SCOPE 59

Nuclear Test Explosions

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Environmental and Human Impacts

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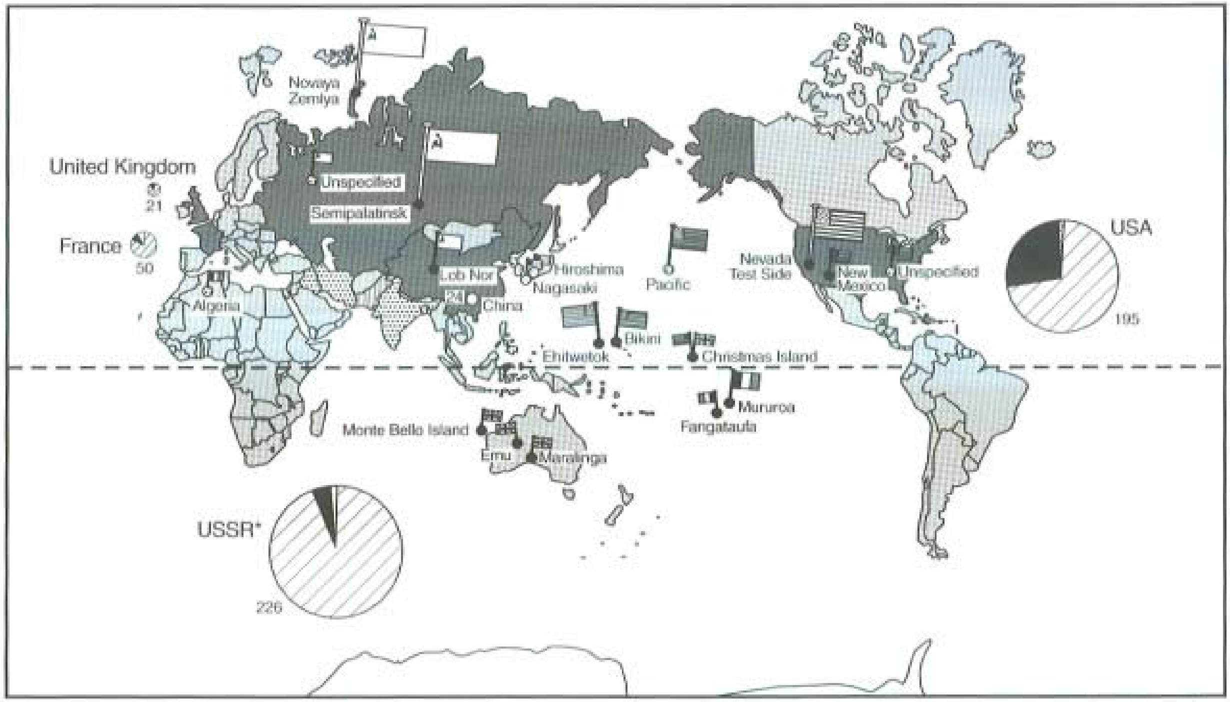

Numbers of explosions at this location

1 explosion — 22 — 122 explosions

- ● location known
- ⊙ location unknown
- ○ Hiroshima, Nagasaki (1945)

Atmospheric nuclear explosions

Nations

- armed
- supposed armed
- development suspected
- unarmed

Kind of explosion

- atmosphere (balloons, rockets, airplanes and towers)
- land and ocean surface
- underground and underwater
- type of test unknown

Numbers of explosions

10 — 200

Contents

Foreword

The Scientific Committee on Problems of the Environment (SCOPE) is one of a number of committees established by the non-governmental group of scientific organizations, the International Council for Science (ICSU). To cover multidisciplinary activities which include the interest of several Unions, ICSU has established 13 Scientific Committees, of which SCOPE is one. Currently representatives of 40 member countries and 22 Unions, Scientific Committees and Associates participate in the work of SCOPE, which directs particular attention to the needs of developing countries. SCOPE was established in 1969 in response to the environmental concerns emerging at the time: ICSU recognized that many of these concerns required scientific inputs spanning several disciplines and several Unions within ICSU. SCOPE's first task was to prepare a report on Global Environmental Monitoring (SCOPE 1, 1971) for the UN Stockholm Conference on the Human Environment. The mandate of SCOPE is to assemble, review, and assess the information available on environmental changes attributable to human activity and the effects of these changes on humans; to assess and evaluate the methodologies of measurement of environmental parameters; to provide an intelligence service on current research; and by the recruitment of the best available scientific information and constructive thinking to establish itself as a corpus of informed advice for the benefit of centres of fundamental research and of organizations and agencies operationally engaged in studies of the environment. SCOPE is governed by the General Assembly, which meets every three years. Between such meetings its activities are directed by the Executive Committee.

This volume reports the findings of the RADTEST (RADiation from nuclear TEST explosions) study, which falls within SCOPE's Health and Environment cluster. This cluster is focused on projects that develop methodologies for assessing chemical risk to human and non-human targets, and use case studies of environmental contamination to assess the health and environmental risks of specific chemicals.

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Preface

The RADTEST study, reported here, was started in April 1993 to assemble information on all the tests carried out on nuclear weapons. It was extended to cover the tests resumed in 1996 by France and China in view of public interest in conclusion of the Comprehensive Test Ban Treaty. Information was also received from India and South Africa. The record of all data available is included to allow study of the releases and their transfer in compartments of the environment and ecosystems as reported in the earlier RADPATH report, 'Radioecology after Chernobyl'. This can be referred to for details, along with the SCOPE ENUWAR report, 'Environmental Consequences of Nuclear War', on methodology, models, isotopes and units.

The three reports give detailed information directed to a specialized scientific readership but can be of use to those with more general interest. They will find information that some early tests in the atmosphere, under water or near the surface, caused high levels of radiation in areas nearby, sometimes because of wind changes or high yield. Because medical records were not available in some cases, reconstruction has been attempted alongside the study of health effects. There is assurance that the 1996 tests gave no release of radioactivity to sea or atmosphere.

The RADTEST programme involved experts from major weapons testing nations including FSU, USA, China, France and UK, besides representatives from international organizations such as the North Atlantic Treaty Organization (NATO), the International Institute for Applied Systems Analysis (IIASA), the International Atomic Energy Agency (IAEA), the International Union of Radioecology (UIR) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). It set up three working groups on: information and database, dose reconstruction, and health effects.

Workshops to present and discuss findings were held periodically throughout the duration of the project. During 1994 two major international NATO Advanced Research Workshops were convened at the International Atomic Energy Agency in Vienna, Austria, and in Barnaul (Siberia) Russia. The Vienna meeting examined the environmental and human consequences of atmospheric nuclear tests and provided an overall view of the American and FSU testing programmes. The Barnaul meeting was concerned with radioactive fallout in the Altai (Siberia) region of Russia, primarily from the early nuclear tests undertaken in the Semipalatinsk test site in Kazakhstan. A third workshop was held early in 1995 in Brussels/Liège, Belgium to examine the methodologies of dose reconstruction, epidemiology, and subsurface transport. A final mini-workshop in October 1996 in Beijing assessed material from French and Chinese tests.

The project was directed by an Executive Committee, guided by a Scientific Advisory Committee (SAC) of minister-level individuals, and monitored by SCOPE's Executive Committee. A single Steering Committee guided the closing stages for synthesis of the findings to a timely conclusion.

An archive of material associated with this (and the previous ENUWAR and RADPATH) project will be maintained at the University of Essex.

Sir Frederick Warner
Chairman, SCOPE-RADTEST

Acknowledgements

Deep gratitude is expressed to the many scientists world-wide who generously devoted their time and expertise to SCOPE's RADTEST programme, without whom this venture would have been impossible. Special thanks are due to Members of RADTEST Scientific Advisory, Executive and Steering Committees for their guidance, which was crucial in bringing the programme to a conclusion. The unique contribution of Professor Charles S. Shapiro, who served as Executive Director during the early stages of the project, is also noted. In the latter part of the project he relinquished his direct involvement in administering the project in order to concentrate on editing the NATO ASI publications resulting from the Vienna and Barnaul meetings.

Grateful thanks are also extended to the many national institutions and academies which generously contributed to the staging of RADTEST's workshops over the period of the project. In particular, NATO funded two Advanced Research Workshops (Vienna/Barnaul); support of Belgian institutions (ONDRAF, SPRI, SCK.CEN) was instrumental in organizing the Brussels/Liège III RADTEST workshop and help from the Japanese Health Foundation secured the venue of the IV Workshop in Beijing.

Support for the SCOPE Unit at Essex, which served as RADTEST's Secretariat, and for associated project activities, was very generously provided by a number of organizations, including The Leverhulme Trust, The Royal Society and the European Commission. The SCOPE Unit headed by Dr Linda Appleby played a crucial role in coordination activities, and was responsible for documentation of the programme, including publication of Newsletters, and in the preparation of the Synthesis SCOPE volume manuscript. Final editing had significant help from Dr Eric Voice.

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1 Synthesis

SIR FREDERICK WARNER

The RADiation from nuclear TEST explosions, or RADTEST, project is one of the Scientific Committee On Problems of the Environment (SCOPE) programmes. It falls within SCOPE's Health and Environment cluster.

The test-explosion of nuclear weapons has made a far larger impact on the world environment than all the operations and accidents with nuclear power generation. This study of the 2419 tests between 1945 and 1998 records the past and present understanding of the results as the weapons have been developed and tested. In sum the tests have yielded explosive energy equivalent to 550 million tons of TNT, with the USA and USSR accounting for 80% of the tests and 90% of the yields. Although there have been extensive global studies on fallout, publication on local effects, especially on human health, has been uneven. The RADTEST study provides much information that until now has been restricted or unavailable.

The areas for nuclear weapons testing were chosen for remoteness from human habitation and observation. Fallout affecting life and health has been studied extensively and publicized in such areas as Nevada, Australia and islands in the Pacific. That information is re-examined here, with new RADTEST studies of the Altai–Semipalatinsk and Novaya Zemlaya regions of the former Soviet Union (FSU) and of the Chinese testing ground at Lob Nor. The most recent tests there are covered as well as the series in French Polynesia. Limited information is available on the tests made by India and Pakistan in 1998.

Models for predicting short and long-term health effects require both meteorological data and population medical records at the time of the explosions and study of the changing patterns over the years until now. Poor medical records have to be interpreted and supplemented by the extensive knowledge from the Hiroshima and Nagasaki bombs and the tests in the Pacific. The object is to establish the pathways by which radionuclides reach human beings and the doses of radiation received by populations and individuals from initial and continuing exposure until the present. Differing systems of radiological protection and medical records in the countries studied have been compared in order to give firmer prediction for any future accidental or deliberate release.

Nuclear Test Explosions: Environmental and Human Impacts
Edited by Sir F. Warner and R. J. C. Kirchmann

One result of RADTEST is a current inventory of radioactivity at or near test sites with potential for remediation or restoration. Activities are in general much lower than those experienced at Hiroshima and Nagasaki. Those at Altai are high enough to have significant health effects and to throw light on the controversial low-dose regimes. In particular, dose reconstruction from the effects on eyes and teeth are being assessed by individual and case-control studies as distinct from the assumptions for populations in cancer prediction. This is of current public and political interest.

The detailed information and discussion in the following chapters start with an introduction to the background of the Report and the contributions of the NATO Workshops in Vienna and Siberia, which included the visit to Semipalatinsk. General conclusions on human, animal and plant irradiation effects from the French case-studies in Polynesia follow, and then the comparable results from the USA, FSU and China.

In Chapter 3 the history of weapon developments opens with the simple fission bombs of World War II, yielding about 20 kt, to the later boosted-fission, hydrogen fusion, and combined fission–fusion–fission weapons. These led to national arsenals with a total of more than 25 000 warheads, mainly around 100 kt but with some up to 1 Mt. The varying yields from the testing of these weapon developments are discussed. The different sites and testing techniques are covered in detail, with summaries of the number of tests with their explosive and radionuclide yields, accurate figures for which have been released only recently. Of the total tests, 541 were in the atmosphere and 1878 underground.

Chapter 4 details the immediate environmental impacts following the formation of different radionuclide compounds and the aerosol transport in the atmosphere and the troposphere. These local, remote and global tropospheric patterns are expressed by mathematical models. These are then used with the actual data on which they are based for the reinterpretation of early tests in the atmosphere. It emerges clearly that the radioactive products from fission reactions vary with the process of detonation, and that firing conditions are of great importance. Contamination of geological formations, water and oil from underground tests is considered in this chapter.

Chapter 5 discusses pathways for external and internal exposure in the human body following inhalation and ingestion of contaminated foodstuffs, looking at specific test-sites and regions. The radioisotopes of iodine, strontium and caesium are of greatest interest because of the amounts released, their ready transfer to human beings via the foodchain and high relative activities because of short half-lives.

Chapter 6 summarizes the estimation of dose to human beings with reference to the test sites in Nevada, South Pacific, Semipalatinsk, Novaya Zemlaya, Lob Nor, Mururoa, Fangataufa and Australia. The variation of local and regional levels and of external and internal irradiation are discussed. Extensive and detailed dose reconstruction from local fallout has so far been carried out only at Nevada. The estimated collective dose to the world's population is 50 times that from the Chernobyl accident. These global levels are of course a small fraction of the exposure to natural background radiation but local contamination can give far higher doses than the average.

Chapter 7 examines in detail the health consequences for exposed populations in the USA, FSU, French and Australian territories. Most fallout exposures of individuals near test sites from high local fallout have already been received. The most highly exposed cohorts face increased health risks and deterministic effects seem to be appearing. Evaluating risks of a stochastic nature requires long-term follow-up.

Chapter 8 discusses fallout models and tries to bring together the different approaches in earlier chapters. The discussion shows that further work is needed to establish models which are better for explanation and prediction.

Many of the differences arise because the capacity of modern computers is now much greater than at the time earlier models were developed. The rate of change is great and demonstrated in the advance between first and second volumes of *SCOPE 28: Environmental Consequences of Nuclear War* in the models of general circulation of the atmosphere. To these there are added the problems of particles, their relation to cloud formation and the special properties of nuclear aerosols, including multispecies with morphologies and properties unlike normal aerosols in the atmosphere.

The approximations made in early models were assessments covering fallout from hundreds of weapons and compromises. Recent developments in understanding microphysics, plume clouds and weather codes have yet to be applied. In particular, formation of particles can now be examined more closely, i.e. particles in the submicron range that were neglected earlier.

There are other difficulties because of the large proportion of material carried along with the small amount of nuclear materials. These difficulties need adding to the modelling of weather and fallout. The chapter ends with suggesting that an immediate jump in capability is now possible, with the elimination of many uncertainties.

The Appendix summarizes the releases of radioactivity from all atmospheric and vented underground tests. Recent tests deep underground have not added to natural radioactivity in the atmosphere or oceans.

This Report should help environmental understanding and guide the making of policy on the testing and control of nuclear weapons. It has been made possible by the commitment of scientists to seek out information previously kept secret for military security. This collaboration world-wide is one of the fruits of the ending of the Cold War. Publication should encourage the open discussion of steps now being considered for the control of nuclear weapon production, including the cessation of testing and targeting, and the detection of clandestine testing. Although the Comprehensive Test Ban Treaty has lessened the fear of nuclear war, it is to be hoped that the international collaboration established by SCOPE-RADTEST will continue—and assist in the safeguarding and disposal of nuclear weapons material.

2 Introduction

R. J. C. KIRCHMANN, L. APPLEBY AND C. S. SHAPIRO

2.1 GENERAL FRAMEWORK

2.1.1 Origin of SCOPE-RADTEST

From 1988 to 1991 SCOPE carried out a project 'Biogeochemical Pathways of Artificial Radionuclides' (RADPATH), which was successfully concluded with the publication of SCOPE 50, *Radioecology after Chernobyl* (Warner and Harrison, 1993). Taking note that the scientific potential of the project had not been fully exhausted, experts at the RADPATH Scientific Advisory Committee Meeting and at the 5th Conference 'Geochemical Pathways of Artificial Radionuclides in the Biosphere' (Puschino, Commonwealth of Independent States, 1991) recommended that SCOPE continued activities in this field.

This proposal was discussed at the 8th SCOPE General Assembly (Seville, Spain, January 1992) and the idea of a new project organization was supported. In May 1992, Professor Charles Shapiro (USA) met with experts in China representing SCOPE's China National Committee and the China RADPATH Committee, which represented 24 institutions within China. These meetings resulted in a statement of agreement that expressed the interest and enthusiasm of China for participation in the proposed study.

On the initiative of Professor Shapiro and the Russian National SCOPE Committee, a meeting of a group of experts from Russia, USA and China was organized in Moscow, 5–7 November 1992: twenty experts attended this meeting. At this meeting, it was decided to narrow the focus of the study to fallout from nuclear tests. A memorandum of understanding was drafted on the organization of a new SCOPE project 'RADTEST' (RADiation from nuclear TEST explosions).

In April 1993, the SCOPE Executive Committee meeting in Paris formally adopted RADTEST as an official SCOPE project. The RADTEST project was established initially within SCOPE's Biogeochemical Cycles Cluster, and subsequently within its Health and Environment Cluster, following a reorganization within SCOPE. In order to conduct the project, a RADTEST Steering Committee (with international members) was appointed, under the chairmanship of

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Professor Sir Frederick Warner, and a central Secretariat was established at the University of Essex, UK, to assist with obtaining and disseminating information relating to the project.

2.1.2 Project objectives

The RADTEST project has been involved in examining the transport, deposition and human health effects of radioactive fallout from nuclear weapons tests through international, collaborative study. The involvement of countries such as Russia, USA, China, France and UK and of other international bodies was achieved, including participation of nuclear scientists who were directly or indirectly involved with nuclear testing. Consequently the project has enabled previously restricted work, including data, models and knowledge about the fate of the release of radionuclides and their possible human health effects, to be discussed and considered for the first time.

An important objective of RADTEST relates to 'bridge building'. One cannot underestimate the potential importance of effective communication and collaboration of scientists who have been involved in studies of the radioactive fallout from nuclear tests. These communities of scientists, heretofore isolated from each other, can establish working relations, collaboration, and trust with each other. This can greatly facilitate scientific consensus, which is necessary in reaching and carrying out agreements at the political level. Such 'bridge building' truly is in the spirit of SCOPE.

RADTEST has focused on the following principal tasks.

1. Updating the inventory of relevant nuclear tests.
2. Establishing an inventory of data on measurements of radionuclide deposition densities and identifying gaps in these data.
3. Comparison of old and, when needed, development of new models of radioactive transport to better understand the deposition densities of radionuclides, both on and near the nuclear test sites, including areas downwind where potentially significant episodes of fallout have occurred (such as the Altai region of Russia).
4. Study of the migration of radionuclides through the biosphere, including all pathways to humans, and the study of the effects on other biota that have impacts on humans, the main focus being the characterization of the nature and magnitude of the dose to humans. This includes dose reconstructions from past events, and also an increased capability for dose prediction from possible future accidental or deliberate explosions.
5. Analysis of the data on effects of these doses (including low doses) on human health.

In order to achieve the project's objectives, RADTEST organized a continuing programme of meetings, information dissemination and coordination activities.

The series of RADTEST workshops commenced with the North Atlantic Treaty Organization (NATO) Advanced Research Workshop (ARW) held in Vienna, Austria (10–14 January 1994). This ARW examined the Environmental and Human Consequences of Atmospheric Nuclear Tests. The second NATO ARW for the RADTEST project was convened in Siberia (5–10 September 1994) and related predominantly to the radioactive fallout in the Altai region of Russia, emanating primarily from nuclear tests undertaken at the Semipalatinsk test site in Kazakhstan. These meetings are reported in detail in section 2.3 and input to them formed the basis for two separate publications (Shapiro, 1998; Shapiro *et al.*, 1998).

A third RADTEST Meeting was held in Brussels/Liège (March, 1995) to examine environmental consequences of local radioactive fallout from nuclear test explosions and the associated health consequences and epidemiology for the exposed population. A final Mini-workshop was held in Beijing, China (19–20 and 23 October, 1996) in order to receive Chinese and French contributions and preliminary manuscripts to enable a synthesis of the project's findings to be prepared.

A series of *ad hoc* meetings was convened during the period between the Belgian and Chinese meetings, in order to advance the synthesis summarizing the findings of the programme. These included informal discussion meetings held in Minsk, Belarus (March 1996) and editorial meetings in Vienna, Austria (April and June 1996). A meeting of Senior Editors was held in Essex, UK (February 1997) to advance the finalization of this synthesis publication.

2.1.3 Logic flow

After summarizing the overall findings of the RADTEST project in the Synthesis (Chapter 1), this volume then examines the background to its establishment, its objectives and how these have been achieved, including issues relating to general concepts. Following a detailed examination of the sites and tests which have been carried out, the volume goes on to examine the environmental effects, including exposure pathways. A consideration of the estimation of doses leads on to a discussion about human health effects.

A key feature of the volume is the comprehensive listing of all tests which have led to releases (including vented underground tests). Finally, the volume examines the conclusions, and recommendations, which may be drawn from the study.

2.2 FROM THE FIREBALL TO HUMAN EXPOSURE

During a nuclear explosion, the fission products, residual fissile material and structural materials associated with the device are raised to sufficiently high temperatures to be present in gaseous form. For explosions detonated in the atmosphere near the surface of the Earth, a considerable amount of volatilized soil or rock material may also be entrained in the fireball (UNSCEAR, 1977a). Some activation products are also generated by neutrons. After an explosion in the atmosphere, the fireball expands rapidly and rises due to buoyancy. As it rises, cooling causes the volatilized debris to condense, forming an aerosol with a wide distribution in particle size. The radioactivity that falls out of the cloud after the explosion is called the radioactive fallout. In the ordinary atomic bomb, for example, for each 20 kt of TNT equivalent of explosive energy, about 1 kg of radioactive material is produced. In this 1 kg of radioactive material are some 90 different radionuclides varying in lifetime from a fraction of a second to many years. This mixture of radioactivity decreases in such a way that for every sevenfold increase in age, the total radioactivity is decreased tenfold (Libby, 1956a). As the inventory of radioactivity produced by the fission reaction changes its characteristics continuously and rapidly after the bomb detonation, the firing conditions are of prime importance in determining the fallout quality and effects.

Many radionuclides present in fallout emit gamma rays and contribute to the dose from external irradiation. The most important from this point of view are a number of short-lived radionuclides, the most significant of which are ^{95}Zr and its daughter ^{95}Nb, and the long-lived ^{137}Cs (UNSCEAR, 1977b). As the time required for ingestion into the body is long, ingestion is unlikely for the shorter-lived fission products, and therefore the principal hazards for close-in fallout are radiation exposures by gamma radiation of the whole body, and by beta radiation on the skin. Over longer times, weeks and months after the explosion, the ingestive hazards begin to become important (Libby, 1956b), see Figure 4.1.

A bomb fired on the surface of the Earth, however, may have an appreciable portion of its radioactivity settled within relatively short distances, whereas bombs fired beneath the surface of the Earth may place essentially no fallout radioactivity in the atmosphere. Therefore, the question of the area of contamination to be expected from nuclear weapons cannot be answered categorically without specifying the degree of contact of the fireball with the surface of the Earth, and probably also specifying the characteristics of this surface. For weapons fired on the surface, the activation of the surface materials is a possibility, but in general it appears that most of the neutrons form stable isotopes and that the amount of radioactivity produced, at least with ordinary surface materials, is relatively small. The principal radioactive products of nuclear weapons are produced in the weapons themselves, and not in the environment (Libby, 1956a).

A consequence of the presence of radionuclides in the environment is the potential for increased radiation exposure of living organisms. The impact of radionuclide releases on organisms may be assessed by consideration of the likelihood and extent of radiation exposure and potential consequential effects (i.e. radiobiological response).

One must also consider the beta doses, which were estimated to be approximately eight times higher than gamma doses, although the depth of penetration of beta radiation as an external dose is very limited. For humans, external beta dose can cause skin burns (as in the Marshallese and Lucky Dragon episodes), but does not give a whole-body dose comparable to gamma rays.

2.3 NATO ADVANCED SCIENCE INSTITUTES

In the course of the RADTEST programme, two North Atlantic Treaty Organization (NATO) Advanced Research Workshops (ARWs) were held in Vienna, Austria (January 1994) and in Barnaul, Siberia (September 1994). These workshops were convened to examine the 'Environmental and Human Consequences of Atmospheric Nuclear Tests' and the 'Long-term Consequences of Nuclear Tests for Environmental and Population Health', respectively. The latter had a particular focus on nuclear tests undertaken at the Semipalatinsk Test Site in the Altai region of Russia.

The complete findings of these ARWs are now published in NATO's ASI series (Shapiro, 1998; Shapiro *et al.*, 1998), however, a brief summary of some of the issues addressed is provided below.

2.3.1 Vienna advanced research workshop

The Vienna ARW examined the results of previous studies undertaken in the former Soviet Union, USA, UK and China.

The Russian studies were related to five principal areas comprising: the source term; modelling and dose reconstruction; environmental data; epidemiology and inventories at sites; tests and explosions. Valuable information concerning nuclear detonations at the Semipalatinsk and Novaya Zemlya test sites was obtained, in addition to information relating to world-wide test sites from the Soviet Radiation Monitoring Network (Ryaboshapko *et al.*, 1998).

The USA studies concerned the Off-site Radiation Exposure Review Project (ORERP) and events at the Nevada Test Site (NTS) and Marshall Islands. Church *et al.* (1990) give an overview of ORERP, which assumes the existence of a relationship between the external exposure and the deposition of radionuclides that enables dose reconstruction at the time of the tests. The total collective dose in the PHASE I area (parts of Nevada, Southern Utah and Arizona) is calculated as 58 000 person-rem (580 person-Sv), whereas in the PHASE II area, which includes all of Utah (including Salt Lake City), the total collective dose is 1 200 000 person-rem (12 000 person-Sv).

Contemporary data, which have recently become declassified, have provided the basis for overviews of the USA atmospheric tests at the Nevada Test Site (NTS), and at the Marshall Islands Test Site. It is expected that these data will be revised upon the declassification of further data. The Marshall Islands Radioecology and Dose Reconstruction Project has concentrated on the dose received at the time of the tests and to native islanders upon return to their homes.

As a consequence of detonations in Australia the potential radiological impact of residual contamination in the Maralinga and Emu Areas of Southern Australia has been studied, in addition to the mortality and cancer incidence in participants of nuclear weapons tests and experimental programmes. However, participants in such programmes show no detectable effect on their life-expectancy or on their risk of developing cancer or other fatal diseases (Darby *et al.*, 1993).

There have been studies in China to investigate nuclear cloud movement and to survey radioactive fallout due to nuclear tests (Yi *et al.*, 1998). The Chinese Ministry of Public Health has established a nationwide environmental radioactivity monitoring and investigation network to evaluate the impact of radioactive contamination from nuclear fallout and related health issues.

2.3.2 Barnaul advanced research workshop

An important issue addressed is dose reconstruction, where there appear to be important differences in the proportion of dose from external, inhalation and ingestion pathways. Much information has been gathered on medical–biological consequences of radiation impacts, and a summary of Altai's medico-ecological situation is given by Shoikhet *et al.* (1994). Their findings reveal a need to improve our understanding of the radiobiological situation there.

The radiological risk for the Altai region, due to nuclear tests at the Semipalatinsk site, has been examined by Algazin *et al.* (1994), revealing that the 29 August 1949 test contributed around 32 000 person-Sv (about 90% of the total collective dose in the region).

Stegnar (1994) reports that the International Atomic Energy Agency's (IAEA) preliminary conclusions from their assessment of the present radiological situation indicates that the dose to those living in surrounding settlements is unlikely to exceed 50 μSv y^{-1} (including a fraction due to general weapons fallout) from artificial radionuclides, which represents only a small percentage of the exposure from natural radioactivity sources.

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3 Nuclear Weapons Test Programmes of the Different Countries

B. B. BENNETT, L. E. DE GEER AND A. DOURY

Following the development of nuclear technology and the use in combat of two nuclear weapons at the end of World War II by the USA, a few other countries carried out both atmospheric and underground tests to develop independent capabilities to design and produce nuclear weapons. The most active periods of atmospheric testing were during the 1950s and in 1961–62, when the USA conducted 217 tests, the former USSR 219 and the UK 33. These countries ended their programmes of atmospheric testing following the signing of the Limited Test Ban Treaty in 1963. Two countries continued less frequent testing in the atmosphere; France carried out 50 tests between 1960 and 1974 and China conducted 22 tests between 1964 and 1980. There have been no further atmospheric nuclear tests since 1980.

All of the countries mentioned above have also conducted tests of nuclear devices underground. These have generally been of lower explosive yield, especially if containment of releases was desired, but they have been numerically more than the atmospheric tests. Two other countries, India and Pakistan, have also conducted underground tests, most recently in 1998. At present, however, underground testing has presumably ceased by all countries, and a treaty to ban these tests has been agreed also, although it has not yet entered into force.

The numbers and yields of the nuclear tests were not officially announced at the time of testing because of their sensitive or classified nature. It is, thus, only with the publication of more recent government reports that an accurate listing of nuclear tests can be provided. Summaries of tests conducted by countries at the various test sites each year are given in tables accompanying this chapter.

This chapter describes the common steps in nuclear weapons development and the types of tests conducted. The test sites were selected at remote locations to prevent contamination of inhabited territories. The global dispersion of radionuclides produced in the explosions could not be prevented, and even some exposures in local populations occurred, as will be discussed in later chapters.

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3.1 DEVELOPMENT OF NUCLEAR WEAPONS

Nuclear weapons are quite complex industrial products that need extensive and ingenious design, development and testing before they can be serially produced and incorporated into a country's military arsenal. A modern warhead may consist of some 1800 separate components. Even the very first nuclear weapons were considered complex systems at the time, although they would now be regarded as being of rather straightforward construction, given that the fissile material is available. The principle of shooting two pieces of uranium of non-critical mass into one another to make the total suddenly critical was used untested in the war; this was the Hiroshima bomb. The Nagasaki implosion bomb was based on a more delicate principle, not so well studied at the time, and it was consequently tested (in the Alamogordo desert in New Mexico, USA) before it was used in combat. Today, however, implosion techniques, where shells of material are made to collapse inwards in a normally spherical geometry, are well enough known, or can fairly easily be studied with modern experimental and computational tools to allow a simple implosion device to go into a stockpile untested.

The five established nuclear weapons states have followed similar paths of steady improvement and development of nuclear weapons, which would not have been possible without extensive testing of the models at full or reduced nuclear yield. The development has progressed from simple fission devices to boosted fission bombs, to thermonuclear weapons and to more specialized weapons systems.

3.1.1 First generation fission bomb

All five nuclear states started with very basic fission devices, based on the implosion technique. In the USA and former USSR it was a very heavy and clumsy sphere with plutonium in the form of a ball in the centre. This design was a starting point, but many improvements were shown to be possible. For example, by creating a void in the plutonium ball, thus forming a shell, acceleration during the implosion could be increased and more efficient compression achieved. Experiments were made with cores utilizing both plutonium and uranium. Many other modifications and small improvements were made in the course of weapons development. Much work also had the goal of tailoring warheads to different launching systems developed for the military forces.

3.1.2 Boosted fission bomb

The next major development step was the introduction of a booster stage. It was not initially self-evident how the yield of a basic fission bomb could be increased. All first-generation fission devices produced a yield in the range of

20 kt, simply because when that amount of energy developed, the fuel disassembled, and the nuclear reactions therefore stopped. This happens when just 10–20% of the fuel has been consumed. A much better utilization of the fuel would be achieved if in some way the number of neutrons available could be increased. The answer to this is boosting, where just a few grams of a deuterium–tritium gas mixture are introduced into the core of an implosion device. When the charge is set off the temperature and pressure build up in the centre to levels sufficient to create a small thermonuclear flame. The deuterium and tritium nuclei fuse, producing a little energy, but more importantly neutrons re-enter the plutonium, causing new fission reactions and boosting the total fission yield significantly, doubling it or in some cases even increasing it by up to a factor of ten. The boosting principle is used to reach higher yields and also to produce more economical charges through better utilization of the expensive fission fuel.

3.1.3 Thermonuclear bomb

Boosting and some other ingenious schemes can increase the yield of a fission bomb to the several hundred kilotonne range. The highest yield test of this kind in the past was 400 kt. If higher yield weapons were needed, a completely new principle had to be developed. This was the thermonuclear bomb. The USA and former USSR worked with difficulty on this concept in the early 1950s. The most direct idea of using a fission bomb to serve as an ignition to increase the temperature and begin the reaction in one end of a cylindrical thermonuclear fuel package did not work at all. The heat simply radiated away, and the fuel did not burn. The problem has been illustrated by a gasoline-impregnated piece of cotton on a piece of wood; ignition and explosion of the cotton fail to ignite the wood.

The solution was the product of quite lateral thinking, as it turned out to be necessary to separate the ignition stage from the fuel and use X-radiation from the primary fission charge to precompress the fuel. This is done by a process called ablation. The thermonuclear fuel is wrapped in a heavy cover, which when heated by the X-rays expands inwards and outwards. The inward impulse then compresses the fuel and makes it dense enough to keep the generated energy from escaping. This principle was first conceived in the USA in January 1951 and then three years later in the former USSR. It was kept secret for a long time until it was accidentally made public in the late 1970s. The development of different types and sizes of thermonuclear charges has been the main impetus for the quite extensive nuclear testing programmes, in atmospheric testing and even more so in underground testing. It has been very important to design carefully the primary charge, almost exclusively a booster, and to tailor its radiation output to the envisaged secondary thermonuclear fuel package.

3.1.4 Third generation nuclear weapons

Enhancement of specific effects of the nuclear explosion has characterized the development of third generation nuclear weapons. The best known is perhaps the neutron bomb, where the neutron output is optimized. The purpose of this was to produce a bomb that would kill soldiers on a battlefield with a minimum of collateral damage. Another name for the neutron charge was ERW, the enhanced radiation weapon. The opposite has also been developed for different purposes, the RRW, the reduced radiation weapon. Weapons optimized to give a large electromagnetic pulse (EMP) are intended primarily to destroy electrical installations over a wide area. The last third generation weapon pursued before the end of the cold war was the X-ray laser. The idea was to have a nuclear device pump a space-borne laser and create a well focused X-ray beam able to destroy enemy missiles in a star-war scenario.

3.2 TYPES OF NUCLEAR TESTS

The development of a nuclear device requires extensive testing. There are, of course, numerous non-nuclear tests carried out on all of the thousands of components and aggregates of components involved. This, however, is not the primary concept of nuclear testing. The definition of a nuclear test is a quite complicated question and has become different in different contexts. For the recently concluded Comprehensive Test Ban Treaty (CTBT), a strict definition was actually avoided. The treaty text bans all nuclear non-zero yield tests without going seriously into a definition. Although it is not too difficult to tell, all facts given, whether a nuclear experiment is a nuclear test or not, all the a priori definitions tried have failed to encompass all that is wanted without accidentally including too much that might impose restrictions on use of nuclear power, basic science experimentation or, perhaps most closely related to nuclear weapons, use of laser or particle beam driven fusion devices.

Between completely non-nuclear testing and full yield nuclear testing of a complete device, there are a few other categories. In *hydrodynamic testing* the functioning of the chemical explosives system is studied, normally the dynamics of the implosion process used to compress the nuclear fuel and initiate the primary nuclear part. The fuel, in this case, can be simulated by non-fissile materials, e.g. natural uranium.

To investigate whether and how the nuclear reactions start, very low nuclear yields can be used, corresponding to less than a kilogram or a few kilograms of TNT. This type of test is called a *hydronuclear test*. Until very late into the CTBT negotiations the nuclear powers wanted hydronuclear tests to be permitted and thus excluded from the ban. Yield limits in the gram and kilogram ranges were discussed before the idea was abandoned.

Safety tests are tests in which a more or less fully developed weapon is subjected to a simulated accident. As weapons are designed to give no, or at least negligible yield in the event of fire, bombardment or accidental dropping, such a test normally involves no nuclear yield. Sometimes a test can, however, be carried to the limit, and a very small nuclear yield may be developed.

In more full scale nuclear testing, the explosions can be carried out at much *reduced yields*. As tailoring the primary to the secondary often is the main purpose, there is no need to let the thermonuclear stage develop fully. This was very important in the past, when the Partial Test Ban Treaty of 1963 directed much testing underground, an environment not very suitable for high-yield tests.

Two further test categories were much discussed in connection with the CTBT, especially outside the negotiation room. These were *computer simulations* and *laser experiments*. Some argued that this would allow those countries that were mastering these techniques to actually design new nuclear weapons without the need for nuclear testing. This was, however, strongly denied by these countries. They explained that their goals for pursuing these techniques were to maintain present arsenals and to solve future problems, such as material ageing and reuse of old designs with partly different or more modern components and materials.

Of all the above-mentioned testing categories, the CTBT clearly bans hydronuclear tests, full-scale and reduced yield tests. Perhaps it can be argued that a successful safety test with absolutely no nuclear yield would be allowed under the CTBT, but many would probably deny that option.

The history of past nuclear testing is becoming better known, as statistics on the testing programmes are being made public. Official statistics on nuclear testing recently issued by nuclear weapons states generally include full and reduced yield tests and safety tests. Hydronuclear tests, which are banned by the CTBT, are not included in the tables. The Russian Federation has stated that they carried out around 100 such tests. It is somewhat of a paradox that a safety test with no nuclear yield at all is included in the statistics, whereas a hydronuclear test of 1 t nuclear yield is not.

A confusion to test statistics is introduced by the fact that many underground tests were carried out simultaneously in what were called salvo experiments. This was mainly done for economical reasons, but such tests also detracted from detection by teleseismic measurements abroad. Today this is within the public domain, and there is no reason to regard one experiment involving five different nuclear devices as one nuclear test when the same experiment carried out during five different days would clearly be considered as five tests.

3.3 NUCLEAR TEST SITES

Tests of nuclear weapons have been carried out at several sites, generally selected by countries for their remote locations. The initial test by the USA was at a military site in New Mexico, but most of the lower yield atmospheric tests and nearly all of the underground tests were conducted at the Nevada Test Site. The high yield atmospheric tests were conducted at Enewetak (Eniwetok) and Bikini Atolls in the Pacific. Other sites utilized for atmospheric tests included Christmas Island and Johnston Island in the Pacific, and three tests were conducted over the south Atlantic Ocean. Some individual underground tests were conducted in Colorado, New Mexico, Mississippi and on Amchitka in the Aleutian Islands off the coast of Alaska.

The former USSR began its tests at the Semipalatinsk Test Site, which is at present within the country of Kazakhstan. There were 116 atmospheric tests with a total yield of 6.6 Mt conducted at this site between 1949 and 1962. In addition, more than 300 underground tests and two cratering experiments were conducted there. The large yield atmospheric tests were conducted at the Northern Test Site Novaya Zemlya in the Soviet Arctic. Missile-launched weapons were tested from the test site near Kapustin Yar in the Astrakhan region of the Russian Federation. Several sites were utilized for individual underground tests other than the Semipalatinsk Site, including locations in the Russian Federation, Kazakhstan, Ukraine, Uzbekistan, and Turkmenistan.

Nuclear test sites utilized by the UK included Emu, Monte Bello Island and Maralinga in Australia and Christmas and Malden Islands in the Pacific. Some underground tests by the UK were done in conjunction with the USA. Tests by China were all at the Lob Nor Test Site in western China. France began testing at two sites in Algeria, but following only a few tests, the test programme was transferred to Mururoa and Fangataufa Atolls in French Polynesia. Underground tests were conducted by India and Pakistan at sites in their respective countries. The first test by India occurred in 1974; five further tests were conducted in May 1998. Following the latter series, Pakistan responded by conducting six underground tests also in May 1998. If all countries accede to the comprehensive nuclear test ban treaty, the history of all nuclear testing may now have been concluded.

3.4 NUMBER AND YIELDS OF NUCLEAR TESTS

It is only within the past few years that the countries that conducted nuclear tests have released accurate information on the number and yields of tests included in their testing programmes. This, therefore, allows a definitive line to be drawn beneath this now concluded practice. The numbers of atmospheric tests at the various test sites and the explosive yields are given in Tables 3.1–3.5. The underground tests, summarized in Table 3.6, are too numerous to give individual dates and locations. In some cases the yields of the tests have only been specified to be within various ranges of energies. Therefore, the total yields cannot yet be accurately known. In order to estimate the total yield of atmospheric tests, the United Nations Scientific Committee on the Effects of

Table 3.1 Atmospheric nuclear tests of the USA.

Test sites	Year	Date and yield of individual tests			Number of tests	Total yield (Mt)
Wartime test and use*	1945	16 Jul: 0021 Mt	5 Aug: 0015 Mt	9 Aug: 0021 Mt	3	0.057
Bikini	1946	30 Jun: 0.021 Mt	24 Jul: 0.021 Mt		2	0.042
	1954	28 Feb: 15 Mt	26 Mar: 11 Mt	6 Apr: 0.11 Mt		
		25 Apr: 6.9 Mt	4 May: 13.5 Mt		5	46.51
	1956	20 May: 3.8 Mt	27 May: 3.5 Mt	11 Jun: 0.365 Mt		
		25 Jun: 1.1 Mt	10 Jul: 4.5 Mt	20 Jul: 5 Mt	6	18.27
	1958	11 May: 1.36 Mt	21 May: 0.0251 Mt	31 May: 0.092 Mt		
		10 Jun: 0.213 Mt	14 Jun: 0.319 Mt	27 Jun: 0.412 Mt		
		29 Jun: 0.014 Mt	2 Jul: 0.22 Mt	12 Jul: 9.3 Mt		
		22 Jul: 0.065 Mt			10	12.02
				Subtotal	23	76.8
Enewetak (Eniwetok)	1948	14 Apr: 0.037 Mt	30 Apr: 0.049 Mt	14 May: 0.018 Mt	3	0.104
	1951	7 Apr: 0.081 Mt	20 Apr: 0.047 Mt	8 May: 0.225 Mt		
		24 May: 0.0455			4	0.399
	1952	31 Oct: 10.4 Mt	15 Nov: 0.5 Mt		2	10.9
	1954	13 May: 1.69 Mt			1	1.69
	1956	4 May: 0.04 Mt	27 May: 0.19 kt	30 May: 0.0149 Mt		
		6 Jun: 0.0137 Mt	11 Jun: 0.008 Mt	13 Jun: 1.49 kt		
		16 Jun: 1.7 kt	21 Jun: 0.0152 Mt	2 Jul: 0.36 Mt		
		8 Jul: 1.85 Mt	21 Jul: 0.25 Mt		11	2.56
	1958	5 May: 0.018 Mt	11 May: 0.081 Mt	12 May: 1.37 Mt		
		16 May: 0.009 Mt	20 May: 59 kt	26 May: 0.33 Mt		
		26 May: 0.057 Mt	30 May: 0.0116 Mt	2 Jun: 0.015 Mt		
		8 Jun: 0.008 Mt	14 Jun: 1.45 Mt	18 Jun: 0.011 Mt		

continues overleaf

Table 3.1 *continued*

Test sites	Year	Date and yield of individual tests			Number of tests	Total yield (Mt)
		27 Jun: 0.88 Mt	28 Jun: 8.9 Mt	1 Jul: 5.2 kt		
		5 Jul: 0.397 Mt	17 Jul: 0.255 Mt	22 Jul: 0.202 Mt		
		26 Jul: 2 Mt	6 Aug: 0 Mt	18 Aug: 0.02 kt	21	16.01
				Subtotal	42	31.7
Nevada	1951	27 Jan: 0.001 Mt	28 Jan: 0.008 Mt	1 Feb: 0.001 Mt		
		2 Feb: 0.008 Mt	6 Feb: 0.022 Mt	22 Oct: 0.1 kt	11	0.111
		28 Oct: 0.0035 M	30 Oct: 0.014 Mt	1 Nov: 0.021 Mt		
		5 Nov: 0.031 Mt	19 Nov: 0.0012 Mt			
	1952	1 Apr: 0.001 Mt	15 Apr: 0.001 Mt	22 Apr: 0.031 Mt		
		1 May: 0.019 Mt	7 May: 0.012 Mt	25 May: 0.011 Mt		
		1 Jun: 0.015 Mt	5 Jun: 0.014 Mt		8	0.104
	1953	17 Mar: 0.016 Mt	24 Mar: 0.024 Mt	31 Mar: 0.2 kt		
		6 Apr: 0.011 Mt	11 Apr: 0.2 kt	18 Apr: 0.023 Mt		
		25 Apr: 0.043 Mt	8 May: 0.027 Mt	19 May: 0.032 Mt		
		25 May: 0.015 Mt	4 Jun: 0.061 Mt		11	0.252
	1955	18 Feb: 0.001 Mt	22 Feb: 0.002 Mt	1 Mar: 0.007 Mt		
		7 Mar: 0.043 Mt	12 Mar: 0.004 Mt	22 Mar: 0.008 Mt		
		29 Mar: 0.014 Mt	29 Mar: 0.003 Mt	6 Apr: 0.003 Mt		
		9 Apr: 0.002 Mt	15 Apr: 0.022 Mt	5 May: 0.029 Mt		
		15 May: 0.028 Mt			13	0.166
	1957	28 May: 0.012 Mt	2 Jun: 1.4 kt	5 Jun: 0.5 t		
		18 Jun: 0.01 Mt	24 Jun: 0.037 Mt	5 Jul: 0.074 Mt		
		15 Jul: 0.017 Mt	19 Jul: 0.002 Mt	24 Jul: 0.01 Mt		
		25 Jul: 0.0097 Mt	7 Aug: 0.019 Mt	18 Aug: 0.017 Mt		
		23 Aug: 0.011 Mt	30 Aug: 0.0047 N	31 Aug: 0.044 Mt		
		2 Sep: 0.011 Mt	6 Sep: 0.197 kt	8 Sep: 0.001 Mt		
		14 Sep: 0.011 Mt	16 Sep: 0.012 Mt	23 Sep: 0.019 Mt		

		28 Sep: 0.012 Mt	7 Oct: 0.008 Mt		23	0.342
	1958	19 Sep: 0.083 kt	29 Sep: 0.002 Mt	10 Oct: 0.079 kt		
		13 Oct: 1.4 kt	15 Oct: 1.2 t	16 Oct: 0.037 kt		
		18 Oct: 0.09 kt	22 Oct: 0.006 Mt	22 Oct: 0.115 kt		
		22 Oct: 0.188 kt	26 Oct: 4.9 kt	26 Oct: 2.2 kt		
		29 Oct: 7.8 t	29 Oct: 0 Mt	30 Oct: 1.3 kt	15	0.018
	1962	7 Jul: 0.02 Mt	14 Jul: 0.02 Mt	17 Jul: 0.02 Mt	3	0.060
				Subtotal	84	1.05
Pacific sites**	1955	14 May: 0.03 Mt			1	0.03
	1958	28 Apr: 1.7 kt			1	0.0017
	1962	6 May: 0.05 Mt	11 May: 0.02 Mt		2	0.07
				Subtotal	4	0.102
Johnston Island	1958	1 Aug: 3.8 Mt	12 Aug: 3.8 Mt		2	7.6
	1962	9 Jul: 1.4 Mt	2 Oct: 0.075 Mt	6 Oct: 0.0113 Mt		
		18 Oct: 1.59 Mt	20 Oct: 0.02 Mt	26 Oct: 0.5 Mt		
		27 Oct: 0.8 Mt	30 Oct: 8.3 Mt	1 Nov: 0.5 Mt		
		4 Nov: 0.02 Mt			10	13.22
				Subtotal	12	20.8
Christmas Island	1962	25 Apr: 0.19 Mt	27 Apr: 0.41 Mt	2 May: 1.09 Mt		
		4 May: 0.67 Mt	8 May: 0.1 Mt	9 May: 0.1 Mt		
		11 May: 0.05 Mt	12 May: 0.5 Mt	14 May: 0.097 Mt		
		19 May: 0.073 Mt	25 May: 2.6 kt	27 May: 0.043 Mt		
		8 Jun: 0.782 Mt	9 Jun: 0.21 Mt	10 Jun: 3 Mt		
		12 Jun: 1.2 Mt	15 Jun: 0.8 Mt	17 Jun: 0.052 Mt		
		19 Jun: 2.2 kt	22 Jun: 0.0815 Mt	27 Jun: 7.65 Mt		
		30 Jun: 1.27 Mt	10 Jul: 1 Mt	11 Jul: 3.88 Mt	24	23.25

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Table 3.1 *continued*

Test sites	Year	Date and yield of individual tests			Number of tests	Total yield (Mt)
South Atlantic	1958	27 Aug: 1.5 kt	30 Aug: 1.5 kt	6 Sep: 1.5 kt	3	0.0045
Summary			Wartime test and use*		3	0.057
			Bikini test site		23	76.8
			Enewetak test site		42	31.7
			Nevada test site		84	1.05
			Pacific sites**		4	0.102
			Johnston Island test site		12	20.8
			Christmas Island test site		24	23.25
			South Atlantic tests		3	0.0045
			Total		195	153.8

* Alamogordo Test Site, New Mexico: 16 Jul. 1945; combat use: Hiroshima 5 Aug. 1945, Nagasaki 9 Aug. 1945.
** N 29° W 126°: 14 May 1955; N 12° E 163°: 28 April 1958; N 4° W 149°: 6 May 1962; N 31° W 124°: 11 May 1962.
*** S 38.5° W 11.5°: 27 Aug; S 49.5° W 8.2°: 30 Aug; S 48.5° W 9.7°: 6 Sep.

Table 3.2 Atmospheric nuclear tests of the former USSR.

Test sites	Year	Date and yield of individual tests			Number of tests	Total yield (Mt)
Semipalatinsk	1949	29 Aug: 0.022 Mt			1	0.222
	1951	24 Sep: 0.038 Mt	18 Oct: 0.042 Mt		2	0.08
	1953	12 Aug: 0.4 Mt	23 Aug: 0.028 Mt	3 Sep: 5.8 kt		
		8 Sep: 1.6 kt	10 Sep: 4.98 kt		5	0.440
	1954	29 Sep: 0.2 kt	1 Oct: 0.03 kt	3 Oct: 0.002 Mt		
		5 Oct: 0.004 Mt	8 Oct: 0.8 kt	19 Oct: 0 Mt		
		23 Oct: 0.062 Mt	26 Oct: 2.8 kt	30 Oct: 0.01 Mt	9	0.082
	1955	29 Jul: 1.3 kt	2 Aug: 0.012 Mt	5 Aug: 1.2 kt		
		6 Nov: 0.25 Mt	22 Nov: 1.6 Mt		5	1.865
	1956	16 Mar: 0.014 Mt	25 Mar: 5.5 kt	24 Aug: 0.027 Mt		
		30 Aug: 0.9 Mt	2 Sep: 0.051 Mt	10 Sep: 0.038 Mt		
		17 Nov: 0.9 Mt	14 Dec: 0.04 Mt		8	1.976
	1957	8 Mar: 0.019 Mt	3 Apr: 0.042 Mt	6 Apr: 0.057 Mt		
		10 Apr: 0.68 Mt	12 Apr: 0.022 Mt	16 Apr: 0.32 Mt		
		22 Aug: 0.52 Mt	26 Aug: 0.1 kt	13 Sep: 5.9 kt		
		26 Sep: 0.013 Mt	28 Dec: 0.012 Mt		11	1.691
	1958	4 Jan: 1.3 kt	17 Jan: 0.5 kt	13 Mar: 1.2 kt		
		14 Mar: 0.035 Mt	15 Mar: 0.014 Mt	18 Mar: 0.16 kt		
		20 Mar: 0.012 Mt	22 Mar: 0.018 Mt		8	0.082
	1961	1 Sep: 0.016 Mt	4 Sep: 0.009 Mt	5 Sep: 0.016 Mt		
		6 Sep: 1.1 kt	9 Sep: 0.38 kt	10 Sep: 0.88 kt		
		11 Sep: 0.3 kt	13 Sep: 0.005 Mt	14 Sep: 0.4 kt		
		17 Sep: 0.05 Mt	18 Sep: 0.004 kt	18 Sep: 0.75 kt		
		19 Sep: 0.03 kt	20 Sep: 4.8 kt	21 Sep: 0.8 kt		
		26 Sep: 1.2 kt	1 Oct: 0.003 Mt	4 Oct: 0.013 Mt		
		12 Oct: 0.015 Mt	17 Oct: 6.6 kt	19 Oct: 0.005 Mt		
		25 Oct: 0.5 kt	30 Oct: 0.09 kt	1 Nov: 2.7 kt		
		2 Nov: 0.6 kt	3 Nov: 0.001 kt	3 Nov: 0.9 kt		
		4 Nov: 0.2 kt			28	0.154

continues overleaf

Table 3.2 *continued*

Test sites	Year	Date and yield of individual tests			Number of tests	Total yield (Mt)
	1962	1 Aug: 2.4 kt	3 Aug: 1.6 kt	4 Aug: 3.8 kt		
		7 Aug: 9.9 kt	18 Aug: 7.4 kt	18 Aug: 5.8 kt		
		21 Aug: 0.05 Mt	22 Aug: 0.003 Mt	23 Aug: 2.5 kt		
		25 Aug: 0.005 Mt	27 Aug: 0.011 Mt	31 Aug: 2.7 kt		
		22 Sep: 0.21 kt	24 Sep: 1.2 kt	25 Sep: 0.007 Mt		
		28 Sep: 1.3 kt	9 Oct: 0.008 Mt	10 Oct: 9.2 kt		
		13 Oct: 4.9 kt	14 Oct: 0.005 Mt	20 Oct: 6.7 kt		
		28 Oct: 7.8 kt	28 Oct: 7.8 kt	30 Oct: 1.2 kt		
		31 Oct: 0.01 Mt	1 Nov: 0.003 Mt	3 Nov: 4.7 kt		
		4 Nov: 8.4 kt	5 Nov: 0.4 kt	11 Nov: 0.1 kt		
		13 Nov: 0.001 kt	14 Nov: 0.012 Mt	17 Nov: 0.018 Mt		
		24 Nov: 0.001 kt	26 Nov: 0.031 kt	1 Dec: 2.4 kt		
		23 Dec: 0.001 kt	24 Dec: 0.007 kt	24 Dec: 0.028 kt	39	0.224
				Subtotal	116	6.62
Totsk, Aralsk	1954	14 Sep: 0.04 Mt			1	0.0035
	1956	2 Feb: 0.3 kt			1	0.0003
				Subtotal	2	0.0038
Novaya Zemlya	1955	21 Sep: 3.5 kt			1	0.0035
	1957	7 Sep: 0.032 Mt	24 Sep: 1.6 Mt	6 Oct: 2.9 Mt		
		10 Oct: 0.01 Mt			4	4.542
	1958	23 Feb: 0.86 Mt	27 Feb: 0.25 Mt	27 Feb: 1.5 Mt		
		14 Mar: 0.04 Mt	21 Mar: 0.65 Mt	30 Sep: 1.2 Mt		
		30 Sep: 0.9 Mt	2 Oct: 0.29 Mt	2 Oct: 0.04 Mt		
		4 Oct: 0.009 Mt	5 Oct: 0.015 Mt	6 Oct: 5.5 kt		
		10 Oct: 0.068 Mt	12 Oct: 1.45 Mt	15 Oct: 1.5 Mt		
		18 Oct: 2.9 Mt	19 Oct: 0.04 Mt	19 Oct: 0.001 Mt		
		20 Oct: 0.44 Mt	21 Oct: 0.002 Mt	22 Oct: 2.8 Mt		

		24 Oct: 1 Mt	25 Oct: 0.19 Mt	25 Oct: 0.1 Mt	24	16.25
	1961	10 Sep: 2.7 Mt	10 Sep: 0.012 Mt	12 Sep: 1.15 Mt		
		13 Sep: 0.006 Mt	14 Sep: 1.2 Mt	16 Sep: 0.83 Mt		
		18 Sep: 1 Mt	20 Sep: 0.5 Mt	22 Sep: 0.26 Mt		
		2 Oct: 0.25 Mt	4 Oct: 4 Mt	6 Oct: 4 Mt		
		8 Oct: 0.015 Mt	20 Oct: 1.45 Mt	23 Oct: 4.8 kt		
		23 Oct: 12.5 Mt	25 Oct: 0.3 Mt	27 Oct: 0.016 Mt		
		30 Oct: 50 Mt	31 Oct: 5 Mt	31 Oct: 0.5 Mt		
		2 Nov: 0.12 Mt	2 Nov: 0.28 Mt	4 Nov: 0.015 Mt		
		4 Nov: 0.5 Mt	4 Nov: 6 Mt		26	92.61
	1962	5 Aug: 21.1 Mt	10 Aug: 0.5 Mt	20 Aug: 2.8 Mt		
		22 Aug: 1.6 Mt	22 Aug: 0.006 Mt	25 Aug: 4 Mt		
		27 Aug: 4.2 Mt	2 Sep: 0.08 Mt	8 Sep: 1.9 Mt		
		15 Sep: 3.1 Mt	16 Sep: 3.25 Mt	18 Sep: 1.35 Mt		
		19 Sep: 4 Mt	21 Sep: 2.4 Mt	25 Sep: 19.1 Mt		
		27 Sep: 17.6 Mt	7 Oct: 0.32 Mt	9 Oct: 0.015 Mt		
		22 Oct: 8.2 Mt	27 Oct: 0.26 Mt	29 Oct: 0.36 Mt		
		30 Oct: 0.28 Mt	1 Nov: 0.24 Mt	3 Nov: 0.39 Mt		
		3 Nov: 0.045 Mt	18 Dec: 0.11 Mt	18 Dec: 0.069 Mt		
		20 Dec: 8.3 kt	22 Dec: 6.3 kt	23 Dec: 0.43 Mt		
		23 Dec: 8.3 kt	23 Dec: 2.4 kt	24 Dec:1.1 Mt		
		24 Dec: 24.2 Mt	25 Dec: 3.1 Mt	25 Dec: 8.5 kt	36	126.1
				Subtotal	91	239.5
Kapustin Yar	1957	19 Jan: 0.01 Mt			1	0.01
	1958	1 Nov: 0.01 Mt	3 Nov: 0.01 Mt		2	0.02
	1961	6 Sep: 0.011 Mt	6 Oct: 0.04 Mt	27 Oct: 1.2 kt		
		27 Oct: 1.2 kt			4	0.053
	1962	22 Oct: 0.3 Mt	28 Oct: 0.3 Mt	1 Nov: 0.3 Mt	3	0.90
				Subtotal	10	0.983
				Total	219	247.1

Table 3.3 Atmospheric nuclear tests of the UK.

Test sites	Year	Date and yield of individual tests			Number of tests	Total yield (Mt)
Australian*	1952	3 Oct: 0.025 Mt			1	0.025
	1953	14 Oct: 0.01 Mt	26 Oct: 0.008 Mt		2	0.018
	1956	16 May: 0.015 Mt	19 Jun: 0.06 Mt	27 Sep: 0.015 Mt		
		4 Oct: 0.0015 Mt	11 Oct: 0.003 Mt	22 Oct: 0.01 Mt	6	0.105
	1957	14 Sep: 0.001 Mt	25 Sep: 0.006 Mt	9 Oct: 0.025 Mt	3	0.032
				Subtotal	12	0.180
Pacific**	1957	15 May: 0.3 Mt	31 May: 0.72 Mt	19 Jun: 0.2 Mt		
		8 Nov: 1.8 Mt			4	3.02
	1958	28 Apr: 3 Mt	22 Aug: 0.024 Mt	2 Sep: 1 Mt		
		11 Sep: 0.8 Mt	23 Sep: 0.025 Mt		5	4.85
				Subtotal	9	7.87
				Total	21	8.05

* Tests at Monte Bello Island: 3 Oct. 1952; 16 May, 19 Jun. 1956; tests at Emu: 14 Oct. 26 Oct. 1953; other tests at Maralinga.
** Tests at Malden Island: 15 May, 31 May, 19 Jun. 1957; other tests at Christmas Island.

Table 3.4 Atmospheric nuclear tests of France.

Test sites	Year	Date and yield of individual tests			Number of tests	Total yield (Mt)
Algerian	1960	13 Feb: 0.067 Mt	1 Apr: 0.003 Mt	27 Dec: 0.002 Mt	3	0.072
	1961	25 Apr: 0.0007 Mt			1	0.0007
				Subtotal	4	0.073
Mururoa and Fangataufa*	1966	2 Jul: 0.028 Mt	19 Jul: 0.05 Mt	11 Sep: 0.11 Mt		
		24 Sep: 0.125 Mt	4 Oct: 0.205 Mt		5	0.52
	1967	5 Jun: 0.014 Mt	27 Jun: 0.12 Mt	2 Jul: 0.022 Mt	3	0.16
	1968	7 Jul: 0.115 Mt	15 Jul: 0.45 Mt	3 Aug: 0.15 Mt		
		24 Aug: 2.6 Mt	8 Sep: 1.28 Mt		5	4.60
	1970	15 May: 0.013 Mt	22 May: 0.224 Mt	30 May: 0.945 Mt		
		24 Jun: 0.012 Mt	3 Jul: 0.914 Mt	27 Jul: 0.05 kt		
		3 Aug: 0.072 Mt	6 Aug: 0.594 Mt		8	2.77
	1971	5 Jun: 0.034 Mt	12 Jun: 0.44 Mt	4 Jul: 0.009 Mt		
		8 Aug: 0.004 Mt	14 Aug: 0.955 Mt		5	1.44
	1972	25 Jun: 0.005 Mt	30 Jun: 0.004 Mt	27 Jul: 0.006 Mt	3	0.011
	1973	21 Jul: 0.011 Mt	28 Jul: 0.05 kt	18 Aug: 0.004 Mt		
		24 Aug: 0.2 kt	28 Aug: 0.006 Mt		5	0.021
	1974	16 Jun: 0.004 Mt	7 Jul: 0.15 Mt	17 Jul: 0.004 Mt		
		25 Jul: 0.008 Mt	15 Aug: 0.096 Mt	24 Aug: 0.014 Mt		
		14 Sep: 0.332 Mt			7	0.61
				Subtotal	41	10.13
				Total	45	10.2

Table 3.5 Atmospheric nuclear tests of China.

Test site	Year	Date and yield of individual tests			Number of tests	Total yield (Mt)
Lob Nor	1964	16 Oct: 0.02 Mt			1	0.02
	1965	14 May: 0.04 Mt			1	0.04
	1966	9 May: 0.3 Mt	27 Oct: 0.02 Mt	28 Dec: 0.3 Mt	3	0.602
	1967	17 Jun: 3 Mt	24 Dec: 0.02 Mt		2	3.02
	1968	27 Dec: 3 Mt			1	3
	1969	29 Sep: 3 Mt			1	3
	1970	14 Oct: 3 Mt			1	3
	1971	18 Nov: 0.02 Mt			1	0.02
	1972	7 Jan: 0.02 Mt	18 Mar: 0.1 Mt		2	0.12
	1973	23 Jun: 2.5 Mt			1	2.5
	1974	17 Jun: 0.6 Mt			1	0.6
	1976	23 Jan: 0.02 Mt	26 Sep: 0.1 Mt	17 Nov: 4 Mt	3	4.12
	1977	17 Sep: 0.02 Mt			1	0.02
	1978	15 Mar: 0.02 Mt	14 Dec: 0.02 Mt		2	0.04
	1980	16 Oct: 0.6 Mt			1	0.6
				Total	22	20.7

Table 3.6 Underground nuclear tests.

Year	Number of tests						
	USA	USSR	UK	France	China	India	Pakistan
1951	1						
1955	1						
1957	5						
1958	15						
1961	10	1		1			
1962	57	1	2	1			
1963	45			3			
1964	48	9	2	3			
1965	39	15	1	4			
1966	49	19		1			
1967	42	23					
1968	72	23					
1969	61	24			1		
1970	60	21					
1971	28	29					
1972	32	31					
1973	27	22					
1974	25	27	1			1	
1975	23	35		2	1		
1976	20	27	1	5	1		
1977	23	36		9			
1978	20	55	2	11	1		
1979	15	52	1	10			
1980	14	43	3	12			
1981	16	37	1	12			
1982	18	34	1	10	1		
1983	19	37	1	9	2		
1984	18	52	2	8	2		
1985	17	10	1	8			
1986	14		1	8			
1987	16	39	1	8	1		
1988	18	29		8	1		
1989	15	11	1	9			
1990	10	8	1	6	2		
1991	9		1	6			
1992	8				2		
1993					1		
1994					2		
1995				5	2		
1996				1	2		
1997							
1998						5	6
Total	910	750	24	160	22	6	6
				Total for all countries:			1878

Atomic Radiation (UNSCEAR) is assigning yields also to these unspecified tests. These yield estimates are, thus, still subject to adjustment, should further information become available. Specific yields for each underground test have not yet been assigned.

The nuclear testing programme of the USA included 210 atmospheric tests, five underwater tests and 815 underground tests (DOE, 1994). As the underwater tests were uncontained, these tests are included with the atmospheric tests in Table 3.1. The use of two nuclear weapons detonated in Japan at the end of World War II are also included; these add to the total number of atmospheric explosions. In 63 underground tests, simultaneous detonation of two to five separate charges occurred. As these can be distinguished as independent tests, the total number of underground tests should be increased by 95 tests. This explains the number of underground tests (910) given in Table 3.6. The total number of tests was 1127. There were 24 underground tests conducted jointly with the UK. These tests are listed with the latter country in Table 3.6.

The former USSR conducted 219 atmospheric tests (including five underwater) and 496 underground tests (MRF, 1996). This gives a total of 715 tests, but an additional 254 charges were detonated in simultaneous underground tests. These are given separate designation in Table 3.6. The total number of tests by the former USSR was, thus, 969.

The UK conducted 21 atmospheric tests and 24 underground tests, the latter jointly with the USA (Johnston, 1995). There were, in addition, 12 safety tests conducted on the land surface, which, although of no yield, are by convention added to the number of atmospheric tests. The atmospheric tests at the various test sites are listed in Table 3.3, and the annual number of underground tests in Table 3.6.

The atmospheric test programme of France is given in Table 3.4. There were 50 atmospheric tests (Doury and Musa, 1996), including five safety tests, and a total of 160 underground tests. The total number of tests was 210. Official information of the nuclear test programme of China is still lacking. The recorded number of atmospheric tests is given in Table 3.5 (UNSCEAR, 1993) and the underground tests in Table 3.6. There were 22 tests of each type, 44 in total. The underground tests of India and Pakistan are recorded in Table 3.6.

From the above enumeration, one derives a total of 2419 nuclear tests carried out by all countries between 1945 and 1998, 541 atmospheric and 1878 underground. The total explosive yield of each atmospheric test has been reported or estimated. The yield of atmospheric tests, 440 Mt, exceeds that of all underground tests, estimated to be 90 Mt. A summary of total numbers and yields of tests for the separate countries is given in Table 3.7. The fission and fusion proportions of the tests have not yet been fully divulged. It will be important to obtain this information in order to determine the amounts of fission, fusion and activation radionuclides produced in these explosions.

Table 3.7 Summary of nuclear testing.

Country	Number of tests			Yield (Mt)		
	Atmospheric	Underground	Total	Atmospheric	Underground	Total
USA	217*	910	1127	154	46	200
USSR	219	750	969	247	38	285
UK	33**	24	57	8.1	2	10
France	50***	160	210	10.2	3	13
China	22	22	44	20.7	1	22
India		6	6			
Pakistan		6	6			
All countries	541	1878	2419	440	90	530

* Includes 22 safety tests and 2 combat explosions.
** Includes 12 safety tests.
*** Includes 5 safety tests.

Estimates of radionuclide production are derived from the fallout measurements that were made throughout the world during the time of testing. These measurements are the starting point for the dose estimates to be discussed in Chapter 6.

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4 Nuclear Explosions and their Environmental Contamination

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4.1 FORMATION AND FRACTIONATION OF RADIONUCLIDES

4.1.1 General characteristics of radionuclides and processes after a nuclear explosion

Most of the contamination from nuclear explosions has resulted from detonations in the atmosphere, especially those near or on the Earth's surface, and from underground detonations that were designed to produce craters.

In order to predict and analyse the atmosphere and terrestrial radioactive contamination it is necessary to know in detail:

1. the nature of the source (size and shape of the radioactive cloud, processes within the cloud, distribution of radioactive particles by size, and distribution of the radionuclides within and on the particles);
2. the meteorological situation (wind velocity with height and precipitation);
3. the distribution of radionuclides on the ground (fallout pattern);
4. the prevalence of foodchains and the intake of contaminated food by animals and humans.

These factors, with additional detail, are indicated in Figure 4.1.

The first two factors determine the character of the atmospheric transport of the debris, the formation of fallout and the principal radiation characteristics, i.e. the external gamma-exposure rate and the radionuclide composition of fallout. These subjects are considered in detail in Izrael (1996).

An atmospheric nuclear explosion produces a radioactive cloud, which depending on the explosive yield, rises to an altitude from several to several tens of kilometres.

A cratering explosion produces a cloud (which rises up to an altitude of several kilometres) and a base surge, which has a height of about 20–25% of the main cloud.

Nuclear Test Explosions: Environmental and Human Impacts
Edited by Sir F. Warner and R. J. C. Kirchmann

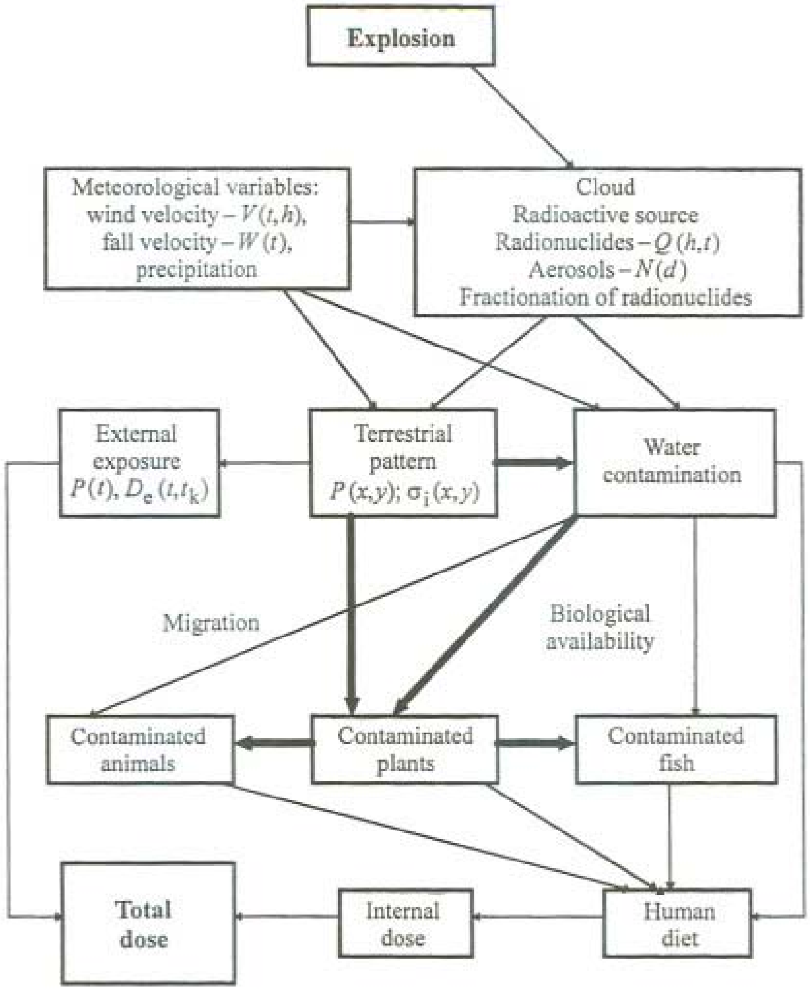


Figure 4.1 The scheme of transformation and transport pathways of radionuclides from nuclear explosions and the consequent atmospheric and terrestrial radioactive contamination.

Radioactive debris consists primarily of fission products and neutron-activation products, both of which may be mixed with a substantial amount of soil and material from the supporting tower and explosion device.

During the first tens of seconds of fireball and cloud formation very important processes occur in the condensation of vaporized products on the particulate matter that may be present. These processes determine the distribution of various radionuclides relative to the size of particles; radionuclides with high melting points tend to be distributed throughout the volume of larger particles, whereas volatile radionuclides tend to be confined to the surface of particles. As small particles contain most of the total surface area available, volatile radionuclides tend to be associated with smaller particles. Later, particles are transported to various distances depending upon their size, among other factors. Thus, the processes that occur during the first tens of seconds play a decisive role in the radionuclide composition of the contamination as a function of distance from the explosion.

4.1.2 Formation of aerosol particle-carriers of radioactivity

A subsurface nuclear explosion ejects into the atmosphere around 5000 t of soil per explosion yield of 1 kt; 180–200 t of this amount is melted, and 1.5 to 25 t kt^{-1} is vaporized (in the case of an underground explosion up to 50–70 t kt^{-1} is vaporized).

In the case of ground-surface explosions less soil (or water, if exploded over water) is ejected into the fireball and the cloud; in the case of atmospheric explosions the cloud may contain essentially only the matter of the device itself. In the latter case, spherical radioactive particles of several micrometres diameter are formed only as a result of the condensation of the material, whereas in the ground (surface) and underground (cratering) explosions, radioactive particles are produced as a result of the fusing of radioactive material with entrained soil.

Two principal types of particles are formed: spherical (or drop-form) particles formed, as a rule, by fusion of silicate material (for example, volcanic rock, obsidian, etc.), which are up to 1–2 mm in size, and angular particles of irregular forms that have not been fused. In addition there are combinations of the two forms.

Radionuclides in spherical particles are distributed either throughout the entire volume, or through a thick layer of the volume. The radionuclides associated with angular, irregular particles are, as a rule, attached to the surface. A substantial amount of experimental data on radioactive particles and their radionuclide composition has been published (Klement, 1964; Izrael *et al.*, 1970a; Izrael, 1973).

The total particle-activity and size distribution for a surface (and underground) explosion (and for the Chernobyl accident) can be expressed by a lognormal law, i.e. activity fraction $A(d_1, d_2)$ connected with particles with diameter from d_1 to d_2 is equal to

$$A(d_1, d_2) = \frac{1}{\sigma\sqrt{2\pi}} \int_{\lg d_1}^{\lg d_2} \exp\left[-\frac{(\lg d - \lg \bar{d})^2}{2\sigma^2}\right] d(\lg d) \tag{4.1}$$

where d is the particle diameter, $\bar{d}$ and σ are distribution parameters.

The above distribution is not strongly related to explosion yield, but it does depend substantially on the soil type. For example, for Nevada soil lg $\bar{d}$ = 2.053 and $\sigma = 0.732$, for coral soil lg $\bar{d}$ = 2.209 and $\sigma = 0.424$ (Stewart, 1956).

Models that describe the movement of radioactive particle distribution in the atmosphere often uses particle fall velocity distributions $N(W)$. For example:

$$N(W) = \frac{a^{n+1}}{\Gamma(n+1)} W^n e^{-aW} \tag{4.2}$$

where W is the particle fall velocity, Γ is the gamma-function, and a, n are distribution parameters. In one particular case studied by Petrov and Pressman (1962) it was found that $n = 2$ and $a = 0.06$.

Vaporized explosion debris transforms into melted (fused) soil particles in accordance with thermodynamic conditions in the fireball as well as with the physical and chemical characteristics of the elements. Soil particles solidify very quickly in the fireball; for example, in about 7 s, in an explosion yield of 20 kt and in about 40 s for an explosion yield of 1 Mt.

4.1.3 Fractionation of radionuclides

The physical and chemical form (i.e. gaseous, intermediate, or refractory) of the radionuclides in a fission-product mass chain during fireball formation is very important in determining the association of radionuclide activity with particle size. Several of the more important mass chains are shown in Table 4.1. It can be seen in Table 4.1 that in the first tens of seconds after the explosion, precursors of ^{89}Sr, ^{90}Sr and ^{137}Cs are in the form of noble gases, ^{89}Kr, ^{90}Kr and ^{137}Xe; therefore the product radionuclides (e.g ^{89}Sr, ^{90}Sr and ^{137}Cs) are not found within the particles that condense during the early post-detonation phases. Rather, ^{89}Sr, ^{90}Sr and ^{137}Cs attach to particles according to the surface area available at the later times when they condense. In contrast, radionuclides such as ^{95}Zr and ^{144}Ce are already in the form of refractory elements within the first seconds and thus are found distributed throughout the volume of particles that condense during the early phases. A value, F_i can be calculated (Izrael, 1973):

$$F_i = \frac{Q_i^{Y}(t)}{Q_i(t)} \tag{4.3}$$

i.e. the relation between the stage the ith chain radionuclide reached by the moment t inside the melted particle $Q_i^{Y}(t)$ and the total amount of radionuclides in the given chain $Q_i(t)$.

The dependence of the total activity, $A(r)$, of the individual radioactive particles on their radius, r, is subject to the power law $A(r) = k \times r^n$, where k is

Table 4.1 Mass chains of certain fission products.

Mass chain	Volatile	Intermediate	Refractory
89	4.4 s* $^{89}Br_{35}$ → (48.2)** → 3.2 min $^{89}Kr_{36}$ (40.7)	→13.4 min $^{89}Rb_{37}$ → (4.1)	50.5 day $^{89}Sr_{38}$ → (0.05) → stable $^{89}Y_{39}$
90	1.6 s $^{90}Br_{35}$ → (27.5) → 33 s $^{90}Kr_{36}$ (56.7)	→ 2.7 min $^{90}Rb_{37}$ → (13.9)	28 yr $^{90}Sr_{38}$ → (0.41) 64 h $^{90}Y_{39}$ → stable $^{90}Zr_{40}$
95	short $^{95}Kr_{36}$ (0.1)	→ 2 s $^{95}Rb_{37}$ → (7.2)	40 s $^{95}Sr_{38}$ → (49.1) → 10 min $^{95}Y_{39}$ → (39.7) → 65 day $^{95}Zr_{40}$ → (3.8) → 35 day $^{95}Nb_{41}$ → → stable $^{95}Mo_{42}$
137	24.4 s $^{137}I_{53}$ → (54.2) → 3.9 min $^{137}Xe_{54}$ (32.5)	→ 30 y $^{137}Cs_{55}$ (2.32)	0.95 → 2.6 min $^{137m}Ba_{56}$ 0.05 → stable $^{137}Ba_{56}$
144	short $^{144}Xe_{54}$ (0.2)	→ 1.5 s $^{144}Cs_{55}$ → (2.7)	3.5 s $^{144}Ba_{56}$ → (49.1) → 15 s $^{144}La_{57}$ → (39.7) → 290 day $^{144}Ce_{58}$ → (3.8) → 17 min $^{144}Pr_{59}$ → → stable $^{144}Nd_{60}$

* Half-life.
** % (Izrael, 1996).

a parameter to be fitted and $2.0 < n < 3.0$, i.e. at $n = 2.0$ contamination is only on the surface of the particle and at $n = 3.0$ contamination is spread throughout the volume of the particle (Figure 4.2).

Thus, the physical processes that occur within the fireballs and which result in different radionuclides being attached to particles of different size, result in the 'fractionation' of radionuclides. Radionuclides that condense at later times attach themselves to particles according to the surface area available, which is always associated with smaller particles. Such smaller particles typically remain airborne for longer times than do the larger particles with the refractory elements distributed throughout their volume.

Radionuclide fractionation can be considered as a deviation of the radionuclide ratio (in particles, zones of radioactive fallout, etc.) from the initial

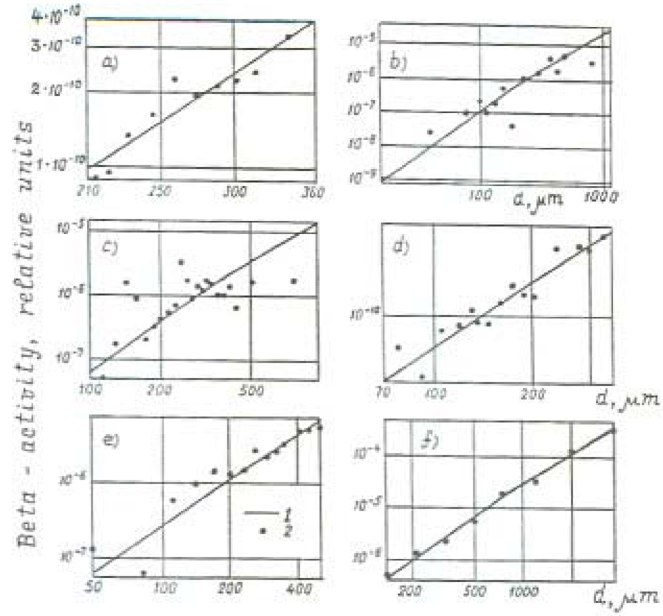


Figure 4.2 Relationship between particle beta-activity and particle size in various experiments: (a) 12 August 1953; (b) 29 July and 5 August 1955; (c) 25 March 1956; (d) 24 August 1956, measurements 3 y after the explosion; (e) 24 August 1956, measurements 3 h after the explosion; (f) 14 September 1961. 1, calculation; 2, experimental data.

ratio at the moment of the explosion. Thus, the fractionation factor of the *i*th radionuclide to *j*th radionuclide is

$$f_{i,j}(t,r) = \frac{n_i(t,r)/n_j(t,r)}{[n_i(t)/n_j(t)]_T} \tag{4.4}$$

where the index T denotes the theoretical ratio of these radionuclides (n is the number of nuclei, t is the time and r is the radius of the particles).

Fractionation factors are important characteristics of atmospheric and terrestrial contamination. They change significantly for different particles and different zones of contamination, even for the same explosion (up to 100 times). To characterize fractionation in a fallout pattern from a given explosion (or for an explosion as a whole) one can construct correlation plots of logarithms of fractionation factors. It is common to make reference to two radionuclides of opposite (by volatility) properties of elements (mass chains); usually these are ^{89}Sr and ^{95}Zr.

Figure 4.3 shows examples of correlation plots for different radionuclides produced by the USSR crater forming explosion named Sary-Uzen, and the

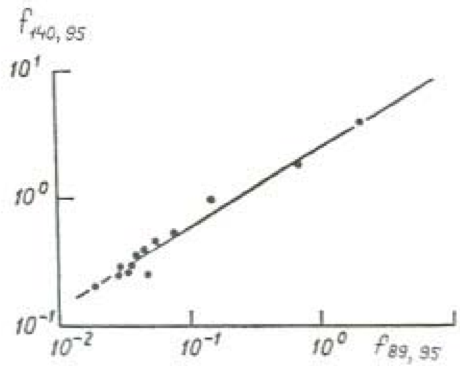


Figure 4.3 Correlation plots of fractionation factors for various radionuclides in the fallout pattern from USSR crater explosion shaft '1003'.

drilled shaft '1003' (Izrael *et al.*, 1970a; Izrael, 1973). A similar correlation plot is shown in Figure 4.4 for an atmospheric explosion (Freiling, 1961).

It follows from the plots that

$$\lg f_{i,89} = a_i + b_i \lg f_{95,89} \tag{4.5}$$

where a_i is the value of the 'cut-off' (ordinate) and $b_i = \text{tg}\,\alpha$ is the slope of the regression line. Values of a_i and b_i depend on the choice of radionuclide k as the reference.

It can be shown (Freiling, 1963) that $b_i = n_{i-2}$ and

$$a_i = \frac{b_i(1-b_i)\sigma^2}{4,6} \neq 1 \tag{4.6}$$

Here, σ^2 is the dispersion in the lognormal distribution of a particle activity and mass by sizes $2 \leq n_i \leq 3$ is the power index of particle size distribution of activity.

It turned out that

$$\lg f_{i,89} = \sqrt{F_i}\,\lg f_{95,89} \tag{4.7}$$

where F_i is determined from equation (4.3) (Figure 4.5).

It is of interest to note that value of v_i is not related to the fission type (unlike the value of the 'cut-off' variable a_i). Values of a_i and b_i depend on the choice of radionuclide, k, as a reference.

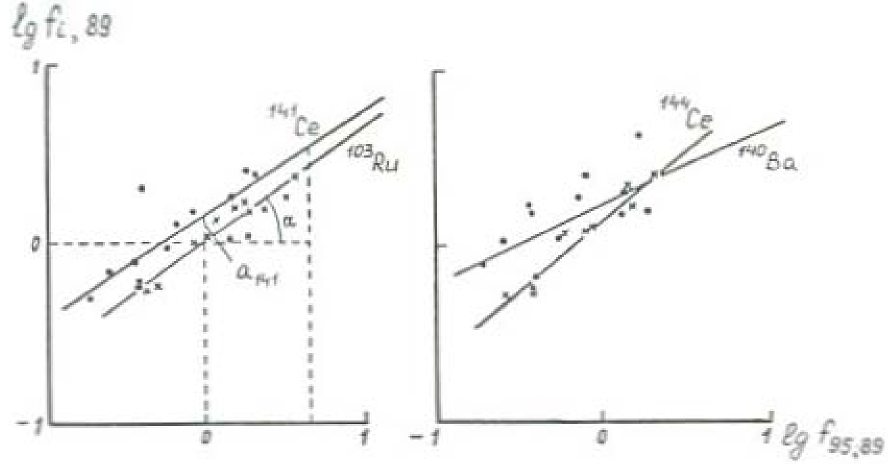


Figure 4.4 Illustrative correlation plot of fractionation factors for an atmospheric nuclear explosion.

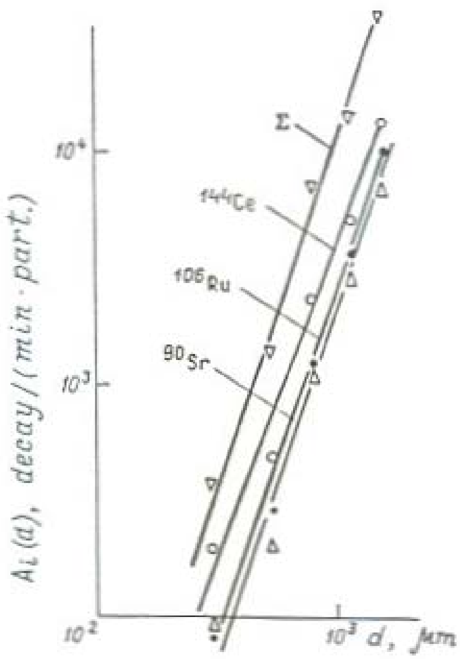


Figure 4.5 Size dependence of various radionuclides activity in particles within the first few seconds of an explosion (data obtained from USSR crater explosion shaft '1003').

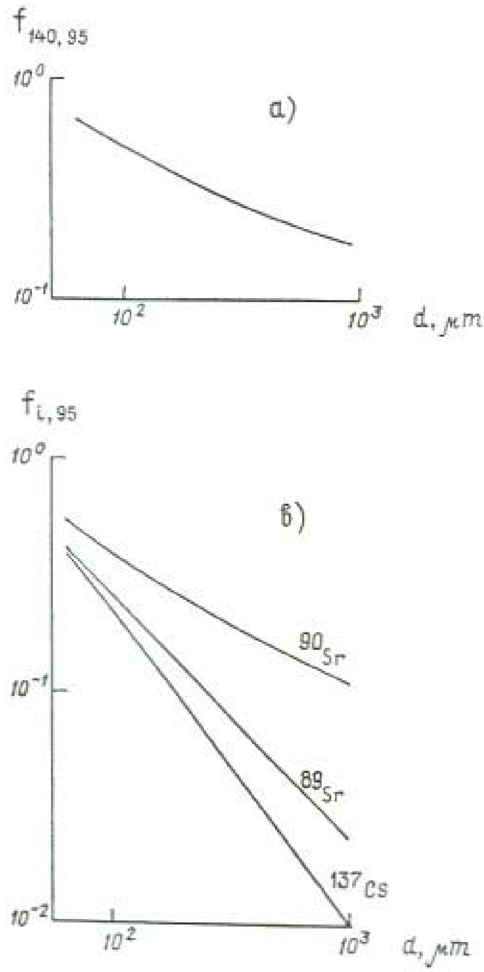


Figure 4.6 The relationship between fractionation factors and particle size for ^{140}Ba (a), ^{89}Sr, ^{90}Sr and ^{137}Cs (b).

Having assumed the respective models of particle activity (distribution with particle size) on the surface of a particle and in the structure of a particle theoretical relationships can be constructed (Izrael, 1973) between fractionation factors for various radionuclides and particle size (Figure 4.6). The application of these models has made it possible to calculate the fraction and distribution of radionuclides deposited within the immediate vicinity of explosions of various yields. The validation of these results with independent material is shown in Figure 4.7. Here we see a correlation plot of calculated values with those

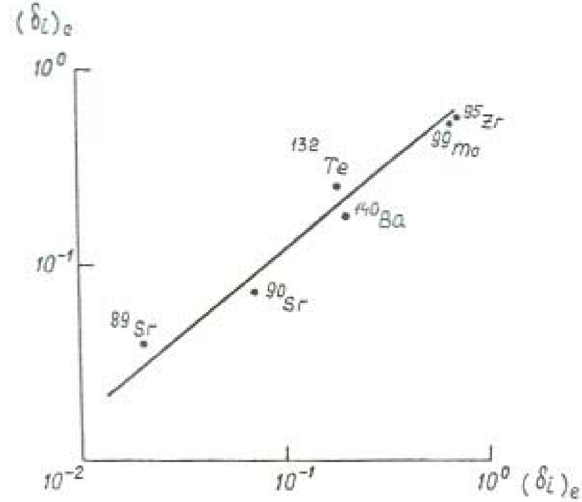


Figure 4.7 Correlation plot of calculated $(\delta_i)_c$ and experimental $(\delta_i)_e$ fractions of radionuclides deposited from fallout in the immediate vicinity of a low-yield ground explosion.

obtained experimentally from fallout in the immediate vicinity of a small explosion (Small-boy) carried out in the USA. These data demonstrate that the experimental and calculated values coincide.

Table 4.2 lists experimentally obtained integral values of lg α_i for fallout patterns from atmospheric and ground-surface explosions (Freiling, 1963).

Further, if one considers fractionation factors at different distances from ground zero their dependence on distance is obvious. Figure 4.8 shows the dependence of fractionation factors (integrated across the pattern) on the distance x/Hu from the ground zero for four crater nuclear explosions in the former USSR (Izrael *et al.*, 1970a). For the normalized distance, x is the distance along the pattern axis, u is the wind speed, and H is the cloud height. A distinct relationship between fractionation factors and distance is observed in this figure.

Table 4.2 Values for lg α_i when correlating various radionuclides from atmospheric nuclear explosions.

Radionuclide	lg α_i	Radionuclide	lg α_i
^{90}Sr	0.32	^{140}Ba	0.43
^{99}Mo	0.11	^{144}Ce	0.94
^{132}Te	0.60	^{237}U	1.04
^{137}Cs	−0.06	^{239}Np	1.05
^{89}Sr	0	^{95}Zr	1.0

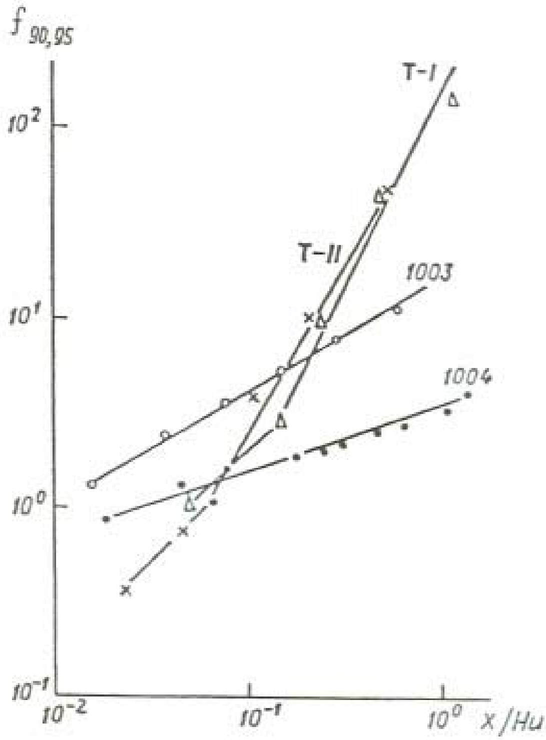


Figure 4.8 Changes of fractionation factors, $f_{90,95}$, with normalized distance x/Hu for various explosions (x, distance along the pattern axis; u, wind speed; H, cloud height).

For radionuclides produced from ground-surface explosions the relative magnitude of fractionation (from 0 to 1 relative to ^{95}Zr, i.e. from 'volatile' to 'refractory') can be presented in the following sequence (Klement, 1964; Izrael, 1973): ^{137}Cs, ^{89}Sr, ^{90}Sr, ^{136}Cs, ^{115}Cd, ^{111}Ag, ^{140}Ba, ^{91}Y, ^{141}Ce, ^{99}Mo, $^{103,106}Ru$, radionuclides of rare-earth elements, ^{95}Zr. For underground nuclear explosions this sequence is as follows (Izrael *et al.*, 1970): ^{137}Cs, ^{89}Sr, ^{90}Sr, ^{140}Ba, ^{91}Y, ^{103}Ru, ^{131}I, ^{132}Te, ^{136}Cs, ^{141}Ce, ^{144}Ce, ^{99}Mo, ^{95}Zr. A large amount of experimental data on the radionuclide composition of airborne and fallout material has been published (Klement, 1964).

It is important to note that the established relationships of the dependence of radionuclide fractionation on volatile precursors produced by nuclear explosions does not, naturally, apply to nuclear reactor accidents. In the case of a reactor accident, for example, the behaviour of all caesium isotopes is similar, but the behaviour of strontium isotopes are different (Izrael *et al.*, 1990). In the case of a nuclear reactor accident such as Chernobyl, the caesium and strontium isotopes behave quite differently, as the volatile precursors of the strontium isotopes have already decayed and strontium itself is not volatile.

4.2 ATMOSPHERIC DISPERSION AND FALLOUT OF RADIONUCLIDES

The spatial pattern of surface radioactivity contamination is formed by the fallout of radioactive particles from the radioactive cloud in passing air masses. One can distinguish a proximal pattern (a few hundred kilometres from ground zero), a remote pattern (formed several days after the explosion) and global fallout occurring over several years, which comprises highly dispersed radioactive particles ejected into the atmosphere and stratosphere.

When describing the pattern one should investigate its spatial pattern (isolines of dose rates or radionuclide deposition density) and determine distinctly the axis of maximum contamination.

4.2.1 Local (proximal) fallout patterns

Patterns from the clouds of high-yield ground and tower-type nuclear explosions are well known (for example, the USA explosions of 1949 on Bikini Atoll and the explosion of 12 August 1953 at the Semipalatinsk Test Site). Figure 4.9 shows spatial distribution of ^{137}Cs contamination density, with the pattern from the explosion of 1953 indicated (Izrael *et al.*, 1994).

It is obvious that spatial distribution patterns will depend much on the size of the cloud and on meteorological conditions, particularly on changes in wind direction at high altitude.

Figure 4.10 shows the relationship between the amount of radioactive products $A(R)$ in various patterns from the explosions of the Semipalatinsk Test Site (Loborev *et al.*, 1994) and the distance R. One characteristic peculiarity of these relationships is that they are power functions:

$$A(R) = A_0 R^{-n} \tag{4.8}$$

Another peculiarity is the occurrence of a conspicuous curve at the beginning of the pattern: it is practically absent in the case of ground explosions, close to ground zero for tower explosions and is variably located depending on the relative height of the explosion for air explosions.

Particularly well studied are patterns of underground cratering explosions (Izrael, 1974). The main characteristics of such explosions carried out in the USA and former USSR are given in Table 4.3. A peculiarity of cratering nuclear explosions is the formation (besides the cloud) of a base surge yield, which results in a circular contamination of the ground zero region (Nordyke

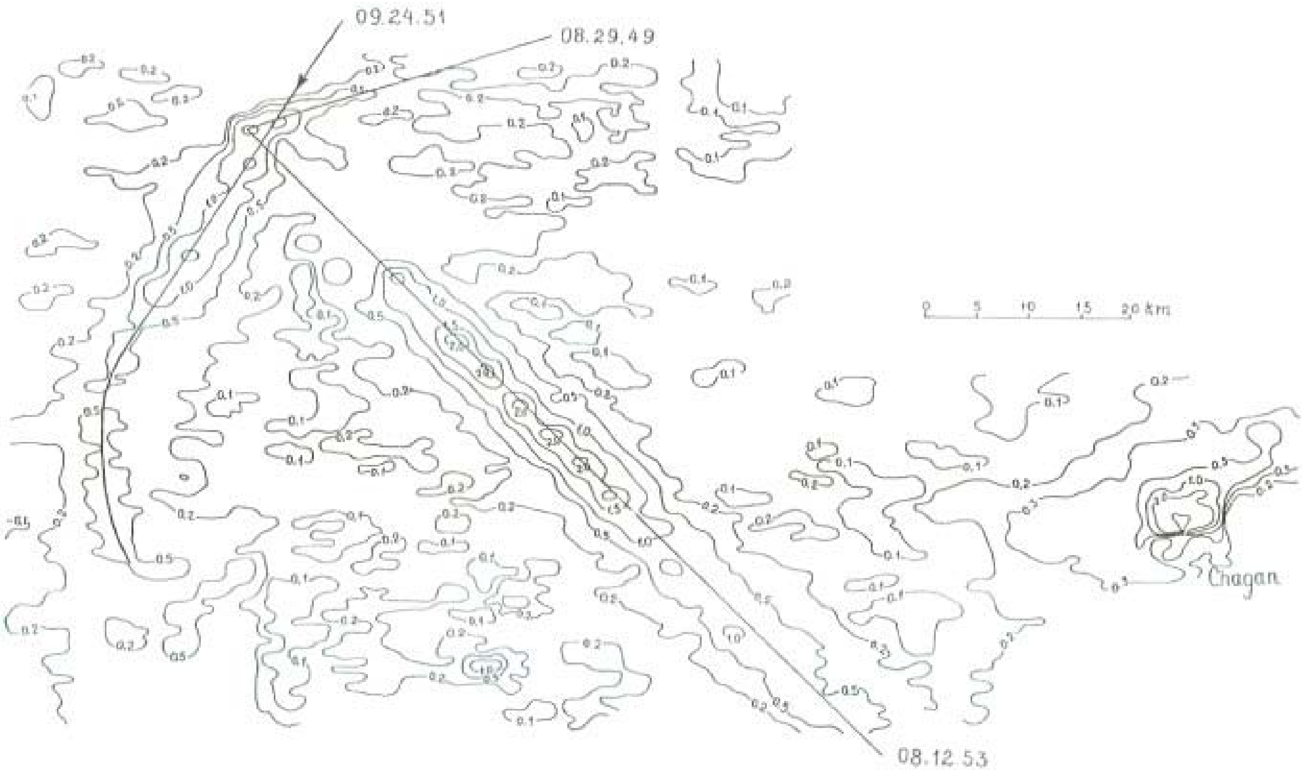


Figure 4.9 The area around the Semipalatisk Test Site contaminated by ^{137}Cs (Ci km^{-2}; multiply by 3.7×10^{10} to obtain becquerels). The survey was undertaken in 1991 (based on Scientific Production Enterprise (SPE) 'Aerogeologia' data). Spatial patterns attributable to individual explosions are shown.

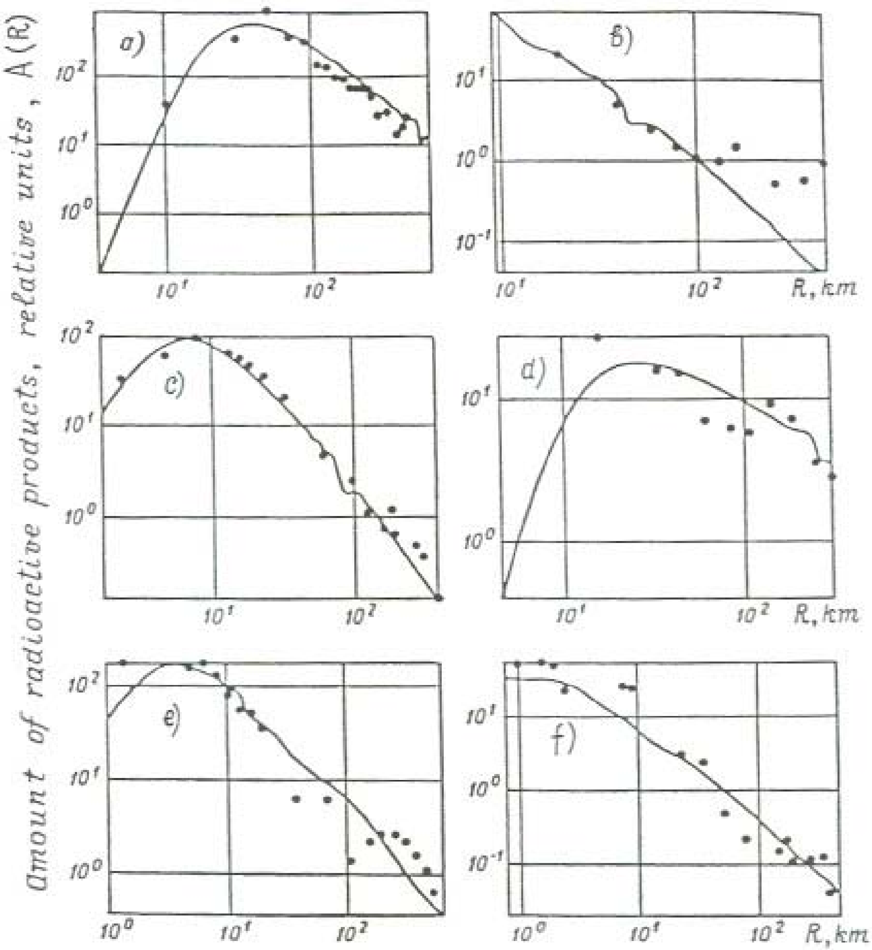


Figure 4.10 Relationship between the amount of radioactive products $A(R)$ in the fallout pattern from the nuclear explosion and distance R from ground zero. Data are for surface nuclear explosions on STS: (a) 12 August 1953; (b) 5 October 1954; (c) 2 August 1955; (d) 24 August 1956; (e) 7 August 1962; (f) 30 October 1962.

and Wray, 1964; Izrael *et al.*, 1970a,b). This contamination, unlike surface contamination, is volumetric in character: i.e. radioactivity is found at depth, down to tens of centimetres and more (Figure 4.11; Izrael *et al.*, 1970b).

Figures 4.12 and 4.13 show the surface pattern of contamination following the underground nuclear explosions '1003' (USSR) (Izrael *et al.*, 1970a) and Sedan (USA) (Klement, 1964). Figure 4.14 shows changes in the dose rate and

Table 4.3 Basic data concerning experimental cratering nuclear explosions*.

Type	Name of the explosion	Country	Yield, kt	Depth, m	$m/kt^{1/3.4}$	Cloud height, m	Amount of material deposited over the pattern***, t	Radioactivity fraction deposited over the pattern, %
Medium yield	'Chagan' ('1004')	USSR	140**	175	41	4800	1400	20
	'Sedan'	USA	104	193	50	3600–4200	1200–1400	4–17
	'Schooner'	USA	30	108	39	4000	340	
Low yield	'Cabriolet'	USA	2.3	52	44.8	120	7	
	'Sary-Uzen' ('1003')	USSR	1.1	48	48	300	35	3.5
	'Danny-Boy'	USA	0.43	33.5	43.2	300	17–30	4–7
Very low yield	'Telkem-1' (T-1)	USSR	0.2	31.4	51	200	0.4	0.2
	'Sulky'	USA	0.092	27.4	56	–	–	–
Row explosion	'Buggy'	USA	1.08 × 5	41.2	41.2	660		
	'Telkem-2' (T-2)	USSR	0.24 × 3	31.4	51	450	1.8	0.3
	'Taiga' ('Canal')	USSR	15 × 3	128				

* All basic data are shown in accordance with official publications (Mikhailov *et al.*, 1996) and (US DOE, 1994).
** Yield on fission is 7 kt in accordance with Mikhailov *et al.* (1996).
*** On power density field.

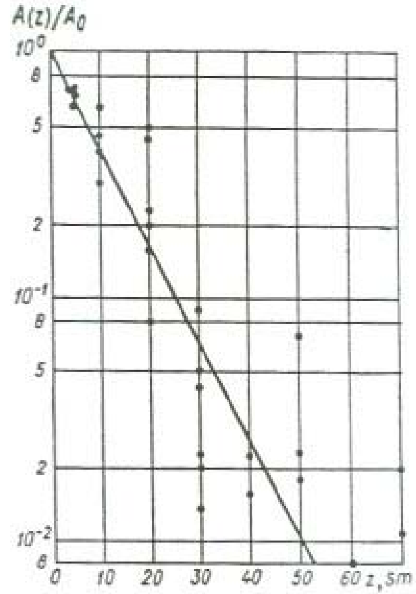


Figure 4.11 The relationship between the specific soil beta-activity and depth in the profile for explosion '1004'.

total amount of radioactive iodine at the ground surface along the plume axis of explosion '1003', and Figure 4.15 shows the relationship between the total amount of ^{131}I and the distance from ground zero for three crater explosions (Izrael *et al.*, 1970b).

4.2.2 Remote pattern (tropospheric fallout)

The remote pattern is characterized by larger spatial scales and much lower contamination densities as compared to the proximal pattern.

Figure 4.16 (Izrael *et al.*, 1995) shows data on the measured activity of radioisotopes ^{95}Zr + ^{95}Nb and ^{103}Ru measured in the USSR after a series of the 1961 high-yield nuclear explosion at the Novaya Zemlya Test Site. In the autumn of 1961, 11 nuclear explosions of more then 1 Mt yield were conducted there, and on 23 and 30 October 1961 two very large devices, with yields of 12.5 and 50 Mt, were exploded (Mikhailov *et al.*, 1996). The explosions were conducted at an altitude of 3.5 and 4 km. The nuclear clouds from all these explosions, having reached a high altitude, spread towards the continental territory of the former USSR (primarily towards the south to southeast). The contamination over a vast area of the former USSR was investigated in April

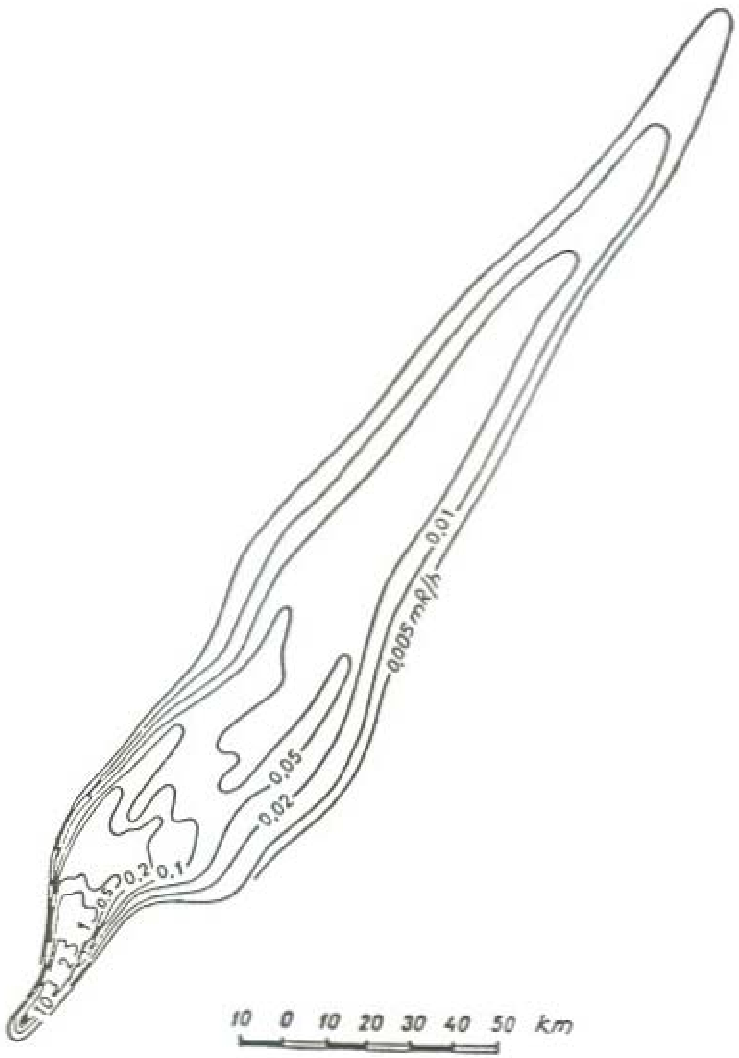


Figure 4.12 Gamma-radiation dose rate distribution in the fallout pattern, one day after explosion '1003'.

1962 by sampling the snow cover present before the nuclear test and which had not melted before sampling.

At least two vast zones of radioactive contamination were found: the first zone in the west of the Ural Mountains (Uralskie Gory), and the second in the Taymyr (Taimyr) peninsula and central Siberia. The maximum surface contamination in April 1962 was: total activity up to 1000 mCi (37 GBq) km^{-2};

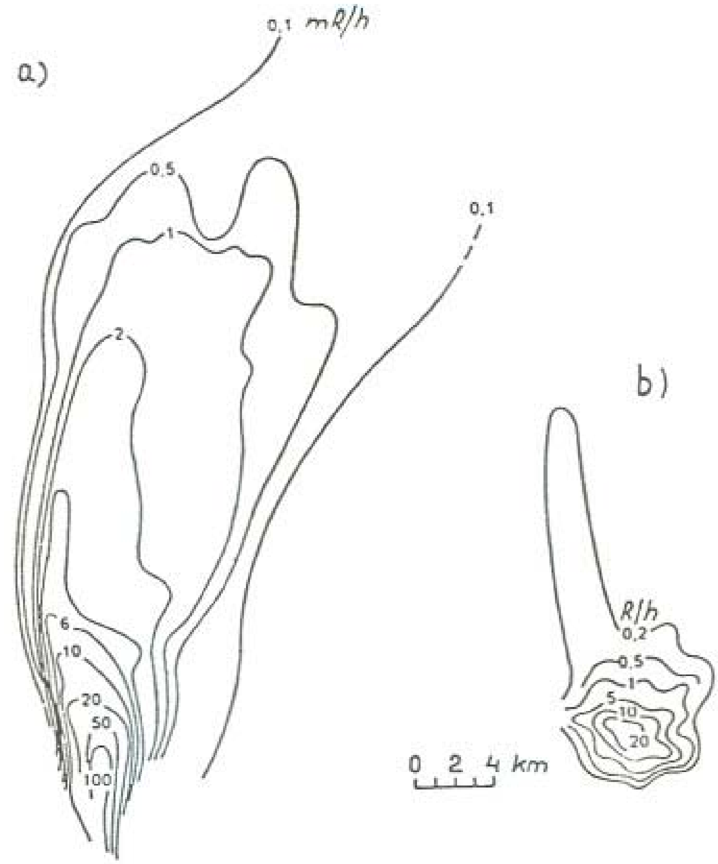


Figure 4.13 Gamma-radiation dose rate distribution in the pattern of fallout contamination (a) and in the pattern of proximal contamination (b) one day after the 'Sedan' explosion.

$^{95}Zr + ^{95}Nb$ up to 300 mCi (11.1 GBq) km^{-2}; ^{103}Ru up to 55 mCi (2.0 GBq) km^{-2}. No noticeable ruthenium isotope fractionation relative to ^{95}Zr was noticed. This contamination corresponds to a maximum external gamma dose radiation of 0.2–0.3 rem (2–3 mSv) between the time the fallout was formed and its complete decay.

In contrast, in the remote fallout from the 'Sedan' crater explosion at a distance of about 1000 km from ground zero, substantial radionuclides fractionation was observed (Table 4.4). It is to be noted that the tritium deposition in the remote fallout from the Chagan crater explosion, shaft '1004' is close to the deposits of other volatile explosion products (Table 4.5).

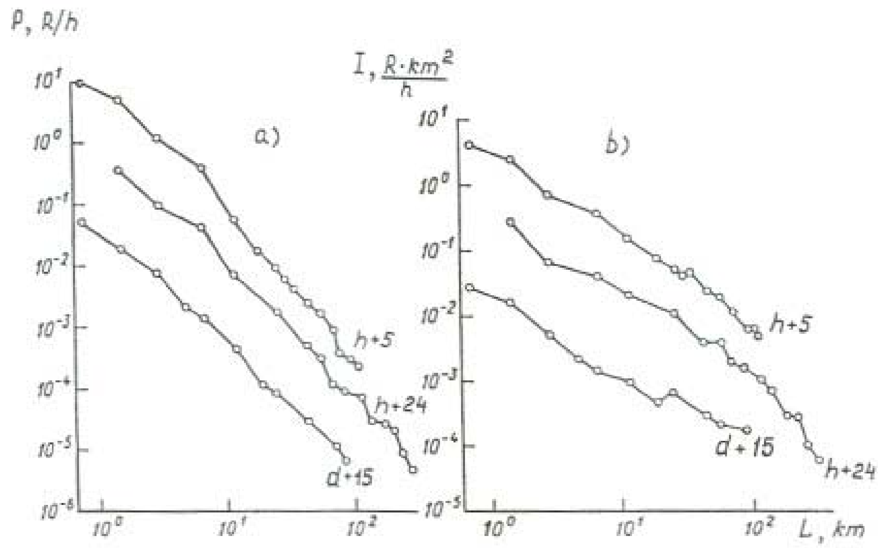


Figure 4.14 Dependence of gamma-radiation dose rates, R/h^{-1} (a) and integral amount of radioactivity, $R\ km^{-2}\ h^{-1}$ (b) on distance *R* along the fallout-contamination axis from explosion '1003'.

A remote pattern of radionuclide fallout was produced by the crater explosion 'Schooner' (USA, NTS, 8 December 1968), as measured over Europe and the USSR.

4.2.3 Global fallout

The products of the very high-yield nuclear explosions reached the higher atmosphere and the lower stratosphere and were transported and deposited globally in a matter of weeks, months and years, mainly in the same latitude belt as the test site.

Figure 4.17 shows the distribution of ^{90}Sr at the Earth's surface in 1963–64 (Klement, 1964). At that time the average deposition density of ^{90}Sr in the Northern Hemisphere (in the band between 70°E and 140°E) was 40 mCi (1.48 GBq) km^{-2}, whereas that of ^{137}Cs was 1.85 times as much. The distribution of ^{137}Cs (contamination density, mCi km^{-2}) of global origin over the territory of the former USSR in the late 1960s is shown in Figure 4.18 (obtained by airborne-gamma survey) (Boltneva *et al.*, 1977).

At first, global fallout included the short-lived radionuclides (^{144}Ce, ^{95}Zr + ^{95}Nb, ^{54}Mn, etc). In total 19.3 MCi (714 PBq) ^{90}Sr, 33 MCi (1.2 EBq) ^{137}Cs

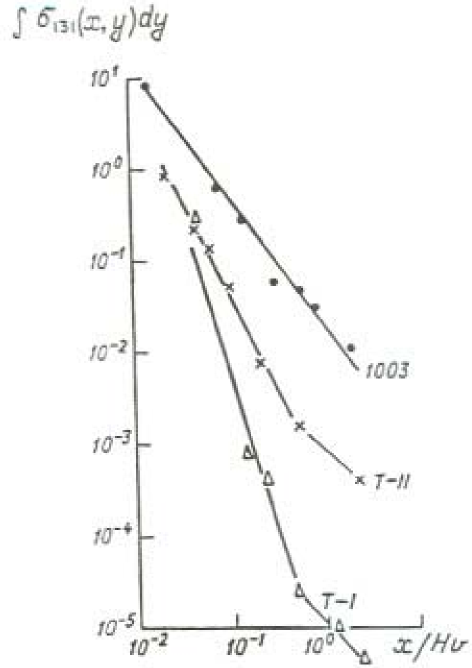


Figure 4.15 The relationship between ^{131}I integral amount and distance along the fallout-contamination axis for three crater explosions.

and up to 1600 MCi (59.2 EBq) of tritium were released into the atmosphere before 1963 (Klement, 1964). It is interesting to note that deposition of ^{137}Cs over central Europe after the Chernobyl nuclear power plant accident is 1.9 MCi (70.3 PBq).

4.2.4 The modelling and prediction of radioactive fallout

Residence times and geographical distribution of the explosion debris and products are determined by the local and global air mass movements and meteorological conditions, as well as by the size and physical properties of the explosion. Any prediction of radioactive contamination deposition requires a detailed knowledge of all processes involved and the physical collection of actual contamination data. This information makes it possible to reconstruct (model) the radioactive contamination source and the various stages of its distribution.

Based on experimental data the contamination source is modelled either as an instantaneous point source (with particles and radioactivity carrier size

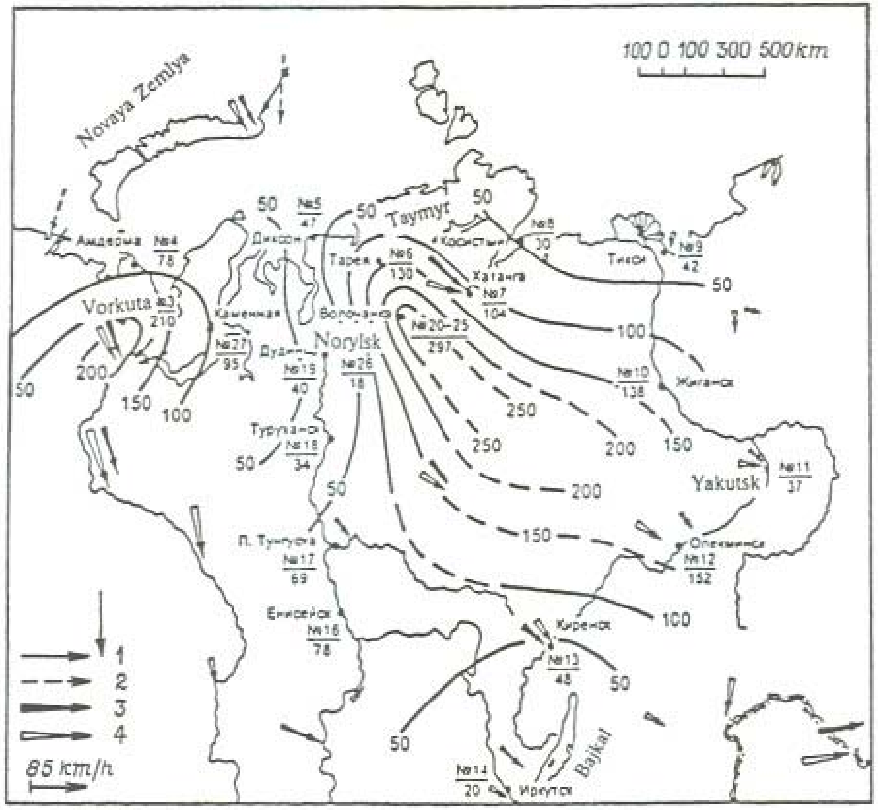


Figure 4.16 A map of the $^{95}Zr + ^{95}Nb$ deposition pattern based on measurement data of 1962. Sample number (numerator) and terrain contamination density by the end of May 1962 in mCi km^{-2} (denominator) are given near the sampling points. Arrows show mean wind velocity direction at 0–15 km height on 23 (1), 24 (2), 30 (3) and 31 (4) October 1961. To convert mCi to becquerels multiply by 3.7×10^7.

distribution, equations (4.1) and (4.2), for settling velocity)—if there is no wind shift—or as a vertical linear source if there is a windshift. Point-source contamination modelling is the most universal. According to experience gained, however, in most cases modelling of an instantaneous point source is more applicable when developing scenarios for variable contamination patterns.

A model for the fallout prediction from atmospheric plumes emanating from underground explosions has been developed. The basic variable in estimating the fallout pattern in the absence of wind shifts in the atmosphere is settling velocity, W, of the radioactive particles. A simplification of the radioactive particle distribution in the base surge and main cloud is assumed such that at

Table 4.4 Relative content (%) of radionuclides in the remote zone of the 'Sedan' explosion (about 1000 km from ground zero).

Radionuclide	Calculation (Izrael, 1974)	Air filter samples (Krey and Fried, 1965)	Fallout samples (Krey and Fried, 1965)
^{89}Sr	40	43	18
$^{90}Sr + ^{90}Y$	0.35	0.25	0.2
^{95}Zr	–	0	0
^{91}Y	–	3.4	2.8
^{103}Ru	–	4.0	2.9
^{106}Ru	–	0.9	0.8
^{137}Cs	0.3	0.8	0.45
^{140}Ba	24	24	33
^{140}La	28	24	33
^{141}Ce	–	0	4.9
^{144}Ce	–	0	0.8
^{99}Mo	–	0.4	1.0

Table 4.5 Tritium fallout over the pattern from explosion '1004' (1965).

Distance from ground zero, km	Precipitation collection period	Tritium concentration in precipitation, TR	Tritium deposition, mCi km^{-2}
200	D+2 – D+14 12 days	29 000 ± 1500	945
450	D+1 – D+13 12 days	8400 ± 1200	500
500	D+10 1 day	11 500 ± 1200	90
500*	D+10 1 day	10 500 ± 200	82
500**	D+2 – D+13 11 days	5300 ± 1000	42
500	D+3 – D+10 7 days	3600 ± 1000	60
550	D+6 – D+14 8 days	8800 ± 1250	240
1800	D+5 1 day	12 900 ± 1500	20
3300	D+3 – D+10 7 days	4700 ± 1000	45
550***	Explosion time	2000 ± 1000	14
4000***	Explosion time	1000 ± 1000	10

* Second sample.
** Third sample.
*** Background samples taken outside the pattern (area of contamination).

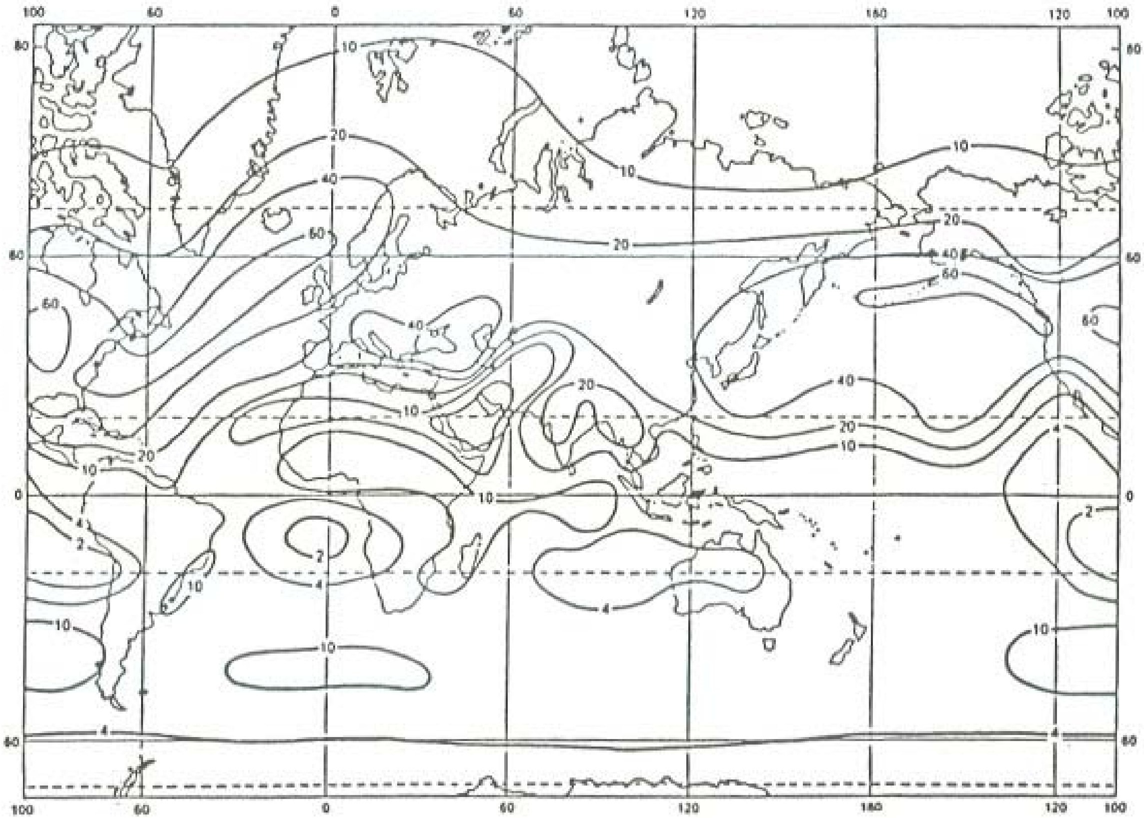


Figure 4.17 The distribution of ^{90}Sr at the Earth's surface 1963–1964.

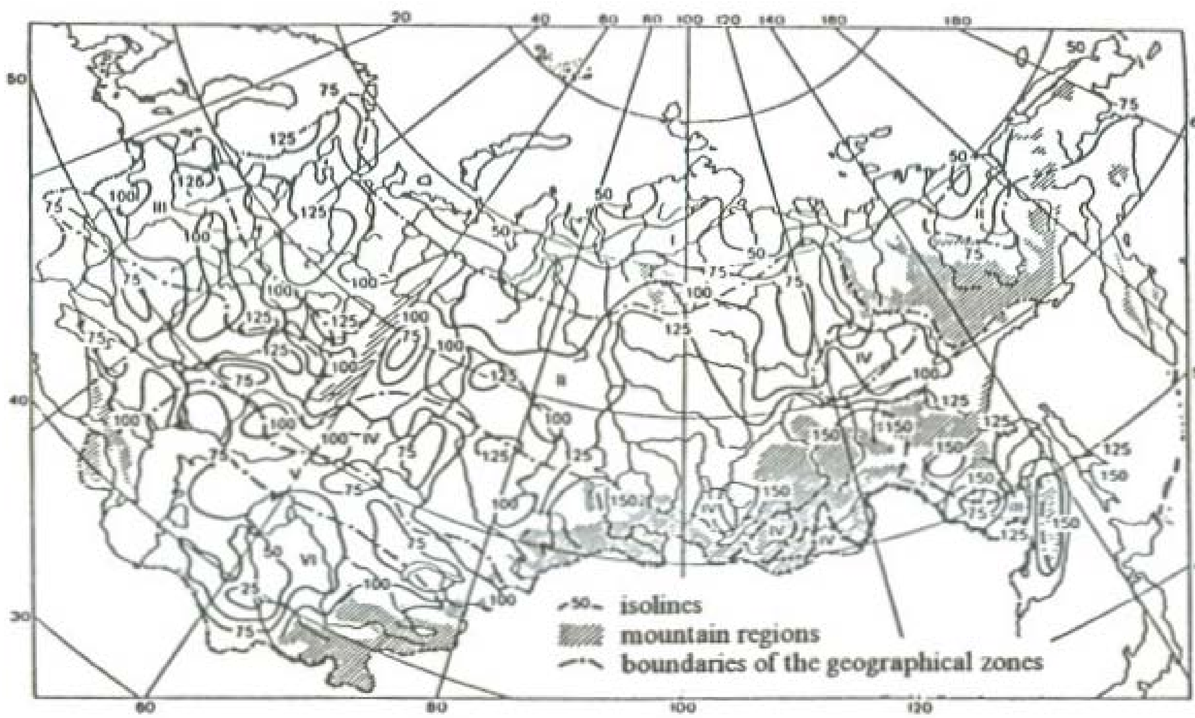


Figure 4.18 The ^{137}Cs contamination density in the former USSR (mCi km^{-2}) revealed by surveys conducted between 1968 and 1974.

altitude H there is a point source of a dispersed aerosol with distribution $N(W)$, for which the observed fallout pattern can be calculated (Petrov and Pressman, 1962; Izrael *et al.*, 1970a). The expression for the fallout pattern resulting from this distribution with an average wind velocity V is

$$p(x,y) = \frac{QHVN\left(\frac{HV}{x}\right)}{\sqrt{2\pi}\sigma_y(x)x^2} e^{-\frac{y^2}{2\sigma_y^2(x)}} \tag{4.9}$$

where Q is the total source strength (Bq), $\sigma_y(x)$ is the dispersion of the distribution $p(x,y)$ in the y direction (km) and $N(HV/x)$ is the volume density of the particles according to the particle settling velocity, $W = HV/x$.

The total radioactivity (in Bq) at $t = h + 1$ hours is related to the explosive power $\bar{P}$ (in kt) by $A_{\Sigma}(h + 1) = 4.5 \times 10^8 \bar{P}$ and the dose rate can be related to the fallout pattern by

$$P(x,y) \cong k_1 p(x,y) \tag{4.10}$$

where $k_1 \approx \dfrac{10^{-5}\ R\ h^{-1}}{\text{Bq}\ km^{-2}}$, $h = 1$ m (h is height of the measurement of the dose rate). For atmospheric explosions $Q = A_{\Sigma}$; for underground explosions $Q = A_{\Sigma} \times I(\bar{h})$, where is $I(\bar{h})$ is the fraction of the total radioactivity released into the atmosphere.

The term $\sigma_y(x)$ may be calculated using equation (4.11)

$$\sigma_y(x) = \frac{\int_{-\infty}^{\infty} p\ (x,y)\mathrm{d}y}{\sqrt{2\pi}\ p\ (x,\ 0)} \tag{4.11}$$

A function of distance from ground zero $\sigma_y(x)$ is described by

$$\sigma_y(x) = (\sigma_0^2 + 0.01x^2)^{1/2} \tag{4.12}$$

where σ_0^2 is related to the horizontal dimension of the main cloud and defines the transverse distribution near ground zero. It is possible to write for the volume density

$$N\left(\frac{HV}{x}\right) = \psi(w) = \frac{0.1\sqrt{2\pi}\ p_t(x,0)(HV)^2}{A \times I(h)} \tag{4.13}$$

Experimental data for explosions '1003', 'Sedan', 'Danny Boy', and 'Neptune' are used to determine the function $\psi(w)$ (see Figure 4.19). In this case $N(w) \approx$

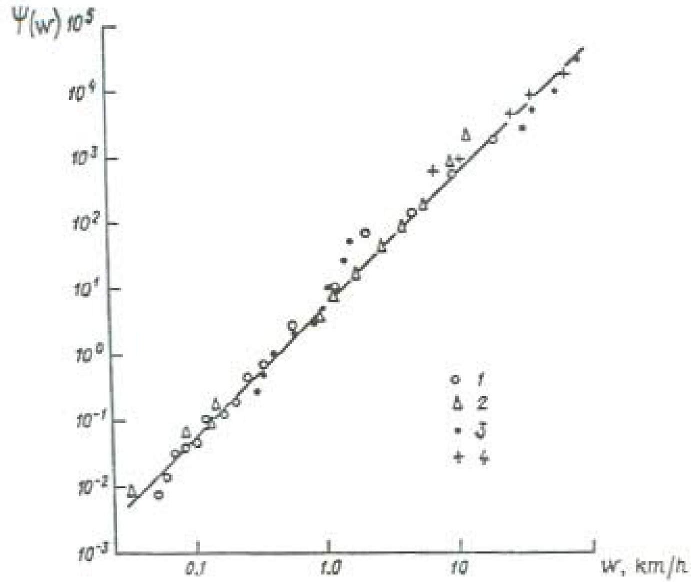


Figure 4.19 The dependence of volume density, $\psi(w)$, on w (particle settling velocity) for fallout patterns from explosions. (1) '1003', (2) 'Danny Boy', (3) 'Sedan', (4) 'Neptune'.

$1/w$ and the intensity for a radionuclide can be estimated by the appropriate function $\psi_i(w)$ using equation (4.9), in this case $Q_i = A_i \times I(\bar{h})$.

A calculation for the fallout patterns resulting from the detonation of a row charge of nuclear explosives may be made by means of equation (4.14) in which N explosives are placed in a line of length L. For the wind direction normal to the row, the doses D_N in the separate fallout tracks are given by

$$D_N(x,y) = ND_1(x,0)\sqrt{\frac{\pi}{2}}\frac{\sigma_y}{L}\left[\phi\left(\frac{L-y}{\sigma_y}\right) + \phi\left(\frac{y}{\sigma_y}\right)\right] \quad (4.14)$$

where $\phi(z) = \sqrt{2/\pi}\int_0^z e^{-t^2/2}\,dt$ is the probability integral.

If for D_1, the dose from a single explosion

$$\sigma_y^2 = (0.1x)^2; \text{ then } D_N(x,L/2) \approx ND_1(x,0) \quad (4.15)$$

with a maximum error of 17% when $L/2\sigma_y < 1$.

Figure 4.20 shows the long-distance radioactive fallout rate for test explosion '1003' using a deposition velocity of $\beta = 3.6 \times 10^{-2}$ km hr^{-1}.

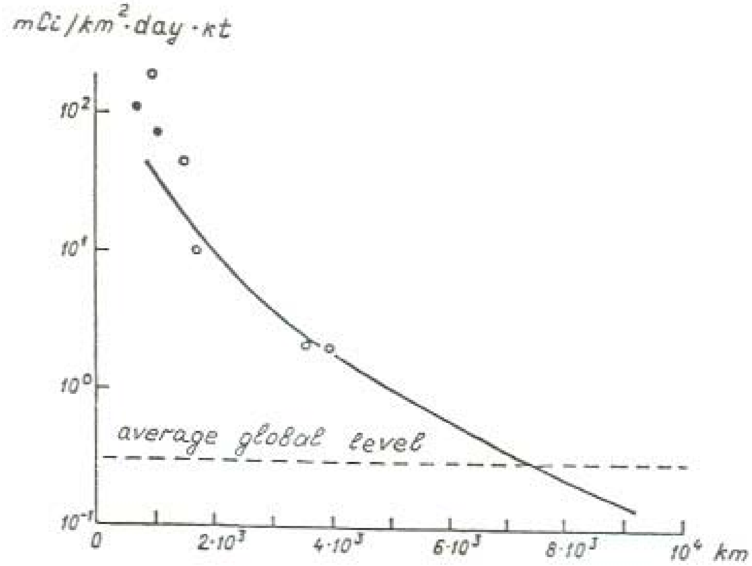


Figure 4.20 The relationship between the radioactive fallout rate and distance for an explosion yield of 1.1 kt.

4.3 LOCAL AND TROPOSPHERIC FALLOUT PATTERNS IN DIFFERENT COUNTRIES

4.3.1 French tests

The French nuclear tests in the atmosphere were carried out at Hamoudia near Reggane in the Algerian Sahara in 1960 and 1961 and on the uninhabited atolls of Mururoa and Fangataufa in French Polynesia from 1966 to 1974 (Doury and Musa, 1996). Fifty tests were carried out, four on barges (in 1966 and 1967), forty-one under other conditions (balloon, tower, aircraft) and five tests of very low energy, so-called 'for security'. The total energy of all tests is equivalent to 10 million tons (10 Mt) of TNT.

The report of Doury and Musa (1996) at the SCOPE-RADTEST Workshop in Beijing, 19–21 October 1996, included surface plots of four proximal (immediate) fallout patterns resulting from the atmospheric nuclear explosions that took place on the atolls of Mururoa and Fangataufa. The characteristics of the explosions are listed in Table 4.6.

The explosions differed from each other both in their power (from 34 to 955 kt), and the heights at which the nuclear devices were situated at the moment of the explosion (from 3 to 480 m). This illustrates the different relationships

Table 4.6 Characteristics of four atmospheric nuclear explosions conducted by France in the Southern Hemisphere.

Date	24.09.66	05.06.71	12.06.71	14.08.71
Name	Rigel	Dione	Enceladc	Rhea
Type of explosion	Barge	Under an air balloon	Under an air balloon	Under an air balloon
Place	Fangataufa	Mururoa	Mururoa	Mururoa
Total power, kt	125	34	440	955
Height of the nuclear device at the moment of explosion, m	3	275	450	480
Height of tropopause, km	12.7	12.9	17.5	–
Height of cloud base, km	7.0	12.0	13.5	15.5
Height of cloud top, km	13	14	17	20

between the amount of the material deposited and the parameters of the explosions and meteorological situations. The pattern shown in Figure 4.21 is characterized by high-dose rate levels up to 100 rad (1 Gy) h^{-1} one hour after the explosion at a distance of up to 70 km, it corresponds to a powerful explosion (125 kt) and a low height of the nuclear device at the moment of explosion. These circumstances led to the generation of a large number of particles, resulting from the melting and evaporation of the device, the barge and seawater, which formed such an intensive pattern at distances exceeding 1000 km from the epicentre.

Figures 4.22–4.24 show configurations of the proximal (immediate) fallout patterns of three atmospheric explosions conducted with the help of air balloons. In spite of great differences in the power of the explosions (34, 440 and 955 kt) the observed dose rates differ only slightly from each other in their proximal (immediate) fallout patterns. They were found to be less than 1 rad (0.01 Gy) h^{-1} even 1 hour after the explosion.

The cumulative fission energy of the French tests can be estimated at 6500 kt, a little less than 3% of the world total. It represents, assuming that all the fission products are about evenly distributed world-wide, an average irradiation equivalent of 11 days of natural radioactivity. The low tropospheric values (in relation to the stratospheric values) are a beneficial result of the explosion technique called 'under balloon'.

4.3.2 UK tests

During the period from 1952 to 1991 the UK carried out 45 nuclear explosions, 21 (1952–1958) being atmospheric, and 24 (1962–1991) underground (*Bulletin of Atomic Scientists*, 1995). All the underground explosions were conducted

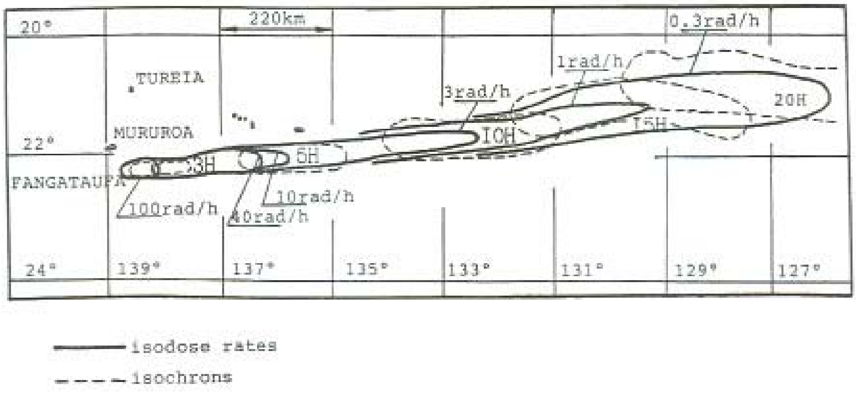


Figure 4.21 Proximal (immediate) fallout (isodose rates and isochrons) pattern of a 125 kt fission test explosion on a barge, Rigel, on 24 September 1966, at Fangataufa.

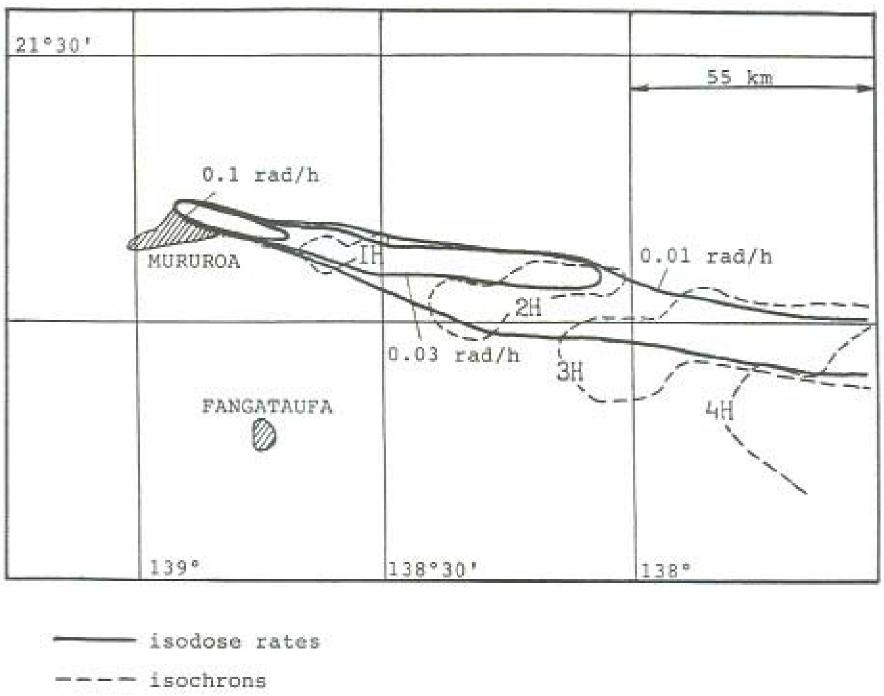


Figure 4.22 Proximal (immediate) fallout (isodose rates and isochrons) of a 34 kt fission test explosion beneath an air balloon (275 m), Dione, on 5 June 1971, at Mururoa.

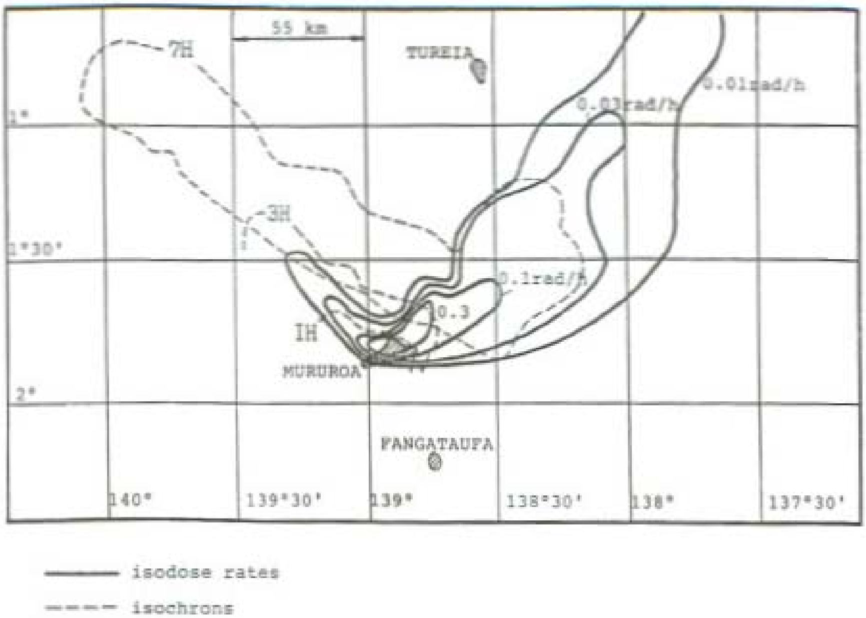


Figure 4.23 Proximal (immediate) fallout (isodose and isochrons) of a 440 kt fission test explosion beneath an air balloon (450 m), Encelade, on 12 June 1971, at Mururoa.

jointly with the USA. They were described in official publications (US DOE, 1994), under the name 'Joint US–UK'. They were conducted at the Nevada Test Site, and their nuclear devices were located in shafts.

On 3 October 1952, surface nuclear explosion 'Hurricane' on the western shore of Trimouille island initiated the atmospheric testing of nuclear weapons by the UK. The power of this explosion was equal to 25 kt (Norris *et al.*, 1994). Following this, from a report (Haywood and Smith, 1990) presented to the SCOPE-RADTEST Panel in Vienna in January 1994, the UK conducted some tests in the Maralinga and Emu areas (southern Australia) in the period of 1953–1957. In order to assess the potential irradiation doses that the future residents of these areas could be exposed to, research activities were conducted in these areas in the late 1980s. To this effect, in addition to the obvious studies, aerial gamma-spectrometric surveys were performed. Some results of these surveys of proximal patterns of ^{241}Am are shown in Figure 4.25 (Maralinga). Figures 4.26 and 4.27 show the values for ^{137}Cs at Maralinga and Emu respectively. As follows from Figure 4.25 the ^{241}Am patterns (from nuclear explosions with plutonium devices) are much pronounced and can be singled out and have more or less one initial position. Figure 4.26 shows quite another picture. Here individual ^{137}Cs patterns relating to separate explosions do not

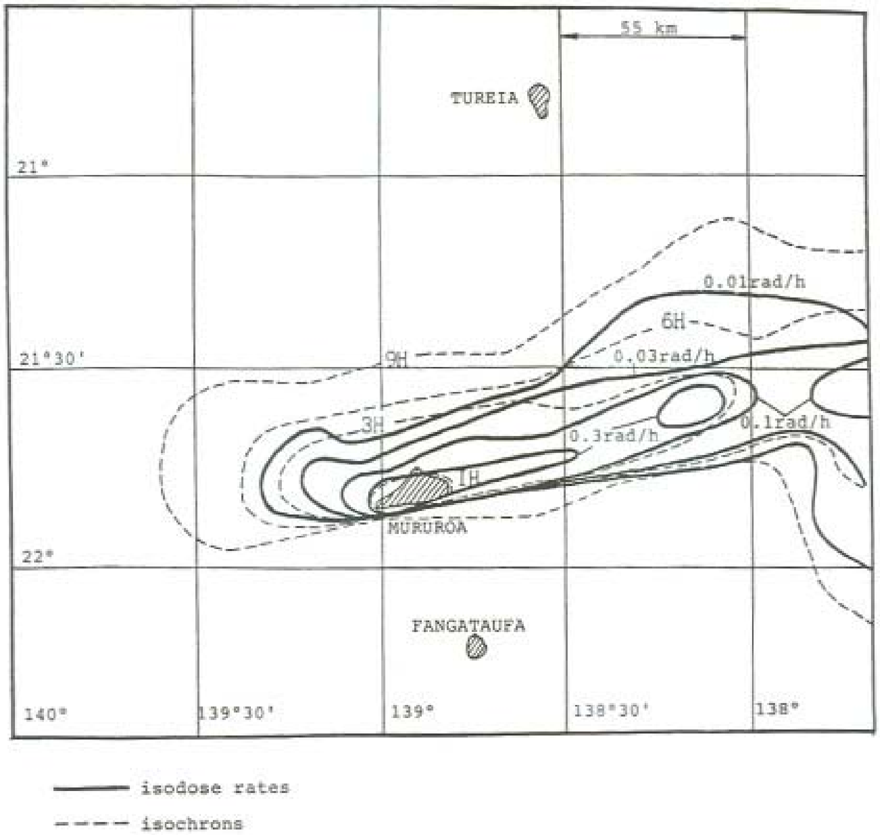


Figure 4.24 Proximal (immediate) fallout (isodose rates and isochrons) of a 955 kt fission test explosion beneath an air balloon (480 m), Rhea, on 14 August 1971, at Mururoa.

stand out against the general pattern of contamination. In contrast, we see two distinctly pronounced and separated ^{137}Cs patterns in the Emu area (Figure 4.27). This must be attributed to the fact that only two explosions (Totem-1, 14 October 1953 and Totem-2, 26 October 1953) were conducted in this area.

4.3.3 USA tests

For the period of nuclear weapons testing from 1945 to 1992 the USA carried out 210 atmospheric and nine crater nuclear explosions (US DOE, 1994). Among these explosions, 129 could potentially have led to surface patterns: 9 crater, 36 barge, 28 surface and 56 tower explosions.

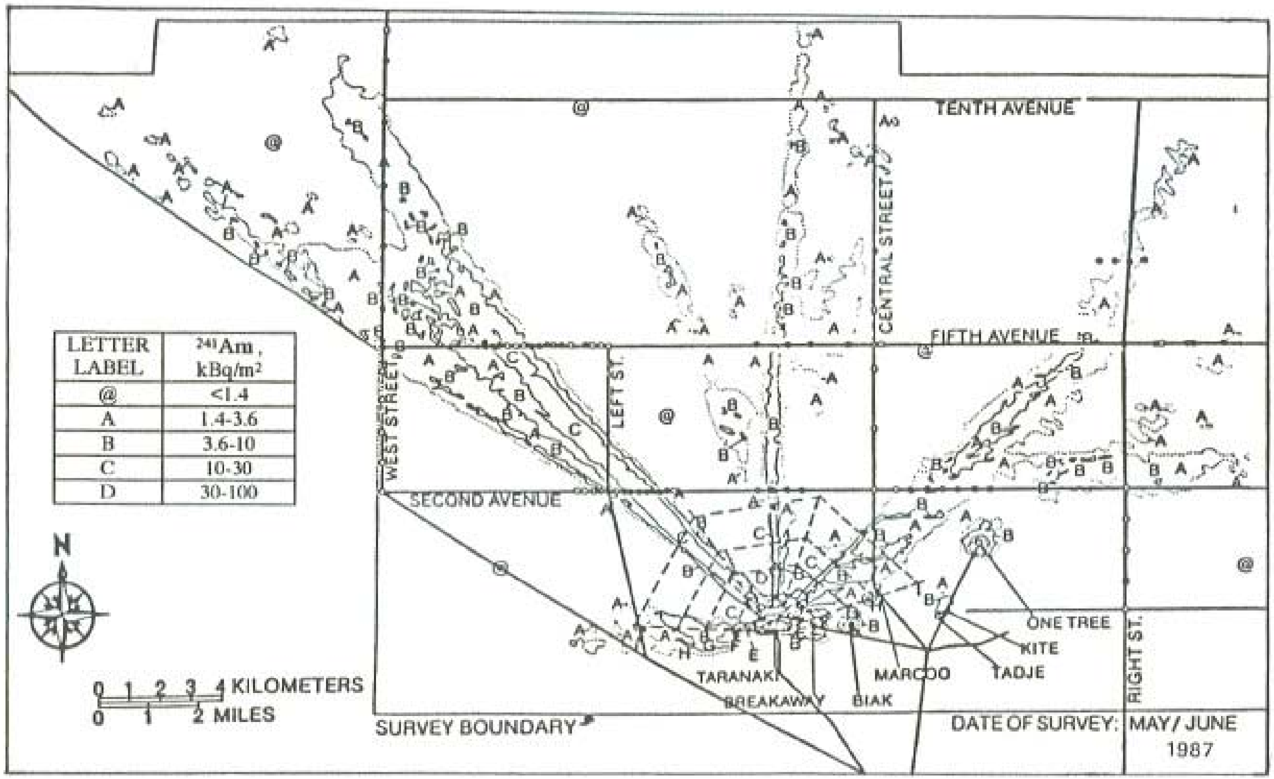


Figure 4.25 Contamination patterns for ^{241}Am in the Maralinga area.

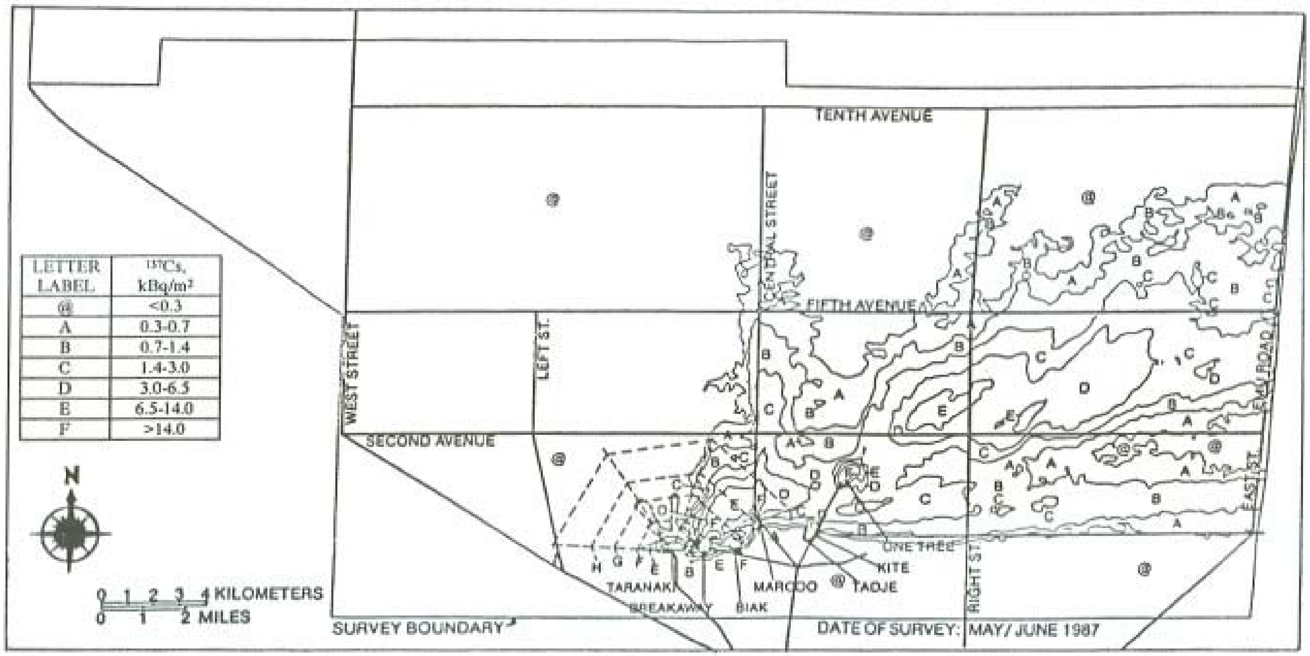


Figure 4.26 Contamination patterns for ^{137}Cs in the Maralinga area.

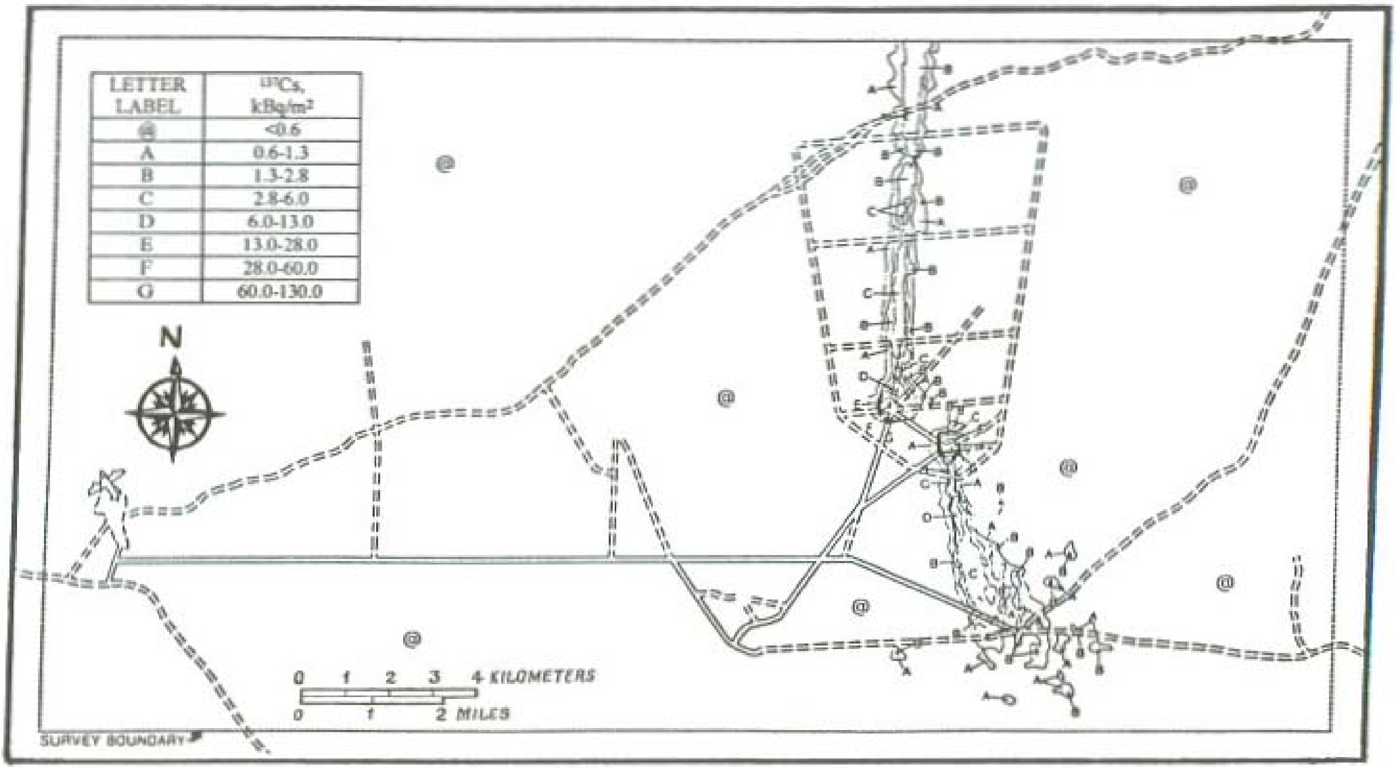


Figure 4.27 Contamination patterns for ^{137}Cs in the Emu area.

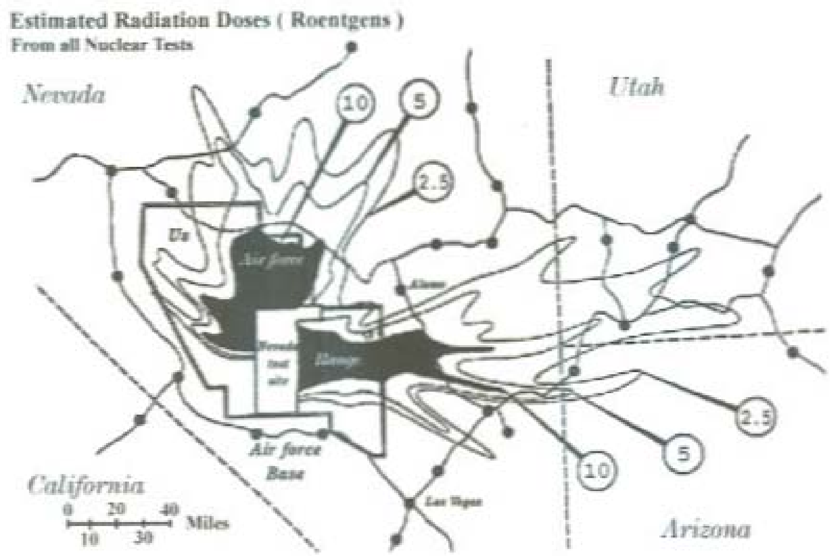


Figure 4.28 Contamination pattern from nuclear tests carried out at the Nevada Test Site up to 1958 (Dunning, 1959). See glossary for conversion of roentgens to grays.

During the testing, the open press published data concerning mainly the radioactive patterns that originated from the crater and surface explosions known as 'Plowshare'; namely 'Danny Boy' (5 March 1962), 'Sulky' (18 December 1964), 'Sedan' (6 July 1967), 'Cabriolet' (26 January 1968), 'Buggy A-E' (3 December 1968), 'Schooner' (8 December 1968). Some information on these explosions is shown in Table 4.3, and Figures 4.13 and 4.19.

Some literature data on the ground radioactivity patterns from single or multiple nuclear explosions are available. In 1959 a work entitled *Fallout from Nuclear Weapons Tests* was published in the USA (Dunning, 1959), in which a generalized map is presented on irradiation doses assessed over areas adjoining the Nevada Test Site for the whole test period before the 1958 moratorium. The map is reproduced as Figure 4.28: the total potential external exposure dose, in roentgens to humans outside the Nevada Test Site, should they have been at one of the points on a permanent basis, are given. At the same time one can assess from the same figure the integrated contamination pattern from the nuclear explosions conducted at Nevada Test Site before 1959: doses of up to 10 roentgens (86.9 mGy) are entirely located in the State of Nevada. Values of 5 (43.5 mGy) and 2.5 roentgens (21.7 mGy) are spread in patches over the States of Utah and Arizona. The densely populated State of California is practically not contaminated.

In the work *Radiological Conditions at the Bikini Atoll, Republic of the Marshall Islands: The Prospects for Resettlement* (IAEA, Vienna, 1996), the ^{137}Cs pattern contamination is provided of the 1993 mapping of soil contamination levels for Bikini Island at Bikini Atoll (Figure 4.29, dose rate, mGy y^{-1}). The survey was conducted in the framework of the Republic of the Marshall Islands Radiological Study (NWRS) using solid-state type detectors installed at a height of 1 m above the soil surface. The isolines of the soil ^{137}Cs contamination density (in a 10 cm layer) at Bikini Island (Bq g^{-1} of dry soil) are shown. These results were obtained by Lawrence Livermore National Laboratory in 1981using aerial gamma-spectrum measurements. The table in Figure 4.29 makes it possible to compare external exposure dose rates and soil contamination densities due to ^{137}Cs. The area of Bikini Island is less than 4.5 km^{-2}, the maximum density values of the soil contamination by ^{137}Cs in the 10-cm soil layer are around 12 Ci (444 GBq) km^{-2}. In addition to ^{137}Cs, the radionuclides ^{90}Sr, $^{239+240}Pu$ and ^{241}Am are fixed in the soil.

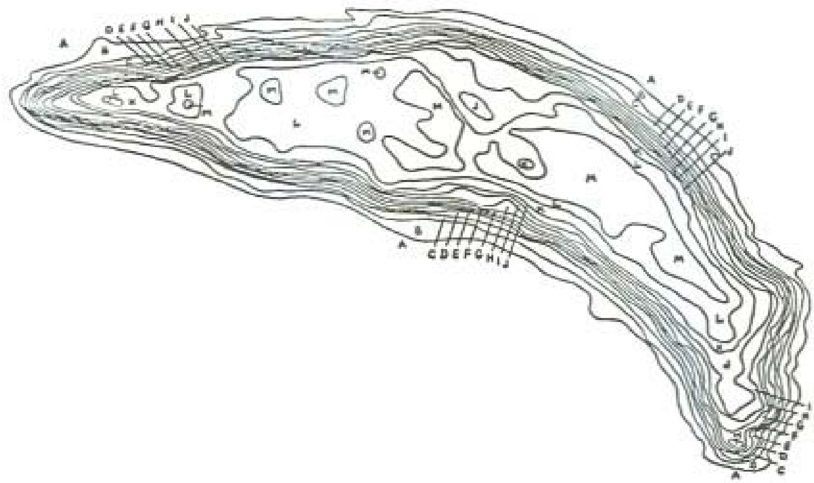
4.3.4 The former USSR tests

The main programme of nuclear weapon testing in the former USSR was carried out at the Semipalatinsk Test Site (STS), where on 29 August 1949 the first national nuclear explosion was conducted; and at the Northern Test Site Novaya Zemlya (NTSNZ), where the last explosion was carried out on 24 October 1990. The total number of nuclear tests conducted within the former USSR Test Sites is 586. In addition, according to the programme of peaceful use of nuclear explosions, 129 nuclear tests were carried out within the former USSR but outside the Test Sites, including 91 tests in the territory of the Russian Federation, two in Ukraine, 33 in Kazakhstan, two in Uzbekistan and one in Turkmenistan (Mikhailov *et al.*, 1996).

For the period of 1949 to 1962 at the Semipalatinsk Test Site, 25 ground nuclear explosions (Mikhailov *et al.*, 1996), i.e. those explosions where the expanding fireball touches the ground surface, were carried out. As a result great amounts of soil were swept into the explosion cloud.

Under these circumstances, particles may be activated and contribute to the radioactive fallout pattern in the direction of the prevailing winds. This pattern has been registered by radmeter equipment at a distance of hundreds of kilometres from the centre (epicentre) of the explosion considered, during the first days, weeks and even months after the explosion. A special survey method was established, which took the height of the flight and the terrain relief into consideration.

In this context it is essential to analyse the generalized map of the proximal fallout patterns (up to hundreds of kilometres) attributable to the STS nuclear tests (Figure 4.30). This generalized map was published for the first time by Logachov (1996). From this map it can be concluded that among the nuclear



CONTOUR AREA	^{137}Cs Gamma Exposure Rate (mGy/a)	Average ^{137}Cs Activity in Top 10 cm of Soil (Bq/g)
A	< 0.009	< 0.007
B	0.009 - 0.026	0.007 - 0.022
C	0.026 - 0.055	0.022 - 0.048
D	0.055- 0.102	0.048 - 0.089
E	0.102 - 0.168	0.089 - 0.148
F	0.168 - 0.292	0.148 - 0.259
G	0.292 - 0.438	0.259 - 0.370
H	0.438 - 0.657	0.370 - 0.629
I	0.657 - 1.02	0.629 - 0.925
J	1.02 - 1.46	0.925 - 1.30
K	1.46 - 2.19	1.30 - 1.85
L	2.19 - 2.92	1.85 - 2.59
M	2.92 - 4.38	2.59 - 3.70

Figure 4.29 The ^{137}Cs gamma-radiation dose rate and average ^{137}Cs activity in the top 10 cm of soil on Bikini Island at Bikini Atoll.

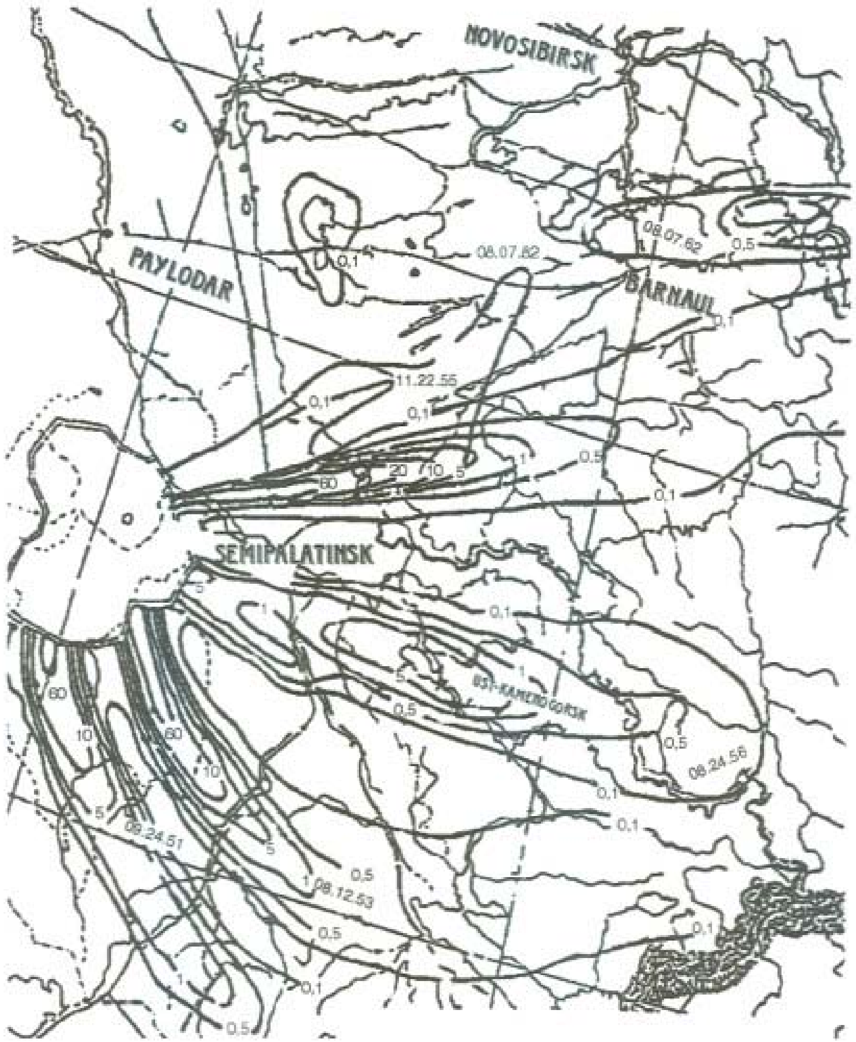


Figure 4.30 Map of fallout patterns from atmospheric and ground surface tests at the Semipalatinsk Test Site. Isodose lines give estimated cumulative unshielded doses on the ground (isodose lines are in roentgens; 24.09.51, etc., is the date of the relevant explosion).

test explosions the following have to be considered as capable of damaging the population of the nearby regions (mainly Semipalatinsk, eastern Kazakhstan and the Altai region of Russia): 29 August 1949 (22 kt, explosion on a tower, 30 m), 24 September 1951 (38 kt, explosion on a tower, 30 m), 12 August 1953 (400 kt, explosion on a tower, 30 m, the first thermonuclear explosion in the former USSR), 22 November 1955 (1600 kt, airdrop, height of explosion, 1550 m), 24 August 1956 (27 kt, explosion on a tower, 100 m), 7 August 1962 (9.9 kt, surface explosion) and 15 January 1965 (140 kt, underground crater explosion). The isolines shown on the map present the total external dose after the complete decay of all the radionuclides.

An airborne gamma-spectrum survey in 1991 was carried out by the Scientific Production Enterprise 'Aerogeologiya', mainly within the STS. It displayed the existence of patterns which can still be observed. They are characterized by levels exceeding 300–500 mCi (11.1–18.5 GBq) km^{-2} attributable to ^{137}Cs, originating from the following nuclear explosions: 29 August 1949, up to 12–18 km in a direct line from the epicentre (probable); 24 September 1951, up to 55–65 km; 12 August 1953, up to 80–95 km; and 15 January 1965 ('Chagan'), up to 13–18 km (see Figure 4.9). As can be seen from Figure 4.9, beyond these distances the pattern of contamination cannot be outlined by a single continuous isoline, and they become indistinguishable from the regional and then the global background fallout levels.

Some information on these and other explosions is provided in Table 4.3 and in Figures 4.8, 4.9, 4.11, 4.12, 4.14, 4.15 and 4.16.

4.3.4.1 The First Nuclear Explosion in the former USSR in 1949

The first test of a nuclear weapon was performed in the former USSR on 29 August 1949. The nuclear device was mounted on a tower at a height of 30 m. The energy release was about 22 kt. The upper nuclear cloud edge reached a height of 7.5–9.0 km. The weather at the time of the nuclear test was very unstable: intermittent rain accompanied by strong gusts. The medium wind speed in the transport layer was 40–60 km h^{-1}, with gusts up to 75 km h^{-1}.

A week later, on 5 September an aerial radiation survey was carried out beginning with the settlement of Dolon located near the STS boundary towards the town of Bijsk. In the period from 7 to 13 September a ground-based survey was performed in human settlements and along the route of the automobile radiation patrol. The gamma-ray intensity was measured using the same instrument. Gamma-radiation, dose-rate airborne measurement data were scaled to a height of 1 m above the ground surface with the help of height coefficients characteristic of a non-fractionated mixture of ^{239}Pu fission products of an age of one week. All measurements were carried out at time $D + 7$ according to the Way–Wigner law, with a decay exponent of $n = 1.2$. These archive data available at STS at the beginning of 1993 are presented in Figure

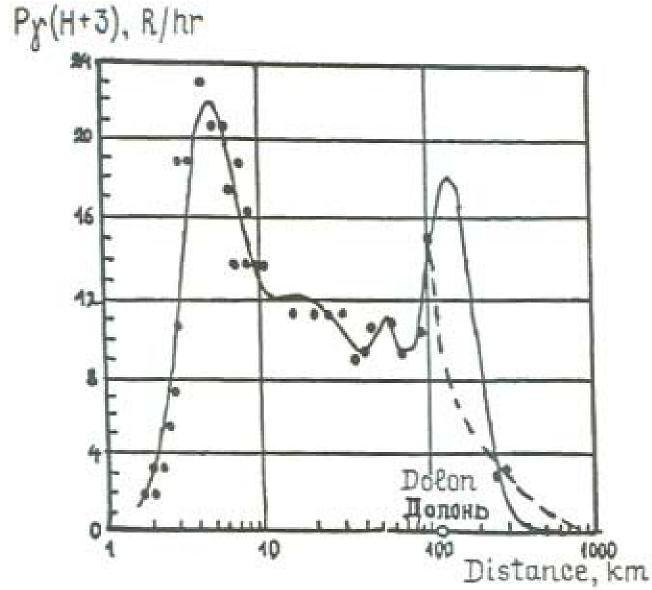


Figure 4.31 Airborne gamma dose rates (filled circles) one week after 29 August 1949 explosion at STS. The continuous line shows experimental data and the possible shape of the curve is shown as a dashed line. The figure is taken from Andrushin *et al.* (1994).

4.31 as filled circles. Approximation of the experimental data carried out at STS is shown as a continuous line (Andrushin *et al.*, 1994), and a dashed line shows the possible shape of this curve.

A reconstructed area of the radioactive fallout pattern, as isolines of gamma-ray doses at complete decay of radioactive fallout, is shown in Figure 4.32. Taking into account the possible errors that could occur when measuring gamma-ray dose rates, calculating exposure doses and interpolating to determine the position of dose isolines, it can be asserted that the maximum error for the terrain gamma-ray dose does not exceed +100%.

4.3.4.2 Formation of an Artificial Reservoir (crater explosion '1004')

On 15 January 1965 the first underground nuclear explosion to create a crater was carried out at the confluence of two rivers—Chagan and Achan-Su. A nuclear device with a power of 140 kt was ignited at a depth of 175 m in slightly watered sandstone with an admixture of lignite–clayey schist. The power originated from the fission reaction is 7 kt of the total value (Mikhailov *et al.*, 1996). As a result of the explosion, a crater was formed with a diameter 400–430 m at the original ground surface, and a depth of about 100 m. Its volume was 6×10^6 m^3.

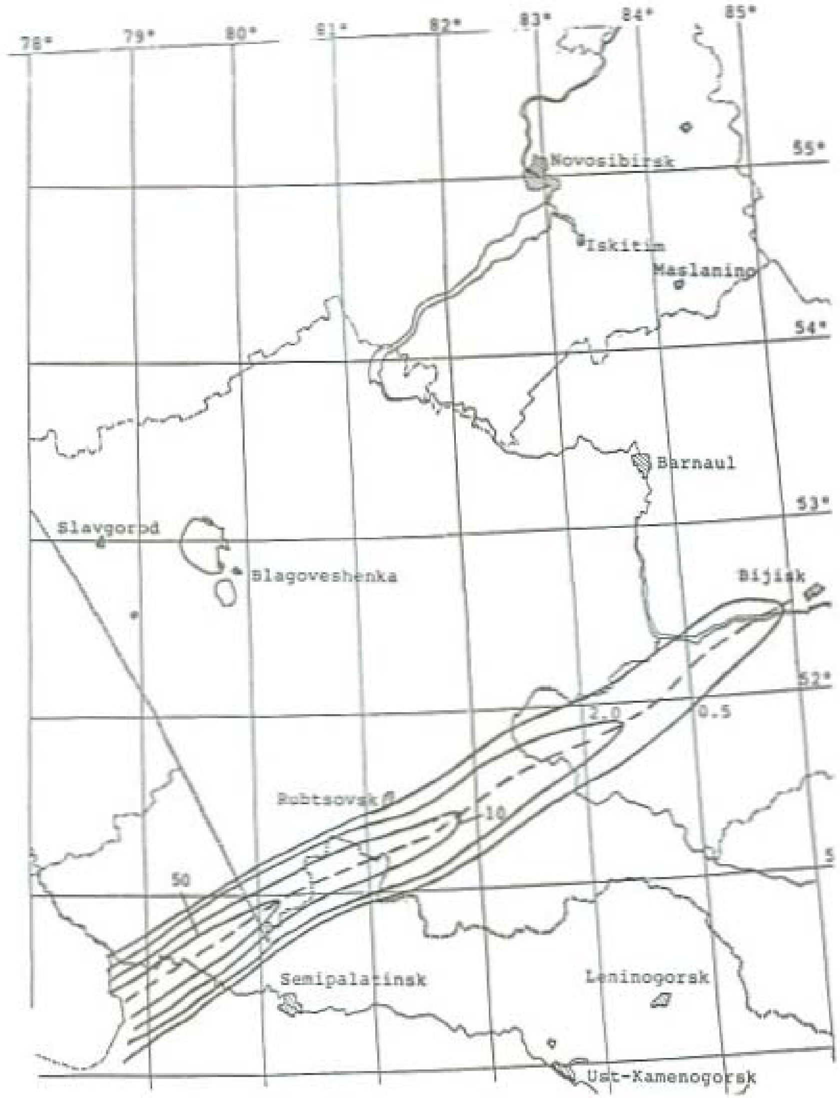


Figure 4.32 Integrated gamma-radiation dose distribution until the complete decay of radioactive fallout (roentgens) for the surface explosion of 29 August 1949.

A characteristic feature of this explosion was the generation of a powerful base surge (by the middle of the second minute), with a diameter 5000 m and a height reaching 2.5 km. It spread to the north, and a formation in the shape of a pillar with a height of up to 2.5 km moved in a northeastern direction. The stabilization height of the radioactive cloud of the explosion was 4.5–4.8 km. The distribution of the radioactivity with depth in the zone of the base surge is shown in the Figure 4.11.

Observation of the radioactive contamination in the proximal zone during the period of immediate radioactive fallout, and also after this period, was carried out by means of ground-based and airborne radiation surveys. Of the total amount of radioactive products generated by the explosion about 20% was deposited within the proximal zone during the immediate phase.

Figure 4.33 shows a map of the radioactive fallout pattern, presented as dose-rate isolines at the ground surface, in mR h^{-1}, 24 h after the explosion. This map was compiled on the basis of an air gamma survey of the territory during the first two days after the explosion.

At present, the mean radiation level is about 0.2 mR (1.7 μGy) h^{-1} in the epicentre zone of the explosion, reaching 4–8 mR (35–70 μGy) h^{-1} at certain observation points. The main gamma emitters are ^{137}Cs and the long-lived radionuclides of induced activity, ^{60}Co and ^{152,154}Eu.

4.3.5 Chinese tests

China started atmospheric nuclear explosion testing in 1964, and a total of 22 tests were conducted (Zhu Changshou *et al.*, 1996), as reported during the SCOPE-RADTEST Workshop in Beijing 13–21 October 1996. In their report to the same Workshop, Zheng Yi *et al.* (1996) referred to the fact that 'the data on yield and type of nuclear burst of these are quoted from the paper by De Geer'. At the Workshop (Beijing, 19–21 October 1996), De Geer presented a report 'Chinese Atmospheric Nuclear explosions from a Swedish Horizon' in which he included a summary of Swedish observations of Chinese nuclear test explosions in the atmosphere during 1964–1980, and Chinese experts presented a number of reports on the problem of radioactive deposition monitoring across the territory of China.

Since the end of 1950 a survey of radioactive contamination in the environment has been conducted in China. A system of investigation and a monitoring network for environmental radioactivity was organized by the Ministry of Health in the early 1960s, and operated by the sanitary–epidemiological stations and medical institutes in every province, autonomous region and municipality throughout China, forming a nation-wide environmental radioactivity monitoring network of 45 stations. The Laboratory of Industrial Hygiene of the Ministry of Health acts as the technical guidance centre.

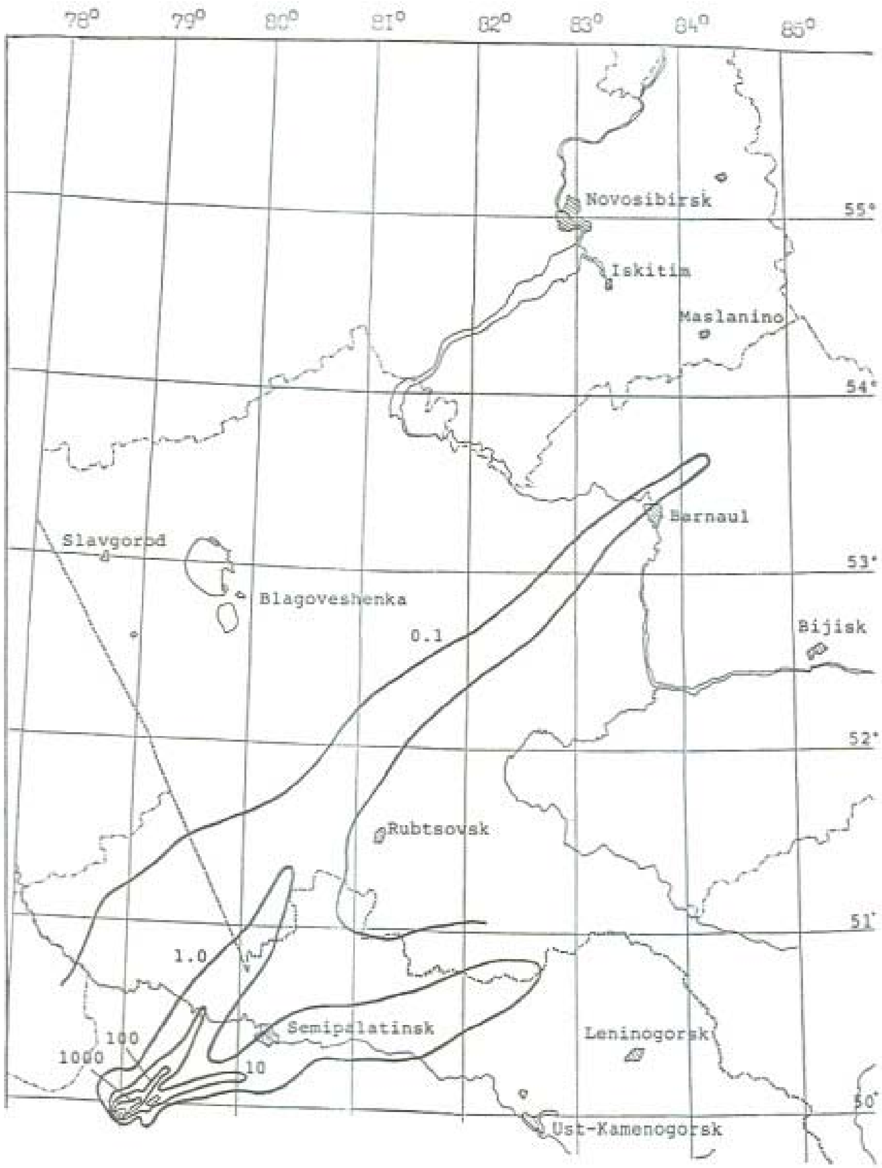


Figure 4.33 A map of dose rate distribution following the crater explosion 'Chagan', 15 January 1965, mR h^{-1} at 'H + 24'.

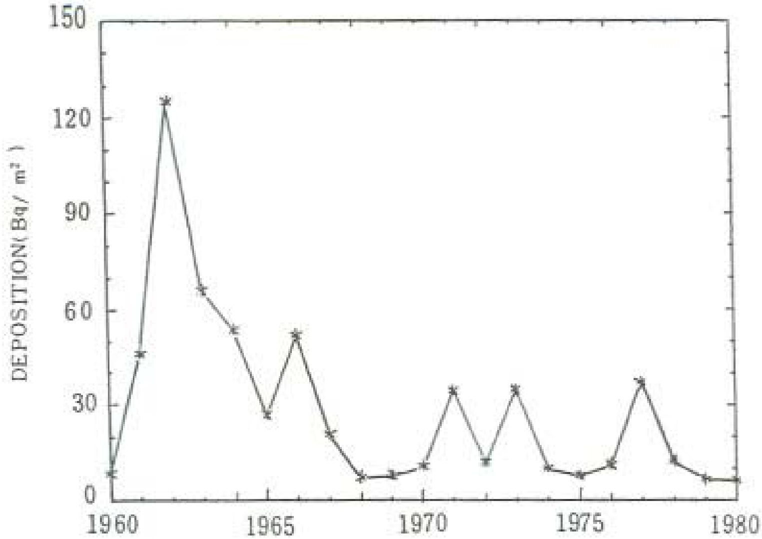


Figure 4.34 Variation of the annual average daily deposition of gross beta activity in China.

The gross beta activity in atmospheric fallout is a simple and sensitive indicator for monitoring the short-term pattern of contamination from radioactive fallout. Monitoring results show that the peak value of the annual average daily deposition of gross beta activity occurred in 1962, which was the result of early fallout from large-scale nuclear weapon explosions in 1962 in central Asia. Smaller peaks occurred in 1966, 1971, 1973 and 1977, registering the radioactive contamination from atmospheric nuclear tests conducted in China (Figure 4.34) during those years.

Environmental contamination from ^{131}I following nuclear explosions was observed in some regions of China. The short half-life of ^{131}I means that it is not well mixed in the atmosphere before deposition or decay. Consequently, concentrations in air or deposition at particular sites vary with meteorological conditions and are not necessarily representative of a larger region nor of a latitudinal band. Environmental contamination of ^{131}I following nuclear explosions in some regions such as in Lanzhou, Xining and Shenyang, was significant. The levels of radioactivity attributable to ^{131}I in some regions in China are listed in Table 4.7. The variation in levels of radioactivity attributable to ^{131}I after the fifth nuclear test in Shenyang is shown in Figure 4.35. The peak value of radioactive contamination by ^{131}I was about 710 Bq m^{-2}. The increased level of radioactive contamination from this source continued for 10 days (Figure 4.35).

Table 4.7 Deposition of ^{131}I in some regions in China.

Test number	Region	Deposition ($kBq\ m^{-2}$)
4	Xi'an	0.33
5	Shenyang	4.8
12	Lanzhou	5.1
15	Lanzhou	10
18	Hohhot	0.22
22	Xining	10

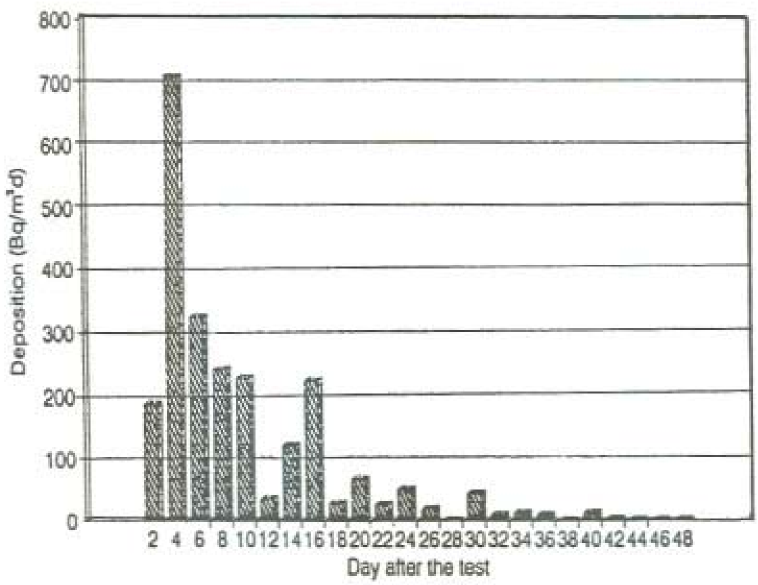


Figure 4.35 Levels of radioactivity as a result of the deposition of ^{131}I after the fifth nuclear test in Shenyang.

4.3.6 Indian tests

It is well-known that in 1974 India carried out an underground nuclear explosion, the only one in its programme at that time. The explosion took place in the Rajasthan Desert (Pokran) on 18 May 1974. Its power was equal to 12 kt. Indian specialists aimed to make this explosion completely contained to prevent any release of radioactive products to the atmosphere. All the material on this problem for inclusion in SCOPE-RADTEST was presented by Dr Mishra, who sent them to Essex on 6 March 1997. Nevertheless, in carrying out the contained explosion, the Indian specialists took complex measures to cope with possible situations arising from releases to the atmosphere. Some of the measures were taken before the explosion, other were taken afterwards.

As an important part of the public and environmental programme for the experiment, a network of meteorological stations located very near surface ground zero was set up several months before the experiment. The climatological data from three meteorological stations (about 100 km from the site in various directions) for three decades and hourly surface and upper atmospheric wind observations from April to June of 1972 and 1973 were examined for planning the experiment. Also 24-, 48- and 72-h forecasts were available to warn of unusual weather changes such as cloudiness, storms, dust storms, etc., if any. On the basis of these observations and site topological considerations, the following conditions of the experiment were arrived at:

1. wind direction from the SW to W, preferably WSW;
2. wind speed—minimum 15 km h^{-1}, maximum 20 km h^{-1};
3. atmospheric stability;
4. no temperature inversions.

These criteria ensured that in the unlikely event of release of radioactivity and formation of a radioactive cloud, the expected direction of cloud travel would have been towards an uninhabited region, i.e. in the ENE sector, until the predicted maximum radiation exposure resulting from the passage of the cloud and deposition of radioactivity on the ground surface reaches insignificant levels.

The wind direction at the time of the experiment was WSW at a mean speed of about 20 km h^{-1}. The experiment was planned to be executed at a time when this wind direction was very constant and corresponding meteorological conditions were favourable. Atmospheric parameter measurements made by a ground-level barograph within a few kilometres of surface ground zero gave no indication of any air blast due to the release of cavity gases.

In addition to two health physics laboratories, a large amount of field monitoring equipment was kept ready. Equipment for on-the-spot checking of fission product contamination of water and vegetation was also provided. Prior to the experiment, several deposition trays and thermoluminescent dosimeters were distributed on a radial grid at 11.25° angular spacing and varying distance intervals. Extensive radiation monitoring of the site and analysis of samples before and after the experiment showed that no radioactivity had been released to the atmosphere during the experiment.

Five underground nuclear explosions (Table 4.8) were carried out by India during the period 11–13 May 1998 at the Pokhran range in the Rajasthan Desert. Their parameters were published in *BARC News Letter*, 172, May 1998.

Table 4.8 The five underground nuclear tests carried out by India in May 1998.

Type	Time	Date	Estimated yield (kt)
Thermonuclear	15.45	11.5.98	45
Fission	15.45	11.5.98	15
Experimental	15.45	11.5.98	~ 0.2
Experimental	12.21	13.5.98	~ 0.5
Experimental	12.21	13.5.98	~ 0.3

4.4 RECONSTRUCTION OF FORMER FALLOUT PATTERNS USING MATHEMATICAL MODELS AND ARCHIVAL DATA

The reconstruction of radioactive patterns and of possible exposure doses of the population from nuclear explosion tests seems a priority task. The reconstruction of radioactivity contamination patterns means the restoration of their main characteristics based on available but incomplete data about the source, the weather conditions, the dose rate, and the distribution of radionuclide contamination. Usually reconstruction has involved the restoration of contamination by patterns formed by incidents that occurred many years previously. Interest in the problems of reconstruction has increased much since the Chernobyl accident.

Modelling of radioactive fallout from past nuclear explosions seems necessary in order to reconstruct (or to be more precise, to construct) the patterns of radioactive contamination, i.e. assess the configuration of the contamination pattern.

In order to perform the reconstruction, it is also necessary to restore the meteorological situation at the time the nuclear tests were conducted. As an aid to reconstruction, use is made of information about the radioactive contamination patterns resulting from previous explosions.

When solving the problem of the transport of contamination from different types of sources, use is made of either numerical methods, for solving a three-dimensional turbulent diffusion equation, or various versions of the Monte Carlo method.

This section deals with the spread of contaminants in the atmosphere based on the trajectory model for particle transport in an inhomogeneous wind field when random deviations from trajectories simulating particles diffusion in the turbulent atmosphere are superimposed on the ordered particle motion. Such approaches have been used in a number of studies, e.g. when implementing the programme on assessing models of long-range radionuclide transport and comparing calculation results with data on radioactive deposition from the Chernobyl accident (the ATMES Programme), established by the CEC in

1992. This calculation technique uses both a one-step for integrating a particle motion equation based on the interpolation formula for horizontal wind speed components and a procedure of plotting random deviations of particle coordinates at each step of the integration. Random deviations, different for different particles, lead to the scatter of their trajectories in space, and, finally, to the scattering of particles depositing on to the underlying surface. The simulation modelling of scattering contaminants consists in this case in the selection of a distribution parameter of random deviations for each step to obtain a correspondence to the real distribution characteristics of deposited radioactive particles in the cloud pattern.

It is found that horizontal scattering of contaminants is approximately described by a two-dimensional Gaussian distribution with a standard deviation

$$\sigma_x(t) \approx \sigma_y(t) \tag{4.16}$$

For the time interval of 1–2 days the standard deviation $\sigma_{x,y} = \alpha\, \mathrm{l}(t)$ (Izrael *et al.*, 1970a) varies with the distance from ground zero $\mathrm{l}(t)$ (scattering regime 1), whereas for long time intervals $\sigma = \sqrt{2Kt}$ (regime 2).

The increment of dispersion from one act of a random deviation of particle coordinates to another is, for the first regime

$$\Delta\sigma_{j-1}^2 = \alpha^2 \mathrm{l}_j^2 - \alpha^2 \mathrm{l}_{j-1}^2 = \alpha^2(2\, \mathrm{l}_{j-1} + \Delta\, \mathrm{l}_{j-1})\Delta\, \mathrm{l}_{j-1} \tag{4.17}$$

where $\Delta\, \mathrm{l}_j = \mathrm{l}_j - \mathrm{l}_{j-1}$ is the distance travelled by the particle along its trajectory between scattering acts. For the second regime

$$\Delta\sigma_{j-1}^2 = 2K\,(t_j - t_{j-1}) = 2K\, \Delta\, t_{j-1} \tag{4.18}$$

where Δt_{j-1} is the time interval between scattering acts.

The sum of random deviations specified in the simulation process as $\sum_{j=1}^{n} C_j\gamma_j$, where γ_j is the sequence of accidental (in quasi-stochastic calculations) numbers equiprobably located in the interval [−1/2, 1/2] with a dispersion $\sigma_\gamma^2 = \frac{1}{12}$ and $C_j\, \sqrt{\Delta\sigma^2/\sigma_\gamma^2}$, determines regimes 1 and 2, correspondingly.

Particles which appeared random (n) form a symmetrical distribution $\pm\frac{1}{2}\sum_{j=1}^{n} C_j$ relative to the zero deviation, with a distribution density maximum at this point (for $n \geq 2$). There are no particles outside the said interval. The interval becomes longer as n increases, and for a limited number of deviations from the centre the distribution asymptotically approaches normal. The best result can be obtained when using group values $\frac{1}{\sqrt{m}}\sum_{i=1}^{m} \gamma_{ji}$ rather than accidental values.

The time step between the acts of particle dispersion is assumed to be constant, Δt = 1 h. The points where the particle is subjected to dispersion according to the initiation process can be dozens of kilometres apart. Even the spatial distribution of these points for the totality of the particles under consideration, is obtained by random variation of the initial step within the limits from 0 to Δt up to the first act of dispersion for different particles. It also provides filling of the whole time period $t > 0$ by acts of dispersion when the number of particles is great.

In the interval between scattering acts one calculates the horizontal particle displacement in the wind field and its settling out by gravity. The particle coordinate values obtained at the end of the interval are supplemented by the random (quasi-stochastic) deviations referred to above, and a new particle location becomes initialized for the next interval of the ordered particle motion, etc., until its deposition on to the underlying surface.

In addition to particle gravitational deposition one takes into account capture by the underlying surface in the surface air layer, by adding the capture rate to the deposition rate, which can have an important influence on the deposition of finely dispersed fractions.

Horizontal particle transport is calculated based on data from the objective analysis of the three-dimensional wind field, presented in the form of latitude and longitude wind speed components on a uniform $2.5° \times 2.5°$ grid for standard isobaric levels. The particle horizontal coordinates are calculated in units of a specified grid $\Delta G = 2.5°$. For this purpose, U and σ_x are multiplied by $180/\pi R \cdot \Delta G \cdot \cos\varphi$, and V and σ_y are multiplied by $180/\pi R \cdot \Delta G$, where R is the Earth's radius and φ is the geographical latitude.

The angular displacement speed specified at the four corners of the square grid under consideration are interpolated to an internal point in the cell (including the cell boundary) by the formulae

$$U = dx/dt = U_1 (1 - x) (1 - y) + U_2 x (1 - y) + U_3 xy + U_4 (1 - x) y$$

$$V = dy/dt = V_1 (1 - x) (1 - y) + V_2 x (1 - y) + V_3 xy + V_4 (1 - x) y \quad (4.19)$$

where $0 \le x \le 1$, $0 \le y \le 1$ are the local coordinates relative to the left lower cell angle (U_1 V_1), and the corners are numerated counter-clockwise.

To integrate the systems of equations (4.19) together with the equation for particle gravity settling

$$dz/dt = - W \quad (4.20)$$

one applies a one-step algorithm, where the solution is given in the form of the Taylor series segment (Demidovich *et al.*, 1967).

$$x_{i+1} = x_i + x'(t_i)\Delta t + \frac{1}{2!} x''(t_i)(\Delta t)^2 + \frac{1}{3!} x'''(t_i)(\Delta t)^3$$

$$y_{i+1} = y_i + y'(t_i)\Delta t + \frac{1}{2!} y''(t_i)(\Delta t)^2 + \frac{1}{3!} y'''(t_i)(\Delta t)^3$$

$$z_{i+1} = z_i - W \cdot \Delta t \quad (4.21)$$

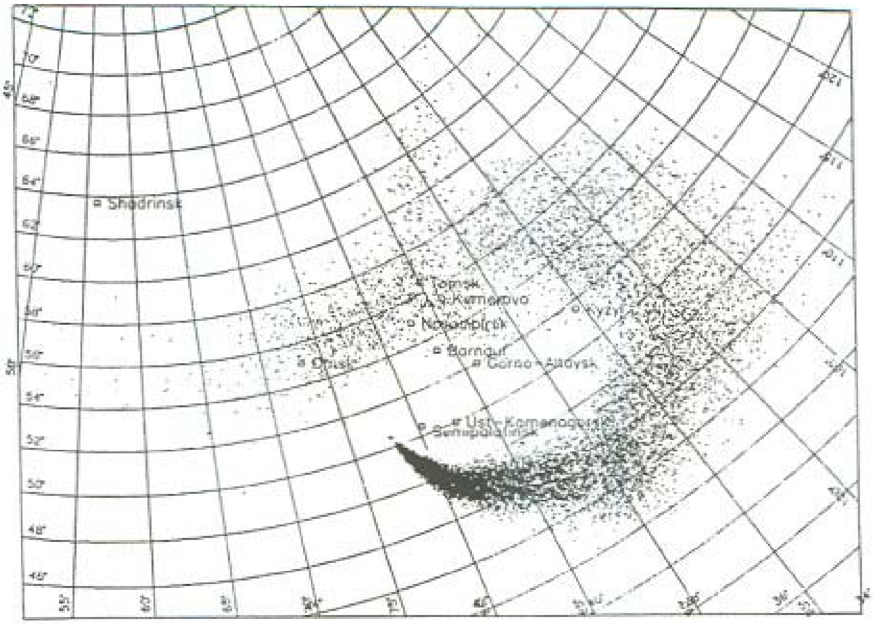


Figure 4.36 Map of calculated particle deposition from the nuclear explosion of 12 August 1953 at the Semipalatinsk Test Site.

where derivatives of the second and higher orders are found through a sequential differentiation system (equation 4.19).

Deposition of contaminants onto the underlying surface is calculated in two stages. In the first stage, one specifies in a source a fictitious particle distribution with gravity sedimentation rates. This provides their relative number in the deposition region under consideration. The coordinates of each particle deposited are calculated.

In Figure 4.36 a map is shown with particles deposited from the nuclear explosion of 12 August 1953 at the Semipalatinsk Test Site. The distribution density of the number of particles of all fractions with height is shown in the form of a truncated symmetric Gaussian distribution $9.6 \leq h \leq 15$ km with a maximum distribution density five times as much as that at the boundaries (*h* is the height of the middle of the cloud).

In the second stage of the calculation one determines the total particle activity for each fraction in accordance with the lognormal distribution of activity over the particle diameter. The deposited particle coordinates found at the first stage (discrete activity distribution) are considered as centres of supplementary continuous activity distribution of fictitious particles on to the underlying surface. This provides a calculation of depositional density and smoothes the statistical scatter of the design data.

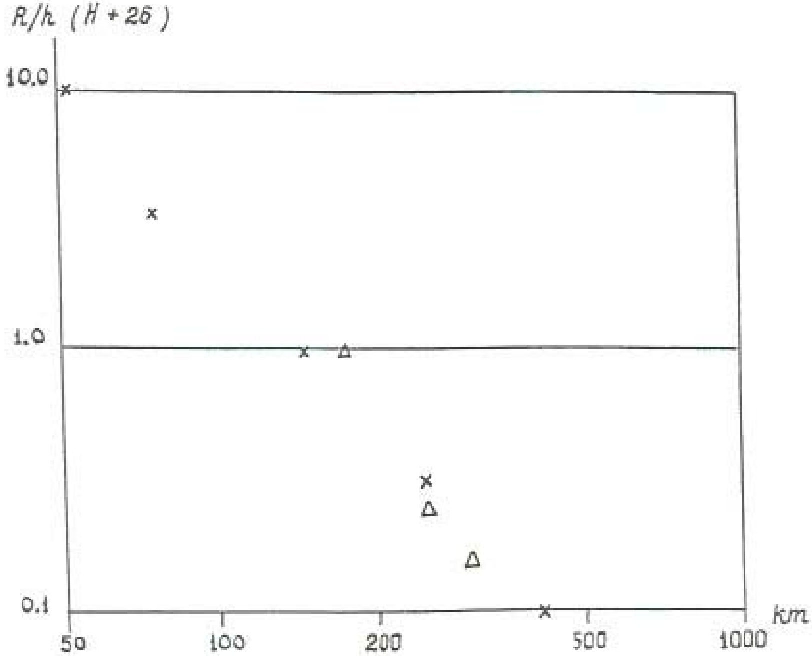


Figure 4.37 Dose rate values in the axis of the cloud pattern after the nuclear explosion of 12 August 1953, 26 hours after the explosion; Δ, measured values (Logachov, 1994); x, calculated values.

For example, one calculates the dose rate distribution in the cloud pattern from the surface nuclear explosion of 12 August 1953. The explosion yield was 400 kt. The calculations were performed for the radioactive particle transport from a linear vertical source with a height distribution of the activity in the form of a truncated Gaussian distribution. Particle size activity distribution is approximated by a lognormal law. In the calculations the distribution parameters are assumed to be the same as those of surface explosions for the Nevada coherent soils: $\lg \delta = 2.053$ and $\sigma = 0.732$ (Stewart, 1956). It is noteworthy that particle activity distribution parameters are related to the type of the soil of the underlying surface, and for the Semipalatinsk Test Site they do not differ much from those given above. Figure 4.37 gives the experimentally measured dose rates in the axis of the cloud pattern from the explosion of 12 August 1953, at 26 h after the explosion compared with the calculated values. Dose-rate distributions in the intermediate and remote zones are shown in Figure 4.38 in the form of isolevels of the dose rate logarithm according to the original data. The calculations show that a vast territory was contaminated by this explosion, including West Siberia and the southern part of the Altai Republic.

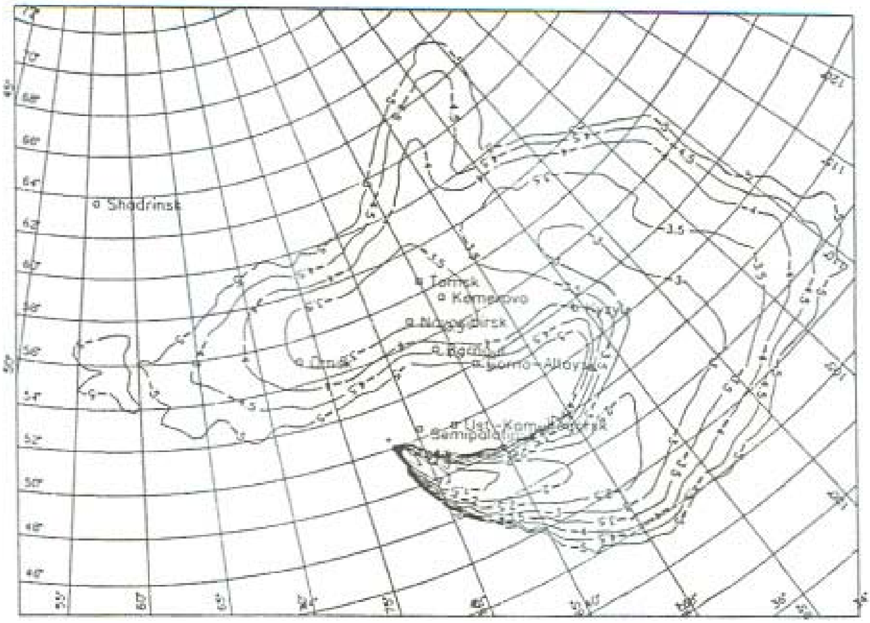


Figure 4.38 Calculated distribution of the dose rate in isolines logarithm isolevels in the intermediate and remote zones dose rate, R h^{-1} (85 mGy^{-1}).

4.5 RADIOACTIVE CONTAMINATION OF GEOLOGICAL FORMATIONS, UNDERGROUND WATER, GAS AND OIL BY UNDERGROUND NUCLEAR EXPLOSIONS

The problems of the underground water contamination from underground nuclear explosions, as well as the contamination of oil and gas where stimulated production is carried out with the help of nuclear explosions, were discussed by Izrael *et al.* (1971). In the broken rock surrounding an underground nuclear explosion, three typical zones can be identified: the initial spherical cavity, the collapsed rock column and an adjoining zone of fractured rock. The geometrical parameters of these zones can be calculated approximately using empirical formulae. The generalized configuration of the destruction zones and their approximate typical dimensions based on numerous studies are given in Figure 4.39 (Izrael *et al.*, 1971).

A spherical cavity is formed as a result of pressure forces in a high-temperature epicentral zone. At the moment cavity formation is over the pressure of the vapour and gases that fill the cavity is approximately equal to the lithostatic rock pressure at ground zero. As a result of the blast wave effect,

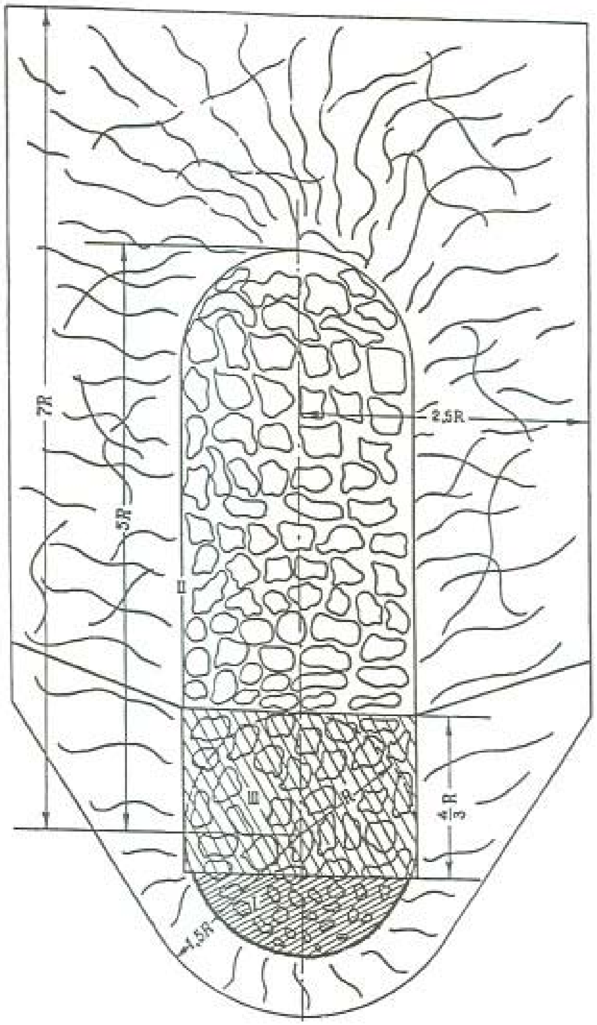


Figure 4.39 Configuration of zones of rock destruction in and around the cavity formed by a contained, underground nuclear explosion.

the zone of collapsed and fractured rocks spreads out around the spherical cavity. In the process of cavity cooling and condensation of the evaporated substances the pressure in the cavity drops. As a result the crushed and fractured upper rocks collapse and form a collapse 'column' or 'tube' (seldomly encountered in the exceptional circumstances of nuclear explosions in plastic rocks such as salt).

The specific nature of the radioactive contamination of all zones of the collapsed and fractured rock is much dependent on conditions at the moment the cavity collapses. Investigations have shown that most of non-volatile radioactive products are concentrated in the fused rock, which when falling in from the cavity walls form a lens in the lower third of the cavity and drag along the rocks that happen to fall into the melt before its solidification. The melt volume is below 5% of the cavity volume.

Gaseous radioactive products, e.g. radionuclides of inert gases as well as their decay products, remain in the cavity until its collapse, although a possible partial release of gas and volatile products through rock fractures cannot be excluded. The cavity collapse causes gases leaving the cavity to quickly fill the vacuum in the collapsed column zone. The fracture zone located outside the collapsed column is filled more slowly by the radioactive gases, because this requires an air exchange or displacement of the air in the fractures.

Radionuclides of inert gases (^{133}Xe and ^{85}Kr), of iodine (^{131}I and ^{133}I), tritium (^{3}H) and of radionuclides of gaseous precursors (^{89}Sr, ^{137}Cs, ^{90}Sr, ^{91}Y, ^{140}Ba) or volatile gases *per se* (^{132}Te, ^{103}Ru, ^{106}Ru, ^{125}Sb) are most important when spreading in broken rocks. Radionuclides of inert gases spread into the collapsed rock zone; if this zone is connected with the ground surface then a jet of inert radioactive gases can be formed in the atmosphere. Radionuclides ^{133}Xe and ^{85}Kr, and to some extent ^{135}Xe, are of greatest importance. Because of their high volatility, the radionuclides of iodine (particularly ^{131}I) are of significant importance as a potential source of contamination of the environment, at least during the first three months after the explosion. Most important for the contamination of broken rocks will be radionuclides of the inert gas decay products: ^{89}Sr, ^{137}Cs, ^{90}Sr + ^{90}Y, ^{91}Y and ^{140}Ba + ^{140}La, because the half-lives of the gaseous precursors of these radionuclides are comparable with the duration of the phases of formation of the 'collapse column'.

Figure 4.40 shows the relationship between the moment of collapse and the amount of radionuclides contaminating the column of collapsed rocks. Independent ^{235}U fission neutron yields are used for the calculation. The results are given in Ci of the *i*th radionuclide per kiloton of fission yield of nuclear explosion.

The maximum volume of zone II (Figure 4.39) is determined by the volume of the fractured rock (in this case the specific rock contamination must decrease with the distance from the centre), and the minimum value V_2 is determined by the volume of the chimney rubble. In this case the rock contamination can be close to uniform.

One more zone (III) must be mentioned (Figure 4.39). In this zone one can detect isotopes of elements that have chemical compounds which are volatile at relatively low temperatures; ^{132}Te + ^{132}I, ^{106}Ru + ^{106}Rh, ^{103}Ru and ^{125}Sb can be considered as typical representatives of this group of radionuclides.

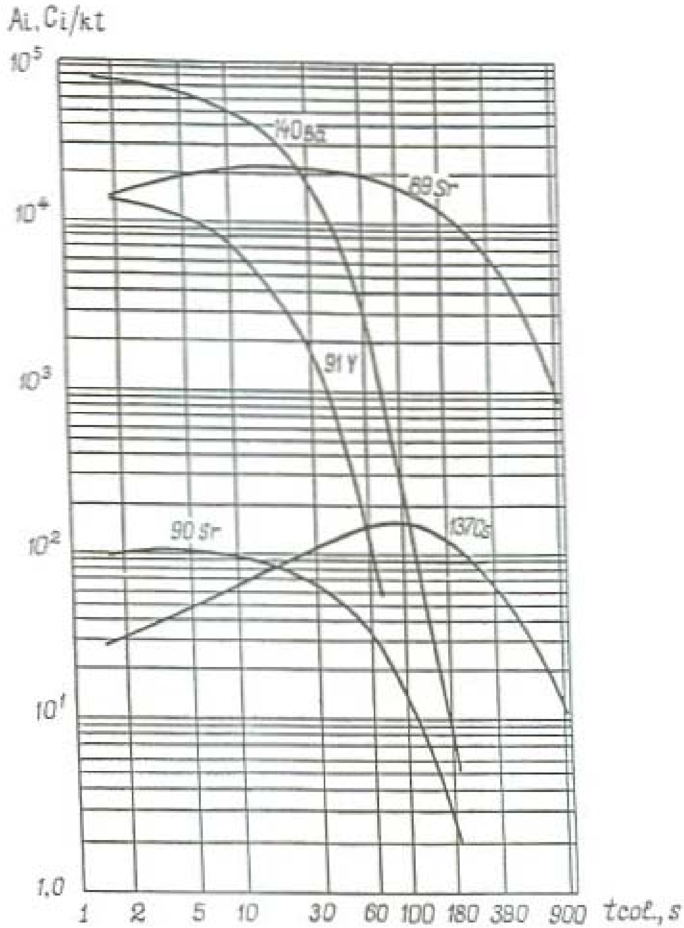


Figure 4.40 The relationship between the activity of various radionuclides contaminating the broken rocks and moment of cavity collapse (LCi = 37GBq).

The secondary processes of migration and post-explosion radionuclide redistribution are mainly linked to their solubility, i.e. to the ability of the radionuclide to transit from explosion products to water solutions. Most underground nuclear radioactive explosion products in the zone of the fragmented rocks are connected with the solidified melt and are not prone to leaching or scavenging. Rocks in the chimney rubble are mostly contaminated on the surface, and this definitely may promote the transfer of radionuclides to water solutions. The same applies to particles produced in cratering explosions. The extent to which radioactive products in a particle pass into the water is variable: for example, particles with a volume activity distribution lose as a whole about 1–4% of the total activity to water.

The solubility data of the radionuclides are related to their gaseous precursor history; the most soluble radionuclides being those adsorbed on particle surfaces after the formation from their gaseous precursors. The solubility of radionuclides without gaseous precursors is very low. The relative solubility with respect to 1.0 for ^{90}Sr, is as follows (Izrael, 1974):

^{89}Sr	^{90}Sr	^{125}Sb	^{140}Ba	^{103}Ru	^{106}Ru	$^{134}Cs, ^{137}Cs, ^{141}Ce$	$^{91}Y, ^{95}Zr, ^{144}Ce, ^{54}Mn, ^{60}Co$
1.25	1.0	0.3	0.24	0.1	0.04	0.02	0.01 – 0.001

The redistribution or subsequent transport of the radioactive debris has been examined previously in the context of hydrological transport. During the year following the '1003' explosion, groundwater flowed into the crater to a total volume of about 500 m^3. Radiochemical studies of the water in the crater were undertaken to examine the way the crater filled and the role played by groundwater in creating artificial reservoirs. The major radionuclides observed were ^{89}Sr, ^{90}Sr, ^{103}Ru and ^{106}Ru. Also detected were ^{125}Sb and ^{137}Cs. It was noted that ^{90}Sr and ^{137}Cs were in cation form.

Groundwater transport of the radionuclides was studied with a network of observation holes established at the '1003' explosion site, at depths of 26 to 50 m, and located from 200 to 700 m from the emplacement hole (Izrael *et al.*, 1970a). Systematic hydrogeological observations were begun two months after the explosion. The authors noted that the crater shape was preserved during one year period and that the water levels in the holes were lowered by 0.7 to 1.3 m. They concluded that infiltration of groundwater into the crater occurred. Measurements in the observation holes confirmed the absence of radioactivity contamination in the holes even after several years following the explosion.

Consider the possibility of radionuclide migration with the underground water, outside. By writing down an ion exchange equation, the reaction constant can be determined and then the K_d, constant, which is referred to as a distribution factor. The letter indicates the relationship of bound ions in solid and in liquid phases. The K_d value changes within the range of 10^1–10^5 for different minerals and radionuclides. The mean K_d values are 10^2–10^3 for ruthenium, 10–2×10^4 (10^5 in some cases) for strontium, and 10^4–2×10^5 for cerium.

The average K_d value for a one-year mixture of fission products is estimated as 370. It is evident that $K_d = 0$ for tritium (Izrael, 1974). Thus the ion exchange processes lessen the potential hazard of underground water contamination, firstly due to decrease of ion transport velocity in comparison to the water flow velocity and secondly due to concentration decrease in migration. The flow velocity of a given substance (F_a) in the underground water can be expressed by the following formula:

$$F_a = F_b/(1 + \rho K_d) \tag{4.22}$$

where F_b is water flow velocity and K_d is the relation on mineral weight to water weight per volume unit of the given mineral and ρ is apparent density of porous medium/void fraction; usually K_d = 4–5. It follows from equation (4.22) that a given ion type velocity migrating with the water, flows at a rate 100 to 1000 times lower than the water flow velocity. For example, ^{90}Sr migration of 1 km distance will take years, even if F_b velocities are relatively high (about 10 m/day^{-1}).

Based on the above data, consider a specific case and assess possible oil contamination when stimulating oil production with nuclear explosions. It is known that the former USSR was first to use a contained nuclear explosion for stimulating oil production. For that purpose, on 30 March 1965, first two devices of 2.3 kt were exploded simultaneously in the oil block, then on 10 June 1965, one more device of 7.6 kt was exploded (Kedrovsky, 1970; Mikhailov *et al.*, 1996). A calculation model is described in detail by Izrael *et al.* (1971a). Here only the input parameters and results are considered.

Radioactive contamination by radionuclides with volatile precursors, such as ^{89}Sr, ^{90}Sr, ^{137}Cs, etc., was determined as a maximum assessment, i.e. with a uniform distribution of 40% of the above radionuclides produced by the explosion in the zone of chimney rubble and fracturing. It was assumed that operating holes were located in the fractured zone. The oil well discharge was assumed to be 30 t day^{-1}. The fractured zone volume in the calculation model considered is about 10^6 m^3, and at a mean rock porosity of about 18% (in the case considered it changed from 0.5 to 35%) and oil specific gravity of 0.86 g cm^{-3} (Kedrovsky, 1970), the specific oil content in the rock equals 0.15 g cm^{-3}. The coefficient of radionuclide transit into the oil was assumed to be equal to 10^{-3}–10^2, which is in a good agreement with values obtained in practice (Kedrovsky, 1971).

The calculated data (Tables 4.9 and 4.10) are confirmed experimentally by oil contamination values in the experimental explosion described (Kedrovsky, 1970, 1971).

The ^{137}Cs concentration, for example, in the oil from a hole at 40 m from ground zero, 2–4 years after the explosion, was below 10^{-9} Ci l^{-1} (37 Bq l^{-1}) (Kedrovsky, 1970).

Among all the applications that have been studied in the USA, the use of nuclear explosives for the stimulation of production from gas reservoirs is the closest to commercial utilization. Two field experiments have been conducted, projects 'Gasbuggy' and 'Rulison' and a number of other gas stimulation experiments are under preparation. 'Gasbuggy' was a 29 kt explosion carried out at a depth of 1292 m in December 1967. It provided the first data in the physical and chemical effects of a nuclear explosion in a gas reservoir. The changes in concentration of tritium and ^{85}Kr in the gas after explosion 'Gasbuggy' are reported by Nordyke (1971).

Table 4.9 The time that oil is delivered into observation holes at different distances from the source.

Distance	0.5 m	1 m	5 m	10 m	50 m
Time	0.6 day	2.5 days	52.5 days	250 days	17 years

Table 4.10 The *i*th radionuclide content in the oil $q_i(t)$ delivered into the oil at various time intervals, Ci l^{-1} (Bq l^{-1})

t	1 day	10 days	60 days	1 year	2 years	4 years
^{89}Sr	$4 \cdot 10^{-9}$	$5 \cdot 10^{-9}$	$4.4 \cdot 10^{-9}$	10^{-10}	$8.5 \cdot 10^{-13}$	$7 \cdot 10^{-15}$
	(147)	(185)	(163)	(3.7)	($13.7\ 10^{-3}$)	($2.6 \cdot 10^{-4}$)
^{137}Cs	$27 \cdot 10^{-11}$	$5 \cdot 10^{-11}$	$7.5 \cdot 10^{-10}$	10^{-10}	$1.4 \cdot 10^{-10}$	$1.7 \cdot 10^{-10}$
	(10)	(1.8)	(128)	(3.7)	(5.2)	(6.3)

4.6 ECOLOGICAL EFFECTS OF NUCLEAR TESTING

Ecological studies have been conducted at several nuclear explosion sites, which include sites of cratering experiments and sites used for testing nuclear weapons.

The effects of the testing programme at these sites cannot, in general, be ascribed solely to radiation, because of the concomitant effects of blast and heat. Furthermore, human exploitation of the natural resources in the test areas has changed markedly as a consequence of the testing programme. Although many significant and complex effects on ecosystems have been observed, the recovery processes following test explosions have been relatively rapid and vigorous. Deleterious effects on marine and terrestrial populations have not been persistent, presumably because of the rapid decline in the intensity of radiation and other impacts, the selective elimination of defective genetic information, and the recolonization of damaged areas with healthy individuals from distant localities (IAEA,1992).

4.6.1 Case study: Mururoa and Fangataufa

A summary is provided of the main results of the ecological studies performed by French scientists at the atolls of Mururoa and Fangataufa, which appears in the conclusions of the Volume III, *Le milieu vivant et son évolution* (Bablet *et al.*, 1995).

4.6.1.1 Consequences of the presence of the 'Centre d'Expérimentation du Pacifique (CEP)' on Terrestrial Flora and Fauna

In 1994, the terrestrial flora, which was destroyed or burnt by the effects of atmospheric tests, is little different from the original flora, both in diversity and in size. However, on some mounds, those nearest to the oldest trials, the size of some plants (Guettarda and Scaevola) is smaller than in 1966. This is attributed to the degradation of the soil, already originally less fertile, by the thermal flash of atmospheric tests. Fangataufa sheltered, in 1966, numerous colonies of birds whose nest sites were spread all over the emerged crown. Their number, which was greatly diminished as a result of the direct effects of the size of the nuclear tests and the disappearance of their habitat, was restored after restoration of their habitat. In 1994, the population of birds was comparable to that in 1966. Meanwhile, species of small size have vanished, and the nests sites are now limited to the motu (mound) of the Pavillon sector. This reduction of the habitat was due to atmospheric tests, but also to the presence of humans and the civil engineering work, which drove the birds towards the most distant and least perturbed mounds. Eventually, the proliferation of the iron tree, *Casuarina equisetifolia*, with an arrangement of branches that does not allow the building of nests could explain the relative standstill of this situation. Experiments have been carried out on germinated nuts of coconut palm trees planted on the mounds nearest to high-energy atmospheric tests, in order to study the fate of vegetation under the conditions of extreme pressure, temperature and radiation. Those that survived do not show any residual anomalies. The consequences of radioactivity induced by the atmospheric tests have been very weak in comparison with the blast and thermal wave. Any after effects of radiobiological origin, that is to say generated by direct irradiation from the atmospheric tests or their fallout, has not been apparent, either in the realm of vegetation or animals.

The underground experiments carried out beneath the raised crown resulted in a compaction of soil around the surface ground zero points. In the south-west sector, where the high-energy shots were carried out, some mounds originally were very slightly raised, but are now immersed and this has caused the disappearance of terrestrial vegetation.

4.6.1.2 Consequences of the Presence of the CEP for the Marine Flora and Fauna

The thermal flash of megaton tests has destroyed a high proportion of superficial coral and mollusc populations, in particular those of the external plates and of the algal crest near the ground zero point of the tests. The whitening of certain surviving colonies, by the loss of their zooxanthellae, has been regularly observed up to the cessation of the atmospheric tests. The phenomenon has introduced a disequilibrium into the ecosystem comparable with that produced after the passage of a tropical cyclone or an abnormally hot summer period. Fifteen years after the end of atmospheric testing, the coral population of those external plates was restored, with a diversity and a rate of recovery comparable with those existing before the tests. The rapidity of this restoration is probably explained by the weak degradation suffered by the substrates. The population of molluscs of these areas has also been re-established to levels comparable with those of 1966, except for *Tecarius grandinatus*, populations of which still remain scattered. The pressure waves induced by the atmospheric and underground tests in the lagoon have resulted in hard substrate degradation and some increase in the rate of sedimentation. From this perspective the underground events had a greater impact on account of their dispersion and the considerable pressure that they generate around the surface ground zero points.

The vitality of the coral communities of the Mururoa and Fangataufa atolls varies greatly from one site to another, from one biotope to another, as a function of the natural environmental conditions and past and present perturbations.

Overall, the recolonization of the coral is active, but the restoration of coral populations following the atmospheric tests is more advanced than in the much more recent underground tests, which have generated a greater degradation of the substrates. The populations often present a young character, with sometimes a dominance of pioneer species, indicating a community still badly structured. Locally, the bioconstructor organisms can strongly compete with substitution populations: soft algae, Zoantharia, Alcyonaria and Actiniaria. In a number of cases, such as the east sector of Mururoa near the base or the navigation routes, the appearance of certain substitution populations can be linked to urbanization or human presence.

On the coral constructions of these sectors, the appearance of populations of Palythoa has been noted since 1969, with the subsequent, often cyclic, development of Zoanthus and Rhodactis. A reduction follows in the species diversity of Madreporaria by elimination of a species that does not tolerate the rise in nutrients and suspended or sedimented materials. The echinoderms and algae offer good examples of the spatio-temporal variability of populations due to perturbations in the surroundings by nuclear experiments. Comparable demographic expansions can be seen in zones near urban waste. On these sites, the strongest densities observed sometimes are attributable to the large quantities of organic material dispersed in the environment. The opening of the Fangataufa passage and, to a lesser degree, the augmentation of exchanges of water with the ocean by the hoa from the southwest of Mururoa, should modify certain populations. This is already most apparent where plankton is concerned. The populations of molluscs of a more open Fangataufa lagoon should evolve towards greater specific diversities and reduction in the density of original dominant species. This tendency seems to be appearing but, taking into account the impact of the nuclear events, it is still too soon for confirmation.

4.6.2 Case study: Nevada Test Site

Extensive searches for ecological changes in contaminated areas have also been carried out at the Nevada Test Site. In most of these studies, however, the contamination consisted principally of mixed fission products, and, except for the work reported by Rhoads and Platt, the more dramatic ecological effects were generally attributed to non-radiological perturbations. The best opportunities for searching for ecological effects from plutonium alone exist (in a number of areas) adjacent to the Nevada Test Site in areas used for 'safety shot' tests. These tests involved detonation by conventional explosives of plutonium in various containment configurations. Studies of small mammals and grazing cattle in these areas have failed to discover any evidence of radiogenic pathology. Varney and Rhoads have examined shrubs in areas assumed to have been contaminated primarily with plutonium. Although their data implied that such shrubs had increased frequencies of chromosomal aberrations to controls, the evidence was not conclusive (Hanson, 1980).

The development of the Plowshare programme and the execution of the SEDAN event stimulated detailed radioecological studies of long-lived radionuclides. The distribution of tritium in the SEDAN ejecta field, climatic effects on this distribution, and inventory data were described in this research: the integrated inventory of radionuclides in SEDAN ejecta indicated that tritium was the most abundant radionuclide on the basis of activity per surface unit. The biological significance of residual tritium at SEDAN crater was evaluated in plant and animal studies

4.6.3 China

In China, the Institute for Application of Atomic Energy, established in 1960 under the auspices of the Chinese Academy of Agricultural Sciences, conducted radioecological experiments to study the behaviour of fission products from fallout origin in crops and soils (Xu Shiming *et al.*, 1996). On-the-spot pot culture experiments on crop plants were performed in the proximal area of a low-altitude nuclear explosion. Other experiments were performed using the fallout collected in the area of nuclear explosion tests. The results show that the fallout (0.5% solubility) contributed a little to the internal contamination of crops via roots. Unfortunately, in most of those experiments, which appear to have been conducted in the 1960s, only measurements of total beta or gamma were carried out, therefore, the valuable information that can be derived from these experiments is limited.

4.6.4 Former USSR

The estimation of genetic effects caused by nuclear tests at the Semipalatinsk Test Site was presented during the II NATO-ARW, Barnaul (Shumny and Shevchenko, 1994). Recurring atmospheric nuclear explosions at this test site contaminated certain areas of Altai from 1949 through to 1962 by as much as 3 Gy, which is enough to cause genetic effects. Mutagenic effects of irradiation in

Altai can be evaluated very approximately by examining organisms that differ in the length of generative cycles and occupy different ecological niches. The succession of generations is accompanied by elimination of mutant variants, and so is an additional factor that prevents an easy analysis. Therefore it was urgent to uncover possible traces of exposures to ionizing radiation in the hereditary material of currently living organisms, among them plants and animals which (or whose ancestors) have ever been exposed to radioactive fallout from the Semipalatinsk nuclear tests. With that objective, the cytogenetic and some biochemical markers of exposure to radiation have been analysed in material from human residents, animal populations (Chironimids) and plant populations (Scotch pine) of the affected Altai areas.

4.6.4.1 Cytogenetic Monitoring of the Natural Populations of Chironomids

There has been a three-time monitoring of seven Chironomid populations of Altai monitored on three occasions in 1992–1993. In some of the regions investigated the dose of ionizing radiation peaked at 3 Gy after the 1949 explosion. Today, soil concentrations of ^{137}Cs near the lakes are two to three times as much as the global fallout background. Study of chromosome polymorphism in the populations of the two species of the Altai Chironomids (*C. tentans* and *C. balatonicus*) revealed wide chromosome polymorphism in all populations studied, both in the polluted regions and in the conventional control. The findings show a difference witnessed by 'bundles' of five to seven unique sequences not reported in any other populations ever studied, except in the Cheliabinsk populations, where the level of radioactivity still remains high. It is noteworthy, that both the Altai and the Cheliabinsk populations are 60–90 generations removed from those exposed to the explosions of 1947 and 1957, respectively. Part of the neutral or adaptive chromosomal anomalies induced by radiation can persist through many generations. The unique sequences therefore may be regarded as 'radiation records' induced in the Chironomid genome following the exposure to radiation, which have persisted for 60–90 generations.

4.6.4.2 Examination of Wild Populations of Plants

Analysis of genetic and cytogenetic parameters of higher plants in Altai populations exposed to ionizing radiations has been performed by a team of scientists from the Institute of Cytology and Genetics of the Siberian Division of the Russian Academy of Sciences and from the Institute of General Genetics of the Russian Academy of Sciences. The Scotch pine (*Pinus silvestris*) is a natural test system for assessing remote genetic hangovers of exposure to radiation. The mutational events induced in the vegetation by nuclear tests may be identified as differences between wild populations from polluted regions and control regions, using a series of parameters, such as pollen fertility, seed production, germination of seedlings, number of cells with chromosomal aberrations in seedlings going through mitosis I, frequency of meiotic anomalies and polymorphism for seed storage proteins. On the whole, this study provides evidence that radioactive pollution of the regions has induced lower pollen viability and fertility, rendering more seeds unviable, giving rise to meiotic anomalies and raising concentrations of rare and null variants of storage protein in the seeds of wild populations of the Scotch pine.

4.6.4.3 Lichen–Reindeer–Human Foodchain

Radioecological peculiarities around the Novaya Zemlya (Russia) test site have been investigated by Ramzaev's team since 1961, with special emphasis on the lichen–reindeer–human foodchain. The studies show that the structure of the lichen could increase the adsorption surface to a value 20 to 100 times greater than in grasses; furthermore the concentration of ^{137}Cs in the thalle is 200 times greater than in the aqueous solution of ^{137}Cs. In the case of ^{90}Sr this factor is 20 times greater. Another interesting observation is that the absence of roots in lichens created the illusion that the radionuclides in soil are inaccessible: actually lichen possess special features in regard to this and in three months lichen can absorb caesium from soil 200 to 400 times more than grasses can. The degree of assimilation of ^{90}Sr from soil is almost the same as in grasses (0.1–0.3%). These peculiarities of lichen have created preconditions for heightened levels of radionuclides (especially ^{137}Cs) in the subsequent portions of the foodchain, such as in reindeer, whose principal fodder for seven to eight months is lichen (Ramzaev *et al.*, 1993).

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5 Pathways for Internal and External Exposure

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5.1 INTERNAL EXPOSURE PATHWAYS

5.1.1 Introduction

The main pathways leading to intake of radionuclides by humans following a nuclear explosion are inhalation of contaminated aerosols or gases and ingestion of contaminated water or foodstuffs as discussed below. Radio-isotopes of iodine, strontium and caesium are of most interest in this respect because they are both released in considerable quantities during nuclear explosions (Chapter 4) and are readily transferred to humans by foodchain pathways and then subsequently absorbed through the gastro-intestinal tract.

5.1.2 Inhalation

Inhalation of radioactive gases and aerosols may occur during the initial passage of the radioactive cloud and at later times as a consequence of resuspension of material previously deposited on vegetation and other surfaces. In this respect, it is necessary to consider both humans and grazing animals, where inhaled material may either be absorbed via the lungs or removed from the lungs to the gastro-intestinal tract for subsequent absorption. For humans, there are internationally accepted models such as those developed by ICRP (1980) for calculating absorption of radionuclides following inhalation, taking into account factors such as particle size and radionuclide composition. Such models are based on ICRP 'reference man' (1975) and therefore may not be entirely appropriate to the populations surrounding nuclear test sites at the time and conditions in which the most significant explosions occurred. Analysis of exposure pathways during the passage of a radioactive cloud is relatively straightforward. It involves application of ICRP models with appropriate modification of parameters to

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take into account factors such as the distribution of particle sizes within the cloud and the physical and chemical form of radionuclides within such particles.

Models for application to grazing animals that form a potential pathway for transfer are not as well developed as are those for humans. According to conditions during the passage of the cloud, it is quite possible that inhalation could contribute to concentrations of radionuclides in animal products. This was demonstrated clearly after the Chernobyl accident where ^{131}I exposure of housed animals via inhalation resulted in contamination of milk, although at much lower concentrations than were observed for animals exposed to similar air concentrations but in free-grazing conditions (Coughtrey *et al.*, 1990).

Analysis of inhalation pathways following a nuclear explosion requires consideration of the extent of ground contamination and the degree to which deposits are resuspended to the atmosphere at various times after the depositional event. Resuspension varies as a function of the nature of the ground surface (e.g. urban or rural conditions), meteorological conditions (e.g. wind speed, rainfall) and physical disturbance, such as that created by agricultural activities (ploughing, rainfall) and urban activities (e.g. street sweeping, spraying with water to reduce dust, etc.). It is particularly sensitive to local climate and environmental conditions.

The importance of the inhalation pathway for an individual member of a potentially exposed population will depend on the following factors.

1. The time of year at which the event occurred (affecting both ground conditions and the person's habits).
2. Location and activity during the passage of the cloud, i.e. whether indoors or outdoors, whether at work or at rest, and the nature and pattern of work.
3. Nature of place of residence following the passage of the cloud, i.e. whether rural or urban.
4. Occupation following the passage of the cloud, i.e. whether working indoors or outdoors and, if the latter, whether involved in activities which result in, or are related to, higher-than-average resuspension.

For grazing animals a further set of factors apply, i.e. their location at the time of passage of the cloud, and their subsequent husbandry and feeding behaviour following passage of the cloud.

Such factors have to be taken into account when estimating exposure to radionuclides that have been released from nuclear explosions. Their nature and relative importance will have differed between test sites, and according to the year in which the most significant event(s) occurred (due to societal changes) and the season of the year in which those tests occurred. Their contribution to uncertainties in estimated doses cannot be ignored.

5.1.3 Ingestion

Ingestion of radionuclides by humans following nuclear explosions can occur from consumption of contaminated vegetable and animal products, water and, in some cases, soil. The latter can be quite important for children. The main pathways that require consideration whilst estimating doses are summarized in Figure 4.1.

Plant products may be contaminated directly as a consequence of deposition of particles, in which case radionuclide intake by humans will depend to a large extent on the manner in which plant-based foodstuffs are prepared prior to consumption. Plant products may also become contaminated indirectly as a consequence of the translocation of radionuclides from foliage or from the soil to the harvested product. In this case the intake by humans is less sensitive to the method of food preparation. For short-lived radionuclides such as ^{131}I, direct contamination tends to dominate over indirect contamination. The opposite applies to longer-lived radionuclides such as ^{90}Sr and ^{137}Cs.

Radionuclides can be transferred to products derived from grazing animals as a consequence of ingestion of contaminated plants, water and soil. Meat and milk are by far the most important pathways in this respect. Radionuclides such as ^{131}I and ^{137}Cs are transferred relatively effectively to both meat and milk, with transfer to milk of goats and sheep more effective than that for cattle. Contamination of meat with ^{131}I is of little significance apart from the thyroid, which is generally not consumed by humans. In contrast, ^{137}Cs is relatively uniformly distributed throughout the body of most grazing animals and is retained with a biological half-life ranging from several days to a few tens of days (Coughtrey *et al*., 1983–86). Contamination of meat with radiocaesium can therefore provide a pathway for protracted exposure of humans according to the extent to which it remains available to the animal via consumption of plants or soil. Radiostrontium tends to be accumulated in the skeletal parts of most animals and therefore is not of relevance for meat products.

The transfer of radionuclides to animal products is sensitive to both diet and animal husbandry. In general, free-ranging animals show higher transfers of radionuclides than do those which are kept in more intensive systems. This is the effect of a combination of factors, such as the areas available for grazing, selectivity during grazing, and the quantity of soil in the diet.

There are wide ranges in reported feed-to-meat and feed-to-milk transfer factors for radionuclides such as ^{90}Sr, ^{131}I and ^{137}Cs. If specific data are not available for specific assessments it is important to select parameter values which relate as much as possible to the particular conditions of the assessment. The use of generic or average values could, in many cases, result in an underestimate of the actual transfer.

The behaviour of radionuclides in aquatic ecosystems can be very complex according to the mechanism of entry, i.e. direct deposition or transfer from the surrounding watershed, initial physical and chemical form of the radionuclide, and the physical, chemical, hydrological and biological characteristics of the ecosystem. Nevertheless, the potential contamination of aquatic organisms, especially fish, with radiocaesium should not be ignored, especially as concentrations can be maintained for prolonged periods where potassium concentrations of the ecosystem are low or where the potential for fixation in mineral sediments is limited.

The transfer of ^{90}Sr, ^{131}I and ^{137}Cs to humans via the foodchain is also dependent on chemical factors such as the background stable iodine content of soils, plants and animals, and nutrient status (potassium in the case of radiocaesium and calcium in the case of radiostrontium). Where concentrations of stable iodine are low, intakes of ^{131}I may be transferred more effectively to milk and blocked less readily by the thyroid. The behaviour of ^{90}Sr in the environment is related to that of calcium. There is good evidence to indicate that its transfer through soil–plant–animal foodchains is related to that of calcium. The link between potassium and radiocaesium is not as clear as is that between calcium and radiostrontium. The long-term availability of ^{137}Cs for uptake by plants is related to the quantity of available potassium in soil as well as to the quantity of specific minerals which can result in adsorption or fixation of the radionuclide. The discrimination between Cs and K is much greater than is that between Sr and Ca.

5.1.4 Ingestion pathways for populations close to test sites

At the time of the most important explosions at different test sites, there were specific environmental and population conditions which were very different from those that are experienced in equivalent populations at the present time. Such conditions could, potentially, have important consequences when reconstructing past exposures. The following sections summarize those factors that are known to have been relevant for specific populations and test sites.

5.1.4.1 Nevada

The main radioecological impact of explosions at the Nevada Test Site (NTS) has been demonstrated to be contamination of milk with ^{131}I. Analysis of radioiodine concentrations in milk has indicated more than an order of magnitude variation in transfer to individual cattle within a herd (Appleby, 1998). As a consequence it was necessary to consider bulk milk and milk from farmyard cattle separately. Additionally, because there are differences between the transfer of radioiodine to goats milk compared with cows milk it was necessary to consider separately the consequences of testing for consumers of goats milk.

During reconstructions of the consequences of testing at NTS, assumptions concerning agricultural practice have proved to be very important, as have assumptions about the distribution of contaminated products, such as milk, to populations outside the area immediately affected by the explosions (Church *et al.*, 1998).

Dose reconstructions at NTS identified the need for application of site-specific data for interception fractions of fallout. Information derived from studies in 1953 indicated interception fractions that were ten times lower than values which would otherwise have been derived from the literature (Appleby, 1998). For wet deposition, experimental studies were required to derive appropriate parameters (Bouville *et al.*, 1998) and it was recognized that local enhanced levels of fallout could be related to thundershower activity (Church *et al.*, 1998).

Mathematical models such as PATHWAY have been applied during reconstructions of doses from testing at NTS. This has required a major investment in analysing data and in selecting parameters which are appropriate to agricultural and other conditions which existed at the time of the tests (Appleby, 1998; Bouville *et al.*, 1998; Church *et al.*, 1998; Coughtrey *et al.*, 1998).

Assessments of the potential impacts of contamination of groundwaters as a consequence of testing at NTS have involved extremely conservative assumptions, for example abstraction of drinking water from wells driven into the contaminated aquifer (Anspaugh, 1995).

5.1.4.2 Semipalatinsk

As at NTS, assumptions concerning interception have proved to be important in dose reconstructions for tests at Semipalatinsk. Data from the 1962 explosion indicate that only particles $<75\ \mu m$ would have contaminated grass and that the availability of young, growing, grass was a major factor in uptake of radionuclides by cattle. Assumptions about changes in solubility with distance also proved to be very important (Gordeev *et al.*, 1998).

Gordeev *et al.* (1998) also reported the results of investigations on a herd of 100 dairy cows located 105 km from the site of test explosions. These investigations were used to derive time-dependent parameters for the uptake of a range of radionuclides to cows milk. They also demonstrated the marked effects of time of year on rate of decline of radionuclide concentration in cows milk, as well as the effects of rainfall following periods of drought.

For bread products, Gordeev *et al.* (1998) reported that the ratio of specific activity in fresh grain to that in grass was 0.22 and provided relationships for estimating specific activity of radionuclides in bread products. In this respect it was noted that there were differences between bread that was produced from 'highest grade' and 'second rate' flour.

Vlasov (cited by Coughtrey, 1998) reported that variability in external dose was only a factor of 0.2 whereas for ingestion doses it was a factor of 1.7. Ingestion doses from agricultural products were between 0.2 and 1.2 times external doses (Shoiket, cited by Coughtrey, 1998). It is not clear why this ratio was higher for Semipalatinsk tests than for NTS tests (Anspaugh, 1995). One factor could be the large differences that existed between diet and lifestyle of the two populations.

Fallout from Semipalatinsk was distributed over large distances and in different directions. Significant differences in deposition and environmental behaviour were observed at different distances from the source, reflecting partially the nature of the affected ecosystem. Some information exists on site-specific transfer factors for Semipalatinsk fallout but such information appears to be far from complete (Coughtrey, 1998).

Studies following excavation of Lake Chagan have demonstrated higher concentrations of radionuclides in horse meat relative to that from cattle. This is thought to reflect differences in grazing habits; horses grazed feather grass and wormwood near to Lake Chagan whereas cattle grazed cultivated pastures (Akhmetov *et al.*, 1994). Additionally, fish and water birds may have provided a possible route for ingestion of radionuclides by the local population. Such pathways have been reported not to provide any danger to human health (Akhmetov *et al.*, 1994).

In a recent study (IAEA, 1997), data on local dietary habits were obtained by talking to local inhabitants. The information obtained indicated that most of the foodstuffs used in settlements close to the test site were locally produced. The principal exceptions were flour, rice and sugar. The diet appeared to be dominated by animal products and bread or other flour-based foodstuffs. Fruit and vegetable production was stated to be variable but generally low and some individuals claimed to eat no fruit or vegetables. Table 5.1 provides a summary of dietary information provided to the IAEA mission. It is not clear to what extent the lifestyles and habits observed in 1994 reflected those that would have pertained during the period of testing at Semipalatinsk. However, the observations that milk and milk products formed a significant contribution to diet, that drinking water was mostly provided from wells, and that fruit and vegetables appeared to be grown in small plots adjacent to houses and farms, are not untypical of what might be expected for the rural populations present in the 1950s and 1960s. If anything, it can be assumed that locally grown or produced foodstuffs would have formed an even greater proportion of diet at that time.

5.1.4.3 Novaya Zemlya

The main radioecological impact of explosions at Novaya Zemlya has been via the lichen–reindeer–human foodchain (Ramzaev *et al.*, 1993). Radionuclide

Table 5.1 Summary of dietary information provided by inhabitants of settlements near the Semipalatinsk site in 1994 (IAEA, 1997).

Location	Source of foodstuff	Foodstuff	Details
Dolon	Home produced	Meat	Beef, mutton, poultry
		Vegetables	Carrots, tomatoes, cabbage, potatoes, cucumbers
		Fruit	Plums, melons
		Milk	Mostly turned into milk products
		Eggs	
	Brought in from elsewhere	Bread	
		Flour	
		Sugar	
		Rice	
		Animal feed	Hay, wheat, barley and millet
Beriozka Farm	Home produced	Meat	
		Milk	No vegetables, no fruit
		Eggs	
	Brought in from elsewhere	Flour	Bread is made at the farm
Akzhar	Home produced	Meat	Beef, mutton, poultry
		Vegetables	Carrots, tomatoes, cabbage, potatoes, cucumbers
		Fruit	Blackcurrants, strawberries
		Milk	Mostly turned into milk products
		Mushrooms	From the woods
	Brought in from elsewhere	Bread	
		Flour	

transfer through this foodchain was approximately 10–100 times more effective than for the grass–cow–human foodchain, and the absorbed doses for radiocaesium and radiostrontium in reindeer were quite close to limits that had been established for persons who worked with radiation. The highest contamination of reindeer occurred in the Kola peninsular (Murmansk Province), some 500–600 km from Novaya Zemlya. Here the transfers appeared to be more efficient than for other areas such as Yakutia.

The critical group for Novaya Zemlya has been established as the aboriginal dwellers of the extreme North who were employed in reindeer breeding operations, herdsmen, reindeer breeders and their family members (Ramzaev *et al.*, 1993). This reflects their consumption of contaminated meat, use of melted snow for drinking and cooking, consumption of freshwater fish, and consumption of partridge meat. The size of the group was estimated at 30 000 persons. A further 300 000 persons (mostly small-city dwellers) also consumed reindeer meat but at much lower rates. Alaskan natives were less at risk due to different practices in herding and the time of slaughtering reindeer.

5.1.4.4 Pacific

The key factor in Pacific tests is whether they occurred over water or land and whether or not the population had been evacuated (Doury, 1996). For the Marshall Islands the main problem was radiocaesium and the terrestrial foodchain (Kirchmann *et al.*, 1993). Assumptions concerning lifestyle proved to be critical in estimating doses due to very specific practices, such as the collection of sap from trees, the drying of fish on roofs, cooking outdoors, and the methods used for collection and storage of water for drinking and washing (Simon, cited by Coughtrey, 1998). Dose estimates proved to be very sensitive to assumptions about the environmental half-life of radiocaesium in contaminated ecosystems.

The behaviour of radiocaesium in tropical ecosystems is very different from that in temperate environments (Kirchmann *et al.*, 1993). This needs to be taken into account when estimating doses and when considering issues such as the migration of radiocaesium to groundwaters.

An IAEA Advisory Group (IAEA, 1998) reviewed the two independent assessments that had been performed to evaluate the potential doses to a population that might live on Bikini Island in the future, and provided the data given in Table 5.2. This serves to demonstrate the great range in food items currently consumed in the region. There is no reason to believe that a similar variety in diet would not have existed at the time of testing of nuclear devices. Table 5.2 emphasizes the importance of breadfruit and coconut in the diet. Coconut appears to have a particularly high uptake of radiocaesium. Little is known of the uptake of radionuclides by many of the listed dietary components.

In 1994, Service Mixte de Surveillance Radiologique et Biologique de l'Homme et de l'Environment (SMSRB) investigated the levels of radioactivity in dietary components of inhabitants of French Polynesia. The study involved 171 samples and a breakdown of the various food types involved is given in Table 5.3 (SMSRB 1994). It emphasizes the diversity in diet of inhabitants of islands.

5.1.4.5 Lob Nor

Very little information has been obtained on the environmental and population characteristics of persons likely to have been affected by explosions at Lob Nor. It can be assumed that, at the time of the explosions, there would have been considerable variability in the environments that were affected and in the living and dietary habits of the affected population.

Liu Ying and Zhu Changshou (1996) commented that potentially critical groups living in the north of China and in Inner Mongolia had not been investigated. Zhu Changshou *et al.* (1996) provided estimates of doses for

Table 5.2 Diet models for adults potentially living on Bikini island (IAEA, 1998).

Food stuff	Local component of an 'imported' foods diet (g day $^{-1}$)	Local foods only diet (g day^{-1})
Reef fish	24.2	86.8
Tuna	13.9	72.0
Mahi mahi	3.56	21.4
Marine crabs	1.68	19.5
Lobster	3.88	35.2
Clams	4.56	58.1
Trochus	0.10	0.24
Tridacna muscle	1.67	11.4
Jedrul	3.08	19.4
Coconut crabs	3.13	24.9
Octopus	4.51	49.0
Turtle	4.34	17.8
Chicken muscle	8.36	31.2
Chicken liver	4.50	17.7
Chicken gizzard	1.66	3.32
Pork muscle	5.67	13.9
Pork liver	2.60	6.70
Pork heart	0.31	0.62
Bird muscle	2.71	26.4
Bird eggs	1.54	22.8
Chicken eggs	7.25	41.2
Turtle eggs	9.36	235
Pandanus fruit	8.66	63.0
Pandanus nuts	0.50	2.00
Breadfruit	27.2	186
Coconut juice	99.1	333
Coconut milk	51.9	122
Drinking coconut meat	31.7	181
Copra meat	12.2	71.3
Sprouting coconut	7.79	122
Marshalese cake	11.7	0
Papaya	6.59	27.0
Pumpkin	1.24	5.44
Banana	0.02	0.58
Arrowroot	3.93	94.9
Citrus	0.10	0.20
Rainwater	313	629
Well water	207	430
Malolo	199	0
Coffee/tea	228	0

Table 5.3 Produce harvested or fished locally or brought in from other islands in French Polynesia (SMSRB, 1994).

Main dietary component	Break down of component
Beverages	Local beer
	Pineapple juice
	Drinking water
	Local milk
Meat	Local goat meat
	Local dog meat
	Local beef
	Local eggs
	Local pork
	Local chicken
Fish	Big eye scad
	Skipjack meat
	Freshwater prawn
	Coral fish
	Yellowfin tuna meat
Sea foods	Clam
	Spiny lobster
	Octopus
	Brisley turban
Leafy vegetable	Cabbage
	Leek
	Lettuce
	Taro leaves
Fruit-type vegetable	Egg plant
	Cucumber
	French beans
	Tomato
	Breadfruit tree fruit
Root vegetables	Carrot
	Manioc
	Turnip
	Sweet potato
	Potato
	Taro roots
	White taro roots
Fruit	Pineapple
	Avocado
	Banana
	Lemon
	Coconut meat
	Mango
	Muskmelon
	Orange and tangerine
	Grape fruit
	Papaya
	Water melon

urban and rural communities and noted higher doses for rural populations compared with urban populations. This effect was attributed to the overall higher dietary intake of rural populations. Regional differences were attributed to differences in the content of cereals in the diet. Hou Jiele *et al.* (1996) noted the occurrence of hot particles at Wulumqi in Xinjiang Province following tests in 1962 and identified a critical group of herdsmen who may have consumed snow meltwater. Liu Ying and Zhu Changshou (1996) noted that milk was not a major dietary component for adults but that the dose to infants was higher than for adults due to intake of ^{131}I with contaminated milk. Zhu Changshou and Liu Ying (1996) noted that the main components of Chinese food are cereals and vegetables but that both milk and fish were significant due to radioecological transfer.

A further and potentially important factor may be dietary intakes of stable iodine. Some of the Chinese Provinces potentially affected by explosions at Lob Nor showed low dietary iodine intakes, in some cases to such an extent that measures were taken for human health purposes (Hou Jiele *et al.*, 1996).

5.1.4.6 Maralinga

Palmer and Brady (1988) provided a very detailed study on the diet and lifestyle of aborigines in the Maralinga area. Cooked meats consumed by aborigines include kangaroo, rabbits, turkey, edible grubs, lizards and goanna. The total bush meat consumed per person per year was approximately 221 kg (605 g day^{-1}). Kangaroo represented the most commonly consumed meat, followed by rabbits and then turkey. Grubs, lizards and goanna were consumed at a much lower rate. All cooked meats were considered to provide a potential for contamination because of preparation on leaves or a piece of cardboard on the ground, the use of earth ovens and the fact that rare meat is moist. Kangaroo was also stored for up to three days in trees during winter prior to consumption.

It was notable that the specific population studied by Palmer and Brady (1988) had not only a very high intake of meat but also of bread and flour. Additionally, relative to the Australian diet in general, the daily intake of eggs was high.

It is clear that the application of average statistics would not account for the likely impacts of past nuclear weapons testing on local aborigine populations that would have been particularly susceptible, both as a consequence of their particular diet and their habits.

5.1.5 CONCLUSIONS

The sites chosen for testing of nuclear devices in the 1950s and 1960s have a number of common factors relevant to pathways for radionuclide transfer.

First they were all in remote locations, i.e. surrounded by large land masses (NTS, Semipalatinsk, Lob Nor, Maralinga), or the sea (Marshall Islands, French Polynesia, Novaya Zemlya). Secondly, because of the location and often hostile environmental conditions, the local populations present at the time of the tests often lived very close to the land, obtaining much of their agricultural produce locally. Water would have been obtained from rainwater (e.g. Marshall Islands), local wells (Semipalatinsk) or melted snow (Novaya Zemlya). In several cases the basic foodstuffs would have represented locally produced meat often raised in semi-natural conditions (e.g. kangaroo at Maralinga, reindeer in areas affected by testing at Novaya Zemlya, and possibly horses at Semipalatinsk), or milk (either the household cow as at NTS or in areas of the Altai affected by testing at Semipalatinsk, or even goats and sheep). Basic diets would have been supplemented by smaller contributions of unusual foodstuffs such as mushrooms (in temperate climates), grubs and lizards (in Australia), and seafood (in island populations).

The environmental conditions associated with the test sites are not, in general, those for which the majority of radioecological information on radionuclide transfer applies. This factor, in conjunction with the specific dietary intakes of the affected populations needs to be taken into account in dose reconstruction studies. Whereas extensive information is available for populations affected by tests at NTS, and some information is available on potential dietary intakes for populations affected by testing in the Pacific, Maralinga and local populations at Semipalatinsk, much less information is available for more distant populations affected by testing at Novaya Zemlya, Semipalatinsk and Lob Nor. Careful consideration of basic radioecological information is required when performing dose reconstructions. The accuracy of such studies would be improved considerably by utilization of site-specific information.

5.2 EXTERNAL EXPOSURE PATHWAYS

5.2.1 Natural radiation sources

5.2.1.1 Cosmic Radiation

Cosmic rays, which originate in space, and solar particles enter the Earth's atmosphere and begin a cascade of secondary interactions and decays. The resultant ionization is a function of both altitude and latitude. The ionizing component of cosmic rays produces, on average, an absorbed dose rate in air of 32 nGy h^{-1} at sea level in the mid-latitudes, corresponding to an effective dose rate of 32 nSv h^{-1}. The neutron component of cosmic rays results in an effective dose rate of 3.6 nSv h^{-1}. The intensities of both components increase with altitude, more so for the neutron component.

Taking into account shielding by buildings for the ionizing component and the distribution of world population with altitude, the population-weighted average annual effective dose from cosmic rays is 380 μSv. The effective dose rate received during a commercial flight is about 3 μSv h^{-1}; the per caput annual effective dose for the world population due to air travel is 2 μSv.

5.2.1.2 Terrestrial Radiation

Exposure to gamma rays from natural radionuclides occurs outdoors and indoors. Surveys by direct measurements of dose rates have been conducted during the last few decades in many countries. National averages range from 24 to 160 nGy h^{-1}

The dose rate in air *outdoors* from terrestrial gamma rays in normal circumstances is around 57 nGy h^{-1}. National averages range from 24 to 160 nGy h^{-1}. Soil and survey data yield similar values. Communities living on mineral sands may well be exposed at two orders of magnitude more.

The gamma-ray dose rate *indoors* is estimated to be 80 nGy h^{-1}, the population-weighted mean of measured values world-wide, and the range of reported national averages is 20–190 nGy h^{-1}. These results are in accordance with values inferred from outdoor measurements and the concentrations of radionuclides in building materials. Applying a coefficient of 0.7 Sv Gy^{-1} to convert absorbed dose rate in air to effective dose and using an indoor occupancy factor of 0.8, the world-wide average annual effective dose from external exposure to terrestrial radionuclides is 0.46 mSv.

In comparing the *indoor* and *outdoor* averages, it is seen that the overall effect of surrounding building materials is to increase the dose rate 40–50%.

The ratio of indoor to outdoor dose rates varies from 0.8 to 2.0. In only two countries, Iceland and the USA, are average absorbed dose rates indoors judged to be less than outdoors. This ratio is sensitive to the structural properties of dwellings (materials, thicknesses and dispositions) and is of limited utility for estimating exposures in particular cases from outdoor data. However, the relatively narrow range of the indoor–outdoor ratio reflects the fact that building materials are usually of local origin and that their radionuclide concentrations are similar to those in local soil. The building materials act as sources of radiation and also as shields against outdoor radiation. In wooden and lightweight houses, the source effect is negligible and the walls are an inefficient shield with respect to the outdoor sources of radiation, so that the absorbed dose rate in air could be expected to be somewhat lower indoors than outdoors. In contrast, in massive houses made of brick, concrete or stone, the gamma rays emitted outdoors are efficiently absorbed by the walls, and the indoor absorbed dose rate depends mainly on the activity concentrations of natural radionuclides in the building materials.

5.2.2 Artificial environmental radiation

5.2.2.1 Deposition

Mechanisms of deposition were discussed in some detail in the UNSCEAR Committee's 1964 report. After entering the troposphere from above, fission products are transported down to the level of the rain-bearing clouds, mainly by turbulent mixing. This downward movement is enhanced over anticyclonic systems and restricted over cyclonic systems. Below this level, the radioactive particles are rapidly washed out by precipitation and deposited upon the surface. In addition, dry removal of fission products takes place through several mechanisms. Dry removal by sedimentation requires particles to be larger than about 5 μm and is important only in local fall-out. Dry deposition of world-wide fallout makes an important contribution to the total fallout only in areas of low rainfall.

Fission products can enter rainwater by processes within the cloud, the so-called rain-out, or can be picked up by raindrops below the cloud, the so-called wash-out. For aerosols of small particle size the wash-out is relatively quite slow so that rain-out is probably the most important wet-deposition process. The small contribution of wash-out processes to total deposition probably accounts for the fact that the activity of fission products in ground-level air does not seem to be greatly influenced by precipitation rates.

5.2.2.2 External irradiation

Several of the artificial radionuclides that are present in fallout emit gamma rays and thereby give rise to an external radiation dose. In addition to various short-lived radionuclides, the most important of which are ^{95}Zr and ^{95}Nb, the main contributor to external gamma radiation is ^{137}Cs, which has a physical half-life of 30 years.

In principle it should be possible to calculate the external doses from the short-lived radionuclides using the deposition data for each radionuclide and appropriate dose-rate conversion factors. For ^{137}Cs the distribution has been assumed to be exponential with a mean depth in the soil of 3 cm. For the short-lived fission products a linear distribution was assumed.

For the short-lived fission products, there is little leaching into the soil before they decay, but for ^{137}Cs, Gale *et al.* (1964) found there was a rapid movement into the soil during the first few years and henceforth the distribution remained fairly static. The amount of penetration depended upon the soil type, but in all cases most of the ^{137}Cs remained in the top 10 cm of soil.

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6 Estimation of Doses

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6.1 INTRODUCTION

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

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

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

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

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

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

6.2 NEVADA TEST SITE (USA)

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

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

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

6.2.1 Status of dose reconstruction

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

The four major dose reconstruction studies are known as:

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

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

6.2.1.1 The ORERP Study of DOE

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

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

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

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

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

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

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

6.2.1.2 The Utah Leukemia Case-control Study

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

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

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

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

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

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

6.2.1.3 The Utah Thyroid Cohort Study

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

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

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

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

6.2.1.4 The NCI Fallout Study

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

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

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

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

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

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

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

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

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

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

6.2.2 Local and regional doses from external irradiation

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

6.2.3 Local and regional doses from internal irradiation

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

6.3 PACIFIC: ENEWETAK AND BIKINI (MARSHALL ISLANDS)

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

6.3.1 Status of dose reconstruction

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

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

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

6.3.1.1 Bikini and Enewetak Atolls

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

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

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

6.3.1.2 Rongelap Island and Utirik Atoll

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

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

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

6.3.1.3 Other Marshall Islands

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

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

6.3.2 Local and regional doses from external irradiation

6.3.2.1 Bikini and Enewetak Atolls

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

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

Assuming that:

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

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

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

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

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

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

6.3.2.2 Rongelap Island and Utirik Atoll

Dose estimates from external irradiation are available for:

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

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

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

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

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

6.3.2.3 Other Marshall Islands

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

6.3.3 Local and regional doses from internal irradiation

6.3.3.1 Bikini and Enewetak Atolls

Dose assessments are available for:

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

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

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

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

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

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

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

6.3.3.2 Rongelap Island and Utirik Atoll

Dose estimates from internal irradiation are available for:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

6.3.3.3 Other Marshall Islands

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

6.4 SEMIPALATINSK (KAZAKHSTAN)

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

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

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

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

6.4.1 Status of dose reconstruction

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

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

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

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

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

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

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

6.4.2 Local and regional doses from external irradiation

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$k^b_i = \frac{a^s_i(d)}{a^\Sigma_i(d)}, \qquad (6.4)$$

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

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

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

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

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

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

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

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

is used for the total of fission products and

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

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

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

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

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

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

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

The moment when fallout ceases is determined by

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

6.4.3 Local and regional doses from internal irradiation

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

6.5 NOVAYA ZEMLYA (RUSSIA)

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

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

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

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

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

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

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

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

6.5.1 Status of dose reconstruction

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

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

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

6.5.2 Local and regional doses from external irradiation

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

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

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

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

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

6.5.3 Local and regional doses from internal irradiation

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

6.6 LOB NOR (CHINA)

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

6.6.1 Status of dose reconstruction

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

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

6.6.2 Local and regional doses from external irradiation

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

6.6.3 Local and regional doses from internal irradiation

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

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

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

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

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

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

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

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

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

6.7 SOUTH PACIFIC: MURUROA AND FANGATAUFA (FRANCE)

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

6.7.1 Status of dose reconstruction

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

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

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

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

6.7.2 Local and regional doses from external irradiation

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

6.7.3 Local and regional doses from internal irradiation

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

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

6.8 EMU, MARALINGA AND MONTEBELLO (AUSTRALIA)

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

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

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

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

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

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

6.8.1 Status of dose reconstruction

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

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

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

6.8.2 Local and regional doses from external irradiation

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

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

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

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

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

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

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

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

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

6.8.3 Local and regional doses from internal irradiation

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

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

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

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

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

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

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

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

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

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

6.10 CONCLUSIONS

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

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

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

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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 ^3H (^3H_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).

	Standardized rate per 10^5 per year (number of cases)			
Age at death	SW Utah	Rest of Utah	Odds ratio	90% confidence interval
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 individials 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

* 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.

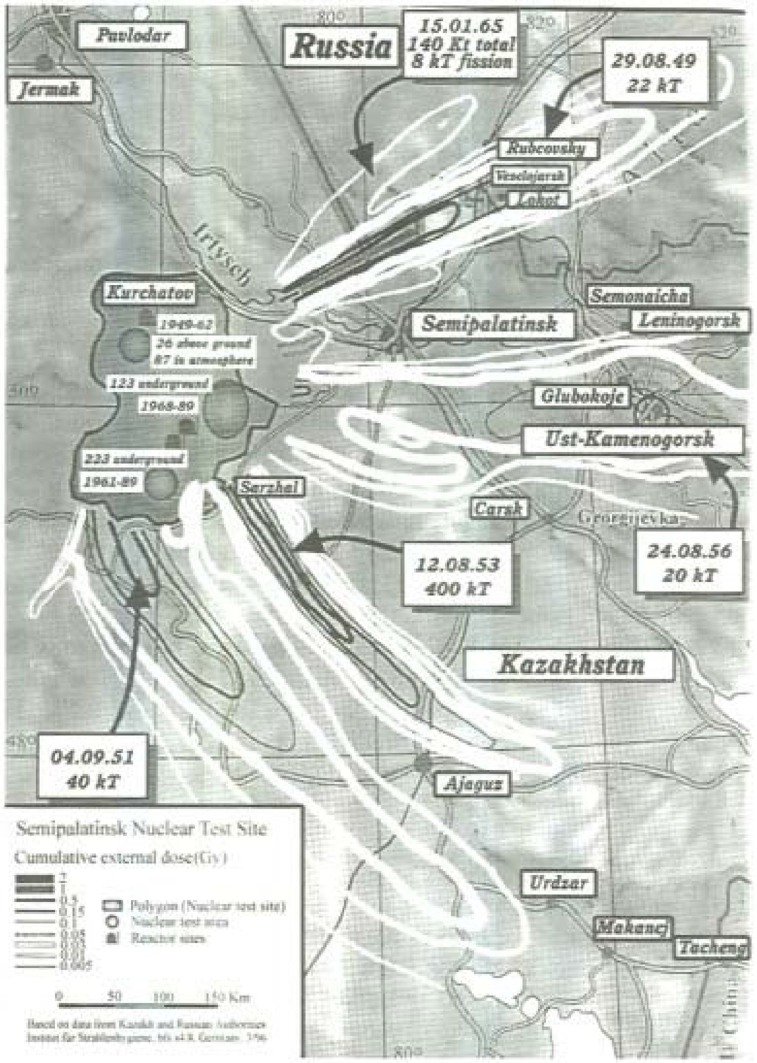

Figure 7.2 Provisional map of fallout trails from atmospheric and ground tests on the Polygon test site near Semipalatinsk. Isodose lines give estimated cumulative unshielded external doses on the ground. Based on data from Kazakhstan and Russian ministries. Boxes give date and bomb yield in kt TNT.

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	10 250	
	Control		10 125	10 000	11 325	11 265	10 950	11 130	11 270	10 950	
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[§].

	Study groups	Year 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 1949	1951	1953	1955	1956	1957	1958	1960	1962	Population (10^3)	Age distribution 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 ≥ 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 ≥ 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,	
	Utah	Geographical		Published	relative increase in leukemia mainly due to low rates in control	
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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8 Fallout Models—Past, Present and Future

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8.1 NUCLEAR TESTS AND THE FIRST FALLOUT MODELS

Most of the energy released by a nuclear explosion is partitioned among blast, thermal radiation, and electromagnetic effects; together they account for all the damage and many of the immediate casualties. Some of the energy associated with these strong effects is involved in the formation and growth of radioactive particles. Although fallout of such particles contributes to immediate casualties, it is also a threat that persists for tens of years. In fact, fallout still continues after the atmospheric tests conducted by the USA, USSR, and UK until 1963, France until 1974 and China until 1980 (De Geer, 1994).

Despite the fact that over time nuclear fallout can cause more casualties than immediate effects, permanently contaminate large areas, and persist for many years, fallout models formulated in the 1960s before the development of modern supercomputers are still in use. As authors of this chapter have shown, such composite models can serve well to assess some past events—as long as the events are reasonably similar to the model's data base and the meteorological conditions are not too different. This is not possible in all cases; as often as not, weapon and weather conditions fall outside the empirical data range. There are two critical limitations: the first involves particle growth in nuclear fireballs; the second, nuclear cloud dynamics and the interaction with actual weather systems.

Aerosol dynamics are traditionally the weak point in weapon environment codes. Emphasis (and millions of dollars) on fireball and transport hydrodynamics has led to increasingly sophisticated analyses and codes. Weapon regime aerosol research, though, has lagged. At present, none of the current models robustly predict radioactive particle size distributions, accurately partition the radioactivity, or even reasonably account for processes controlling the formation of particles.

Most aerosol subroutines or deposition codes borrow heavily from conventional microphysics technology, which works fine (most of the time) for ambient environments and natural processes. From the nuclear aerosol

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perspective, however, there are critical limitations: nuclear aerosols are likely to pass through widely varying thermodynamic regimes outside normal aerosol environments; and, nuclear aerosols are multispecies with morphologies and properties unlike normal atmospheric aerosols. Each compromise—especially in high-energy weapon environments—profoundly reduces solution fidelity. Recent developments in microphysics, plume, cloud and weather codes have yet to be applied to nuclear fallout. Except in a few select cases, approximations that were acceptable for assessing fallout from hundreds or thousands of weapons in a general exchange, fail when precision is needed.

In the 1950s several modellers noted that fallout depends directly on the particle size distribution of radioactive particles, which in turn depends on the size distribution of non-radioactive particles as well as vapours of the bomb casing, entrained dust, and water (Stewart, 1956; Adams *et al.*, 1960). Although the microphysics processes accounting for particle formation and growth were recognized, the high-resolution solutions for nuclear cloud sweep-up (dust) concentrations, size distributions as well as temperature, velocity and turbulence fields required to complete a first principle model were beyond computer capabilities at that time; they have become available only in the last few years.

The technical problem is easily summarized: N(100) kt of dust from several kilometres around the burst are drawn into a nuclear fireball that radiates N(10)–N(100) kt of thermal energy; added to that mix is N(10) kt of water, and N(0.1) kt of smoke. Each of these materials has special properties that influence the growth of radioactive particles and the subsequent fallout cloud dynamics.

In the mix of hundreds of kilotons of material added to the nuclear fireball, the weapon adds roughly 100 kg of radioactive material. The first task of a fallout model is to determine how it forms, attaches, grows through diffusion processes and coagulates with other particles. The partition of radiation both to large and submicron particles and the interactions with smoke, dust, and water in the nuclear cloud determines immediate, intermediate- and long-term fallout dose. No model does this at present.

Nuclear clouds are embedded in natural weather systems and deposition is either by settling of radioactive particles or episodic deposition by rain. Weather controls deposition, but there is an important connection or feedback with the nuclear aerosol. The special physical and chemical properties of the nuclear cloud determine the partition between interstitial dry particles and those captured by water. Both influence deposition and most importantly the timing of rain formation. A little earlier and some areas are spared fallout, while other areas are heavily dosed. The degree that a nuclear aerosol influences deposition depends on the type of weather system it is embedded in; impacts for deep and shallow convective systems, occult deposition, urban area clouds, and dry settling are different.

Smoke adds a large number of submicron particles that are (mostly) nucleation centres for water (Pittock *et al.*, 1989). Should those particles dominate, a nuclear fog could form thus delaying the formation of large particles (that fallout rapidly). Dust is just the opposite, creating large particles that fallout rapidly leading to heavily dosed regions. At the other end of the spectrum, high burst heights entrain little if any material into the nuclear cloud; and submicron radioactive particles form that settle very slowly, reaching the ground months or years later.

Model builders used nuclear test data from atmospheric test programmes conducted on three continents in the 1960s to construct empiricisms that prescribe the size distribution of radioactive particles. This approach compensated for limited computer power and the corresponding poor resolution of fireball hydrodynamics solutions. Several approximate models were developed (Pittock *et al.*, 1989). The advantage here is that real data are used in assessments; the glaring disadvantage is that it is very risky to extrapolate the empiricisms to other yields, soil conditions, urban targets, and meteorologies.

One to two orders of magnitude difference in fallout occurs depending on whether the particle size distribution (PSD) is given by commonly used log-normal, r^{-3} or r^{-4} distributions. In fact, new microphysics models (Small *et al.*, 1994), now show that there may not be a natural distribution that fits all burst conditions and yields. Nevertheless, as long as weather conditions are similar and target conditions match those in Nevada, Semipalatinsk, Novaya Zemlya and the Pacific, the 1960's generation of models provides reasonable fallout assessments. The next generation models promise a family of far more versatile models.

8.2 CREATION OF RADIOACTIVE PARTICLES

Both immediate and long-term fallout depend initially on molecular and submicron scale interactions. There are other factors, such as height of burst, yield, bomb construction and the mass entrained, that matter a great deal, but the important fallout physics occurs at a microscale. The fast formation of large particles or condensation of bomb vapours on large entrained particles account for immediate effects and fallout patterns around and downwind of targets. The very small particles—those $< 1\ \mu m$—can account for one-half or more of the radioactivity and are responsible for fallout long after the burst. Such particles, initially lofted to high altitudes, are the continuing global legacy of atmospheric bursts (De Geer, 1994). Moreover, it is the very small (submicron) particles that most readily percolate, via many pathways, through the environment, with a pervasive impact on human health and ecological systems (Warner and Harrison, 1993).

The energy balances associated with particle evolution are complex and act through telescoping scales. The balance of heat and work in the expanding fireball regulates the formation and growth of particles. Part of the fireball thermal radiation vaporizes dust lifted off the ground by mechanical (blast) forces and entrained into the rising fireball by winds generated by the decaying buoyancy. The vaporized dust is a source of potential energy that is only released as the vapour nucleates and grows by condensation. From several kilometres around the burst, as much as 10^9 to 10^{11} g of dust are drawn into the fireball; and over tens of seconds, 10^{12} to 10^{14} calories are radiated from the rising cloud. The evolution of particles at molecular and micron scales is shaped by balances of kilotons of energy and mass. Fallout over continents depends on the evolution of submicron particles. The physics is entwined in many scales and the details are important.

The early nuclear cloud models crudely approximated the formation of particles. The PSDs are based on sweep-up formulations and modified at coarse resolution either by simplistic microphysics formulations that omit major particle interactions or by empiricisms borrowed from natural cloud models. Neither approach faithfully accounts for all the interactions responsible for particle growth in nuclear clouds. Furthermore, particles smaller than 1 μm are usually neglected entirely. This is a critical flaw; such particles play a major role in the formation of radioactive particles. The consequence of approximating the microphysics is extreme uncertainty in the calculated PSD and, by extension, low confidence in fallout predictions or assessment of radioactive clouds.

Particle formation in nuclear clouds takes place in a fast thermodynamic environment. Not only do particles evolve in the rapidly cooling fireball, but they also quickly grow during the very fast rise to high stabilization altitudes. There are many paths: some particles form in the early seconds as the fireball plasma cools and the gas converts initially to molecular clusters and finally after successive waves of condensation to multicomponent solids; other particles grow by condensation on nuclei entrained by the rising cloud and by coagulation. Because of the large thermodynamic gradients any process can be reversed. Particles grown in one area of the cloud can be evaporated or 'broken' apart in high-temperature regions. Moreover, soil, smoke, or organic particles entrained by the cloud ablate when suddenly fluxed into the vortex core. Such processes continue for tens of seconds after the burst.

The microphysics is greatly influenced by the amount of entrained (swept-up) material. A number of factors determine how much material is added, but it mostly depends on the height of burst. Close to the ground, mass equal to one-third of the weapon yield is brought into the cloud; for burst heights greater than 120 m/kt$^{-1/3}$ only the bomb debris contributes to the microphysics.

The rising fireball also entrains low-level humid air and the water vapour condenses and freezes in a highly surpersaturated environment during the fast rise to high altitude. Stabilization in the stratosphere is not unusual. The nuclear cloud water microphysics may differ considerably from natural cloud processes. The rise is at much higher velocity, leading to greater supersaturation and a much altered balance of nucleation, condensation, and coagulation.

Moreover, the very high particle concentrations established by incipient particle formation, smoke particles added by immediate nuclear fires and the fireball processing of entrained dust provide an excess of condensation sites for the available moisture. In such conditions it is unlikely that normal cloud parameterizations apply.

More than one material is involved in nuclear cloud calculations: the radioactive bomb debris (which decays with time), entrained materials such as SiO_2, Al_2O_3, smoke, organic ground litter, and water. Particles may be either pure or mixed with varying fractions of the primary materials. Of special concern is the very small mass $N(10^5$ g) of radioactive material (plus neutron activated material) in a cloud with $N(10^{11}$ g) of dust and other materials. The radioactive mass is negligible compared with the entrained mass, but for fallout it is the meaningful quantity. Moreover, the radioactive material which is transformed from a plasma to a frozen solid can serve as nuclei for other condensing vapours, can itself condense on other particles, or can remain as a pure radionuclide.

There are several processes peculiar to nuclear cloud microphysics calculations. Radioactive decay produces high-energy electrons and concentrations of ion pairs; they rapidly recombine but nevertheless can accelerate nucleation, condensation, coagulation and even the breakup of large agglomerates. Turbulence forced by large shear and large temperature gradients increases coagulation rates and mixes the small amount of radioactive material throughout the cloud. Because of the very large temperature gradients, thermophoresis is important near the vortex core. Despite the fact that these and other effects may occur only for a short time and possibly only in a small area of the fireball, they may be important in determining the formation and growth of particles and the partition of radioactivity across the size distribution.

New models, enabled by the massive increase in computing power, couple high-resolution hydrodynamic solutions of the nuclear fireball with solutions of the microphysics general dynamic equation (GDE) for multispecies aerosols (Small *et al.*, 1994). The new hydrocode capabilities provide the detailed thermodynamic (pressure and temperature) and velocity–turbulence maps needed to 'drive' a microphysics calculation of radioactive particle formation and growth. Such calculations accounting for the first 10–60 s following a burst require several hours of CRAY simulation time.

Solution of the GDE describes the change in concentration of particles (n) of species κ by the fundamental microphysics processes of nucleation, coagulation, and condensation (evaporation), ablation and breakup:

$$\frac{\partial}{\partial t}n^{\kappa}(v,t) = \sum_{\lambda}\left\{\frac{1}{2}\int_0^v E_{\kappa,\lambda}(\xi, v-\xi)n^{\kappa}(\xi,t)n^{\lambda}(v-\xi,t)d\xi - n^{\kappa}(v,t)\int_0^{\infty}E_{\kappa,\lambda}(\xi,v)n^{\lambda}(\xi,t)d\xi\right\}$$

$$-\frac{\partial}{\partial t}(n^{\kappa}(v,t)g(v,t)) + S^{\kappa}(v,t) - n^{\kappa}(v,t)R(v,t)$$

The integrals in the GDE represent the formation of particles of volume v by collision of small particles and depletion in this size class by collision of particles of volume v with any other particle. E_κ is a collection kernel that prescribes collision rates for different forcings. The rates relate either to velocity differences caused by shear, turbulence, Brownian motion, or different settling velocities, or to phoretic forces due to gradients in temperature, concentration, or charge.

The third term accounts for growth by condensation. $g(v, t)$ distinguishes evaporation and ablation, because solid particles suddenly immersed in a high-temperature environment lose mass (independent of the difference in vapour pressures). The last two terms are source and loss terms. Sources include nucleation of particles from supersaturated vapour, evaporation of component(s) from mixed particles leaving a pure particle, and breakup of very large particles by aerodynamic or electric forces. Losses can occur as a result of condensation of vapour on pure particles, coagulation of different species particles, and complete evaporation of particles.

The GDE regulates the competition for vapour and balances the competing microphysics processes such as nucleation, ablation, condensation, evaporation, coagulation and breakup; it is solved in particle radius space and thus seamlessly melds with driver models providing the fireball–cloud thermodynamic field. The GDE balances all the effects together, thereby apportioning pure and mixed particles the correct growth. Solutions specify particle concentration $n^\kappa(v, t)$ for each species (κ) tracked from the nuclear plasma to definition of respirable and deposited radioactive products. The formulation is nonlinear, underscoring that approximations based on a simple superposition of effects are bound to be incorrect.

The next generation of fallout models combining high-resolution fireball–nuclear cloud solutions with interactive solution of the microphysics GDE and advanced cloud transport models will provide superior assessments of nuclear events and impacts on environment and humans.

8.3 WEATHER AND FALLOUT

In the troposphere, weather determines the fate of the radioactive particles or nuclear aerosol. Winds and thermals advect, moisture scavenges and precipitation rains or washes aerosols (fallout) from the atmosphere. The influence is not entirely one way, however; aerosols control cloud formation and thus influence the radiation budget, which in part drives the weather, and most importantly when, where and how much precipitation occurs. The feedback is important and underscores the interactive nature of fallout physics. The interaction of nuclear aerosols and weather is especially important because departure from 'normal' aerosol properties means that rainout and washout patterns are significantly changed. Here, the influence of smoke, dust, and entrained water play a critical role.

The path is direct. Particle morphology, concentration and most importantly chemical properties determine the probability of nucleating water. Multispecies (nuclear aerosol, dust, water, salt, pollutants) microphysics processes are highly competitive, with the largest soluble particles capturing the available moisture and other particles remaining dry in interstitial air. Compared with particles nucleating water, dry particles have very low washout rates. If the nuclear particle is soluble, fallout can be high.

This simple physics accounted for the highly non-uniform deposition pattern of Chernobyl fallout (Warner and Harrison, 1993). Shallow short-lived convective systems deposited much of the $^{137}Cs/^{134}Cs$ in small areas of Sweden, Wales, and Belarus (fallout near Gomel was 1500 Bq m^{-2}). Although the updraft–precipitation pattern was effective in rainout and washout of Cs, much of the interstitial radionuclide aerosol was vented through the top of the system. Other hot spots near hill tops resulted from increased deposition of soluble radionuclides in feeder–seeder cloud systems formed by orographic enhancement. Fallout of the dry components was hemispheric, but low dose and innocuous (although unneeded).

Fallout models currently approximate the aerosol–weather interaction using conventional cloud microphysics. Although such approaches can estimate particle growth, which influences settling speed, they are poor predictors of episodic rain or scavenging—both of which are important for accurate fallout assessments.

There are many advantages to using implicit engineering formulations (such as those based on Kessler (1969) type bulk parameterizations or (more recently) on semispectral Berry–Reinhardt parameterizations (Chaumerliac and Rossett, 1989)). They are keyed to easily calculated bulk measures of the aerosol; they execute rapidly, require little storage and generally are simple to apply. The detail is often impressive, with some versions determining 21 types or forms of particles all based on a few 'bulk' parameters.

The only difficulty is that most of the time, the prescriptions are of questionable accuracy. They can be correct in some cases, especially if the embedding weather duplicates the average conditions the empiricism was built for; generally they are not. Comparisons at different times and by different groups have shown that deviations from actual conditions can be quite large (Soong, 1974; Shiino, 1983; Lee and Hong, 1987; Kogan, 1991). This is not surprising because average weather conditions are usually a poor assumption—poor for cloud prediction over a target, and likewise poor for prediction of winds and rain in specific (battlefield, target, or vacation) areas.

Similarly, bulk microphysics formulations based on *average aerosols* (despite impressive pedigree) poorly approximate particle growth in 'non-average' clouds, cloud development over urban areas, dry deposition, rainout, washout, occult deposition, not to mention chemical changes caused by particle ageing and solubility. The latter is especially relevant as it controls an important pathway for agent integration in terrestrial and aquatic systems and thus influences lethal dose and persistence (Warner and Harrison, 1993).

Nuclear aerosols as a class impose additional constraints on using 'regular' microphysics approximations, because wartime aerosols are not regular atmospheric aerosols. They have different concentrations, morphologies, properties, and behave differently in the atmosphere.

Particle concentration along with the size distribution is a key parameter in all implicit systems. Rate processes such as growth by condensation and coagulation are prescribed as long as concentrations and distributions reasonably represent the empiricism. Greater concentrations that may lead to fog or marine layers rather than accelerated growth of cloud particles (not all clouds rain) generally are not well modelled. Similarly, engineering approximations rarely if at all recognize different balances caused by rapid changes in supersaturation (characteristic of high-energy nuclear clouds). Small *et al.* (1994) showed that such rapid changes in nuclear aerosols lead to episodic nucleation, formation of submicron particles, and eventually multimode size distributions. Departure from average conditions may imply a considerable uncertainty in the eventual size distribution and ultimate rainout, washout, or dry deposition—or simply put, uncertainty in the fallout. Moreover, such uncertainties carry forward and, for example, influence estimates of toxic resuspension.

Particle morphology is an important topic that remains to be included in fallout models. Departures from spherical geometry lead to different growth rates for condensation or evaporation (saturation vapour pressures are lower) and for coagulation (cross-sections and aerodynamic properties change). Both processes control particle development and thus fallout velocity; coagulation influences in-cloud growth as well as capture by raindrops or washout. Uncertainty in those quantities translates directly to uncertainty in the location and intensity (dose) of fallout. Moreover, uncertainty in chemical and physical agent properties impacts calculation of infiltration and migration through pervious surfaces and consequently ecological impacts and decontamination requirements. Growth rates for non-ideal particles is a current area of emphasis in the aerosol community, and extensions of classical microphysics theory could be developed for non-spherical geometries.

Chemical and photic ageing are suitable for treatment in explicit first principle models because changes generally occur in one species and the dynamics of multispecies interactions are changed. Treatments that prescribe process rates for nucleation, condensation/evaporation, and coagulation based on bulk parameters, such as concentration and saturation ratios, have difficulty modifying those rates to reflect chemical or photic change in surface properties. In such cases, accuracy and fidelity depend not only on the microphysics empiricism (and predicting whether the aerosol is shielded by clouds, exposed to sunlight, etc.), but also on whether the appropriate physics is even included.

Similar issues apply to chemical processes, such as surface ageing that changes particles' affinity to water (hydrophobic to hydrophilic), phase changes for elements such as ^{131}I (three forms are possible—gaseous, particulate and methyl), exchangeable form and solubility of elements such as ^{137}Cs and ^{90}Sr.

An immediate jump in capability can be implemented for nuclear aerosols by including new explicit, multispecies, microphysics capabilities with current weather (stochastic or deterministic) algorithms. Uncertainties of using 'normal' aerosol approximations for nuclear aerosols will be eliminated. Moreover, explicit calculation of nuclear size distribution, properties, and changes by chemical, photic and microphysics processes ties in with and provides all the right information for human and ecosystem impact models.

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Appendix: Types and List of Tests

INTRODUCTION

This appendix lists tests which have been carried out by the major weapons testing nations, China, France, UK, USA and USSR that have led to releases of radioactivity. In addition to these the first test undertaken by India, in 1974, was an underground test causing no release. Although India recommenced nuclear testing in May 1998, conducting a total of five further tests (comprising three on Monday, 11 May and a further two tests on Wednesday, 13 May), they have not been reported to have caused any release to the atmosphere. These underground explosions occurred at the Pokhran nuclear test ground, located in the northwestern state of Rajasthan. A review of these tests appeared recently in *Nature* (Jayaraman, 1998). Subsequently, on 28 May 1998, Pakistan undertook its first nuclear weapons test, exploding five devices in the Chagai region of their southwestern Baluchistan Province. A sixth device was detonated two days later.

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Table A1 Nuclear tests by China.

Date	Time UTC	Name	Type	Place	Energy (kt) Fission	Total	Altitude (m)	Tropopause (hm)	Cloud Head (hm) Base	Top
16/10/64	07:00	1	Tower		20	20				
14/05/65	02:00	2	Air drop		40	20–40				
09/05/66	08:00	3	Air drop		300	200–500				
27/10/66		4	Missile		20	10–30				
28/12/66		5	Tower		300	200–500				
17/06/67	19:08	6	Air drop		1700	3000				
24/12/67		7	Air drop		20	10–25				
27/12/67	07:30	8	Air drop		1200	3000				
29/09/69	08:40	10	Air drop		2000	3000				
14/10/70	07:30	11	Air drop		2000	3000				
18/11/71	06:00	12	Tower		20	20				
07/01/72	07:00	13	Air explosion		20	< 20				
18/03/72	06:00	14	Air explosion		100	20–200				
27/06/73	04:00	15	Air explosion		1600	2000–3000				
17/06/74	06:00	16			600	200–1000				
23/01/76	06:00	18			20	< 20				
26/09/76	06:00	19	Air explosion		100	20–200				
17/11/76	06:00	21	Air explosion		2250	4000				
17/09/77	07:00	22	Air drop		20	< 20				
15/03/78	04:00	23	Air explosion		20	< 20				
14/12/78		25			20					
16/10/80	04:30	26			450	200–1000				
		$\sum$ 22								

Table A2 Nuclear tests by France.

Date	Time UTC	Name	Type	Place	Energy (kt)		Altitude (m)	Tropopause (hm)	Cloud Head (hm)	
					Fission	Total			Base	Top
13/02/60		Gerboise bleue	Tower	Reggane	67	67	100	154	110	150
01/04/60		Gerboise blanche	Surface	Reggane	3	3	0	–	30	50
27/12/60		Gerboise rouge	Tower	Reggane	2	2	50	–	25	40
25/04/61		Gerboise verte	Tower	Reggane	0.7	0.7	50	–	20	30
02/07/66	15:34	Aldébaran	Barge	Mururoa	28	28	0	141	65	95
19/07/66	15:05	Tamouré	Air	Mururoa	50	50	1000	156 101	110	150
21/07/66	12:00	Ganymède	Safety	Mururoa	0	0	12	155	–	–
11/09/66	17:30	Betelgeuse	Balloon	Mururoa	110	110	470	148	100	180
24/09/66	17:00	Rigel	Barge	Fangataufa	125	125	3	127	70	130
04/10/66	21:00	Sirius	Barge	Mururoa	205	205	10	128	120	180
05/06/67	19:00	Altair	Balloon	Mururoa	15	15	295	159	65	110
27/06/67	18:30	Antares	Balloon	Mururoa	120	120	340	123	105	180
27/06/67	17:30	Arcturus	Barge	Mururoa	22	22	0	156	50	95
07/07/68	22:00	Capella	Balloon	Mururoa	115	115	463	127	110	175
15/07/68	18:00	Castor	Balloon	Mururoa	450	450	650	163	145	215
03/08/68	21:00	Pollux	Balloon	Mururoa	150	150	490	124 166	105	185
24/08/68	18:30	Canopus	Balloon	Fangataufa	–	2600	520	96 164	140	240
08/09/68	19:00	Procyon	Balloon	Mururoa	–	1280	700	123 154 123	155	240
15/05/70	18:00	Andromède	Balloon	Mururoa	13	13	220	147	75	110
22/05/70	18:30	Cassiopée	Balloon	Mururoa	–	224	500	131	115	175
30/05/70	18:00	Dragon	Balloon	Fangataufa	–	945	500	126	150	210
24/06/70	18:30	Eridan	Balloon	Mururoa	12	12	220	142	85	120

continues overleaf

Table A2 *continued.*

Date	Time UTC	Name	Type	Place	Energy (kt)		Altitude (m)	Tropopause (hm)	Cloud Head (hm)	
					Fission	Total			Base	Top
03/07/70	18:30	Licorne	Balloon	Mururoa	–	914	500	106	150	240
27/07/70	19:00	Pégase	Balloon	Mururoa	0.05	0.05	220	165	20	20
02/08/70	19:00	Orion	Balloon	Fangataufa	–	72	400	154	105	165
06/08/70	19:00	Toucan	Balloon	Mururoa	–	594	500	149	140	190
05/06/71	19:15	Dione	Balloon	Mururoa	34	34	275	129	120	140
12/06/71	19:15	Encelade	Balloon	Mururoa		450		175	55	170
					–			110		
04/07/71	21:30	Japet	Balloon	Mururoa	9	9	230	141	55	90
08/08/71	18:30	Phoebe	Balloon	Mururoa	4	4	230	135	–	50
14/08/71	19:00	Rhéa	Balloon	Mururoa	–	955	480	–	155	200
25/06/72	19:00	Umbriel	Balloon	Mururoa	0.5	0.5	230	123	–	25
30/06/72	18:30	Titiana	Balloon	Mururoa	4	4	220	167	27	60
27/07/72	18:40	Obéron	Balloon	Mururoa	6	6	220	166	65	85
31/07/72	22:30	Ariel	Tower (safety)	Mururoa	0.001	0.001	10	158	10	16
21/07/73	18:00	Euterpe	Balloon	Mururoa	11	11	220	150	64	95
28/07/73		Melpomène	Balloon	Mururoa	0.05	0.05	270	147	18	23
								108		
18/08/73	18:15	Pallas	Balloon	Mururoa	4	4	270	150	18	55
24/08/73	18:00	Parthenope	Balloon	Mururoa	0.2	0.2	220	152	14	25
28/08/73	18:30	Tamara	Air	Mururoa	6	6	–	153	45	75
13/09/73	15:42	Vesta	Tower (safety)	Mururoa	0	0	4	143	–	5
16/06/74	17:30	Capricorne	Balloon	Mururoa	4	4	220	120	41	69
01/07/74	17:30	Bélier	Tower (safety)	Mururoa	0	0	5.6	152	1.8	3.1
07/07/74	23:15	Gémeaux	Balloon	Mururoa	–	150	312	155	120	185
17/07/74	17:00	Centaure	Balloon	Mururoa	4	4	270	–	–	–
25/07/74	17:30	Maquis	Air	Mururoa	8	8	250	–	–	–
28/07/74		Persée	Tower (safety)	Mururoa	0.001	0.001	5.6	–	–	–
14/08/74	00:30	Scorpion	Balloon	Mururoa	–	96	312	–	–	–
24/08/74	23:45	Taureau	Balloon	Mururoa	14	14	270	–	–	–
14/09/74	23:30	Verseau	Balloon	Mururoa	–	332	433	–	–	–

Table A3 Nuclear tests by UK*.

Date[†]	Time UTC	Name	Type	Place	Energy (kt) Fission	Energy (kt) Total	Altitude (m)	Tropopause (hm)	Cloud Head (hm) Base	Cloud Head (hm) Top
03/10/52		Hurricane	Ocean surface burst	Off Trimouille Island, Monte Bello Islands, Western Australia		25	-3		Indistinct	30.48
14/10/53		Totem 1	Tower mounted	Emu Field, South Australia		10	31		24.38	42.67
26/10/53		Totem 2	Tower mounted	Emu Field, South Australia		8	31		30.48	70.10
16/05/56		Mosaic 1	Tower mounted	Trimouille Island, Monte Bello Islands, Western Australia		15	31		45.72	67.06
19/06/56		Mosaic 2	Tower mounted	Alpha Island, Monte Bello Islands, Western Australia		60	31		67.06	109.73
27/09/56		Buffalo 1	Tower mounted	One Tree, Maralinga Range, South Australia		15	31		79.25	100.58
04/10/56		Buffalo 2	Ground surface burst	Marcoo, Maralinga Range, South Australia		1.5	0		18.29–22.86	27.43–36.58
11/10/56		Buffalo 3	Air dropped—air burst over land	Kite, Maralinga Range, South Australia		3	150		–	–
21/10/57		Buffalo 4	Tower mounted	Breakaway, Maralinga Range, South Australia		10	31		82.30	115.82
		Grapple:								
15/05/57		Short Granite	Air dropped–air burst over ocean	Off Malden Island, Pacific Ocean		300[‡]	2200			
31/05/57		Orange Herald	Air dropped—air burst over ocean	Off Malden Island, Pacific Ocean		720[‡]	2400			
19/06/57		Purple Granite	Air dropped—air burst over ocean	Off Malden Island, Pacific Ocean		200[‡]	2400			
14/09/57		Antler 1	Tower mounted	Tadje, Maralinga Range, South Australia		1	31		19.81	35.05

continues overleaf

Table A3 *continued.*

Date[†]	Time UTC	Name	Type	Place	Energy (kt) Fission	Energy (kt) Total	Altitude (m)	Tropopause (hm)	Cloud Head (hm) Base	Cloud Head (hm) Top
25/09/57		Antler 2	Tower mounted	Biak, Maralinga Range, South Australia		6	31		54.86	73.15
09/10/57		Antler 33	Balloon suspended—air burst over land	Taranaki, Maralinga Range, South Australia		25	300		48.77	853.44
08/11/57		Grapple X	Air dropped—air burst over ocean	Off Christmas Island, Pacific Ocean		1800[‡]	2200			
28/04/58		Grapple Y	Air dropped—air burst over ocean	Off Christmas Island, Pacific Ocean		3000[‡]	2500			
		Grapple Z:								
22/08/58		Pennant	Balloon suspended—air burst over land	Christmas Island, Pacific Ocean[§]		24[‡]	450			
02/09/58		Flagpole	Air dropped—air burst over ocean	Off Christmas Island, Pacific Ocean		1000[‡]	2800			
11/09/58		Halliard	Air dropped—air burst over ocean	Off Christmas Island, Pacific Ocean		800[‡]	2600			
23/09/58		Burgee	Balloon suspended—air burst over land	Christmas Island, Pacific Ocean[§]		25[‡]	450			

* Tests joint with USA listed Table A4.

[†] Dates according to Greenwich Mean Time.

[‡] Ministry of Defence best estimates of the yields of the Christmas and Malden Island tests made available October 1993 together with revisions to heights of explosions.

[§] Over the southeast peninsula of the island.

Table A4 Nuclear tests by USA.

Date	Time UTC	Name	Type	Place*	Energy (kt) Fission	Energy (kt) Total	Altitude (m)	Tropopause (hm)	Cloud Head (hm) Base	Cloud Head (hm) Top
16/07/45		Trinity	Tower	Alamogordo, New Mexico		21				
30/06/46		Able	Airdrop	Bikini		21				
24/07/46		Baker	Underwater	Bikini		21				
14/04/48		X-ray	Tower	Enewetak		37				
30/04/48		Yoke	Tower	Enewetak		49				
14/05/48		Zebra	Tower	Enewetak		18				
27/01/51		Able	Airdrop	NTS		1				
28/01/51		Baker	Airdrop	NTS		8				
01/02/51		Easy	Airdrop	NTS		1				
02/02/51		Baker-2	Airdrop	NTS		8				
06/02/51		Fox	Airdrop	NTS		22				
07/04/51		Dog	Tower	Enewetak		81				
20/04/51		Easy	Tower	Enewetak		47				
08/05/51		George	Tower	Enewetak		225				
24/05/51		Item	Tower	Enewetak		45.5				
22/10/51		Able	Tower	NTS		< 0.1				
28/10/51		Baker	Airdrop	NTS		3.5				
30/10/51		Charlie	Airdrop	NTS		14				
01/11/51		Dog	Airdrop	NTS		21				
05/11/51		Easy	Airdrop	NTS		31				
19/11/51		Sugar	Surface	NTS		1.2				
29/11/51		Uncle	Crater	NTS		1.2				
01/04/52		Able	Airdrop	NTS		1				
15/04/52		Baker	Airdrop	NTS		1				
22/04/52		Charlie	Airdrop	NTS		31				
01/05/52		Dog	Airdrop	NTS		19				
07/05/52		Easy	Tower	NTS		12				
25/05/52		Fox	Tower	NTS		11				
06/01/52		George	Tower	NTS		15				
05/06/52		How	Tower	NTS		14				

continues overleaf

Table A4 *continued.*

Date	Time UTC	Name	Type	Place*	Energy (kt)		Altitude (m)	Tropopause (hm)	Cloud Head (hm)	
					Fission	Total			Base	Top
31/10/52		Mike	Surface	Enewetak		10 400				
15/11/52		King	Airdrop	Enewetak		500				
17/03/53		Annie	Tower	NTS		16				
24/03/53		Nancy	Tower	NTS		24				
31/03/53		Ruth	Tower	NTS		0.2				
06/04/53		Dixie	Airdrop	NTS		11				
11/04/53		Ray	Tower	NTS		0.2				
18/04/53		Badger	Tower	NTS		23				
25/04/53		Simon	Tower	NTS		43				
08/05/53		Encore	Airdrop	NTS		27				
19/05/53		Harry	Tower	NTS		32				
25/05/53		Grable	Airburst	NTS		15				
04/06/53		Climax	Airdrop	NTS		61				
28/02/54		Bravo	Surface	Bikini		15 000				
26/03/54		Romeo	Barge	Bikini		11 000				
06/04/54		Koon	Surface	Bikini		110				
25/04/54		Union	Barge	Bikini		6900				
04/05/54		Yankee	Barge	Bikini		13 500				
13/05/54		Nectar	Barge	Enewetak		1690				
18/02/55		Wasp	Airdrop	NTS		1				
22/02/55		Moth	Tower	NTS		2				
01/03/55		Tesla	Tower	NTS		7				
07/03/55		Turk	Tower	NTS		43				
12/03/55		Hornet	Tower	NTS		4				
22/03/55		Bee	Tower	NTS		8				
23/03/55		Ess	Crater	NTS		1				
29/03/55		Apple 1	Tower	NTS		14				
29/03/55		Wasp Prime	Airdrop	NTS		3				
06/04/55		High Altitude	Airdrop	NTS		3				
09/04/55		Post	Tower	NTS		2				
15/04/55		Met	Tower	NTS		22				

05/05/55	Apple 2	Tower	NTS	29
15/05/55	Zucchini	Tower	NTS	28
14/05/55	Wigwam	Underwater	Pacific	30
01/11/55	Project 56 No.1	Surface	NTS	0
03/11/55	Project 56 No. 2	Surface	NTS	0
05/11/55	Project 56 No. 3	Surface	NTS	No yield
18/01/56	Project 56 No. 4	Surface	NTS	Very slight
04/05/56	Lacrosse	Surface	Enewetak	40
20/05/56	Cherokee	Airdrop	Bikini	3800
27/05/56	Zuni	Surface	Bikini	3500
27/05/56	Yuma	Tower	Enewetak	0.19
30/05/56	Erie	Tower	Enewetak	14.9
06/06/56	Seminole	Surface	Enewetak	13.7
11/06/56	Flathead	Barge	Bikini	365
11/06/56	Blackfoot	Tower	Enewetak	8
13/06/56	Kickapoo	Tower	Enewetak	1.49
16/06/56	Osage	Airdrop	Enewetak	1.7
21/06/56	Inca	Tower	Enewetak	15.2
25/06/56	Dakota	Barge	Bikini	1100
02/07/57	Mohawk	Tower	Enewetak	360
08/07/56	Apache	Barge	Enewetak	1850
10/07/56	Navajo	Barge	Bikini	4500
20/07/56	Tewa	Barge	Bikini	5000
21/07/56	Huron	Barge	Enewetak	250
24/04/57	Project 57 No. 1	Surface	NAFR	0
28/05/57	Boltzmann	Tower	NTS	12
02/06/57	Franklin	Tower	NTS	0.14
05/06/57	Lassen	Balloon	NTS	0.0005
18/06/57	Wilson	Balloon	NTS	10
24/06/57	Priscilla	Balloon	NTS	37
01/07/57	Coulomb-A	Surface	NTS	0
05/07/57	Hood	Balloon	NTS	74
15/07/57	Diablo	Tower	NTS	17
19/07/57	John	Rocket	NTS	About 2
24/07/57	Kepler	Tower	NTS	10
25/07/57	Owens	Balloon	NTS	9.7

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Table A4 *continued.*

Date	Time UTC	Name	Type	Place*	Energy (kt) Fission	Energy (kt) Total	Altitude (m)	Tropopause (hm)	Cloud Head (hm) Base	Cloud Head (hm) Top
26/07/57		Pascal-A	Shaft	NTS		Slight				
07/08/57		Stokes	Balloon	NTS		19				
18/08/57		Shasta	Tower	NTS		17				
23/08/57		Doppler	Balloon	NTS		11				
30/08/57		Franklin Prime	Balloon	NTS		4.7				
31/08/57		Smoky	Tower	NTS		44				
02/09/57		Galileo	Tower	NTS		11				
06/09/57		Wheeler	Balloon	NTS		0.197				
06/09/57		Coulomb-B	Surface	NTS		0.3				
08/09/57		Laplace	Balloon	NTS		1				
14/09/57		Fizeau	Tower	NTS		11				
16/09/57		Newton	Balloon	NTS		12				
23/09/57		Whitney	Tower	NTS		19				
28/09/57		Charleston	Balloon	NTS		12				
07/10/57		Morgan	Balloon	NTS		8				
06/12/57		Pascal-C	Shaft	NTS		Slight				
09/12/57		Coulomb-C	Surface	NTS		0.5				
28/04/58		Yucca	Balloon	Pacific		1.7				
05/05/58		Cactus	Surface	Enewetak		18				
11/05/58		Fir	Barge	Bikini		1360				
11/05/58		Butternut	Barge	Enewetak		81				
12/05/58		Koa	Surface	Enewetak		1370				
16/05/58		Wahoo	Underwater	Enewetak		9				
20/05/58		Holly	Barge	Enewetak		5.9				
21/05/58		Nutmeg	Barge	Bikini		25.1				
26/05/58		Yellowwood	Barge	Enewetak		330				
26/05/58		Magnolia	Barge	Enewetak		57				
30/05/58		Tobacco	Barge	Enewetak		11.6				
31/05/58		Sycamore	Barge	Bikini		92				
02/06/58		Rose	Barge	Enewetak		15				
08/06/58		Umbrella	Underwater	Enewetak		8				

10/06/58	Maple	Barge	Bikini	213
14/06/58	Aspen	Barge	Bikini	319
14/06/58	Walnut	Barge	Enewetak	1450
18/06/58	Linden	Barge	Enewetak	11
27/06/58	Redwood	Barge	Bikini	412
27/06/58	Elder	Barge	Enewetak	880
28/06/58	Oak	Barge	Enewetak	8900
29/06/58	Hickory	Barge	Bikini	14
01/07/58	Sequoia	Barge	Enewetak	5.2
02/07/58	Cedar	Barge	Bikini	220
05/07/58	Dogwood	Barge	Enewetak	397
12/07/58	Poplar	Barge	Bikini	9300
14/07/58	Scaevola	Barge	Enewetak	0
17/07/58	Pisonia	Barge	Enewetak	255
22/07/58	Juniper	Barge	Bikini	65
22/07/58	Olive	Barge	Enewetak	202
26/07/58	Pine	Barge	Enewetak	2000
01/08/58	Teak	Rocket	Johnston Island Area	3800
06/08/58	Quince	Surface	Enewetak	0
12/08/58	Orange	Rocket	Johnston Island Area	3800
18/08/58	Fig	Surface	Enewetak	0.02
27/08/58	Argus I	Rocket	South Atlantic	1–2
30/08/58	Argus II	Rocket	South Atlantic	1–2
06/09/58	Argus III	Rocket	South Atlantic	1–2
12/09/58	Otero	Shaft	NTS	0.038
17/09/58	Bernalillo	Shaft	NTS	0.015
19/09/58	Eddy	Balloon	NTS	0.083
21/09/58	Luna	Shaft	NTS	0.0015
26/09/58	Valencia	Shaft	NTS	0.002
28/09/58	Mars	Tunnel	NTS	0.013
29/09/58	Mora	Balloon	NTS	2
05/10/58	Colfax	Shaft	NTS	0.0055
05/10/58	Hidalgo	Balloon	NTS	0.077
08/10/58	Tamalpais	Tunnel	NTS	0.072
10/10/58	Quay	Tower	NTS	0.079
13/10/58	Lea	Balloon	NTS	0.0014

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Table A4 *continued.*

Date	Time UTC	Name	Type	Place*	Energy (kt) Fission	Total	Altitude (m)	Tropopause (hm)	Cloud Head (hm) Base	Top
14/10/58		Neptune	Tunnel	NTS		0.115				
15/10/58		Hamilton	Tower	NTS		0.0012				
16/10/58		Dona Ana	Balloon	NTS		0.037				
17/10/58		Vesta	Surface	NTS		0.024				
18/10/58		Rio Arriba	Tower	NTS		0.09				
22/10/58		Socorro	Balloon	NTS		6				
22/10/58		Wrangell	Balloon	NTS		0.115				
22/10/58		Rushmore	Balloon	NTS		0.188				
24/10/58		Catron	Tower	NTS		0.021				
24/10/58		Juno	Surface	NTS		0.0017				
26/10/58		Ceres	Tower	NTS		0.0007				
26/10/58		Sanford	Balloon	NTS		4.9				
26/10/58		De Baca	Balloon	NTS		2.2				
27/10/58		Chavez	Tower	NTS		0.0006				
29/10/58		Evans	Tunnel	NTS		0.055				
29/10/58		Humboldt	Tower	NTS		0.0078				
30/10/58		Santa Fe	Balloon	NTS		1.3				
30/10/58		Blanca	Tunnel	NTS		22				
30/10/58		Titania	Tower	NTS		0.0002				
15/09/61		Antler	Tunnel	NTS		2.6				
16/09/61		Shrew	Shaft	NTS		Low				
01/10/61		Boomer	Shaft	NTS		Low				
10/10/61		Chena	Tunnel	NTS		Low				
29/10/61		Mink	Shaft	NTS		Low				
03/12/61		Fisher	Shaft	NTS		13.4				
10/12/61		Gnome	Shaft	Carlsbad, New Mexico		3				
13/12/61		Mad	Shaft	NTS		0.5				
17/12/61		Ringtail	Shaft	NTS		Low				
22/12/61		Feather	Tunnel	NTS		0.15				
09/01/62		Stoat	Shaft	NTS		5.1				
09/02/62		Armadillo	Shaft	NTS		7.1				

15/02/62	Hard Hat	Shaft	NTS	5.7
19/02/62	Chinchilla	Shaft	NTS	1.9
19/02/62	Codsaw	Shaft	NTS	Low
24/02/62	Platypus	Shaft	NTS	Low
01/03/62	Pampas (Joint UK)	Shaft	NTS	9.5
03/05/62	Danny Boy	Crater	NTS	0.43
08/03/62	Brazos	Shaft	NTS	8.4
15/03/62	Hognose	Shaft	NTS	Low
28/03/62	Hoosic	Shaft	NTS	3.4
31/03/62	Chinchilla II	Shaft	NTS	Low
14/04/62	Platte	Tunnel	NTS	1.85
25/04/62	Adobe	Airdrop	Christmas Island area	190
27/04/62	Aztec	Airdrop	Christmas Island area	410
02/05/62	Arkansas	Airdrop	Christmas Islansd area	1090
04/05/62	Questa	Airdrop	Christmas Island area	670
06/05/62	Frigate Bird	Rocket	Pacific	—
07/05/62	Paca	Shaft	NTS	Low
08/05/62	Yukon	Airdrop	Christmas Island area	100
09/05/62	Mesilla	Airdrop	Christmas Island area	100
11/05/62	Muskegon	Airdrop	Christmas Island area	50
11/05/62	Swordfish	Underwater	Pacific	Low
12/05/62	Encino	Airdrop	Christmas Island area	500
12/05/62	Aardvark	Shaft	NTS	40
14/05/62	Swanee	Airdrop	Christmas Island area	97
19/05/62	Eel	Shaft	NTS	4.5
19/05/62	Chetco	Airdrop	Christmas Island area	73
25/05/62	Tanana	Airdrop	Christmas Island area	2.6
27/05/62	Nambe	Airdrop	Christmas Island area	43
08/06/62	Alma	Airdrop	Christmas Island area	782
09/06/62	Truckee	Airdrop	Christmas Island area	210
10/06/62	Yeso	Airdrop	Christmas Island area	3000
12/06/62	Harlem	Airdrop	Christmas island area	1200
13/06/62	Des Moines	Tunnel	NTS	2.9
15/06/62	Rinconada	Airdrop	Christmas Island area	800
17/06/62	Dulce	Airdrop	Christmas Island area	52
19/06/62	Petit	Airdrop	Christmas Island area	2.2

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Table A4 *continued.*

Date	Time UTC	Name	Type	Place*	Energy (kt)		Altitude (m)	Tropopause (hm)	Cloud Head (hm)	
					Fission	Total			Base	Top
22/06/62		Otowi	Airdrop	Christmas Island area		81.5				
27/06/62		Bighom	Airdrop	Christmas Island area		7650				
27/06/62		Haymaker	Shaft	NTS		67				
28/06/62		Marshmallow	Tunnel	NTS		Low				
30/06/62		Bluestone	Airdrop	Christmas Island area		1270				
06/07/62		Sedan	Crater	NTS		104				
07/07/62		Little Feller II	Surface	NTS		Low				
09/07/62		Starfish Prime	Rocket	Johnston Island area		1400				
10/07/62		Sunset	Airdrop	Christmas Island area		1000				
11/07/62		Pamlico	Airdrop	Christmas Island area		3880				
11/07/62		Johnnie Boy	Crater	NTS		0.5				
13/07/62		Merrimac	Shaft	NTS		Intermediate				
14/07/62		Small Boy	Tower	NTS		Low				
17/07/62		Little Feller I	Surface	NTS		Low				
27/07/62		Wichita	Shaft	NTS		Low				
29/09/62		Allegheny	Shaft	NTS		Low				
02/10/62		Androscoggin	Airdrop	Johnston Island area		75				
06/10/62		Bumping	Airdrop	Johnston Island area		11.3				
12/10/62		Roanoke	Shaft	NTS		Low				
12/10/62		Wolverine	Shaft	NTS		Low				
18/10/62		Chama	Airdrop	Johnston Island area		1590				
19/10/62		Bandicoot	Shaft	NTS		12.5				
20/10/62		Checkmate	Rocket	Johnston Island area		Low				
26/10/62		Bluegill 3 Prime	Rocket	Johnston Island area		Submegaton				
27/10/62		Calamity	Airdrop	Johnston Island area		800				
30/10/62		Housatonic	Airdrop	Johnston Island area		8300				
01/11/62		Kingfish	Rocket	Johnston Island area		Submegaton				
04/11/62		Tightrope	Rocket	Johnston Island area		Low				
09/11/62		St. Lawrence	Shaft	NTS		Low				
27/11/62		Anacostia	Shaft	NTS		Low				
24/04/63		Kootanai	Shaft	NTS		Low				

24/04/63	Paisano	Shaft	NTS	Low
15/05/63	Double Tracks	Surface	NAFR	0
25/05/63	Clean Slate I	Surface	NAFR	0
29/05/63	Pleasant	Shaft	NTS	Low
31/05/63	Clean Slate II	Surface	NAFR	0
05/06/63	Yuba	Tunnel	NTS	3.1
06/06/63	Apshapa	Shaft	NTS	Low
09/06/63	Clean Slate II	Surface	NAFR	0
25/06/63	Kennebec	Shaft	NTS	Low
27/09/63	Carp	Shaft	NTS	Low
14/11/63	Anchovy	Shaft	NTS	Low
04/12/63	Barracuda	Shaft	NTS	Low
	Sardine	Shaft	NTS	Low
12/12/63	Eagle	Shaft	NTS	5.3
20/12/63	Tuna	Shaft	NTS	Low
23/01/64	Oconto	Shaft	NTS	10.5
30/01/64	Club	Shaft	NTS	< 20
12/02/64	Solendon	Shaft	NTS	< 20
13/02/64	Bunker	Shaft	NTS	< 20
12/03/64	Handicap	Shaft	NTS	< 20
13/03/64	Pike	Shaft	NTS	< 20
14/04/64	Hook	Shaft	NTS	< 20
17/04/64	Bogey	Shaft	NTS	< 20
29/04/64	Pipefish	Shaft	NTS	< 20
07/05/64	Driver	Shaft	NTS	< 20
14/05/64	Backswing	Shaft	NTS	< 20
11/06/64	Ace	Shaft	NTS	< 20
25/06/64	Fade	Shaft	NTS	< 20
30/06/64	Dub	Shaft	NTS	< 20
17/07/64	Cormorant (Joint UK)	Shaft	NTS	< 20
23/07/64	Links	Shaft	NTS	< 20
19/08/64	Alva	Shaft	NTS	4.4
05/11/64	Handcar	Shaft	NTS	12
05/12/64	Drill (Source-Lower)	Shaft	NTS	3.4
	Drill (Target-Upper)	Shaft	NTS	< 20
16/12/64	Parrot	Shaft	NTS	1.3

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Table A4 *continued.*

Date	Time UTC	Name	Type	Place*	Energy (kt)		Altitude (m)	Tropopause (hm)	Cloud Head (hm)	
					Fission	Total			Base	Top
18/12/64		Sulky	Shaft	NTS		0.092				
29/01/65		Tern	Shaft	NTS		< 20				
12/02/65		Alpaca	Shaft	NTS		0.33				
16/02/65		Merlin	Shaft	NTS		10.1				
18/02/65		Wishbone	Shaft	NTS		< 20				
19/02/65		Seersucker	Shaft	NTS		< 20				
14/04/65		Palanquin	Crater	NTS		4.3				
22/04/65		Chenille	Shaft	NTS		< 20				
07/05/65		Tee	Shaft	NTS		7				
16/06/65		Diluted Waters	Shaft	NTS		< 20				
17/06/65		Tiny Tot	Tunnel	NTS		< 20				
22/07/65		Pongee	Shaft	NTS		< 20				
27/08/65		Centaur	Shaft	NTS		< 20				
01/09/65		Moa	Shaft	NTS		< 20				
		Screamer	Shaft	NTS		< 20				
23/11/65		Kermet	Shaft	NTS		< 20				
16/12/65		Emerson	Shaft	NTS		< 20				
22/01/66		Reo	Shaft	NTS		< 20				
03/02/66		Plaid II	Shaft	NTS		< 20				
05/03/66		Red Hot	Tunnel	NTS		< 20				
07/03/66		Finfoot	Shaft	NTS		< 20				
		Cinnamon	Shaft	NTS		< 20				
23/04/66		Fenton	Shaft	NTS		1.4				
25/04/66		Pin Stripe	Shaft	NTS		< 20				
12/05/66		Tapestry	Shaft	NTS		< 20				
02/06/66		Pile Driver	Tunnel	NTS		62				
15/06/66		Double Play	Tunnel	NTS		< 20				
12/09/66		Derringer	Shaft	NTS		7.8				
11/11/66		Ajax	Shaft	NTS		< 20				
18/11/66		Cerise	Shaft	NTS		< 20				
22/11/66		Vigil	Shaft	NTS		< 20				

13/12/66	New Point	Shaft	NTS	< 20
13/12/66	Sidecar	Shaft	NTS	< 20
19/01/67	Nash	Shaft	NTS	39
26/01/67	Rivet II	Shaft	NTS	< 20
03/03/67	Mushroom	Shaft	NTS	< 20
06/04/67	Heilman	Shaft	NTS	< 20
26/06/67	Midi Mist	Tunnel	NTS	< 20
29/06/67	Umber	Shaft	NTS	10
31/08/67	Door Mist	Tunnel	NTS	< 20
21/09/67	Marvel	Shaft	NTS	2.2
25/10/67	Cognac	Shaft	NTS	< 20
18/01/68	Hupmobile	Shaft	NTS	7.4
24/01/68	Brush	Shaft	NTS	< 20
26/01/68	Cabriolet	Crater	NTS	2.3
05/03/68	Russet	Shaft	NTS	< 20
25/03/68	Milk Shake	Shaft	NTS	< 20
23/04/68	Scroll	Shaft	NTS	< 20
28/05/68	Adze	Shaft	NTS	< 20
25/06/68	Funnel	Shaft	NTS	< 20
25/06/68	Sevilla	Shaft	NTS	< 20
09/08/68	Imp	Shaft	NTS	< 20
27/08/68	Diana Moon	Shaft	NTS	< 20
29/10/68	Hula	Shaft	NTS	< 20
08/12/68	Schooner	Crater	NTS	30
12/12/68	Tyg-A	Shaft	NTS	< 20
	Tyg-B	Shaft	NTS	< 20
	Tyg-C	Shaft	NTS	< 20
	Tyg-D	Shaft	NTS	< 20
	Tyg-E	Shaft	NTS	< 20
	Tyg-F	Shaft	NTS	< 20
12/12/68	Scissors	Shaft	NTS	< 20
15/01/69	Packard	Shaft	NTS	10
20/03/69	Barsac	Shaft	NTS	< 20
30/04/69	Blenton	Shaft	NTS	20 to 200
27/05/69	Ipecac-A	Shaft	NTS	< 20
	Ipecac-B	Shaft	NTS	< 20

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Table A4 *continued.*

Date	Time UTC	Name	Type	Place*	Energy (kt) Fission	Energy (kt) Total	Altitude (m)	Tropopause (hm)	Cloud Head (hm) Base	Cloud Head (hm) Top
12/06/69		Tapper	Shaft	NTS		< 20				
27/08/69		Pliers	Shaft	NTS		< 20				
10/09/69		Rulison	Shaft	Grand Valley, Colorado		40				
12/09/69		Minute Steak	Shaft	NTS		< 20				
20/09/69		Kyack-A	Shaft	NTS		< 20				
		Kyack-B	Shaft	NTS		< 20				
01/10/69		Seaweed-C	Shaft	NTS		< 20				
		Seaweed-D	Shaft	NTS		< 20				
		Seaweed-E	Shaft	NTS		< 20				
16/10/69		Seaweed-B	Shaft	NTS		< 20				
29/10/69		Pod-A	Shaft	NTS		Total 16.7				
		Pod-B	Shaft	NTS						
		Pod-C	Shaft	NTS						
		Pod-D	Shaft	NTS						
13/11/69		Scuttle	Shaft	NTS		1.7				
10/12/69		Tun-A	Shaft	NTS		< 20				
		Tun-B	Shaft	NTS		< 20				
		Tun-C	Shaft	NTS		< 20				
		Tun-D	Shaft	NTS		< 20				
21/04/70		Snubber	Shaft	NTS		12.7				
01/05/70		Hod-A	Shaft	NTS		< 20				
		Hod-B	Shaft	NTS		< 20				
05/05/70		Mint Leaf	Tunnel	NTS		< 20				
21/05/70		Manzanas	Shaft	NTS		< 20				
26/05/70		Hudson Moon	Tunnel	NTS		< 20				
26/05/70		Flask-Green	Shaft	NTS		< 20				
		Flask-Yellow	Shaft	NTS		< 20				
		Flask-Red	Shaft	NTS		< 20				
28/05/70		Piton-C	Shaft	NTS		< 20				
28/05/70		Piton-A	Shaft	NTS		< 20				
		Piton-B	Shaft	NTS		< 20				

13/10/70	Scree-Acajou	Shaft	NTS	< 20
	Scree-Alhambra	Shaft	NTS	< 20
	Scree-Chamois	Shaft	NTS	< 20
28/10/70	Truchas-Chacon	Shaft	NTS	< 20
	Truchas-Chamisal	Shaft	NTS	< 20
	Truchas-Rodarte	Shaft	NTS	< 20
16/12/70	Avens-Andorre	Shaft	NTS	< 20
	Avens-Alkermes	Shaft	NTS	< 20
	Avens-Asamite	Shaft	NTS	< 20
	Avens-Cream	Shaft	NTS	< 20
18/12/70	Baneberry	Shaft	NTS	10
29/06/71	Camphor	Tunnel	NTS	< 20
24/11/71	Diagonal Line	Shaft	NTS	< 20
25/09/80	Riola	Shaft	NTS	1.07
31/03/84	Agrini	Shaft	NTS	< 20
06/04/85	Misty Rain	Tunnel	NTS	< 20
22/03/86	Glencoe	Shaft	NTS	29
10/04/86	Mighty Oak	Tunnel	NTS	< 20

* NTS, Nevada Test Site; NAFR, Nellis Air Force Range.

Table A5 Nuclear tests by USSR.

Date	Type	Location	Energy (kt)	Notes
29/08/49	ground	S-NTS	22	First Soviet nuclear test
24/09/51	ground	S-NTS	38	
18/10/51	airdrop	S-NTS	42	
12/08/53	ground	S-NTS	400	Boosted fission device
23/08/53	airdrop	S-NTS	28	
03/09/53	airdrop	S-NTS	5.8	
08/09/53	airdrop	S-NTS	1.6	
10/09/53	airdrop	S-NTS	4.9	
14/09/54	airdrop	Near Totsk	40	Military exercise
29/09/54	airdrop	S-NTS	0.2	
01/10/54	airdrop	S-NTS	0.03	
03/10/54	airdrop	S-NTS	2	
05/10/54	ground	S-NTS	4	
08/10/54	airdrop	S-NTS	0.8	
23/10/54	airdrop	S-NTS	62	
26/10/54	airdrop	S-NTS	2.8	
30/10/54	ground	S-NTS	10	
29/07/55	ground	S-NTS	1.3	
02/08/55	ground	S-NTS	12	
05/08/55	ground	S-NTS	1.2	
21/09/55	underwater	NZ-NTS	3.5	First test at NTSNZ
06/11/55	airdrop	S-NTS	250	
22/11/55	airdrop	S-NTS	1600	First test of thermonuclear charge prototype
02/02/56	ground	Near Aralsk	0.3	Missile launch from MTR
16/03/56	ground	S-NTS	14	
25/03/56	ground	S-NTS	5.5	
24/08/56	airdrop	S-NTS	27	
30/08/56	airdrop	S-NTS	900	
02/09/56	airdrop	S-NTS	51	
10/09/56	airdrop	S-NTS	38	
17/11/56	airdrop	S-NTS	900	
14/12/56	airdrop	S-NTS	40	
19/01/57	space	Kapustin Yar?	10	First air nuclear explosion with missile launch from MTR
08/03/57	airdrop	S-NTS	19	
03/04/57	airdrop	S-NTS	42	
06/04/57	airdrop	S-NTS	57	
10/04/57	airdrop	S-NTS	680	
12/04/57	airdrop	S-NTS	22	
16/04/57	airdrop	S-NTS	320	
22/08/57	airdrop	S-NTS	520	
26/08/57	airdrop	S-NTS	0.1	Safety test
07/09/57	ground	NZ-NTS	32	The only surface at NTSNZ
13/09/57	airdrop	S-NTS	5.9	
24/09/57	airdrop	NZ-NTS	1600	First air test at NTSNZ
26/09/57	airdrop	S-NTS	13	
06/10/57	airdrop	NZ-NTS	2900	
10/10/57	underwater	NZ-NTS	10	
28/12/57	airdrop	S-NTS	12	
04/01/58	airdrop	S-NTS	1.3	
17/01/58	airdrop	S-NTS	0.5	
23/02/58	airdrop	NZ-NTS	860	

Table A5 *continued.*

Date	Type	Location	Energy (kt)	Notes
27/02/58	airdrop	NZ-NTS	250	
27/02/58	airdrop	NZ-NTS	1500	
13/03/58	airdrop	S-NTS	1.2	
14/03/58	airdrop	S-NTS	35	
14/03/58	airdrop	S-NTS	40	
15/03/58	airdrop	NZ-NTS	14	
18/03/58	airdrop	S-NTS	0.16	
20/03/58	airdrop	S-NTS	12	
21/03/58	airdrop	NZ-NTS	650	
22/03/58	airdrop	S-NTS	18	
30/09/58	airdrop	NZ-NTS	1200	
30/09/58	airdrop	NZ-NTS	900	
02/10/58	airdrop	NZ-NTS	290	
02/10/58	airdrop	NZ-NTS	40	
04/10/58	airdrop	NZ-NTS	9	
05/10/58	airdrop	NZ-NTS	15	
06/10/58	airdrop	NZ-NTS	5.5	
10/10/58	airdrop	NZ-NTS	68	
12/10/58	airdrop	NZ-NTS	1450	
15/10/58	airdrop	NZ-NTS	1500	
18/10/58	airdrop	NZ-NTS	2900	
19/10/58	airdrop	NZ-NTS	40	
19/10/58	airdrop	NZ-NTS	<0.001	
20/10/58	airdrop	NZ-NTS	440	
21/10/58	airdrop	NZ-NTS	2	
22/10/58	airdrop	NZ-NTS	2800	
24/10/58	airdrop	NZ-NTS	1000	
25/10/58	airdrop	NZ-NTS	190	
25/10/58	airdrop	NZ-NTS	<0.1	
01/11/58	air	Kapust.Yar	10	MTR
03/11/58	air	Kapust.Yar	10	MTR
01/09/61	airdrop	S-NTS	16	
04/09/61	airdrop	S-NTS	9	
05/09/61	airdrop	S-NTS	16	
06/09/61	airdrop	S-NTS	1.1	
06/09/61	air	Kapust.Yar	11	MTR
09/09/61	ground	S-NTS	0.38	
10/09/61	airdrop	S-NTS	2700	
10/09/61	airdrop	S-NTS	12	
10/09/61	airdrop	S-NTS	0.88	
11/09/61	airdrop	NZ-NTS	0.30	
12/09/61	airdrop	NZ-NTS	1150	
13/09/61	airdrop	NZ-NTS	6	
13/09/61	airdrop	S-NTS	0.001–20	
14/09/61	ground	S-NTS	0.4	
14/09/61	airdrop	NZ-NTS	1200	
16/09/61	airdrop	NZ-NTS	830	
17/09/61	airdrop	S-NTS	20–150	
18/09/61	airdrop	NZ-NTS	1000	
18/09/61	ground	S-NTS	0.004	
18/09/61	airdrop	S-NTS	0.75	
19/09/61	ground	S-NTS	0.03	

continues overleaf

Table A5 *continued.*

Date	Type	Location	Energy (kt)	Notes
20/09/61	airdrop	S-NTS	4.8	
20/09/61	airdrop	NZ-NTS	150–1500	
21/09/61	airdrop	S-NTS	0.8	
22/09/61	airdrop	NZ-NTS	260	
26/09/61	airdrop	S-NTS	1.2	
01/10/61	airdrop	S-NTS	3	
02/10/61	airdrop	NZ-NTS	250	
04/10/61	airdrop	S-NTS	13	
04/10/61	airdrop	NZ-NTS	1500–10 000	
06/10/61	airdrop	NZ-NTS	4000	
06/10/61	air	Kapust.Yar	40	MTR
08/10/61	airdrop	NZ-NTS	15	
11/10/61	underground	S-NTS	1	First Soviet tunnel V-1 underground test
12/10/61	airdrop	S-NTS	15	
17/10/61	airdrop	S-NTS	6.6	
19/10/61	airdrop	S-NTS	0.001–20	
20/10/61	airdrop	NZ-NTS	1450	
23/10/61	underwater	NZ-NTS	4.8	
23/10/61	airdrop	NZ-NTS	12 500	
25/10/61	airdrop	NZ-NTS	300	
25/10/61	airdrop	S-NTS	0.50	
27/10/61	water surface	NZ-NTS	16	
27/10/61	space	Kapust.Yar	1.2	First Soviet space explosion
27/10/61	space	Kapust.Yar	1.2	
30/10/61	airdrop	NZ-NTS	50 000	Highest yield Soviet test
30/10/61	airdrop	S-NTS	0.09	
31/10/61	airdrop	NZ-NTS	5000	
31/10/61	airdrop	NZ-NTS	150–1500	
01/11/61	airdrop	S-NTS	2.7	
02/11/61	airdrop	S-NTS	120	
02/11/61	airdrop	NZ-NTS	280	
02/11/61	airdrop	S-NTS	0.6	
03/11/61	ground	S-NTS	<0.001	
03/11/61	airdrop	S-NTS	0.9	
04/11/61	airdrop	S-NTS	15	
04/11/61	airdrop	NZ-NTS	150–1500	
04/11/61	airdrop	NZ-NTS	6	
04/11/61	ground	S-NTS	0.2	
02/02/62	underground	S-NTS	0.001–20	
01/08/62	airdrop	S-NTS	2.4	
03/08/62	airdrop	S-NTS	1.6	
04/08/62	airdrop	S-NTS	3.8	
05/08/62	airdrop	NZ-NTS	21 100	
07/08/62	ground	S-NTS	9.9	
10/08/62	airdrop	NZ-NTS	150–1500	
18/08/62	airdrop	S-NTS	7.4	
18/08/62	airdrop	S-NTS	5.8	
20/08/62	airdrop	NZ-NTS	2800	
21/08/62	airdrop	S-NTS	20–150	
22/08/62	airdrop	NZ-NTS	1600	
22/08/62	water surface	NZ-NTS	6	
22/08/62	airdrop	S-NTS	3	

23/08/62	airdrop	S-NTS	2.5
25/08/62	airdrop	NZ-NTS	1500–10 000
25/08/62	airdrop	S-NTS	0.001–20
27/08/62	airdrop	NZ-NTS	4200
27/08/62	airdrop	S-NTS	11
31/08/62	airdrop	S-NTS	2.7
02/09/62	airdrop	NZ-NTS	80
08/09/62	airdrop	NZ-NTS	1900
15/09/62	airdrop	NZ-NTS	3100
16/09/62	airdrop	NZ-NTS	3250
18/09/62	airdrop	NZ-NTS	1350
19/09/62	airdrop	NZ-NTS	1500–10 000
21/09/62	airdrop	NZ-NTS	2400
22/09/62	ground	S-NTS	0.21
24/09/62	airdrop	S-NTS	1.2
25/09/62	ground	S-NTS	7
25/09/62	airdrop	NZ-NTS	19 100
27/09/62	airdrop	NZ-NTS	>10 000
28/09/62	airdrop	S-NTS	1.3
07/10/62	airdrop	NZ-NTS	320
09/10/62	airdrop	S-NTS	8
09/10/62	airdrop	NZ-NTS	15
10/10/62	airdrop	S-NTS	9.2
13/10/62	airdrop	S-NTS	4.9
14/10/62	airdrop	S-NTS	0.001–20
20/10/62	airdrop	S-NTS	6.7
22/10/62	airdrop	NZ-NTS	8200
22/10/62	space	Kapust.Yar	300
27/10/62	airdrop	NZ-NTS	260
28/10/62	airdrop	S-NTS	7.8
28/10/62	space	Kapust.Yar	300
28/10/62	airdrop	S-NTS	7.8
29/10/62	airdrop	NZ-NTS	360
30/10/62	ground	S-NTS	1.2
30/10/62	airdrop	NZ-NTS	280
31/10/62	airdrop	S-NTS	10
01/11/62	airdrop	S-NTS	3
01/11/62	airdrop	NZ-NTS	240
01/11/62	space	Kapust.Yar	300
03/11/62	airdrop	NZ-NTS	390
03/11/62	airdrop	NZ-NTS	45
03/11/62	airdrop	S-NTS	4.7
04/11/62	airdrop	S-NTS	8.4
05/11/62	ground	S-NTS	0.4
11/11/62	ground	S-NTS	0.1
13/11/62	ground	S-NTS	<0.001
14/11/62	airdrop	S-NTS	12
17/11/62	airdrop	S-NTS	18
24/11/62	ground	S-NTS	<0.001
26/11/62	ground	S-NTS	0.031
01/12/62	airdrop	S-NTS	2.4
18/12/62	airdrop	NZ-NTS	110
18/12/62	airdrop	NZ-NTS	69
20/12/62	airdrop	NZ-NTS	8.3
22/12/62	airdrop	NZ-NTS	6.3
23/12/62	airdrop	NZ-NTS	430

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Table A5 *continued.*

Date	Type	Location	Energy (kt)	Notes
23/12/62	airdrop	NZ-NTS	8.3	
23/12/62	airdrop	NZ-NTS	2.4	
23/12/62	ground	S-NTS	<0.001	
24/12/62	ground	S-NTS	0.007	
24/12/62	ground	S-NTS	0.028	
24/12/62	airdrop	NZ-NTS	1100	
24/12/62	airdrop	NZ-NTS	24 200	
25/12/62	airdrop	NZ-NTS	3100	
25/12/62	airdrop	NZ-NTS	8.5	Last Soviet air test

Glossary

Absolute risk model: Assumes that the radiation-induced cancer risk is independent of spontaneous rate but only a direct function of the radiation dose.

Absorbed dose: Quantity of energy deposited from incident radiation per unit mass of absorber. The SI unit is the Gray, symbol Gy. 1 Gy = 1 joule per kg.

Actinides: Series of 15 elements in Group IIIA of the Periodic Table with atomic numbers 89 (actinium) to 103 (lawrencium) and including uranium and the transuranics.

Activation: Induction of radioactivity in a stable element by irradiation, usually by neutrons.

Activation product: Radionuclide generated by the irradiation of a stable nuclide.

Activity: The intensity or strength of a radioactive source: the number of atoms disintegrating per unit time and emitting detectable radiation, regardless of source mass. The SI unit is the Becquerel, symbol Bq

1 Bq = 1 disintegration per second

The earlier unit was the Curie, symbol Ci

$1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$

Activity median aerodynamic diameter (AMAD): The diameter of a unit-density sphere with the same terminal settling velocity in air as that of the aerosol particle whose activity is the median for the entire aerosol.

Adsorption: Uptake of a substance by physical or chemical reaction on the accessible surface of a solid or at a liquid interface.

Aerosol: Solid or liquid particles suspended in a gas.

Alpha particle: Doubly positively-charged particle, an ^{4}He nucleus comprising two protons plus two neutrons, emitted during the decay of some radionclides.

Atom: The smallest unit of an element, comprising a positive nucleus with orbiting electrons.

Atomic mass: The mass of an atom in multiples of a unit defined as one twelfth of the mass of the nucleus of an isotope of carbon, ^{12}C. The mass of a single proton or neutron thus approximates to this unit. Hence the atomic mass of an isotope of any element is approximately equal to the total number of protons and neutrons in the nucleus, symbol A.

Atomic number: The number of protons in the nucleus of an atom. Symbol Z.

Becquerel: The SI unit of radioactivity, symbol Bq.

1 Bq = 1 disintegration per second on average

For multiple units see Table in appendix.

Beta particle: An elementary charged particle emitted during the decay of many radioisotopes. When the isotope is on the neutron-rich side of the line of stability, the particle is the negative electron. If on the proton-rich side, the particle is of identical mass and charge but positive, known as the positron.

Biological cycling: General term covering biologically-mediated transformations and pathways.

Biological half-life: The time in which a biological system eliminates by natural processes half the amount of a foreign substance that has entered. This does not include the spontaneous decay of the foreign substance, such as a radionuclide, for which see under "Effective half-life".

Biota: The flora and fauna of a given region.

Case-control study: A method of epidemiological study comparing the background and life-styles of confirmed cases with those of closely-comparable control subjects not having the given health problem.

Cluster: The elevated numerical incidence of a given morbidity within a defined geographical area.

Coefficient of variation: The standard deviation divided by the value of the parameter considered.

Cohort: A group of subjects of the same relevant category (age sector, gender, specific background, etc., as required) studied progressively over time.

Cohort study: Epidemiological study comparing exposures in a given cohort with morbidity incidence.

Collective dose: The product of the average individual dose in a population group and of the size of that population group.

Collective dose commitment: The integral over infinite time of the collective dose rates delivered to the world's population as a result of a specific practice (in this case, the nuclear weapons tests). The actual radiation exposures may occur over many years after the explosions have taken place and may be received by individuals not yet born at the time of the explosions.

Collective effective dose: Product of the mean effective dose to a group or population from a given source and the number of individuals in the group. The unit is the person-sievert. (Definition in agreement with UNSCEAR, 1993.)

Committed equivalent dose: Integral or equivalent dose-rate in a given tissue or organ over time following an intake of radioactive material. Definition in agreement with European Union.

Concentration factor: Ratio of element or nuclide in a specific organ or tissue of the consumer to that in what was consumed, or to that in the environmental medium.

Critical group: Sub-group of the public most affected by a given release of radioactivity.

Curie: The earlier non-SI unit of radioactivity, symbol Ci.

1 Ci = 3.7×10^{10} disintegrations per second.

Daughter: Stable or radioactive nuclide resulting from the decay of a parent radionuclide, sometimes down a chain of radioactivity daughters.

Decay: The transformation of a radionuclide, usually by the emission of radiation, into a more stable nuclide, sometimes via less-stable intermediate daughters.

Decay constant: That fraction of a given initial number of atoms of a radioactive nuclide which decays in unit time.

Decay-corrected fallout: Measured contamination corrected for radioactive decay to give activities at time of initial fallout.

Decay product: A nuclide, radioactive or stable, resulting from the decay of a radionuclide. See under "Daughter".

Decontamination: The removal or 'clean-up' of radioactivity.

Deposition velocity: The ratio of the activity deposited per unit surface area per second to the activity per unit volume of air in contact.

Deterministic health effect: Non-stochastic effects. Human health consequences whose occurrence and severity are a direct function of radiation dose, sometimes above a threshold.

Disintegration: See 'Decay'.

DNA: Deoxyribonucleic acid, macromolecules in the cell nucleus carrying all genetic information.

Dose: A general term denoting the quantity of radiation or energy absorbed per unit of mass. For special purposes, it must be appropriately qualified. If unqualified, it refers to absorbed dose. The unit of absorbed dose used in the traditional system of units is the rad (1 rad = 100 erg g^{-1}). In the SI system of units, the unit of absorbed dose is the gray (Gy). One Gy = 100 rad = 1 J kg^{-1}.

Dose commitment: The integral over infinite time of the effective doses delivered to the world's population by specific events or practices (UNSCEAR, 1993).

Dose rate: Absorbed dose per unit time.

Ecosystem: An environmental unit, including all relevant physical features and all living organisms which function within it.

Effective dose: The sum of the equivalent doses in all tissues and organs of the body, weighted by their radiosensitivity defined by a Quality Factor. The unit is the Sievert, symbol Sv, which since the Quality Factor is dimensionless, can be defined in SI units: 1 Sievert = 1 Joule per kilogram.

Effective half-life: The time in which a radionuclide within a biological system is reduced to half its activity by the combined action of radioactive decay and biological elimination.

Electron: An elementary particle with a unit negative electrical charge and a mass 1/1837 that of the proton. Electrons surround the positively charged nucleus and determine the chemical properties of the atom.

Electron-volt: A unit of energy equal to the energy gained by an electron accelerating through a potential difference of one volt, Symbol eV. 1 eV = 1.6×10^{-12} erg. For multiple units see appendix.

Element: Substance comprising only atoms of the same atomic number.

Enrichment: The process of increasing the proportion of a chosen isotope of an element.

Epilation: Loss of hair.

Equivalent dose: The product of the absorbed dose in the tissue considered and of the radiation weighting factor of the radiation that causes the absorbed dose. Because the radiation weighting factor is dimensionless, the unit for equivalent dose is the same as that for absorbed dose, J kg^{-1}. However, the unit for equivalent dose has a special name: the sievert (Sv). Since the radiations that are considered in this report are the beta and gamma radiation, for which the radiation weighting factors are taken to be equal to one, the numerical value of the equivalent doses estimated in this report, expressed in sieverts, are the same as those of the absorbed doses, expressed in grays.

Exposure: A measure of the ionisation generated by gamma or X-radiation. The SI unit of exposure is the coulomb per kilogram, C kg^{-1}. The earlier unit, used in places in this report, is the Roentgen, symbol R, defined as 1 e.s.u. of ions of each sign generated per cm^3 of air at ntp.

1 R = 83.8 ergs absorbed per gram of air at ntp.

Hence 1 R = 2.58×10^{-4} coulombs per kilogram.

and 1 R = 8.73×10^{-3} Gray

1 Gray = approximately 115 Roentgen.

Exposure route: The pathway by which a radionuclide irradiates a biological system. The main human external exposure routes are radiation from a cloud or a ground deposit. The main internal exposure routes are by inhalation, ingestion, absorbtion through skin or entry through cut or wound.

External dose: Dose from sources of ionizing radiation located outside the body.

Fallout: The radioactive debris from a nuclear detonation deposited on the ground from an airborne cloud. Can be local, regional or global.

Fission: The exoenergetic break-up of the nucleus of an atom into two or more smaller nuclei. It may be spontaneous or follow the absorbtion of an emergetic particle, usually a neutron, e.g.:

$$^{235}U + {^1n} = {^{95}Mo} + {^{139}La} + 2{^1n} + 200 \text{ MeV}$$

Fission yield: The percentage of fissions leading to a particular nuclide by direct formation or by decay of precursors.

Fission product: Nuclides (radioactive or stable) resulting from fission, directly or by the subsequent decay of primary fission fragments.

Fusion: The forming of a single atomic nucleus from two light nuclei, with the release of energy e.g.:

$$^{2}H + {^3H} = {^4He} + {^1n} + 17.6 \text{ MeV}$$

Gamma radiation: Photon of high-energy electromagnetic radiation (wavelength of less than 0.01 nm) emitted in some radioactive decay processes and causing ionisation.

Genetic effects: Viable mutants of genomes that can be transmitted from parent to offspring.

Gray: The unit of absorbed dose in the SI system, symbol Gy. 1 Gy = 1 Joule per kg.

Half-life: Time in which half the nuclei of a given radioisotope disintegrate.

Health detriment: An estimate of the reduction of length and quality of life after exposure to ionising radiation.

Health registry: A data base for morbidity and mortality rates in cohorts or populations.

Hot particles: Radioactive fallout particles of a few microns or less in dimensions but with activities up to several orders of magnitude higher than the generality of fallout.

Incidence: Frequency of events, e.g. the development of cancer in a population.

Internal dose: Dose to internal organs and tissues from radioactivity inside the body.

Ionisation: The adding or removing of electron(s) from a neutral atom or molecule to form an ion.

Irradiation: Exposure of matter to ionising radiation.

Isotope: Nuclide of a given chemical element which while having the same number of protons, Z, in its nucleus has a different number of neutrons, N, and hence a different atomic mass, A.

Lanthanides: A series of 15 elements in Group IIIA of the Periodic Table with atomic numbers 57 (lanthanum) to 71 (lutetium). Also known as the 'rare earths'.

Leaching: Removal of the soluble component of a porous solid by the permeation of water.

Mass number: Total number of protons plus neutrons in the nucleus of a given atom. Symbol A.

Molecule: The smallest particle of a compound capable of independent existence while retaining its chemical properties.

Natural radiation: Ionising radiation in the environment from naturally-occurring radioactive elements and cosmic rays. In the non-ionising context, infra-red, ultra-violet, solar, etc.

Neutron: Uncharged elementary particle of approximately unit atomic mass.

Nucleus: The positively-charged core of an atom, composed to protons and neutrons.

Nuclide: The isotopes of all elements, each characterized by its number of protons, Z, and the sum of its protons and neutrons, A. (Sometimes, in addition, by the energy state of the nucleus.) A distinct nuclide, even if an unstable isomer, must be capable of existing for a measureable time.

Parent radionuclide: A radionuclide which yields a daughter nuclide on disintegration.

Person-sievert: A unit of collective dose obtained by multiplying the average effective equivalent dose by the number of people exposed.

Plowshare: Name given to nuclear tests carried out in the USA that were intended for civilian purposes.

Plutonium: A transuranic chemical element of the actinide series in Group IIIA of the Periodic Table, atomic number 94.

Proton: Positively-charged elementary particle of approximately unit atomic mass.

Quality factor: Factor to take account of the different degrees of damage to tissues and organs by different types and energies of radiation.

Rad: Earlier non-SI unit of absorbed dose. 1 rad = 100 erg g^{-1} = 0.01 J kg^{-1} = 0.01 Gray.

Radioactive decay: Spontaneous disintegration of the nucleus of a radionuclide.

Radioactive equilibrium: The establishment of a radionuclide parent-daughter equilibrium in which the activity of the daughter is exactly equal to that of the parent.

Radioactivity: Emission of particles or electromagnetic radiation from the nuclei of unstable atoms in their attempts to attain stability.

Radiobiology: The study of the involvement, use or consequences of radioactivity in biological systems.

Radionuclide: An unstable nuclide which emits energy (gamma rays) or electric charge (beta rays) or matter (alpha particles) in order to attain greater stability, sometimes via a chain of less-stable daughters.

Rainout: The removal of aerosols from the atmosphere by rain.

Relative risk: Assumes that radiation-induced cancer risk is proportional to spontaneous rate, i.e. increasing considerably with age; fits risk for solid tumours in the survivors of Hiroshima/Nagasaki quite well.

Rem: Earlier non-SI unit of equivalent radiation dose. The produce of the absorbed dose in rads and the Quality Factor of the radiation. 1 rem = 0.01 sievert.

Resuspension factor: The ratio of the concentration factor of a radionuclide in air to the ground surface contamination from which the airborne activity arises.

Risk coefficient: The statistical probability that a particular stochastic effect will occur per unit dose; depending on a wide range of factors.

Roentgen: The earlier unit of ionisation by X-rays or gamma, used in places in this report. Symbol R. Defined as the X-ray or gamma beam which will generate one electrostatic unit of ions of each sign per cm^3 of air at ntp. The unit relies on the uncertain determination of air ionisation energies and for this reason the Roentgen is now generally replaced by an SI unit of absorbed radiation dose, the coulomb per kilogram.

1 R = 83.8 ergs absorbed per gram of air at ntp.

Hence 1 R = 2.58×10^{-4} coulombs per kilogram.

and 1 R = 8.73×10^{-3} Gray

1 Gray = approximately 115 Roentgen.

Sievert: The unit of equivalent radiation dose, symbol Sv. The product of the absorbed dose in Grays and the Quality Factor of the radiation. Although strictly not an SI unit, the Sievert can be defined in SI units since the Quality Factor is dimensionless: 1 Sv = 1 joule per kilogram.

SI units: Système Internationale. The agreed system of scientific units based primarily on the kilogram, metre, second, ampere, kelvin, mole and candela.

Skin burns: Acute skin reaction to ionizing radiation, may lead to local destruction of epidermis and dermis and finally scars.

Somatic change: Change occurring in biological tissue other than the germ cells.

Sorption: A general term for the processes of adsorption, absorption and persorption.

Spent fuel: Nuclear reactor fuel in which neutron-absorbing fission products have accumulated sufficiently to inhibit the chain reaction.

Stochastic: Pertaining to random variables.

Stochastic health effect: Effects whose probability of occurrence in an exposed population is a direct function of dose. These effects are commonly regarded as having no threshold. Hereditary effects and some somatic effects, especially carcinogenesis, are regarded as being stochastic (see also 7.2.2).

Teratogenic: Inducing defects in a developing embryo or foetus.

Transuranic: Chemical elements with atomic numbers above uranium, ^{92}U.

Tritium: A hydrogen isotope, ^{3}H, with a nucleus of one proton and two neutrons. Radioactive, with half-life of 12.4 years.

Tritium ratio, TR: A unit tritium concentration of one ^{3}H atom in 10^{18} atoms of ^{1}H, giving an activity of 0.118 Bq per kg of water.

Uncertainty: The range of values within which the true value is estimated to lie. It is a best assessment of the range of possible inaccuracies from both random and systematic error.

X-radiation: Electromagnetic radiation of a wavelength from 10nm ("soft" X-rays) down to 0.01 nm ("hard" X-rays), emitted in the radioactive decay of some nuclei. (See also Gamma radiation, which continues the electromagnetic spectrum downwards below 0.01 nm.)

Yield (energy yield): The total energy released in a nuclear explosion. Usually expressed as the tonnage of TNT which would generate the same energy. 1 kiloton of TNT is taken to release 10^{12} calories, corresponding to the complete fission of approximately 57 g of ^{235}U or 58 g of ^{239}Pu.

Radiation Units

(After: Warner, F. E. and Harrison, R. M. (1993) *Radioecology after Chernobyl*, John Wiley & Sons Ltd, Chichester.)

Quantity	SI unit	Symbol	Non-SI unit	Symbol	Conversion
Activity	becquerel	Bq	curie	Ci	1 Bq = 2.7×10^{-11} Ci
Absorbed dose	gray	Gy	rad	rad	1 Gy = 100 rad
Dose equivalent	sievert	Sv	rem	rem	1 Sv = 100 rem

Metric Multiples and Sub-multiples

In the metric system of weights and measures, designations of multiples and sub-divisions of any unit may be arrived at by combining with the name of the unit the following prefixes:

E (exa),	meaning 10^{18}	m (milli),	meaning 10^{-3}
P (peta),	meaning 10^{15}	μ (micro),	meaning 10^{-6}
T (tera),	meaning 10^{12}	n (nano),	meaning 10^{-9}
G (giga),	meaning 10^{9}	p (pico),	meaning 10^{-12}
M (mega),	meaning 10^{6}	f (femto),	meaning 10^{-15}
k (kilo),	meaning 10^{3}	a (atto),	meaning 10^{-18}

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