exposure.

Prevalence of Chronic Non-malignant Diseases The study's main cohort comprised men and women from the registry of the Institute of Regional Medico-Ecological Problems, Barnaul. These people lived in the same settlements and survived till 1 January 1993. Residents of 33 settlements of five Altai districts were chosen for the cohort and divided into three dose groups in accordance with levels of mathematical expectations of probable effective doses without relation to their dispersion. Residents of 12 settlements of five districts with ED 0.010–0.179 Sv were assigned to the first group, residents of 14 settlements of three districts with ED 0.180–0.349 Sv were assigned to the second group, residents of seven settlements of two districts with ED $\geq$ 0.350 Sv were assigned to the third group.

A total of 5063 individuals (2054 men and 3009 women) was drawn for the main cohort with the ratio of men to women being 1:1.46.

The control cohort consisted of two groups of individuals who matched the study group in age, that is they were born before April 1950. Residents of 21 settlements of nine northwestern, northern, eastern and central Altai districts not affected by the test of interest were enrolled in the first group. The second group comprised individuals who had arrived at the exposed areas after the detonation. They lived in 16 settlements of four irradiated districts.

The controls consisted of 9921 individuals (4005 men and 5916 women) with a ratio of men to women of 1:1.35.

Total prevalence rates of diseases of the endocrine, nervous, cardio-vascular, genito-urinary, osteomuscular systems, diseases of respiratory and digestive organs, the skin and subcutaneous fat, nervous disorders in all dose groups of the main cohort exceeded the rates in the control cohort. Among exposed subjects the highest prevalence for all diseases was found in the group with maximum ED (in the third group) while the lowest prevalence rate was registered in the second group, with the first group occupying an intermediate position. This was characteristic for men and women in all age strata. Whereas the total prevalence of diseases of all the above classes among male controls was 3341.3 (3274.4–3408.1), in the third dose group it was 6376.5 (6181.4–6583.4), in the first dose group it was 4970.4 (4778.0–5179.0) and in the second dose group it was 4050.7 (3875.9–4210.0), i.e. RR was 1.91 (1.85–1.97), 1.49 (1.43–1.55) and 1.21 (1.16–1.26), respectively. For women in the dose group with the maximum ED (the third group), RR ranged from 1.87 to 1.96, in the first group it ranged from 1.55 to 1.65 and in the second group it ranged from 1.28 to 1.36 as compared with the control cohort. It is noteworthy that prevalence of a total of diseases among women exceeded that in men in both main and control cohorts.

A similar picture could be seen in the totality of diseases of inner organs (diseases of the endocrine, cardio-vascular, genito-urinary systems and diseases of respiratory and digestive organs). The RR in men was 1.84 (1.75–1.93) in the third dose group, 1.41 (1.32–1.50) in the first group, and 1.12 (1.06–1.18) in the second group, whereas in women it was 1.96 (1.91–2.02), 1.56 (1.50–1.62) and 1.29 (1.25–1.34), respectively. It is notable that individuals exposed as children (under 15 y of age) ran a higher risk of all diseases. In the third dose group the RR for the totality of all diseases was 2.03 (1.93–2.13) among men aged < 15 y at exposure, and 1.78 (1.70–1.87) for men aged > 15 y at exposure, while among women it was 1.97 (1.90–2.05) and 1.83 (1.78–1.88), respectively.

The prevalence of all diseases of the endocrine system, digestive, metabolic and immune disorders (class III, ICD-9) among women in all dose groups was higher than in the control cohort, maximum estimates being in the third dose group. Among women exposed as children to highest doses (the third group), RR was 2.73 (1.97–3.28), 2.17 (1.72–2.65) in the first group and 1.69 (1.38–2.06) in the second group, and among individuals at age > 15 y at exposure, RR was 2.27 (1.91–2.64) for the third, 1.83 (1.39–2.32) for the first, and 1.53 (1.24–1.90) for the second dose groups.

Among men, an elevated risk of the diseases of this class in general was constantly registered in all age strata exclusively in the dose group with the highest ED (the third group), while such a risk was found only for individuals exposed as children in the other two dose groups. Estimation of prevalence of thyroid diseases showed that despite being the same among women in all dose groups, prevalence rates were considerably higher in both age strata than in the control cohort. In general the RR with these diseases was 3.69 (2.84–4.80) for the first, 2.48 (1.90–3.22) for the second and 3.05 (2.39–3.87) for the third groups.

Prevalence of circulatory diseases among men in the first and third dose groups exceeded that among controls in all age strata, with RR for the entire male cohort being 1.66 (1.55–1.77) in the third and 1.40 (1.29–1.52) in the first dose group. Prevalence in the second group did not differ from that of the control cohort. Unlike men, an elevated risk of all circulatory diseases was noted among women in all age and dose groups. It attained highest values in the third dose group and was 1.94 (1.86–2.02) for the entire cohort. The minimum value of the risk was derived in the second dose group at 1.25 (1.17–1.32), the first dose group occupied an intermediate position, with the risk being 1.67 (1.57–1.77).

Prevalence studies of respiratory diseases indicated that only men in the third group had an elevated risk for the totality of diseases of this class, being 1.69 (1.48–1.92) and 1.39 (1.19–1.61) for individuals aged under and above 15 y at exposure, respectively.

For the totality of digestive diseases as well as for some specific diseases of this class (ulcers, chronic gastritis, chronic diseases of the liver and cirrhosis,

cholelithic disease and chronic cholecystitis) the risk was elevated among men in the first and third dose groups in all age strata and in the second group only among men exposed as children. The RR was 1.81 (1.61–2.03) for the totality of digestive diseases, respectively 2.40 (1.85–3.12) and 1.56 (1.05–2.23) for the gastric and duodenal ulcer, 2.29 (1.97–2.66) and 1.74 (1.42–2.12) for chronic gastritis, 2.60 (1.31–4.16) and 2.23 (1.62–2.99) for chronic diseases of the liver and cirrhosis, 3.11 (2.66–3.64) and 1.96 (1.56–2.45) for cholelithic disease and chronic cholecystitis. In case of diseases of the intestine, in the third and second dose groups, elevated risk was noted at any age at exposure but in the first group only among individuals with age < 15 y at exposure.

The prevalence study of diseases of the genito-urinary system among men demonstrated that for the totality of the diseases it was higher than among controls, in all age strata in the first and third dose groups and among men irradiated as children in the second group. Individuals exposed as children ran a higher risk than those aged > 15 y at exposure, e.g. in the third group RR was 3.76 (2.89–4.89) and 1.48 (1.13–1.92), respectively. A similar situation could be seen in the other two dose groups.

Neurotic disorders (neuroses, neurocirculatory distonia) among both sexes were more frequently registered in the second and third groups, the latter having the highest prevalence. For men of the third group relative risk was 3.34 (2.94–3.54) and among women it was 1.63 (1.43–1.85), while in the second group it was 1.44 (1.17–1.76) and 1.30 (1.12–1.50), respectively. Subjects irradiated as children had a higher risk, which was 4.26 (3.12–5.09) among men and 2.26 (1.96–2.60) among women, being 2.18 (1.68–2.82) and 1.05 (0.83–1.31) among men and women at age > 15 y at exposure, respectively.

In cases of diseases of the eye and its annexes among both sexes, only in the third group was risk elevated, being 1.67 (1.21–1.80) and 1.64 (1.43–1.74), respectively. Risk rates of the age strata showed no differences.

Special attention was paid to a pathology such as the cataract. Its highest prevalence was found in the third dose group, being 2.01 (1.67–2.41) for men and 2.35 (2.11–2.63) for women.

The analysis of diseases of the osteomuscular system demonstrated that risk was significant in general for class X (ICD-9) as well as for some groups of diseases (arthropathies and osteochondropathies) among both sexes in all dose groups, especially in the first group.

The analysis indicated that prevalence of diseases of the endocrine, nervous, cardio-vascular, genito-urinary, osteomuscular systems, respiratory and digestive organs, the skin and subcutaneous fat, and mental disorders among exposed persons exceeded that of the non-exposed persons for both sexes and in all age-at-exposure groups. Most substantial values were found among individuals irradiated as children to doses 0.350–1.809 Sv. The prevalence of diseases was higher among women than among men in all age and dose groups.

7.3.3 Marshall Islands, Pacific, USA

From 1946 to 1958, 66 atomic weapons with a total explosive yield of more than 100 Mt were detonated at two atolls (Bikini and Enewetak) of the Marshall Islands. Due to misjudgements in weather predictions, a large thermonuclear test on 28 February 1954 (Bravo, 15 Mt) led to the contamination of the inhabited islands of *Rongelap, Allingnae* and *Utirik*. Despite an earlier routine of temporary relocations, financial constraints and experiences from the first thermonuclear blast had led to a change in policy, requiring evacuations only if justified by local fallout (Cronkite *et al.*, 1997). Due to an unpredicted shift in winds and concomitant problems with cloud-tracking planes, information on the amount of unpredicted fallout emerged slowly and evacuation by plane and ship took place only on 3 March. At Rongelap, about 200 km away from Bikini, external gamma doses in air were in the range of 1.9 Sv. Extremely high organ doses resulted from short-lived iodine and tellurium. For *Rongelap*, average thyroid doses for adults, children of 9 y and children of 1 y were estimated at 12, 22 and 52 Gy. Maximum values for the same age groups reached 42, 82 and 200 Gy, respectively. Doses lower by about a factor of seven were received by the Utrik population (Simon, 1997; Howard, 1997). The number of highly exposed persons was 249, 12 were exposed *in utero*. Exposures of inhabitants at other atolls in the Marshall islands are estimated to be considerably lower.

7.3.3.1 Acute and Deterministic Health Effects

About 25% of the Marshallese but only 5% of the military personnel experienced itching and burning of the skin from high surface beta doses. Skin lesions, ulcers, which subsequently became infected, and sometimes patchy epilation (hair loss) occurred (Cronkite *et al.*, 1997). After healing, depigmented scars, particularly on the feet, were evident. Bathing, changing of clothes or wading in the sea was shown to reduce skin effects considerably. Blood counts showed a reduction of granulocytes to about one-fourth of the normal values. Due to low platelet counts, few cases of excessive bleedings developed. One of five women pregnant at time of exposure experienced a stillbirth.

In view of the highly visible acute effects, considerable but sometimes poorly coordinated efforts were undertaken to secure proper long-term medical care for those affected. Cultural barriers and growing bitterness and resentment towards the USA even led to a temporary boycott of medical teams. Later findings include a slight increase in miscarriages and stillbirths. Regular examination of the eyes did not show radiation-induced cataracts. Some children, especially boys less than 10 y of age lagged in growth. It was shown that this was a result of hypothyroidism and subsequent thyroxin therapy was able to correct growth deficiencies. Thyroid dysfunction was the major late effect. Since 1966 the exposed Marshallese population is on a lifetime thyroxine

replacement therapy in the hope of reducing the development of malignancies of the thyroid gland.

7.3.3.2 Long-term Health Effects

As expected from the high organ doses, a considerable increase in benign and malignant thyroid conditions was recorded (Howard *et al.*, 1995). In the most heavily exposed groups from Rongelap and Ailinginae, comprising 86 people, 23 developed benign thyroid nodules and five developed thyroid cancer. In the highest exposed group, nodule prevalence rose quicker and reached 59% in children under the age of 10 at the time of the bomb. In retrospect these findings were first indications of the higher sensitivity and lower latency for thyroid carcinomas in young children, as found later in the near-field of Chernobyl. A study by Hamilton *et al.* (1987) also considered possible effects on the thyroid gland in people living on 12 additional atolls in the Marshall Islands previously considered unexposed. A relatively high prevalence of thyroid nodules was also found on Likiep, Wotje, Lae, Ujae and Wotho. A correlation of nodule occurrence both with distance from Bikini and angle from main fallout trails was postulated. The prevalence rate seemed to decrease approximately threefold for every 160 km distance and twofold for every 10° angle. Preliminary results from further studies show similar but non-significant findings (Fujuimori *et al.*, 1996; Takahashi *et al.*, 1997).

In view of the small group affected, increases in the incidence of other malignancies will be difficult to discern. One case of myeloblastic leukemia developed in a boy aged 19 y, exposed to 1.9 Gy at 1 y of age. The probability of a radiation causation is to be considered high.

In addition to the direct biological effects of ionizing radiation, psychosocial stress from displacement and major changes in lifestyle, diet, job opportunities, etc. is an important factor in the affected Marshallese communities. Some of them have been subjected to repetitive relocation ('nuclear nomads') leading to major psychological trauma.

7.3.3.3 Japanese Fishermen

The Bravo explosion also exposed 23 fishermen aboard a Japanese fishing vessel, the *Fifth Fukuryu Maru* (the *Lucky Dragon*). The distance from ground zero to the ship was only 190 km at the time of explosion. Starting about 3.5 h after the explosion, white ashes began to fall on the vessel and continued for several hours. The crew fell sick, returned to their home port and were subsequently hospitalized with acute radiation syndromes in Tokyo. Early measurement data indicated a specific activity of up to 4×10^{10} Bq g^{-1} in the coral reef ashes that fell on the ship (Kumatori *et al.*, 1980). Estimates of the resulting external doses for individual members of the crew ranged from 2 to 7

Gy for two weeks. High skin contaminations were found on unprotected parts of the body. Thyroid doses from inhaled and ingested ^{131}I, ^{133}I, and ^{135}I were estimated from measurements after return. The internal contribution was in the range from 0.8 to 4.5 Gy. Since most of the dose was delivered by short-lived fission products, acute effects, such as prodromal syndrome (fatigue, headache, nausea, vomiting, diarrhoea, anorexia), conjunctivitis, skin lesions, and epilation occurred. Haematological changes were examined from 16 March and were compatible with the above dose estimates. One fisherman died a few months after exposure, probably due to serum hepatitis contracted in the course of numerous blood transfusions (Kumatori *et al.*, 1980). Examinations of spermatopoiesis showed a drastic decrease in the number of spermatozoa in all cases that were examined. Recovery took up to 2 y. Thirty-six healthy children were born to the crew members in the 13 y following the incidence. Two spontaneous abortions and one stillbirth, all in the period 1956 to 1960, were recorded (Eisenblud, 1997). With the exception of residues of skin lesions and slight disturbances of liver function in several fishermen, the long-term follow-up showed that the health status of the cohort returned to normal.

7.3.4 Novaya Zemlya

The near-field of Novaya Zemlya, the second of two major atmospheric bomb test sites in the former USSR, was evacuated before the onset of the nuclear tests; accordingly, no acute human radiation exposures were reported from this area. However, the large amounts of fission products released to the environment led to an elevated deposition of ^{137}Cs, ^{90}Sr, and other longer lived radionuclides in territories beyond 60° N latitude, especially in the Murmansk province, the northwestern Russian districts of Nenetsk, and Komi ASSR (Ramzaev *et al.*, 1993). The lichen–reindeer–human foodchain caused internal exposures in reindeer breeding communities up to 10 mSv effective dose per 3.7×10^9 Bq km^{-2}. About 30 000 persons in the far North of Russia were thought to consume 250 g of venison per day. Another 300 000 persons in small northern communities still have elevated consumption rates compared with city dwellers. A maximum measured body burden of 1.8×10^5 Bq (5 μCi) causes an annual dose of 8 mSv (Ramzaev *et al.*, 1993). Cancer death rates in the native population of the far north are quite high. For all cancers and for oesophagus, rates of 276 and 131 per 100 000 y^{-1} are reported, where the All-Union values are 125 and 6.9, respectively (Ramzaev *et al.*, 1993). However, a comparison of the cancer rates in the different regions of the far north showed a negative correlation with ^{137}Cs body burdens of reindeer and humans, the eastern regions Yakutia and Chukotka showing the lowest ^{137}Cs values but displaying the highest cancer rates (Ramzaev *et al.*, 1993). Climate stress and an unhealthy food basket was shown to correlate much better with elevated oesophageal cancer.

7.3.5 Australia (Maralinga, Emu, Monte Bello Islands)

Operations involving only devices with yields in the kiloton (kT) range took place off the Monte Bello Islands in Western Australia, or at Emu Field or at the Maralinga Range in South Australia. There were 12 separate detonations with total yields at each site of 100 kT (three tests), 18 kT (two tests) and 61.5 kT (seven tests) respectively. In addition there was an experimental programme, mostly at the Maralinga Range, which comprised a series of minor trials together with clean-up operations. This resulted in a long-term local problem near ground-zero sites from the dispersal of about 25 kg ^{239}Pu in the course of small-scale experiments with non-nuclear explosions. In view of the low estimated maximum individual doses of less than 1 mSv, no visible health effects are to be expected. The resulting collective dose for the entire Australian population is estimated at 700 person-Sv and therefore only a fraction from the dose resulting from global fallout from atmospheric testing in Australia (Wise and Moroney, 1992). Personnel from the UK were based at the last locations for the trials, and personnel responsible for the aircraft that sampled radioactive clouds from the explosions were based in Western Australia.

7.3.6 Malden and Christmas Islands, UK and USA

Operations with higher yields took place at Malden Island and Christmas Island in the Pacific. There were nine separate detonations with total yields at each site of 1.22 Mt (three tests) and 55.6 Mt (six tests) respectively. No critical exposures or health effects to native inhabitants were reported.

7.3.7 Algeria

Four fission tests, containing one of medium energy (67 kt) and three of low energy (3, 2, and 0.7 kt, respectively), in the desert zone of southwest Reggane in the Algerian Sahara marked the beginning of the French nuclear tests programme. Very little information on dosimetric data or local contaminations of agricultural systems from these four tests has been published. It is possible, however, that beginning with some measurement of radionuclide concentrations in the atmosphere arising from personal archives (Doury, 1960, 1961), and from simple calculation, to proceed to some tentative dose reconstructions from which general tendencies can be deduced. Out of the first four French tests only the first one needs attention, with radiological consequences estimated at few mSv to a small number of people. Populations or agricultural areas possibly concerned were remote enough from ground zero or possible fallout trajectories.

7.3.8 French Polynesia (Fangataufa and Moruroa)

Moruroa and Fangataufa, the atolls where the French army performed 44 atmospheric nuclear tests from 1966 to 1974, are situated in the Tuamotu–Gambier archipelago, which is the largest and the most sparsely populated archipelago in Polynesia. The Gambier islands, and atolls of the Tureia, Hao, Tekakoto, Reao and Nukutavake communes are less than 500 km from Moruroa. All these atolls are within the 140° part of the circle stretching from east-southeast to north-northeast of Moruroa. Hence they are more likely to have been contaminated by the nuclear tests, which were optimized to preserve Papeete, 1250 km west-northwest from the test site.

De Vathaire and le Vu (1996) studied overall and cancer mortality in French Polynesia between 1984 and 1992 giving special attention to possibly exposed and non-exposed communities in the Tuamotu–Gambier archipelago. In the study period 8217 deaths were registered in a mainly Maori population of about 160 000. The age-standardized annual mortality rate was 1098 and 769 per 100 000 for males and females, respectively. A large fraction of cause of death was poorly specified, ranging from 21% in the Society islands to 62% in the Tuamotu–Gambier archipelago. A total of 1222 cancer deaths were registered, leading to an annual death rate of 167 and 131 per 100 000 for males and females, respectively. Female cancer mortality rates were above average in the Tuamotu–Gambier region. The excess was due to cancers of the digestive tract, lung, genital organs, and breast cancer. A comparison of rates between possibly exposed and non-exposed communities in the Tuamotu–Gambier archipelago yielded no indications of an increase in those islands and atolls located less than 500 km from Moruroa. Because of the small population involved (11 000 persons), the power of this comparison is very low. Cancer rates in French Polynesia, among Maoris in New Zealand and Hawaiians in Hawaii were found to be quite similar. However, mortality due to lung and digestive tract cancers for both sexes and to prostate cancer for males was lower, whereas death rates attributed to oral cavity and bladder cancers in men and to thyroid cancer in females were higher in French Polynesia.

In July 1996 a cancer incidence study was started by unit 351 of the French National Institute of Health and Medical Research.

7.3.9 Lob Nor, China

The Chinese test site in Lob Nor, Sinkiang, western China, experienced 22 tests with a total yield of 22 Mt. It seems that thanks to a late start of the nuclear testing programme in 1964, the threat of exposure to local populations was well known and properly taken into consideration. Five small (0.02 Mt each) and a larger test of 0.3 Mt were detonated on the surface. Only limited information is available on local deposition following the tests. Available information on

unshielded external exposures in the range up to 0.5 mGy (Zheng *et al.*, 1996), on internal doses, from ^{90}Sr and ^{131}I (< 2.5 mSv thyroid dose and < 0.13 mSv effective dose), indicate that cumulative effective and thyroid gland doses were generally too low to produce significant health effects. Estimates of external doses in areas 400 to 800 km downwind from the test site in Ganso Province ranged from 0.02 to 0.11 mSv, with an average of 0.04 mSv. Whether small nomadic local communities, for example those depending heavily on dairy products from sparsely vegetated areas, might have surpassed the above values remains to be elucidated.

7.3.10 Other Sites

Additional test sites with little or no open literature on local contaminations include:

1. the first US test on 16 July 1945 in New Mexico;
2. four US tests in the Pacific Ocean, including two underwater explosions;
3. three US high altitude rocket tests in the Atlantic (38° to 50°S);
4. a large number of US rocket and air drop tests near Johnston and Christmas Islands;
5. two USSR tests near Totsk, Aralsk.

Although media reports from unverified sources indicate additional secret small atmospheric bomb tests outside the areas considered in the preceding sections, no local contaminations and therefore no local exposures and health effects are known. Claims on the explosion of a device during military exercises in the former USSR and on an Israeli/South African test in the Southern Indian Ocean belong to this category.

7.3.11 Test Participants

Personnel involved in setting up and evaluating the explosions were subject to external exposures and contaminations, especially in the early tests. Military units and ships belonging to the navy were sometimes close to explosions, as it was their duty to secure the sites, but sometimes also quite simply because of the immense interest caused by the early tests. Little is known about dose recordings from the earliest bombs. Especially in the course of these tests, it has to be assumed that in all affected nations a considerable number of technical personnel, military servicemen and others were exposed to various levels of radiation. There are a few study groups, for which declassified material is available. Assessments of exposures and of health status—in comparison to national statistics—were published in the open literature in the case of British

and US (Johnson *et al.*, 1996) test participants. Despite the considerable interest and media coverage in the UK and USA for this topic, individual doses are generally below those experienced by the most affected civilians. Information on the Chinese, French and former USSR experience is not available at this time.

7.3.11.1 British Test Participants

Over 27 000 persons took part in the UK tests; the largest proportion of men (39.5%) came from the Royal Air Force (RAF), with rather smaller proportions from the Royal Navy (RN), and the Army (29.5% and 27.1%, respectively). Less than 4% of the men were civilians. Only a minority of test participants (11.2%) were National Servicemen and two-thirds of these were in the Army. Overall, about one man in seven was an officer (here civilians of social class 1 are included with officers). The ratio of officers to other ranks was about one to ten in the RN and the Army but about one to five in the RAF. The operations that took place at the Monte Bello Islands chiefly involved the RN. The RN also supplied almost half the personnel for Operation Grapple. For operations at the Maralinga Range, and also for the later operations at Christmas Island, the RAF supplied the largest number of men. The Army provided support in all test locations. The proportion of visits that were made by AWE (Atomic Weapons Establishment) personnel was small at all operations except Totem at Emu Field. About three-quarters of test participants were involved in only a single operation, but a few participated in as many as eight. Civilians tended to be involved in more tests (average of two per man) than servicemen (average of 1.3 per man).

A large analysis of the health status of the test participants has been published (Darby, *et al.*, 1993), which involved comparing the mortality and incidence of cancer in 21 358 men who took part in the tests with those in 22 333 controls and followed up to 1991. In the period more than 10 y after initial test participation, mortality was found to be low compared with that expected from national rates both for all neoplasms and for all other causes of death (SMRs of 0.84 and 0.82, respectively), and rates in test participants and controls were very similar (RR = 0.97, 90% CI 0.91, 1.04 for incidence of all neoplasms and RR = 1.02, 90% CI 0.96, 1.08 for mortality from all causes of death other than neoplasms). Rates were also examined for leukaemia and 26 other types of cancer, and for 15 other causes of death. It is concluded that participation in the nuclear weapon testing programmes has not had a detectable effect on the participants' expectation of life, or on their risk of developing cancer or other fatal diseases. The suggestion from a previous study that participants may have experienced small hazards of leukaemia and multiple myeloma was not supported by further follow-up, and the excesses observed previously are likely to have been a chance finding, although the

possibility that test participation may have caused a small risk of leukaemia in the early years after the tests cannot be completely ruled out.

The total collective gamma dose recorded for test participants in the study was 17 person-Sv. The largest contribution was for Operation Grapple Z, for which a collective dose of 3.8 person-Sv was estimated.

7.3.11.2 US Servicemen and Weather Observers

Operation CROSSROADS (the first two tests in the Marshall Islands and the world's fourth and fifth atomic explosions) were conducted at Bikini Atoll in 1946. Over 40 000 US military servicemen were observers and participants. Some servicemen boarded ships soon after the tests, washed radioactivity from the decks and completed various tasks and experiments. Only in 1985 the Congress of the United States ordered epidemiological studies. Mortality experience of those servicemen was evaluated by the US National Research Council (Johnson *et al.*, 1996) by comparison with a similar cohort of non-participating veterans. All-cause mortality of the participants was slightly increased over non-participants by 5% ($p < 0.001$). Smaller increases in participant mortality for all malignancies (1.4%, $p = 0.26$) or leukemia (2%, $p = 0.9$) were not statistically significant. In the absence of individual doses, activities such as boarding target ships after the test were taken as a surrogate of exposure. The slight increase in mortality remained stable across these groups. Therefore, it was concluded that these results do not support a hypothesis that radiation had increased cancer mortality over that of non-participants (Johnson *et al.*, 1996).

Twenty-eight US Army and Air Force weather observers were affected by the Bravo fallout on Rongerik Atoll. Evacuation 22 to 28 h after onset of fallout and decontamination procedures helped in keeping external doses in the range of 330 to 430 mSv. Organ doses from incorporated radionuclides were estimated at 2.3 Sv and 1.15 Sv for the thyroid and the lower large intestinal wall, respectively. No information on health consequences in this cohort is available at this time (Simon, 1997).

7.3.12 Global exposures

Dose assessments (see Chapter 6) show that dose rates and annual doses from weapons test fallout averaged over the world's population always remained a small fraction, i.e. less than 10%, of natural and civilian anthropogenic exposures. Thus, possible health risks were and will always be much too small to be discernible except in those localized populations discussed in earlier sections. A comparison of the collective committed effective dose to the world population from fallout (about 3×10^7 person-Sv (UNSCEAR, 1993)) with other global sources of ionizing radiation indicates that the total hypothetical risk to human

health from atmospheric bomb tests equals that from 2.4 y of global exposures to ionizing radiation from all other sources. This excess exposure and its potential effects are spread over thousands of years due to the important contribution of long-lived ^{14}C. Using an ICRP cancer risk coefficient of 5×10^{-2} Sv^{-1} and assuming a linear dose–effect relationship down to annual doses in the range of a few mSv, the global health effects from the collective committed dose from atmospheric testing would convert into 1.5 10^6 deaths over the next 10 000 y. In view of the many uncertainties involved, the wisdom of such projections is rightfully disputed.

7.4 INTERCOMPARISONS AND VALIDATIONS

A widely accepted assessment of the environmental and health effects of atmospheric bomb tests will have to be based on validated local and national databases. Declassification of important data is under way in most areas. In order to harmonize the raw data and to allow pooling of findings from individual experiences, independent assessments of the information available are needed. In many cases, data gathered for strictly military purposes will have first to be transformed, to be of use for radioecological modelling. Up until the present, international involvement in the analysis and remediation of the effects of atmospheric bomb tests is nil in most afflicted areas. Given the high level of professionalism within the teams involved in all aspects of atmospheric bomb tests, intercomparisons will probably not produce significant corrections to classified or already available evaluations of environmental and health effects. For example, a first intercomparison exercise between two Russian institutes and a German institute to measure ^{137}Cs, ^{90}Sr, and ^{239}Pu in the environment, showed little variation between the results obtained by the different laboratories. This finding stands in positive contrast to the experience of IAEA after Chernobyl, where results of ^{90}Sr measurements from local laboratories were sometimes erratic, and generally overestimated the actual contamination.

Health records are available for certain periods from some of the areas affected by atmospheric bomb tests. Military and political secrecy interfered with health related research, but there is no evidence of bias or tampering with primary data. In line with different developments of biomedical sciences in different countries, classification schemes for medical diagnoses and pathology differ sometimes between the former Eastern bloc and Western countries. For early occurring responses, such as acute deterministic effects and leukemias, a quantitative picture of radiation-induced changes in population health may have to be reconstructed from scant and sometimes incomplete data. As in the case of shorter-lived radionuclides, any loss of time in approaching these unsolved aspects will diminish the chances for a trustworthy and open evaluation of radiological assessments of the past.

7.5 CONCLUSIONS

Fifty years after Hiroshima and Nagasaki and the ensuing nuclear arms race, the open assessment of past, present and future health risks from atmospheric bomb tests is an important responsibility of the global scientific community. Considerable suffering was created first by poor professional judgements but later also by secrecy, neglect, and a lack of responsibility by many in charge of the bomb tests. Table 7.11 sums up critical health effects noticed in the most heavily exposed groups in the near-field of atmospheric tests, or anticipated from information on radiation doses experienced due to radioactive clouds and fallout. At this time, practically all exposures of significance to individuals residing in the near-field of atmospheric bomb test sites have already been received. Thus, prevention of additional exposures is now mainly restricted to ground-zero sites. Projections of health effects based on dose assessments were substantiated by acute radiation effects in the most highly exposed cohorts. Since the potentially more important stochastic risks, such as cancer or hereditary diseases, express themselves only years to decades after exposure, a validation of the predictions of this class of damage can only result by long-term follow-up of the potentially affected populations, and on a projection of future risk. Table 7.12 gives an overview of the most critically affected populations. Table 7.6 indicated the first results from some of the epidemiological studies of persons exposed in the near-field of the tests.

A provisional account of collective doses in populations greatly affected by local fallout from atmospheric bomb tests indicates up to 40 000 person-Sv in about 100 000 persons. Using UNSCEAR (UNSCEAR, 1994) risk coefficients for high dose/high dose rate exposures, about 4000 excess cases of radiation-induced death may result from these exposures. Based on provisional data from the former USSR, most of the cases would occur as a result of exposures around Semipalatinsk. These projections assume that a considerable part of excess morbidity and mortality is still to be experienced in coming decades. Renewed efforts, mainly in so far poorly assessed areas of the former USSR, are needed to properly assess exposures and health effects and to establish a system of health care and compensation for those suffering from the tests.

In addition to projected health risks from exposures to ionizing radiation, psychosocial stress resulting from fear, secrecy and poor information, may have had a negative influence on public health. To help populations in coping with somatic and psychosomatic effects of the atmospheric bomb tests, a health care system with specialized services needs should be set up in all affected areas. Cancer and birth-defect registers are also needed so that all information can be collected and made available for analysis. Risk assessments for radiation protection at the workplace, in medicine, and at home have to rely predominantly on epidemiological data from cohorts and/or exposure

Table 7.11 Summary table of critical health effects experienced in populations exposed to atmospheric testing.

	Health effect	Exposure path	Critical populations	Examples
Acute radiation effects	Nausea, diarrhoea	Whole-body irradiation from cloud and ground contamination	Natives not instructed to shelter	Marshallese, near-field of Semipalatinsk, fishermen
	Skin burns, skin ulcers	Skin contamination with fission products	Natives, especially children not instructed to decontaminate	Marshallese, near-field of Semipalatinsk, fishermen
	Epilation	Scalp contamination with fission products	Natives, especially children not instructed to decontaminate	Marshallese, near-field of Semipalatinsk, fishermen
	Temporary thyroid dysfunction	Inhalation and ingestion of short-lived iodines	Children drinking local milk, eating local produce	Marshallese, near-field of Semipalatinsk*
	Temporary sterility	Whole-body irradiation	Sexually active males	Fishermen
	Miscarriages	Whole-body irradiation	Pregnant women	Near-field of Semipalatinsk*
	Birth defects	Whole-body irradiation during organogenesis	Embryo/fetus in weeks 8 to 16	Near-field of Semipalatinsk*
Protracted deterministic effects	Growth retardation from chronic hypothyroidism	Inhalation and ingestion of short-lived iodines	Children drinking local milk, eating local produce	Marshallese, near-field of Semipalatinsk*
	Scars	Skin contamination with fission products	Natives, especially children not instructed to decontaminate	Marshallese
Stochastic effects (cancer, effects in next generation)	Leukaemias	Whole-body irradiation	Children	Near-field of Semipalatinsk*
	Thyroid tumours and carcinomas	Inhalation and ingestion of short-lived iodines	Children drinking local milk, eating local produce	Marshallese, near-field of Semipalatinsk
	Other solid tumours	Whole-body irradiation	Higher risk in children	Near-field of Semipalatinsk*
	Genetic effects	Gonadal exposure at younger age	Prospective parents	Effect too small to be seen against large background

* Not yet validated.

Table 7.12 Estimates on affected populations and collective doses.

Test	Population near-field (> 250 mSv effective dose)	Collective dose (person-Sv)	Reference
Bikin (Bravo)	245 (Islanders)	160	(Eisenblud, 1997)
	23 (Japanese fishermen)	80*	(Kumatori *et al.*, 1980)
Semipalatinsk	10 000 (near-field)	(20 000)	
	40 000 (Altai)	(20 000)	(Loborev *et al.*, 1994)
UK tests	21 400 (test participants)	17	

* Educated guess.

situations quite atypical for routine radiation protection. The most important data set covering the full range of age groups—the survivors of the bombings of Hiroshima and Nagasaki—is the result of a single radiation flash lasting only seconds. Differences in effects per unit dose, between such an instantaneous exposure and chronic irradiation, were shown to be large with regard to most biological endpoints in experimental systems, but are difficult to transfer to humans. Here, local exposures from atmospheric bomb tests may potentially allow improvement of the human database in the direction of more relevant exposure situations and may contribute to narrowing down uncertainties for DDREFs for the most important organs and sites in radiation carcinogenesis. Possibly important confounders, such as ethnicity leading to different lifestyles, or different genetically determined susceptibilities, may also be addressed.

In view of the large data sets already gathered by national specialists, international collaboration should first concentrate on the analysis of available data. Only after a careful assessment of available information on contaminations, doses and health effects it is possible to proceed towards additional activities for validation exercises and for supplementary efforts in dose reconstruction and recording and classification of health effects. Theoretically, all important contributions to the collective dose may be reconstructed, but cost and time constraints will often prevent a full retrospective assessment. Direct measurements that can be useful include fallout patterns of long-lived fission and activation products, thermoluminescence dosimetry on tiles and bricks from buildings inhabited at the time, and modern biological and biophysical methods, such as FISH (fluorescence *in situ* hybridization) for stable chromosomal aberrations or ESR on tooth enamel or dentin as an indicator for individual cumulative doses. Internal exposures from ingested and inhaled radionuclides are important in some cases, but difficult to assess retrospectively. The level of ^{90}Sr may still be measured in autopsy samples, or directly in heavily exposed individuals, as shown recently. For potentially important contributions from ^{131}I and ^{137}Cs, only indirect methods are feasible at this time.

Table 7.13 Selected epidemiological studies and first results.

Region	Population	Study design	Cohort size	Status	Results	Reference
Bikini	Islanders	Cohort	245	Ongoing	Acute effects, thyroid tumours and carcinomas	(Cronkite *et al.*, 1997)
	Japanese fishermen	Cohort	23	Ongoing		
	Servicemen	Cohort	40 000	Published	Acute effects, skin lesions (slight increase in overall mortality)	(Johnson *et al.*, 1984)
Nevada	Utah	Case-control	1177	Published	(Slight increase in leukemia)	
	Utah/Nevada	Cohort	2473	Published	Borderline significant for benign and malignant thyroid gland neoplasms considerable, relative increase in leukemia mainly due to low rates in control	
	Utah	Geographical		Published		
Semipalatinsk	Near-field	Cohort	10 000	Ongoing	Acute effects, thyroid carcinomas, 'most cancers'	(Rosenson *et al.*, 1996)
	Altai	Cohort	40 000	Ongoing	'Most cancers'	
UK tests	Test participants	Cohort	21 400	Published	No effects in latest follow-up	

* Not significant, 'causal relation or claim doubtful'.

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REFERENCES

Algazin, A. I., Demin, V. F., Gordeev, K. I., Guryeva, V. A., Kiselev, V. I., Lazarev, A. F., Loborev, V. M., Shoiket, Ja. N. and Sudakov, V. V. (1995) Radiation impact of nuclear weapon tests at the Semipalatinsk Test Site on the Altai Region population. *International Symposium of Environmental Impact of Radioactive Releases*. IAEA-SM-339/82, International Atomic Energy Agency, Vienna.

Beck, H. L. and Krey, P. N. (1983) Radiation exposures in Utah from Nevada nuclear tests. *Science*, **220**, 18–24.

Belagev, S. T., Deronim, V. F., Shoiket, V. I., Kiselev, A. I., Alzazin, A. L., Zaitsev, E. V. and Kelgado, V. B. (1994) Estimation of radiological health risks of nuclear tests at the Semipalatinsk test site for actual region population. *Vestnik*, **4**, 12–21.

Beluzerov, E. S. and Dzhasybaeva, T. S. (1993) *Social-Economic Aspects of Human Health*, Gylym, Almaty.

Burkart, W. (1996) Radioepidemiology in the aftermath of the nuclear program of the former Soviet Union: unique lessons to be learnt. *Radiation and Environmental Biophysics*, **35**, 65–73.

Cronkite, E. P., Conard, R. A. and Bond, V. P. (1997) Historical events associated with fallout from BRAVO Shot-Operation Castle and 25 y of medical findings. *Health Physics*, **73**(1), 176–186.

Darby, S. C., Kendall, G. M., Fell, T. P., Good, A. A., Conquest, A. J., Jackson, D. A. and Haycock, R. G. E. (1993) *Mortality and General Incidence 1957–1990 in UK Participants in the UK Atmospheric Nuclear Weapon Tests and Experimental Programmes NRPB-R266*. National Radiological Protection Board, Chilton, Oxfordshire.

De Vathaire, F. and le Vu, B. (1996) Cancer mortality in French Polynesia between 1984 and 1992. *British Journal of Cancer*, **74**, 1680–1681.

Doury, A. (1960, 1961) Personal communication.

Eisenblud, M. (1997) Monitoring distant fallout: the role of the Atomic Energy Commission Health & Safety Laboratory during the Pacific Tests, with special reference to the events following BRAVO. *Health Physics*, **73**(1), 21–27.

Fujuimori, K., Takahashi, T., Ohtomo, Ho., Simon, S. L. and Trott, K. R. (1996) Preliminary medical findings of the Marshall Islands Nationwide Thyroid Study. In: Nagataki, S. and Yamashita, S. (eds), *Nagasaki Symposium, Radiation and Human Health*, pp. 167–174. Elsevier Science, Amsterdam.

Gusev, B. I., Rosenson, R. I. and Abylkassimova, Zh. N. (1996) The dynamic of the oncological incidence among the population of some districts of the Semipalatinsk Region exposed to radiation from nuclear explosions. In: Hoshi, M., Takada, J., Kim, R. and Nitta, Y. (eds), *Proceedings of the Second Hiroshima International Symposium on Effects of Low-level Radiation for Residents near Semipalatinsk Nuclear Test Site*, Hiroshima, July 1996, pp. 153–194.

Hall, E. J. (1994) *Radiobiology for the Radiologist*. Lippincott, Philadelphia.

Hamilton, T. E., van Belle, G. and Lo Gerfo, J. P. (1980) Thyroid neoplasia in Marshall Islands exposed to nuclear fallout. *J. Am. Med. Assoc.*, **258**, 629–636.

Howard, J. E., Heotis, P. M., Scott, W. A. and Adams, W. H. (1995) *Medical Status of Marshallese accidentally exposed to 1954 BRAVO fallout radiation: January 1988 through December 1991*. BNL 52470, DOE/E-0493. Brookhaven National Laboratory.

Howard, J. E., Vaswani, A. and Heotis, P. (1997). Thyroid disease among the Rongelap and Utirik population—an update. *Health Physics*, **73**(1), 190–198.

Johnson, C. J. (1984) Cancer incidence in an area of radioactive fallout downwind from the Nevada Test Site. *Journal of the American Medical Association*, **251**, 230–236.

Johnson, J. C., Thaul, S., Page, W. F. and Crawford, H. (1996) Mortality of veteran participants in the CROSSROADs nuclear test. *Health Physics*, **73**(1), 187–189.

Kerbow, R. A., Till, J. E., Simon, S. L., Lyon, J. L., Thomas, D. C., Preston-Martin, S., Rallison, M. L., Lloyd, R. D., Stevons, W. (1993) A cohort study of thyroid disease in relation to fallout from nuclear weapons testing. *J. Am. Med. Assoc.*, **270**, 2076–2082.

Kumatori, T., Ishihara, T., Hirashima, K., Sugiyama, H., Ishii, S. and Myoshi, K. (1980) Follow-up studies over a 25-year period on the Japanese fishermen exposed to radioactive fallout in 1954. In: Hübner, K. F. and Fry, S. A. (eds), *The Medical Basis for Radiation Accident Preparedness*, pp. 33–54. Elsevier North Holland, Amsterdam.

Land, C. E. (1979) The hazards of fallout or of epidemiological research? *New England Journal of Medicine*, **300**, 431–432.

Land, C. E., Mackay, F. W., Machado, S. G. (1984) Childhood leukemia and fallout from the Nevada nuclear tests. *Science*, **223**, 139–144.

Loborev, V. M., Shoiket, J. N., Lagutin, A. A. *et al.* (1994) Radiation impact of the Semipalatinsk Test Site on the Altai region and problems of quantitative assessment of this impact. *Bulletin of the Research Programme 'Semipalatinsk Test Site/Altai'*, **1**, 10–26.

Lyon, J. L., Klauber, M. R., Gardner, J. W. and Udall, K. S. (1979) Childhood leukemias associated with fallout from nuclear testing. *N. Eng. J. Med.* **300**(8), 397–402.

Machado, S. G., Land, C. E. and Mackay, F. W. (1987) Cancer mortality and radioactive fallout in southwestern Utah, *Amer. J. Epidemiol.*, **125**(1), 44–61.

NAS (1991) *Health Effects of Exposure to Low Levels of Ionising Radiation (BERV)*. National Academy Press, Washington, D.C.

Ramzaev, P. V., Miretski, M. N., Troitskaya and Dudarev, A. A. (1993) Radio-ecological pecularities around the Novaya Zemlya (USSR) atomic testing range. *International Journal of Radiation Hygiene*, **1**, 1–13.

Ron, E., Lubin, J. H., Shore, R. E., Mabuchi, K., Modan, B., Pottern, L. M., Schneider, A. B., Tucker, M. A. and Boice, J. D. Jr. (1995) Thyroid cancer after exposure to external radiation: a pooled analysis of seven studies. *Radiation Research*, **141**, 259–277.

Rosenson, R., Gusev, B., Hoshi, M. and Satow, Y. (1996) A brief summary of radiation studies on residents in the Semipalatinsk area 1957–1993. In: *Nagasaki Symposium, Radiation and Human Health: Proposal from Nagasaki*, pp. 127–146. Elsevier, Amsterdam.

Shoikhet, Y. N. *et al.* (1994) Estimation of radiological health risk of nuclear tests at the Semipalatinsk Test Site for the Altai Region population. *Bulletin of the Research Programme 'Semipalatinsk Test Site/Altai'*, **4**, 12–21.

Simon, S. L. (1997) A brief history of people and events related to atomic weapons testing in the Marshall Islands. *Health Physics*, **73**(1), 5–20.

Simon, S. L., Lloyd, R. D., Till, J. E., Hawthorne, H. A., Gren, D. C., Rallison, M. L.

and Stevens, W. (1990) Development of a method to estimate thyroid dose from fallout radioiodine in a cohort study. *Health Phys.*, **59**(5), 669–91.

Stevens, W., Thomas, D. C., Lifon, J. L., Till, J. E., Kerbar, R. A., Simon, L., Lloyd, R. D., Eigham, N. A. and Preston-Martin, S. (1990) Leukemia in Utah and radioactive fallout from the Nevada test site. A case-control study. *J. Am. Med. Assoc.*, **264**(5), 585–591.

Takahashi, T., Trott, K. R., Fujimori, K., Simon, S. L., Otomo, H., Nakashima, N., Takaya, K., Kimura, N., Konno, T., Satomi, S. and Shoemaker, M. (1997) An investigation into the prevalence of thyroid nodules and thyroid cancer on Kwajalein Atoll, Marshall Islands. *Health Physics*, **73**(1), 199–213.

UNSCEAR (1982) *Sources and Effects of Ionizing Radiation*. United Nations Scientific Committee on the Effects of Atomic Radiation 1982 Report, Wien, United Nations, New York.

UNSCEAR (1984) *Sources and Effects of Ionizing Radiation*. United Nations Scientific Committee on the Effects of Atomic Radiation 1984 Report, Wien, United Nations, New York.

UNSCEAR (1993) *Sources and Effects of Ionizing Radiation*. United Nations Scientific Committee on the Effects of Atomic Radiation 1993 Report, Wien, United Nations, New York.

UNSCEAR (1994) *Sources, Effects and Risks of Ionizing Radiation, Annex A. Epidemiological Studies of Radiation Carcinogenesis*. E.94.IX.11, United Nations Scientific Committee on the Effects of Atomic Radiation, United Nations, New York.

Weiss, E. S. (1967) Surgically treated thyroid disease among young people in Utah, 1948–1962. *American Journal of Public Health*, **57**, 1807–1814.

Weiss, E. S. (1971) Thyroid nodularity in southwestern school children exposed to fallout radiation. *American Journal of Public Health*, **61**, 241–248.

Wise, K. N. and Moroney, J. R. (1992) Public health impact of fallout from British nuclear weapons tests in Australia, 1952–1957. ARL/TR-105, Yallambie, Melbourne.

Zaridze, D. G., Li, N., Men, T. and Duffy, S. W. (1994) Childhood cancer incidence in relation to distance from the former nuclear testing site in Semipalatinsk, Kazakhstan. *International Journal of Cancer*, **59**, 471–475.

Zheng, Y., Mao, Y. and Li, J. (1996) Long range atmospheric transportation and fallout of nuclear test radioactive debris. *SCOPE-RADTEST International Workshop*, Beijing.