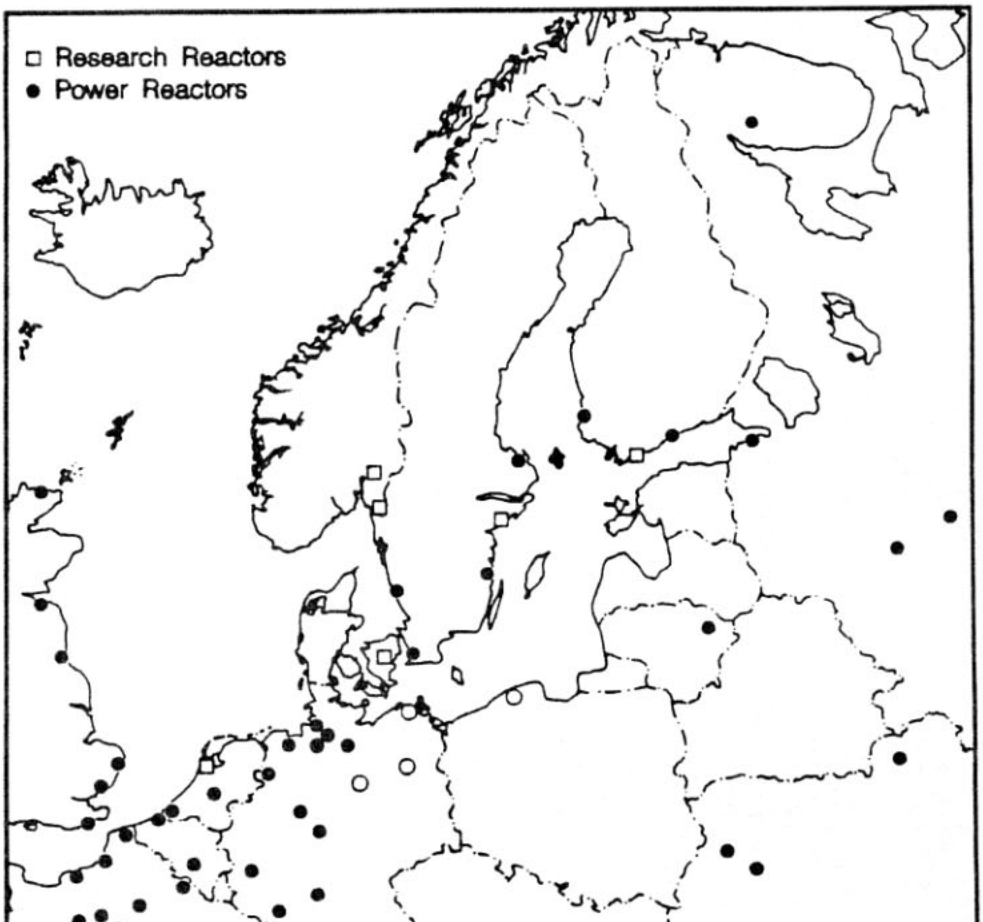
Nuclear Safety

Disposal of Radioactive Wastes from the Cleanup of Large Areas Contaminated in Nuclear Accidents

- A Literature Survey

Nordiske Seminar- og Arbejds- rapporter
1992:524



Nordisk kerne-sikkerheds-forskning | Nordisk kärn-säkerhets-forskning | Pohjoismainen ydin-turvallisuus-tutkimus | Nordic nuclear safety research

Disposal of Radioactive Wastes from the Cleanup of Large Areas Contaminated in Nuclear Accidents

- *A Litterature Survey*

Airi Paajanen and Jukka Lehto,
University of Helsinki, Department of Radiochemistry,
Unioninkatu 35, SF-00170 Helsinki, Finland

February 1992

Nordic Nuclear Safety Research Program 1990-93. Projekt KAN-2

CONTENTS

PREFACE

This literature survey is part of the work carried out in a project of the Nordic Nuclear Safety Program 1990-93. The project deals with the management and disposal of radioactive wastes resulting from the cleanup of large areas contaminated by fallout from nuclear accidents. The purpose of the project is to improve the preparedness of the Nordic Countries to deal with the consequences of nuclear accidents. In the project three different scenarios, one for urban, one for agricultural and one for forest environment, will be worked out in 1991-93. The present literature survey compiles the relevant information available in the literature.

DEFINITIONS

Deposition velocity (V_d):

$$V_d(Z_d) = \frac{F(Z_d)}{X(Z_d)}$$

where Z_d is the distance from the surface at which V_d is determined, $F(Z_d)$ the flux of the contaminant towards the surface, and $X(Z_d)$ the concentration of the contaminant at the same distance (Ro90).

Retained wet deposition is the amount of radioactive material retained on a given surface after cessation of the precipitation which carried the material (Ro90).

Runoff is the fraction of the precipitation falling on a surface which is not retained there but may carry away part of the accompanying radioactive materials (In89).

Washoff refers to the fraction of activity attached to or on the surface that is subsequently removed by precipitation (In89).

Weathering refers to the removal of deposited activity by any adventitious process, for example, resuspension and dispersion by rain and wind, and it includes washoff (In89).

1. INTRODUCTION

As a result of nuclear accidents large areas may be contaminated by radioactive fallout. Major accidents may contaminate thousands of square kilometers with initial activity higher than 10 MBq/m^2. The accidents that can cause a large-scale contamination are: a) melt-down and/or explosion and fire at nuclear power plants; b) explosion or fire at the storage sites for medium- or high-active waste solutions; and c) an accident involving nuclear weapons. Radioactive fallout deposited on the ground is a radiological hazard to humans living in the contaminated area. The radiation dose received is caused by external exposure from the radioactive material on the ground or in the air and by internal exposure from the inhalation and from the ingestion of contaminated foodstuffs.

The contaminated areas may have to be cleaned up to protect the population from radiological hazards. The cleanup measures may include the decontamination of houses, streets, gardens and fields, and the stabilization or isolation of contamination. Decontamination means the removal of radioactive material from contaminated surfaces or the removal of the contaminated surfaces in order to reduce the remaining activity on the surface. In stabilization the contamination is fixed on the surface to decrease its mobility. Radioactivity can also be isolated by covering it with a layer of clean material, such as concrete or soil or by deep ploughing to remove the contamination from the upper layer of soil (In89).

Most of the cleanup measures result in the formation of radioactive waste that should be disposed of in a safe manner. The removal of contaminated soil and vegetation will generate huge amounts of waste. Prior to any decision on which cleanup measures will be taken, it should be known how to dispose of the resulting waste. There are many factors affecting the distribution of contamination and, consequently, also the volumes and physical forms of the waste. The distribution of contamination on different surfaces is very much dependent on whether the deposition took place in dry atmospheric conditions or whether it came down with rain. In dry deposition the contamination is mostly retained on upper surfaces (roofs, canopies) and on vegetation. In wet deposition a higher proportion moves to lower surfaces and soil. The effect of the season on waste is obvious: in the growing season the activity is retained by vegetation more readily than in other seasons. In the winter the contaminated snow and ice may be the most important source for waste. The time period between deposition and cleanup is also very important. If, for example, contaminated grass is cut immediately after dry deposition, most of the activity can be removed, but if not the subsequent rains and rottening of the grass will move the contamination into litter and soil.

The waste coming from the clenaup work is mainly low-active. The experience of the management and disposal of low- and intermediate-level waste from nuclear power plants and other nuclear facilities is extensive. Experiences of the disposal of contaminated soil in hundreds of thousands of cubic meters have been obtained in the cleanup of uranium mill tailings sites and nuclear weapons test sites. This experience is, however, only partly useful when considering the waste problem in major nuclear accidents. First, the amounts of waste may be extremely large when vast contaminated areas are to be cleaned up after an accident. Second, the accident situation is always unexpected, although tentative planning for such situations may exist. Under normal circumstances planning and the actual operation may take years, whereas in case of an accident cleanup work may have to be started immediately.

2. DESCRIPTION OF THE NUCLEAR ACCIDENTS TAKEN AS EXAMPLES IN THIS SURVEY

This chapter describes the nuclear accidents which have resulted in a large-scale contamination of the environment outside nuclear facilities and have required cleanup of large areas. In additon to these accidents, this survey describes the management and disposal of uranium mill tailings and the cleanup of a nuclear weapons test site, in which experiences of large-scale handling of radioactive waste have been obtained.

a) The Chernobyl accident in 1986

In April-May 1986, a melt-down and explosion of a 1000 MW graphite-moderated reactor took place in Chernobyl, the USSR. The activity released from the reactor was about 2 10^{18} Bq (5 10^{7} Ci), of which about 4 10^{16} Bq (10^{6} Ci) was ^{137}Cs and 10^{16} Bq (2 10^{5} Ci) ^{90}Sr. The accident resulted in a high contamination of thousands of square kilometers in the Ukraine and Belorussia. In June 1986, the dose rate was higher than 20 mR/h in the most severely contaminated area (870 km^{2}) close to the plant, and the corresponding surface activity was about 300 MBq/m^{2} (Table 1). Hundreds of thousands of people were evacuated. The town nearest to the plant, Pripyat (50,000 inhabitants), was completely evacuated (In89).

Table 1. Estimated surface activity in a 30 km zone around the Chernobyl Nuclear Power Plant on 26 June 1986 (In89).

Area of zone (km^{2})	Activity (MBq/m^{2})
870	210-370
480	60-110
1100	30-60
2780	20-30

b) The Kyshtym accident in 1957

In September 1957, a tank containing high-active waste solution, exploded at a plutonium separation plant in Kyshtym, the USSR, about 100 km south of Sverdlovsk. About 10^{16} Bq (2 10^{6} Ci) of fission products was released. The short-lived nuclides ^{144}Ce and ^{95}Zr accounted for 91 % of the total released activity. The long-term radiological hazard was caused by ^{90}Sr, which accounted for 5.4 % of the activity, 4 10^{15} Bq (5.4 10^{4} Ci). The radioactive deposition took place in dry atmospheric conditions. An area of a total of 15,000 km^2 was contaminated with ^{90}Sr activity higher than 3.7 kBq/m^2 (0.1 Ci/km^2) (Table 2). The population in that area numbered 270,000 (Ro91b).

Table 2. ^{90}Sr contamination levels and areas after the Khystym accident in 1957 (Ro91b).

^{90}Sr contamination		Area
(Ci/km^2)	(MBq/m^2)	(km^2)
0.1-2	0.0037-0.074	15,000
2-20	0.074-0.74	600
20-100	0.74-3.7	280
100-1000	3.7-37	100
1000-4000	37-136	17

c) The Palomares accident in 1966

In January 1966, an American B-52 bomber, carrying four nuclear weapons, exploded in the air at the elevation of 10 km over Palomares, Spain. No nuclear explosion took place, but two of the four bombs broke when impacting on the ground; one at the distance of 0.5 km from Palomares and the other at 2 km. Palomares had 2000 inhabitants at that time. A total of 255 hectares was contaminated with Pu: 2.2 hectares had a contamination level higher than 460 μg/m^2, 17 hectares between 54-460 μg/m^2 and the rest below 54 μg/m^2 (Ir68,DNA75).

d) The Thule accident in 1968

In January 1968, an American B-52 bomber, carrying four nuclear weapons, crashed on the sea ice off Thule, Greenland. Both the aircraft and the weapons disintegrated, but no nuclear explosion took place. The aircraft debris and the plutonium from the disintegrated weapons were distributed over an area of about 22 hectars. A total of 3.2 kg of plutonium was distributed on the ice. Table 3 shows the distribution of Pu (La70).

Table 3. Distribution of plutonium on the surface of sea ice near Thule, Greenland (La70).

Contamination boundary (mg/m^2)	Enclosed area (m^2)
380	1,970
112	11,000
8	24,900
2.4	39,000
0.26	110,000
0.06	223,000

e) The Goiania accident in 1987

In September 1987, a cancer therapy unit, containing 5 10^{13} Bq (1375 Ci) of ^{137}Cs, was opened by two scavengers and the metal parts were sold as scrap in Goiania, Brazil. The capsule containing the Cs salt was also damaged resulting in widespread contamination. Hundreds of people were contaminated in Goiania, which has one million inhabitants, of which 112,000 were monitored. About ten sites (houses, junkyards, hospitals etc.), in total about 5000 m^2, were contaminated to the extent that cleanup was necessary (Ro90,Vi90).

f) The Ciudad Juárez accident in 1983

In December 1983, a teletheraphy unit, containing 1.7 10^{13} Bq (450 Ci) of ^{60}Co in form of 6000 pellets, was dismantled and used as scrap metal in foundries in Ciudad Juárez, Mexico. This resulted in the contamination of thousands of tons of metal products, several foundries and streets, and hundreds of houses. The accident required a large-scale cleanup program both in Ciudad Juárez and Chihuahua (Mo90).

g) The Cosmos 954 accident in 1978

In January 1978, a Soviet nuclear-powered satellite Cosmos 954 disintegrated and the debris fell down to the earth in the Canadian Northwest Territories. The debris spread over a 1000-km path. Only about 65 kg of the debris were recovered, which is only a fraction of the total satellite mass, assumed to be several tons (Tr84).

h) Cleanup of the nuclear weapons test site at the Enewetak atoll

In the years 1948-58, a total of 43 nuclear weapons tests were carried out by the USA at the Enewetak atoll, in the Pacific Ocean. The atoll consists of 40 islands, with a total area of 713 hectares. Due to the tests, contamination levels on 4 islands were higher than 15 kBq/kg (400 nCi/kg) of soil and on 8 islands 1.5-15 kBq/kg (40-400 nCi/kg) of soil. In the years 1977-80, a large-scale cleanup program was carried out in the contaminated islands (DNA81).

i) Cleanup of the uranium mill tailings site in Salt Lake City

In the mid-1980s, a uranium ore processing plant was cleaned up in Salt Lake City, USA. In the years 1951-1964, the plant produced about 2 million tons of uranium mill tailings which were stored in piles on site. The tailings contained about 5 10^{13} Bq (1500 Ci) of ^{226}Ra. This waste was transported by train to the South Clive disposal site, 140 km from Salt Lake City (USDOE84).

j) Cleanup of the uranium mill tailings site in Port Hope

In Port Hope, Canada, 70,000 m^3 of ^{226}Ra contaminated soil (2000 Bq/kg) was removed from a uranium mill tailings site by trucks to a disposal site 350 km from Port Hope.

3. CLEANUP OF URBAN AREAS

3.1 Distribution of Radioactive Contamination

In urban areas, radioactive fallout is distributed on a variety of surfaces, notably on the roofs, walls and interiors of buildings, on roads and streets, and on shrubs and lawns in parks and gardens. The relative distribution of contamination on various surfaces depends largely on whether the deposition took place with precipitation or under dry conditions. The amount of radioactive contamination is considerably smaller in the case of dry deposition, and the contamination is mainly deposited on roofs and streets, on the leaves of trees and shrubs, and on lawns. During wet deposition, roofs, streets, trees and shrubs are washed by precipitation, which causes more contamination to accumulate on the ground and into the sewage system. The ensuing precipitation moreover leaches contamination from the topsoil deeper down. The distribution of contamination following deposition further depends on particle resuspension, caused, for example, by the wind, vehicle traffic and possible cleanup measures (Ro87a,Ro87b,Ro90,Sa87,Ja87,Wa82,Wa84a).

Under dry deposition, the deposition velocity of particles is the highest onto rough and uneven surfaces, such as trees and shrubs, bare soil and grass. The deposition velocity on grass increases with the grass mass per unit area, so that it is higher on lawns with high and dense grass than on mown lawns. The deposition velocity of particles on roofs and bare soil is of the same order as on mown grass. It is, however, lower on streets and other paved grounds than on roofs, and lowest on the walls of buildings (Ro87a).

Compared with dry deposition, radioactive fallout deposited with precipitation may cause a considerably higher local radioactive fallout even relatively far from the source of release, as could be observed after the Chernobyl accident.

Radioactive materials deposited with precipitation may be intercepted on the surfaces of buildings and streets or washed out in the runoffs. Materials having arrived previously as dry deposition may also be washed off the surfaces by precipitation.

In Risö, Denmark, it was observed that Silicon-coated roofs retained 20-30% of the cesium deposition from the first wet deposition following the Chernobyl accident. In more porous roofing materials, the amount of cesium retained was greater (60-90%), depending on the type of roofing materials (Ro87b). Relatively small amounts of cesium were washed out of asphalt and concrete streets by rain, the amount of cesium retained being 80-84% (Ro90).

Later on, relatively small amounts of radioactive materials would be washed off surfaces merely as a result of weathering (Ro87b,Sa87,Wa82,Wa84a). In Risö, Denmark, only 1% of the cesium from the Chernobyl wet deposition retained on the roofs was removed over the 8-month follow-up (Ro87b). In England, the cesium retained in certain roofing materials was found to be over 50% after the Chernobyl fallout. However, on semi-glazed hard tiles only 3% of the cesium was retained (Sa87).

Due to weathering including vehicle traffic, radioactive materials are removed more quickly from asphalt and concrete streets and parking lots than from roofs (Ja87,Wa82,Wa84a). In Munich, most of the wet deposition from Chernobyl was removed from asphalt and concrete paved urban areas during the first few days. The removal for cesium was 50-70% due to precipitation, vehicle traffic and regular street cleaning operations. About 70% of the cesium initially retained was removed over roughly one year. However, only 40% of the cesium was removed from cobbled streets (Ja87). The removal of radioactive materials from asphalt and concrete surfaces also depends on how old the coating is, so that active materials are more quickly removed from new than aged coatings. Hardly any activity is removed from old asphalt surfaces

(Wa82,Wa84a).

Table 4 shows the relative distribution of the wet deposited cesium on various surfaces in urban areas immediately following the fallout and two years later (Ro90).

Table 4. Relative distribution of wet deposited cesium in urban areas (5-10 mm of precipitation) (Ro90).

Surface	Immediately after dep.	2 years later
Grassed area	1	1
Paved areas		0.01-0.05
- heavy traffic	0.4-0.8	
- light traffic		0.05-0.2
Roofs	0.3-0.9	0.1-0.7
Walls	0.01-0.03	0.01-0.03

The above Table 4 shows that walls are only slightly contaminated by wet deposition, and contamination will not be carried away with precipitation. The contamination levels of roofs, streets and other paved areas during wet deposition are similar to each other. Part of the radioactive material is, however, removed from impermeable surfaces by rainfall, so that less contamination is retained on roofs and paved areas than in grassed areas. Especially from porous roofing materials radioactivity is removed very slowly.

Roed has estimated that, considering how much time people spend in different urban environments (buildings, streets, gardens etc.) and the amount of deposition on different surfaces, it is the trees and the gardens that are major contributors to the accumulation of radiation doses (Ro90). The role of trees in the radiation dose is clearly smaller during wet deposition than during dry deposition.

3.2 Cleanup Methods

The purpose of cleanup is to remove radioactive material, or at least reduce the ensuing radiation dose. The methods can be divided into three main groups (Wa84b,Ro86):

a) Methods for removing contamination without damaging the surface - sweeping, vacuum sweeping, firehosing, water jetting and regular cleaning;

b) Methods for removing the top layer of the contaminated surface, parts of the surface or the whole surface - sand blasting, planing, scraping, spalling, cutting vegetation, removing surface soil, renewing roofs, or demolishing buildings;

c) Methods for fixing contamination onto the surface or introducing it deeper into the contaminated site - painting, ploughing, turning the soil, turning flagstones or repaving roads.

The most practicable methods for cleaning up widespread contamination are those involving readily available equipment which is easy to use and efficient in cleaning up large areas quickly. The goal is to reduce radiation doses, but the cleanup measures should be optimised taking the obtainable decontaminaton level and the cost into consideration.

Roed has summed up the cleanup methods of surfaces in urban areas. The obtainable decontamination factors (DF), and the dose reduction factor (DRF), and the cost of cleanup methods (USD/ECU) per unit area are given for radiocesium in Table 5 (Ro90).

The decontamination factor and the dose reduction factor vary considerably according to different cleanup methods. The highest DF is obtained by removing the contaminated surface layers. The applicable methods, such as sandblasting or planing and spalling asphalt or concrete surfaces, however, require a lot of work and special equipment and are therefore slow and costly.

Table 5. Cost and effectiveness of cleanup measures for urban surfaces (Ro90).

Surface	Reclamation procedure for radiocesium	DF-DRF factor	Cost (USD,ECU/m^2)
Windows	Cleaning	10	2
Roads	Sweeping	1-5	0.04
Asphalt	Vacuum sweeping	1-5	0.04
Concrete		1-5	0.04
Grass	Cutting	2-10	0.016
Roads	Firehosing	1-10	0.1
Asphalt	Water-jetting	1-10	0.1
Concrete		1-10	0.1
Roofs		1-5	3
Walls		1-5	1
Roads(asphalt)	Planing	>100	3
Walls	Sandblasting	>100	10
Roofs	Sandblasting	3-100	20
Grass,soil	Removal of surface	4-10	0.2
Trees	Cutting, defoliation	10-100	7
Garden	Digging	6	1
Fields,parks	Ploughing	15-50	0.1

In Table 5, the range of the DF is relatively wide for several methods. The reduction of activity levels through cleanup measures often depends on the conditions prevailing during the contamination, such as dry or wet deposition, as well as the amount, intensity and duration of precipitation (Ro90). In addition, the efficiency of cleanup methods, such as sweeping, vacuuming or washing, used for removing contamination without damaging the surface, largely depends on factors such as the size of contaminated particles, the surface material and the time elapsed since the fallout took place (Wa84b,Ro86). Standard sweepers, for example, are inefficient in collecting particles smaller than 10 μm, a typical particle size in fallout occurring far from the source of release. Even though the results obtained using the above methods are not so good, their advantage is the availability of equipment, relatively fast treatment of surfaces and comparatively low cost.

Taking into account the results shown in Table 5 above, and the radiation doses to which different surfaces expose people, first priority in cleanup measures should be given to decontamination of gardens and trees, and the second to that of roads and streets. Cleaning up surfaces like roofs and walls with the methods available is relatively unefficient and very expensive (Ro90).

3.3 Radioactive Waste Arising From Cleanup

All the above cleanup measures, excluding those listed under c) at the beginning of chapter 3.2, i.e. fixing contamination in situ, generate radioactive wastes. When planning cleanup operations, we have to consider the management, transportation and disposal of the wastes on the basis of their quantity and physical form. The greatest volume of wastes is produced by removing vegetation and the surface soil from gardens and parks. For example, if 10 cm of topsoil is removed at a residential site measuring 500 m^2, the result is 50 m^3 of waste. In addition, the trees and shrubs to be removed add to the amount of waste considerably. Decontamination of roads and other paved areas by removing the contaminated surface layer, as well as demolishing contaminated buildings also generate a lot of waste. Sweeping and vacuum sweeping roads and other bare surfaces generate relatively small amounts of waste which moreover is collected into the sweeper thus facilitating the collection and management of the wastes. Firehosing or water jetting-buildings and streets produce enormous amounts of contaminated water which end up in waste water treatment plants via the sewage system. As a result, sewage sludge from those plants will be radioactive waste.

3.4 Experiences In Cleaning Up Urban Areas

Experiences in cleaning up urban areas affected by radioactivity have been obtained in the Soviet Union after the Chernobyl accident, and in Brazil in the town of Goiania.

In the Chernobyl area, the cleanup of towns and populated centres was undertaken soon after the accident had taken place (In89). Buildings were cleaned mainly by washing their surfaces with a decontamination solution containing hydrophilic surface active agents in water or acid solutions. The solution was sprayed on outer surfaces in quantities of 10-15 $l\ m^{-2}$, and the surfaces were washed after the treatment (Ko90,In89). Firehosing was also used when washing the buildings and streets. As a result, the radiation level in some buildings was reduced to the background level, whereas on other surfaces and roofs that method proved ineffective. After the buildings had been washed, radioactivity in the earth near the walls became 2-2.5 times higher (In89). A 5-10 cm thick layer of topsoil was removed, in small garden areas manually (In92). By the summer 1987, about 600 population centres, a total of about 60,000 houses and other buildings, had been decontaminated (In89). In 1987, the town of Chernobyl, which had not been as severely affected as the town of Pripyat, had been totally decontaminated and several buildings had been taken into use to house the cleanup personnel (Va88). In the town of Pripyat, the cleanup operations were performed twice (Va88,Sa90). In 1988 it was decided, however, that the town of Pripyat would not be used any more, and in the year 1990 only two research laboratories were still operational (Sa90). In 1990, the gamma activity level was found to be practically on the same level both in the decontaminated and nondecontaminated areas of Pripyat (Ar91).

In the town of Goiania, the actual cleanup measures were concentrated on relatively small separate sites with gardens, residential buildings and storages (Vi90). The total area subject to the cleanup measured 5000 m^2. There were seven main sites, five of which had very heavily contaminated spots with a dose rate of 50 up to 2000 mSv h^{-1}. The most severely contaminated spots were removed first, after which all waste paper and scrap was removed from the area. The trees were felled, the apartments were evacuated, and all loose objects were removed and treated as radioactive waste. Loose materials had to be removed manually before heavier equipment could enter the area. On three sites the buildings were so badly contaminated that they had to be demolished with excavators, and their metal frames were cut into pieces. On other sites the buildings were cleaned up. Part of the floors to which the contamination had been fixed were removed, and the floors were covered with a new concrete layer. The contaminated soil was removed from the sites, and the area was covered either with uncontaminated soil or concrete (Vi90). The contamination had spread with the wind, humans and animals from the areas in which the ^{137}Cs source had been broken up and the contaminated parts had been treated (Am91,Si91). Gardens and buildings within a radius of about 50 m around the actual site had to be cleaned up. The contaminated fruit were picked and the branches of the trees were cut. As 60% of the cesium on the residential sites had accumulated in the 1.5 cm thick surface soil, it was carefully removed manually in layers of about 1.5 cm until the acceptable dose rate level of 0.8

µGy h^{-1} or the acceptable concentration level of 22.5 Bq kg^{-1} was obtained (Am91).

Chemical and physical methods were used in decontaminating the buildings. The roofs were water-jetted and the ceilings vacuum swept. The roofs of two buildings had to be removed due to inefficient washing methods. Paint was scraped off the walls with sandpaper. The floors, mainly of concrete, were treated with chemical substances, with acid, and washed with a suspension containing Prussian Blue, which acts as a fixation agent for cesium. From the most heavily contaminated parts of the floors, the surface was removed with a jewelry drill and electrical appliances. The most seriously contaminated were the bathrooms and other washrooms, and large quatities of active material had to be removed from them and their vicinity before the acceptable surface contamination level of 3.7 Bq cm^{-2} was reached. Altogether almost 50 buildings were decontaminated (Si91). Affected domestic animals, like dogs, pigs, rabbits and fowl were killed and treated as radioactive waste (Mi90a). The cleanup measures in Goiania produced a total of 3340 m^3 of active waste, of which 130 m^3 contained 72 % of the cesium (Me89).

In the towns of Ciudad de Juárez and Chihuahua ^{60}Co pellets and metal pieces contaminated with ^{60}Co were collected and stored in concrete containers and steel barrels. Contaminated soil was removed and contaminated streets were cleaned up. 814 buildings were demolished totally or partially. The cleanup work produced 21,000 m^2 of radioactive waste (Mo90).

4. CLEANUP OF RURAL AREAS

4.1 Distribution of Radioactive Contamination

By rural areas we mean areas outside towns, excluding forests and water systems.

In rural areas, radioactive contamination is deposited onto vegetation and the soil. The relative distribution depends on the nature and density of the vegetation. During wet deposition, particularly in areas with scanty vegetation, most of the activity ends up in the soil, whereas during dry deposition and in areas of high and dense vegetation the result is the opposite. Distribution is largely dependent on seasons, so that vegetation retains more activity during the growing period.

The deposition velocity of particles from dry deposition onto lawns covered with high grass may be sixfold compared to mown lawns (Ro87a). In the Chernobyl area it was observed after the fallout that about 80% of the radioactivity had remained in the grass on dense grassland, whereas for sparse grassland the figure was only 40% (Si89). Two or three months after the accident, when the short-lived radionuclides had decayed, only some 10% of active materials still remained on open natural grassland in the Chernobyl area, while the greater part was in the uppermost 1 cm thick layer of topsoil (Iz88). Even though part of the radioactive materials are washed into the ground with rain, activity residues at the end of the growing period may be higher in vegetation which was lush when the fallout arrived. Of the total fallout deposited on surfaces in the Chernobyl fallout area, 0.5-3% remained in the vegetation during the first growing period (Ve90).

In the soil, the radionuclides are associated with minerals, and their vertical migration is rather slow. On natural grasslands in the Chernobyl area, the migration of radionuclides from the surface soil deeper into the soil was observed only 5-6 months after the fallout (Iz88). Consequently, active material was exposed to weathering for a long period, which results in the resuspension of contamination. The mobility of rainwater along the ground surface and the amount of material carried by it depend on vegetation, the intensity of the rainfall, the permeability of the ground, the roughness of the surface, and the slope. Washoff is insignificant in areas covered with vegetation, whereas significant amounts of active materials may be washed off bare soil with rainfall, and then accumulate in catchment areas (Me60,Ro70). A yet more significant factor is resuspension in which the wind raises the deposited active dust back into the air and carries it to unaffected areas. In Palomares, for example, the original contaminated area of 255 ha grew into 263 ha due to resuspension (DNA75), and in Kysthym it has been estimated that about 40 km^2 of the total fallout area of 15,000 km^2 had been caused by resuspension (Te90).

The behaviour of cesium and strontium in the soil depends on the clay content, the amount of organics, the pH, and the concentration of exchangeable ions in the soil (Hä74,Ni62,Ju70,Ma89). Cesium is readily associated with mineral soil, especially with clay, and it is released from clay minerals only in small amounts (Hä74,Ni62,Ma89). Cesium is not equally easily associated with soil containing organics, and it is therefore more readily released from such soil (Hä74). Strontium is rather easily associated with different soil types but it is released from mineral soil more easily than cesium. Strontium is rather tightly bound to soil containing organics, from which it is released more slowly than from mineral soil (Hä74,Ju70). The released strontium may moreover occur as chelates or complexes, depending on the pH (Ju70). The pH of soil is normally around 5, and under such conditions unassociated strontium mainly appears in ionic form (Ju70,Ma89). The retention of cesium and strontium increases with the increasing pH, and they are less easily changed into the soluble form

(Hä74,Ju70). Other important ions in the soil are potassium and calcium which occur as ions exchangeable and competing with cesium and strontium for ion exchange sites. Concentrations of potassium and calcium have a considerable effect on the transfer of ^{137}Ci and ^{90}Sr into plants through roots (Ma89).

As the soil is able to retain radionuclides very efficiently, they remain in the surface soil for many years or even for many decades. It was found in 1973 that about 80% of the strontium, originating in the nuclear weapons tests carried out in the United States, had remained in the 0-10 cm thick upper layer, and over 90% in the 0-20 cm thick upper layer in undisturbed soils poor in lime. Over 90% of cesium and plutonium, which are retained in the soil better than strontium, appeared in the 0-10 cm thick upper layer in the surface soil (Ha74). As late as 25 years after the accident in Kysthym, over 90% of the strontium, which at the initial phase remained in the 0-2 cm thick upper layer, remained in the 2-10 cm thick upper layer in undisturbed soil. The vertical migration rate of strontium in the soil in the Kysthym area was 0.3 to 0.5 cm a^{-1}, and that of cesium 0.15 to 0.25 cm a^{-1} (Te90). The vertical migration of radionuclides, however, depends largely on soil type and the amount of precipitation.

4.2. Cleanup Methods

The cleanup methods used in rural areas affected by radioactive contamination can be divided into two main groups (Me71,Do81):

a) Methods for cutting and removing the contaminated vegetation and contaminated surface soil;

b) Methods for preventing the uptake of radionuclides by plants, without removing the contamination - ploughing, fertilizing, liming and other soil amendments, irrigation and leaching, and changing the production.

4.2.1 Removing Vegetation and Surface Soil

Removing contaminated vegetation yields highly varying results, as the amount of radioactive material that remains in the vegetation depends on its density and the conditions under which the contamination took place. In field experiments simulating dry deposition, less than 40%, and after irrigation only less than 20% of activity was removed as a result of cutting standing mature rye crop, (Ja73). Vegetation on fields can be removed with conventional crop-harvesting machines, such as grass-forage harvester, mower, hay rake and baler. Removing dry vegetation, however, can raise a cloud of dust which exposes the workers to radioactivity and spreads active material into decontaminated areas (Ja73).

Depending on the thickness of the layer to be removed and the soil type, radioactive material can be removed totally or almost totally by removing the surface soil. If the ground is covered with lush vegetation, it must first be cut, as it may interfere with the removal of thin layers of earth. Field experiments simulating radioactive fallout have yielded the following results: Over 90% of active contamination was removed when the thin upper sod layer was cut, removing the roots and only little earth (Me71). 80-99% of activity was removed with the upper 5 cm layer (Ja73). The roughness of the ground, soil type, cobblestones and big root balls, however, may deteriorate the result. Only 50-60% of activity was removed from the soil in a ripe cornfield when the surface soil was removed with a scraper after the corn had been threshed (Ja73). Standard earthmovers, such as planers, bulldozers and various scrapers can be used for removing the surface soil (Me71,Ja73). Rough surfaces can be somewhat more easily removed with bulldozers than with scrapers or planers (Me71). In wet clay soil, a heavy scraper which collects the removed soil in a tank may start sinking as the load grows and, as a consequence, the thickness of the layer to be removed increases (Ja73).

The advantage of removing surface soil is that active contaminaton can be almost totally removed. The disadvantages are the slow soil stripping, the need for equipment not used in ordinary farming and therefore not readily available, such as scrapers equipped with tanks. The peeling rate of a scraper with a blade width of 3.6 m is less than 0.5 ha per hour (Ja73). That method moreover generates considerable amounts of waste, and land productivity decreases as the nutritious humus layer is removed.

Vacuum sweepers can also be used on cut meadows. Treating clover grass twice with a vacuum sweeper removed 40-50% of the active material spread on the grass. When the damp meadow was swept with a vacuum sweeper with steel bristles, the first sweeping removed about 75% of the activity and the second almost 90% (Ja73). Vacuum cleaning is moreover an efficient method of removing active material from sandy ground (Sh89). In the United States, 92% of ^{241}Am activity in the Nevada nuclear weapons testing area was removed after four vacuumings. A vacuum cleaner mounted on a truck was used, similar to the one used for cleaning parks in towns, and the soil was dampened prior to vacuuming. Compared with standard earthmoving, the cost was lower (Sh89). Vacuuming is, however, applicable in certain types of areas only.

In Palomares, a layer of about 5 cm was removed from the surface soil in areas where the contamination levels exceeded 460 µg of Pu m^{-2}. The ground was scraped into piles with graders, and was later on transported into an interim storage. The remaining plots, where the levels still exceeded the acceptable levels, as well as areas where the grader could not be operated, were removed with spades. A total of 900 m^{3} was removed from an area of 2.2 ha (DNA75), whereafter the alpha activity of the soil was at the background level (Ir68).

On the Enewetak islands, vegetation was first removed from areas requiring the removal of soil. A loader with a four-in-one bucket was used to tear the shrubs off the ground with their roots. With this method, less ground was removed and the soil was less mixed up than if the vegetation had been removed with a bulldozer. When the piled up shrubs had become sufficiently dry, they were burnt. The ashes were either removed or left on the ground, depending on their activity levels. The soil was removed with a bulldozer which proved to be faster and more efficient than the grader or the front-end loader (DNA81). As the distribution of radionuclides in the ground varied considerably in different areas (Gu75), the soil was removed in layers of 15 cm (DNA81). The activity concentration was determined after each removed layer. The operation was continued until the required concentration level was reached. The $^{239,240}Pu$ content level was 40 pCi/g on islands intended for human settlement, 80 pCi/g on islands intended for farming, and 160 pCi/g on those used for growing fodder. Some earth was removed from five islands. The trenches of active waste that existed on some islands were also removed. Of the 40 islands forming the Enewetak atoll, the level set for human settlement was reached on 30 islands, that for farming on 7 islands, and that for fodder growing on 2 islands. The island of Runit, where the waste was buried, was interdicted even though it had been partly cleaned (DNA81).

4.2.2 Ploughing and Soil Amendments

Methods like ploughing and adding fertilizers and other soil amendments can be applied in less severely affected areas. Ploughing transfers surface contamination deeper into the soil and blends the active materials with a larger volume of earth. Activity concentrations in the soil decrease as the volume of earth that retains radionuclides increases. Regular ploughing, where the earth is turned to a maximum depth of 30 cm, does not yield a perfect turnover of earth layers, and part of the radioactive material continues to remain on the surface.

In Palomares, where the soil was first ploughed with a standard plough down to 30 cm and the surface was tilled, the highest plutonium concentrations appeared at 15-25 cm from the surface (Ir68). If the soil is deep ploughed down to about 100 cm, most of the active material appears deeper than 75 cm (Ja73). The uptake of strontium by grass, cabbage and sugarbeet, however, is reduced only by 40-50%, and by soybean only by less than 20% compared with land where strontium is homogenized to the top 20 cm by tillage. When sodium carbonate was spread on the ground before deep ploughing to slow down root growth, the plant uptake of strontium decreased by over 90% compared with land regularly tilled, and by little less than 90% compared with deep ploughed land (Ja73). The results of deep ploughing, however, vary widely depending on the depth of ploughing, the plants grown, the soil and weather conditions (Me71). The disadvantages of deep ploughing are the need for special equipment not readily available, the slow working pace, and decrease in land productivity. It will moreover be very difficult to remove the contamination later on, should deep ploughing not prove successful. The benefit of deep ploughing is, however, that subsequent regular ploughing and tillage will not raise the contaminated layer back to the surface, and therefore deep ploughing contributes to a more significant and more permanent reduction in activity levels.

Adding potassium, phosphate fertilizers and lime in connection with ploughing and tillage reduces to some extent the uptake of cesium and strontium by plants, depending very much on the properties of the land (Me71,Lö90). Under favourable conditions, adding potassium fertilizers and ploughing reduce the uptake of cesium by crops by a factor of 10-20 (Lö90). On the other hand, adding potassium and, in particular, nitrogen in the ammonium form may enhance the uptake of cesium by plants. It has been suggested that ammonium and potassium release cesium associated with soil into soluble form (Sc65).

After the accidents in Chernobyl and Kyshtym, large areas contaminated with radioactive fallout were ploughed, tilled and harrowed to bring down the activity level and to retain material from being carried with the wind and rain (Ko90,In89,Ni90). After the Chernobyl accident, production of agricultural products was prohibited in the areas, where the contamination level was higher 1.5 MBq/m^2, and the fields in these areas were decided to be afforested. In the areas, where the contamination level was lower than 1.5 MBq/m^2, several reclamation measures were taken (As88). Hundreds of hectares at Chernobyl were tilled, and sown with grass (Ko90). As a result, the contamination level of the grass was 8-10 times smaller than in untilled lands (Iz88). After the grass has grown, mixed forest has been planted on part of the lands (Ko90). The goal is to gradually sow grass and plant forests on waste land and less productive farmland in the Ukraine and Belorussia, altogether about 40,000 ha (Ko90). After harvesting, the sod layer was also removed from farmlands in the vicinity of the damaged nuclear power plant. In some cases a latex emulsion was used to fix the sod. In some areas, the surface layer was also removed, whereas the majority of the contaminated fields, hundreds of thousands of hectares of land, were deep ploughed, adding lime, potassium and phosphate fertilizers, as well as a clay suspension or zeolite (In89). After one year following the treatment, the activity concentration in the agricultural products was lower by a factor of 1.5-3 (Il88).

After the Khyshtym accident, the areas with contamination higher than 74 MBq/m^2 were interdicted. In the area of Chelyabinsk and Sverdlov totally 106,000 hectares of agricultural land was drawn out of production (Ni90). The severely contaminated, in total about 500 animals, were slaughtered and the carcases were buried (Ar91). Ploughing was the main reclamation method used in rural areas. Altogether 20,000 ha of contaminated land was ploughed to normal depth over the two years following the accident. During the subsequent two years, areas where the contaminated surface layer had not been adequately covered up in the ploughing, a total of 6200 ha, were deep ploughed to over 50 cm (Ni90). This yielded a 2-7 times reduction in the ^{90}Sr concentration of agricultural products. Using amendments and agents, which enhance the fixation of strontium in soil, such as calcium, sulphate, phosphate and silicates, decreased the ^{90}Sr concentration by a factor of 2-4. The removal of surface soil (5-10 cm), which cleanup method was used only on a small area, reduced the ^{90}Sr concentration 5-15 fold (Ro91c).

In Palomares, too, part of the affected area was ploughed. The plots whose contamination levels were 5-460 µg of Pu m^{-2} were irrigated and ploughed to 30 cm, after which the surface layer was homogenized by tilling. Plots with a contamination level below 5 µg of Pu/m^{-2} were only irrigated. In rocky waste lands, which could not be ploughed, the upper limit was 77 µg of Pu/m^{-2}. Also those areas were irrigated with water. The ploughed area was 115 ha, as was the irrigated land. Plants with count rates over 200 cpm were removed and those with rates under 400 cpm were burnt in a dry riverbed near the coast in the night when the wind blew toward the sea. Plants with count rates over 400 cpm were treated as waste (DNA75). The alpha activity of tomatoes and beans grown in those areas after the cleanup was slightly higher than in the reference area, but the contamination was mainly on their surfaces (Ir68).

4.3 Radioactive Waste Arising From Cleanup

The cleanup of rural areas produces essentially two types of radioactive waste: contaminated soil and contaminated vegetation (trees, shrubs, crops, hay etc.). Removing the surface layer generates enormous amounts of waste: removing the top 5 cm from an area of one hectare, for example, produces 500 m^3 of waste. If the land is skimmed soon after the fallout when the contamination has not yet penetrated deep into the ground, the soil need to be removed only in thinner layers, which reduces the volume of the waste generated. The amount of vegetation to be cut is considerable but varies widely from case to case. The removed vegetation can be partly left to decompose on site before further treatment, which reduces the volume of the wastes to be disposed of and thus facilitates their further treatment. Radioactive waste is moreover generated as contaminated animals are slaughtered, and the manure of cattle fed on contaminated fodder is another source of active waste.

5. CLEANUP OF FOREST AREAS

5.1 Distribution of Radioactive Contamination

In forests radioactive fallout is deposited onto trees, understory vegetation, litter and the soil. The relative distribution is largely dependent on the thickness and nature of the vegetation. Under dry deposition and in areas with thick forestation the deposition mainly remains in the leaves and needles. Under wet deposition and in areas with a sparse tree stand, deposition leaches into the understory vegetation, litter and the soil in larger quantities.

The canopies accumulate and intercept particles from dry deposition. Consequently, the deposition velocity of radioactive particles arising from dry deposition is greater in forests than in open meadows (Ro87a,Bu89). Depending on the quantity and density of the leaves and the intensity and duration of rain, the canopy may intercept a considerable amount of rain and accompanying active material.

In Chernobyl and in Kyshtym it was observed that, in the first phase after the accident, 80-90% of the radioactive fallout in the forests had remained in the canopies (Iz88,Te90). In the Chernobyl area it was observed 2-3 months after the fallout, when the short-lived radionuclides had decayed and part of the material had been removed with rain and wind, that the activity remaining on pine needles was merely 10%, while over 90% had been retained in the understory vegetation and the litter (Iz88). On the contrary, in the Kysthym area the active residues in the canopies of coniferous trees continued to be 40-50% and in the canopies of deciduous trees 10-20% eight months after the accident, even though the leaves had regrown in the meantime. The contamination level of strontium in pines in the Kysthym area reduced to 0.02% and in birches to 7% over a period of 20-25 years (Te90).

Part of the radioactive material from nuclear fallout, however, deposits directly onto the litter and continues into the soil. In coniferous forests in Chernobyl, cesium from the fallout was distributed over the whole litter layer, and 10-20% of it had moved to mineral soil. After the first summer following the accident, the greatest amount of cesium was still in the top litter layer (Si89). The radionuclides may be strongly intercepted on needles, and their migration from litter into mineral soil takes longer in coniferous forests than in deciduous forests where the decomposition of litter is faster. In the United States it was observed in a forest that the cesium and plutonium discharges from the near-by nuclear fuel reprocessing plant had raised the cesium and plutonium contents of litter under pinetrees slightly higher than that under deciduous trees. Moreover, the proportion of plutonium in litter in pine forests was higher than that for cesium, suggesting that plutonium is more easily attached to litter than cesium (Ad81).

As the trees and understory vegetation in forests protect the ground against erosion, and the litter layer intercepts and slows down the migration of radioactive material into mineral soil, the radionuclides remain in the surface layers for years. The depth distribution of radionuclides is therefore greater in open areas than in forests, and similarly greater in areas with a sparse than those with a thick tree stand (Gu75,Mi90b).

5.2 Cleanup Methods

There are two principal methods for treating a large forest contaminated by radioactive fallout:

a) The trees, understory vegetation and litter will be partially or totally removed;

b) The area will be interdicted for a certain time.

The choice of the appropriate method depends on the damage caused by exposure to radiation, the location of the forest, the use of the area and later regional planning, as well as the forest stand, age and planned felling operations (In89).

5.2.1 Removing Vegetation and Litter

If trees receive a considerable radiation dose, their cell tissue is damaged, which affects their growth, or the trees may even die. As the ability of needles to intercept contamination is greater, they are more easily damaged than deciduous trees whose radiation resistance is ten times higher than that of coniferous trees (Iz88). It was clearly seen after the Chernobyl and Kyshtym accidents. Pines in the forests near the Chernobyl plant that had received a dose exceeding 10 Gy (1000 rad) died, while the deciduous trees in that area did not suffer from the radiation. During the autumn after the accident and the following spring, 400 ha of forests were dying (Iz88). At least 200 ha of the contaminated forests were felled. The trees, the understory vegetation and the litter were removed and buried into 1.5-2 meter deep ditches and the whole area was covered with a 0.5-1 meter layer of clean sand. These measures decreased the radiation level near the Chernobyl plant by a factor higher than 100 (Ko90). Later on the area was sown with a mixture of grass and rye, and a couple of years after the grass had grown, new trees were planted (Ko90).

Contamination from the Kyshtym accident caused damages to the forests on a large area. Coniferous trees, that received a dose of 30-40 Gy (contamination level 6.7 MBq $^{90}Sr/m^2$), had died until autumn 1959 on an area of 20 km^2. Birches, that had received a dose of 200 Gy (150 MBq $^{90}Sr/m^2$), died on an area of 5 km^2 (Sp91). Trees from these ded forests were cutted and were disposed of in piles covered with soil (Ar91).

As contaminated forests can act as a secondary source of contamination for a long time, they should be removed from the vicinity of residential and agricultural areas before those areas will be cleaned up. Similarly, it might be warranted to remove forests from the vicinity of watersystems whose water is used for drinking and industrial purposes, as well as along highways and railroads where the dust from vehicle traffic contributes to raised activity levels in the air (In89). In the Kyshtym area, for example, where the accident took place in the autumn at the end of the growing period, 20-70% of the contamination in wild plants was due to external contamination caused by the wind during the first year after the accident (Te90).

The trees can be removed with a harvester. Logs and other useful trunks can be used, for example, as chips in power plants running on fuel peat, or in the wood processing industry under control for radioactive releases. The logging refuse can be collected and removed with a loader with a four-in-one bucket. Removing young tree stands, understory vegetation and litter is, however, more difficult, as the stubs and roots hamper the use of earthmovers. It may be necessary to carry out the work mainly manually in order to avoid mixing up the litter and the soil by tearing off smaller trees, shrubs and stubs. At least the bigger stubs could be left in the ground in areas to be reforested. The affected forests may be removed only partially by felling and removing big trees and their logging wastes.

The contaminated tree stands and understory vegetation could also be burnt. It is, however, advisable to avoid using that method, as radioactivity is concentrated in the ashes, and it may be difficult to remove all active ashes from a large area. The wind may moreover raise and spread the active material contained in the ashes, and expose the rescue workers to internal radiation (In89).

Seen the relatively small reduction in the radiation dose brought about by removing forests and the considerable cost due to work and to the great volume of wastes, the removal of forests should be weighed very carefully beforehand and the operations should be restricted to the most important areas only (In89).

Radioactive waste may moreover arrive from areas outside the area subject to cleanup, such as power plants using contaminated peat as fuel. In Finland, for example, there are vast peatlands and several peat fueled power plants, and over half of the peatlands were situated in the area where the deposition from the Chernobyl accident was > 6000 Bq m^{-2}. As a consequence, the ^{137}Cs content of the ashes from peat plants that were mainly run on peat obtained from the fallout area was, during the couple of subsequent heating periods, elevated to the extent that part of the ashes were buried as waste (Mu89). The amount of ashes buried in Finland annually was about 1000 truck loads.

5.2.2 Interdiction of Forests

If a large forested area which is used solely for wood production is severely contaminated it can be isolated until the radioactivity is reduced to acceptable levels through natural purification and the decay of radionuclides (In89). An area may moreover be interdicted if the cleanup measures are likely to cause serious or permanent damage to the sensitive ecosystem. The access and use of areas may be made subject to limitations, for example, areas not frequently visited by people and areas like certain forests, swamps, wastelands and rocky lands which cannot be taken into use efficiently.

6. CLEANUP OF AQUATIC SYSTEMS

6.1 Distribution of Radioactive Contamination

In aquatic systems, i.e. lakes, rivers, seas and oceans, radioactive fallout is first diluted due to the flow and mixing of water bodies. The radioactive material, which is attached to particles, deposis to the bottom sediment. The sedimentation rate depends on the size and density of the particles. Part of the soluble radioactive material attaches to the solid suspended matter present in the water and sediments on the bottom. The distribution of contamination in water systems is not only affected by direct fallout but also by waters flowing from catchment areas and resuspended radioactive dust carried by the wind.

In big lakes and in oceans the mixing of surface contamination with water bodies depends on the season. In the Black Sea, for example, the fallout from the Chernobyl accident, that took place in early May, was mixed homogeniously with the surface and medium layers only by the autumn, and with the entire water body only during the winter (Va90).

Precipitation occurring soon after the fallout carries away loose or loosely attached material from the contaminated catchment area into the water systems. In the Chernobyl area, the rains that occurred less than two months after the fallout caused considerable momentary fluctuations in the beta activity of the River Pripyat (Va90). In rivers with a high flow rate, water bodies change quickly, and, as a result, the activity in their waters soon diminishes. At the same time, radioactive contamination accumulates and is distributed into downstream lakes or into the sea or ocean where the radioactivity is diluted as it blends with a larger water body. During that process, part of the radioactivity is moreover removed by sedimentation, especially in the discharge areas of rivers.

Also the meltwater from snow and the spring floods may wash off radioactivity from the contaminated area into water systems. The floods in the post-accident spring alone transported about 12 TBq (330 Ci) of ^{137}Cs and ^{90}Sr from the Chernobyl area into the Kiev Reservoir. About 40% of the cesium in the floodwater was associated with solid suspended matter. This figure is also the fraction of ^{137}Cs from the flood period waters that has been estimated to have remained and sedimented in the Kiev Reservoir (Va90).

Cesium is strongly associated with soil minerals (Hä74,Ma89), and therefore it sediments on the bottom along with the solid suspended matter present in the water. On the contrary, strontium remains mainly in the aqueous phase (Hä74,Ma89), and it may be present in the water for a long time before sedimentation. Therefore the strontium concentration of water may rise in the initial phase, and a decrease occurs mainly by dilution.

In the Chernobyl area water systems, 15-40% of cesium and only less than 5% of strontium appeared in solid suspended matter. Consequently, cesium was removed from water gradually by sedimentation as the water bodies flowed downstream the Dnepr Cascade, whereas the strontium concentrations merely showed some dilution. During the first year, an estimated 2 TBq (50 Ci) of ^{137}Cs and 20 TBq (500 Ci) of ^{90}Sr were discharged from the Chernobyl area into the Black Sea via the Dnepr Cascade (Va90).

As the radionuclides migrate deeper into the soil, the impact of precipitation on the transfer of radioactive materials from the contaminated catchment area diminishes. In Sweden, it has been estimated that 1.9% of ^{137}Cs, originating from a recent fallout from a nuclear weapons test, was transported into the small lake Ulkesjön from the catchment area of the lake. The corresponding figure for accumulated ^{137}Cs was 0.56 % (Ca78).

The radionuclides gradually sediment on the bottom along with solid suspended matter. It was observed in the United States that plutonium and cesium from nuclear weapons tests had accumulated only in certain areas at the bottom of Lake Michigan, and the biggest amounts occurred in the bottom sediment near estuaries. In the early 1970s, 97% of $^{239,240}Pu$ and 95% of ^{137}Cs from nuclear weapons tests resided in the bottom sediment of that lake (Ed75).

There are several factors that affect the leaching of cesium, strontium and plutonium from catchment areas, their sedimentation in water and distribution on the bottom. Therefore the impact of erosion and the sedimentation process may also vary considerably in different water systems.

6.2 Cleanup Methods

There are no particular cleanup methods for treating widespread radioactive contamination in water systems. It is only possible to reduce or prevent the washoff of radioactive substances into watersystems from contaminated catchment areas and the flow of the contaminated water into downstream watersystems. The exposure of humans to radiation can be reduced by banning or restricting the use of contaminated fish and other aquatic animals for human consumption and the use of contaminated water, for example, for irrigation of crops, as well as by improving the cleanup of surface waters used for domestic and commercial purposes.

After the Chernobyl accident, various measures were taken to protect watersystems in that area (Iz89,Ko89). Earth dams and embankments were constructed in areas near the plant to prevent the leaching of contaminated substances. Several wells were drilled to monitor possible contamination of the groundwater especially by ^{90}Sr. No strontium arising from the fallout was, however, observed in the groundwater during the follow-up over the first 1.5 years (Iz89). More than 100 non-overflow and filtration dams were constructed in smaller rivers to retain radionuclides. The riverbanks of the Pripyat were embanked and reinforced and the riverbed was dredged to resist springfloods. In the following few years, the riverbanks and the alluvial land were sown with grass, and trees were planted there to protect the soil against erosion (Ko89).

Because of the risk of flooding, dams can be constructed only in rivers with a low flow rate. They are moreover not applicable in areas where the melting snow and ice in the spring or heavy rain in the autumn cause flooding. This method is moreover very expensive and not likely to be very effective. If the dams are demolished before the amount of radionuclides in the loose bottom sediment have decreased considerably, the sediment that has accumulated behind the dams will be washed, together with the accompanying radionuclides, into downstream water systems during the following high tide. An example of this is the spread of PCB in the Hudson River in the United Stated in the early 1970s when a crid dam used for log driving was dismantled upstream (He79). Riverbeds behind the dams should be dredged before dismantling the dams, or the dams should be left there until the amount of radionuclides will have decreased as a result of physical decay or some other way. If dredging is undertaken, it will produce large amounts of sludge not easy to treat, and the backwater must also be treated.

The active waste present in contaminated water systems has mainly been produced by drinking water treatment plants which take raw water from the surface waters in the fallout area. In Finland it was observed after the Chernobyl accident that about 50% of ^{137}Cs in raw water was removed by a standard aluminium sulphate precipitation (Sa88). Strontium in ionic form, however, was not removed by a regular purification process of raw water. Special measures may be needed to purify seriously contaminated surface water into drinking water, and ion exchange is usually the most effective method (Pe72).

7. CLEANUP OF CONTAMINATED AREAS IN WINTER

7.1 Distribution of Radioactive Contamination

In the winter, the behaviour of radioactivity on surfaces depends on the snow and ice cover, on the frozen ground and on the conditions under which the contamination takes place, i.e. whether a dry or wet deposition has occurred.

In Norway, field experiments were carried out to determine the removal of radioactivity under summer and winter conditions from tar-paper roofs covered with crushed shale. It was observed that 40% of the cesium spread on dry roofs corresponding to summer conditions was removed with rainwater and the meltwaters of snow over the 8-month follow-up. Similarly, 40% of the cesium spread on roofs covered with wet snow was washed off with snow and rain over 3 months, while 65% of the cesium spread on a roof covered with snow and ice was washed off over 4 months (Qv84a).

The runoff of radioactivity with meltwaters from frozen and snowy meadows was also studied in Norway. About 30% of cesium was run off with meltwaters from meadows where the snow started melting 7 weeks after the spread of cesium, and the melting took 8 days (Qv84b). As the experiment was repeated with strontium under different weather conditions where the melting of the snow started 3 days after the spread of strontium and took 16 days, 54% of the radioactivity spread on the meadow ran off with meltwaters and rainfall (Qv86). In both experiments it was observed that the largest amount of radioactivity was removed from the meadows with the first meltwaters (Qv84b,Qv86).

7.2 Cleanup Methods

Radioactivity deposited on snowy and frozen surfaces can be removed rather efficiently with standard equipment used for clearing snow. In field experiments carried out under favourable weather conditions in Norway, where loose snow was removed with a tractor bucket from a frozen parking lot, over 99% of the contamination was removed with the snow (Qv84b). Similar results have been obtained in the United States in field experiments carried out under favourable winter conditions. As the contaminated snow was removed from paved areas with snow ploughs or graders, less than 5% of the contamination remained on the surface. As the frozen surface was then swept mechanically, merely 3% of the contamination remained in the area (Me82).

However, the results obtained by removing contaminated snow and ice may vary considerably, depending on the prevailing conditions. For example, if ice and compact snow appear on a street or road only in irregular stains, while the rest of the surface is bare, relatively little contamination can be removed by removing the snow. In Norway, only 25% of contamination was removed from such a road together with snow using a tractor bucket (Tv90).

As the fallout conditions and the weather may vary considerably in the winter, the choice of the appropriate cleanup method and the obtainable Decontamination Factor depend on the prevailing conditions and the affected sites. Frozen regular surfaces covered with snow can be decontaminated quickly and efficiently with standard snow clearing equipment, but removing snow from uneven surfaces, such as ploughed fields, gardens and forests may prove difficult and slow even under favourable conditions. Part of the contamination can be removed by collecting meltwaters into ditches and holding ponds. In the winter, the amount of organic waste is considerably smaller than in the summer, whereas contaminated water and slot may be abundant.

Cleanup measures for removing radioactive fallout under severe arctic conditions have been experimented with in Greenland after the Thule accident and to some extent also in Canada after the disintegration of the Cosmos 954 satellite above the Northwest Territories.

At Thule, the debris from the airplane and nuclear weapons were collected manually into sacks, which were piled up and protected with wire netting, so that the wind would not spread the debris again (Dr70). The contaminated black snow and ice were gathered in mounds with a planer, and the spread of the snow by the wind was prevented by freezing their surfaces with a foam spray. The cleanup of the site whose area was about 6 ha (La70) produced altogether about 6700 m^3 of waste (Hu70). After the cleanup, carbonized sand was spread on the ice to speed up the melting process (Dr70). In the final report it was estimated that about 93% of the plutonium had been removed in the cleanup (Mc70). In radioecological experiments, carried out the following summer, only a slight increase was observed in the ^{239}Pu concentration of seawater in the affected area. The ^{239}Pu content in the bottom sediment below the collision site was about 100-fold compared with background activity level, and further away about tenfold. Increased concentrations of ^{239}Pu appeared as far as 20 km from the collision site. Bottom-feeding shellfish and fish also showed somewhat higher ^{239}Pu concentrations which, however, were not high enough to necessitate restrictions on their consumption (Aa70).

The Cosmos 954 satellite which disintegrated above the Canadian Northwest Territories caused a relatively small local fallout. The most difficult task under the severe winter conditions was to find the radioactive debris that had spread over was to find under severe winter conditions the radioactive debris that had spread over a large area and was buried in snow. The satellite debris and the radioactivity spread over an area of about 124,000 km^2 in small pieces and particles (Tr84), and they were located in the snow by using aircraft and helicopters equipped with gamma monitors (Ai78). Despite thorough searches, only about 65 kg of metal satellite parts were found, some with a dose rate even higher than 5 Gy h^{-1}. In addition, over 4000 smaller radioactive particles with a diameter of 0.1-1.0 mm and a dose rate of approximately 0.1-1.0 mGy h^{-1} were found (Tr84). The material was collected into plastic-coated lead cases with pliers, and a small amount of snow was removed with a spade from around the site and packed in plastic containers (Ai78). Even though radioactivity had spread over a vast area, it did not produce very much waste.

8. TREATMENT OF WASTE PRIOR TO DISPOSAL

Radioactive wastes arising from the cleanup of contaminated areas can be treated before final disposal in order to reduce their volume and to solidify them. Volume reduction diminishes the need for final disposal sites, and solidification of wastes facilitates the transport of wastes to the final disposal site and also improves their durability.

8.1 Solid Waste

Compaction and incineration are the methods generally used for reducing the volume of low- and intermediate-level wastes (In83).

Compaction can be used especially to reduce the volume of demolition waste and contaminated furnishings. Big objects can first be crushed or torn up and big metal parts cut into pieces mechanically. The space available in waste containers after compaction can be filled with backfill material, such as concrete, so that they will be ready for final disposal after they have been closed up and monitored. The advantage of compaction is that the waste can be compressed and the binding materials added already during the cleaning operations before transport, which contributes to lower transport costs and improved transport safety, and the waste can moreover be disposed of directly. The volume reduction factor for compaction, usually within 3-10, depends very much on the waste material and the compaction pressure of the equipment (In83). Waste compaction and cementation were used when treating the waste that arose from the cleanup of the town of Goiania (Mi89).

If there is access to a waste incineration plant, the wastes can be classified into combustible and non-combustible wastes. Also in that case they can be compacted to cut down transport costs. The advantage of incineration is the resulting large volume reduction, whereas the disadvantages are the extra costs arising from the sorting and transport of the wastes.

The biggest amount of active wastes arising from the cleanup of a large contaminated area are, however, the contaminated vegetation, the soil, and the asphalt and concrete, crushed stone and flagstones. The contaminated vegetation can be incinerated in a waste incineration plant, or it can be collected and covered up in temporary mounds from which it can be transported to final disposal sites after the decomposition of the organics. Waste containing small amounts of organics can be buried in the final disposal together with the contaminated soil. However, the amount of organics in the earth should not exceed approximately 5% of the total amount of solid waste, otherwise the cover structure of the waste trench or mound may crack due to the sinking of the waste caused by the the decomposition of the organics (In92).

The contaminated soil and the asphalt and concrete wastes may be transported and disposed of without pretreatment. They can be compacted at the disposal phase by rolling on site.

As the cleanup of a contaminated area usually produces very large amounst of soil to be treated as waste, studies have been carried out in the United States on the separation of plutonium from earth in connection with the cleanup operations of areas where nuclear weapons tests are carried out and of other areas contaminated by plutonium. The conventional ore extraction method has proved the most applicable (Br88,Ga80). Figure 1 shows the pilot plant equipment used to separate Pu from earth at the Johnston atoll.

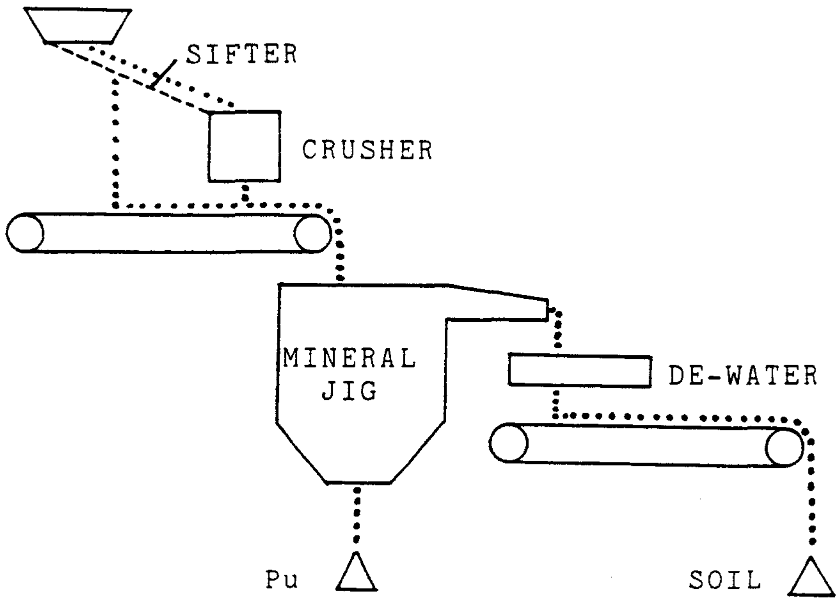


Figure 1. Diagram of the pilot plant equipment used to separate Pu from earth at the Johnston atoll (Br88).

The crushed and sieved soil is led along a conveyor belt into a funnel-shaped mineral separation tank from which flowing water washes the lighter earth through a drying equipment. The heavier earth, which contains Pu, descends to the bottom of the tank, and it can be removed. The water that flows from the separation tank is recirculated into the tank. The separation principle is the same as in gold panning. At the Johnston atoll, the Pu concentration of the soil was over 40 kBq kg^{-1} before extraction, and 500 Bg kg^{-1} after it. About 90% of the soil treated was decontaminated in the first separation. When the Pu-enriched soil was passed through the plant a second time, the overall volume reduction was apprimately 98 %. On the basis of the pilot plant test, a full-scale plant was devised for the treatment of contaminated soil at the Johnston atoll, and it was estimated that all the plutonium-contaminated soil at the atoll, altogether 100,000 m^3, could be cleaned up in four years (Br88).

Carcasses contaminated with radioactivity may require special treatment before they are buried. In Goiania, the contaminated domestic animals were slaughtered and the carcasses were injected with a formaline solution to prevent the formation of gases generated during biological decomposition. In addition, lime and charcoal were used to bind the cesium released from the carcasses (Mi90a).

8.2 Liquid Waste

As conventional nuclear energy production generates large amounts of radioactive waste solutions, several methods have been developed for their treatment and solidification. The most widely known cleanup methods are precipitation, ion exchange and evaporation. Cementation or bituminization are generally used for solidifying residual liquors and sludges or ion exchangers (In84b).

The washings from urban areas and the melt waters of snow and ice account for the largest amount of liquid wastes arising from the cleanup of contaminated areas. Part of the washings may be absorbed into the soil adjacent to buildings, streets and roads, and the soil will then be removed and treated as waste. The washings as well as the rainwater and meltwater are carried from vast paved areas into waste water treatment plants through rainwater drains. A regular waste water treatment process may not remove radionuclides to the extent necessary, and therefore a radionuclide separation process and a waste solidification system might be added temporarily. In older towns, water may discharge along rainwater drains directly into water systems. Leading and collecting washings from streets, parking lots and other paved surfaces in such areas is more difficult and necessitates the construction of specific ditches, embankments and holding ponds. The effluents must moreover be transported to a waste water treatment plant in separate tanks or by road tankers .

Precipitation is a simple and relatively cost effective cleanup method for low-and intermediate-level effluents. The Decontamination Factor is, however, rather low: 10-100 for beta- and gamma-active effluents, and $>10^3$ for alpha-active effluents. Also the volume reduction factor is low (10-100), especially when the residual sludges are solidified wet. When the sludges are dried, the volume of residue diminishes, and the reduction factor may then vary within 200-10^4, depending on the chemical and physical properties of the waste and on the treatment method (In84b).

Precipitation was used in the handling of the waste water from the cleanup of the town of Goiania. ^{137}Cs was precipitated with nickel ferrocyanide from waste solution treated with nitric acid, and the resulting sludge was cemented. The decontamination obtained was about 97 % (Mi90a).

Ion exchange and evaporation are more efficient treatment methods for waste solutions than precipitation. The DF values obtained with ion exchange are approximately 10^2-10^3, and with evaporation 10^4-10^5. By combining these two methods, even a DF of 10^6 can be obtained. The volume reduction factor may be of the same order as that of dried precipitation waste, depending very much on the technical solutions. Ion exchange and evaporation are usually more expensive than precipitation (In84b).

The waste solution transported from Thule to the Savannah River waste treatment plant in the USA, had a volume of 2600 m^3 and contained plutonium. It was filtered, monitored and directed into a seepage basin. Only a small portion was evaporated, and the concentrated waste was stored in a tank for high-level wastes (Fe77).

9. TRANSPORT OF RADIOACTIVE WASTES

The transport of radioactive wastes from the contaminated area to the disposal site depends on the distance between the disposal site and the area to be cleaned up, and on the location of the disposal site. If the disposal site is not within the controlled area, the wastes will have to be transported along public routes, and either international or corresponding national rules and regulations will have to be complied with when packing and transporting the radioactive wastes. Observance of these regulations is not required if the transportation takes place in the controlled area (In92).

General safety factors to be observed in the transport of radioactive wastes (In92,In85b,In87,In88):

a) Preventing the spread of waste material during transport. When transporting large quantities of low-level solid waste, like soil, the load can be covered with a tarpaulin and a polyethylene film. The spread of waste material with air currents or the spill of liquid wastes can, however, be prevented by imposing speed limits. Should the transport involve several loadings and unloadings outside the controlled area, the wastes must be packed in containers.

b) Determining contamination levels on the external surfaces of packages and vehicles after loading and unloading, and decontaminating them if necessary. Determining the radiation level on the outer surfaces, and introducing emergency labels. Loose waste material should be removed from the outer surfaces of containers and vehicles, and their surfaces should be monitored after decontamination. The cleanup and monitoring of the vehicles is usually performed when moving from the contaminated area into a decontaminated or clean area, and after unloading in the storage area.

c) Routing and timing. The safest and shortest route should be selected. Crossing densely populated areas should be avoided when transporting wastes from the controlled area. Timing should be determined so as to avoid rush hour traffic.

d) Monitoring the transport route. The dropping or spill of waste during transport may contaminate the transport route. Especially when wastes are transported outside the controlled area, the route should be monitored regularly.

e) Preparedness for transport accidents. When transporting radioactive wastes outside the controlled area, the vehicle should carry emergency equipment, including a communications system, fire extinguisher, radiation monitor, and equipment needed for the segregation of an area, such as stakes, ropes and signs.

f) Monitoring and registering the quantity, physical and chemical form and activity of the transported wastes. The total amount and activity of the wastes can be determined on the basis of individual waste loads. A control system based on waybills further ensures a safe transport and arrival at the storage place. Computers and telemetry can be used when transporting large quantities of waste.

g) Protecting cleanup workers and the general public against exposure to radiation. When working in a contaminated area, the workers must use the statutory protective clothing and, under dusty conditions, a respirator. Where necessary, an extra filtration system may be added to the cabs of transport vehicles, and extra shielding may be installed between the cab and the platform when transporting more active or concentrated wastes. Workers should always leave the contaminated area via washing rooms and the contamination detector.

9.1 Transporting Wastes Within the Controlled Area

Solid wastes, such as contaminated soil and vegetation, can be removed within short distances (100-200 m) directly into a storage mound, trench or natural basin with bulldozers or scrapers (In89). Yet a large number of waste disposal sites in a vast area are not a good solution in view of long-term control. It can only be used as an interim solution in the absence of adequate hauling equipment or an appropriate final disposal site, and for preventing the resuspension of contamination.

Centralized waste disposal includes the loading, transport and unloading of wastes. It is possible to use heavier hauling equipment in closed areas than on public roads. Big trucks or dump trucks can be used for transporting soil and other solid wastes, and different types of loaders - wheel loaders, front end loaders, backhoe loaders, force feed loaders with a conveyor - can be used for loading, depending on their availability and suitability under the specific circumstances. The wastes can be dumped directly into the final disposal facilities from the trucks or dump trucks. Dry and dusty wastes can be sprayed with water to bind the dust. Also within the closed area, the dispersion of contaminated material to uncontaminated or decontaminated zones during transport should be prevented by covering the waste loads and decontaminating the vehicles (In89, In92).

In the Chernobyl area, the removed soil was first collected into mounds in the middle of the decontaminated area, and then loaded with wheeled or tracked loaders onto dump trucks, lorries and other hauling vehicles available. The platforms of the vehicles were covered with a polyethylene film before and after loading, and the loads were moreover covered with a tarpaulin. The vehicles were decontaminated and monitored at the boundary of the zones with lower activity levels (In92).

Dump trucks were used also at the Enewetak atoll (DNA81). The wastes were first transported into mounds on the beach and were then moved to storage sites to the island of Runit or to the lagoon. The transport took place by sea on vessels or lighters, depending on their access to the islands. Different methods were used for loading the waste onto the vessels. Part of the debris was transported in 20 ton dump trucks, loaded from the mounds with bucket loaders, and the vehicles were transported on the vessels and lighters to the burial site at the lagoon. The debris was unloaded with a crane mounted on a lighter which was anchored at the lagoon. The contaminated soil was dumped from the trucks onto the vessels, or the vessels were loaded with dump trucks or bucket loaders straight from the mounds. The smaller vessel could carry 25-40 m^3 of waste at a time and the bigger 80-90 m^3, depending on the physical form of the wastes. The bigger vessel moreover carried a loader which could be used for unloading the waste. The waste loads on the dump trucks and vessels were covered with a tarpaulin for the transport. When transporting contaminated soil on the islands, the loads were moreover dampened with seawater before applying the tarpaulin. After each working day, the vessels were washed with seawater at the lagoon (DNA81).

9.2 Transporting Wastes Outside the Controlled Area

Waste arising from the cleanup of a vast area contaminated by a nuclear accident is likely to be classified as LSA-II (Low Specific Activity) which, in accordance with international regulations, must be transported in industrial packages (In92,In85b). However, large amounts of waste can be transported under special arrangements under which the shortcomings in packaging and transport methods can be offset by operational controls (In87,In92). The transport of wastes is supervised and accompanied by a radiation protection specialist who is prepared also for emergency situations. Emergency equipment must be made available for the escort. Where necessary, the convoy may also include a police or a fire engine (In87,In88).

Radioactive wastes can be transported outside the controlled area by road, rail or water. The choice of transport method is based on its safety and cost effectiveness.

At Goiania, the ^{137}Cs waste packed in barrels and metal containers was transported on trucks to an interim storage site located at 20 km (Ro91b). After loading the containers, the vehicles were monitored with a surface contamination detector and equipped with warning signs. In case of emergency situations, the transports were escorted by a radiation protection specialist and the police. In urban areas, the speed limit was set at 20 km h^{-1}, and on highways at 40 km h^{-1}. Communication during the transport took place via radio. After unloading, the trucks were once more monitored for possible contamination and, where necessary, they were decontaminated before the return trip (Ro91b). Altogether 275 truck loads of waste were transported to the interim storage site during the cleanup operations at Goiania (Vi90).

Large amounts of low-level waste have been transported safely even over long distances by road and rail in connection with the dismantling of closed-down uranium plants and the cleanup of the surrounding areas. In Canada, almost 70,000 m^3 of soil contaminated with radium and arsenic, together with other solid wastes from the cleanup of areas where uranium mill tailings had been produced, were transported from the city of Port Hope over a distance of 350 km to be buried at the repository of the Chalk River Nuclear Laboratories (In92). Trucks of 20 m^3 were used in the transport operations. Before loading, a polyethylene film was stretched over the platform to prevent the dropping of contaminated material during transport. After the loading, the vehicles were decontaminated, and the load was covered with a tarpaulin and weighed. The transport took place along public roads. The route was monitored regularly for possible contamination but there were no signs of any waste dropping during the transport. The loads were checked again at the unloading site and samples were taken to determine their activity concentrations. The waste was unloaded by dumping from the top of a ridge straight down to a natural valley. Before the return trip, the vehicles were washed and monitored for surface contamination (In92).

Radioactive wastes can be transported also by rail, provided that there is a railroad between the cleanup and the disposal sites. The cost of rail transport may exceed those of direct road transport if double or triple loading and unloading is required, like in a truck-train-truck combination. Even in the case of shorter distances, transport by train is less cost-effective than by truck. However, transport by rail is often a safer alternative because the public roads, or side roads not well-suited for heavy traffic, can then be avoided. It is moreover easier to shield the operational staff from exposure to radiation during rail transport (In92).

In the United States, 1,880,000 m^3 of radium-contaminated soil and mill tailings were moved by rail from the area around the Virto Chemical uranium plant, Salt Lake City, over 140 km to the South Clive desert area (Ra86). At Salt Lake City, the waste was loaded with a backhoe loader onto dump trucks of 32 m^3 and 45 m^3. The waste was dumped via a loading ramp straight into the rail cars. Two rail units of 75 cars were used, one of which was being loaded while the other one was being unloaded. At South Clive the waste was unloaded by clamping one carful at a time with a turnover. The waste was transported to the storage site on dump trucks. The rail cars were washed and monitored after each loading and unloading (Ra86). Spread of the contaminated material during transport was prevented by covering the truck loads with a tarpaulin, and the waste in the rail cars was sprayed with a polymer surfactant (In92).

If an accident resulting in the discharge of radioactivity occurs far away in foreign territory, various techniques, such as the truck-ship-train-truck may have to be used when transporting the waste into the home country. This was the case after the accidents at Palomares and Thule.

At Palomares, the debris from the disintegrated aircraft and nuclear weapons were first collected into containers, then transported by truck to the nearest airport and flown to Texas, the United States (DNA75). The rest of the waste to be transported out of Spain, i.e. the contaminated soil and vegetation, were piled up in heaps, loaded onto trucks and transported to an interim storage site. Wooden boxes that could be sealed were used on the trucks to prevent the dispersion of contaminated material during transport. Water sprays, and in the most severely contaminated areas, light sprays of diesel oil were applied to bind the dust. Also the roads were irrigated to prevent the spread of dust by the trucks. An interim storage was established in the area where the other bomb had fallen and in whose vicinity there was no human settlement. A silo-shaped trench measuring about 760 m^3 was excavated and the wastes were unloaded there. As soon as the transport arrangements had been completed, the waste was packed in metal barrels of 200 l, reinforced on site with metal hoops before they were filled. A third of the barrels was filled with vegetation, and the rest with contaminated soil. After the barrels had been sealed, their outer surfaces were cleaned and monitored. Special transport roads were constructed from the cleanup site to the storage site and further to the Mediterranean coast. The filled up barrels were transported on trucks to the waterfront and loaded onto lighters by a roller conveyor system. Before loading, the outer surfaces of the barrels were monitored once more for contamination. As the big cargo ship could not go ashore at Palomares and the intention was to avoid transporting radioactive wastes by road over long distances in Spain, the waste barrels were moved from the shore onto the cargo ship by flat-bottomed lighters. There was a total of 1150 m^3 of waste with an activity range of 0-300,000 cpm, the activity mostly being lower than 40,000 cpm. All the waste was packed in 4819 barrels which were transported by cargo ship to Charleston port in the United States where they were moved onto rail cars and transported to the Savannah River active waste storage site. Altogether 26 rail cars were needed for the transport operation which was supervised and escorted by two radiation protection specialists (DNA75).

A similar transport of active wastes was carried out from Thule, Greenland, to the United States. The waste to be transported was mostly in liquid form. The debris from the aircraft and from the nuclear bombs was gathered in heaps and was loaded in containers which were placed on the platforms of trucks, and the waste was moved to an interim storage site (Dr70). The snow that had been collected into windrows was loaded with a mechanized loader into wooden cases placed on the truck platform, and the boxes were covered for the transport with a tarpaulin. At the boundary of the contaminated and the clean zones, the loads were cleaned by sweeping, and they were taken to the control station where the drawing vehicle was changed into a new one (Dr70). The snow was dumped with a crane into 95,000 l fuel oil tanks equipped with a specially constructed metal chute. A total of 67 tanks were needed to store up the contaminated snow. As moving and transporting big and nearly full tanks was difficult, the water was pumped into smaller 7000 l containers (Ot70). The rest of the waste was solid waste which amounted to 4 tanks of 95,000 l and 217 barrels of different sizes. The tanks and containers were moved on a truck platform to the harbour where they were loaded onto two cargo ships. Once the wastes had arrived at Carlston port in the United States, they were moved onto trains. The first rail transport comprized 66 and the second 81 cars. The waste was stored at Savannah River (Ot70).

10. DISPOSAL OF RADIOACTIVE WASTES

10.1 Interim Storage

In the absence of final disposal facilities, or when planning and constructing them, it may become necessary to store up the waste in interim storages. Interim storages may also be needed for sludges and liquid wastes whose concentration and solidification may take a long time. Interim storage may be applied also for waste rich in organics and whose volume may reduce considerably as the result of the decay and degradation of the organics.

In the Chernobyl area, where great amounts of radioactive waste had to be disposed of very quickly at the initial stage when no final disposal sites or facilities were yet available, the waste was stored up in surface mounds near the removal sites. The storage sites were located far from water systems and their catchment areas. The bottoms of the waste mounds were lined to prevent the washoff of liquids. The waste, which, in addition to the contaminated earth, contained large amounts of vegetation and other organics, was collected in mounds with bulldozers. The mounds were first covered with a polyethylene film and then with clean earth. As the zone was closed off, a ditch was dug around it and warning signs were posted there (In92).

As it was necessary to bring down the high radiation levels in the areas surrounding Chernobyl and prevent the spread of radioactive materials very quickly, also another interim solution was used for storing the contaminated material. The logs from forests which had died due to radiation, as well as the logging waste, other vegetation and the removed litter were buried in ditches of 1.5-2.0 m deep, after which the area was covered with a 0.5-1.0 m thick layer of clean sand. An estimated $4x10^6$ m^3 of radioactive wastes have been buried at nearly 800 sites in the areas near Chernobyl (Ko90).

At Goiania, the radioactive waste was stored up in a sparsely populated area at 20 km from Goiania (Me89,Ro91b). The waste barrels and containers were placed on 0.2 m thick concrete platforms in an open area, either 32 barrels in two layers or 8 containers on each platform. The waste showing the highest activity levels was placed in the middle of the platforms. Altogether 6 platforms were needed and they were equipped with water collecting drains. The containers and barrels were covered with a waterproof tarpaulin (Me89,Mi90a).

10.2 Final Disposal

10.2.1 Selecting the Final Disposal Site and the Disposal Method

When disposing of radioactive wastes the general principle is that the wastes must be disposed of in such a way that there is no unacceptable detriment to humans and the environment. Therefore, the repository and the disposal method must be selected and realized so that the migration of radionuclides from the waste with water is prevented, and intrusion by humans, animals or the roots of plants is hampered. The waste must moreover be shielded against erosion. The disposal measures must be planned and carried out so that the workers and the general public will be protected from radiological hazards at all operational stages and in case of accidents (In81a,In84a).

In a normal situation, selecting a disposal site for radioactive waste and designing the disposal facility and method is a complex and time-consuming process which involves geographical, ecological, climatic, structural, economic, social and safety analytical studies (In82). The main considerations in the choice of a disposal site are the hydrogeological and ecological characteristics of the area, land use and future land needs, as well as social and economic factors (In81a). In general, the disposal site should be chosen in an area where natural shielding could be made use of. An ideal site is, however, rarely available. The disposal of wastes could be improved by engineered barriers and waste treatment methods, for example, by compacting the waste, by using immobilization materials as backfill and in the structures of the disposal facility, by using flow barriers and drainage, and by shielding the waste against erosion and intrusion (In81a,In84a,In85a). Following the closure of the repository, containing long-lived radionuclides, institutional control is required to ensure that the requirements of radiation protection will be met (In84a,In85a).

Low-activity wastes, which mainly contain ^{90}Sr and ^{137}Cs radionuclides, usually require a disposal which will last for a few hundred years (In92).

In the case of an accident where large amounts of radioactive waste must be disposed of promptly, the situation differs greatly from the normal. The disposal site or sites usually must be selected very quickly using data from possible previous regional studies. The cost of loading, packing and transporting large amounts of waste is a significant consideration. Time is another constraint when constructing disposal facilities, and therefore the materials needed in the structure of engineered barriers and backfill should be readily available. It should moreover be possible to carry out the constructing and the disposal with machines and equipment normally available. Therefore the use of a bedrock facility or concrete trenches, which may take several months or even years to construct, is likely to be very limited (In92,In89).

10.2.2 Shallow Ground Disposal

Burying the waste into the ground is a method commonly used especially in the disposal of community wastes, and it has been applied already for several decades in many countries also for disposing of radioactive waste (In85a).

The impermeability of the burial trench structure and the stability of radioactive substances in the waste and in the repository can be improved with engineering and chemical methods. Figures 2 and 3 illustrate different alternatives for the use of engineered barriers in the structure of a waste trench (In92).

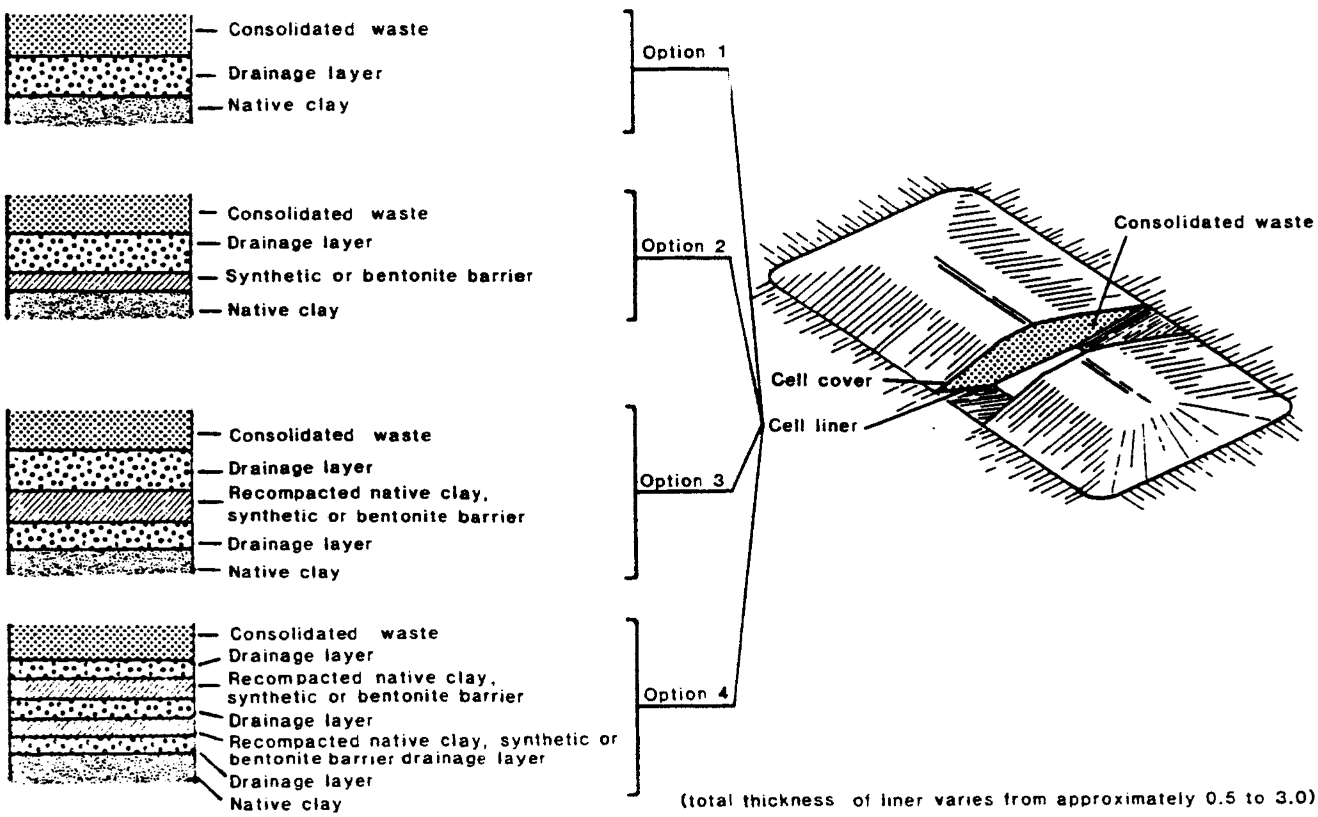


Figure 2. Different designs for waste burial trench lining (In92).

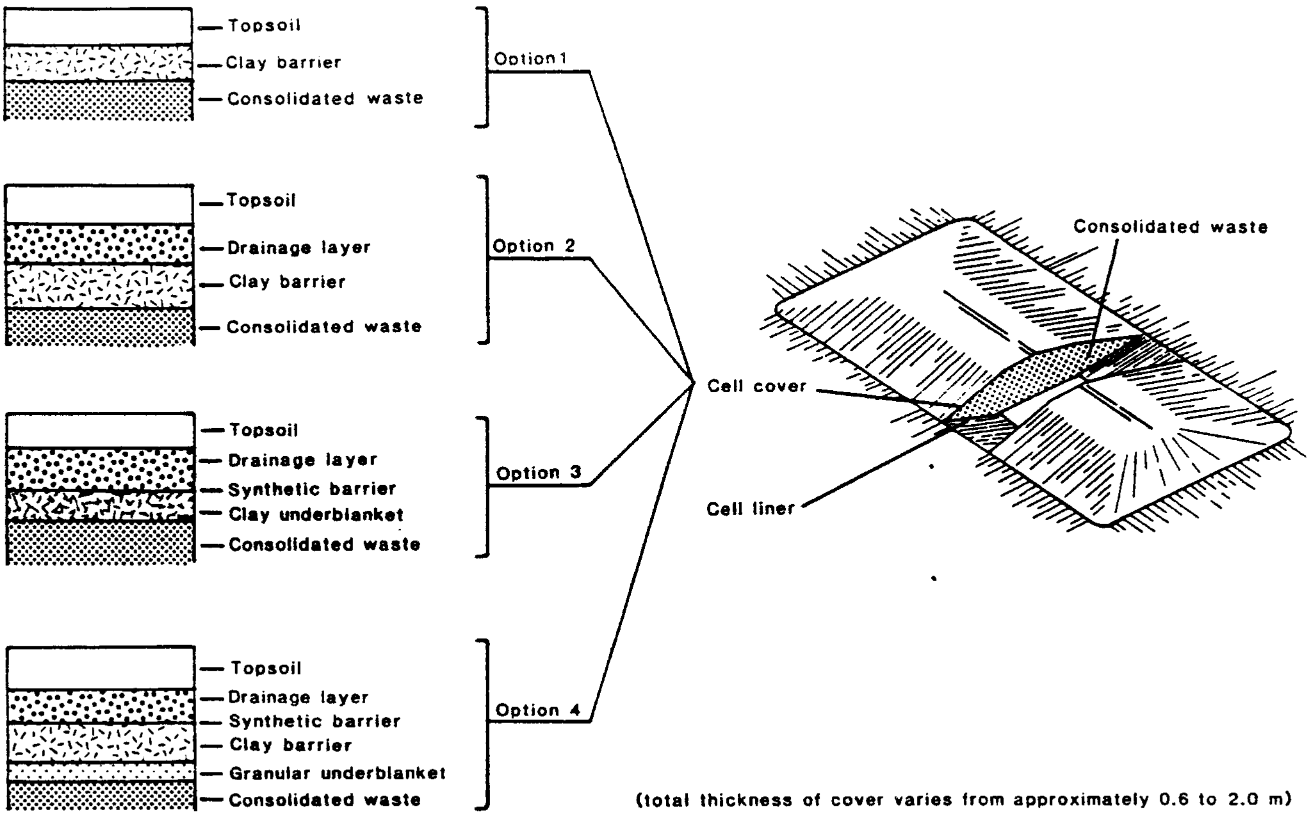


Figure 3. Different designs for waste burial trench capping (In92).

The structure of a waste trench can be relatively simple in clayey soils and under favourable conditions. A simple moisture barrier may be sufficient as lining (Fig. 2, Alternative 1). The trench will be covered with a layer of clay, which will prevent the intrusion of rainwater, surface water, animals and plant roots into the waste. The clay layer will be covered against erosion with top soil (Fig. 3, Alternative 1). Radioactive wastes can be buried into the ground safely by using engineered barriers or increasing their thickness, by choosing materials with a higher retaining capacity, and by the canalization of groundwater, rainwater and meltwater (Figs 2, 3 and 4). A layer constructed of rubble, reinforced concrete or similar materials to prevent the intrusion by humans, animals or plants can be omitted, provided that the burial trench will be kept under control until the radioactivity of the waste will have decreased to an acceptable level (In92).

Waste burial trenches dug into the soil are usually shallow trench-type excavations and the angle of the slope of their walls varies between 45° - 90°, depending on the type and properties of the soil. The bottom of the trench is usually above the ground water table. The surface of a covered trench may be at ground level or it may form a small mound. Depending on the physical form and activity of the waste and the permitted total load of the trench, the waste can also be arranged in layers in a mound (Fig. 2), so that the burial trench will accommodate a considerably larger amount of waste. The access of surface waters is prevented by digging ditches around the area (Fig. 4).

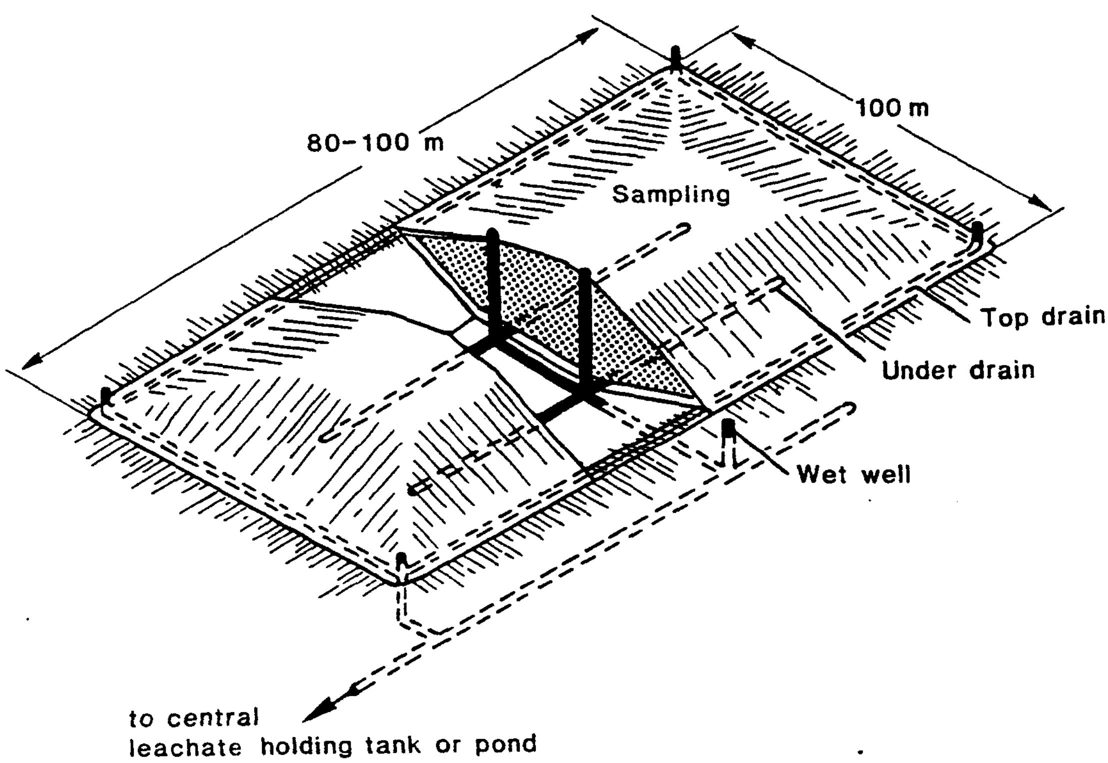


Figure 4. Drainage of a waste burial trench

In humid areas water may accumulate in the trenches if host soils are of low permeability. If the cap has developed cracks, the accumulation of water can lead to an overflow of the trenches on the ground (Fi84,Pr77). The accumulation of water at the bottom of the trench can be prevented by subsurface drainage, and the moisture situation can be monitored through connecting pipes and collecting wells (Fig. 5). The possible migration of radionuclides can also be detected at an early stage.

In the Chernobyl area, the burial method illustrated in Figures 3 and 4, i.e. semi-cavity-semi-mound, was used in the final disposal of low- and intermediate-level wastes. That method allowed more than 10,000 m^3 of waste to be disposed of in one large trench (In92). The bottom and the walls of the trench were lined with clay. The clay layer at the bottom was 1.0 m thick. The waste was covered and levelled with a 0.6 m thick layer of native soil, on top of which was spread a 0.5 m thick clay layer. A 1.0 m thick layer of native soil was applied as the erosion barrier. The waters were directed around the trench, and each trench was equipped with a sampling well. The disposal site was fenced off and illuminated (In92).

In shallow ground burial the walls and the roof of the trench can also be constructed of concrete. A new concrete trench structure, which is more resistant to intrusion and changes in weather conditions, was recently designed at the Chalk River Nuclear Laboratories in Canada, where low- and intermediate level wastes have been buried into the ground ever since 1946. The trench is designed to be located in a free-draining sandy dune. Figure 5 illustrates the overall structure of a closed waste trench placed in the ground (Ha86).

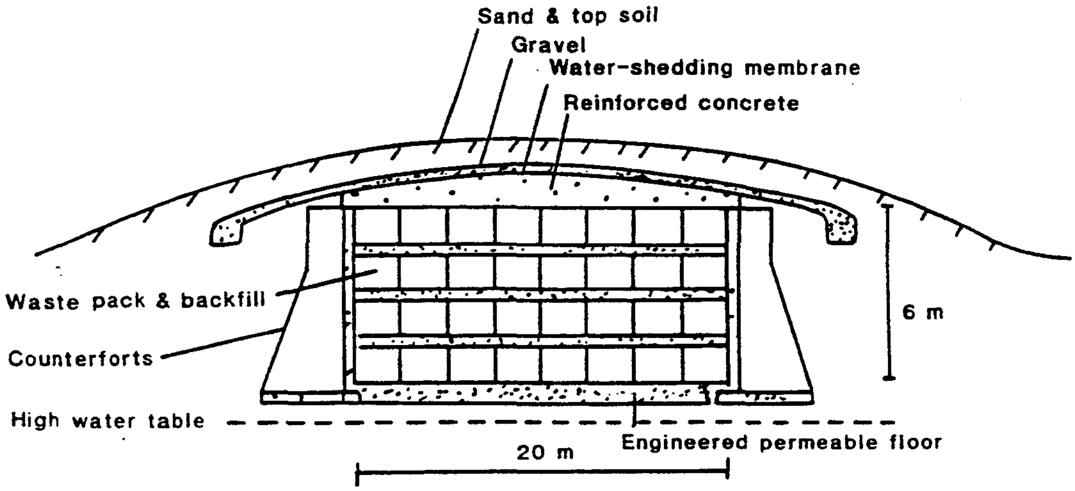


Figure 5. Cross-section of the reinforced concrete waste trench designed at the Chalk River Nuclear Laboratories (Ha86).

The walls and the roof which they support are made of reinforced concrete. There is a clayey sand layer at the bottom. Native illite clay in a 5% mixture was chosen as it showed an adequate sorption of radionuclides and suitable hydraulic conductivity (Bu86,Ha86). The clay and sand layer is shielded with a capillary layer of gravel. Sand will also be used as backfill material between the waste packages. The 1 m thick concrete cover, which will close the trench, will be shielded against moisture either with bitumen, epoxy coatings or a thick polymer sheet. The upper layer of soil, which is 1-2 m thick, will consist of layers of gravel, sand, cobbles and topsoil. The trench is nearly 100 m long, 20 m wide and 6 or 8 m deep, depending on the thickness of the sand dune and the ground water table. The trench has been divided into three 33 m long separate compartments. It has been estimated, that out of the total capacity of 12,000 m^3, about 8,000 m^3 will be filled with packed waste and the rest with backfill material. The total activity of the waste to be buried is estimated at

900 TBq (24,000 Ci). The structure of the trench has been designed to last 500 years. In the initial safety analyses, it has been estimated that the structure may have to be under institutional control for 50-100 years (Ha86).

In Mexico, the ^{60}Co waste from the cleanup after the Ciudad Juáres accident was buried into the ground in trenches isolated with concrete in an arid and remote area at 70 km from Ciudad Juáres (Mo90).

The wastes from the Palomares and Thule accidents were disposed of at the Savannah River active waste disposal site in the United States, where radioactive waste has been buried into the ground already for almost 40 years. By 1982, about 370,000 m^3 of low-active waste with an estimated 370 PBq (10^7 Ci) activity had been buried in that area. In addition, about 15 PBq (0.4×10^6 Ci) of transuranic wastes were stored up in mounds (St84). Due to the climate, soil type and location, a fairly simple burial method and trench stucture can be used in that area. Usually the trenches are 100-300 m long, 6 m wide and 6 m deep, and their bottom is at least 3 m above water table (Fe77). As the soil contains a sufficient amount of clay, no engineered barriers are normally used when burying ordinary low-level waste. It is moreover not required that the LLW should be packed, so the waste from their own plant is buried directly into the ground as such. Native soil is used as backfill material and to close the trench. The earth layer covering the trench must be at least 1.2 m. The surface of the closed trench shall be left at ground level to prevent erosion by surface water and the wind. In addition, the impact of erosion will be reduced by sowing the area with shallow-rooted grass (Fe77).

The waste barrels shipped from Palomares were buried at Savannah River into two trenches, which were exceptionally closed with a 3 m layer of earth (Fe77).

The aircraft debris and other solid wastes shipped from Thule, as well as the storage and shipping tanks for ice and water were buried into three trenches (Fe77).

Surveillance of the wastes buried at Savannah River includes a regular follow-up of the migration of radionuclides through wells drilled at different depths, also situated outside that area. With the exception of tritium, no significant migration of radionuclides into ground water has been observed (St84). As it has been found that plants, especially the long-rooted species, accumulate radioactivity, herbicides have been used to combat excess vegetation. Vegetation has moreover been removed and buried as waste. Various solutions for capping and covering materials have been studied at the plant (Fe77).

10.2.3 Surface Mounds

Disposing waste in surface mounds is an equally common method as shallow ground land disposal. Both methods are used simultaneously or in combination, as at the Centre de la Manche disposal site in France (In85a). Disposing waste in surface mounds may moreover be a safer alternative in an area which does not adapt well to waste burial, for example, because of a high water table .

In principle, the structure of a surface mound is similar to that of a waste burial trench, featuring buffer and intrusion barriers and water canalization layers (Figs 2 and 3). Figure 6 illustrates the structure of a mound in which the usual clay layer has been replaced by a polyethylene film and geotextiles (In92).

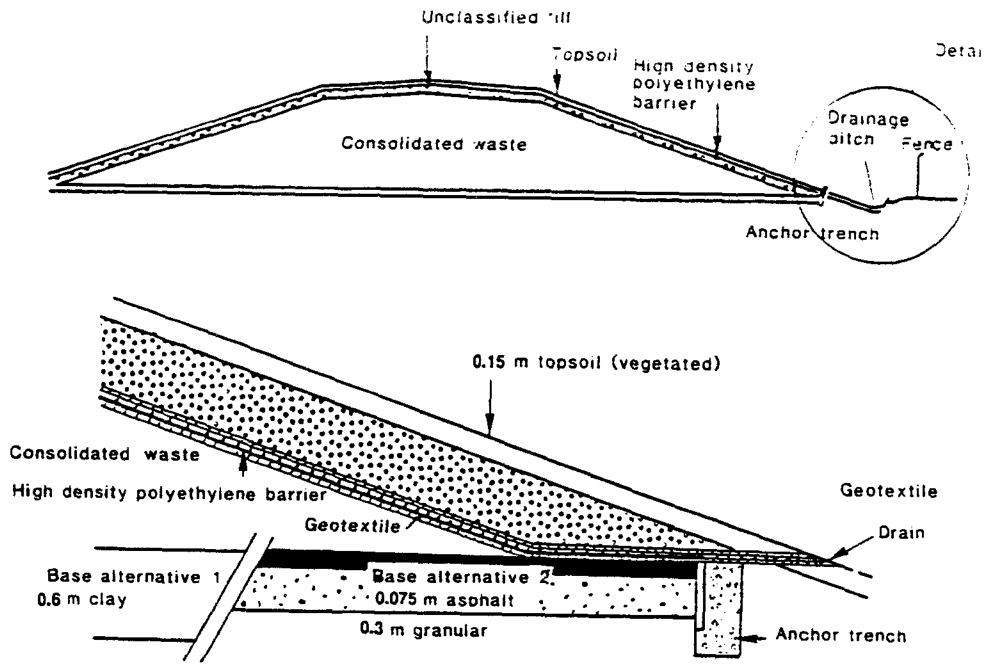


Figure 6. Detailed cross-section of a surface mound (In92).

Active wastes disposed of in surface mounds often require a fairly heavy shielding against wind, surface water, rain and other types of intrusion. Sand, gravel, cobbles or similar materials can be used for the intrusion and moisture barrier. Surface waters will be directed into a collecting ditch around the mound by placing the cap in the right angle of gradient. Also the bottom should be bevelled towards the edges so that no moisture would gather under the waste mound. There are several alternatives for lining, depending on the soil type, its moisture and the climatic conditions. Figure 6 illustrates two solutions: lining with a mere 0.6 m clay layer, or with a 0.3 m gravel layer covered with 0.075 m thick asphalt layer (In92).

In humid climates, where melt waters and frost heaving must be considered, the structure of a durable and safe mound may be rather massive. For example, the total thickness of the cap of a mound planned to be situated at West Valley, New York, is nearly 5 m (Bl86). The low-active liquid from the waste water solidification process, immobilized in concrete, as well as other waste from the cleanup and decontamination of the area, a total of 13,300 m^3 of waste, would be stored into that mound. It has been estimated that 3,700 m^3 of the waste has an activity of 2.2 PBq (6×10^4 Ci), including about 70 TBq (2×10^3 Ci) of ^{241}Pu (Bl86).

Mounds with a similar structure, used for disposing the mill tailing wastes of uranium, may also be used for disposing great amounts of waste in an area contaminated by a nuclear accident. As nuclear waste mainly contains ^{90}Sr and ^{137}Cs, the capping of the mound may be lighter than when disposing uranium mill tailings in which the predominant radionuclide is the long-lived ^{226}Ra (1600 a), whose daughter nuclide ^{222}Rn usually requires a thick buffer barrier (In92).

In the United States, the mill tailings of uranium and other cleanup wastes, a total of 1,880,000 m^3, were disposed of in a big mound at South Clive, Salt Lake City, Utah (Ra86,USDOE84). The structure and dimensions of the surface mound are illustrated in Figure 7.

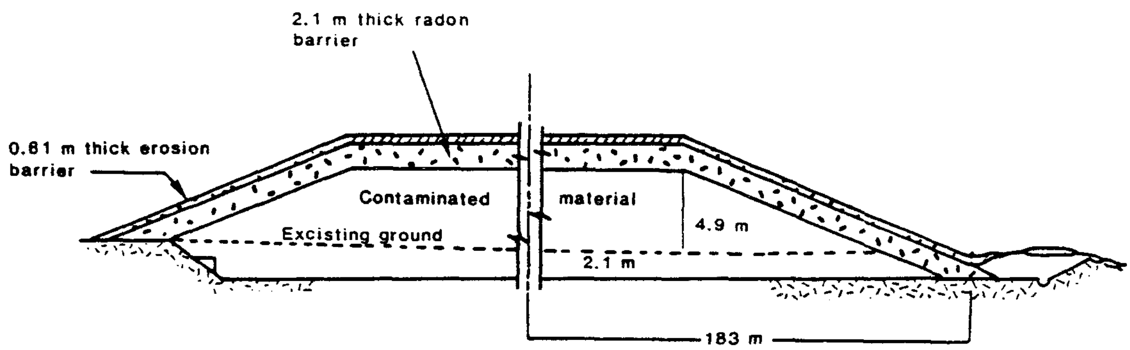


Figure 7. The structure of a surface mound at South Clive (Ra86).

The external dimensions of the mound are 671 m in length and 366 m in width. The topsoil was removed from the site and used as a covering material, and therefore part of the bottom of the mound is a couple of meters under ground. No lining on the bottom was used. Instead, the waste was compacted against the ground. The composition of the underlying soil ranges from fine- and medium-grained sands to silty clays, and the water table is 7.6-10.7 m below the ground surface (Ra86). The South Clive area is an arid desert (USDOE84). The layer which prevents the release of radon was constructed of clay, and the erosion and intrusion barrier of blasted rock (Ra86).

10.2.4 Natural Valleys and Basins

Valleys with a suitable geological structure and natural basins have been used for disposing of especially uranium mill tailings. Basins and valleys can also be used in emergencies where large amounts of solid low-active cleanup wastes must be disposed of, provided that there is a suitable valley in the contaminated area or in its vicinity. Figure 8 shows the basic structure of a typical valley dam designed for disposing uranium mill tailings (In81b).

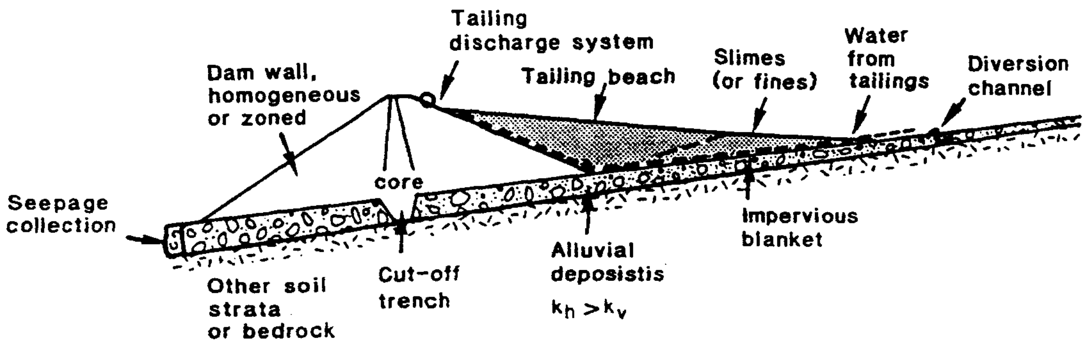


Figure 8. Cross-section of a valley dam closed off with an impoundment (In81b).

The confinement basin is formed by constructing an embankment across the valley at the downstream end. Where necessary, the bottoms and the walls of the basin will be levelled, compacted and lined with low-permeability material, such as clay or clayey soil. The infiltration of surface waters into waste is prevented by drainage. The filled up basin is covered with regular capping materials. The covered area is likely to be vast and therefore exposed to erosion. The average depth of wastes in the basin is low, as the waste layer becomes shallower towards the edges. Since the valley is closed off by natural barriers from three sides, a relatively short dam embankment is usually required, which cuts down the construction costs. Extra costs may arise from the uneven and irregular bottom and walls of the valley which may hamper the installation of any liner and the compaction of the waste into the basin (In81b).

Almost 119,000 tons of low-active waste soil, mostly uranium mill tailings, containing, in addition to radium, also arsenic, was buried into a valley in the Chalk River area, Canada. Together with the waste soil were buried also cleanup wastes from the Port Hope area, such as concrete flags, blocks, logs and tree roots (Ki85). In the east, the valley bordered on the bedrock, and in the west on a ridge of dune sand. After the removal of logs and slash, the contaminated soil was spread in the valley and compacted with a bulldozer in layers of 0.7 m. Sand was spread against the bedrock to isolate the waste from the rock. In the section bordering on the sandy ridge, the waste was compacted directly against the ridge. The basin was filled with wastes up to 1 m from the top of the ridge. The waste layer was almost 12 m at the thickest, and the area covered by waste was about 1.5 ha. The area was first covered with native clayey silt whose thickness was 0.3 m. On top of that layer was spread a 0.7 m sandy layer to prevent the leaching of the clay layer and the intrusion of roots into it. A sandy topsoil layer of 0.15 m was applied as the upper layer (Fig. 9). A ditch was dug on the side of the bedrock to direct the surface waters flowing down the rock to run around the waste basin (Ki85).

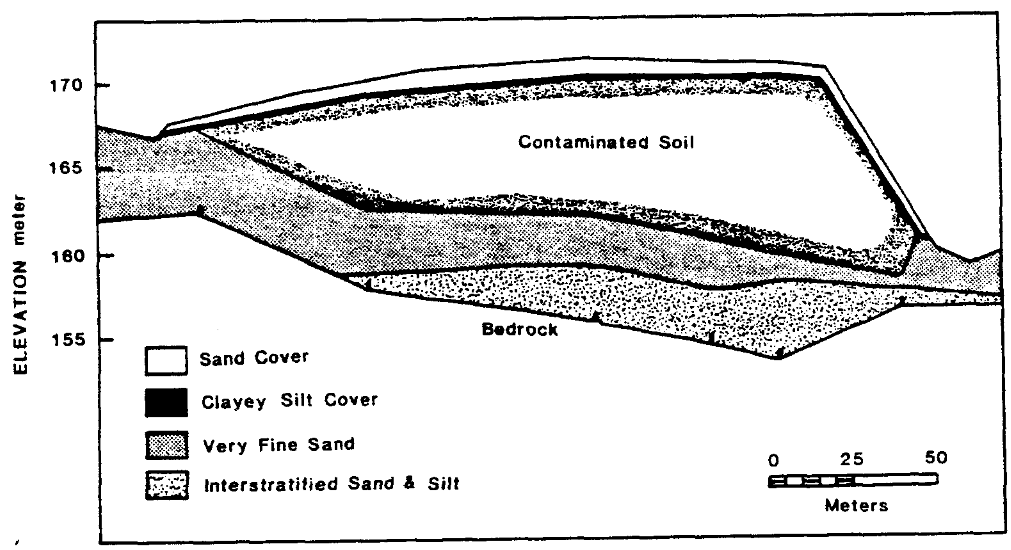


Figure 9. Cross-section of a filled-up valley (Ki85).

The impermeability of the capping layers, however, presented problems already after the first winter. The clayey layer had cracked during the winter, which may have been partly due to the settling of the underlying waste soil and probably the drying and shrinkage of the covering clay. Sand had infiltrated the cracks, preventing their self-sealing by swelling. It was observed that especially during heavy rain, water infiltrated the waste, causing the dissolution of arsenic and washing it downwards. Three years later, small amounts of arsenic were found to have migrated also into the sandy layer under the waste, but none was found in the groundwater. No migration of radium was observed (Ki85).

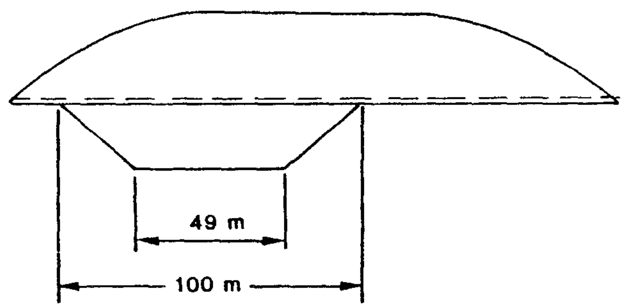
10.2.5 Old Mines and Pits

Great amounts of low-active solid cleanup waste can also be emplaced in a closed down underground mine or open pit, if they are situated relatively near. The climate, the water table and its fluctuations, flowing surface waters and wall permeability are some of the factors to be considered when assessing the suitability of an old mine or pit for disposing radioactive wastes (In92).

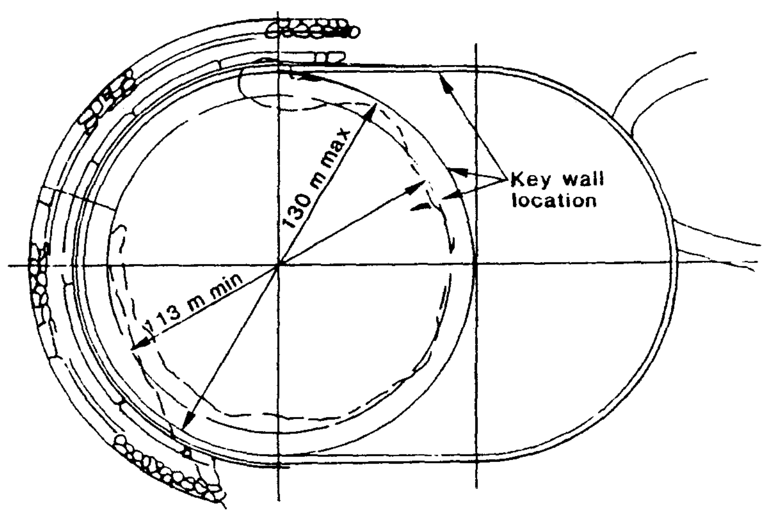
Shafts and open pits are usually located deep below the normal groundwater level. Water and moisture often permeate into the caverns through cracks and breaks present in the bedrock and through fractures in the walls caused by mining. Also the migration of radionuclides can occur through these cracks. Rough walls may moreover hamper the installation of liners and barriers, and special techniques may be necessary for installing and compacting the wastes. Old mines and pits usually require careful and time-consuming geological and hydrogeological studies before they can be used for disposing radioactive wastes.

In Germany, low- and intermediate-level wastes are intended to be disposed in the old iron ore mine at Konrad. The galleries are very dry, and they are situated in clayey soil at the depth of 1000-1200 m. It has been estimated that 500,000 m^3 of wastes can be disposed of in that mine (Ri88).

Craters created by a nuclear explosion, like the one at the Enewetak atoll, where the radioactive debris and soil were buried, may be compared with open pits. The waste was buried in the Cactus crater in the northern part of the island of Runit (Yvonne) which was the most severely contaminated area at the atoll (DNA81). The crater was 11 m deep with a diameter of 105 m. The trench was designed as a 9-m-high mound with a dome-shaped roof. As the final amount of wastes was not known when the work was started, an extension up to the volume of 153,000 m^3 was reserved outside the crater (Fig. 10).



Cactus ctrater design profile



Cactus crater container design overhead

Figure 10. Structure of the Cactus crater disposal dome (DNA81).

A mole was constructed on the ocean side of the crater to protect the dome structure against the shock of waves. The construction material was mined at the island of Runit. A concrete wall of 0.6 m was constructed around the crater at about 3.7 m from the edges, and the wall was set in a solid coral reef at the minimum depth of 0.3 m, or 2.4 m where no uncracked solid reef existed. The outer edge of the wall was left at 0.3 m above the reef.

The diameter of the final trench was 113 m and the height 7.5 m. The bottom of the crater was of severely contaminated coral, which had cracked, causing radioactive substances to leak into the lagoon. It was estimated that the cemented waste soil, which was to be compacted tightly onto the bottom, would isolate the bottom to some extent.

The contaminated soil, collected in stock piles on the island of Runit, was sieved and mixed with concrete, attapulgite clay and seawater into a sludge which was pumped into the crater. Attapulgite was used mainly to improve the flow of the sludge. The sludge was transported from the mixing site to the pumping site on transit mixtrucks, which mixed the sludge already in transit. Where pumping could not be used due to temporary technical problems, the sludge was hardened in ditches, dug into the ground, and the flags were transported to the crater with bulldozers. So was the coarser and bigger debris, which was buried with the sludge. The upper part of the dome was constructed of a mixture of soil and concrete, mixed on site. The soil was spread in layers of 0.15 m, the dry concrete was mixed with it, the layer was sprayed with seawater and compacted with a vibratory roller-compactor. The dome was closed with 0.46 m thick concrete flags (DNA81). Altogether 79,600 m^3 of wastes, with a total activity of about 544 GBq (14.7 Ci), were disposed of in the crater. In addition, less active debris was buried at three different sites in the lagoon (DNA81).

10.2.6 Bedrock Caverns

Disposing low- and intermediate-level waste into galleries and caverns in the bedrock has been studied, and plans have been drawn up in many countries (Ri88,O186,Ma86,Be88). Final diposal sites in the bedrock are usually designed for solid or solidified packed wastes.

In Sweden, for example, a final disposal facility for low- and intermediate-level wastes, constructed in crystalline bedrock 60 m below the sea bed, at about 1 km from the port of Forsmark, was taken into use a couple of years ago (Fig. 11) (Ri88,Fo86).

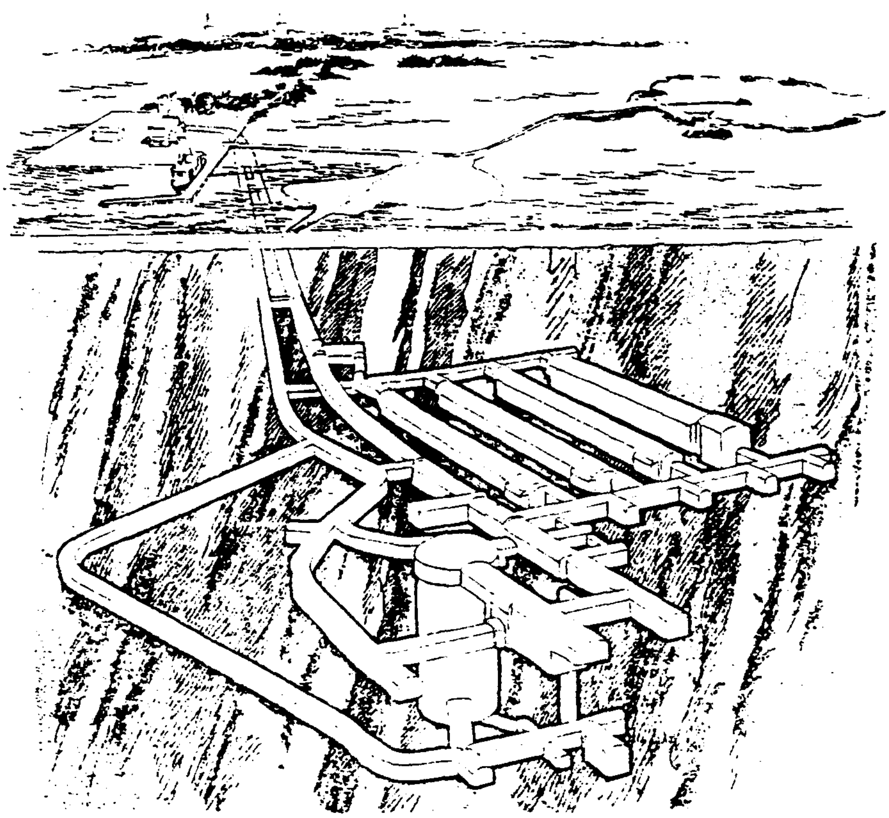


Figure 11. Disposal facility for low- and intermediate-level wastes in the bedrock at Forsmark, Sweden (Fo86).

Operational and decommissioning waste from 12 nuclear plant units, as well as waste from research, hospitals and industrial plants will be disposed of in that facility. The total radioactivity of the wastes to be disposed of is estimated at 10 PBq (3 10^5 Ci). Prior to disposal, the wastes will be solidified and packed. Intermediate-level wastes will be disposed of in concrete silos, which have been isolated from the bedrock with bentonite. Bentonite will also be used as backfill material in the silos (Ri88,Fo86).

Waste from emergency situations, which may have been concentrated before solidification, such as washing fluids, sludges, or ashes from incineration, can be disposed of in the bedrock, provided that there is a facility available. Disposing other types of waste, such as contaminated soil, into the bedrock may be a more expensive alternative than disposing them in surface mounds or shallow ground burial.

11. REFERENCES

Aa70 Aarkrog, A., 1970, "Radio-Ecological Investigations", *Project Crested Ice*, G.E. Torres, ed., USAF Nuclear Safety, Kirtland AFB, NM, AFRP 122-1

Ad81 Adriano, D.C. et al., 1981, "Fallout of Cesium-137 on a Forest Ecosystem in the Vicinity on a Nuclear Fuel Reprocessing Plant", *Health Phys.* **40**, 369

Ai78 Aikman, B., 1978, "Operation Morning Light", *Sentinel(Ottawa)* **14**, 4

Am91 Amaral, E.C.S. et al., 1991, "Distribution of ^{137}Cs in Soils Due to the Goiânia Accident and Decisions for Remedial Action During the Recovery Phase", *Health Phys.* **60**, 91

Ar91 Arkhipov, N.P. et al., 1991, "Measures (and their Effectiveness) to Improve the Radiological Situation Given the Particular Features of the Contamination Caused by the Kyshtym and Chernobyl Accidents", in: *Proc. Seminar on Comparative Assesment of the Environmental Impact of Radionuclides Released during Three Major Nuclear Accidents: Kyshtym, Windscale, Chernobyl*, Vol II, pp. 977-992, Report EUR 13574.

As91 Asmolov, V.G. et al., 1988, "The Accident at the Chernobyl Nuclear Power Plant: One Year After", in: *Nuclear Power Performance and Safety*, Vol. 3, IAEA, Vienna, pp. 103-147, IAEA-CN-48/63.

Be88 Beale, H., 1988, "Repository Design & Development", *Nucl. Eng.* **29**, 38

Bl86 Blickwedehl, R.R., 1986, "Design and Performance Assessment of an Above Grade Disposal Structure", in: *Proc. 2nd Int. Conf. on Radioactive Waste Management*, pp. 68-72 (Toronto: Canadian Nuclear Society).

Br88 Bramlitt, E.T., 1988, "Plutonium Mining for Cleanup", *Health Phys.* **55**, 451

Bu86 Buckley, L.P. et al., 1986, "Evaluation of Backfill Materials for a Shallow-depth Repository", in: *Proc. 2nd Int. Conf. on Radioactive Waste Management*, 7-11 September, pp. 212-216 (Toronto: Canadian Nuclear Society)

Bu89 Bunzl, K. et al., 1989, "Interception and Retention of Chernobyl-derived ^{134}Cs, ^{137}Cs and ^{106}Ru in a Spruce Stand", *Sci. Total Environ.* 78, 77

Ca78 Carlsson, S., 1978, "A Model for the Movement and Loss of ^{137}Cs in a Small Watershed", *Health Phys.* 34, 33

DNA75 Defense Nuclear Agency, 1975, *Palomares Summary Report*, AD-A955702 (Springfield VA: NTIS)

DNA81 Defense Nuclear Agency, 1981, *Radiological Cleanup of Enewetak Atoll*, AD-A107997 (Springfield VA: NTIS)

Do81 van Dorp, F. et al., 1981, *Agricultural measures to reduce radiation doses to man caused by severe nuclear accidents*, Commission of the European Communities Report EUR 7370

Dr70 Dresser, G.S., 1970, "Host Base Support", *Project Crested Ice*, G.E. Torres, ed., USAF Nuclear Safety, Kirtland AFB, NM, AFRP 122-1

Ed75 Edgington, D.N. and Robbins, J.A., 1975, "The Behaviour of Plutonium and Other Long-Lived Radionuclides in Lake Michigan", in: *Proc. Int. Symp. on Impacts of Nuclear Releases into the Aquatic Environment*, SM-198/40 (Vienna: IAEA)

Fe77 Fenimore, J.W. and Hooker, R.L., 1977, *Assessment of Solid Low-Level Waste Management at the Savannah River Plant*, Du Pont de Nemours and Co., Savannah River Laboratory, Aiken, SC, DPST-77-300

Fi84 Fischer, J.N. and Robertson, J.B., 1984, "Geohydrologic Problems at Low-Level Radioactive Waste Disposal Sites in the United States of America", in: *Proc. Int. Conf. on Radioactive Waste Management*, CN-43/183 (Vienna: IAEA)

Fo86 Forsström, H.G., 1986, "Progress of the Swedish Radioactive Waste Management Program", in: *Proc. 2nd Int. Conf. on Radioactive Waste Management*, pp. 33-40 (Toronto: Canadian Nulear Society)

Ga80 Garnett, J.E. et al., 1980, *Initial Testing of Pilot Scale Equipment for Soil Decontamination,* Rockwell International Corp., Golden, CO, RFP-3022

Gu75 Gudiksen, P.H. and Lynch, O.D.T.,Jr., 1975, "Radioactivity Levels in Eniwetok Soil", *Health Phys.* 29, 17

Ha74 Hardy, E.P.,Jr., 1974, *Fallout Program, Quarterly Summary Report*, USAEC Health and Safety Laboratory, New York, NY, HASL-286

Ha86 Hardy, D.G. and Dixon, D.F., 1986, "Safety and Cost Assessments for Disposal in a Prototype Shallow Land Burial Facility", in: *Proc. 2nd Int. Conf. on Radioactive Waste Management*, pp. 418-426 (Toronto: Canadian Nuclear Society)

He79 Henningson, J.C. and Thomas, R.F., 1979, "Hudson River Cleanup", *Environmental Decontamination*, G.A. Cristy and H.C. Jernigan, ed., Oak Ridge National Laboratory, Oak Ridge, TN, CONF-791234

Hu70 Hunziker, R.O., 1970, "The Commander's Point of View", *Project Crested Ice*, G.E. Torres, ed., USAF Nuclear Safety, Kirtland AFB, NM, AFRP 122-1

Hä74 Häkkinen, U.L. and Lakkanen, E., 1974, "The Adsorption and Extraction of ^{90}Sr and ^{137}Cs in Finnish Soil", in: *Proc. Int. Symp. on Comparative Studies of Food and Environmental Contamination*, SM-175/37 (Vienna: IAEA)

Il88 Il'in, L.A. and Pavlovskij, O.A., 1988, "Radiological Consequences of the Chernobyl Accident in the Soviet Union and Measures Taken to Mitigate Their Impact", in: *Nuclear Power Performance and Safety*, Vol. 3, IAEA, Vienna, pp. 149-166, IEAA-CN-48/33.

In81a International Atomic Energy Agency, 1981, *Shallow Ground Disposal of Radioactive Wastes, A Guidebook*, Safety Series No. 53 (Vienna: IAEA)

In81b International Atomic Energy Agency, 1981, *Current Practices and Options for Confinement of Uranium Mill Tailings*, Technical Reports Series No. 209 (Vienna: IAEA)

In82 International Atomic Energy Agency, 1982, *Site Investigations for Repositories for Solid Radioactive Wastes in Shallow Ground*, Technical Reports Series No. 216 (Vienna: IAEA)

In83 International Atomic Energy Agency, 1983, *Treatment of Low- and Intermediate-Level Solid Radioactive Wastes*, Technical Reports Series No. 223 (Vienna: IAEA)

In84a International Atomic Energy Agency, 1984, *Design, Construction, Operation, Shutdown and Surveillance of Repositories for Solid Radioactive Wastes in Shallow Ground*, Safety Series No. 63 (Vienna: IAEA)

In84b International Atomic Energy Agency, 1984, *Treatment of Low- and Intermediate-Level Liquid Radioactive Wastes*, Technical Reports Series No. 236 (Vienna: IAEA)

In85a International Atomic Energy Agency, 1985, *Operational Experience in Shallow Ground Disposal of Radioactive Wastes*, Technical Reports Series No. 253 (Vienna: IAEA)

In85b International Atomic Energy Agency, 1985, *Regulations for the Safe Transport of Radioactive Material*, Safety Series No. 6, and Supplement 1986 (Vienna: IAEA)

In87 International Atomic Energy Agency, 1987, *Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (1985 Edition)*, Safety Series No. 37, 3 Edition (Vienna: IAEA)

In88 International Atomic Energy Agency, 1988, *Emergency Response Planning and Preparedness for Transport Accidents Involving Radioactive Material*, Safety Series No. 87 (Vienna: IAEA)

In89 International Atomic Energy Agency, 1989, *Cleanup of Large Areas Contaminated as a Result of a Nuclear Accident*, Technical Reports Series No. 300 (Vienna: IAEA)

In92 International Atomic Energy Agency, (in press), *Disposal of Material from the Cleanup of Large Areas Contaminated as a Result of Nuclear Accident*, Technical Reports Series No. XXX (Vienna: IAEA)

Ir68 Iranzo,E., 1968, "First Results from the Programme of Action Following the Palomares Accident", Paper presented at the *3rd Symp. on Radiological Protection of the Public in a Nuclear Mass Disaster*, 24 May - 1 June, Interlaken, Switzerland

Iz88 Izraehl, Yu.A. et al., 1988, "The Ecological Consequences of the Radioactive Contamination of the Natural Environment in the Region of the Chernobyl Atomic Power Station Accident", *Sov. At. Energy* **January**, 33

Iz89 Izraehl, Yu.A., 1989, "Study of Radioactive Contamination of the Environment Caused by the Chernobyl Nuclear Power Plant Accident: Main Results", in: *Proc. Int. Symp. on Environmental Contamination Following a Major Nuclear Accident*, SM-306/121 (Vienna: IAEA)

Ja73 James, P.E. and Menzel, R.G., 1973, "Research on Removing Radioactive Fallout from Farmland", *U.S. Dept. Agric. Tech. Bull.* **No. 1464**

Ja87 Jacob, P. et al., 1987, "Reduction of External Exposure from Deposited Chernobyl Activity by Run-off, Weathering, Street Cleaning and Migration in the Soil", *Radiat. Prot. Dosim.* **21**, 51

Ju70 Juo, A.S.R. and Barber, S.A., 1970, "The Retention of Strontium by Soils as Influenced by pH, Organic Matter and Saturation Cations", *Soil Sci.* **109**, 143

Jä90 Järvinen, P., 1990, "Radiological Protection Considerations in the Use of Ash from Chernobyl Contaminated Peat Fuel, in: *Proc. Int. Symp. on Environmental Contamination Following a Major Nuclear Accident*, SM-306/58P (Vienna: IAEA)

Ki85 Killey, R.W.D. and Myrand, D., 1985, *The Movement of Water, Arsenic, and Radium at a Chalk River Waste Management Area 1979-1983*, Atomic Energy of Canada Limited, Chalk River, Ontario, AECL-8639

Ko90 Komarov, V.I., 1990, "Radioactive Contamination and Decontamination in the 30 km Zone Surrounding the Chernobyl Nuclear Power Plant", in: *Proc. Int. Symp. on Environmental Contamination Following a Major Nuclear Accident*, SM-306/124 (Vienna: IAEA)

La70 Langham, W.H., 1970, "Technical and Laboratory Support", *Project Crested Ice*, G.E. Torres, ed., USAF Nuclear Safety, Kirtland AFB, NM, AFRP 122-1

Lö90 Lönsjö, H. et al., 1990, "Effects of Remedial Measures on Long Term Transfer of Radiocaesium from Soil to Agricultural Products as Calculated from Swedish Field Experimental Data", in: *Proc. Int. Symp. on Environmental Contamination Following a Major Nuclear Accident*, SM-306/32 (Vienna: IAEA)

Ma86 Mansson, N.L. et al., 1986, "Disposal of Low and Intermediate Level Waste in Rock Caverns", in: *Proc. 2nd Int. Conf. on Radioactive Waste Management*, pp. 60-67 (Toronto: Canadian Nuclear Society)

Ma89 Mascanzoni, D., 1989, "Plant Uptake of Activation and Fission Products in a Long-Term Field Study", *J. Environ. Radioact.* **10**, 233

Mc70 McRaney, W.K., 1970, "Radiological Monitoring", *Project Crested Ice*, G.E. Torres, ed., USAF Nuclear Safety, Kirtland AFB, NM, AFRP 122-1

Me60 Menzel, R.G., 1960, "Transport of Strontium-90 in Runoff", *Science* **131**, 499

Me71 Menzel, R.G. and James, P.E., 1971, "Treatments for Farmland Contaminated with Radioactive Material", *U.S. Dept. Agric. Handbook* **No. 395**

Me82 Meredith, J.L. et al., 1982, abs., "Cold Weather Decontamination Study-McCoy 4, Part 1", *Cleanup and Treatment of Radioactively Contaminated Land Including Areas Near Nuclear Facilities*, C.S. Fore and R.A. Faust, ed., Oak Ridge National Laboratory, Oak Ridge, TN, ORNL/EIS-199

Me89 Mezrahi, A. and Xavier, A., 1989, "Management of the Radioactive Wastes Arising from the Accident in Goiânia, Brazil", in: *Proc. 1989 Joint Int. Waste Management Conf. on Low and Intermediate Level Radioactive Waste Management*, 22-28 October, pp. 281-284 (New York: The American Society of Mechanical Engineers)

Mi90a Miaw, S.T.W. et al., 1990, "Waste Management in the Goiânia Accident - the Contribution of the Waste Treatment Division of the Nuclear Technology Development Centre", in: *Proc. Int. Symp. on Recovery Operations in the Event of a Nuclear Accident or Radiological Emergency*, SM-316/16 (Vienna: IAEA)

Mi90b Miller, K.M. et al., 1990, "^{137}Cs Fallout Depth Distributions in Forest Versus Field Sites: Implications for External Gamma Dose Rates", *J. Environ. Radioact.* **12**, 23

Mo90 Molina, G., 1990, "Lessons Learned During the Recovery Operations in the Ciudad Juárez Accident", in: *Proc. Int. Symp. on Recovery Operations in the Event of a Nuclear Accident or Radiological Emergency*, SM-316/53 (Vienna: IAEA)

Mu89 Mustonen, R., 1989, *Turvevoimalaitosten tuhkan radioaktiivisuusvalvonta Tshernobylin onnettomuuden jälkeen*, Finnish Centre for Radiation Protection and Nuclear Safety, Helsinki, STUK-B-VALO 60 (in Finnish)

Ni62 Nishita, H. et al., 1962, "Influence of Stable Cs and K on the Reactions of Cs137 and K42 in Soils and Clay Minerals", *Soil Sci.* **94**, 187

Ni90 Nikipelov, B.V. et al., 1990, "A Radiation Accident in the Southern Urals in 1957", *Sov. At. Energy* **February**, 569

Ol86 Olivier, J.-P., 1986, "Radioactive Waste Management in OECD Countries, National Programmes and Joint Activities", in: *Proc. 2nd Int. Conf. on Radioactive Waste Management*, pp. 12-17 (Toronto: Canadian Nuclear Society)

Ot70 Otten, L.J.,Jr., 1970, "Removal of Debris from Thule", *Project Crested Ice*, G.E. Torres, ed., USAF Nuclear Safety, Kirtland AFB, NM, AFRP 122-1

Pe72 Pesonen, T. et al., 1972, *Radionuklidien poistuminen vedenkäsittelyssä, osa II: strontium-90*, Finnish Centre for Radiation Protection and Nuclear Safety, Helsinki, SFL-B3 (in Finnish)

Pr77 Prudic, D.E. and Randall, A.D., 1977, *Ground Water Hydrology and Subsurface Migration of Radioisotopes at a Low-Level, Solid Radioactive-Waste Disposal Site, West Valley, New York*, U.S. Geological Survey, Open-File Report 77-566

Qv84a Qvenild, C. and Tveten, U., 1984, *Adsorption of Cs-137 onto Two Different Types of Roof Materials During Summer and Winter Conditions*, Institute for Energy Technology, Kjeller, IFE/KR/E-84/013+V

Qv84b Qvenild, C. and Tveten, U., 1984, *Decontamination and Winter Conditions*, Institute for Energy Technology, Kjeller, IFE/KR/E-84/014+V

Qv86 Qvenild, C. and Tveten, U., 1986, *Run-off of Strontium with Melting Snow in Spring*, Institute for Energy Technology, Kjeller, IFE/KR/E-86/003+V

Ra86 Rager, R.E. and Roshek, M.W., 1986, "Geotechnical and Construction Considerations of the Salt Lake City UMTRA Project", in: *Proc. 2nd Int. Conf. on Radioactive Waste Management*, pp. 747-751 (Toronto: Canadian Nuclear Society)

Ri88 Rippon, S., 1988, "The SFR-Sweden's LLW/ILW Repository", *Nucl. News* **August**, 112

Ro70 Rogowski, A.S. and Tamura, T., 1970, "Environmental Mobility of Cesium-137", *Radiat. Bot.* **10**, 35

Ro86 Roed, J., 1986, *Reclamation of Urban Areas*, Risø National Laboratory, Roskilde, RISØ-M-2554

Ro87a Roed, J., 1987, "Dry Deposition in Rural and in Urban Areas in Denmark", *Radiat. Prot. Dosim.* **21**, 33

Ro87b Roed, J., 1987, "Run-off from and Weathering of Roof Material Following the Chernobyl Accident", *Radiat. Prot. Dosim.* **21**, 59

Ro90 Roed, J., 1990, *Deposition and Removal of Radioactive Substances in an Urban Area, Final Report of the NKA, Project AKTU-245*, Risø National Laboratory, Roskilde

Ro91a Rosenthal, J.J. et al., 1991, "The Radiological Accident in Goiânia: the Initial Remedial Actions", *Health Phys.* **60**, 7

Ro91b Romanov, G.N. et al., 1991, "The Kyshtym Accident: Cause, Scale and Radiation Characteristics", in: *Proc. Seminar on Comparative Assessment the Environmental Impact of Radionuclides Released during Three Major Nuclear Accidents: Kyshtym, Windscale, Chernobyl*, pp. 25-40, Commission of the European Communities Report EUR 13574

Ro91c Romanov, G.N. et al., 1991, "Comparative Analysis of the Effectiveness of Measures to Protect the Public from Radiation Following the Kyshtym Accident", in: *Proc. Seminar on Comparative Assessment of the Environmental Impact of Radionuclides Released during Three Major Nuclear Accidents: Kyshtym, Windscale, Chernobyl*, Vol. II, pp. 957-965, Report EUR 13574

Sa87 Sandalls, F.J., 1987, "Radiocaesium on Urban Surfaces After Chernobyl", *Radiat. Prot. Dosim.* **21**, 65

Sa88 Saxén, R., 1988, Personal Communication, Finnish Centre for Radiation Protection and Nuclear Safety, Helsinki

Sa90 Salo,A., 1990, Personal Communication, Finnish Centre for Radiation Protection and Nuclear Safety, Helsinki

Sc65 Schulz, R.K., 1965, "Soil Chemistry of Radionuclides", *Health Phys.* **11**, 1317

Sh89 Shinn, J.H. et al., 1989, "Results of a Cleanup and Treatment Test at the Nevada Test Site: Evaluation of Vacuum Removal of Pu-contaminated Soil", *Health Phys.* **57**, 771

Si89 Silant'ev, A.N. et al., 1989, "Vertical Soil Migration of Radionuclide Fallout from the Chernobyl Accident", *Sov. At. Energy* **September**, 221

Si91 da Silva, C.J. et al., 1991, "Considerations Related to the Decontamination of Houses in Goiânia: Limitations and Implications", *Health Phys.* **60**, 87

Sp91 Spirin, D.A. et al., 1991, "The Consequences of the Kyshtym Accident for Flora and Fauna", in: *Proc. Seminar on Comparative Assesment of the Environmental Impact of Radionuclides Released during Three Major Nuclear Accidents: Kyshtym, Windscale, Chernobyl*, Vol. II, pp. 809-819, Report EUR 13574.

St84 Stone, J.A. et al., 1984, "Shallow Land Burial of Solid Low-Level Radioactive Wastes, 30 Years of Experience at the Savannah River Plant", in: *Proc. Int. Conf. on Radioactive Waste Management*, CN-43/270 (Vienna: IAEA)

Te90 Ternovskij, I.A. et al., 1990, "Radioactive Cloud Trace Formation Dynamics After the Radiation Accident in the Southern Urals in 1957", in: *Proc. Int. Symp. on Recovery Operations in the Event of a Nuclear Accident or Radiological Emergency*, SM-316/55-3 (Vienna: IAEA)

Tr84 Tracy, B.L. et al., 1984, "Health Impact of Radioactive Debris from the Satellite Cosmos 954", *Health Phys.* **47**, 225

Tv90 Tveten, U., 1990, ed., *Environmental Consequences of Releases from Nuclear Accidents, A Nordic Perspective, Final Report of the NKA, Project AKTU-200*, Institute for Energy Technology, Kjeller

USDOE84 U.S. Department of Energy, 1984, *Final Environmental Impact Statement, Remedial Actions at the Former Vitro Chemical Company Site, South Salt Lake*, USDOE, Washington, DC, DOE/EIS-0099-F

Va88 Varley, J., 1988, "Report from Chernobyl", *Nucl. Eng. Int.* **March**, 18

Va90 Vakulovskij, S.M. et al., 1990, "Radioactive Contamination of Water Systems in the Area Affected by Releases from the Chernobyl Nuclear Power Plant Accident", in: *Proc. Int. Symp. on Environmental Contamination Following a Major Nuclear Accident*, SM-306/115 (Vienna: IAEA)

Ve90 Vetrov, V.A. et al., 1990, "Accumulation of Chernobyl Radionuclides in Agricultural Plants During 1986-1988 in Relation to Contamination Conditions and Soil Characteristics", in: *Proc. Int. Symp. on Environmental Contamination Following a Major Nuclear Accident*, SM-306/116 (Vienna: IAEA)

Vi90 Vinhas, L.A., 1990, "Decontamination of the Highly Contaminated Sites in the Goiânia Radiological Accident",in: *Proc. Int. Symp. on Recovery Operations in the Event of a Nuclear Accident or Radiological Emergency*, SM-316/13 (Vienna: IAEA)

Wa82 Warming, L., 1982, *Weathering and Decontamination of Radioactivity Deposited on Asphalt Surfaces*, Risø National Laboratory, Roskilde, RISØ-M-2273

Wa84a Warming, L., 1984, *Weathering and Decontamination of Radioactivity Deposited on Concrete Surfaces*, Risø National Laboratory, Rosklide, RISØ-M-2473

Wa84b Warming, L., 1984, *Forced Decontamination of Fission Products Deposited on Urban Areas*, Risø National Laboratory, Roskilde, RISØ-M-2472

Disposal of Radioactive Wastes from the Cleanup of Large Areas Contaminated in Nuclear Accidents

- A Literature Survey

Disposal of Cleanup Wastes after Nuclear Accidents -
a literature study of the treatment, transportation and disposal of cleanup waste after nuclear accidents.

The Nordic Committee for Nuclear Safety Research - NKS
organizes pluriannual joint research programmes. The aim is to achieve a better understanding in the Nordic countries of the factors influencing the safety of nuclear installations. The programme also permits involvement in new developments in nuclear safety, radiation protection, and emergency provisions.
The three first programmes, from 1977 to 1989, were partly financed by the Nordic Council of Ministers.

THE 1990-93 PROGRAMME
The current programme, running until the end of 1993, comprises four areas:

*	Emergency preparedness	(The BER-Programme)
*	Waste and decommissioning	(The KAN-Programme)
*	Radioecology	(The RAD-Programme)
*	Reactor safety	(The SIK-Programme)

The programme is managed - and financed - by a consortium comprising the Danish Civil Defence and Emergency Planning Agency, the Finnish Ministry of Trade and Industry, Icelands's National Institute of Radiation Protection, the Norwegian Nuclear Energy Safety Authority, and the Swedish Nuclear Power Inspectorate. Additional financing is offered by the IVO and TVO power companies, Finland, as well as by the following Swedish organizations: KSU, OKG, SKN, SRV, Vattenfall, Sydkraft, SKB.

ADDITIONAL INFORMATION is available from
the NKS secretary general, POB 49, DK-4000 Roskilde, fax (+45) 46322206

Nordisk Ministerråd

ISBN 92 9120 033 6
ISSN 0906-3668

Disposal of Radioactive Wastes from the Cleanup
of Large Areas Contaminated in Nuclear Accidents

1992:524