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Cleanup of Large Areas Contaminated as a Result of a Nuclear Accident

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1989

CLEANUP OF LARGE AREAS CONTAMINATED AS A RESULT OF A NUCLEAR ACCIDENT

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FOREWORD

During the last 30 years, the development of commercial nuclear power and its supporting nuclear fuel cycle facilities has in general been associated with an excellent record of nuclear safety. Nuclear facilities are sited, designed, constructed, operated and decommissioned according to strict requirements and regulations to protect the environment and ensure the safety of the workers and the public. In spite of all precautions, the possibility of an accident which would result in the release of unacceptable amounts of radioactive materials or unacceptable exposures cannot be excluded. Therefore, it is desirable to plan in advance for emergency action to protect both the facility personnel and the public.

A number of measures are available to protect the public in the event of an accident at a nuclear facility resulting in the release of significant amounts of radioactive material. One of the protective measures which could be implemented in the intermediate phase (days to weeks after the accident) and the late phase (several weeks to years) is decontamination of large areas. Experience at Chernobyl shows that the main long term radiological consequence to the population will probably be external exposure from radioactive fallout deposited on the ground. In the USSR, the contribution of this external exposure from Chernobyl is expected to rise from 53% in the years following the accident to 60% of the total dose commitment. Therefore, it would appear logical that some preliminary planning for the cleanup of contaminated areas should be done.

An Advisory Group Meeting on the cleanup of very large areas after a nuclear accident was held in Vienna from 23 to 27 November 1987. The meeting was attended by 17 experts from 9 Member States and one international organization. The participants discussed and revised a preliminary report on the subject written by B.W. Church (USA), M. Pick (UK), C.G. Welty Jr. (USA) and the IAEA Scientific Secretary, M.A. Feraday of the Division of Nuclear Fuel Cycle. After the meeting, the report was revised by the IAEA Secretariat and the final report was approved by the members of the Advisory Group.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

National governments establish strict requirements and regulations to ensure that nuclear facilities are sited, designed, constructed, operated and decommissioned so as to protect the health and safety of the plant personnel and the public. In spite of all precautions, the possibility of an accident which results in the release of significant amounts of radioactive material cannot be excluded. Since the released radioactivity may adversely affect persons and property outside a nuclear plant, it is prudent to plan in advance emergency actions required both on and off site to limit and mitigate the impacts resulting from such accidents.

The IAEA has published general guidance and recommendations on emergency planning and preparedness for situations where an accident at a nuclear power plant may involve the need for off-site remedial actions and the implementation of protective measures [1–3]. Protective measures that could be implemented to protect the public in the event of an accident at a nuclear facility which results in the release of significant amounts of radioactive material are shown in Table I and range from sheltering of people to the decontamination of lands and buildings. The selection of protective measures which are appropriate for particular hazards during and following an accident must take into account factors such as the type of facility and accident, the source term, data on the affected area, particularly population density and distribution, attendant risks and in particular the time-scale associated with the accident. The time-scale can be classified as follows [3]:

(a) *The early phase* which extends for some hours from the start of the accident. The immediate risk from an airborne release may be inhalation of radioactive material and/or external irradiation from the radioactive plume.
(b) *The intermediate phase* which may extend from days to weeks after the early phase. In this phase the risks may be due to external radiation from ground depositions, internal radiation from the inhalation of resuspended radioactive particles or internal radiation from the ingestion of contaminated food or water.
(c) *The late phase* which may extend from several weeks to several years. The risk here may be due to consumption of contaminated food or water and contamination of the environment.

Table I gives some general guidance on the application of the protective measures to the different time scales associated with an accident. The implementation of these protective measures involves cost, inconvenience and risk to the public so the hazard or social cost associated with a remedial measure must be justified by the resulting reduction in risk [4, 5]. Any intervention will be appropriate only if its resulting detriment to health and social life will be less than that resulting from further radiation exposures.

TABLE I. APPLICABILITY OF PROTECTIVE MEASURES [3]

Protective measure	Phase		
	Early	Intermediate	Late
Sheltering	**	*	–
Radioprotective prophylaxis	**	*	–
Control of access and egress	**	**	*
Evacuation	**	**	–
Personal protective methods	*	*	–
Decontamination of persons	*	*	*
Medical care	*	**	*
Diversion of food and water supplies	*	**	**
Use of stored animal feed	**	**	**
Decontamination of areas	–	*	**

** Applicable and possibly essential.
* Applicable.
– Not applicable or of limited application.

Note: The protective measure of removing domestic animals in the food chain from pasture and putting them on stored animal feed is not an immediate protective measure beneficial to humans; nevertheless, if the situation warrants, the earlier the animals are put on stored feed the greater may be the dose savings at a later point when animal products begin to enter the food chain.

The principles which apply in setting intervention dose levels at which measures for the protection of the public should be taken are outlined in Ref. [5]. This guidance is expressed in terms of dose ranges corresponding to each protective measure. However, decision making during an emergency would be more rapid and effective if the intervention levels were expressed in terms of the radionuclides present in materials. Therefore the IAEA has prepared a report giving information on the principles for setting derived intervention levels (DILs), environmental pathways and ranges of radionuclides of potential radiological significance and procedures for evaluation [6]. These DILs are the practical expression of the intervention dose level, given in terms for example of $Bq \cdot m^{-3}$ or $mSv \cdot h^{-1}$. The report also provides specific radionuclide levels in various environmental materials and foodstuffs at which controls on their use or consumption may need to be implemented as well as appropriate caveats to guide the user with regard to the application and limitations of the numerical values provided.

Although much work has been done [1–7] on the implementation of many of the protective measures shown in Table I, one area which has not been examined in detail is the cleanup of large areas, including cleanup techniques, their applicability to diverse areas and the planning required to implement them safely and efficiently. These topics are discussed in this report. The term 'cleanup' includes decontamination, stabilization or isolation of contamination, together with the transport and disposal of the wastes arising from the cleanup. Decontamination is the removal of radioactive contaminants with the objective of reducing the residual radioactivity level in or on materials, persons or the environment. Decontamination can occur as a result of actions by humans or as a result of natural processes such as precipitation. Stabilization of the radioactivity means fixing it in some manner so that it is no longer a detriment to the environment, for example by incorporating the radionuclides into an insoluble compound. The radioactivity could 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. Also there may be subregions within the affected area where other possible alternatives such as 'do nothing' or interdiction of the area would be preferable and these are also discussed.

Since many areas contaminated with radioactive or other toxic substances have been cleaned up in the past, the question may arise as to how the cleanup of very large areas following accidental release of activity is different. The decontamination and cleanup of buildings and sites is a normal step in the final decommissioning of any nuclear facility. Also, there is considerable operational experience in the cleanup, removal and disposal of large volumes (100 000 to 300 000 m^3) of uranium mill tailings [8]. The sites are cleaned up so that the residual activity is below the levels which are of regulatory concern and the site can be released for restricted or unrestricted use. The techniques and instrumentation are available to characterize the residual radioactivity in a nuclear installation during decommissioning and ensure that residual activity levels in the released site are below regulatory concern. Improved techniques and instruments are continually being developed [9].

However, before the planned decontamination and decommissioning of nuclear facilities and sites commences, detailed plans would have been made and approved by regulatory authorities, teams of trained people and special equipment gathered and the sites well characterized. In addition, the potential pathways by which radioactivity resulting from decommissioning can reach humans would have been fairly well identified.

In contrast, in the event of a serious accident at a nuclear facility which results in widespread and serious contamination of the environment, the uncertainties are much greater and the action plans cannot be as well defined as for planned events. For example, in the case of cleanup of contamination after a serious accident:

(a) Land areas to be cleaned up could be very large and include many hundreds of square kilometres.

(b) The geological and topographical features in the affected area can include a wide spectrum of conditions instead of a well defined site. These features could include various soil types, rocky areas, shale, lakes, swamps, rivers, hills, mountains and a myriad of other features.
(c) The vegetation could include grass, underbrush, crops and forests.
(d) Climatic conditions can seriously inhibit cleanup and cause further spread of contamination.
(e) The affected area could be highly populated and contain many buildings.
(f) Skilled workers and monitoring/cleaning equipment may not be readily available in the required numbers.

These and many other uncontrollable factors complicate the planning and implementation of the cleanup of very large areas contaminated as a result of a serious accident at a nuclear facility and the prediction of the pathways to the environment and man. In addition to normal emergency measures, special emergency planning directly associated with the cleanup and disposal can minimize uncertainties arising from the above problems.

2. PURPOSES OF THE REPORT

The purposes of the report are to provide an overview of the methodology and technology available to clean up contaminated areas and to give preliminary guidance on matters related to the planning, implementation and management of such cleanups. This guidance will help ensure that such cleanups can be performed as safely, efficiently and quickly as possible under adverse conditions if it is decided that this type of intervention is required. The information is directed at emergency planners, regulators and other decision makers who are responsible for such emergency planning.

However, it must be kept in mind that the information given here is preliminary. Further work is desirable both in Member States and the IAEA to produce better guidance on the planning, implementation and management of such complex cleanup operations. Further guidance is especially required on the overall operational management of such tasks.

3. SCOPE

This report provides an integrated overview of important aspects related to the cleanup of very large areas contaminated as a result of a serious nuclear accident, including information on methods and equipment available to: characterize the affected area and the radioactive fallout; stabilize or isolate the contamination; and clean up contaminated urban, rural and forested areas. The report also includes brief sections on planning and management considerations and the transport and disposal of the large volumes of wastes arising from such cleanups. Other publications will cover the latter topics in more detail.

For the purposes of this report, nuclear accidents which could result in the deposition of contamination over large areas if the outer containment fails badly include:

(a) An accident with a nuclear weapon involving detonation of the chemical high explosive but little, if any, nuclear fission. Fragments of ^{239}Pu could be dispersed over an area probably less than several square kilometres. The accidents in Greenland and at Palomares, Spain were of this type.

(b) A major loss of medium/high level liquid waste (HLLW) due to an explosion/fire at a storage site for such waste. A major fracture in a storage tank for HLLW should not result in large areas of contamination unless the spilled liquid quickly reaches a waterway or natural drainage lines.

(c) An accident at a nuclear power plant (NPP), for example a loss of coolant accident, which results in some core disruption and fuel melting. The major release from such an accident would be the volatile fission products such as I, Cs, Ru and Te, along with small amounts of less volatile products such as Sr, La and Ce. The Three Mile Island (TMI) accident was of this class but with no significant loss of containment. In most modern NPPs, such an accident would only result in serious contamination outside the facility if there was no outer containment building or if the containment building failed.

(d) An accident at an NPP involving an uncontrolled reactivity excursion resulting in the violent ejection of reactor core material and rupture of the containment building. A large percentage of the fission products would be released as a result of a fire or the subsequent exothermic oxidation or melting of all or part of the fuel. The Chernobyl accident was in this class and it resulted in the widespread dissemination of particulate matter and aerosol fission products. A major chemical explosion/fire at a nuclear fuel reprocessing plant could also be in this general class if the containment failed.

However, the planning and technical data provided in this report could also be applied to other accidents involving the spread of radioactive or toxic chemical contamination.

4. PLANNING THE CLEANUP

4.1. INTRODUCTION

The cleanup of very large areas contaminated as a result of a serious accident at a nuclear facility could cost hundreds of millions of dollars and cause risks and inconvenience to the public. If it is decided that the resulting detriment to health and social life of this kind of intervention would be less than that resulting from further exposures, all reasonable means should be used to minimize the costs and detriment to humans of such a cleanup. The best way of doing this is by ensuring that proper planning, co-ordination and management of activities are enforced at all stages.

The potential detriment to the public if such an accident does occur and the affected area is not cleaned up in a reasonable time will depend on many factors such as the damage to the core and containment, source term, distance from the source, population distribution and density, weather conditions, downstream use of water and other protective measures that have been implemented. For example, if serious contamination of a heavily populated urban area was not cleaned up quickly to acceptable levels, the resulting health, social and financial costs of caring for the displaced persons would be very serious and much greater than if the accident occurred in a remote area. Loss of wages and economic output for the area would also be a major economic problem.

To minimize the potential detriment to humans and the environment in the event of such an accident, national and local governments should be encouraged to prepare plans to define the required management structure and their initial actions, identify essential equipment, collect available data required to analyse the potential effects and implement and manage cleanup activities.

Preparations for the cleanup should be divided into two phases: preliminary planning which is done before the accident happens and detailed assessment and planning which is initiated at the onset of the accident. As for all emergencies, formal planning for such a complex cleanup operation is a prerequisite to ensure that this type of intervention can be quickly and efficiently made so as to mitigate the adverse effects of the accident.

In both the preliminary and final cleanup plans, the rationale behind the planned actions and the goals for cleanup should be clearly defined.

The rationale behind the decision whether to implement decontamination/stabilization or do nothing to large affected areas should be carefully and fully established beforehand, probably in the form of DILs worked out using international principles [6] and site or country specific data. In addition to the DIL, the decision making process should include socioeconomic, political and psychological factors, the type of area, population distribution, environmental impact of cleanup, availability of cleanup equipment/personnel as well as normal cost–benefit analysis, etc.

A decision to implement cleanup of an area would be appropriate only if the detriment to health and the social and economic cost of implementing the cleanup will be less than the detriment resulting from further radiation exposure and/or exclusion of the population from the area.

The major goal of cleanup would be to reduce, as soon as is feasible, the contamination levels such that the dose to humans through direct exposure or food pathways would be acceptable by removing or immobilizing the contamination. The goal is generally expressed in terms of cleanup criteria (Section 4.2.2). Even if the dose to humans via direct exposure is acceptable, removal of contamination may be required if pathway analyses indicate that the food path, especially where long lived emitters are involved, could become a problem in the future. Terrestrial and aquatic pathways may be important in some scenarios and should be considered in the development of criteria [10]. Models for assessing the radiological input on aquatic organisms are also available [11]. Societal and political acceptability could influence the objectives of the cleanup. In the past, some cleanup actions have had to be repeated because society no longer accepted past actions.

The rationale, goals and timing of the cleanup could vary from country to country and from site to site and would depend on a great many factors including: societal expectations, wealth of the country, availability of equipment, land usage and population density.

4.2. PRELIMINARY PLANNING

4.2.1. Introduction

In the following sections, the preliminary and final planning for cleanup are discussed in general terms. In subsequent sections, certain important elements of the implementation of the cleanup plan are discussed in more detail, for example characterizing the affected area and the contaminants, stabilization of the radioactivity, decontamination techniques, transport and disposal of wastes and safety and radiation protection practices.

The degree of preliminary planning should be in relation to the probability of occurrence of an accident and the potential detriment to the public if it does happen. Since the probability of occurrence of a serious nuclear accident such as Chernobyl is expected to be very low, it is unlikely that local governments around nuclear facilities will be willing to spend large amounts of money and expend considerable effort in preparing detailed preliminary plans for the decontamination of large areas. However, since the potential consequences of such an accident are very large, especially in an urban area, some planning for cleanup seems judicious.

Ideally, some preliminary planning for cleanup should be done for areas around large nuclear facilities which have the potential to spread unacceptable amounts of radioactive material in the event of a serious accident. The plan would then be upgraded as details of the accident are received and reviewed. The cost of such preplanning should not be large since many of the data required will already be available and only need to be collected and correlated.

For example, a programme is in progress in France [12] to develop the planning and techniques required for cleanup after a nuclear accident. This programme, called RESSAC (rehabilitation of soils and subsurfaces following an accident), is being used to determine land use patterns around 21 nuclear sites in France and develop sensitivity criteria to determine the priority of cleanup as well as cleanup techniques. During the preplanning phase, a state of the art bibliography [13] on decontamination techniques was compiled to select the techniques that could be tested by the RESSAC programme.

A preliminary plan would contain both generic and site specific information.

4.2.2. Generic information

Examples of the type of generic information that would be relevant to all or many of the facilities in a country are as follows:

(a) Cleanup criteria

The decision to implement the cleanup of a contaminated area is made on the basis of the derived intervention level for this protective measure. Once the decision to implement such a cleanup has been made, cleanup criteria must be available to define the specific radionuclide concentration limit/gamma exposure level which must be achieved by the workers doing remedial action. In addition, criteria for the release of the whole or part of the area for unrestricted or restricted use must be available to allow the return of the population and/or reuse of the land for agriculture, etc.

The development of such criteria which relate dose-to-humans to contamination levels using pathway analysis is difficult for small sites and extremely difficult for large diverse regions. In practice, different acceptance criteria may be set for different zones or situations in large contaminated areas. For example, much higher residual activity levels may be acceptable for remote rural, forest or desert areas and for buildings with good shielding properties or low occupancy.

It is beyond the scope of this report to give detailed guidance on the development of such criteria since it is a specialized task. However, the criteria should be based on internationally accepted risk levels translated into acceptable dose limits. Concentration limits for radionuclides in soil, water, air and food or acceptable radiation levels can be derived using suitable pathway analysis and, where possible, realistic site specific parameters.

In the past, various criteria have been used for the release of sites from decommissioned reactors, mine/mill facilities or contaminated areas such as Enewetak or Palomares [14]. For example, USNRC Regulatory Guide 1.86 [15] has been used in the USA and elsewhere for the cleanup of reactor and other sites.

During the final planning of the cleanup (Section 4.3) these criteria would have to be reviewed for suitability and applied in a site specific manner in various zones during implementation of the plan.

(b) Co-operative agreements

Information should be available on the co-operative agreements between various levels of government and between the Member States and other Member States and/or international organizations related to sharing of expertise, equipment, facilities and personnel.

(c) Methods and equipment to implement the cleanup

Current national and international reports should be available on the best methods and equipment for implementing the cleanup of various land use classes (urban, farming, forests, etc), as well as research and experience in these areas.

The technological aspects of the various parts of the cleanup are reviewed as follows:

- Characterizing the affected area (Section 6)
- Deposition of contamination on surfaces (Section 7)
- Characterizing the contamination (Section 8)
- Stabilization of contamination (Section 9)
- Decontamination techniques and equipment (Section 10)
- Interdiction of an area (Section 11)
- Application of cleanup technology to situations involving high radiation fields (Section 12)
- Loading and transporting large volumes of wastes (Section 13)
- Disposal of large volumes of wastes (Section 14)

(d) Radiological safety and protection plan

A preliminary outline of the radiological protection and safety plan including the logistics of implementing such a large scale operation should be prepared. Section 15 gives some information on such a plan.

This generic information could be gathered by federal and/or state authorities and provided to those responsible for planning the cleanup at each major nuclear facility. The final (post-accident) planning related to the application of this generic information is discussed in Section 4.3. The management aspects related to the planning and implementation of cleanup activities are discussed in Section 5.

4.2.3. Site specific information

In addition to the generic data, certain site and/or facility specific information should be available in the preliminary plan for the area surrounding a particular facility. This information should include:

(a) *Source term*

The types of radionuclides and the total potential source term in any nuclear facility should be readily available from the facility owner. The radionuclides and source term which would be released from the facility to the environment and the physical and chemical form of such releases can be roughly estimated for various accident scenarios. This kind of information should be made available for decision making during the preliminary planning stage. Although the development of various accident scenarios and scenarios for the release to the environment resulting from such accidents could be done by local authorities using international guidelines, it might be better to do this at the national or international level, especially for facilities of the same type and design.

(b) *Characteristics of the affected area*

This information would be obtained by applying to the affected area the generic methodology outlined in Section 6.

(c) *Organizational aspects of the planning and implementation of the cleanup* (see Section 5).

(d) *Preliminary zonal control plan* (see Section 5).

(e) *Environmental monitoring database for the area*

This information is required so that cleanup teams know what background radiation levels existed before the accident. In some countries this type of data might be available in the immediate vicinity of the nuclear facility as a prerequisite to licensing or in broader areas in connection with national radiation mapping programmes. Techniques are available to assess these background levels rapidly and fairly accurately using airborne monitoring techniques (Section 8.2).

(f) *Statistical sampling plans*

Statistical sampling plans are required for various regions to determine the distribution and concentration of the deposited radionuclides and to ensure that cleanup of this fallout is done properly. Factors to be considered as part of the statistical sampling plan include: sample acquisition and analysis [16], grid system configuration and alignment [17, 18] and sample size requirements. The type and number of samples required will be different for urban, rural, forest and farmland and for different types of soil. For example, only surface activity measurements may be required for impermeable soils, whereas core samples may also be required for permeable soils such as sand. Since sample acquisition and analysis could involve a considerable cost in defining the problem and developing solutions, it is essential that these be carried out in a cost effective manner [16].

Following the initial monitoring assessment to define the extent of contamination there will be a need to estimate in more detail the spatial distribution (pattern) and the total amount of radioactivity present over the region to assess the situation and plan for possible remedial actions. For these purposes, it is usually best if the data are collected on a centrally aligned or triangular grid system to ensure that all areas of the region are represented. Statistical sampling methodologies which have proven to be very effective in the cost effective cleanup of radionuclides at the Nevada Test Site and at Enewetak Atoll, and of dioxin in Missouri, USA are given in Refs [17, 18].

(g) *Confirmatory monitoring plan*

A concerted and well planned effort is required during and following a cleanup to independently ensure that the contamination levels have been reduced to the accepted level. This monitoring for compliance with release criteria includes activities such as:

- ensuring that the instruments, analytical methods and procedures have adequate sensitivity and are appropriate to the radionuclides which are present
- ensuring that the procedures are being followed
- collecting archive samples for future reference
- summarizing the verification activities in a report to confirm that compliance with release criteria has been achieved.

(h) *Data management plan*

Technical means should be developed for identifying, recording, collating, categorizing and assessing information received on items such as: samples taken, volumes of wastes, radionuclide content of wastes and where each truckload of waste is disposed of. It should be made clear that critical data points and the location of disposal sites or trenches should be surveyed and the information recorded (see also Section 8.3).

(i) Analysis of cleanup options

A preliminary analysis should be made to determine which cleanup options would best reduce the detriment in various zones in the affected region. Preliminary decisions can be made on such things as:

- interdiction versus decontamination
- most probable cleanup techniques for certain areas or surfaces
- evaluation of the trade-off between cleanup standards and decontamination costs
- sequence of cleanup steps for selected areas, e.g. vacuuming before hosing, crop removal before ploughing.

Computer programs such as the one described in Ref. [19] may be useful in this type of analysis.

(j) An assessment of resources

The preliminary plan should include a list of equipment and facilities required for the cleanup. This list should be compared with the availability of similar resources in the region or elsewhere that could be called on, for example resources in nuclear facilities, military bases and industry. Equipment such as radiation instruments, cleanup equipment, large trucks and remotely controlled equipment would be of interest. Preliminary data on potential disposal areas should be collected if possible.

(k) An assessment of personnel requirements

The preliminary plan should include details of the management structure required to prepare the final plan and to implement and co-ordinate the cleanup (Section 5.2). Key personnel should be listed with their telephone numbers so they can be contacted quickly in the event of a cleanup emergency.

Details of the personnel requirements for cleanup teams for various types of area (urban, rural, forest, etc.) and for special facilities such as disposal sites and decontamination centres should also be available. Although some of this information is generic in nature, it should be applied in a site specific manner during planning.

(l) Cost-benefit analysis for cleanup

For very large diverse areas, decisions will have to be made regarding the level of cleanup in various zones. Decisions of this type will require some form of cost-benefit analysis to ensure that the limited resources are used to achieve the best overall result. During the preliminary planning, tentative decisions on the level of cleanup for each type of zone should be made to assist in the final decision making when details of the accident and areas affected are known.

(m) Other factors in decision making

Factors other than those listed above should be considered in the decision making process related to the type of remedial actions employed and the timing. The factors include: environmental impacts, short and long term interdiction of land or buildings, the dose burden on cleanup personnel, and socioeconomic and psychological impacts.

The elements of this preliminary plan should be reviewed periodically to ensure that the information is still current and relevant.

4.3. FINAL PLANNING

If an incident at a nuclear facility should result in the release of significant amounts of contamination and it is decided that decontamination of areas is required, the organization managing the operation should review and update all parts of the preliminary plan described in Section 4.2 in the light of new information, and assemble the human and other resources required to implement the cleanup and disposal operations.

If no preliminary plan is available and a background database has not been established, the work-load of the planning organization is increased considerably and the implementation of the decontamination actions may be delayed. All aspects of the planning should be correlated with other response organizations.

Assuming that some preliminary planning for cleanup has been done, the final planning would be carried out in parallel with the preliminary characterization of the contamination at the onset of the accident. The characterization of the contamination and knowledge of the extent and types of areas affected would permit planners to determine boundaries and define zones needing special attention or special equipment.

One of the most important steps in the final plan is to review the rationale, goals and cleanup criteria established during preliminary planning in the light of the actual circumstances after the accident. The rationale and goals must be clearly defined and correlated with other emergency actions which are taking place to get the full support of the governments, various agencies, the public and the scientific community. Although the goals are established on the basis of information available at the beginning of cleanup, they may be changed as more information arises from items such as the details of the distribution and concentration of radionuclides in various zones from the airborne monitoring programme and the difficulty of cleaning up various areas. The cleanup criteria, which should be defined in useful units such as $\mu Sv \cdot h^{-1}$ or $Bq \cdot g^{-1}$, should also be reassessed as required in the light of the accident.

The final management plan must tie together all elements linked to the cleanup of the area and be co-ordinated with other emergency plans. The plan will include subplans on items such as: contamination characterization, details of the cleanup methods and equipment selected from various zones, logistics and supply, health physics support, technical support, transportation, and packaging and disposal. These components are not significantly different than those for the planning required for many large scale radiological operations in the nuclear industry except that much more planning and co-ordination with other agencies are required. The size of the contaminated area and the logistic support required would also be greater. However, some relevant information on these topics is available from the cleanup of medium size contaminated areas such as Enewetak [14] and from mill tailings experience [8].

It is beyond the scope of this report to outline the elements of the subplans and the overall operational plan. However, some of the important aspects related to managing such a cleanup are briefly described in Section 5.

4.4. PLANNING THE IMPLEMENTATION

The implementation of a cleanup must be based on a well defined final plan if it is to be safe, efficient and cost effective. Although the safety and radiation protection aspects of the plan are paramount in the implementation, the cleanup work must be done in an efficient and cost effective manner because of the extremely high cost of an operation of this magnitude.

To implement the plan effectively and safely requires that the following personnel, equipment and facilities be available:

— a good management team
— well trained and dedicated monitoring, sampling, maintenance and cleanup crews
— mobile monitoring instrumentation and radiochemical laboratories
— a data management programme for storing and analysing information
— equipment and techniques for cleaning up the contamination
— means of loading, transporting and disposing of the wastes

— decontamination facilities for equipment and personnel at the interfaces between the clean and contaminated areas and at the disposal unloading area
— health physics and radiation protection supplies and equipment.

Some management aspects related to implementation of the cleanup plan are given in Section 5.3.2.

5. MANAGING THE CLEANUP

5.1. INTRODUCTION

The effectiveness of any of the off-site emergency measures shown in Table I will depend to a large extent on how well the management organization plans, co-ordinates, implements and manages the activities required to meet the emergency situation.

Guidance is available [1] to assist public authorities to prepare for and manage emergencies at nuclear power plants. The authorities responsible for planning the emergency arrangements should put particular emphasis on:

(a) Designating one uniquely identified person, hereinafter called the 'emergency director', with an appropriate number of specifically nominated substitutes, to have executive authority for directing the public authorities emergency organization.
(b) Providing each of the following to assist the emergency director:
  (i) Senior nuclear safety advisers
  (ii) Senior radiation protection advisers
  (iii) Field survey and sampling teams
  (iv) Liaison with police, military forces and similar organizations
  (v) Liaison with authorities who control water supplies and agricultural and aquatic products
  (vi) Liaison with medical services and hospitals
  (vii) Liaison with weather bureaux.

It is recommended that the public authorities emergency organization should also include at all stages of planning senior advisers to plan and implement the cleanup, whether or not the decontamination of an area is implemented. The reasons for having such advisers as senior members of the emergency organization are as follows:

(1) For serious accidents, the implementation of such a cleanup could be required within days or weeks of the accident, especially if large urban areas are seriously affected.

(2) The cost of such a cleanup could be enormous. These costs can be significantly reduced by prompt implementation of a technical plan developed with full knowledge of the actions planned by other parts of the emergency organization.
(3) It is not practical, safe or cost effective to develop and implement a technical plan of such magnitude in a short time unless preliminary planning has been done and updated as part of the emergency organization.
(4) If the cleanup is delayed or carried out inefficiently, the detriment to health and social life and the inconvenience to the public and the workers will increase significantly, especially in urban areas where the population has been evacuated.

The emergency director should ensure that the public authorities emergency plan and the operating organization emergency plan have been prepared and are fully co-ordinated [1]. The preplanning for the cleanup of contaminated areas should be included as part of and be fully integrated with all aspects of their plans.

To be effective, the management plan for cleanup should clearly identify the management structure and how this structure interrelates with other emergency teams. In particular, areas of potential overlap and conflict between groups should be identified and jurisdiction clearly indicated, for example control of cleanup zones, monitoring of contaminated areas and dissemination of information to the media and the public.

5.2. MANAGEMENT STRUCTURE FOR CLEANUP

Reference [1] states that an emergency co-ordination centre should be preselected and the emergency director work from there to exercise co-ordinated control during the implementation of the public authorities emergency plan. The centre should be large enough to house the director, his deputies and advisers and others whose duties require them to be present. The senior adviser for cleanup activities should be part of this group.

If the emergency director decides to implement large scale cleanup activities, a separate room or rooms should be set up as a cleanup control centre, especially if the cleanup is to continue for many months. This control centre, which should be connected directly with the emergency co-ordination centre (Fig. 1), would be used by the cleanup management team to prepare and implement the final plan and to exert overall control of the cleanup. The management team could, for example, consist of the cleanup director and his advisers on topics such as: radiation protection and safety, surveying and sampling, urban and rural cleanup, transportation, disposal and data management. The final cleanup plan and the implementation strategy would be developed by the cleanup team under the supervision of the emergency director.

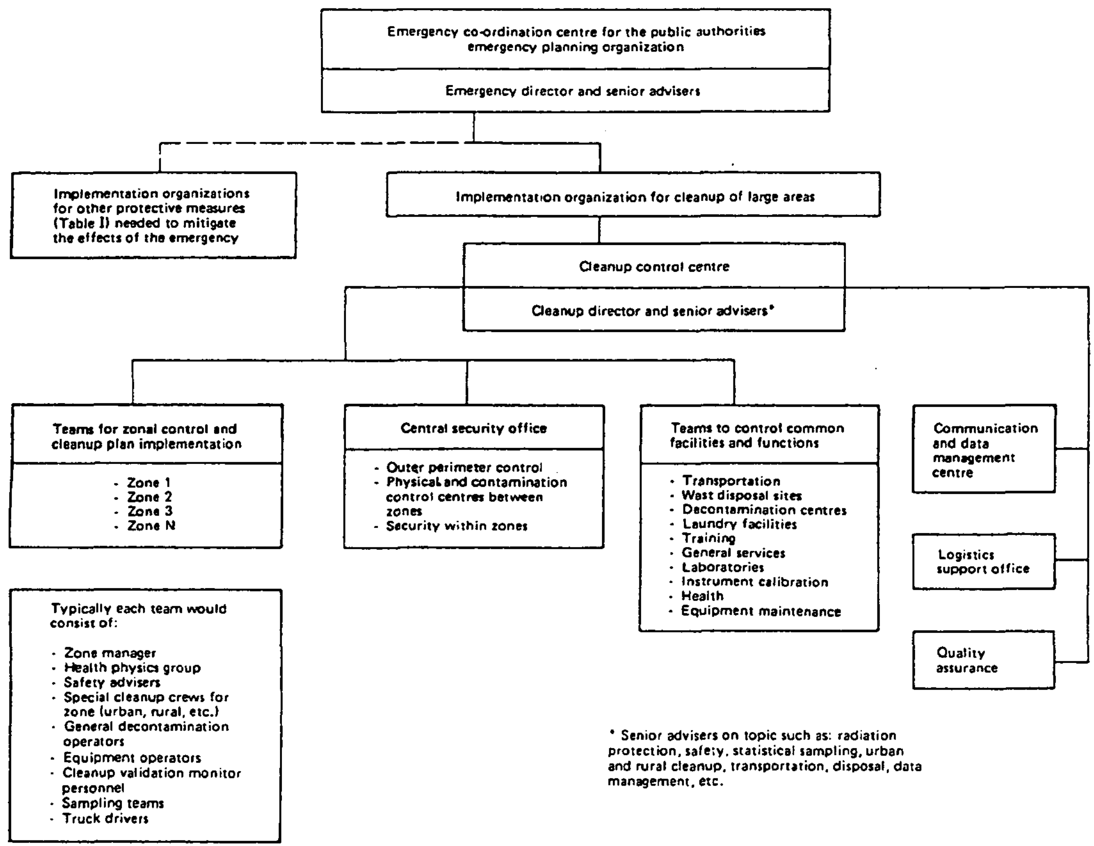

FIG. 1. Management structure for cleanup of contaminated areas.

In certain cases, for example cleanup after a nuclear weapons accident or waste transportation accident, the cleanup control centre may have to be mobile.

The control centre should also include items such as:

— The generic and site specific data gathered as part of preliminary and final planning for cleanup (Section 4).
— Maps showing the current status of the radioactive contamination levels in the defined zones.
— Maps showing information such as control check points, decontamination centres, status of the cleanup, transportation routes, disposal areas, etc.
— Communications equipment and operators, including direct contact with contamination monitoring and cleanup groups in each zone and teams controlling common facilities/functions (Fig. 1).
— Computer centre for data acquisition, analysis, plotting and recording. The system could be used to calculate, record and assess radiological survey data and occupational doses, status and location of major equipment, waste transportation waybill data, location and status of disposal sites, etc.

If the cleanup continues for many months, the public authorities emergency organization may revert to its normal standby status and some of its responsibilities may be delegated to the cleanup organization. These responsibilities could include: public relations; information flow to local and national authorities, the public and the media; enforcement of zonal control; liaison with other organizations such as the police, public health authorities and the facility owner; and assessment of doses to the public. During the first few months of the emergency, central control and co-ordination of these responsibilities would probably lie with the emergency director to minimize confusion.

In addition to the central management team, the cleanup organization would probably consist of:

(a) Field teams for zonal control and cleanup plan implementation. Each team should consist of a zone manager and enough special personnel and equipment to clean up the zone in a safe and efficient manner. The make-up of a typical team could, for example, be as shown in Fig. 1.
(b) Teams for the control and operation of common facilities such as waste disposal sites, and the co-ordination of other common functions such as transportation systems (Fig. 1).

The number of field teams and their make-up would depend on accident and site specific factors such as the size of the affected area, the type of zones (urban, rural, etc.), the number of people affected, the urgency for cleanup, and the availability of trained teams and suitable equipment. The teams would probably specialize in the cleanup of one type of area, for example urban, farmland or forests.

The cleanup organization described above is given only for illustrative purposes. The exact organizational structure, the number of field teams and their make-up would vary considerably depending on factors such as: site and accident specific conditions, scale of the accident, availability of equipment and trained staff, local infrastructure, urgency of cleanup, etc.

5.3. MANAGING THE PLANNING AND IMPLEMENTATION

5.3.1. Psychological and social considerations

It has been clearly demonstrated that accidents at nuclear facilities and the resulting (or anticipated) spread of contamination can have serious psychological and social impacts on individuals and communities. For a very serious accident, such as at Chernobyl, where large areas are actually seriously contaminated, these impacts can be very traumatic.

It is therefore very important that the psychological and social aspects related to such accidents be included right from the start along with the safety, health, technological and administrative aspects in defining, managing and implementing the cleanup plan.

The perceived risks and anxieties associated with the accident and with the subsequent application of protective measures can be reduced significantly if the government, media and population are kept well informed about the accident, its consequences and the rationale and objectives of the protective measures. By seeking where possible co-operation or at least an understanding with influential and affected groups of the public, safe, balanced and lasting solutions can be achieved.

For people who have been evacuated from their areas, it is important that the reasons for further interdiction, the present status of cleanup and expected return date be explained. In addition, the population should be made aware of the difficulties involved in cleaning up such large diverse areas.

After the areas have been cleaned to specified levels, education and awareness programmes should be initiated for those returning to the areas so that they are aware of the presence of residual activity, the potential long term hazards and the steps they can take to minimize such hazards. This knowledge should reduce the anxiety of the population.

Any proposed programmes for long term monitoring of contamination in the area and of the health effects on the population should be thoroughly explained so as to reduce anxiety and also to get future co-operation for such activities.

The organization managing the planning, co-ordination and implementation of the cleanup programme should ensure that these psychological and social considerations are given serious attention by managers at all levels.

5.3.2. Managing the final planning and implementation

The types of information that should be developed by the management team during preliminary planning, and upgraded during final planning are discussed in Section 4 and are summarized in Table II. The generic techniques and equipment required to carry out the plans are described in Sections 6–15.

TABLE II. SUMMARY OF ITEMS TO BE INCLUDED IN PRELIMINARY AND FINAL PLANS[a]

Rationale and goal for cleanup (Section 4.1)

Characterizing the affected area (Section 6)

Radiological characterization
— source term estimate (Section 4.2.3)
— environmental monitoring database (Section 4.2.3)
— characterizing the contamination (Section 8)
— statistical sampling plan to validate cleanup (Section 4.2.3)
— cleanup criteria (Section 4.2.2)
— confirmatory monitoring plan (Section 4.2.3)

Managing the cleanup
— management structure for cleanup (Section 5.2)
— analysis of cleanup options (Section 4.2.3)
— co-operative agreements (Section 4.2.2)
— data management plan (Sections 4.2.3 and 8.3)
— planning the implementation (Section 4.4)

Logistic support for cleanup
— availability of cleanup methods and equipment (Sections 9 to 12)
— provision of required resources (Section 4.2.3)
— provision of required personnel (Section 4.2.3)
— location of national/regional resources (Section 4)
— availability of trucks and loaders (Section 13)
— availability of remotely operated equipment (Section 13)

Transportation plan (Section 13)

Waste disposal plan (Section 14)

Radiation protection and safety plan (Section 15)

[a] The information in the preliminary plan is updated periodically before the accident and modified to form the final plan after the accident using accident specific data.

In addition, it is very important that the management team identifies how the subelements of the plan (Section 4) interrelate and interact in an overall operational cleanup plan so there will not be delays in implementation. Although it is beyond the scope of this report to outline in detail the elements of an overall management and operational plan for the cleanup of very large areas, it is recommended that future work be done to define in more detail these important managerial and operational aspects.

In this section, some of the key management considerations in planning and implementing the cleanup are briefly discussed.

After an accident has occurred, a rapid survey of the immediate vicinity of the site would be made by emergency radiation monitoring teams, with particular emphasis being given to more densely populated areas [1]. On the basis of information gathered by the teams using simple rapid techniques, the emergency coordination centre will take effective initial protective measures, e.g. issuance of radioprotective prophylactic drugs, sheltering or evacuation.

At the same time, the senior advisers for cleanup in the emergency coordination centre would review the status of the preliminary plan and alert designated candidates for cleanup director and senior advisers for the cleanup control centre (Fig. 1). If the emergency director decides that no cleanup is required, no further actions would be taken. However, if the emergency director decides that cleanup actions will be required, the cleanup director and his senior advisers would be appointed and the cleanup control centre established.

From a management viewpoint, the subsequent final planning and implementation would proceed in parallel with each other and be closely interrelated. The management team would have to develop an overall operational plan integrating all of the individual cleanup elements to ensure that implementation of the cleanup proceeds as smoothly as possible. Further work on the development of the elements of an overall operational plan for cleanup of very large areas is required and it is recommended that such work be done.

In these discussions it is assumed that the cleanup criteria, rationale and goals for the cleanup have been defined and the senior advisers to the cleanup director are assembling the resources and teams of personnel required to clean up the area. Some of the major managerial actions would be as follows:

(a) Define cleanup priorities

The first task in defining cleanup priorities is to produce a detailed map of the type, mix, concentration and spatial distribution of the radionuclides released (Section 8) and relate these data to the characteristics of the affected area, especially population density, land usage, types of building, etc. (Section 6). With this information, the management team in conjunction with the emergency director can delineate cleanup zones and determine which area should be cleaned up first. Table III gives

TABLE III. EXAMPLES OF GENERAL CATEGORIES FOR PRIORITY DECONTAMINATION AFTER A NUCLEAR ACCIDENT

Categories		Cleanup priority		
		High	Medium	Low
I	Residential areas			
	— large developments	×		
	— remote single residence		×	
II	Other structures			
	— hospitals	×		
	— businesses		×	
III	Water sources			
	— primary municipal source	×		
	— secondary water source		×	
	— recreational use			×
IV	Agricultural land			
	— foodstuff products	×		
	— non-food products		×	×
	— gardens	×	×	
	— grazing, etc.	×		
V	Forests			
	— commercial forest		×	
	— non-utilized areas			×
VI	Roads, rights of way			
	— primary	×		
	— secondary		×	
VII	Remote areas			
	— deserts, forests, etc.			×
VIII	Plant site and adjacent buildings	×		

Note: From the results of pathway analyses, the above categories could be weighted on the basis of the resultant dose equivalents and the percentages of total area encompassed in the particular land use.

examples of cleanup priorities which could be assigned to different categories. The assignment of actual priorities can only be made on a site specific basis after the details of the accident are defined and the implications of other off-site emergency measures are evaluated.

(b) *Implement the cleanup*

The cleanup would probably be implemented in stages as the cleanup teams are assembled and trained and equipment and facilities are made available. Each team must have a working knowledge of the means of applying the special cleanup techniques, preferably on a large scale, required for their particular zone. The rate of implementation of the cleanup would be determined by factors such as the number of teams available, the equipment available, the efficiency of the cleanup techniques, the effectiveness of the monitoring and sample analysis teams, the urgency to return people to the area, weather conditions, etc.

For cases such as Chernobyl, where the facility emitted radionuclides for a relatively long period, the first objective would be to get the damaged facility under control so no further releases occur.

(c) *Co-ordinate the cleanup*

The management team must ensure that all components of the cleanup are developed and implemented in an integrated and co-ordinated manner. Some examples are:

(i) The rate of cleanup must be matched to the output of the confirmatory monitoring teams so that contamination is not left behind. The instruments used must be appropriate to the radionuclides present and suitable monitoring protocols must be developed to ensure efficiency of monitoring, especially with newly trained monitoring staff.

(ii) The laboratory support must be able to meet the projected sample load and provide results in a timely manner so evacuation crews are not kept waiting to see if more material must be removed.

(iii) The ability to handle, interpret and use the data provided from a multitude of sources must be well developed, along with the means of communicating the results to the appropriate team (see Section 8.3).

(iv) The disposal site capacity and transport system must be matched to the cleanup rate.

(v) The lessons learned by teams should be fed back as rapidly as possible to other teams and into the training programme.

6. CHARACTERIZING THE AFFECTED AREA

During preliminary planning, the objectives of characterizing an area which is likely to become contaminated as a result of an accident at a nuclear plant are as follows:

(a) To assist the cleanup team to get a good knowledge of the affected area, including such things as land types and usage, geology, hydrogeology and population distribution. The information should enable the team to assess how the affected area interrelates with surrounding regions and the implications to affected communities of actions taken.
(b) To assist in the selection of the best cleanup methods for individual zones.
(c) To select potential disposal sites and transport routes.
(d) To understand the hydrogeological systems and select area specific parameters for use in computer codes so that pathway analyses can be done and the impact of cleanup assessed.

The collection of data should start with those which are most readily accessible and then proceed to the least accessible data. The information should be reviewed periodically to ensure that it is relevant and up to date.

Good maps and regional atlases are invaluable sources of information; these include road and city maps, topographic maps and survey maps prepared by government agencies or industry. These maps show things such as road systems, urban and rural regions, land contours, surficial geology, natural resources, mineral deposits, land use, groundwater contours and surface water systems. Both large and small scale maps are very useful in analysing the area and its interconnection with other areas.

Other sources of information include aerial photographs, demographic data and projections, land use forecasts and agricultural, forestry and mining industry data. Other information comes from the siting, environmental assessment and licensing of facilities such as power plants, dams, municipal and town waste disposal areas. In many countries, these data are readily available but they need to be collected and collated by those in charge of planning the cleanup.

Classification of various zones within an affected area will be helpful in assessing the impact of cleanup and the techniques to be used. In one major study [20], seven natural ecosystems and two general land use classes were defined and the ecological impact of various cleanup techniques and land restoration on these classes were examined. The seven ecosystems were: forest, prairie, deciduous and coniferous forests, mountains, tundra and coastal intertidal marshes. The two managed land use classes of ecosystems (agriculture, urban/suburban) overlap the natural ecosystems. These generic ecosystems/classes should be useful in characterizing areas in general.

TABLE IV. TYPES OF DATA REQUIRED TO CHARACTERIZE, ANALYSE AND MODEL TERRESTRIAL SYSTEMS

Geological characterization

Stratigraphy — stratigraphic relations with surficial deposits, as well as rock underlying the site or having potential hydraulic connections with regional aquifers

Lithology — including mineralogy, texture and fabric (grain size parameters) and classification

Structure and discontinuities in both soil and rock influencing groundwater flow

Hydrological/hydrogeological

Regional hydrogeology — including description of groundwater and surface water systems, recharge/discharge zones, natural surface drainage, limits of the hydrological system, flow directions, interrelation with surrounding water systems

Parameters — for example for the soil: hydraulic conductivity, permeability, porosity, anisotropy, water holding parameters, hydraulic potential; for water systems: flow velocity and volume in summer and winter, lakes without surface inlet/outlets

Geochemical/geotechnical parameters — for example: partition coefficient (K_d), grain size distribution, clay mineralogy, ion exchange capacities, soil pH, surface and groundwater chemistry

Techniques — including: laboratory studies, borehole logging, remote sensing, in situ tests and measurements, airborne and ground geophysical surveys, geological field mapping

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However, more detailed analyses will generally have to be done to get the information required to model the affected area, predict the interaction of the contamination with the soil and determine the pathways to man. The type of information required and some of the means of obtaining the data are shown in Table IV. Procurement of enough data to accurately characterize each zone in the affected area would be very costly. However by using available information and selective sampling, a fair understanding of the geology, hydrogeology and geotechnical aspects of the area can be determined.

If the whole area is fairly homogeneous and simple geologically then sample requirements and modelling will be much less onerous.

One widely used system for classifying soils, the Unified Soil Classification System [21], gives major soil divisions, field identification procedures, information required to describe the soils and laboratory classification criteria. The major soil divisions are:

(a) Coarse grained soils

(i) gravels	— clean gravel, little or no fines — gravel with appreciable amount of fines
(ii) sands	— clean sands, little or no fines — sands with appreciable amounts of fines

(b) Fine grained soils

(i) silts and clays	— liquid limit is less than 50%
(ii) silts and clays	— liquid limit is greater than 50%

(c) Highly organic soils

For urban areas, a good knowledge of the types of buildings and the materials and surfaces which may require decontamination is important so that suitable cleanup techniques can be used.

7. DEPOSITION OF CONTAMINATION ON SURFACES

The type of nuclear facility and the nature of the accident determine the radionuclides which could be released and the chemical/physical form of the released contaminants. These two factors along with the weather conditions prevailing at the site and surrounding areas during and shortly after the accident will determine the geographical extent of the affected area, the decrease in level of the contamination with increasing distance from the facility and regional hot spots resulting from washout.

The most likely types of accidents which could cause heavy and widespread fallout (Section 3) are those involving an uncontrolled reactivity excursion at a nuclear power plant resulting in the violent ejection of reactor core material (d) and the explosion/fire type of accident (b) involving irradiated fuel or HLLW. The deposition could include large fragments of fuel near the reactor and deposition of fine radioactive particulate and soluble fission products over a large area.

The chemical and physical form of the contaminants, the mechanism of contamination of the surface and the physical and chemical state of the surface will probably have an important bearing on the potential for subsequent decontamination. In general, the depositing material will be as aerosols, small particles or vapours. For instance, the mean particle size within the containment at a nuclear power plant after an accident [22] was less than 3.5 μm so the size released to the atmosphere should also be less than that. In contrast, fallout particles from a nuclear explosion are normally fairly large ($\gg 10\ \mu m$) in the vicinity of the detonation site [23, 24]. Data from Chernobyl indicate that the size of on-site aerosol particles containing plutonium and transuranic elements varied from less than one to tens of micrometres in size (Annex A).

Since much of the caesium contamination resulting from the above types of accident will be soluble, rain washoff could relocate some of it before it becomes fixed on urban surfaces.

Contamination from the release of radioactivity following an accident will arrive on surfaces by washout, dry deposition or a combination of both, depending on the weather conditions. Under some weather conditions, for example fog and low cloud, occult deposition or the wetting of surfaces through condensation of airborne moisture can also be an important mechanism. The term washout (W) refers to removal of radioactivity by rain, including incorporation of radioactivity into growing raindrops and removal of particles from air below the cloud by falling raindrops. It is generally expressed as:

$$W = \frac{\text{activity per unit mass of rain}}{\text{activity per unit mass of air}}$$

The fission products washed out of the atmosphere into raindrops can be deposited on the surface in several ways:

(a) The rainfall is insufficient to produce any runoff and all the contamination remains on the surface after the water has evaporated.
(b) The rainfall is heavy enough and the slope of the surface is such that runoff occurs. Some of the contamination is intercepted and retained by the surfaces during runoff. The time that the contamination in the rain remains in contact with the surface can vary from a few minutes to hours depending on surface slope and rate of rainfall.

For dry deposition, the contamination is carried as an aerosol or by attachment to atmospheric dust particles which eventually settle on a surface. Dry deposition is generally described by the deposition velocity (V_g), where

$$V_g = \frac{\text{Activity deposited per unit area of ground}}{\text{Volumetric concentration of activity} \times \text{exposure time}}$$

Detailed measurements of radioactivity deposited in the UK from the Chernobyl accident [25] illustrate the widely noted importance of rainfall patterns on washout. For example, the highest levels of ^{137}Cs were associated with regions of highest rainfall, with the maximum level being 10 000 $Bq \cdot m^{-2}$ at Holmrook in Cumbria. Levels at other locations in Cumbria were as low as 110 $Bq \cdot m^{-2}$, consistent with the steep local variations in rainfall at the relevant time. At other sites in the UK where contamination levels and rainfall were lower, a substantial proportion of the ^{137}Cs was deposited by dry deposition. At Chilton in Oxfordshire, the V_g value for ground contamination was calculated to be 0.03 $cm \cdot s^{-1}$, whilst on vertical brick walls it was <0.001 $cm \cdot s^{-1}$, i.e. a factor of 30 less. The deposition velocity of ^{137}Cs onto vertical brick walls in Denmark ranged from 0.003 to 0.070 $cm \cdot s^{-1}$ [26].

Generally, deposition velocities are higher over areas with dense vegetation, for example trees or shrubs, where they become limited only by transport of material to the ground by the turbulent flow. Typical maximum values for V_g are likely to be around 1.0 $cm \cdot s^{-1}$ (although higher values can occur via occult deposition). Over relatively smooth areas such as building materials, deposition velocities will be much lower.

Such a difference in deposition velocities was shown in Ref. [27] where V_g values for ^{137}Cs on walls were as low as 0.001 $cm \cdot s^{-1}$; on road surfaces the values were 5 times higher. They rose further by a factor of 5–10 for rough surfaces such as bare soil, roofs and clipped grass. The values for trees and bushes were even higher.

The relative importance on the indoor dose rate of radioactivity deposited inside buildings compared with that deposited outside depends on the degree of shielding provided by the building and on the relative deposition indoors and outdoors.

In Refs [24, 28] it is shown that total indoor exposures would be increased by a factor of 2 if the indoor deposition is greater than 2% of the deposition on a lawn. Post-Chernobyl measurements after dry deposition indicate that indoor contamination with ^{137}Cs is several per cent of the deposition on a lawn. Such high contamination on internal surfaces would influence significantly the exposure in multistorey houses or at other locations with comparatively better shielding. These considerations would not apply where most of the activity has been deposited by wet deposition processes which result in little or no deposition indoors. There, the main consideration would be avoidance of transport of activity indoors by foot traffic or subsequent wind blown dust particles. Nevertheless, decontamination of indoor surfaces needs serious consideration in overall plans.

Grassed surfaces are likely to experience higher V_g values than building surfaces, but probably somewhat below the typical maximum values of about 1.0 $cm \cdot s^{-1}$. It is quite probable that at least in a suburban environment the contamination on vegetation in gardens, for example on trees, shrubs, vegetables and grass, will exceed that on building surfaces.

When considering decontamination of urban surfaces it is essential to know where decontamination will be most efficient in dose reduction.

The dominant source of indoor dose in a typical European house could be the gamma radiation from highly contaminated trees in front of windows, from lawns, roofs and even light shafts. Therefore trees and other vegetation close to a house should be monitored to determine if they should be removed.

For multistorey buildings, roofs will assume lesser importance for the lower floors. The lower deposition velocity on walls, the greater shielding offered by some forms of construction (e.g. brick and stones) and the relative difficulty of decontaminating rough and porous surfaces may mean that the decontamination of walls may not be cost effective in terms of dose reduction.

8. CHARACTERIZING THE CONTAMINATION

8.1. INTRODUCTION

Before any cleanup action can be initiated, a detailed picture of the type, characteristics, mix, concentration and spatial distribution of the radionuclides released as a result of the accident must be determined. A preliminary assessment would be based on a knowledge of the radionuclides in the facility, operational and emergency monitoring instrumentation in or near the plant, weather conditions and initial preliminary assessment of the accident. However, this information may be inadequate to assess the actual distribution and concentration of radionuclides in the affected area to permit the cleanup operation to commence in an efficient manner.

Characterization efforts should be designed to provide information to determine which, if any, cleanup actions should be initiated in various zones. The precision and accuracy of the conclusions resulting from characterization data analyses should be in proportion to the cost sensitivities associated with each cleanup alternative. That is, as the cost of the remedy increases, the need for more precise knowledge of waste characteristics and volumes also increases. Conversely, data needs should be limited by some predetermined, acceptable cost risk. For low cost alternatives, as an example, it may be acceptable to incur a relatively large error in waste volume estimates; while higher cost alternatives will tend to require more precise estimates. Accordingly, a phased approach to characterization that optimizes data quality objectives versus the cost of acquisition and analyses should be considered. General guidance on using a phased approach is given below.

(a) Screening surveys

Initial efforts should be directed to delineating areas of major concern. In situations involving widespread contamination, aerial surveys are a cost effective method for rapidly delineating and quantifying such areas. Assessment of aerial survey data may provide sufficient information to support design of interim measures necessary to mitigate the effects of high levels of contamination, or be used to locate areas requiring further definition. Aerial surveys are usually incapable of precisely locating contamination boundaries, or pinpointing hot spots. Ground based scanning systems mounted in vans or trucks are capable of better definition, but require more time, and are limited to areas which have relatively good access.

(b) Boundary definition surveys

Precise delineation of the limits of the contamination can be accomplished using hand held instruments that are sufficiently sensitive to detect levels of concern. Mobile scanning systems may be used if access is sufficient to provide the desired level of definition. The outer boundaries of the contamination should be well marked and mapped to aid future characterization and/or remedial action efforts.

(c) Waste characterization

Knowledge of characteristics and volumes of the waste arisings may be necessary for assessment of various remedial action alternatives. In such cases, laboratory analyses of the environmental media of concern should be obtained to correlate isotopic concentrations with field instrument readings and to help predict contaminant behaviour in the environment. Depending on the local surface geology and hydrology, subsurface soil samples, sediment samples and down-hole gamma logging data should be analysed to evaluate migration. Additional field readings may be required to better define waste volumes. In this case, an approach utilizing systematic measurements within an established grid may be applicable. This approach requires that a reproducible grid of appropriate dimensions be established, and that radiation measurements be recorded at marked grid intersections. Data should be carefully verified and documented. Data usefulness is greatly enhanced by utilization of mapping techniques (activity ($Bq \cdot kg^{-1}$) and/or dose rate ($\mu Sv \cdot h^{-1}$) isopleths), found in commercially available computer software.

8.2. MONITORING EQUIPMENT AND TECHNIQUES

In this section the methods available to characterize the actual distribution and inventory of released material are briefly described.

The techniques include: airborne and vehicle borne monitors, semi-portable and hand held instruments, air and soil (surface and subsurface cores) sampling, etc. It is beyond the scope of this report to review in detail the types of detectors and analytical techniques which are available for such purposes. However, examples of

FIG. 2. Helicopter equipped with one NaI(Tl) gamma ray sensor on each side for use in rapid area surveys. The gamma signals, flight path, altitude and meteorological data are fed into an onboard data acquisition system for ground based studies. (Credit: Scintrex Ltd.)

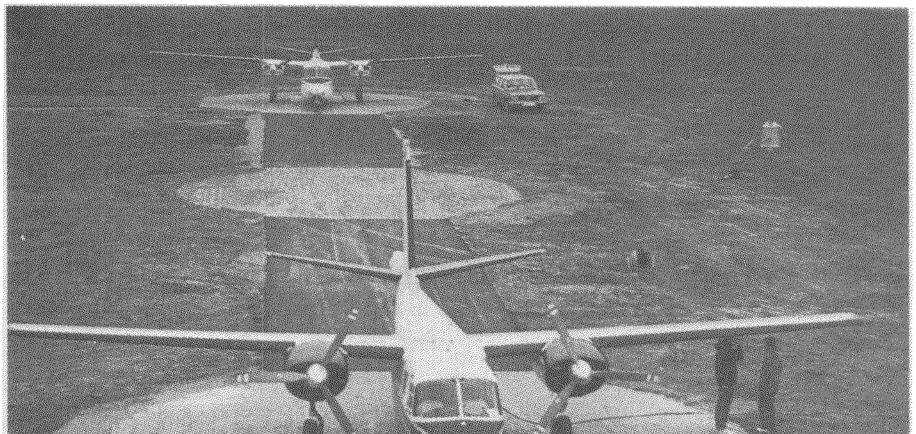


FIG. 3. Calibration pads for airborne and ground gamma spectrometers. (Credit: Swedish Geological.)

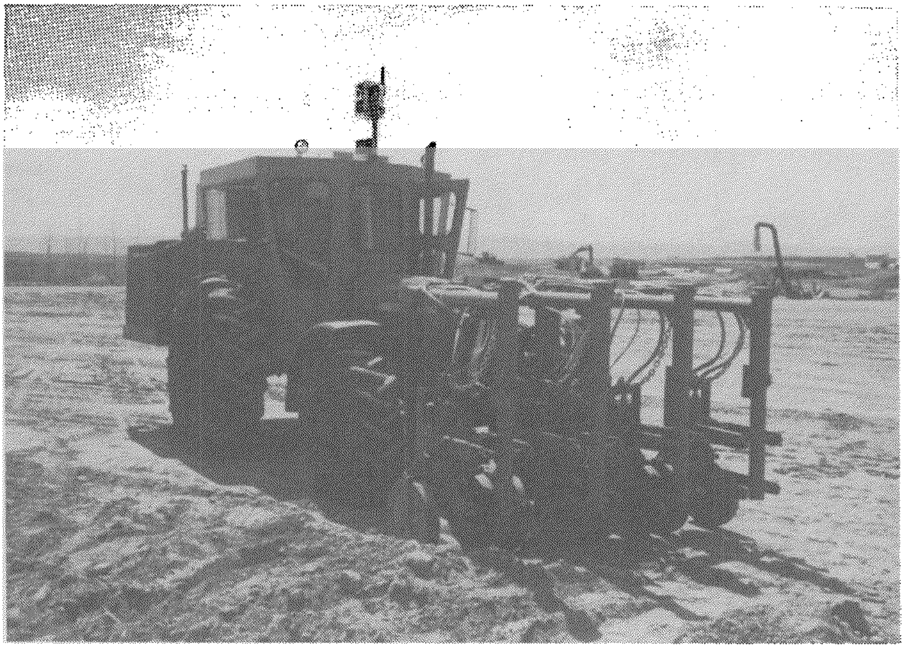


FIG. 4. Tractor borne surface contamination monitor for all types of terrain to scan a 2.5 m wide strip at 3 km·h⁻¹ using four NaI(Tl) gamma detectors mounted at the front. The system is coupled with microwave telemetry for rapid scanning, automatic data entry and plotting. Paint sprayers behind the detectors automatically mark hot spots for cleanup crews. (Credit: USDOE, M.K. Ferguson, Chem-Nuclear Systems.)

special pieces of equipment which should be very useful are briefly described. References [9, 29] may be consulted for further details.

For many years remote gamma sensing from aircraft has been an effective way of rapidly locating, monitoring and mapping gamma activity on the ground [30, 31]. Helicopters or fixed winged aircraft can be used as the platforms for sensitive NaI or germanium detectors to measure total gamma count rate. Helicopters are used for low level work where maximum sensitivity is required. Positioning of the aircraft during surveys is accomplished with microwave locating systems which feed indicators to guide the pilot accurately along preselected routes. Gamma signals, flight path, altitude and meteorological data are fed into an onboard data acquisition system for post-flight analysis. Gamma survey data overlaid on aerial photographs indicate the location of the contamination very accurately. Identification of the gamma emitting radioisotopes is done using a germanium detector, a multichannel pulse height analyser and computer. This information is immediately useful for planning purposes. Depending on the radionuclide mix, it may also serve as data with sufficient

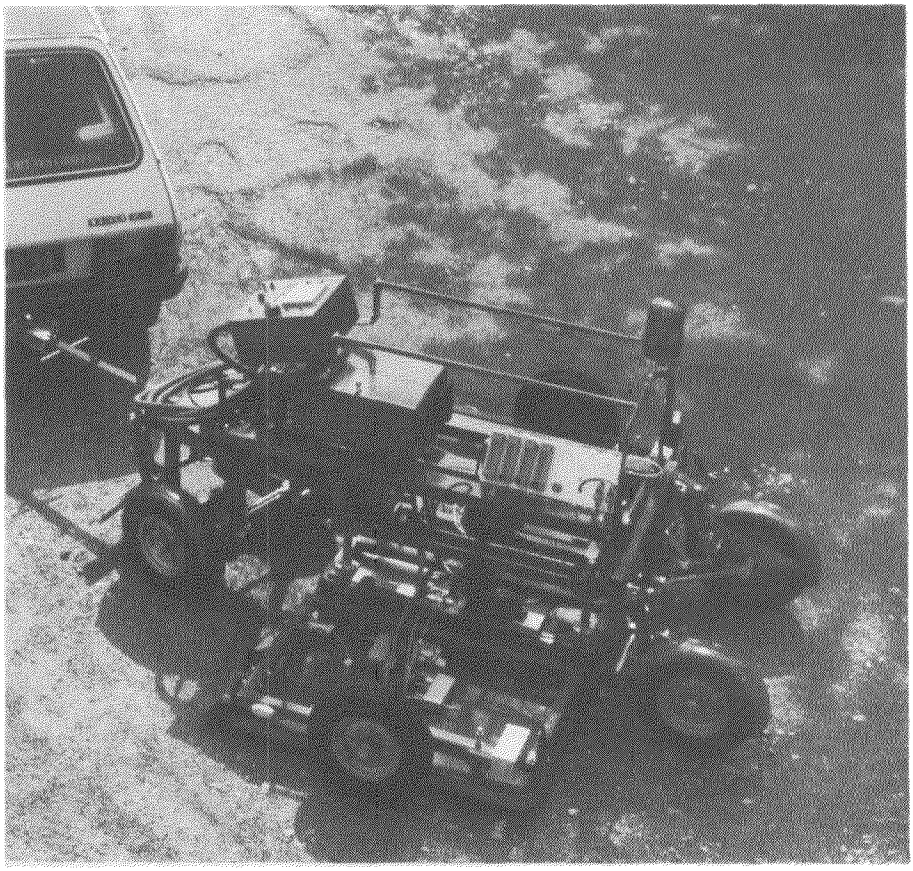


FIG. 5. Road contamination monitor consisting of a gas flow proportional counter (Ar–10% CO_2) mounted on a vehicle drawn trailer. The effective width of the monitor is 180 cm. For alpha/beta/gamma contamination. (Credit: NOVELEC/CEA.)

integrity to guide initial cleanup actions. These systems are also useful for a final survey to confirm that the cleanup meets the required standards. Figures 2 and 3 show examples of a helicopter mounted unit and calibration pads for such units, respectively.

Vehicle borne monitoring systems can be equipped with more elaborate equipment including microwave and UHF ranging systems. Alternatives include satellite global positioning systems and possibly inertial navigation. Since vehicle borne systems can more easily monitor at one spot longer, traverse more slowly and get closer to the contamination, such systems generally provide improved detection sensitivities and greater resolution of changing contamination. The ability to resolve

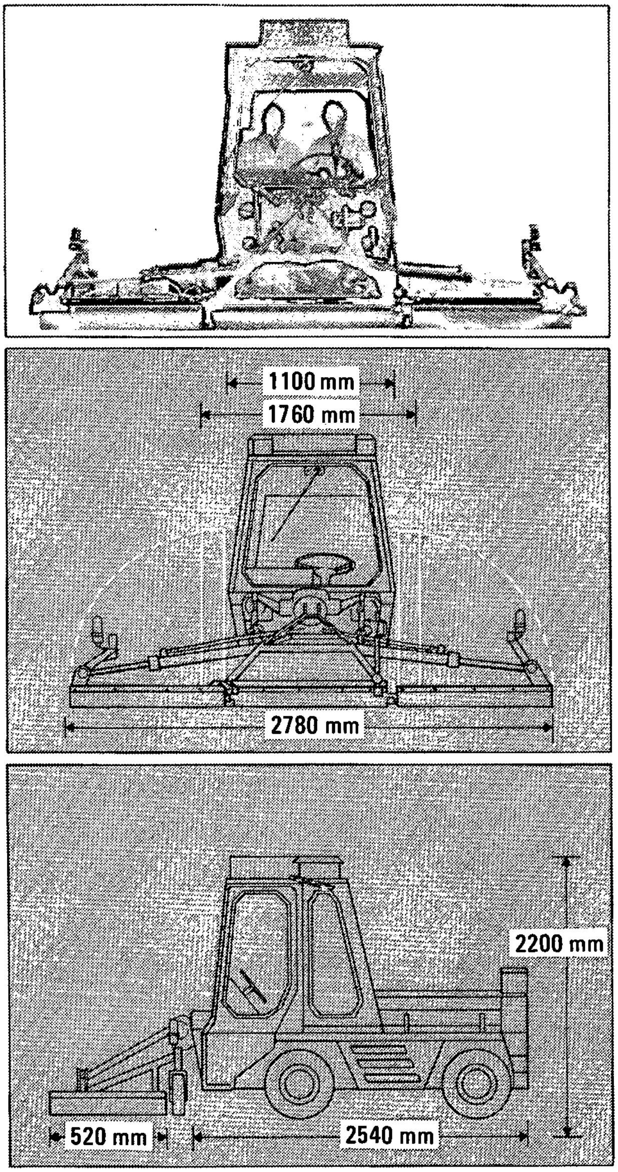


FIG. 6. Road survey monitor consisting of 10 gamma compensating gas flow proportional counters (Ar–10% methane) mounted on the front of the vehicle. Sensitive area of each beta/gamma counter is 600 cm^2. Separate counters are provided for gamma and beta/gamma monitoring to allow detection of beta contamination in a background gamma field. (Credit: British Nuclear Fuels plc.)

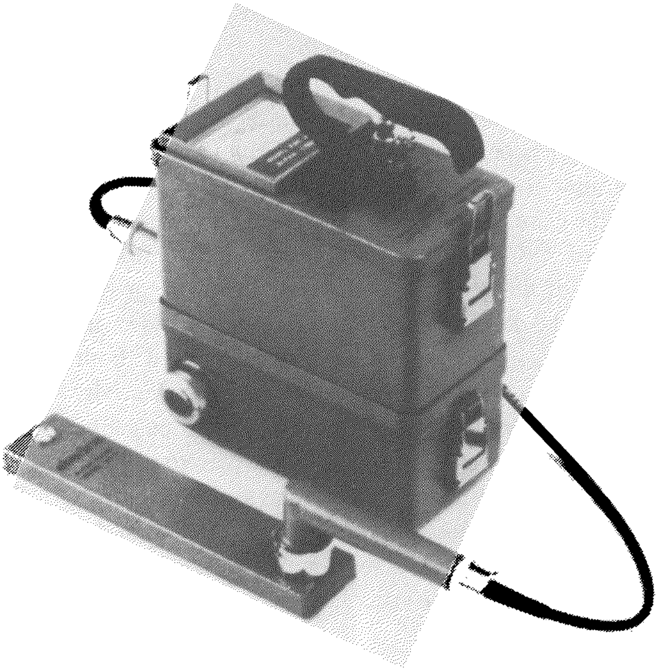


FIG. 7. A portable high resolution germanium diode spectrometer system capable of measuring transuranics, activation products and fission products at sensitivities below the uncontrolled release criteria limits for the USA. (Credit: Battelle Pacific Northwest Laboratories.)

changing concentrations can be very important if it gives the opportunity to show that certain areas need no further cleanup. A variety of ground based systems are available. Figure 4 shows a system (called RTRAK) which is currently in use for large scale cleanup in the Uranium Mill Tailings Remedial Action Project in the USA. The tractor borne gamma scanning system is coupled with microwave telemetry to conduct rapid scanning, automatic recording of location, complete coverage of the area of interest and automatic data entry and plotting. Figures 5 and 6 show other representative types of such monitoring systems. Information on the types of remotely operated monitoring devices used at Chernobyl is given in Appendix A.

Very sensitive high volume Ge-Li detectors have been used on a variety of vehicles and platforms and in many geometries [32]. They improve the ability to interpolate data between measurement points if large samples are either collected or measured in situ. Several workers have reported the advantages of mounting such detectors on extendable booms with repeatable fixed geometries. With this technique it is possible to scan over a large area and this improves the statistics and quality control of the analyses [32].

In developing the plan for monitoring for contamination distribution and inventory, the required laboratory analyses should not be overlooked. To completely characterize the contamination in an area, chemical analyses are required, especially if the contamination has penetrated well below the surface. Such samples are also required to determine the ratios of various radionuclides in the contamination. For example, if only the gamma activity is monitored after an accident at a nuclear power plant, the ratios of ^{137}Cs to ^{90}Sr must be determined from soil radiochemical analysis. Similarly, if the ^{241}Am photon is used to map the associated ^{239}Pu, the ratio of Am/Pu must be determined by radiochemical analyses. In cases where these ratios are not constant, significant soil analysis is required. Both fixed and mobile analytical laboratories could be considered, depending on needs.

In addition to the sensitive airborne and vehicle borne gamma survey systems, a wide variety of hand held alpha, beta and gamma detectors are available for ground verification of the activity, especially on buildings and equipment [9]. Portable high resolution germanium diode spectrometer systems have been developed which are capable of measuring transuranics, activation products and fission products at sensitivities below uncontrolled release criteria. Figure 7 shows one example of this type of instrument.

Experience in the United States Department of Energy (USDOE) remedial action programmes involving the cleanup of thousands of hectares indicates that a hand held sodium iodide detector, coupled with a ratemeter, is a most effective tool for locating surface depositions of gamma emitting radionuclides. Sensitivities as low as 0.1 $Bq \cdot g^{-1}$ for ^{226}Ra and 0.1 $Bq \cdot g^{-1}$ for depleted uranium can be achieved without the need for expensive spectrometer systems. This approach is also used in these programmes to identify hot spots after completion of the remedial action. A recent development couples this scanning technique with an ultrasonic location device to provide for automated data acquisition and computer produced isopleth mapping. Such hand held or back pack equipment is reported to offer substantial operational advantages such as low cost, ruggedness and mobility.

During preliminary planning, minimum performance standards should be specified, when possible, for the instruments and techniques used in the monitoring and sample analysis programmes, including: minimum sensitivity for radionuclides expected to be present, error and confidence levels. It is beyond the scope of this report to specify required sensitivity, error and confidence levels and other related parameters since such factors are dependent on energy, radionuclide and time, and require specialized knowledge (see, for example, Refs [29–31]).

A large number of individuals and groups will be taking radiation measurements and samples for analysis during cleanup. Since it is important that measurements are made in a consistent and reproducible manner and appropriate instruments are used, protocols should be established during preliminary planning for instrument usage. These protocols should define parameters such as measurement time and distance of instrument from surface. Since personnel having little or no past experience in radiation monitoring may have to be involved, these protocols for instrument usage should be quite explicit and suitable training programmes should be established.

The specific locations of key radiation measurements should be well defined and recorded so that they can be subsequently checked after a regional cleanup operation or during final release of an area. These data points would also be useful for observing changes in environmental radiation readings which could result from the migration of radionuclides from elsewhere.

8.3. DATA MANAGEMENT

During preliminary planning, the goals and requirements for the data management plan (Section 4.3.2(h)) should be clearly defined. If during the actual cleanup, feedback of monitoring results is required daily to assist in decision making for soil cleanup and removal operations, the data management techniques must be able to process the input data to allow such decisions to be made. For example, during the Enewetak cleanup [32], monitoring data collected before and after soil removal on the vehicle borne gamma spectrometer tape storage system were shipped back 30 km to the support base at the end of each day. At the base the data were analysed and combined with soil analyses to produce ^{239}Pu and ^{240}Pu isoconcentration areas on grid maps. The information was then sent back to the decision makers for planning follow-up activities. This type of close support is necessary for high working and cleanup efficiency and subsequent radiological verification [33].

Flow diagrams for the monitoring and chemical analysis data joined to time charts for the operation can reveal potential bottlenecks in the data flow. From this type of analysis, it can readily be determined how much lead time is required for soil sampling to prevent holdups. The flow diagram/time chart analyses also permit survey requirements to be closely defined. Time constraints and data demands can be used to determine the data collection capacity required in the field and laboratory. Because demands on data processing will be heavy, it is important that well developed protocols and quality assurance programmes be set up. To remove soil which was clean or to have to go back later to clean up areas missed in the analysis can be costly errors which significant effort should be made to avoid. Therefore the data must be of high quality and provided on time so that the operation will run smoothly and be cost effective.

Special data management needs arise in the event of a very large accident such as Chernobyl, especially if large urban areas are affected. At Enewetak and at most of the uranium mill tailings cleanup projects in various parts of the world, large urban areas were not involved. For a very large cleanup involving urban areas, the amount of data required to safely and efficiently manage the cleanup/decontamination of buildings, land and water systems and for the transport and disposal of waste could be very large. The data recording and management teams would have to be bigger and well integrated and the planning more detailed. The connection and data feedback between the central data management computer and the small mobile computers with the field units and analytical laboratories would have to be well developed.

Further work is required to assess the data management requirements to ensure that the cleanup of very large areas seriously contaminated with radioactive or other toxic materials can be done safely and efficiently.

9. STABILIZATION OF CONTAMINATION

Following a serious nuclear accident which results in widespread contamination, the detriment to man from the radioactive contaminants can be reduced by the decontamination methods described in Section 10, by interdiction of the contaminated area (Section 11) or by using coatings to stabilize the contamination using the techniques described in this section.

The objectives of using coatings to stabilize or immobilize radioactive contamination on soils, buildings, roads and equipment are to:

(a) Reduce the spread of contamination to clean areas.
(b) Reduce the airborne inhalation hazards.
(c) Decontaminate surfaces by incorporating the contamination in a removable coating.
(d) Reduce the volume of radioactive waste generated. If the contamination is in an area which does not contribute to radiation doses and it arises predominantly from relatively short lived radioisotopes, it may be desirable to stabilize it and leave it to decay.

In most but not all cases, the application of surface stabilizers is a short term corrective action which would be followed by further decontamination.

A large number of stabilizers/fixatives are commercially available and these are generally classified as chemical, mechanical, physical or chemical with mechanical characteristics. In Ref. [20], the authors review a large number of generic and commercial soil stabilizers. The stabilizers are grouped as organic or inorganic and rated according to their:

— preferred applicability to various land types and land use classes
— hazard level
— durability
— application methods, and
— effect on vegetation recovery.

Reference [34] also lists stabilizers which are available, including various proprietary compounds, petroleum products (which are commonly called road oils) and asphalt-like materials.

Chemical stabilizers are liquid or solid additives that alter the physical properties of the treated surface. One preferred type [35] which is being tested is polyvinyl alcohol; this is non-toxic and non-flammable, can be applied by brushing, rolling or spraying, is abrasion resistant and can be removed by washing with a dilute basic solution. In some cases stabilizers will bind soils for short periods but will eventually break down, for example, resin/water emulsions.

Mechanical stabilizers are used to physically cover the contamination without modifying the physical properties of the soil or surface. They include concrete and asphalt covers, manufactured materials like polyvinyl films or erosion control nets, sandbags and rock rip-rap.

Physical stabilization of soils can be carried out by using heat, electricity or cold to change the physical properties.

Following the Chernobyl accident, it was reported [36] that the USSR sprayed rapid polymerizing solutions from a helicopter onto the site, the roof of the turbine buildings and sides of roads to stabilize the contamination, reinforce the upper layers of the soil and prevent the spread of dust.

Another approach to stabilization is to combine it with shielding. For example, 5 cm of concrete would reduce the gamma radiation levels from ^{137}Cs by a factor of about 3 and would fix the contaminants. This could be a more cost effective solution for car parks or some roadways than removal and disposal of the contaminated surface, particularly if waste disposal sites are limited.

In urban areas, stabilization of contamination on areas which do not require decontamination and which will not be subject to weathering could be considered. For example, vertical building walls may have lower contamination levels than roof surfaces and may not need to be decontaminated. In this case stabilization of the contaminants by a polymer spray, painting, etc., would reduce resuspension from the surface and should also reduce additional contamination when the roof surfaces are washed down.

10. DECONTAMINATION TECHNIQUES AND EQUIPMENT

10.1. INTRODUCTION

Generally, the stabilization of contaminants (Section 9) is a short term remedy which is followed by procedures to decontaminate the affected areas and remove the contaminants.

Decontamination of materials, equipment, buildings and sites to permit operation, inspection, maintenance, modification or plant decommissioning to be done safely has been an integral part of the nuclear industry since its inception. A large number of decontamination techniques and a large variety of chemical mixtures have been developed over the years to assist in removing contamination from all kinds of surfaces and these are continually being improved [37–39]. These techniques also include means of decontaminating reasonably large areas of land which have been contaminated by mining/milling wastes, nuclear test fallout, etc.

To achieve a good decontamination factor (DF), a decontamination process must be selected on the basis of site specific considerations taking into account a wide variety of parameters such as:

- Type of material: metal, asphalt, concrete, soil, wood, etc.
- Type of surface: rough, porous, coated (paint, plastic, etc.)
- Composition of contaminant: activation or fission products, actinides, etc.
- Chemical and physical form of contaminant: solubility, aerosol, flocculent particles, complex compound with other materials, etc.; for many decontamination processes, the smaller the particle, the more difficult it is to remove from a surface
- The decontamination factor required
- The proven efficiency of the process
- The method of deposition; the distribution of the decontamination and its adherence to the surface can depend on whether the deposition was wet or dry.

Other factors which are important in selecting the method and equipment, but which do not affect the DF are:

- Availability, cost and complexity of the decontamination equipment
- The need to condition the secondary waste generated
- Occupational and public doses resulting from decontamination
- Other safety, environmental and social issues
- Availability of trained staff
- The amount of work involved and the difficulty in decontaminating the equipment used for the cleanup if it is to be reused.

In summary, the final decontamination process selected will depend on the best overall balance between the above factors to minimize the overall impact and net detriment to people using the most cost effective means.

In the following sections, the methods available for decontaminating buildings, equipment, roadways, large land areas, forest and water systems are examined. Some of the relevant experience in using these processes is also described.

10.2. DECONTAMINATION OF BUILDINGS, EQUIPMENT AND PAVED SURFACES

10.2.1. Introduction

Much of the past decontamination experience at nuclear facilities relates to the cleanup of buildings, equipment and paved surfaces in or adjacent to nuclear reactors and other facilities during normal operations or decommissioning. Experience is also available from the cleanup after accidents such as at the TMI power reactor [40] or the NRX research reactor [41]. Decontamination experience ranges from the cleanup of highly active components or buildings in reprocessing plants or in other facilities after a serious accident, to operations on slightly contaminated equipment or buildings being released for unrestricted use. Extensive experience has also been obtained in the USSR following the Chernobyl accident. (See Annex A.)

However, there has been less attention to the development of methods suitable for large scale application to urban areas and to urban construction materials following a nuclear accident. Many of the techniques suitable for nuclear plants and sites may be too expensive for application on the scale required in an urban environment or too aggressive to be acceptable on aesthetic grounds. Accessibility and recovery of the radioactive wastes generated by decontamination procedures are also likely to present more difficult problems in an urban environment.

The processes currently being used to decontaminate concrete and metal structures and equipment are reviewed in Ref. [38]. Experience in applying some of these techniques to the cleanup of large urban areas are discussed in the following sections. The methods range from simple physical cleaning techniques, including allowance for natural weathering, to fairly sophisticated physical and chemical procedures. Some of the methods described use industrial equipment such as road sweepers which are readily available in many industrialized countries and which can be operated by relatively unskilled personnel. In other cases specialized techniques such as pavement grading and sand blasting require skilled personnel and special consideration of airborne contamination problems.

The application of simple manual processes such as vacuum cleaning or washing with detergent are not discussed here, although such techniques would be applicable for cleaning outdoor and indoor contamination [37, 38].

In an urban environment, there will be a large number of building designs, surface finishes, roof covers, a variety of outdoor equipment and many different paved surfaces. Building surface finishes can range over smooth tile, concrete, brick, wood and many other surfaces. Paved surfaces can be concrete or asphalt, and may be new, cracked, broken or porous. Outdoor equipment can include motor vehicles, power transformers, bicycles, etc.

The large range of buildings, surfaces and occupancy factors met in an urban environment means that several cleanup criteria would be required since it would be much more difficult to clean certain types of surfaces and in many cases it would not be necessary to clean to the same level. It may be possible to leave relatively inaccessible areas contaminated, for example the tops and sides of high buildings, provided that the contamination is fixed and does not affect those in the building. The cleanup levels required for certain industrial sites having low occupancy and no routine public access could be less restrictive than those for areas with heavy public usage, such as shopping centres, which may require very rigorous decontamination to reduce the collective dose equivalent and prevent the transfer of radioactivity into buildings via footwear and clothing.

In reviewing the experimental data for cleanup, it must be kept in mind that much of the work done so far was for the decontamination of areas contaminated by fallout from nuclear weapons. Fallout particles from nuclear weapons tests tend to be much greater than 10 μm in diameter, while those deposited from a reactor accident would probably be less than a few micrometres in diameter, except possibly in the immediate vicinity of the reactor. Many flushing and vacuuming techniques are not effective on very small particles.

10.2.2. Precipitation runoff, washoff and weathering

In the studies described below, *runoff* is defined as that fraction of the precipitation falling on a surface which is not retained there but may carry away part of the accompanying radioactive materials. *Washoff* (not to be confused with washout (see Section 7)) refers to the fraction of activity attached to or on the surface that is subsequently removed by precipitation. *Weathering* refers to the removal of deposited activity by any adventitious process (for example resuspension and dispersion by vehicle traffic) and includes washoff. Runoff of water from a surface will occur when there is saturation of the underlying material. On relatively impervious surfaces (such as glass and metal) with steep gradients, the majority of precipitation will probably run off, whereas on porous horizontal surfaces (concrete or asphalt), only under heavy rainfall conditions will there be substantial runoff.

Studies have been carried out in Norway [42] on the removal of ^{134}Cs from samples of typical roof materials. The ^{134}Cs was applied to the roof materials in solution. For material applied during dry weather, one normal rainfall (7 mm in two days) removed more than 70% of the caesium from a plastic coated steel roof material and only 3% from a tar-paper covered shale roofing material. After 8 months, 39% had been removed from the tar-paper and 78% from the steel. In a second series of experiments, the ^{134}Cs was applied to tar-paper roofs covered with wet snow and a stable layer of ice and snow. After 4 months, 41% (snow) and 65% (ice and snow) of the activity had been removed. The runoff water during this period was equivalent to 143 mm of precipitation. It was concluded that the rate at which activity was removed from roofs depended on the roof material and whether it was initially dry or coated with snow/ice, the amount of rainfall and the condition of the roof. Dirty, cracked or moss covered roofs may retain more contamination.

At a workshop held at Roskilde in June 1987, results of a study of the retention of caesium from the Chernobyl accident on roof surfaces in the vicinity of Sellafield five months after deposition, primarily under wet conditions, were presented [43]. Retention was described using an interception/retention factor (IRF) defined as the ratio between ^{134}Cs on the roof surface and on the soil assuming no significant loss occurred. For a variety of roof materials, IRF values varied from 0.16 to 0.68, with an average of about 0.4. Many more data on long term weathering of radioactivity from surfaces should become available from measurement programmes put into operation after Chernobyl.

It was proposed many years ago that weathering of ^{137}Cs in soil [44] could be described as a combination of exponential functions:

$$W(t) = A \exp(-\lambda_A t) + B \exp(-\lambda_B t)$$

where $A + B = 1$ and λ_A and λ_B represent short term and long term weathering decay constants. The short term constant is likely to represent removal of radioactivity which has not yet become fixed, whilst the long term factor ($T_{1/2} \simeq 100$ a for ^{137}Cs in soil) will represent physical erosion of the substrate. For ^{137}Cs and ^{90}Sr in soil, radioactive decay is likely to be a more rapid process than physical erosion.

Measurements on three lawns in Bavaria after the Chernobyl accident suggest that the above equation for the reduction of the dose rate due to migration of caesium in the soil underestimates the exposure [45]. The time dependence of the activity fixed on paved areas after Chernobyl has been expressed by the following function [45]:

$$Q = a\,(b \cdot e^{-0.693\, t/t_w} + 1 - b)$$

where a is the initially retained component
  b is the fraction of initially retained component which decreases exponentially with the half-life t_w.

The value of a was found to be about 0.4, that of b in the region from 0.4 to 1.0 and t_w about 66 to 92 days, with one exception of 183 days.

The runoff of contaminated precipitation from roofing materials has also been considered by Danish workers [46]. The ^{137}Cs concentration arising from weapon fallout was monitored in rainwater and in runoff water from various roofing materials. It was found that although a substantial amount of runoff generally occurred, the concentration of ^{137}Cs in the runoff water was much lower than in the rainwater. On aged roofing materials, ^{137}Cs in the runoff amounted to between 44 and 86% of ^{137}Cs in the rain. However, on similar new roofing materials the removal was somewhat lower, only 31 to 50%. It was postulated that the higher runoff from aged roofing materials was due to prior saturation of adsorption sites.

Studies have been conducted in Denmark on weathering of concrete and asphalt surfaces contaminated with ^{86}Rb as a surrogate for caesium [47, 48]. The reduction in dose rate from a one year old concrete surface was about a factor of 2 after 100 days, for new asphalt a similar reduction was achieved after 60 days. Older concrete surfaces showed a lower reduction and for aged asphalt there was virtually no loss.

Unfortunately, no systematic studies of long term weathering from building surfaces appear to have been carried out. However, it has been noted [49] that on roof surfaces in the vicinity of the Sellafield plant in the UK, of the caesium arriving at the surface from 1957 to 1984 inclusive, much less than 15% remains attached to the surface today. Unfortunately, it is not possible to determine whether the material was removed by weathering over this period or whether it was lost in the initial runoff from surfaces.

10.2.3. Motorized sweeping and vacuum sweeping

In urban areas of industrialized countries, motorized road sweepers and vacuum sweepers are used for cleaning roads and parking areas; hence such equipment should be readily available. Vacuum sweeping is the more attractive procedure since it not only cleans the surface but also picks up the displaced contamination more effectively.

However, the removal efficiency for small contaminated particles, typical of those from a reactor accident, is likely to be low for these types of equipment. Tests have shown [50] that the overall removal efficiency of typical urban equipment for coarse particles was less than 50% and for smaller particles was very low — less than 15% for particles smaller than 43 μm. It is possible, however, that improvements in efficiency for collection of small particles could be made without great cost on the basis of the results of studies on improved street sweepers for controlling inhalable particulate matter [51]. Using a main sweeper pick-up head fitted with air jets to blast the surface and lift street dust, overall particle removal efficiencies of up to 90% have been reported. Although cleanup efficiencies might be variable, it is good practice to remove dry loose particulate material using this process before applying a liquid cleaner which could fix the contamination or cause it to penetrate porous surfaces. Even if only marginal decontamination is achieved, the amount of waste produced is minimal because there are no added reagents. Therefore, it is recommended that where access is possible, vacuum sweeping should be considered as the initial decontamination process for buildings, equipment and paved surfaces.

Since many sweepers collect the particulate material in a container on the vehicle, the dose to the operator will increase unless the container is shielded and/or water filled (which prevents dust emission as well as providing shielding).

10.2.4. Firehosing

The removal of simulated particulate fallout using firehosing was investigated by the US Naval Defense Laboratory in the 1960s. In tests on paved surfaces [52, 53], decontamination factors of 10 for smoothly textured and 2 for roughly textured surfaces when contaminated with >44 μm size particles were obtained. In other tests in the USA [54] using plutonium particles with an average diameter of 0.8 μm on asphalt and concrete surfaces, DFs of 10–12 for asphalt and of 4–40 for concrete were obtained after hosing with water at a pressure of 2800–4900 kPa.

In recent experiments in Denmark [47, 48], ^{86}Rb, ^{134}Cs and ^{103}Ru dissolved in water were sprayed on asphalt and concrete roads sloped to let water run off. The roads ranged in age from 1 to 24 years and were in various states of repair. A single firehosing two days after deposition gave a maximum DF of 2. Significantly, almost no decontamination of ^{86}Rb was noted after 30–40 days, although for ^{103}Ru the DF was 1.2 independent of time. The addition of detergent or potassium fertilizer did not improve the removal rate.

Decontamination factors of up to 2 from firehosing have also been noted by other workers for roof materials contaminated with ^{137}Cs fallout from weapon tests. It seems likely that firehosing could be a potentially useful technique provided it can be applied fairly promptly after an accident and depending on the particle size and texture of the surface. It relies on the contaminants still being in an accessible particulate or soluble form on the surface of materials where it can be redissolved or resuspended into the runoff water created. Obviously, as time elapses the likelihood of rainfall (without runoff) washing contamination further down into the matrix becomes greater.

The practicality of firehosing, and also high pressure water jetting which is discussed in the next section, will depend upon the accessibility of drainage routes. Most road surfaces are provided with adequate storm drainage routes and firehosing of roads as soon as possible after an accident would seem to be a desirable step. However, if the firehosing merely shifts contamination to areas where it can become adsorbed more easily, then it may actually have a detrimental effect. For instance, movement of contamination from roofs or vertical surfaces of buildings to ground level could lead to a higher dose commitment.

Firehosing should also be useful for decontaminating buildings and equipment having smooth impermeable surfaces. It will be less effective for permeable, porous, rusty or cracked surfaces. The big advantage of firehosing is that the equipment is readily available in most areas.

During firehosing, large volumes of contaminated water could be produced. Great care should be taken to ensure that as far as practicable this water does not result in the contamination of drinking water supplies or of other areas. If the technique is used for widespread washing of buildings and roads, containing the water will be a major task.

These comments apply also to water jetting (Section 10.2.5), but to a lesser extent.

10.2.5. High pressure water jetting (hydrolasing)

Jets of water at high pressure (20 to 70 MPa) have been used to decontaminate equipment and interior surfaces of buildings. For example, DFs of up to 1000 were obtained on (unidentified) floor surfaces during the TMI cleanup [40]. At TMI an average cleaning rate of 90 $m^2 \cdot h^{-1}$ was achieved using a three-man crew.

10.2.6. Steam cleaning

Cleaning the painted or steel lined walls of contaminated hot cells has been effectively done in many places with a jet using low pressure steam usually mixed with detergent. The steam can remove some or all of the paint from the surface depending on paint type and condition.

In tests on semi-glazed engineering bricks, DFs of up to 1.6 were obtained using this technique but in general it was not very effective [49]. However, this technique should be useful if a large proportion of the contamination is included in a surface layer of dirt and it may clean such surfaces more rapidly than hosing.

Steam cleaning has limited applicability to larger outside surfaces because it requires special equipment which may not be readily available. It should be useful, however, for cleaning vehicles and equipment at fixed decontamination centres or in buildings.

10.2.7. Aqueous methods incorporating chemical additives

Numerous proprietary solutions are available for decontaminating surfaces at ambient temperature under non-aggressive conditions. Generally, these reagents contain various combinations of detergents and complexing agents. One reagent which has been in common use for cleaning the painted surfaces of fuel transport flasks is SDG-3, which was originally developed in the UK at the Atomic Weapons Research Establishment, Aldermaston. It consists of a mixture of Comprox A (a proprietary wetting agent), sodium sulphate, sodium carbonate, citric acid and EDTA. For fuel transport flasks it is particularly effective at removing surface dirt, for which ^{137}Cs in particular had a very high affinity. However, ^{137}Cs which had permeated into the paint was almost impossible to remove without taking the paint off. It is likely that the effectiveness of this washing procedure could be increased by incorporation of a detergent to loosen surface dirt. Such solutions are worth considering for strontium contamination. However, for caesium contamination there are no cheap innocuous complexing agents available. Compounds such as crown ethers which can be designed to complex with caesium are toxic and expensive.

The effectiveness of washing procedures can be improved by the addition of various inorganic ions (Na^+, K^+, Cs^+, NH_4^+) to exchange with adsorbed Cs^+ [49]. It was found that a dilute solution (0.05M) of ammonium nitrate was effective in removing caesium adsorbed on a number of common urban construction materials. This reagent, as agricultural fertilizer, is readily available in large quantities, which is an important factor. Spraying with dilute ammonium nitrate solution always resulted in the displacement of some caesium; in some cases as much as 90% of the caesium was displaced in less than 3 hours. The most difficult material to decontaminate was clay tile, which lost only 38% of its caesium in 20 hours. In general, aged weathered materials were most amenable to decontamination with ammonium nitrate. The similarity of decontamination factors for a number of these materials suggested that the caesium may have been adsorbed on a surface layer of algae. This technique has so far only been applied on a laboratory scale. Further development is needed for full scale application for extended periods, for the collection and disposal of the radioactive waste arisings, and for very large scale use, consideration of the possible contamination of groundwater supplies.

10.2.8. Abrasive jet cleaning

Abrasive jet cleaning including both wet and dry procedures with various types of grit has been employed on a large number of occasions in the nuclear industry. These applications range from heavily contaminated pipework with the contamination fixed in oxide on the surface, to lightly contaminated surfaces. Typical abrasives which have been used include sand, glass beads, metallic beads and soft materials such as nut shells and rice hulls. Abrasive jetting has been shown to be a very

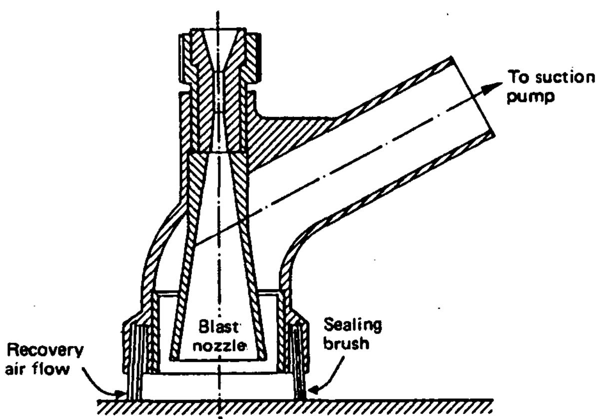


FIG. 8. Abrasive jet blast gun with sealing arrangement.

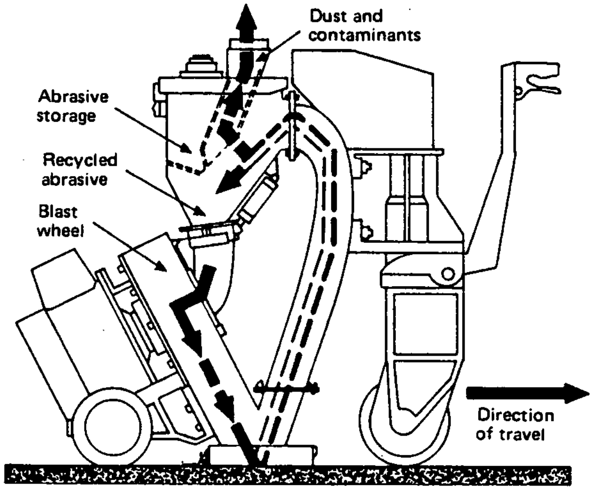


FIG. 9. Portable abrasive blasting equipment. (Credit: Blastrac.)

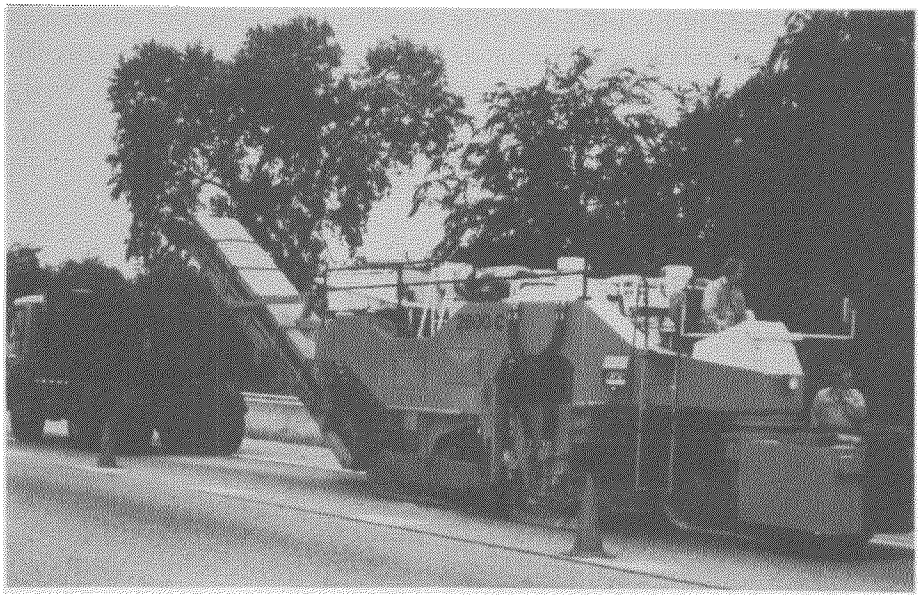


FIG. 10. Cold planer for removing a layer from concrete and asphalt surfaces. (Credit: Wirtgen.)

efficient method, with DFs of 10–100 being obtained. Wet sandblasting of houses has been used as a restoration procedure. However, it is a relatively costly (about US $10/m^2$), labour intensive procedure which would be difficult to apply on a large scale. One of the major problems would be containing the wastes produced though equipment is available incorporating vacuum brush techniques (Fig. 8) [55]. However, careful health physics control of the operation would be required to ensure that people were not exposed to radioactive aerosols and that contamination was not spread. From the aerosol generation viewpoint, wet abrasive blasting may be a better procedure. However, this has the disadvantage that both the water and the abrasive must be retained and monitored for disposal.

One of the advantages of abrasive blasting is that the equipment, such as that shown in Fig. 9, is commercially available and there is considerable cleaning experience on various surfaces. For freshly contaminated surfaces with the radioactivity on the outside, good decontamination factors can be obtained. In principle, equipment could be operated remotely, although for complex surfaces involved setting-up might be required.

10.2.9. Road planing/grinding

The removal of a fairly precisely defined layer, typically 1–3 cm from the surface of asphalt or concrete roads, using commercial equipment such as that shown in Fig. 10 is a common procedure during road resurfacing. Both cold planing for asphalt and concrete and hot planing for asphalt are used. The planers can cut the surface with hard bits at speeds up to 4.5 $km \cdot h^{-1}$ and milling widths up to 2.1 m and load the milled surface rubble directly into a truck. Although the use of such equipment to remove a layer of contaminated material from a road surface has not been reported, it is likely that very effective decontamination could be achieved. Costs for cleaning contaminated surfaces would be higher than for normal road work since methods to keep contaminated dust from spreading would be required, for example wetting surfaces and spraying the rubble. Extra costs would arise if there were special requirements for disposal of the wastes.

Such road planers, using different types of cutters for the removal of layers of earth and direct loading into trucks, might also have application in areas with fairly flat surfaces.

Smaller scale remotely operated scarifiers (Fig. 11) have been used during the cleanup of various nuclear plants.

A large number of hand held and large commercial grinders (Fig. 12) are available for removing thin layers of contaminated material from the surface of concrete. Some of the technology employed is an extension of highway grinding processes developed in the 1970s.

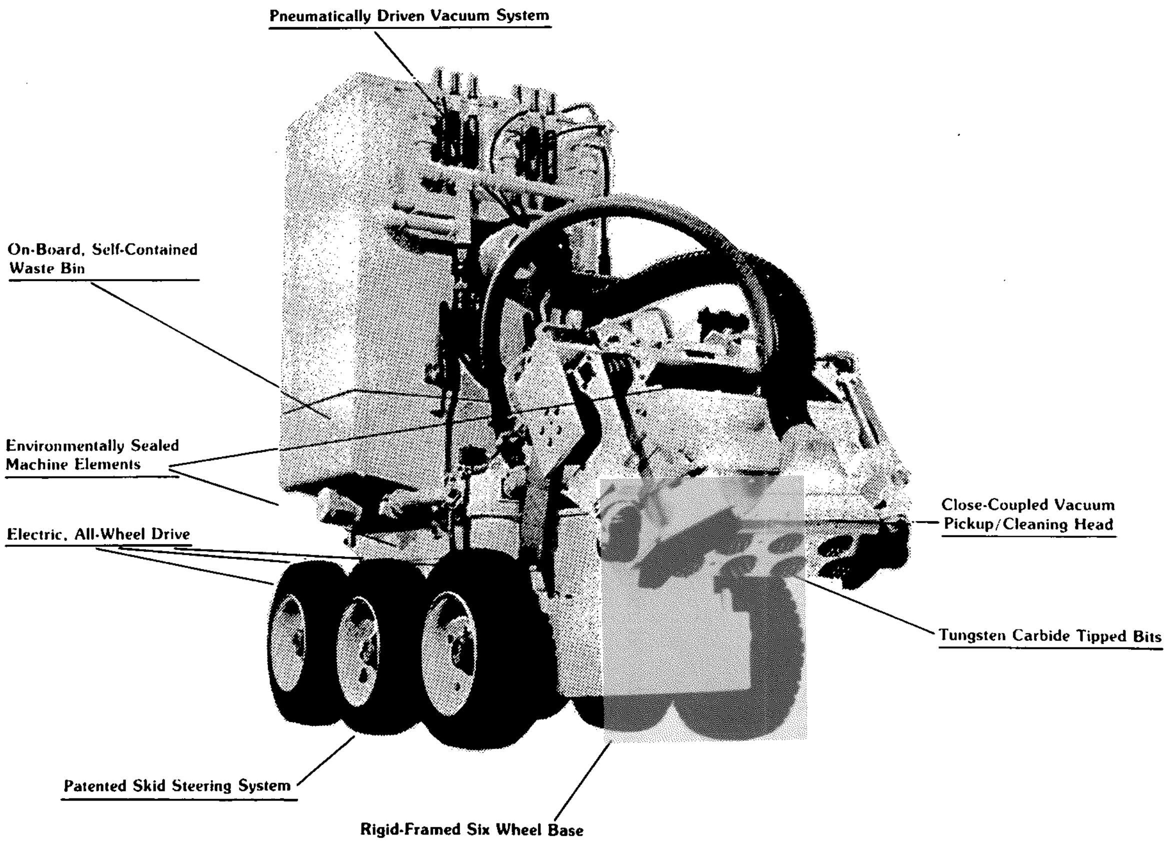


FIG. 11. Remotely operated scarifier that vacuums, filters and collects all rubble. During active operation it is wrapped in plastic to minimize contamination of the vehicle. (Credit: Pentek Inc./Electric Power Research Institute.)

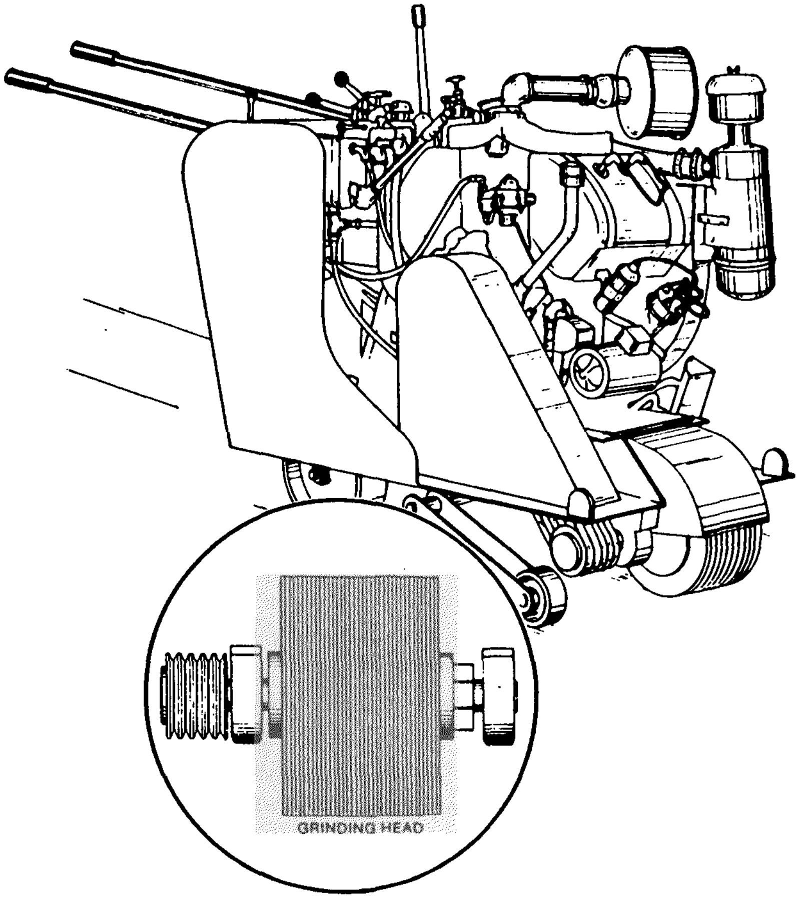


FIG. 12. Heavy duty floor grinder.

Road planers and grinders have limited applicability and would be expensive compared to certain other techniques. However, in some cases the use of such equipment may be the only answer.

10.2.10. Spalling

A variety of spalling techniques have been developed to remove the contaminated surfaces of concrete without removing the entire layer. These techniques are particularly useful for vertical surfaces which cannot be cleaned with a road planer or grinder. These methods include: drill and spall, high pressure jet spalling, flaming spalling and high frequency microwave spalling. These are described in more detail in Ref. [38]. In most of these techniques, an air cleaning system is required to minimize the spread of contaminated dust. These techniques are quite labour intensive and are only likely to have application to smaller areas or hot spots that cannot be cleaned in other ways.

10.2.11. Gels and foams

To reduce the large volumes of liquid radwaste generated when components are decontaminated by soaking or spraying, gels and foams containing decontamination reagents have been developed. The foam or gel holds the reagents at the surface, permitting them to react with the contamination. Vacuum techniques can be used to remove the foam; both gels and foams can be rinsed from the surface with water.

The foams are generated by blowing compressed air into a mixture of the foam stabilizing chemical and the decontamination chemical which is being used. The compressed air and foam chemicals are mixed in a tee in a piping manifold and are pushed by the compressed air through the hose. Foam will cling to ceilings and the undersides of equipment. In one cleanup operation in a reprocessing facility [56], an alkaline detergent blend of foam was used initially to remove a heavy soil/grease layer from stainless steel, followed by the use of a nitric acid and foam mixture.

Tests show that certain types of PuO_2 contamination on linoleum floors and painted walls[1] can be reduced on average by over 80% (DF = 5) by vacuuming followed by foam cleaning [57]. The foam was easily applied to all surfaces. On complex or horizontal surfaces, the foam layer was generally about 65 mm thick and collapsed after 20–30 minutes. The layers on vertical surfaces were usually about 25 mm thick and would collapse after a few minutes.

The incorporation of various decontamination agents into foams has been studied [58] and a number of such foams and gels are commercially available. The possible use of a foaming agent incorporating the ammonium nitrate decontamination agent described in the previous section might be worth investigating. The liquid volume required to achieve thorough wetting of a porous surface might be reduced considerably. Since it is possible to incorporate mineral acids and complexing agents into foams and probably also gels, these might be useful for decontaminating metal and concrete surfaces.

A polyurethane foam technique has been developed for removing contamination on rough urban surfaces such as lawns and flower beds. In this method, the different components of the foam are applied separately and they penetrate into the soil before polymerization. After polymerization, 1–2 cms of soil are incorporated into the layer along with any radioactivity that is in the soil. Scraping the layer off the surface can remove up to 99% of the contamination in many cases [12].

10.2.12. Strippable coatings

Strippable coatings are liquids or gels which are applied to surfaces, allowed to dry, and then stripped from the surface, carrying with them the loose contamination. The stripped film must be strong enough to be removed from the surface in as few pieces as possible. In a similar fashion to the gels and foams described above, various decontamination chemicals can be added to the film.

Strippable coatings are ideal for large scale recovery operations, especially for structures and large pieces of equipment, since they can be applied easily and quickly to large areas and require minimum equipment and personnel. Although these coatings can be applied by brushes or rollers, a pressurized spray system is best for large areas since it coats without disturbing the contamination. Loose contamination is trapped during the curing process and removed with the layer, which is easy to handle and dispose of. Two strippable coatings which are being developed [35] are waterborne vinyl resin and polybutyl dispersion, both of which are non-flammable, non-toxic and abrasion resistant. The degree of decontamination which occurs depends on the type of surface, the physical and chemical properties of the contamination particles and the adherence. In one example, horizontal surfaces in a plutonium contaminated facility (70 000 Bq/100 cm^2) were decontaminated to 170 $Bq \cdot cm^{-2}$ using one application of strippable coating.

Strippable films were employed at TMI to remove contamination from concrete floors of the auxiliary building [40]. A strippable film containing a polyalcohol, EDTA, sodium carbonate and glycerine has been employed to decontaminate a wide range of surfaces [59] including PVC, ceramics, aluminium, chrome-plating, steel, glass, resin and painted wood. Films were easily removed from all but the most porous surfaces. Average DFs of 10 were obtained for most surfaces, which compared favourably with those obtained by soaking in decontamination chemicals. One disadvantage of strippable coatings is that they require careful removal, generally by hand, and thus a considerable radiation dose may be incurred. This may limit their application on a large scale, although a cleaning rate of about 0.06 man-hours/m^2 was achieved at TMI [40].

10.2.13. Cleanup of indoor contamination

Contamination of indoor surfaces in urban buildings is likely to occur by infiltration of radioactive aerosols during dry deposition, by infiltration of contaminated dust particles or by transport of activity indoors by foot traffic (Section 7).

Cleanup of dust borne and foot borne contamination on smooth surfaces can probably be achieved by vacuuming and/or washing and scrubbing. Cleanup of radioactive aerosols on smooth surfaces could probably be accomplished only by washing/scrubbing. It is unlikely that more severe methods of cleanup, for example firehosing or steam cleaning, would be warranted or acceptable.

Cleanup of rough surfaces (curtains, rugs, rough wooden floors, etc.) could be more of a problem. Vacuuming may be partially successful for dust borne particles. Removal of curtains and rugs for washing/dry cleaning might be required if excessive contamination remains. The cleanup of activity on indoor household surfaces needs further work.

10.2.14. Decontamination of equipment

During a cleanup operation, a large amount of equipment will be used, including various vehicles, hosing, pumps, specialized units, instrumentation and clothing. These all run the risk of becoming contaminated, thereby giving an additional dose to operators and requiring further decontamination operations. Where possible, simple protective measures should be used on equipment to facilitate its subsequent decontamination. Painting, strippable coatings and protective plastic covers applied in advance as a temporary protection are possible measures which could be taken.

Well organized decontamination centres for equipment are required, especially at the transition between dirty and clean zones. These may consist of simple monitoring and washdown facilities for trucks at disposal areas and transition zones, in addition to centres having special decontamination equipment.

The organizing team should, where possible, make use of available expertise, equipment and facilities for decontaminating equipment. For example, it may be possible to convert garage facilities or standard car wash facilities to clean vehicles and other equipment since they have high pressure hoses, detergent cleaning, steam cleaning and hoist facilities. However, before wet washing, equipment and vehicles should be vacuumed to remove as much loose contamination as possible. Both wet and dry vacuum cleaners having filtered outlets should be available at cleanup stations.

Planning should include provision for the containment and treatment of waste water generated during cleanup.

Certain cleanup centres may contain specialized equipment for reclaiming valuable pieces of equipment and instruments. Examples are: freon systems for cleaning electrical equipment, instruments, greasy items, clothing, etc.; ultrasonic baths for cleaning tools, pumps, components, general equipment, etc.; and various chemical baths. Whether or not these specialized techniques and others such as electropolishing are used, and the timing of such use, will depend on the accident scenario, the availability of equipment and trained staff, the need for such techniques, etc.

During the cleanup of very large areas, the decontamination of clothing, overshoes, respirators and the other types of personal equipment used by the cleanup crews will be a major problem requiring access to laundry and cleanup facilities. Various designs of laundry and cleanup facilities for active clothing and gear are readily available for routine and emergency use. These facilities may also be required to clean up materials which have been contaminated by indoor deposition (Section 10.2.13).

10.2.15. Guidance on the selection and application of decontamination methods

The previous subsections reviewed a number of decontamination procedures which could be used for various surfaces during large scale cleanup operations. A summary of the techniques (including simple vacuuming and washing) most appropriate to various surfaces is given in Table V. The techniques are shown in order of approximate cleanup cost per unit area.

Some techniques such as vacuuming and fire hosing can be applied relatively quickly by unskilled personnel. In other cases, e.g. abrasive blasting, much more planning, especially with attention to health physics precautions and waste disposal, would be required.

Table VI lists equipment which would be required or useful for cleanup of an urban environment along with the skill requirements to operate such equipment. Equipment for monitoring or decontaminating personnel is not included in this list.

In general, it is recommended that vacuum sweeping and/or vacuuming be considered as the initial decontamination process, especially if the contamination is in the form of dry loose particulate material. Even if only marginal decontamination is achieved, the amount of waste produced is minimal and the process does not fix the contamination to the surface or cause it to penetrate porous surfaces. Use of this equipment in areas of medium to high activity would not be possible unless shielded or remotely operated equipment is available. The use of vacuum cleaning for the inside of urban buildings and smooth building surfaces should be beneficial.

Firehosing is also recommended under controlled conditions, especially on smooth surfaces such as roads and parking lots which need to be cleaned up quickly. However, it should only be used if suitable drainage routes are available and contamination of drinking water does not occur. Firehosing should also be useful for decontaminating certain types of roofs, buildings and equipment having smooth impermeable surfaces. Care must be taken to ensure that the process does not just shift the contamination from high surfaces to ground level, resulting in higher dose commitments.

If vacuuming followed by firehosing is not successful in cleaning up heavily contaminated areas, more aggressive methods such as abrasive cleaning, road planing or paint removal would be required.

Examples of results achieved in decontaminating brick and concrete surfaces contaminated with small (0.1–2 μm) radioactive particles are given in Table VII. It can be seen that the DFs vary from 1 to 20 and are roughly inversely proportional to the rate of working. This is important to bear in mind; a more efficient decontamination will generally take longer, and it is important to establish at the outset what

TABLE V. SUMMARY OF DECONTAMINATION PROCEDURES MOST APPROPRIATE FOR VARIOUS SURFACES

	Increasing cost												
	Vacuum cleaning[a]	Washing with detergent	Sweeping or vacuum sweeping	Fire-hosing	Water jetting	Steam cleaning	Aqueous with chemical additions	Gels, foams	Strippable coatings[b]	Abrasive cleaning[b]	Spalling	Road planing	Remarks
Plastics	—	A		B	B			A	A				
Asphalt/concrete paving	—	B	C^+	C^+	C^+					B		A	Use of modified street cleaners should be considered
Concrete walls	—	B		B	B	B	B	B	B	B	A		
Metal surfaces	—	B	B	B	B	B	B	B	B				Applicability depends on accessibility of surfaces
Metal machines	—	B		C	C	B	B	B	B				Reduced efficiency for complex machines
Glass	—	A		B			A	A	A				

Painted surfaces	—	B	C	C	B	B	A	Commercial stripping solutions should be effective
Roofs metal	—	B	(As for metal surfaces but accessibility could be a problem for some techniques)					
Roofs other	—	C		C	Spray with dilute ammonium nitrate			Development of some form of roof irrigation device to keep surfaces wet for a number of hours is required
Unpainted wood	—	C		C				Scraping/ sanding may be effective
Brick walls	—	C		C+			A+	

[a] Good DFs if surface is smooth or if contamination is in the form of small particles or is attached to dust. Much less effective if contamination has penetrated below the surface or is in the form of aerosols.

[b] For use on limited areas.

A: Good DFs.
B: Good DFs depending on surface finish and type and depth of contamination.
C: Variable DFs depending on surface condition and type of contamination.
+ Further investigations of applicability for surfaces contaminated with reactor accident fallout required.

TABLE VI. EXAMPLES OF EQUIPMENT WHICH COULD BE REQUIRED/USEFUL FOR CLEANUP OF URBAN ENVIRONMENT

	Likely availability	Skilled personnel required to operate or install
Industrial vacuum cleaners	A	Z
Vacuum brushing street cleaners	B	Z
Fire tenders and hoses	A	X
Water jet cleaners	B	Y
Steam cleaning apparatus	B	Y
Pumps, sprays, perforated pipes	A	X
Chemicals — detergents, ammonium nitrate, strippable coatings, gels, foams, paints	A	X
Scaffolding, ladders	A	Y
Road planers	B	X
Abrasive blasters	B	X
Water tanks — water supply, etc.	A	X
Large trucks, loaders, graders	A	Y
Airborne activity monitors	C	X
Health physics equipment	C	X
Large ultrasonic and freon baths	C	Y
Deep ploughs	B	X

A — Should be easy to acquire/requisition at short notice
B — Limited availability
C — Likely to be resource limited
X — Essential
Y — Desirable
Z — Not essential.

Equipment for monitoring and decontaminating personnel also required.

the ultimate goals of the cleanup are. An initial superficial decontamination could remove loose and easily distributed contamination and allow more ready access to an area pending the provision of more rigorous decontamination techniques.

For decontamination of buildings a detailed survey of individual surfaces will be required. It is likely that contamination levels on different roofing materials will vary substantially. Work performed in the UK on the use of a dilute solution of ammonium nitrate for removing ^{137}Cs from a selection of roofing materials shows that DFs of up to 10 may be achievable using this simple technique [49].

During the cleanup of urban areas, every effort should be made to select decontamination processes that minimize the spread of contamination from exterior to interior surfaces. Interior contamination would generally cause higher dose commitments than contamination outside the building (Section 7). When using road planing, sweeping, abrasive cleaning and other processes which could raise dust, methods to minimize dust spread should be used.

During preparations for the decontamination of urban areas, detailed attention must be given to the current and future use of the facilities involved. It is possible that where particular surfaces or geometries have led to gross accumulation of contamination, isolation of the area may be a more cost effective solution than decontamination.

TABLE VII. EXAMPLES OF RESULTS ACHIEVED IN DECONTAMINATING BRICK AND CONCRETE SURFACES WITH 0.1–2 μm RADIOACTIVE PARTICLES [60]

Method	Rate of working (minutes/m^2)	Remaining (%)	DF
Vacuum cleaner with brush and sand	1	80	1.3
	2	70	1.4
	4	55	1.8
High pressure washer — 8 MPa	0.2	55	1.8
	2	28	3.6
	10	10	10
'Magic broom' (pedestrian push broom, high pressure washer/collector)	1.3	40	2.5
'Detex' — setting peel-off latex			
One application	4	30	3.3
Two applications	8	10	10
Steam cleaner	5	25	4
Grit blast (small machine)	30	5	20

This section has given a few suggestions regarding the selection of equipment and methods for the cleanup of various surfaces. It is not possible to give a ready recipe for the selection of the best processes for cleaning up diverse urban areas. Such a selection can only be done by experts in decontamination technology who have assessed the area, the accident and the equipment available.

10.3. DECONTAMINATION OF LARGE LAND AREAS

10.3.1. Introduction

Many of the decontamination techniques described in Section 10.2 are not appropriate to the cleanup of large land areas. This section briefly reviews the special methods used to decontaminate such areas. In addition, the detriment to the workers and the public can be reduced by stabilizing the contaminants (Section 9) and/or by interdicting the area (Section 11).

During the planning stage, it is important to select land cleanup methods that will least affect the viability of the land to produce beneficial crops and minimize the ecological damage to the soil, vegetation and animals. The selection of the proper technique will also make reclamation of the land following cleanup easier.

A generic assessment of the ecological impact of land restoration and cleanup techniques for various land types and land use classes in the USA is given in Ref. [20]. The areas examined for cleanup ranged from 0.01 to 10 km^2. Conclusions about the effects of cleanup on the soil, vegetation and animals in an area are summarized in Table VIII using a ranking of 0 to 5 for each cleanup method. The interpretation of these rankings is:

0 — causes no measurable change in the ecosystem
1 — preferred technique because adverse environmental effects on recovery and side effects of treatment are minimal
2 — conditionally acceptable because of significant impact by the treatment and/or the equipment upon the area
3 — acceptable as a 'last resort' cleanup to remove exceptionally hazardous material while incurring maximum acceptable impact
4 — causes unacceptable damage but can be used as an interim cleanup if the injury is erased during the final treatment
5 — not applicable to the land type for which it is proposed.

The rankings considered the environmental insult generated during the cleanup, the physical possibility of restoring the area to its original productive state, side effects caused by the equipment needed to perform the cleanup, the impact upon the environment adjacent to the cleaned up area, and the social acceptance of the cleanup work. Not all treatments were expected to be evaluated with all land types; the exceptions are indicated in the table.

It should be emphasized that the conclusions given in Ref. [20] are very specific to the land types discussed in the report and the conclusions only provide general guidance. Table VIII is only included for illustrative purposes.

The selection of the most suitable methods of cleaning up large areas of contaminated land and restoring it to productive use is complicated by:

- the topography of the area to be cleaned up
- the large number of possible natural ecosystems and land uses
- the large number of vegetation types
- the large variation in the characteristics of soil classes
- the complex behaviour of radionuclides with different soils
- the varied response of the contamination to different weather conditions
- the ecological impact that different cleanup techniques have on different natural ecosystems and land restoration.

The final selection of the methods to be used to clean up an area must consider accident specific and site specific factors such as the type of contamination, how it was deposited, soil types, value of the land, alternative land use, population distribution, size of the affected area and the equipment available. Many techniques and types of equipment will be required for cleanup after any serious accident. The methods selected should reduce the beta/gamma radiation to acceptable levels, prevent radioisotopes such as ^{90}Sr, ^{137}Cs and actinides from entering the food chain and have minimal ecological impact. In addition, the methods must be safe, practical and cost effective because of the logistic problems and huge costs associated with the cleanup of such large areas and the need to dispose of the wastes.

In general, the cleanup methods can be classified as physical, chemical and agricultural or some combination of these. The more important methods are described in the following sections.

10.3.2. Physical and chemical methods

10.3.2.1. Introduction

The cleanup of land can be carried out by selectively separating the radionuclides from the soil matrix, by deep ploughing to remove the contamination from the surface and the root zone or by removing the vegetation and/or top layer of soil containing the contaminants.

The volume of wastes arising from the cleanup would be smallest for deep ploughing and largest for layer removal. The volume of wastes from the separation technique would depend on how well the separation could be done. The cost of storing, transporting, additional treatment and/or disposal of contaminated soils and vegetation is an important factor in selecting the proper method. For example, if the

TABLE VIII. SUMMARY OF CONCLUSIONS ABOUT THE EFFECTS OF VARIOUS CLEANUP MEASURES ON THE SOIL, VEGETATION AND ANIMALS IN VARIOUS LAND USE CLASSES AND LAND TYPES [20]

	Land use classes		*Land types*						
	Suburban	Agriculture	Coastal/ intertidal marshes	Tundra	Mountain, subalpine	Coniferous forest	Deciduous forest	Prairie	Desert
Natural rehabilitation	4	4	4	3	4	4	4	3	4
Chemical stabilization	4	3	3	5	2	2	2	5	2
Clear cutting vegetation	4	3	3	5	2	2	2	5	3
Stumping and grubbing	4	3	3	5	3	3	3	5	4
Scraping and grading (<5 cm)	3	1	3	1	2	2	2	1	4
Shallow ploughing (<10 cm)	4	1	5	5	4	4	3	1	4
Deep ploughing (10–20 cm)	4	1	5	4	4	4	3	1	4
Soil cover (<25 cm)	2	1	2	2	3	3	3	2	4
Soil cover (25–100 cm)	4	1	3	4	4	4	4	3	4
Remove plough layer (10 cm)[a]	2	1	3	1	2	1	1	1	4
Remove shallow root zone (<40 cm)	4	1	3	2	3	2	2	1	4
Remove scraping and grading, mechanically stabilize	1	1	2	1	1	1	1	1	4
Remove plough layer (10 cm), mechanically stabilize	1	2	2	2	3	2	2	1	4

Remove shallow root zone (<40 cm), mechanically stabilize	4	2	3	2	3	3	3	2	4
Remove scraping and grading, chemically stabilize	2	2	4	5	3	3	2	1	4
Remove plough layer (10 cm), chemically stabilize	2	2	4	5	3	3	2	2	4
Remove shallow root zone (<40 cm), chemically stabilize	4	3	4	5	4	4	4	3	4
Barriers to exclude people	3	2	1	1	1	1	1	3	1
Barriers to exclude large and small animals	3	3	3	3	3	3	3	3	1
Mechanical stabilization by hard surface	5	4	b	b	b	4	4	3	4
Application of sewage sludge	a	1	b	b	b	0	0	b	b
High pressure washing (<3 cm)	a	a	b	b	3	b	b	b	b
Flooding (3 to 30 cm)	a	a	b	b	5	b	b	b	b
Soil amendments added	a	4	b	b	b	b	b	b	b

[a] Increases the severity of scraping and grading.
[b] Outside the scope of this work.

disposal area is a long distance from the wastes, transportation costs could exceed all other costs if the layer removal technique was used.

10.3.2.2. Physical and chemical separation of radionuclides from the soil

Separation of radionuclides from soil is desirable since it can significantly reduce the volumes of wastes which have to be transported and disposed of. In principle, this technique is applicable only to coarser grained soil or gravel in which the radionuclides are associated with fine grained particles which can easily be separated. The technique is most practical if the area to be decontaminated is relatively small. However, since physical separation of radionuclides is almost always associated with the removal of the clay fraction of the soil matrix, the process will result in a decrease in soil fertility. If the land is to be used for crop production, addition of fertilizers after the cleanup will be necessary to restore land fertility.

Two physical techniques have been investigated, inertial separation and gravitational separation. The decontamination of soils using these methods can be carried out using water, chemical wash solutions or chemical separation processes.

Laboratory studies in the USA demonstrated the feasibility of using inertial techniques to separate the fine clay–silt fraction particles containing plutonium from soils of high quartz sand content [61]. Approximately 95% of the plutonium was associated with the clay–silt fraction and the remaining 5% with the sand fraction which constituted about two-thirds of the total soil. The process, which consisted of scrubbing and washing with water, appears to be adaptable to commercial sand scrubbing and classifying equipment.

Bechtel used a similar washing and screening process to decontaminate railroad ballast (mainly crushed stone) contaminated with the sand fines of uranium ores. This was accomplished by tumbling the material through a drum with a screen and introducing a high pressure water spray. The washed fines were allowed to settle, and the water was reused [62].

At the Rocky Flats plant in the USA, initial testing of pilot scale equipment for inertial washing with chemical solutions in a self-contained plant capable of cleaning 9.1 t of soil per hour showed that the concept is feasible with a reduction in plutonium of about 99% [63]. The proposed process consists of scrubbing plutonium-contaminated soil with a wash solution containing a dispersing solution, followed by screening and hydrocloning to separate clean gravel. The fines would subsequently be removed from the wash solution, which would be recycled. Further work is required before full scale operation could be considered.

At the Idaho National Engineering Laboratory [64], an estimated 10 million cubic metres of soil were contaminated with ^{90}Sr, ^{137}Cs and ^{60}Co. Investigators assessed the feasibility of decontaminating the soil by chemical separation processes similar to those used in mineral ore dressing. The various processes proposed are basically leaching processes. In situ, heap, vat and thin layer leaching processes were investigated for effectiveness and cost. The vat approach was found to be the most efficient method and one of the least expensive.

In the USSR, studies have been made on the theoretical aspects of decontamination of soils containing ^{90}Sr as well as the role of leaching methods, ion exchange and complex formation in soil decontamination [65]. The most promising compounds are chlorides of Fe, Ca, Na, K and Al. The Al^{3+} compounds were most effective in decontaminating soils but are toxic to plants. Iron and calcium compounds were less effective but are more readily available and less costly. Large quantities of exchange reagents are required to remove relatively small quantities of strontium. It was concluded that this method of decontamination of strontium from soils is appropriate for very small areas only.

Pilot studies on wet gravitational separation techniques using off-the-shelf water flotation equipment demonstrated that DFs in the vicinity of 90% were possible in separating Pu and Am from soils [66]. After the tests, the contaminated soil was volume reduced by 90%. The fine soil particles associated with the Pu/Am in the filter cake or settling pond need to be treated further for disposal.

The economics and practicality of these techniques for different radionuclides and soil types need to be assessed.

10.3.2.3. Deep ploughing

Deep ploughing has been investigated to a limited extent in several countries as an alternative to the removal of the contaminated soil layer. Typically, a tractor drawn trenching plough is used to completely invert a thick layer of soil, placing the active top 10 cm at the bottom and moving the deep clean layers to the top. In theory, with this method the major part of the activity would be placed well below the lower boundary of the roots of the crop. However, ploughing does not result in the perfect turnover of soil layers and some mixing of layers occurs. The extent of this mixing has been investigated to some extent but further work needs to be done. Before a decision is made for deep ploughing, an evaluation of the impact on soil fertility and productivity should be conducted. The impact of deep ploughing appears to be influenced by the type of soil and the crops grown.

A good review of treatments (including ploughing) for farmland contaminated with radioactive material is given in Ref. [67]. Field plot experiments in the USA indicate that the placement by deep ploughing of ^{89}Sr in a layer 37 cm deep in silt loam soil did not reduce the uptake by soybeans compared with rotary tillage into the top 15 cm of soil. In similar experiments in the USSR [65] in a soddy leached soil that encouraged shallow rooting of plants, the uptake of mixed fission products was compared for placements 30 and 70 cm beneath the surface. In general, the uptakes from the deeper placements over three or four successive years were about one-tenth of those from shallow placement. The authors also reported on field tests to reduce radiostrontium uptake. Deep ploughing to 50 cm in the USSR on leached chernozem soil reduced the average uptake of ^{90}Sr by oats to 60% of the uptake after discing 10 cm. In the UK, ploughing up to 30 cm had little effect on the uptake of ^{89}Sr by deep-rooted crops, but the deepest ploughing resulted in the least uptake for shallow-rooted grass pasture.

The authors of Ref. [67] subsequently did research on deep ploughing and other methods of removing radioactive fallout from farmland consisting of either a silt loam or a sandy loam [68]. Machinery which would be readily available for treatment of farmland was used for the tests. Deep ploughing using a 90 cm deep moldboard plough resulted in most of the radionuclides being placed at 69 cm depth or lower. In other experiments, rotatilling produced a uniform distribution of radioactivity to a depth of about 20 cm. Although the uptake by deep-rooted crops after deep ploughing was less than after rotatilling, the crops still took up much ^{85}Sr. When sodium carbonate was ploughed under with the radioactive soil, uptake was much less. The authors concluded that burying the radioactivity with a large plough is costly and ineffective in reducing the uptake of radioactivity for deep-rooted crops. However, deep ploughing should be effective in reducing the potential for direct contact with radionuclides on the soil surface, external radiation from surface contamination and pickup by shallow-rooted crops.

A more optimistic view of the benefits of deep ploughing is given in Ref. [65]. The author seems to have concluded that deep ploughing was the most effective soil decontamination method, particularly for the type of agricultural area involved. A special plough was used to invert the soil layer, placing the contaminated soil at the bottom and the clean soil on top. A reduction in the level of contamination by a factor of 10 was reported for deep ploughing to about 70 cm. Deep ploughing to 75 cm followed by application of sodium carbonate/isopropylphenyl carbonate mixture (which prevents root intrusion) achieved a reduction in the uptake of ^{90}Sr by soybeans by a factor of 1000. The author noted that the long term effects of combined treatment of soils have not yet been demonstrated and expressed concern about the potential effect on soil fertility.

In Sweden, deep placement experiments (simulated deep ploughing) were carried out on soils in which the contamination had either a homogeneous distribution in the top 25 cm of soil or was buried at a depth of 27–29 cm under clean soil. Deep placement reduced the soil–plant transfer coefficient for both Cs and Sr to about 35–45% compared to the homogeneous distribution. The plants included clover grass, cereals, oil seed crops and sugar beet [69].

In a recent review on the reclamation of contaminated soils, Winteringham [70] concluded that ploughing will reduce the surface radiation levels, extend the vertical distribution of the contamination layer and reduce the potential of transport of radionuclides by erosion and runoff. The effects of these will depend on how deep the ploughing is and how well it is turned over, as well as the type of soil involved. In addition, ploughing also encourages the downward leaching of radionuclides as a result of dispersion and increased exposure to infiltrating water. This effect would depend on the type of soil and how well the radionuclides are bonded. In Ref. [70], the author states that the effects of ploughing on soil-plant transfer are not large.

It is evident that further study is required to determine when and if ploughing should be used as a cleanup procedure. The primary benefit would be the reduction in external radiation levels at the surface. The benefit regarding soil–plant transfer will depend on the depth of ploughing, soil type, how the ploughing affects the vertical distribution, the root depth of plants, etc. Even for acceptable circumstances, the cost–benefit advantage of ploughing versus other methods and the depth of ploughing must be carefully considered. In some areas, the presence of land drainage systems and subsurface items such as cabling may limit the depth to which land can be ploughed. In a discussion of the logistics of deep ploughing [71], it was concluded that 33 fully equipped deep ploughs would be required to treat an area of 100 km^2 within a year.

If deep ploughing is used, the replacement of deep-rooted plants by shallow-rooted plants may be desirable.

After the Chernobyl accident, contaminated crops were shallow ploughed under in some parts of Europe. While shallow ploughing of plant material is an effective fertilization technique, its application for dose reduction is of doubtful benefit since there is no reduction in the radionuclide content of the system. Moreover, the radionuclides are then placed in the presence of fresh organic matter which could influence their mobility.

10.3.2.4. Removal of vegetation

Since under certain conditions vegetation can intercept almost all of the fallout, its removal could be an effective method of decontaminating certain areas.

The removal of low vegetation, crops and crop residues has been examined in France [12] as a method of decontaminating land areas. Field experiments have shown that different crops intercept different amounts of fallout. For example, under dry deposition mature wheat can collect as much as 70% of the fallout and mature corn 90% for a similar crop density. Dose reduction up to an order of magnitude can be achieved under certain conditions with this method.

Removal of sod was found to be an effective way of reducing surface activity (by 94%) but it was time consuming [68]. The radiation hazard was also greater since the contaminated sods were carried by hand. Removal of sod layers using mechanical methods is also possible. Tests also showed that the removal of mulch (5 to 25 t/ha) reduced the activity by 95–100% if the fallout was wet but was less effective for dry fallout (28–50%). Mowing and collecting sudangrass removed less than 40% of the radioactivity.

Studies in the USSR show similar results [65]. The sods were cut with knives; sudangrass and soybeans were removed by harvesters and manually and mulch was removed with rakes. The percentage of radioactivity removed was very similar to

FIG. 13. Forage harvester used in experiments to remove all kinds of crops in the French RESSAC programme [12]. (Credit: Renault.)

FIG. 14. Machine used to reduce underbrush and small trees to chips in the RESSAC programme [12]. (Credit: Cimat.)

the rates mentioned above for similar vegetation. No data on external dose or resuspension are available for operations under these conditions.

The removal of contaminated vegetation appears to be an effective method of decontaminating land under certain conditions. The effectiveness of the technique depends on the density and type of vegetation, on the nature of the contaminant and the method of application (wet/dry). In any event it may be necessary to remove surface vegetation to permit subsequent treatment of the soil surface (Section 10.3.2.5).

For large areas, brush and small trees can be removed using cabling or anchor chaining. In cabling, a 45–60 m long steel cable is dragged between two tractors travelling on parallel courses. The cable breaks off or uproots brush and can be used where the brush breaks easily and is not willowy. In anchor chaining, a heavy (up to 50 kg/link) chain is dragged by two tractors to break or uproot vegetation including small trees. The ground is more disturbed with anchoring than with cabling. Grassy vegetation can be cut using a mower. The ecological effects of clear cutting vegetation on various land types and land use classes can be seen in Table VIII.

In France, a forage harvester (Fig. 13) was used in experiments to remove all kinds of crops. This machine, which is normally used for ensilage of green corn, is available in all agricultural areas. It is reported that the resuspension of radionuclides is less than 1%. Also in this programme [12], underbrush and small trees were reduced to wood chips using equipment such as that shown in Fig. 14. In thick forests, large trees would have to be removed to open paths so that the underbrush or fallen leaves can be collected. Larger machines are available for cutting large trees into chips.

When vegetation is defoliated and allowed to dessicate, it may be desirable to apply a bitumen emulsion or synthetic polymer spray to reduce suspension of contamination during collection, compaction, transportation and disposal. Dead vegetation and very dry soils can cause severe resuspension problems unless they are stabilized or dampened.

10.3.2.5. Removal of surface soil

Studies and decontamination projects in the USSR, the USA and other countries show that many common types of earth moving equipment such as graders, bulldozers and scrapers can be effective in removing a layer of contaminated soil. The earth moving machines can be used to efficiently remove layers of material (sod, soil, etc.) as thin as 5–15 cm or thicker than 35 cm and transport the soil distances of 150 m without reloading or stopping [65]. The contaminated earth is either moved into piles and hauled away or buried directly in a depression or specially excavated trenches.

The effectiveness of any procedure depends greatly on the type of terrain and soil and the land use class. If the cleanup is done while the contamination lies on the surface of the soil, then careful removal of a layer slightly greater than the irregularities in the surface should remove all of the contamination. The removal of contamination will not be complete if the irregularities and fissures in the surface are deeper than the surface layer removed or if spillage occurs. Removal of a layer of soil will be less effective as a decontamination method if the radioactivity has moved down the soil profile. The rate at which the move down occurs depends on the ground cover, the soil type and the amount of precipitation following deposition.

This type of decontamination method is most effective in flat, relatively large areas having fine grain compacted earth. The efficiency of removal of the surface layer is affected by surface unevenness, soil texture, moisture content and vegetation cover. In some cases it may be advantageous to remove part of the vegetation cover before removing the layer of soil (Section 10.3.2.4). If the surface is coarse grained or gravel the contamination may have seeped to considerable depth, making this type of decontamination less effective.

The basic objectives of the cleanup work in the USSR were to decrease the levels of beta/gamma activity and prevent ^{90}Sr from entering the food chain. Since the ^{90}Sr was found to be sorbed in the top 5–10 cm layer of soil, it could be removed by stripping off the top layer using earth moving equipment. The investigators concluded that mechanical decontamination is not applicable when ^{90}Sr disperses through the soil, as may occur in loams or sandy loams or in regions of excessive precipitation [65].

Field studies were carried out on small plots of land in the USSR to test the suitability of road equipment for decontaminating soils. Various approaches to preparing the surfaces were attempted, including tilling, disking, rolling, aerating and spraying with asphalt emulsion to enhance the removal of the top soil layer [65]. Road equipment used included: road graders with high intake (2.17 m); high intake bulldozers (3.3 m); and automatic loading scrapers with different shovel capacities. A removal efficiency of 80–100% of the radioactivity in soils was attained with all equipment. Contaminant removal was more complete in loamy than in the more porous sandy loam soils. The author cautioned that the results of these studies may not be representative of similar decontamination activities involving larger land areas.

During the cleanup and rehabilitation of Enewetak by the US Government, extensive use was made of heavy earth moving equipment. Because of its porous nature, strontium and caesium penetrated well into the soil. A typical ^{90}Sr profile in the soil for an Enewetak island [72], shows that the specific activity of strontium decreased with a half-thickness of 8.4 cm in the top 30 cm of soil. In the 30–85 cm depth, the half-thickness increases to 22 cm. Because of the soil contamination profiles, the shallowness of the soils and unavailability of replaceable humus material, it was decided not to remove soils contaminated with strontium and caesium, but to restrict the agricultural use and human access to certain island areas to control exposures to within established dose criteria for island residents. However, land areas totalling 33 ha were cleaned up using soil stripping and excavation methods to reduce plutonium soil concentrations to below 1.6 $Bq \cdot g^{-1}$ of soil. Contaminated soil and debris were removed using standard earth moving equipment and deposited in existing test craters immediately adjacent to the islands and in the lagoon within the atoll.

In most experiments on surface soil, 80–99% removal of surface contamination was usually attained for silt loam/sandy loam soils by using graders, scrapers and bulldozers and removing about 5 cm of soil.

In the Palomares incident in Spain in 1966, plutonium from two thermonuclear bombs was scattered over an area of approximately 2.3 km^2. The cleanup operation involved removal of contaminated vegetation and a 10 cm layer of soil from the most contaminated area of about 0.02 km^2. The rest of the affected area was irrigated thoroughly, ploughed to a depth of approximately 30 cm and subjected to a light homogenization [73].

The logistics of removing surface layers of soil from large areas have been investigated [68, 71]. Using road graders and scrapers, decontamination times varied from 4 to 10 hours per 0.01 km^2. To decontaminate an area of 100 km^2 in one year, 12 large scrapers would be required. About 90% of the area would be cleaned up while 10% would be needed to dispose of the contaminated soil.

Work reported in Ref. [67] indicates that a rotating broom sweeper with steel bristles removed about 75% of the contamination from a moist soil with a thin cover

FIG. 15. High capacity scraper used in the coal industry (26 m^3). (Credit: TEREX.)

FIG. 16. High capacity loader. (Credit: Dresser.)

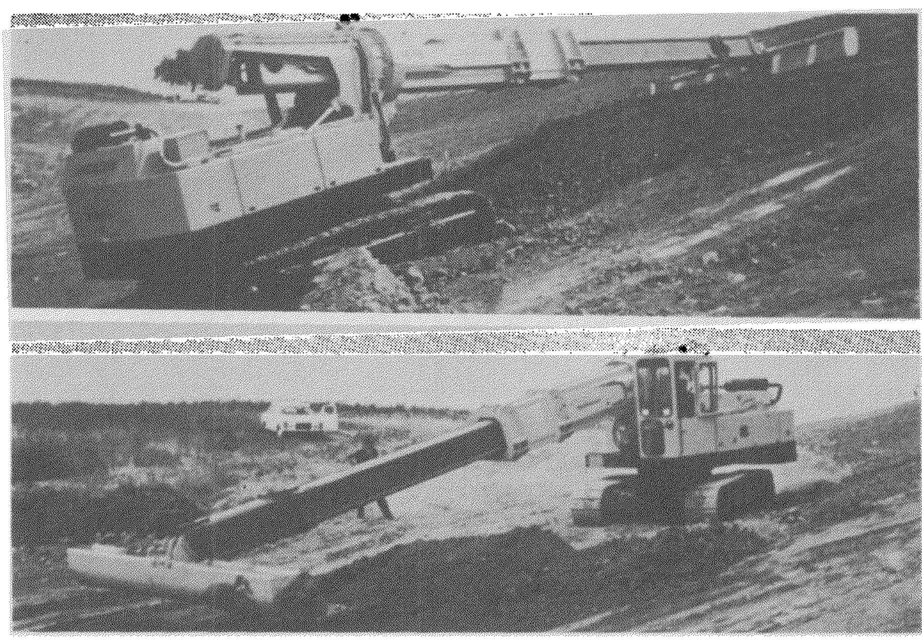


FIG. 17. Machine for removing a layer of soil from steep slopes. (Credit: Wieger Maschinenbau GmbH.)

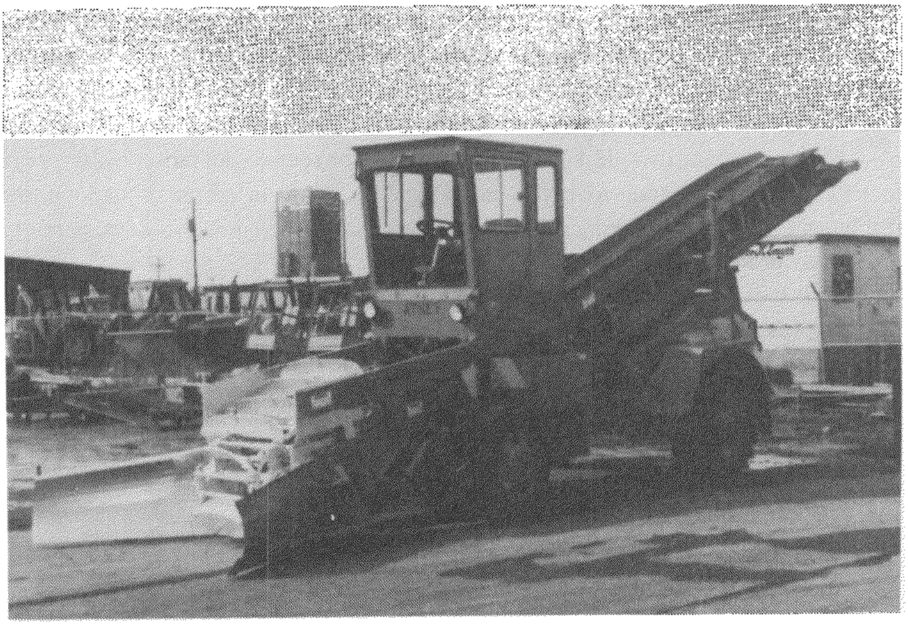


FIG. 18. Force feed loader with 25 foot (~8 m) main conveyor. The moldboard is adjustable and tapered. (Credit: Athey Products Corp.)

of fescue. A second pass resulted in almost 90% removal of contamination. A sweeper with plastic bristles was less effective. Subsequently [68], the authors did some experiments using a streetsweeper with a steel wire brush sweeping debris onto a conveyor belt which delivered to a hopper, and with a motorized vacuum sweeper with centrifugal fans. The power driven street sweeper cutting 5 cm deep removed about 90% of the contamination in three passes. The advantage of this method is that it leaves the topsoil relatively undisturbed. They concluded that the sweeper wheels would have to be modified for use on the rough terrain of farmland. Vacuuming, with and without other treatments such as soil pulverizing, was not an effective method of removing contamination from soil.

In addition to the many designs of standard size graders, scrapers, tractors and loaders, many types of large capacity earth movers are available (see, for example, Figs 15 and 16). In some cases, some of this equipment has been modified for remote operation. An example is the remotely operated equipment (Annex A) which was used in the cleanup of land after the Chernobyl accident.

Another machine which is commercially available and which may be of value in removing a layer of soil from steep slopes is shown in Fig. 17. For very large scale cleanup of relatively flat areas, the use of high capacity direct load machines such as the one shown previously for cleaning asphalt (Fig. 10) might be worth considering. Figure 18 shows a force feed loader which was used to remove a layer of soil contaminated with polychlorinated biphenyl (PCB) and load it directly onto a truck [74]. Similar machines were used during the cleanup at Chernobyl (Annex A).

These machines would have to be modified for remote operation if they were to be used in the cleanup of highly contaminated areas. In certain situations, the machines could be used with shielded cabs and suitable ventilation or respiratory devices to protect the driver.

A key element to prevent the spread of contamination during earth removal is dust suppression; this can be achieved by water sprays. Another method to fix the contamination is to spray the earth with an asphalt emulsion (Section 9) which dries and glues the soil components together for removal of the layers.

Past experience with the cleanup of contaminated soil indicates certain features which would be desirable in graders and other earth moving equipment, such as:

- — smooth cutting surface (teeth tend to smear contamination)
- — ability to skim layers of soil as thin as 10 cm and transport large volumes short distances (up to 200 m) with minimal spillage
- — ease of control and good vision by the operator.

Just as important as selecting proper equipment for cleanup is the selection, training and supervision of operators and the planning of the campaign to ensure efficiency and thoroughness. The use of mobile monitoring systems is a very time and cost effective means to ensure the effectiveness of the cleanup processes.

Table VIII summarizes some generic conclusions about the ecological effects of these cleanup methods on the soil, vegetation and animals in various land types and land use classes.

In summary, it appears that the removal of surface soil can be an effective method of decontaminating certain types of soil such as clay loam without doing serious ecological damage. However, the application of this technique to fragile ecosystems should only be made as a last resort and only if subsequent rehabilitation actions are conducted.

Equipment must be selected to suit a particular land area and accident situation. There is no method which is best for all circumstances. The use of special large scale industrial equipment in the cleanup of areas contaminated with radioactive and toxic pollutants is worth investigating further.

10.3.3. Biological decontamination of soil using plants

In Section 10.3.2.4, the cleanup of land areas by the physical removal of the vegetation (plants, sod, etc.) onto which the contamination had been deposited was examined. In this section the possibility of actually decontaminating the soil by using plants to biologically pick up the radionuclides from the soil followed by removal of the plants is briefly reviewed.

Several workers have examined the possibility of biological decontamination of soils using plants [75–77]. For example, the uptake of radionuclides by clover from a loam soil has been studied [77]. A single crop of Ladino clover in a laboratory study removed 4.42 and 0.13% of ^{90}Sr and ^{137}Cs, respectively. Over a period of 516 days, nine crops of Ladino clover removed 23.69 and 0.72% of ^{90}Sr and ^{137}Cs respectively. Since conditions in the field would not be expected to result in maximum uptake, the efficiency of decontamination under field conditions would be expected to be lower.

On the basis of current literature data, this technique does not appear to be practical for widespread usage even though it is feasible. However, it might have some application in special cases, for example to decontaminate interdicted land in an undisturbed state over a long period of time. Further studies are needed to determine the full potential of this technique. Factors that need to be considered include: the most appropriate plant species, conditions that will maximize radionuclide uptake, the number of crops required to reduce soil concentrations to an acceptable level, harvesting practices and costs, and plant processing and disposal methods and costs. This approach to soil decontamination should be considered in the context of other options that may be available, such as the use of chemicals and fertilizers to reduce the uptake of radionuclide contaminants in soil during the productive use of land following a contaminating event.

10.3.4. Restoring land to productive use

In many cases, contaminated land could eventually be reclaimed and returned to productive use. The return to productive use can be assisted by:

(a) The eventual reduction in residual activity levels in the soil by natural means;
(b) Decontamination of the land followed by reclamation measures such as fertilization;
(c) Deep or shallow ploughing in combination with the addition of chemicals or adsorbents to reduce the uptake of residual radionuclides in plants;
(d) Using the land to grow non-food/feed crops.

To make restoration of land following decontamination easier, it is important in the planning stage to select decontamination methods that will least affect the viability of the land to subsequently produce beneficial crops and minimize ecological effects on soil, vegetation and animals. In addition, the planners should decide on which remedial actions are required to restore productivity to the land after cleanup.

Numerous research workers have addressed the problem of revegetating land following remedial actions and mining activities. Revegetation is particularly difficult in arid areas. Irrigation including drip irrigation with the application of nutrients has been successfully applied [78, 79]. Most of these studies address revegetation from the point of view of stabilization of soils rather than increasing direct beneficial use. However, the land must first be stabilized if it is eventually going to be put to productive use. Various techniques investigated for encouraging growth of vegetation include the addition of topsoil and treatment with fertilizer, straw, clay, minerals, pH modifying chemicals and other substances.

An action required in response to one need may provide a remedy for another problem, for example the addition of fertilizers and minerals to farmland after removal of the top layer will not only reconstitute the soil but may result in decreased uptake of ^{90}Sr, ^{137}Cs and transuranic elements [70, 80]. Overlaying the soil with clean topsoil from nearby lands with an overabundance of topsoil should also be considered in certain cases. This process will not only increase nutrients but will dilute radionuclide concentrations in the root zone of crop plants. However, for certain land types and land use classes this action may not be desirable (Table VIII).

Various workers have addressed practices that may be effective in returning land to productive use by reducing the uptake and retention in plants of radionuclides following a contaminating incident. Increased availability of isotopic or chemically related elements can reduce the soil-plant transfer of radioactive isotopes [70]. The use of liming and increased pH will decrease the uptake of strontium and the application of potassium/phosphorous fertilizers will reduce the uptake of caesium. The uptake of potassium rich fertilizers reduced the uptake of ^{137}Cs by an order of magnitude in a variety of tropical crops [81]. Reduction in the pickup of contamination, however, does not always occur after the application of chemical elements. For example, application of stable cobalt enhanced the accumulation of ^{60}Co in plants. To get a reliable estimate of the usefulness of such techniques to assist in the reclamation of contaminated land the following considerations should be kept in mind. Adding fertilizers or chemical analogues creates a competition with the radionuclide at the plant root absorbing zone, and therefore a lower contamination level in the plant should be expected. However, a similar competition may also occur at the soil absorbing sites, resulting in an increase in bioavailability and higher levels of contamination in the plant. Therefore, depending on the chemical nature of the radionuclide, the soil type and the plant species, a reduction or increase of the plant contamination level may then occur. Much insight into the basic principles of soil and root absorption has to be obtained before these methods can reliably be applied to reclaim land.

Other workers have investigated agents that will scavenge the radionuclide and cause it to be unavailable for uptake by plants. For example, grandallite, an abundant mineral, and various ureaformaldehyde resins have been used for this purpose with some success in the laboratory [82, 83].

The complexing agent EDTA in solution has been investigated for removing ^{90}Sr from soils [84]. However, ions other than strontium form stronger complexes with EDTA and would compete with strontium. Therefore, it may be necessary, following the stripping process, to replace certain desirable soil nutrients such as calcium to make the soil fertile again.

Selective removal of ^{137}Cs from soil poses a more difficult problem owing to the lack of suitable complexing agents. Although compounds such as crown ethers will complex caesium, they are quite toxic and very expensive. Hence they would not be suitable for application on a large scale. These techniques with complexing agents may have serious drawbacks since most of them more effectively bind the micronutrients indispensable for healthy plant growth, and these will not be fully restored by fertilization techniques. The cost-benefit analysis of such practices moreover, will need careful consideration.

Land may be reclaimed and used for productive purposes, even if there is some residual contamination, by the judicious selection of crops. For example, the cultivation of non-food/feed crops such as cotton, flax and timber could be considered if food crops would contain unacceptable concentrations of radionuclides. Again, the content of radionuclides such as ^{90}Sr should be very low in corn since it has one of the lowest mineral contents of all grains and would be safe to grow on contaminated land.

Land could also be restored to productive use by growing sugar and oil producing crops since most of the radioactivity in the refined products would be removed during processing. However, if the by-products, such as sugarbeet pulp, are fed to animals for meat production, the indirect contribution of radionuclides to the human diet would have to be considered.

Changed practices such as the planting of deep-rooted rather than shallow-rooted crops would be expected to reduce the uptake of radionuclides unless the activity has penetrated well below the surface as a result of deep ploughing or for natural reasons.

The available information on the reclamation of land and land use does not constitute a body of facts that can be translated into specific and precise guidance to be followed in agricultural practices after a contamination incident. However, current information and experience that is now being accumulated in the aftermath of the Chernobyl accident should be helpful in selecting practices that will enhance the beneficial use of land.

10.3.5. Decontamination of soil and vegetation in an urban environment

The decontamination of soil in large rural or agricultural areas has been considered in detail in previous sections. Some of the physical techniques described may be applicable to areas such as parks, grass verges, etc. in urban areas if it is possible for large items of equipment to gain access. However, in many urban and especially suburban environments a multitude of gardens, small plots of land, etc., will exist where access will be difficult. As described in Section 7 on deposition velocities, it is possible that the uptake of contamination by garden vegetation could be much higher than on building surfaces. In addition, for garden surfaces, unlike roofs and pavements, etc., there will be little possibility of any initial runoff of radioactivity. Rainfall is likely to wash contamination from vegetation into the soil, where in the case of caesium it will largely remain in the top few centimetres. Hence it is quite possible that in a typical suburban house and garden the contamination per unit area could be substantially greater (perhaps an order of magnitude or more) in the garden than on the house. The situation could therefore arise where radiation doses to people living in the house are dominated by the radionuclides deposited in the garden soil.

The first step in decontaminating a garden area would be the removal of as much vegetation as possible, particularly from areas closest to the building. Grass cuttings, vegetables, flowers, shrubs and tree foliage may have to be removed. The removal of a soil surface layer (5–10 cm) from a garden area of 200 m^2 could generate up to 20 m^3 of soil wastes and possibly an equal volume of vegetation. The physical removal of this 40 m^3 of material from a garden with no access for large machinery would be an onerous task and might have to be accomplished mainly by manual means. Another approach is to remove superficial barriers such as fences and clean up the yards using small loaders and other equipment.

The 40 m^3 of wastes from the garden would probably far exceed wastes generated in cleaning up the building exterior. Transport and disposal of this waste material would be a major problem. It is possible that interim solutions would have to be found. However, it is difficult to predict what would be acceptable to the public at large. Possible interim solutions such as storing contaminated vegetation and soil in a cordoned-off mound on the site may have to be accepted.

Reduction in the amount of wastes to be transported might be achieved by waiting for vegetation to die back. However, a long delay might be required. For instance, in temperate climates if a release occurred early in the growing season it would be necessary to wait 8–9 months before die-back of vegetation occurred. In some tropical climates, growth takes place all year and there would be no season when the bulk of vegetation would be at its minimum. One option would be the application of defoliants which can kill plants quickly. The vegetation would be left to dessicate, thereby decreasing in bulk and weight.

However, large areas of dead vegetation would represent a fire hazard and this would have to be guarded against. Although defoliants such as paraquat are invariably toxic, they would tend to be absorbed in the surface layers of soils scheduled for removal and disposal. The use of toxic defoliants could impose more restrictive disposal requirements for soil than for soils just contaminated with low level radioactivity.

10.4. DECONTAMINATION OF FOREST AREAS

The migration of radionuclides in forest stands has not been as thoroughly studied as their migration on other farmlands [85]. Fallout can result from a one-time event such as an emergency at a nuclear facility or occur over a prolonged period as a result of weapons tests. The use of global fallout for studying the distribution, redistribution and circulation of radionuclides is difficult because fallout occurs over many years with large fluctuations from year to year and even from season to season. The use of experimentally applied radionuclides deposited by aerial means to study migration encounters difficulties mainly as a result of the necessity of introducing the deposition over considerable areas because of the large dimensions of arboreal plants.

The fate of radioactive particles deposited from air onto the canopy of arboreal vegetation depends on many factors. The capture of radioactive fallout particles onto the plant cover is known as primary interception and is defined as the ratio of the quantity of radionuclides intercepted per unit area to the total quantity falling per unit area. The extent of interception depends on the plant cover characteristics, plant spacing, time of year, weather conditions, whether the deposition is dry or wet, etc.

Experiments simulating moist fallout onto well established pine forests showed that as much as 90% of the radioactive fallout could be intercepted by the canopy [85]. For very close coniferous stands, complete interception of radioactive fallout is possible. However, for deciduous trees the percentage of primary interception can vary widely since they remain defoliated for a considerable part of the year.

The fall of leaves from deciduous trees in the autumn is important in the migration of radionuclides which were intercepted on the leaves. A significant part of the intercepted fallout could migrate to the forest floor. The migration of intercepted radionuclides due to the biological shedding process is slower in coniferous forests since the life span of the needles can be as long as three to ten years.

A considerable part of the radionuclides deposited on the canopy could be absorbed into the needles and leaves under certain conditions [86]. The amount of absorption depends to some extent on the length of time the radionuclides are trapped in the canopy, plant physiology, nutrient cycling, etc. The duration of fallout on the canopy depends on such factors as the season, climatic conditions and tree species.

Once the radionuclides reach the forest floor, their mobility from the litter to the soil depends on the litter composition, climatic conditions, soil conditions and whether the fallout has been absorbed into the litter or not. The decomposition of litter from deciduous trees in wet climates is relatively quick (less than a year in rain forests). The radionuclides and nutrients are then available for pickup by plants or leaching.

For coniferous forests, the decomposition rate for litter is low, mainly as a result of a high lignin content in the needles, low microbial activity in the soil and low soil pH. Only a small fraction of the nutrients, and therefore the radionuclides, will be released and made accessible to plants during litter decomposition. Most nuclides will be immobilized in the soil. The time for turnover of humus material and hence the liberation of nuclides could be several hundred years [86]. Furthermore, the uptake efficiency in forest trees could be considerably lower than on agricultural lands [87, 88], as indicated by experience from nutrient flow in fertilizer studies. Digging soil animals (like earthworms) are rare in most coniferous ecosystems in contrast to the situation in deciduous forests so there will be a very low vertical transport in the soil profile of radionuclides attached to the litter on coniferous forest sites.

The deposited radionuclides have the potential to contaminate the new growth of trees and understory vegetation, surface water and groundwater, farm crops, game animals and aquatic organisms. Some organisms may be migratory in habit, and move out of the contaminated area, thus transferring radionuclides to clean areas (local, national or international) where they will be available for cycling into that environment. Some of these migrants, particularly birds, mammals and fish, could be harvested at some distance from the contaminated area, and consumed by hunters and fishermen or enter the commercial marketplace.

In the period immediately following the accident, an initial assessment of the available monitoring data will be required to decide whether immediate short term mitigating actions are necessary. If large forest areas are heavily contaminated but are used solely as a forestry resource then these areas may be interdicted to prevent external radiation doses to man. Forest areas would receive a very low priority in the decontamination decision making process since the radionuclide accumulation in old growth lumber is a slow process.

Mitigating actions may be required, however, if the area will continue to be used for purposes other than forestry, such as a watershed for major public drinking water supplies, farming, road, rail and power line rights of way, or access to mining operations or installed telecommunications equipment. External radiation exposures to people required to use rights of way could be reduced if the trees and understory adjacent to the travel routes were removed with mechanical equipment and disposed of under controlled conditions. The decisions on the future use, and need for decontamination and/or interdiction of multi-use forested areas heavily contaminated with long lived radionuclides will depend upon detailed monitoring data and assessment of the radiological impact of radionuclides available on the medium-to-long term transport pathways. Prohibiting specific forest area uses, for example dairy farming, collection of edible fungi and berries, hunting and fishing, may have to be considered. For very limited areas, and where considered absolutely essential, removal of the understory and topsoil may be considered, depending on the exposure scenarios, but such actions will need a careful assessment of the cost-benefit aspects.

If the degree of contamination does not result in a radiation dose that would restrict entry of people to the forest areas, it is unlikely that the standing old growth lumber resources to be used as timber will be sufficiently contaminated in themselves to pose any problem. Burning contaminated trees and undergrowth, as an alternative to removal and disposal, should generally not be permitted since it will increase the concentration of radioactivity in the residual ash, which will have to be disposed of, and may result in resuspension of radioactive aerosols. Before any reforestation of cleared land that has become contaminated, the long term impact should be assessed. In existing contaminated forests, where workers remove bark from lumbered trees and dispose of slash and understory, and where the lumbered trees are used in the production of pressed board, wood fibre and pulp, monitoring of both workers and products may be required depending on the degree of contamination. Monitoring or restriction of other activities such as farming, hunting, fungi collection and recreation will need to be assessed separately, depending upon the circumstances.

10.5. DECONTAMINATION OF AQUATIC ECOSYSTEMS

In Sections 10.2–10.4, the means of decontaminating and cleaning up terrestrial ecosystems have been discussed. This section deals with the decontamination and cleanup of aquatic ecosystems ranging from flowing rivers to stagnant pools. Compared with buildings, lands and forests, the control of the spread of contamination to and in aquatic systems and the cleanup of such systems poses more difficult problems for which no satisfactory solutions are currently available.

The primary aim should be to prevent contaminated water from reaching sources of drinking water and commercial water used for irrigation or harvesting aquatic food products or recreation purposes. The second objective should be the cleanup of such systems if they do become contaminated.

While little can be done to protect bodies of water adjacent to a site at which a nuclear accident occurs from the direct airborne deposition of released radionuclides, steps can be taken to minimize waterborne contamination, especially in the immediate vicinity of the damaged facility.

For frozen rivers and lakes, the deposited radioactivity can be removed using some of the techniques described above for soils.

Apart from airborne deposition, water systems immediately adjacent to the damaged facility can be contaminated by runoff water used at the time of the accident for fire fighting or after the accident to wet down an area to reduce resuspension or to decontaminate buildings.

Away from the damaged facility, contaminated runoff could occur from activities similar to those described above and also as a result of seepage from inadequately designed storage areas for the large volume of wastes arising from the accident.

Control of the spread of contaminated water to adjacent aqueous systems can most effectively be achieved by pre-accident planning and a good knowledge of the groundwater and surface water pathways.

Movement of contamination in surface waters can be controlled by proper siting of temporary ditches, dykes and dams and the use of holding ponds. The water in the holding ponds may have to be decontaminated subsequently using conventional treatment processes before its discharge. Any contaminated sediment would have to be removed and disposed of.

Movement of contaminated groundwater can be controlled by placing hydraulic barriers in-ground so that groundwater flow is diverted away from critical surface water systems. As an alternative, in-ground hydraulic bypasses could be used to divert the groundwater flow around the damaged facility. Other methods include the use of radionuclide buffers such as clay particles dispersed in the soil before, in or after the hydraulic barrier to absorb radioactive species.

Runoff water resulting from precipitation on urban or rural areas may contain significant amounts of radionuclides. In urban areas, these waters are sometimes combined with houseshold effluents and treated in a sewage plant. The degree of treatment provided can vary but significant quantities of radionuclides could be removed, resulting in a sludge that could become a significant source of external radiation to the plant operators and require special disposal procedures. Contamination of lakes and rivers as a result of runoff from watersheds needs to be considered in the planning stage. Special water treatment facilities may become necessary downstream of the accident where drinking water supplies are extracted.

Since many nuclear plants are situated close to inland fresh water systems which are usually heavily utilized by domestic and industrial users, any contamination will have an immediate impact. When bodies of water used by the public are significantly contaminated either by direct deposition, or as the result of inadvertent releases of contaminated water, monitoring followed by radiological pathway analysis needs to be conducted to predict the potential radiological consequences and to determine whether decontamination procedures need to be implemented. Pre-accident planning and analysis should have identified users of downstream drinking water supplies, irrigation and commercial users, alternative water supplies and/or the availability of emergency water treatment facilities, and major fishery resources. Initial monitoring efforts will determine the concentrations of the major radionuclides and whether public usage of the water for drinking or irrigation purposes should be immediately banned or restricted. Detailed radiological dose assessments will determine whether harvesting of aquatic products, recreational uses, and commercial uses should be banned or restricted. Follow-up monitoring studies will provide the data for predictive assessments on the effective half-life of the radionuclides in the various components of the ecosystem. Over the long term, contamination of the benthic sediments and shoreline is likely to pose the major problem, i.e. external dose, that may require remedial action.

In the larger lakes and flowing rivers, volumes, flow rates and the degree of mixing are important since they will determine the degree of dilution that can be achieved before downstream usage. While sedimentation processes will be effective in reducing the concentrations in the water column over the short term, they will present a long term problem.

Where sedimentation does occur in large systems, particularly behind major dams, the long term release from sediment to water and the subsequent radiological impact upon the users of these systems will have to be assessed. Remedial actions other than providing increased flow from upstream storage or restrictions on specific usages will be difficult. In cases of significant contamination of water and sediment in ponds and lakes by long half-life radionuclides, the inflow rivers and streams may have to be diverted. Where only isolated pockets of contaminated sediment occur, with significant predicted impacts, natural sedimentation may mitigate the problem. Dredging, or capping these areas with clean sediments, may provide an alternative remedial method.

There is some information available on the ultimate fate of radionuclides deposited in lakes. About 95% of the caesium entering Lake Michigan from atmospheric fallout now resides in sediments [89]. In a study of the movement of ^{137}Cs over a number of years in a small lake and watershed in Sweden [90], it was shown that about 90% of the ^{137}Cs in the lake was present in bottom sediments. A study of the behaviour of fallout in the Baltic Sea [91] showed that ^{137}Cs levels were much lower than those of ^{90}Sr. It was concluded that ^{137}Cs was more efficiently removed and also that waters entering the Baltic Sea tended to be depleted in ^{137}Cs in comparison with ^{90}Sr. It appears that caesium may be efficiently removed by silts containing clay minerals, whereas strontium has a greater tendency to remain in the aqueous phase.

Leaching tests carried out on silts in the Trombay area of India have shown that ^{137}Cs is held tenaciously by montmorillonite clays whereas ^{90}Sr can be leached from silts [92]. Studies in the USSR of the fate of ^{90}Sr in 13 natural water bodies show that after 2–2.5 years between 78 and 94% of the added activity became associated with surface sediments by means of sorption and ion exchange. Eventually, ^{90}Sr concentrations in these lakes were reduced by factors of 10–100 below initial levels but concentrations in bottom-feeding fish did not change significantly over the period from 4 to 14 years after the contamination. It appears that a possible decontamination option for water courses would be to add silt containing clay minerals such as montmorillonite to aid the natural sedimentation processes and fix the contamination. This procedure would relocate rather than remove the radionuclides from the system. Hence, although the water might be made usable for water supplies and recreation, precautions covering consumption of bottom-feeding fish could still be necessary.

In the case of marshes, streams, small ponds and slow moving rivers, natural sedimentation may significantly reduce the availability of some radionuclides. Remedial techniques for significant sediment concentrations in small bodies of water may involve diversion of the inflow followed by draining of contaminated ponds, capping or removal of the sediments for disposal at approved sites, and restoration of the area. In some marsh areas regular harvesting of the vegetation and burial at approved sites may be considered as an alternative remedial action.

It should be recognized that remedial actions for the decontamination of lake systems are not only difficult from an engineering point of view but also very expensive. Detailed cost-benefit analyses will be necessary in order for the decision maker to balance the cost of mitigation against the achievable reduction in dose both to the public that uses the systems and to the aquatic organisms that inhabit the ecosystems.

In a recent study [93] of the fate of Chernobyl fallout in Mediterranean waters, it was shown that biological activity could provide a rapid mechanism for the removal of radioactivity from surface waters to deeper levels via settling of dense faecal pellets. It seems likely that radionuclides deposited in the marine environment as a result of a reactor accident will become widely dispersed by both vertical and horizontal mixing processes. In view of the enormous scale of the oceanic marine environment it seems unlikely that any deliberate decontamination procedures could ever be envisaged. Moreover, dilution in the ocean will usually be so large that no decontamination would be necessary. Protection can be achieved by imposing bans or limits on the consumption of seafood.

11. INTERDICTION OF AN AREA

Previous sections have reviewed various ways of mitigating the detrimental effects of radionuclides deposited in the soil by stabilizing them (Section 9), by cleaning up the contamination (Section 10) or by growing special crops. This section briefly reviews an alternative to decontamination, namely interdiction of the area.

Interdiction of an area for short or long periods is the simplest means of mitigating the radiation exposures to the population due to widespread contamination.

The cost of interdiction of economically important areas could be quite high and in general it is less expensive to decontaminate such areas rather than interdicting the land for long periods [24]. On the other hand, the interdiction of limited-use land such as grazing lands, certain forests, mountaineous areas and marshes would involve small economic penalties. However, since this type of area would only receive limited use normally, its interdiction would not greatly reduce radiation exposures to the public.

12. APPLICATION OF CLEANUP TECHNOLOGY TO SITUATIONS INVOLVING HIGH RADIATION FIELDS

The previous sections described equipment and techniques as they might be applied to clean up areas having low or intermediate radiation levels. Under these conditions normal protective clothing, respirators and radiation protection procedures would be used and equipment would be fitted with light shielding, fresh air respirators or sealed cabs. Generally the effects on the performance of equipment would be minimal.

However, experience during the cleanup of highly contaminated areas at TMI, Chernobyl and elsewhere shows that heavy shielding or remotely operated equipment are necessary to reduce occupational exposures to acceptable levels (Annex A). The efficiency and durability of both the machine and operators are affected by these conditions. For example, the heavy shielding required to protect operators can result in overloading of the chassis of vehicles and more frequent breakdown of units. In addition, the high radiation fields can cause rapid breakdown of the controls of remotely controlled vehicles and other electronic components.

Experience in the use of equipment in high radiation fields in other parts of the nuclear industry (hot cells, fuelling machines, robots) shows that special electronic and mechanical components, television systems, oils, seals, etc. can be used in such high radiation fields.

Remotely operated equipment should be designed or procured using the following criteria:

- Machines should be reliable, durable and as simple in design and operation as possible, consistent with doing the job efficiently.
- Machines should be designed for easy decontamination, maintenance or component replacement. Modular and standardized components should be used where possible.
- The design should be extensively tested before being committed to the actual task. Quality control on all units should be high.
- Components should be radiation tolerant to total doses up to 10^6 Gy. This is possible using special electronics, shielded miniaturized equipment, radiation resistant hoses and hydraulic oils, etc.
- Components should be suitable for operation in difficult environments. Factors such as temperature (–40 to +50°C), humidity, dust and chemical activity should be considered.
- The man/machine interface must be considered in the control of the machine to ensure that the performance of the operator is not seriously degraded.

In addition, the equipment must have the lifting capability, flexibility, tool handling ability, etc. to do the tasks assigned to it.

Although it would be desirable to design and construct specific equipment for the cleanup, much of the equipment which would actually be available would be commercial units. There are, however, some specially designed remotely operated bulldozers, small track vehicles and remotely operated equipment which has been used in high radiation fields. Procurement of such vehicles for use in the high radiation fields close to a damaged facility would be desirable. It is recommended that a catalogue of such equipment be started and kept up to date.

Experience in the USSR and the USA shows that radio controlled vehicles are preferable for working outside the plant while cable controlled vehicles are preferred inside because of the problems associated with the reflection and absorption of radio signals on walls.

The quality and the training of operators who will be employed in high radiation fields should be the best available. Great care should be taken to minimize the doses received by these workers because of the long time periods involved in the cleanup. The occupational exposures can be reduced by:

- using remotely operated equipment
- using shielding and ventilated work places
- thoroughly training the operators on the equipment and clearly specifying the tasks.

13. LOADING AND TRANSPORTING LARGE VOLUMES OF WASTES

Large volumes of contaminated soil, concrete, asphalt, equipment, vegetation, etc. could arise from the cleanup of a large area contaminated as a result of a serious accident at a nuclear power plant. The removal of a thin (average thickness of about 5 cm) layer of contaminated material from a 7 km radius around a damaged facility could result in 8×10^6 m^3 of waste which has to be transported to a disposal site and buried. The loading and moving of such large volumes of soil is time consuming and expensive but the experience is not unique.

For example, during the construction of large earth dams, millions of cubic metres of inactive soil and concrete have to be loaded and moved. It is also common to load and move large volumes of product and waste rock in mining.

Operational experience on the procedures, techniques and equipment actually used to safely load, transport and dispose of large quantities of soil containing low concentrations of radioactivity can be found in the literature. For example, in Canada 70 000 m^3 of ^{226}Ra contaminated soil (2 Bq$\cdot$g^{-1}) were gathered from an urban area and loaded into trucks during the Port Hope cleanup [94] and transported to a disposal site 350 km away in 20 m^3 dump trucks without incident. The wastes were covered with a tarpaulin during transport. In the USA, remedial actions have been completed to clean up a 51 ha uranium mill site in Utah and move 2.16×10^6 m^3 of contaminated soil by train to a disposal site about 140 km away [95]. The total cost to clean up, load and transport the waste and construct the final disposal site is about US $55 million.

During the cleanup of very large contaminated areas, the loading and transportation of much of the wastes to the disposal site could probably be accomplished using conventional earth moving equipment from the construction industry. Some modifications may be beneficial, such as the addition of shielding between the driver's cab and the box of the dump truck. If the disposal site is located within the cleanup area, much larger equipment such as that used on the site in major civil engineering and mineral extraction projects could be used.

The loading of the contaminated soil could be done:

(a) Using equipment such as wheeled or tracked loaders and excavator loaders with capacities of 30 m^3 or more. The material would first be moved into piles using conventional grader/planers or bulldozers with wide blades.
(b) Using a force feed loader with a conveyor which can pick up a layer of soil or soil from large windrows and dump it directly onto a truck (Fig. 18). On flat surfaces it may be possible to use a modified road planer (Fig. 10).
(c) Using vacuum pickup systems for certain types of soil under dry conditions.

Water spraying equipment, to dampen soils during handling under very dry conditions, may be useful to minimize dust production.

Highly contaminated soil from locations close to the damaged facility may have to be sealed in appropriate containers for transport. Remotely operated equipment or units with shielded/air filtered cabs would be required.

The contaminated wastes could be transported using one or more of the following techniques:

(1) Moving the layer of contaminated soil directly into depressions or specially excavated trenches using scrapers, bulldozers or graders. The soil can be moved 100–150 m without reloading or stopping.
(2) Loading the soil into dump trucks for transport to the disposal site. Rear dumping trucks are available with capacities of up to 250 t.
(3) Loading the soil into railway cars for transport to the disposal site. The choice of rail transport depends on the availability of railway lines in the vicinity of the cleanup and disposal sites. If double or triple handling of material is required, as in a truck–rail–truck transportation system, Canadian analyses suggest that rail transport is not cost effective for distances less than a few hundred kilometres. However, the economic factor in the decision may be offset by the fact that rail transport results in smaller radiation exposure to transportation workers and involves less interaction with the public than does truck transport.

Loading and transportation costs for contaminated bulk soils are typically in the range US \$0.1–0.2 per cubic metre per kilometre in North America.

Effective management and control systems will be required to move and dispose of large quantities of earth safely. The protection of the operational staff and the environment must be important factors during the planning and cleanup. One of the biggest problems on a job of such magnitude may be to ensure continual maintenance of safety and health physics procedures once the job becomes routine.

In planning for the loading and transport of these wastes there are certain basic requirements:

- a modified waybill control technique in conjunction with a data handling system to control the loading, transport and disposal of wastes;
- well defined transportation routes and truck control points to ensure compliance with the routing plan;
- truck cleanup areas and monitoring points either at the dump site or between the contaminated and clean zones;
- an emergency response plan for implementation in the event of a transportation accident.

14. DISPOSAL OF LARGE VOLUMES OF WASTES

14.1. INTRODUCTION

The objective of disposing of radioactive wastes is to confine the radionuclides within the respository site until they no longer represent an unacceptable risk to the environment and the public. A repository should fulfil two important and related functions in this regard: firstly to limit dispersion of the radionuclides contained in the wastes by water-borne and airborne pathways and to protect the waste from surface and near surface deteriorating processes such as erosion or intrusion by humans, burrowing animals or deep-rooted vegetation [96].

The radionuclides of longer term concern in the soil after an accident at a nuclear power plant are ^{90}Sr and ^{137}Cs, both with a half-life of approximately 30 years. After about 300 years, the concentrations of these radionuclides in soil would be about 0.1% of the concentrations after the accident. Therefore, a storage facility capable of containing these wastes for several hundred years should be suitable for most of the soils collected.

The type of facility selected for disposal of the soil will be dictated by many factors, including the availability of equipment to move the wastes, the volumes to be moved, the distances involved, the availability of natural or man-made disposal sites such as quarries, mines or depressions and the hydrogeology and geology of the area. The basic factors which must be considered in order to achieve a suitable disposal repository system are: the quantity and nature of the wastes, the engineering features incorporated into the repository design, the site characteristics and the time period allowed for institutional control [96]. Conditions are combined in the safety assessment (Fig. 19) to achieve a disposal system that will meet the regulatory or desired environmental protection requirements. For example, a special cover to prevent intrusion by humans would not be required if the institutional control period is expected to be longer than the hazardous life of the wastes.

While the specifics of any accident will affect the disposal plan, some general guidance can be offered regarding disposal of large volumes of contaminated soils.

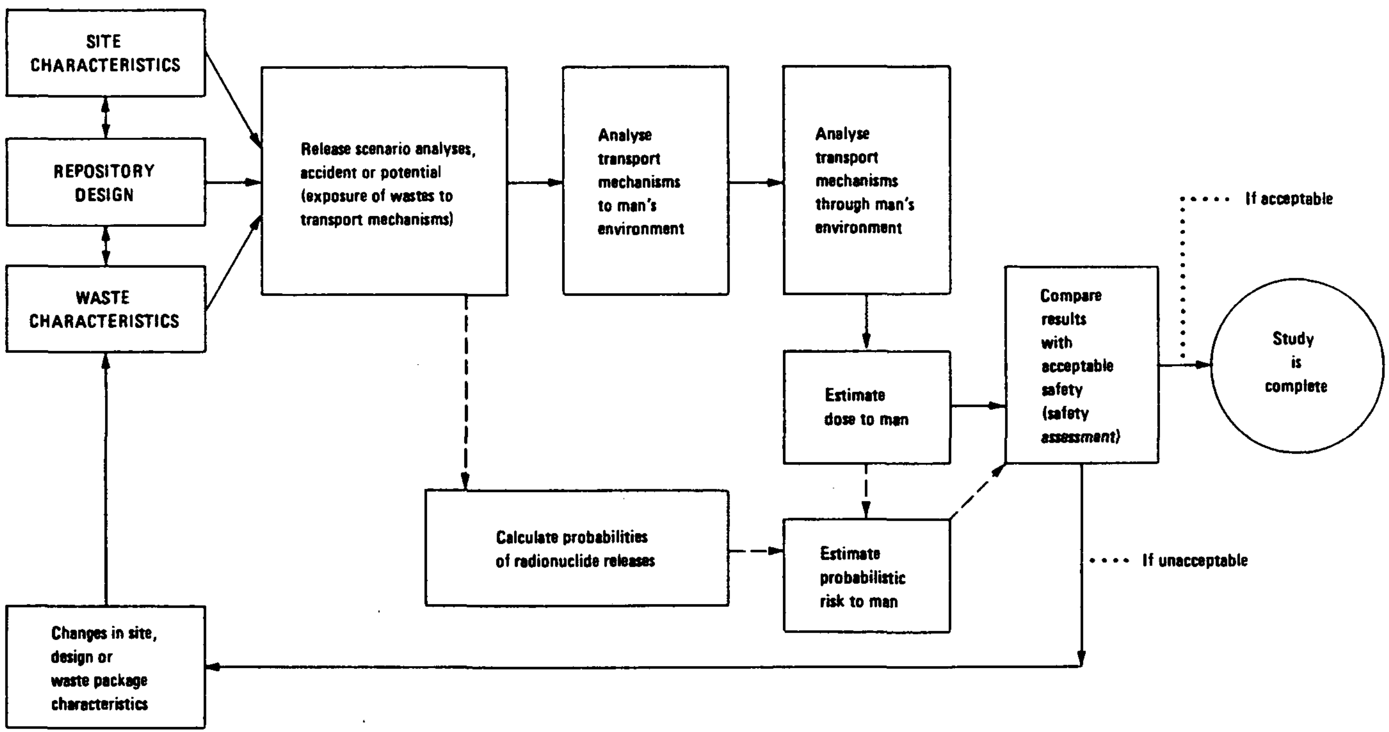


FIG. 19. Relationship between safety analysis activities [101]. Dashed lines indicate additional activities when analysing probabilistic safety.

14.2. METHODS FOR STORING/DISPOSING OF LARGE VOLUMES OF WASTES

A variety of generic designs are available for the storage/disposal of the very large volumes of contaminated soil and other bulk materials arising from the cleanup after a major nuclear accident. These designs include:

(a) *Natural basins or valleys.* For a valley, an embankment may be required at the downstream end to form a basin. Ideally, these impoundments should be situated at the head end of a natural drainage area. Flow diversion channels could be constructed around the area to control erosion and long term seepage.

(b) *Specially dug trenches.* If suitable transportation is not available, it may be necessary to dig many smaller trenches and bulldoze the wastes into these. The clean fill could be used as a cover and/or to raise the trench walls above the normal ground level. With this approach it may be more difficult to delineate the outer perimeter of the trench and keep track of the many facilities. In addition, small trenches do not use land efficiently. The use of large trenches or specially dug pits is being considered in some countries for the long term storage of uranium mill tailings to eliminate the risks associated with possible embankment failures in other facility designs. Large trenches or pits using this engineering technology or that used for well engineered municipal disposal areas could also be constructed for the disposal of large volumes of contaminated soil.

(c) *Mined out quarries or open pit mines.* The possibility of using these depends on climate, groundwater depth and variability, permeability of rock walls, susceptibility of the pit to flooding, etc. If a particular quarry is considered especially desirable, some of the above problems can be reduced by using engineered features such as a rock filled hydraulic bypass, clay lining and a clay–rip–earth cover.

(d) *Underground mines.* Some wastes could be disposed of in underground mines which no longer have any valuable mineral resources. The usefulness of this approach would depend on many factors, including groundwater depth and movement through the mine and susceptibility to flooding. These aspects could be difficult to characterize at short notice.

(e) *Large mounds.* The mounds would be covered with clay, other soil and/or a rip-rap cover of rock.

Details of methods to construct and close out such facilities are given elsewhere, for example in Refs [8, 97–99]. If necessary, the impoundment facility could be lined with clay (if available) or other impermeable barriers to minimize leakage. Siting of the disposal facility on an area of impermeable clay geology would

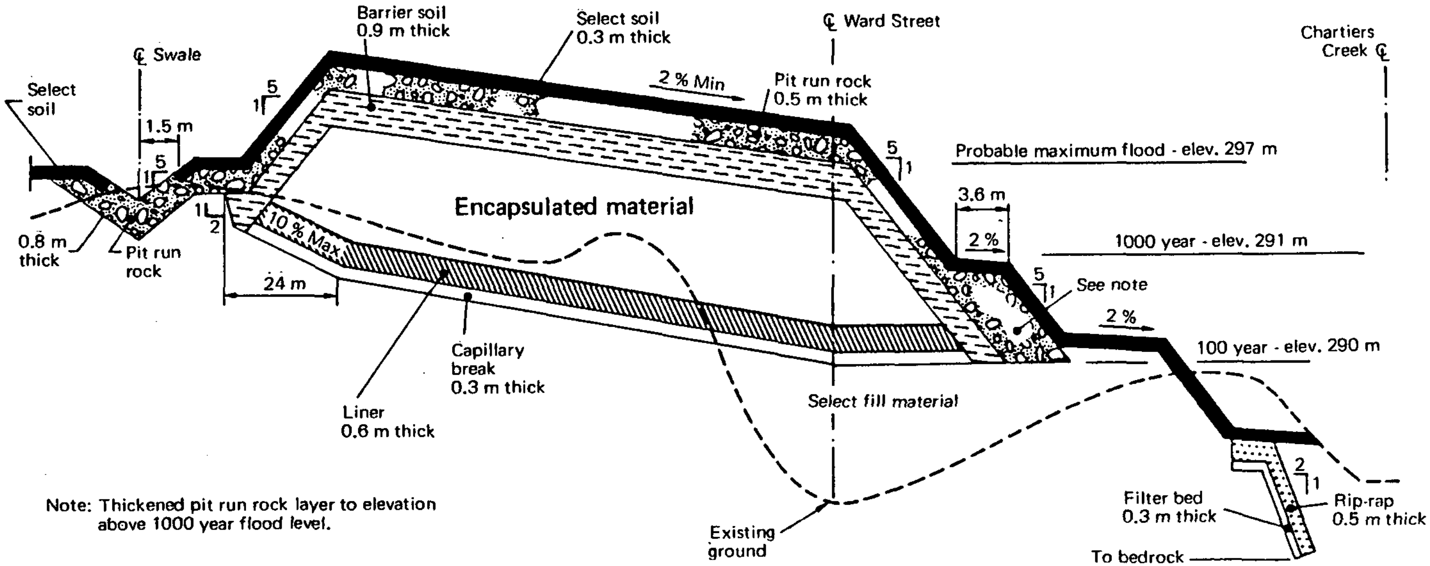


FIG. 20. Typical cross-section (not to scale) through encapsulation area of the uranium mill tailings remedial action project site at Canonsburg, PA.

eliminate reliance on the integrity of an engineered clay liner. Infiltration of precipitation into the waste can be controlled using an impermeable cover such as clay and suitable drainage. Intrusion by man, animals or plants into the wastes can be minimized using a rock rip-rap and/or thicker cover.

Examples of disposals or planned disposals of large volumes of low level radioactive wastes are available. For the cleanup of the uranium mill tailings site in Utah (Section 13), the $2.16 \times 10\ m^6$ of waste will be buried in a disposal pit specially designed to minimize pollution of the groundwater. In other remedial action in the USA, about 800 000 m^3 of tailings were disposed of at Shiprock, using a mounded configuration [98]. The design employs a cap of low permeability clay and an erosion and intrusion resistant barrier of rock. Figure 20 is a schematic representation of a similar design of impoundment for the disposal of about 200 000 m^3 of tailings at Canonsburg [99]. This design also includes a low permeability clay liner.

In Canada, designs have been prepared for the disposal of 880 000 m^3 of uranium processing residues and associated contaminated soils both in large trenches excavated in glacial till and in caverns in limestone at a depth of about 100 m. The cavern disposal concept would probably require more lead time than the alternatives [94].

Impoundment facilities are currently in use to hold very large volumes of uranium mill tailings during the operational phase of the mill. In these operations, the uranium tailings are pumped as a slurry to fill up impoundments based on some of the generic designs described. The latest facilities are being designed and closed out so that the release of pollutants such as ^{226}Ra, radon, acids and heavy metals will stay within authorized limits for at least 1000 years. Although the soil arising from a reactor accident will not be in a slurry form, much of the generic information on the construction and closeout of certain designs of mill tailing impoundment facilities would be of great use in designing and building disposal sites for contaminated soils [8].

The methods for managing the contaminated wastes arising from the Chernobyl accident are briefly discussed in Annex A.

The wastes from areas very close to an accident may require special handling and disposal. For example, selected wastes may be collected in containers and buried under the low level wastes. If long lived actinides are present in significant concentrations, the wastes may have to be disposed of in special disposal areas.

In many countries, disposal facilities require institutional control and monitoring programmes until they are finally closed out, using features which prevent intrusion and control seepage within regulatory limits.

The cost to clean up, transport and dispose of large volumes of contaminated material will be high and may have some impact on the selected cleanup criteria through cost–benefit analysis.

The costs of cleaning up large areas contaminated by uranium tailings in the USA [100] range from about US $1150 to US $1960 per 1000 m^2 (Table IX).

TABLE IX. RANGE OF COSTS FOR LARGE SCALE CLEANUP OF AREAS CONTAMINATED BY URANIUM TAILINGS IN THE UNITED STATES [97]

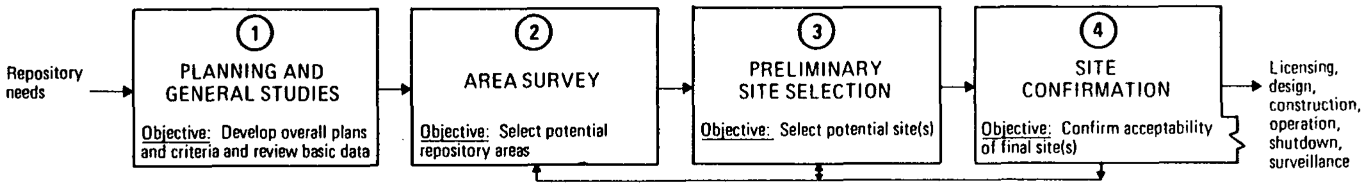
	US $/1000 m^2
Site characterization to delineate contamination	80–175
Evacuation of contaminated materials	500
Confirmatory monitoring of excavated areas	70–285
Health physics and operational environmental monitoring	500–1000
TOTAL	1150–1960[a]

[a] Lower costs reflect greater cost effectiveness for cleanup of larger areas.

These costs include characterization, excavation, confirmation of cleanup to required standards and operational health physics monitoring. In an urban cleanup, costs for soil stripping could be considerably higher — up to several thousand dollars per residential property. The total cleanup and disposal costs for tailings range from about US $5 to US $60 per cubic metre of soil with the major variants being the complexity of cleanup, transportation distance, disposal facility design and availability of materials such as clay and rock used in the facility engineering.

14.3. SITE SELECTION

The choice of the location and the method of disposal can be dictated by many factors including economics, availability of equipment, the radionuclides involved, the climate and the availability of disposal sites and their characteristics. The cost of loading, packaging and transporting the very large volumes of wastes from contaminated land can significantly influence the choice of disposal site. Societal implications can also be important but this factor will probably not have a large effect in an emergency situation.



1 Planning and general studies	2 Area survey	3 Preliminary site selection	4 Site confirmation	
• Establish plans and timetable, and allocate resources • Define waste types, conditioning, quantities • Establish overall repository performance criteria	• Modify and expand plan as necessary	• Modify and expand plan as necessary		Continue site confirmation studies based on new data
• Establish criteria for area selection	• Establish criteria for preliminary site selection • Identify areas that meet area selection criteria	• Establish criteria for site confirmation • Identify potential site(s)	• Select favourable site(s)	
• Review site selection factors and techniques. Identify potential host rocks	• Select and inventory potential host rock types • Characterize potential areas	• Select host rocks for investigation • Characterize preliminary sites	• Select specific host rock(s) • Characterize site(s) in detail	
• Review data needs and site investigation techniques	• Select detailed site investigation techniques	• Expand site investigation techniques as required	• Expand site investigation techniques as required	
• Develop repository concepts	• Develop conceptual repository designs for potential host rock types	• Develop preliminary repository designs	• Develop detailed repository designs	
• Review nuclide migration mechanisms, pathway models and data	• Modify nuclide migration models; apply models generically for potential host rock types	• Test models with data and modify as necessary; apply models for potential sites	• Modify models from new data; apply models for specific site(s) for long-time predictions	
• Review/select safety analysis methods; perform generic safety analysis and sensitivity analysis to define important parameters	• Modify methodology as necessary; perform safety analyses for different rock types	• Expand and modify methodology as necessary; perform safety analyses for specific rocks and areas	• Expand and modify methodology as necessary; perform detailed safety analyses on specific site(s)	

Note: At each stage of the site investigations, societal, ecological and national legislative issues are considered. The regulatory body should be involved according to national requirements. The term rock in this table includes all earthen materials including unconsolidated material such as soil (see Glossary).

FIG. 21. Idealized sequence of investigations for site selection [101].

TABLE X. HYDROGEOLOGICAL CONSIDERATIONS IN SITE SELECTION

Map/Literature review

Geology
Topography
Precipitation
Evapotranspiration
Nearest surface water
Nearest water use or discharge point

Field reconnaissance

Preliminary	*Intermediate*
Type of disposal media	Existing geological faults
Prevailing wind direction	Disposal media
Relief	Sorption capacity
Subsidence	Thickness
Slope stability	Engineering properties
Flooding potential	Permeability
Erosion potential	Effective porosity
Depth to water table	Structure
Depth to fractured bedrock	Hydraulic gradients
	Hydrological budget
	Hydrological complexity
	Adequate water supply
	Monitorability
	Remediability

Detailed site analysis

Three dimensional head distribution
Disposal media and underlying site geology (including nearest confined aquifer)
- Water chemistry
- Stratigraphy
- Ion exchange capacity
- Moisture content of unsaturated zone
- Soil moisture tension
- Transmissibility

Natural fluctuation of water table
Flow data for nearest streams including underflow
Water table contour map
Possible measures for groundwater manipulation

The idealized sequence of investigation for the selection of any waste disposal site has four general phases:

— planning and general studies
— area survey
— preliminary site selection
— site confirmation.

Figure 21 shows details of these four phases for a rock repository for low/intermediate level wastes [101]. The hydrogeological considerations applied in selecting a site for shallow land disposal of radioactive wastes are given in Table X.

During the preliminary planning, potential sites for the disposal of very large volumes of contaminated wastes could be examined using available data or new core samples if funding is available. However, since even the selection of potential sites could be a very sensitive issue, it may only be possible to do this study in a generic manner and to match repository designs with generic sites in the area.

15. RADIATION PROTECTION AND SAFETY

15.1. INTRODUCTION

Radiation protection and safety planning and implementation are inherent parts of all nuclear activities and are especially important in the cleanup of very large contaminated areas.

During the last 35 years, considerable work has been done on the development of the principles of radiation protection (for example, Refs [102–108]) and on the techniques and instrumentation required to implement these principles. A wide variety of instruments are available for personnel monitoring, air monitoring and the detection and measurement of all types of radioactivity. These principles and techniques are demonstrated daily at nuclear facilities around the world and have been applied successfully to small and large cleanup tasks. Such tasks include the rehabilitation of seriously damaged reactors, the cleanup of large contaminated sites and areas, the decommissioning of nuclear facilities for unrestricted use and regular maintenance procedures in operating facilities.

Most countries operating nuclear power plants have statutory emergency planning procedures to cope with accidental releases of radioactivity. Experience gained through emergency exercises together with technological developments in monitoring equipment and data handling and the impetus provided by incidents such as TMI have led to continual improvements in these procedures. Developments were highlighted at an IAEA Symposium [7] on Emergency Planning and Preparedness in 1985.

To protect public health in the event of a nuclear accident, methods for determining derived intervention levels have been published [6] (see Section 1). These ensure timely application of protective measures. Decontamination of land and property is one such measure which may be considered during the intermediate and late phases.

During the cleanup of land and property, the radiation protection and safety programme has two basic components:

(a) Ensuring the protection of the workers and the public during the cleanup.
(b) Ensuring that the cleanup meets certain criteria so that the people returning to their homes do not receive uncontrolled exposures. The present section of the report does not deal with this particular aspect of radiation protection and it is assumed that the confirmatory monitoring plan has verified that the cleanup has met the stipulated criteria.

The following subsections briefly discuss the question of a radiation protection and safety plan for the protection of workers during cleanup and the implementation of such a plan. It is assumed that for a seriously contaminated area the population would have been evacuated before cleanup starts. The application of other protective measures such as controlling the intake of contaminated food by the public is outside the scope of this report.

15.2. RADIATION PROTECTION AND SAFETY PLAN

After a serious accident has occurred, the preliminary radiological plan would be updated and tailored to meet the specific accident situation.

This plan should (as far as is possible considering the emergency conditions and the large number of people involved) include a comprehensive radiation monitoring programme [103, 107] which provides for the measurement, evaluation and recording of all exposures incurred by individuals through different pathways. The plan should also deal with practical matters related to the implementation (Section 15.3) of the programme including such things as the training and classification of personnel, the duties and responsibilities of various groups in all aspects of the cleanup (e.g. handling, transport, disposal) and the use of protective clothing [103].

The plan should also include a list of required equipment, facilities and personnel needed to implement the radiation protection programme and details of where these resources could be obtained.

The extent to which the monitoring programme for the general public could be achieved if relocation has not been carried out and cleanup is proceeding would depend on the number of people involved and the availability of trained staff and equipment [103–107].

15.3. IMPLEMENTATION

During the implementation of the cleanup operations a great many factors must be controlled or initiated to ensure that radiation protection and safety are maintained. These include [107]:

(a) Specification of the type and extent of monitoring to be done
(b) Selection, testing, calibration, maintenance and issue of suitable instruments and dosimeters
(c) Monitoring and sample collection
(d) Processing and interpretation of individual monitoring data
(e) Interpretation of area monitoring data
(f) Maintenance of adequate records and provision of the means to report such records
(g) Quality assurance
(h) Provision of trained staff for the above activities
(i) Provision of materials and supplies to protect workers, including respirators, disposable clothing and airpacks.

A major consideration in radiological planning in any decontamination measure is the radiation dose which decontamination workers will be allowed. The limits should be set according to the recommendations of the International Commission on Radiological Protection (ICRP) and IAEA, taking into consideration the emergency situation. It is possible that decontamination operations might be dependent upon a small number of key individuals such as health physics personnel and could be placed under severe pressure if such personnel are exposed to high doses early in a cleanup programme, thus ruling them out of future activities. Management of dose and manpower resources would be of crucial importance.

The Basic Safety Standards for Radiation Protection [104] outline a formal system of dose limitation based on justification of a practice, optimization of protection and compliance with specified dose limits. This system is intended to apply whenever the source of radiation exposure is under control. After a major nuclear accident which results in the widespread contamination of areas, a temporary loss of control may occur and during this time it may not be possible to fully comply with the specified dose limits. However, by the time the cleanup programme starts, the public will have been evacuated from the area and the authorities will have re-established control. Also, the justification and optimization principles still apply. In such a case, the risks taken to clean up the area need to be balanced against those that might prevail if cleanup does not proceed. These discussions and the continually changing situation will place a great burden on the health physics staff and those controlling the cleanup to ensure that adequate effort is put into the planning and implementation of each stage to avoid unnecessary exposure of workers and the general public. Further guidance on acceptable dose limits in such circumstances is required.

In considering the cleanup of areas shortly after the accident, a decision will have to be made whether to implement cleanup actions immediately and thus cause higher occupational doses or wait until short lived isotopes have died off and/or weathering has reduced the radiation levels. The decision may be to stabilize the contamination using airborne sprays to prevent resuspension followed by a delay before actual cleanup starts. The timing of such actions must be decided by the cleanup director at the time of the accident and will depend on a great many factors including: the timing of the decision by the emergency director to implement cleanup, the weather conditions and the area involved.

Monitoring of airborne contamination levels is a more time consuming procedure than the measurement of dose rates since air samples must be collected for a period of several minutes and then counted. Although it would be possible after deposition to monitor the gamma dose rate over an area and be certain that it would not increase, for airborne contamination this would not be the case. The levels of airborne contamination could vary quite markedly with weather conditions. To protect decontamination personnel it might be necessary to wait until the probability of airborne contamination levels exceeding an appropriate threshold had been reduced. An alternative strategy would be for decontamination personnel to use respiratory protection devices. However, use of such equipment would inevitably lead to increased working times, thus possibly increasing the radiation dose received.

16. CONCLUSIONS AND RECOMMENDATIONS

Although there is a great deal of information available on the decontamination of nuclear facilities and the cleanup of small and medium size land areas, further work is required on many aspects, for example:

(a) The development of better methods for the cleanup of urban areas including a better understanding of the basic supplementary processes such as deposition on various surfaces and the importance of weathering.
(b) The application of these processes to actual areas to get field experience, minimize contamination of other surfaces, prevent contamination of water supply systems, etc.
(c) The development of the elements of an overall operational and management plan for cleanup of large areas to ensure that the implementation and coordination of such massive programmes are carried out safely, efficiently and in a cost effective manner.
(d) The development of important subelements of this overall operational plan including:

— cleanup criteria
— confirmatory monitoring and sampling plans

— statistical sampling and quality assurance plans
— data management
— definition of required resources and personnel.

(e) The means to restore agricultural areas to productive use including a better insight into the use of various additives to immobilize radionuclides in the soil and minimize root pick-up. Further work on other soil cleanup methods is also required.

This report gives an integrated overview of the important methods and techniques available to clean up large areas contaminated as a result of a serious nuclear accident. The review includes information on the methods and equipment available to characterize the radioactive fallout, cleanup contaminated urban, rural and forested areas and stabilize contamination. Brief discussions on planning and managing a cleanup and on the transport and disposal of wastes are also presented.

Plans are currently in progress to prepare companion IAEA publications on the overall operational planning for the implementation and management of large area cleanups and on the loading, transportation and disposal of very large volumes of contaminated soil.

It is recommended that:

(1) Information on the planning, implementation and management of cleanup should be included in the preparedness plan for emergencies at nuclear plants.
(2) Consideration be given to including senior advisers on planning and implementing cleanup as part of the public authorities emergency organization.
(3) Research be continued in the areas described above.
(4) An international information base be developed giving details on the availability of remotely operated equipment for use in the monitoring and cleanup of highly contaminated areas.

It is concluded that much of the preliminary planning for cleanup would be generic in nature and could be common to many countries. It is also concluded that even minimum preliminary planning for cleanup will yield important dividends in safety and cost effectiveness if such a plan is ever required.

Annex A

THE CLEANUP AFTER THE ACCIDENT AT THE CHERNOBYL NUCLEAR POWER PLANT

A.1. INTRODUCTION

The Chernobyl nuclear power station is situated in the eastern part of a large region known as the Byelorussian-Ukraine Woodlands beside the River Pripyat, which flows into the Dniepr (Fig. 22). The region is characterized by a relatively flat landscape with very minor slopes down to the river. About half the area is used for farming, the remainder is forested. The soils are mainly fine grained clay and sandy-loam with some coarse grained soils.

The total length of the Pripyat before it flows into the Dniepr is 748 km and its catchment area at the point where it passes the power plant is 106 000 km^2. The river is 200–300 m wide with an average flow rate of 0.4–0.5 m/s. The average volume flow is 400 m^3 per second.

In 1986, about 49 000 people lived in Pripyat, west of the plant's 3 km exclusion zone, and 12 500 lived at Chernobyl, the regional centre 15 km south-east of the plant [109, 110].

In early 1986, the Chernobyl site had four 1000 MW(e) RBMK reactors operational and two more under construction 1.5 km away. The RBMK reactors are direct cycle, boiling water, pressure tube, graphite moderated reactors. The four operating reactors were built in pairs (Fig. 23), sharing common buildings and services. Unit 4 became operational in 1984. Figure 24 shows the location of the four operational reactors and their cooling reservoir.

On 26 April 1986 a severe accident, the most serious ever at a nuclear power plant, occurred at the fourth unit of the Chernobyl nuclear power station.

The reasons for the accident and the sequence of events are described in detail elsewhere [109, 110]. As a result of a prompt critical excursion and a very rapid increase in power, energy released in the fuel fragmented it into minute pieces. The hot fuel particles reacted with the coolant to cause a steam explosion resulting in the destruction of the reactor core and associated structures. A second steam explosion occurred within seconds and hot fuel and graphite were ejected from the destroyed reactor building. Radioactive fission products continued to be released from the damaged facility for about nine days after the incident as a result of burning of graphite and oxidation of the fuel.

Immediately after the accident, a specialist team was sent from Moscow to the site to assist local authorities and plant management. A centralized emergency centre with authority and powers to direct the response organization was established.

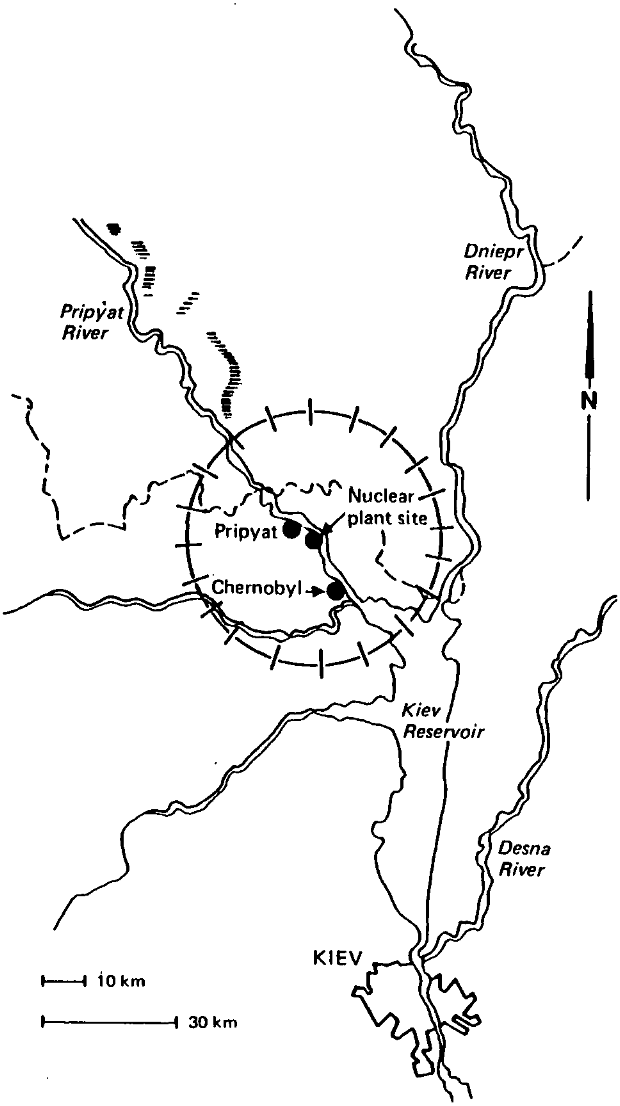


FIG. 22. The Chernobyl/Kiev area.

Meteorological and radiological monitoring with the help of aeroplanes and helicopters were organized. Immediate emergency response measures such as keeping people indoors, iodine prophylaxis and evacuation were carried out. About 135 000 people were evacuated from a zone having a 30 km radius around the plant (Fig. 22).

This annex briefly reviews information related to the decontamination and cleanup of the plant site and surrounding areas and the transport and disposal of the large volume of contaminated wastes.

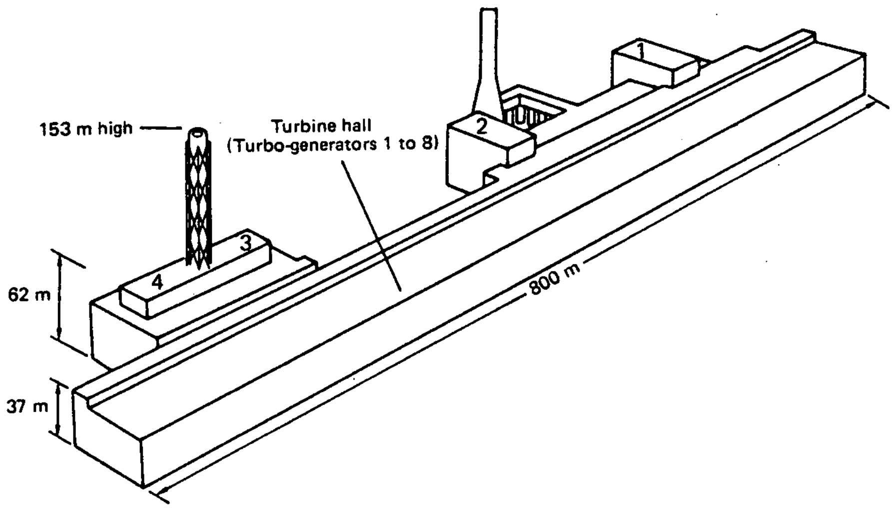


FIG. 23. General layout of the Chernobyl power plant, showing the placement of the four reactors.

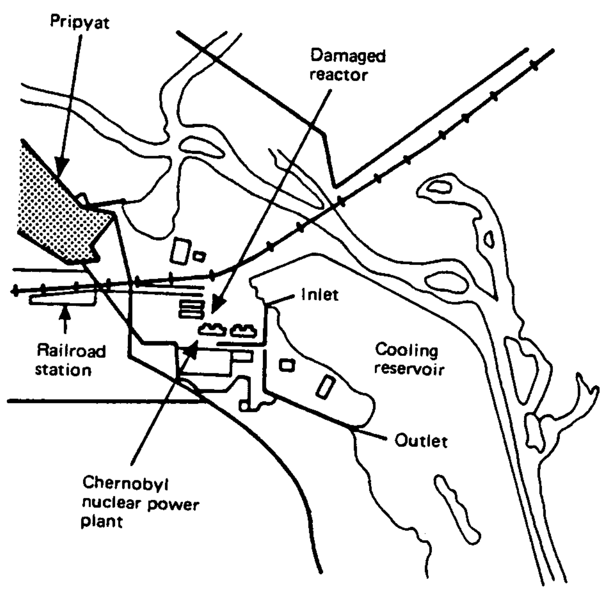


FIG. 24. General site area of the Chernobyl power plant.

A.2. RADIOLOGICAL EVALUATION

At the time of the accident, the core inventory in the reactor was about 4×10^{19} Bq (10^9 Ci). The isotopic composition of the inventory and the percentages released are shown in Table XI. It is estimated that up to 2×10^{18} Bq (5×10^7 Ci) were released from the fuel during the accident, not counting releases of Xe and Kr. Escape of radionuclides from the fuel does not necessarily imply that these all escaped from the plant since there were opportunities for entrapment of released material. Approximately half of the radioactivity released from the reactor

TABLE XI. CORE INVENTORIES AND TOTAL RELEASES

Element	Half-life (d)	Inventory[a] (Bq)	Percentage released
Kr-85	3930	3.3×10^{16}	~100
Xe-133	5.27	1.7×10^{18}	~100
I-131	8.05	1.3×10^{18}	20
Te-132	3.25	3.2×10^{17}	15
Cs-134	750	1.9×10^{17}	10
Cs-137	1.1×10^4	2.9×10^{17}	13
Mo-99	2.8	4.8×10^{18}	2.3
Zr-95	65.5	4.4×10^{18}	3.2
Ru-103	39.5	4.1×10^{18}	2.9
Ru-106	368	2.0×10^{18}	2.9
Ba-140	12.8	2.9×10^{18}	5.6
Ce-141	32.5	4.4×10^{18}	2.3
Ce-144	284	3.2×10^{18}	2.8
Sr-89	53	2.0×10^{18}	4.0
Sr-90	1.02×10^4	2.0×10^{17}	4.0
Np-239	2.35	1.4×10^{17}	3
Pu-238	3.15×10^4	1.0×10^{15}	3
Pu-239	8.9×10^6	8.5×10^{14}	3
Pu-240	2.4×10^6	1.2×10^{15}	3
Pu-241	4800	1.7×10^{17}	3
Cm-242	164	2.6×10^{16}	3

[a] Decay corrected to 6 May 1986 and calculated as prescribed by the Soviet experts.

was deposited in the 30 km zone. Although some pieces and particles of fuel were ejected from the reactor, most of the releases, other than fission gases, were aerosols.

The accident differed from those which are usually considered in radiological assessments of hypothetical accidental releases from nuclear power plants in that the releases were prolonged, with major releases occurring for several days. The releases varied in rate and radionuclide composition over time and the meteorological conditions were complex. These characteristics led to a very complex pattern of atmospheric dispersion on the ground. Moreover, the scale of contamination of the plant site and surrounding areas was unprecedented.

The radiological site surveys carried out immediately after the accident provided information on the state and location of the fuel and graphite ejected from the core by the explosion, the radionuclide distribution and concentration, and preliminary information on the chemical forms of the discharged material. From this information, the levels of contamination that would confront cleanup personnel were established.

The site contamination levels were established using:

— aerial gamma photography
— aerial gamma scanning with collimated detectors
— alpha and gamma spectroscopy and beta measurements on soil samples
— gamma spectroscopy of aerosol samples drawn at elevations of about 3 m and 200 m on site
— gamma scanning using different types of remotely controlled radiation devices to monitor the most highly contaminated areas on the site (Section A.5.3).

An important task was to establish the location of the fuel by gamma scanning the rooms within the plant. An initial estimate that about half of the fuel was in the machine room proved incorrect. The error was attributed to imprecise gamma scanning measurements. The radiological survey showed that 0.3–0.5% of the fuel was deposited on the site. A considerable part of the core debris was located within the reactor vault between the biological shield and the remainder of the core and in the pipes running below the core.

Visual site observation confirmed that only a small amount of graphite was ejected from the plant. Most of the graphite remained in the reactor well. It is estimated that about 10% (250 t) of the graphite burned.

A partial qualitative assessment of the size of on-site aerosol particles containing plutonium and transuranic elements showed that they varied from less than one to tens of micrometres in size.

Measurement of the contamination levels in the 30 km zone in rural and urban areas was carried out using airborne, land-vehicle borne and manual methods (Fig. 25). Figure 26 shows the gamma field distribution around the plant on 29 May 1986 after most of the short lived activity had decayed. Table XII shows that in the

FIG. 25. Measuring radioactivity levels in rural areas near the Chernobyl nuclear power plant. (Credit: USSR State Committee on the Utilization of Atomic Energy.)

worst zone (870 km^2) the surface activity was caused by 185–320 PBq (5–8.7 MCi) of contamination.

On the basis of survey results, the area within a 30 km radius was divided into three zones:

(1) A special zone 4–5 km around the plant, where no entry of the general population is foreseeable in the near future and where no work besides that required at the installation will be permitted;
(2) A 5–10 km zone where partial re-entry and special activities may be allowed after some time; and
(3) A 10–30 km zone where the population may eventually be allowed to return and agricultural activities may be resumed, but which will be subject to a strict programme of radiological surveillance.

Access and egress controls for personnel and vehicles were established at zone boundaries to reduce the spread of contamination. Arrangements were made for transferring working personnel from one vehicle to another to minimize vehicle borne movement of contamination. Strict dosimetric monitoring of any transport leaving a zone is enforced and vehicle and equipment decontamination centres at zone boundaries were established.

Calculations were also made to assess the long term radiological consequences of the accident in the whole Soviet Union [111]. The results indicate that:

(a) External exposure from the radioactive cloud and internal exposure due to inhalation of radioactive substances will not be large.

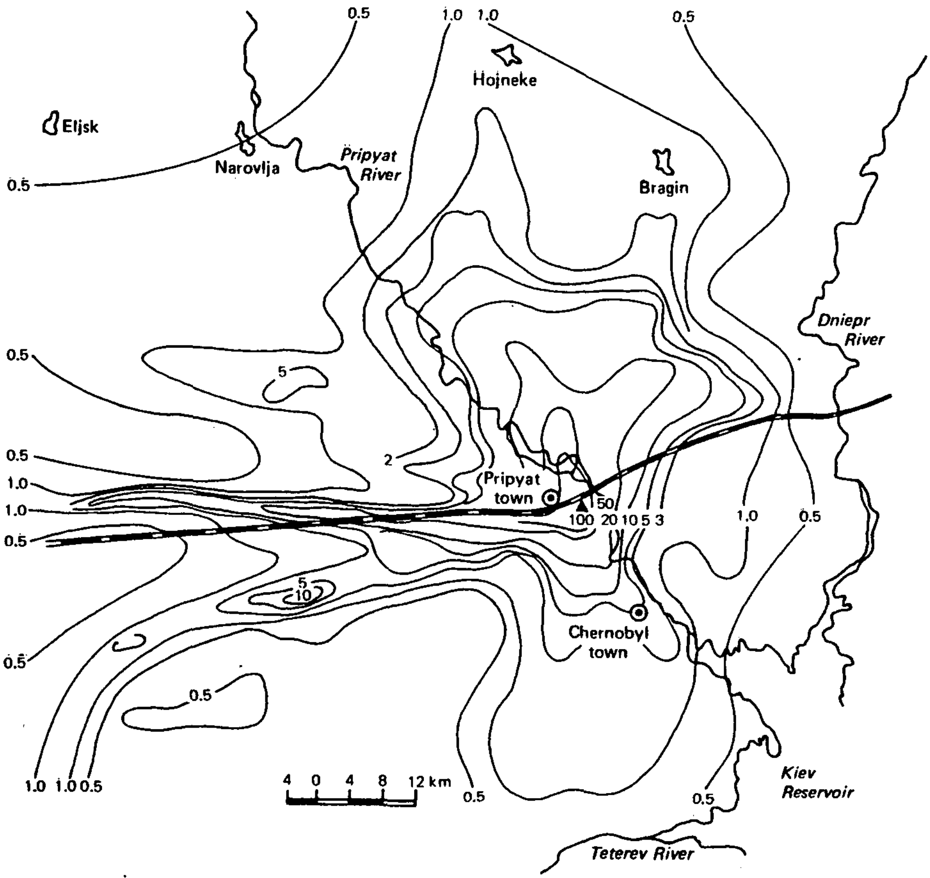


FIG. 26. Gamma field distribution (mR/h) on 29 May 1986. (1 R = 258 μC/kg.)

TABLE XII. ESTIMATED SURFACE ACTIVITY IN A 30 km ZONE AROUND THE DAMAGED REACTOR ON 26 JUNE 1986

Range of activity (mR/h)	Area of zone (km^2)	Activity	
		Absolute (MCi)	Relative (%)
>20	870	5–8.7	63.0
10–20	480	0.8–1.4	10.2
5–10	1100	1–1.7	10.8
3–5	2780	1.3–2.2	16.0
Total	5230	8–14	100.0

Note: 1 R = 258 μC/kg;
1 Ci = 37 GBq.

(b) The main contribution to the dose received by the Soviet population will be external exposure from radioactive fallout deposited on the ground. Its relative contribution will rise from 53% in the year following the accident to 60% of the dose commitment to the public.

(c) For the lifetime dose, the main role is played by ^{137}Cs, whose contribution to the overall external exposure of the public from radioactive fallout on the ground is 70%.

(d) Internal exposure resulting from ingestion of contaminated foodstuffs is the most controllable exposure pathway. Assessments show that a reduction of 5–20 in individual doses received by the public in the most heavily contaminated areas could be achieved in comparison with regions where banning of contaminated milk was not taken because the ^{131}I levels did not reach the relevant threshold level.

The decontamination work carried out in the 30 km zone played a major role in reducing the external gamma radiation exposure received, particularly in regions near the damaged facility. This work also significantly reduced the possibility of inhalation of radionuclides as a result of secondary dust formation.

A.3. CLEANUP OF THE SITE

A.3.1. Introduction

The cleanup of the plant buildings and site commenced immediately after the releases from the damaged reactor were stopped. The cleanup of the site and nearby areas was more difficult than expected owing to the different decontamination techniques required for the different terrains, and the wide variety of buildings, components and structural materials and technological equipment located in open places. Items which required cleanup included: concrete, asphalt and metal surfaces, gardens, shrubs, woods, water bodies, different roofing materials, farmland and forests.

Other factors which influenced the choice of technique were: the density and distribution of structures, and the position and configuration of equipment which might determine the practicability of using machines and mechanical/chemical decontamination. An important criterion in the highly active zone for selecting methods to decontaminate roofs was the load bearing capacity. The shielded vehicles were too heavy to use.

In general, the exposure dose rate at the location being cleaned up determined the basic technique used: unshielded equipment, biologically shielded units or robots (Section A.5). In all cases, attention was paid to possible unforeseen circumstances which could jeopardize the safety of the operator. These criteria were of utmost importance in evaluating the suitability of methods and equipment for cleanup close to the damaged reactor.

During the cleanup of the buildings and site, a variety of techniques were used, including simple washing and scrubbing of surfaces, firehosing, removal of layers of soil and the use of robotically controlled cleanup equipment. In some cases the contamination was covered with a layer of clean material such as concrete for long term protection.

In June 1986, construction was started on a complex of hydraulic emergency structures to prevent further contamination of the groundwater and surface water in the plant area as a result of cleanup activities. These structures include:

- a filtration-proof wall in the soil along part of the perimeter of the site of the power plant and wells to lower the water table;
- a drainage barrier for the cooling pond;
- a drainage cutoff barrier on the right bank of the Pripyat river;
- a drainage interception barrier in the south-west section of the plant;
- drainage water purification facilities.

In addition, in preparation for the 1987 spring high water, more than 100 protective and filtering dykes were constructed on rivers and watercourses flowing through contaminated terrain to reduce the erosion of radionuclides into the water [112].

In October 1986, a new organization, Kombinat, was set up and given responsibility for all civilian activities within the 30 km exclusion zone, including all cleanup work. It is now located in the decontaminated town of Chernobyl [113]. About 10 000 civilians are working in the 30 km zone: 4000 in connection with the nuclear power plants and 6000 doing decontamination [113]. About 500 people are working on the decontamination of Units 5 and 6, which are under construction.

In the following sections, details of the cleanup of the inside of the buildings on the site and the site itself are briefly described.

A.3.2. Decontamination of the inside of buildings

The surfaces of indoor equipment and rooms of the other three units of the nuclear power plant were contaminated through the ventilation system, which continued to operate for some time after the accident. The highest radiation levels were recorded for individual horizontal sections of the surfaces in the turbine building since this was contaminated for a prolonged period through the damaged roof.

The gamma radiation levels on 20 May 1986 were 0.1–1 $mGy \cdot h^{-1}$ for Unit 1 and 0.2–6 $mGy \cdot h^{-1}$ for Unit 2.

During the entombment of the destroyed Unit 4, inner concrete partition walls were built in the turbine hall between the third and fourth units and in several other locations to isolate the damaged facility and the radioactive debris from Unit 3. A metal partition wall was built in the turbine hall between the second and third units.

Firehosing was widely used to clean up the interior surfaces of the undamaged buildings. Some compartments were washed manually by wiping with rags soaked in decontamination solutions. The composition of the decontamination solutions was varied to take into account the washable nature of the materials (plastic, steel, concrete and various covers) and the nature and level of the contamination. Steam cleaning was also used.

After decontamination, the gamma radiation levels in Units 1 and 2 dropped by a factor of about 10 to levels of 0.02–0.1 $mGy \cdot h^{-1}$. Beta levels were generally reduced to less than 2000 beta particles/($cm^2 \cdot min$) for service compartments and 8000 beta particles/($cm^2 \cdot min$) for limited access areas.

The decontamination work for Units 1 and 2 was completed at the beginning of the third quarter of 1986 and they were back in operation by the end of 1986. The decontamination work on Unit 3 was completed in late 1987 and the unit was back in operation in December 1987.

Removal of the contaminated soft cover on the tops of the buildings has been carried out using special adhesive substances which are applied by remote methods to the contaminated parts of the roof and then removed by cranes [112]. Following completion of a portion of the planned work, the dose rate in the turbine hall of Unit 3 had dropped sharply by the end of July 1987 to 0.07–0.5 $mGy \cdot h^{-1}$.

A.3.3. Cleanup of the plant site

During the accident, radioactive material was scattered over the plant site and on the roofs of the turbine building and the third unit. The site, the walls and the roofs of other buildings also received considerable fallout of radioactive aerosols and dust. Contamination levels on the site were uneven. Initially, the gamma radiation levels from the damaged facility greatly exceeded the levels from the dispersed contamination.

Once the releases from the damaged facility were stopped, rapidly polymerizing solutions were sprayed from a helicopter (Fig. 27) onto the site, the roof of the turbine buildings, sides of the roads and other areas to stabilize the contamination and fix it in place and prevent resuspension of radioactive particles. The stabilizers also bound the upper layer of soil together for easier removal.

For the cleanup, the site was divided into three zones and the sequence of zone cleanup was based on:

(a) the need for personnel to do other work in the facilities in a zone;
(b) the principle 'from dirty to clean', taking into account the wind rose;
(c) the need for subsequent work involved in the starting of other units.

The cleanup in each zone was carried out in the following order:

(1) Radioactive debris and contaminated equipment were removed from the site using remotely controlled or biologically protected equipment (see Section A.5).
(2) Roofs of buildings were cleaned using remotely controlled equipment. External surfaces of the building were washed down using firehosing. Firehosing was effective on smooth surfaces but not very effective on rough surfaces.
(3) A layer of soil 5–10 cm thick was removed and loaded into drums, which were stored in the solid waste storage vault of the fifth unit. This was the major decontamination method used for the site.
(4) Where required, concrete slabs or clean soil were placed over residual hot spots.
(5) Concrete slabs and earth were covered with a film-forming material.

The rate of cleanup ranged from 15 000 to 35 000 m^2 per 24 hours. As a result of these measures, the overall background around Unit 1 was reduced to 0.2–0.3 $mGy \cdot h^{-1}$ even before the damaged unit was entombed. After entombment of damaged Unit 4 and further decontamination inside the buildings and on the site, the radiation levels are approaching the pre-accident background levels. By the end of 1987, the levels were down to 0.04 $mGy \cdot h^{-1}$ at 120 m from the concrete envelope over the damaged Unit 4 [113]. These results show that the decontamination techniques applied to the site and buildings were quite effective.

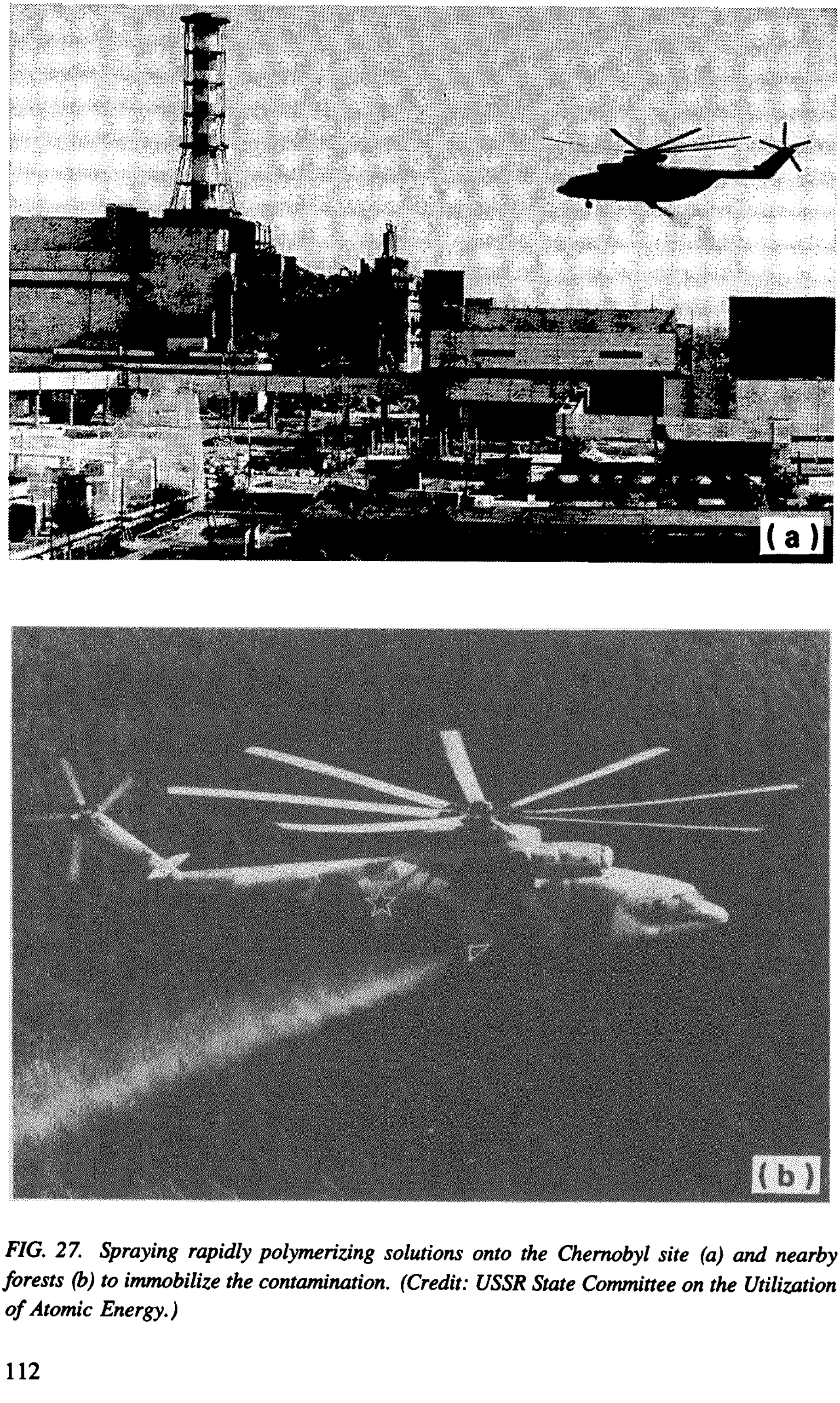


FIG. 27. Spraying rapidly polymerizing solutions onto the Chernobyl site (a) and nearby forests (b) to immobilize the contamination. (Credit: USSR State Committee on the Utilization of Atomic Energy.)

The most difficult and time consuming cleanup job was the decontamination of the huge electrical switchyard in front of the nuclear power plants [113].

A wide variety of remotely operated vehicles were used during the early stages of the cleanup when radiation fields were very high. Some of these are described in Section 5.3. The vehicles were used for monitoring, cleanup of high radiation sources, removal of obstacles, etc. For initial radiation monitoring, more than ten types of remotely controlled means were used, mainly Soviet made devices but also several from the Federal Republic of Germany, Japan, Poland, Finland and other countries.

A.4. CLEANUP OF THE 30 km ZONE

Following the release of activity from the damaged Unit 4, considerable redistribution of the deposited activity occurred, particularly during the first four months, as a result of active biological and atmospheric processes such as growth, development and dying of plants, rain and wind. The loosely attached parts of the radioactive fallout on the surface of soil, vegetation, roads and buildings experienced considerable redistribution. In coniferous forests, such redistribution could carry on for many years until all needles have been renewed.

For these reasons, the radiation conditions within the 30 km zone continued to change over the two year period after the accident, particularly in regions with high contamination level gradients. Therefore, measures taken to decontaminate populated areas sometimes only gave temporary improvement in certain regions.

Starting in mid-1986, a group under M. Arkhypov, the Head of the Laboratory of Land Reclamation [114], studied the condition of the environment in the 30 km zone and conducted experiments on contaminated areas to see if they could be brought back into productive use.

Soil samples were taken from all the fields at the collective and state farms in the region. These samples were analysed and cartograms were drawn showing the contamination levels and indicating radionuclides.

It was found that most of the discharged radionuclides were fixed to the soil and therefore not very mobile when moving through the biological chain (soil, plants, animals, man). These radionuclides are dangerous as long as they are on the surface and can be carried by the wind together with dust. They can be neutralized by ploughing into the soil where they are immobilized and will decay with time. Application of binding elements before ploughing increases the efficiency of such operations.

Regions found to contain significant concentrations of long lived radioisotopes of strontium and iodine could be treated with lime, zeolite, clayey suspension or similar substances to bind them chemically to the soil. This would be followed by normal ploughing.

A set of special treatments were recommended according to the soil type, vegetation cover, climatic conditions, composition and type of radionuclides and other specific conditions. These treatments included decontamination, changing the traditional system of soil cultivation, use of special dust suppression compounds, changing harvesting and crop processing methods and adding chemicals.

As a result of this and other work, guidelines were issued by the USSR State Commission for the Agricultural Industry, and a range of agrotechnical and agrochemical measures designed to make agricultural products fit for consumption were implemented in contaminated regions of the Ukraine, Byelorussia and the RSFSR in 1986 and 1987 [111].

With regard to surface contamination on vegetation and soils in 1986, agricultural harvesting of crops was carried out in the exclusion zone and strict control zone using special measures worked out by the State Agricultural Programme of the USSR and Ukraine SSR and the USSR Ministry of Health. The special requirements for this work were as follows:

— mechanical cultivation of soils was kept to a minimum to reduce dust formation;
— the grain and industrial crops were harvested by direct combine harvesting and, depending on the contamination level, were used (after being stored) for food purposes, fodder, seed and industrial processing;
— after the harvesting of perennial grasses and winter crops, lime, mineral fertilizers and sorbents were added to the soil to increase fertility and reduce entry of radionuclides into the new crops.

After harvesting, the surface layer of turf was removed in certain areas, especially near the damaged facility, and thus reduced contamination significantly. In some cases the turf was consolidated using a latex emulsion (SKS-65 gp). Removal of a layer of soil, which was done in a few areas, was also a very effective cleanup method.

Deep ploughing was carried out and large quantities of inorganic fertilizer were applied to hundreds of thousands of hectares of contaminated land. Work is under way to ameliorate the detrimental effects in meadows and pastures. Lime, phosphoric and potassium fertilizers and certain sorbents (zeolite) are being added to reduce the transfer of radioactive substances from soil to crops.

In the first year following the implementation of these measures, the levels of radioactivity in produce were reduced by a factor of 1.5–3. Full implementation of all the recommended agricultural practices will probably result in a substantial reduction in exposure of the population from food.

As a result of cleanup of lands using the above techniques and others, it was reported [114] that it would be possible from a scientific viewpoint to start agricultural work on about half of the 30 km zone in the spring of 1987. However, such work was not then started owing to other social, economic, technological and

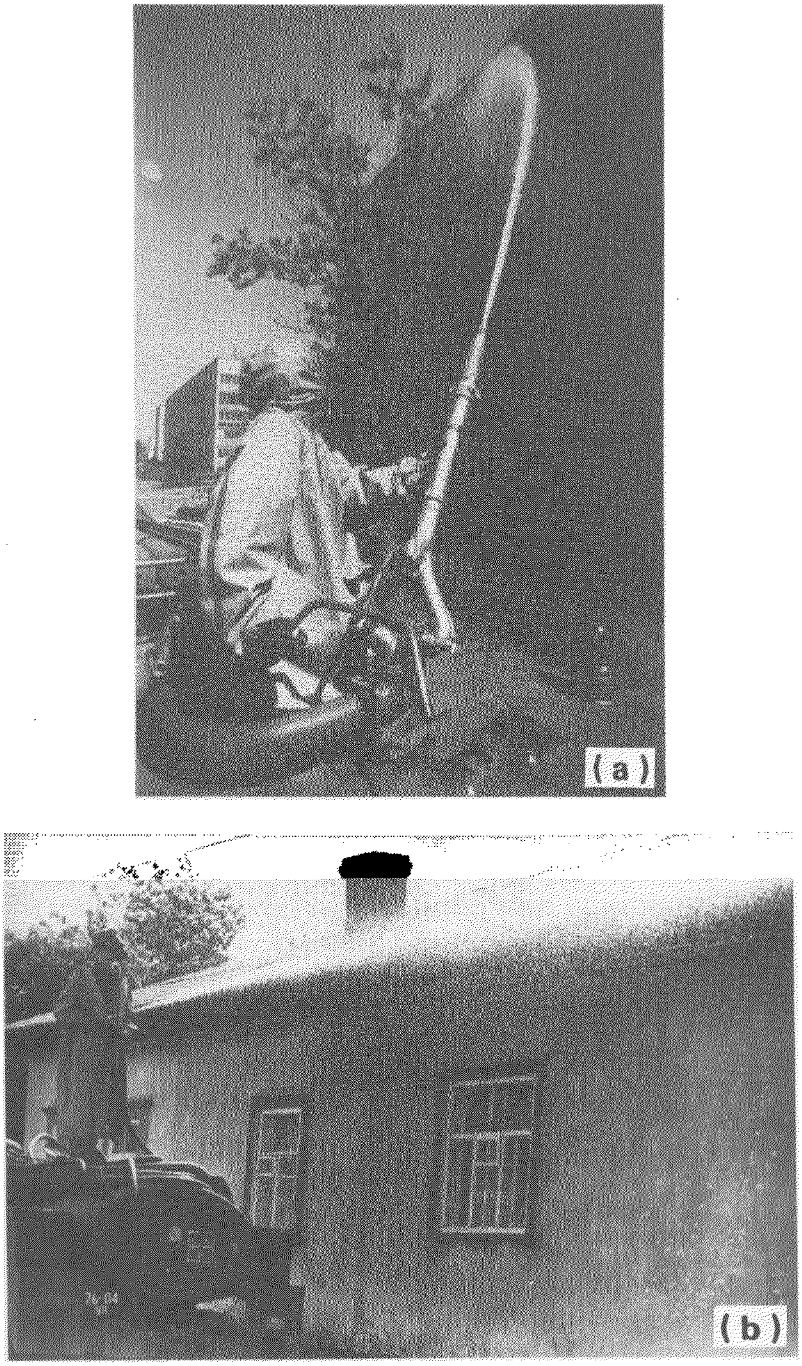


FIG. 28. Decontamination of the walls (a) and roofs (b) of buildings in the town of Chernobyl. (Credit: USSR State Committee on the Utilization of Atomic Energy.)

psychological aspects of the problem. Farming on such levels will require proper selection of crops and farming methods and adherence to the technological specifications laid down.

Research has shown the forests act as accumulators of radioactive substances, first in the crown and then in the forest litter. The radionuclides fixed in the litter will be excluded for a long time from the radiation chains. At present, the majority of experts believe that the best way to deal with contaminated forests is to increase the fire prevention service. An area of pine trees adjacent to the site received a lethal dose of radiation and the trees have now been removed [113].

The levels of radioactive contamination on houses and buildings in the 30 km zone varied widely depending on the distance from the plant, wind direction and other atmospheric conditions prevalent during the release. Typical building materials include bricks, painted and bare wood, slate and metal.

Decontamination of the urban areas was started shortly after the releases from the reactor were stopped. Decontamination of buildings was mainly done by spraying the surfaces with a decontamination solution at a flow rate of 10–15 $L \cdot m^{-2}$ (Fig. 28). Firehosing was also used to some extent on buildings and for cleaning roads. As a result of the decontamination, the radiation levels on some buildings dropped to the background levels for the region. However, such cleanup actions were not effective on all types of surfaces and roofs.

After washing of the buildings, the radioactive contamination on the earth adjacent to the walls increased about 2–2.5 times. This earth was removed with bulldozers and sent for disposal.

By the summer of 1987, a great amount of work had been carried out in decontaminating populated areas. About 600 populated centres and almost 60 000 houses and other buildings and structures had been decontaminated [111, 114]. Residents of over 16 villages in the outer part of the zone have returned home. However, cleanup of the towns close to the nuclear plant requires more work.

The whole of the small town of Chernobyl, which was not as badly affected as Pripyat, has been decontaminated and many of the buildings are being used as hostels for cleanup personnel during their duty tours [113].

The first decontamination of Pripyat, including decontamination of buildings and removal of all topsoil, was completed in 1986. Apartment blocks in part of the town were decontaminated a second time and will be used to house a new enterprise called Spetsatom. This group was set up to render assistance in case of accidents at nuclear power plants and evaluate technology that might be used in emergencies, for example protective clothing and remotely operated equipment [113]. Pripyat is also the centre for control and radiation monitoring and includes the computer centre which processes data from the 2000 radiation monitors used throughout the 30 km zone.

A.5. EQUIPMENT USED FOR THE CLEANUP

A.5.1. Introduction

Three categories of technology were used for performing the cleanup of the site of the Chernobyl nuclear power plant: biological protection, remote control and ordinary road building and obstacle removal equipment [115].

Essentially, the cleanup in the vicinity of the reactor consisted of removing the contaminated surface layer of soil and at selected sites suctioning up dust or covering the source with fill or concrete. The removed material was loaded into containers and transported to disposal sites.

A.5.2. Equipment with biological protection

Biological protection of workers was applied on a wide scale and classified into three subgroups according to the attenuation factor (AF) required to bring the radiation levels in the operators' workplace down to an acceptable level:

(a) An AF of not less than 1000 (100 mm of lead) was required for radiation levels of grays per hour;
(b) An AF of 100–200 for hundreds of milligrays per hour;
(c) An AF of 5–20 for tens of milligrays per hour.

In addition to shielding, workers' cabs contained other features and life support systems. For example, the conventional bulldozers, obstacle removal machines, etc. were also equipped with television viewing periscopes and/or lead glass peep holes, leaktight cabins with filtered air supplies, internal and external dosimeters, radio communication, etc. To make decontamination of the machines easier, they were coated on the outside with epoxy paint and on the inside with plasticized material.

All machines were also filled with automatic connecting devices so they could be removed in case of breakdown.

Although the biological protection performed as required, there were some problems with the first machines. For example, the frames and springs of some units had difficulty sustaining the 8–10 t of shielding applied in subgroup (a). This weight also reduced the stability, manoeuverability and ease of control of the machines. The view was generally limited. This experience suggests that such equipment should be designed specifically for these tasks if possible.

A.5.3. Remotely operated equipment

A.5.3.1. Introduction

In addition to conventional equipment and vehicles, a variety of remotely operated vehicles were used during the cleanup of the Chernobyl site. The principal tasks included reconnaissance, obstacle clearance, technological jobs and decontamination.

(a) Reconnaissance

Vehicles were used here for visual examination, measuring temperatures and radiation fields and sampling soil, dust and material in fields up to 10^3 Gy·h^{-1} and under chaotic and undefined physical conditions. They were also used to record or transmit the data collected. These vehicles must be reliable, have good agility and viability.

(b) Obstacle clearance

The vehicles used must have adequate power and tools to be able to clear the way for people, machinery or remotely controlled devices, and must be able to deal with the opening of locked or jammed doors/hatches and recovery of disabled vehicles.

(c) Technological jobs

The jobs include drilling holes for the installation of sensors, laying communication and power lines and the maintenance and repair of unserviceable equipment.

(d) Decontamination

In a highly radioactive environment, the robotic devices used must be able to perform all the regular decontamination functions including:

— collection of radioactive debris and soil;
— holding and manipulation of decontamination equipment;
— decontamination of equipment, buildings and sites.

The vehicles used were generally not true robots but operator controlled vehicles having a variety of feedback devices. However, the intelligence capability of the vehicles should be high enough to reduce operator fatigue in repetitive tasks such as taking samples or radiation monitor readings.

The criteria for such vehicles are outlined in Section 12 of the main report.

In Section A.5.3.2 some of the vehicles that were used to perform the above tasks during the cleanup at Chernobyl are briefly described. Further information on these devices is given in Refs [115–117].

A.5.3.2. Remotely operated vehicles used at Chernobyl

A total of over 50 units of remotely controlled vehicles from the USSR, the Federal Republic of Germany, Finland, Poland, Japan and other countries were used during the cleanup. All machines were found to perform satisfactorily and reliably, although most have some shortcomings.

The Beloyarets is a remotely wire controlled track vehicle designed to collect and remove radioactive debris. The 1400 kg vehicle has an operating range of 220 m

FIG. 29. Manually operated bulldozer cleaning up soil having low concentrations of radioactivity. The vehicle could also be operated remotely. (Credit: USSR State Committee on the Utilization of Atomic Energy.)

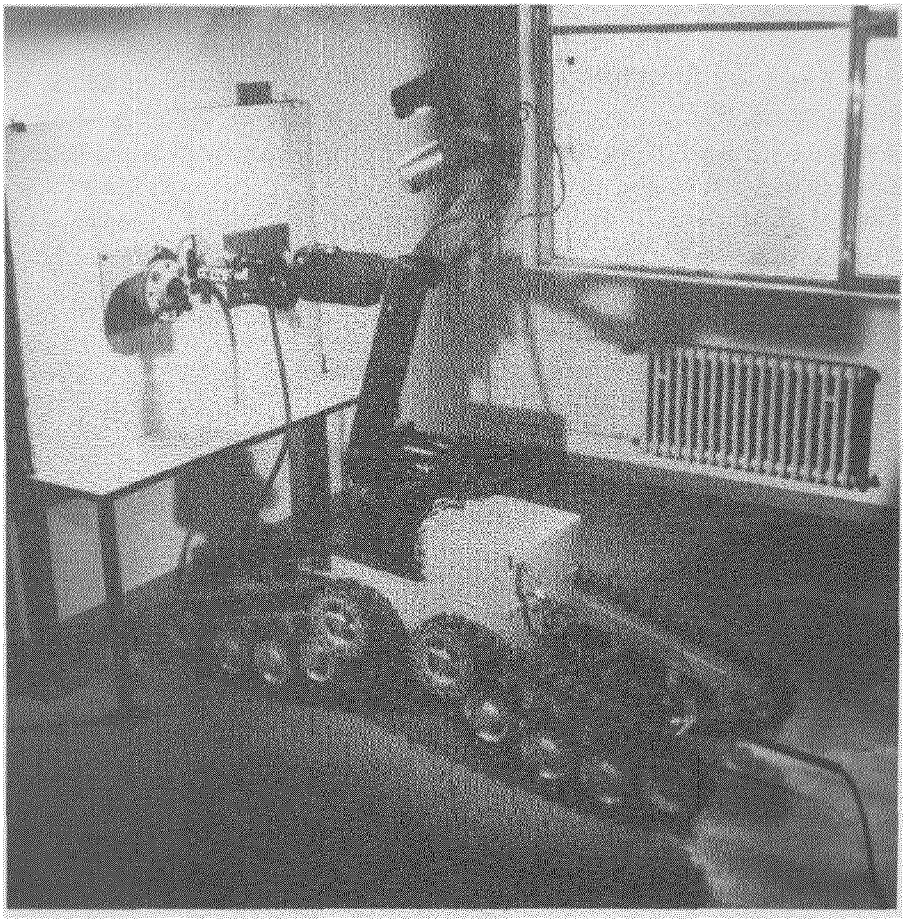


FIG. 30. Self-propelled wire guided vehicle with manipulator, lighting equipment and television camera. (Credit: KHG Karlsruhe.)

and was equipped with a bulldozer blade, a manipulator with a load capacity of 60 kg, a gamma monitor, three television cameras with zoom lenses and a wire layer. It was used to do radiation surveying on some roofs adjacent to Unit 4 and to clear debris.

The Pylesos is a 250 kg remotely wire controlled (up to 140 m) vehicle with a television camera. It is designed to decontaminate porous surfaces which could not be cleaned with detergents or adsorbing films. The surfaces were decontaminated by removing a layer several micrometres thick from metallic, ceramic, plastic and painted surfaces. The dust was sucked up into a storage tank and the clean air exhausted. The surface activity was reduced by a factor of 2–3 following decontamination with chemical compounds. Decontamination of porous materials such as concrete was not effective using this vehicle.

The Trosokhod is a 6 kg wire controlled vehicle which was designed to carry out regular monitoring of radiation levels, the composition of aerosol fractions and gas. The vehicle was capable of travelling along a rope guide at about 2 m per minute.

FIG. 31. Remotely operated vehicle used to clean up the roof of the reactor halls. The vehicle is a modified version of the USSR moon vehicle. (Credit: USSR State Commission on the Utilization of Atomic Energy.)

The robotic system STR-1 consisted of a 1110 kg radio or wire controlled track vehicle with a 500 m range furnished with a 2 m wide bulldozer blade, three television cameras and a charger. This vehicle was used to clear away obstructions and remove radioactive debris. It was also used to carry out radiation measurements and clean roof surfaces. The wire guided STR-1 broke down and had to be removed for repairs. There was no evidence that the failure was caused by radiation damage. However, there was a perceptible loss in light transmission of the television camera lenses and periodic malfunction of the radio control system.

The TRG-1, 2 and 3 robotic systems consisted of 1800 kg electrically driven crawler mounted vehicles controlled by wire to a range of 250 m. They were equipped with a bulldozer blade, two television cameras and a wire layer. The TRG-1 failed as a result of mechanical damage while cleaning up the roof of the turbine hall. The television equipment on the TRG-2 failed after seven days in high radiation fields. The TRG-3 damaged its rear view camera and became immobilized after it got tangled in sling ropes. The TRG vehicles were underpowered for the cleaning jobs and there were problems with the control wire getting between the tracks. This type of tractor was also manually operated and used to clean up areas having lower contamination levels (Fig. 29).

The MF-3 is a self-propelled wire guided tracked vehicle (Fig. 30) having four independent tracks, a manipulator with changeable grippers and appliances, lighting equipment and a television camera. It was used for indoor inspection of the turbine hall and for removing radioactive debris and graphite from the roof of Unit 3. The device helped to put 300 pieces of contaminated waste into containers for disposal. The vehicle got to the roof of Unit 3 under its own power by climbing stairs. Considerable difficulties in its operation were caused by the lack of a device for letting out and reeling in the control wire. Several other faults were corrected.

Most other vehicles were lifted onto the roofs by means of large cranes. Figure 31 shows a remotely operated vehicle which was used on top of the reactor hall to clean up debris. This vehicle is a modified version of the USSR moon vehicle.

A.5.3.3. Operational problems

The main operating difficulties with the remotely controlled devices during the Chernobyl cleanup include:

(a) Inadequate reliability of both the mechanical parts and control systems. The control systems failed most frequently as a result of high radiation doses.
(b) Failure of some vehicles to overcome obstacles.
(c) Tangling of the control cable with obstacles or even with the machine. Cable stowing devices improved the performance.
(d) Inability to decontaminate a vehicle quickly and thoroughly after it had worked in the active zone.

(e) Lack of modular components which can be replaced quickly when failures occur.

Despite all the problems, the use of remotely operated equipment was indispensible for certain cleanup tasks such as cleaning up roofs.

A general comment which applies to all the remotely controlled road-building types of machine is that the operator did not have a satisfactory view and little feel for the loading. As a result, nearly all the earth decontamination work was done using biologically protected machines [115].

The main problem with shielded vehicles was that the weight of the shielding reduced the stability, manoeuverability and ease of control of the machines. The weight also prevented the use of such vehicles on roofs.

A.6. TRANSPORTATION AND DISPOSAL OF CONTAMINATED WASTES

The most highly contaminated earth and rubble from the clean up of the Chernobyl site was loaded into drums and sent for storage in the solid waste storage vault of Unit 5. These drums will eventually be sent to a normal disposal site.

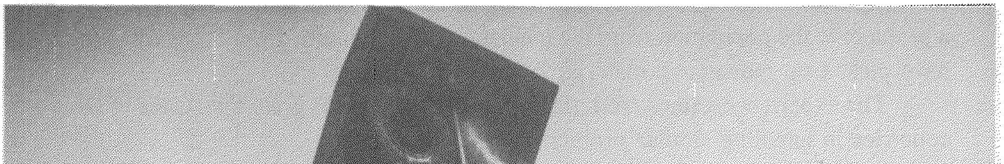


FIG. 32. Decontamination of trucks used to transport contaminated waste to disposal areas. The waste in the trucks was covered by a tarpaulin during movement to minimize spillage. (Credit: USSR State Committee on the Utilization of Atomic Energy.)

The large volumes of less active material on the site and in areas close to the site were bulldozed into piles using shielded and/or non-shielded machines, loaded into trucks and transported to several storage/disposal areas which had been established near the nuclear power plant site. Most of the waste was transported to the storage/disposal sites in trucks (Fig. 32).

Much of the low level radioactive waste was placed into specially dug pits which were lined with clay or other impermeable material. The waste was made into a mound which continued above the normal ground level. The mounds were covered with a layer of clay and a layer of soil and then seeded to produce a vegetative cover. The seepage from these sites is being monitored.

Although most trees were left to let nature do the decontamination, some trees near the site were cut down, bulldozed into deep trenches and covered with soil. The bottoms of the trenches were above the water table.

A.7. CONCLUSIONS

A great deal of progress has been made in cleaning up the surface contamination within the 30 km zone or in stabilizing the contaminants so that they do not pose a problem to the population from the inhalation of dust and/or from foodstuffs which have picked up radioactive material from the soil.

The experience gained from this cleanup should be of great assistance to other countries in handling similar problems.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Preparedness of Public Authorities for Emergencies at Nuclear Power Plants, Safety Series No. 50-SG-G6, IAEA, Vienna (1982).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Preparedness of the Operating Organization (Licensee) for Emergencies at Nuclear Power Plants, Safety Series No. 50-SG-O6, IAEA, Vienna (1982).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Planning for Off-Site Response to Radiation Accidents in Nuclear Facilities, Safety Series No. 55, IAEA, Vienna (1981).

[4] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Protection of the Public in Event of a Major Radiation Accident — Principles for Planning, ICRP Publication 40, Pergamon Press, Oxford and New York (1984).

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Principles for Establishing Intervention Levels for the Protection of the Public in the Event of a Nuclear Accident or Radiological Emergency, Safety Series No. 72, IAEA, Vienna (1985).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, Derived Intervention Levels for Application in Controlling Radiation Doses to the Public in the Event of a Nuclear Accident or Radiological Emergency, Safety Series No. 81, IAEA, Vienna (1986).

[7] Emergency Planning and Preparedness for Nuclear Facilities, (Proc. Symp. Rome, November 1985), IAEA, Vienna (1986).

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Current Practices and Options for Confinement of Uranium Mill Tailings, Technical Reports Series No. 209, IAEA, Vienna (1981).

[9] INTERNATIONAL ATOMIC ENERGY AGENCY, Factors Relevant to the Recycling or Reuse of Components Arising from the Decommissioning and Refurbishment of Nuclear Facilities, Technical Reports Series No. 293, IAEA, Vienna (1988).

[10] NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS, Radiological Assessment: Predicting the Transport, Bioaccumulation and Uptake by Man of Radionuclides Released to the Environment, NCRP, Bethesda, MD (1988).

[11] NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS, Radiation Effects on Aquatic Organisms, NCRP, Bethesda, MD (1988).

[12] GRAUBY, A., LEGRAND, B., CAMUS, H., First Results of the RESSAC Programme, Commissariat à l'énergie atomique, Paris (in preparation in French).

[13] LAYLAVOIX, F., et al., Recovery of Agricultural Soils After an Accidental Release of Radionuclides into the Atmosphere: Our Present Understanding of the Subject, Commissariat à l'énergie atomique, Paris (to be published in French).

[14] UNITED STATES DEFENSE NUCLEAR AGENCY, The Radiological Cleanup of Enewetak Atoll, Rep. FCD-NA-O Plan 600–77, Washington, DC (1981).

[15] UNITED STATES NUCLEAR REGULATORY COMMISSION, Termination of Operating Licenses for Nuclear Reactors, Regulatory Guide 1.86, Washington, DC (1974).

[16] GILBERT, R.O., Statistical Methods for Environmental Pollution Monitoring, Van Nostrand Reinhold, Princeton, NJ, and New York, NY (1987).

[17] GILBERT, R.O., SIMPSON, J.C., Kriging for estimating spatial pattern of contaminants: potential and problems, Environ. Monitor. Assess. **5** (113–135) 1985.

[18] GILBERT, R.O., BARNES, M.G., Tran-Stat-19, The Use of Kriging for Estimating the Spatial Distribution of Radionuclides and Other Spatial Phenomena, Rep. PNL-SA-905, Battelle Pacific Northwest Laboratories, Richland, WA (1980).

[19] TAWIL, J.J., STRENGE, D.L., "Decontamination analysis of a radiologically contaminated site, Computer Applications in Health Physics (Proc. Symp. Pasco, USA, February 1984), Health Physics Soc., Richlands, WA (1984) 6001.

[20] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, The Ecological Impact of Land Restoration and Cleanup, Rep. EPA-520/3-78-006, Washington, DC (1978).

[21] JOHNSON, H.V., et al., Geotechnical Quality Control: Low-Level Radioactive Waste and Uranium Mill Tailings Disposal Facilities, Rep. NUREG/CR-3356, USNRC, Washington, DC (1983).

[22] BUNZ, H., KORYO, M., SCHOCK, W., "Influence of source term parameters on aerosol behaviour in core melt-down accidents in LWRs", paper presented at Mtg on Nuclear Aerosol in Reactor Safety, Gatlinburg, 1980.

[23] LINSLEY, G.S., CLARK, R.H., "Assessing the radiological consequences of surface contamination in urban areas — areas of uncertainty and their resolution", paper presented at 6th International Congress of Fachverband für Strahlenschutz e.V., Berlin (West), May 1984, Vol. 2, 731–734.

[24] UNITED STATES NUCLEAR REGULATORY COMMISSION, Calculation of Reactor Accident Consequences, Appendix K of Appendix 6, Rep. WASH-1400, Washington, DC (1975).

[25] CAMBRAY, R.S., et al., Observations on radioactivity from the Chernobyl accident, Nucl. Energy **26** 2 (1987) 77–101.

[26] ROED, J., Deposition velocity of caesium-137 on vertical building surfaces, Atmos. Environ. **17** (1983) 663–664.

[27] ROED, J., Dry deposition in rural and urban areas in Denmark, Radiat. Prot. Dosim. **21** 1/3 (1987) 33–36.

[28] JACOB, P., MECHBACH, R., Shielding factors and external dose evaluation, Radiat. Prot. Dosim. **21** 1/3 (1987) 79–85.

[29] HULOT, M., et al., State of the Art Review on Technology for Measuring and Controlling Very Low Radioactivity in Relation to the Decommissioning of Nuclear Reactors, Rep. EUR-10643, Commission of the European Communities, Luxembourg (1986).

[30] DAHLSTROM, T.S., "Status of aerial survey emergency preparedness and ground support equipment, calibration and sensitivities", paper presented at ANS Topical Mtg on Radiological Accidents, Perspectives and Emergency Planning Preparedness, Bethesda, September 1986; Rep. CONF-860932 (1986).

[31] JOBST, J.E., "A history of aerial surveys in response to radiological incidents and accidents", ibid.

[32] GIACOMINI, J.J., MILLER, F.R., Jr., "Statistical aspects of the cleanup of Enewetak Atoll", paper presented at Workshop on Environmental Decontamination, Oak Ridge, December 1979; Rep. CONF-791234 (1981).
[33] BERRY, H.A., BURSON, Z.G., "Developing a comprehensive and accountable data base after a radiological accident", paper presented at ANS Topical Mtg on Radiological Accidents, Perspectives and Emergency Planning Preparedness, Bethesda, September 1986; Rep. CONF-860932 (1986).
[34] TAWIL, J.J., BOLD, F.C., A Guide to Radiation Fixation, Rep. PNL-4903, Pacific Northwest Laboratories, Richland, WA (1983).
[35] ALLEN, R.P., ARROWSMITH, H.W., McCOY, M.W., "New decontamination technologies for environmental applications", paper presented at Workshop on Environmental Contamination, Oak Ridge, December 1979; Rep. CONF-791234 (1981).
[36] Nuclear Engineering International (October 1986) 2–9.
[37] INTERNATIONAL ATOMIC ENERGY AGENCY, Decontamination of Nuclear Facilities to Permit Operation, Inspection, Maintenance, Modification or Plant Decommissioning, Technical Reports Series No. 249, Vienna (1985).
[38] INTERNATIONAL ATOMIC ENERGY AGENCY, Decontamination and Demolition of Concrete and Metal Structures During the Decommissioning of Nuclear Facilities, Technical Reports Series No. 286, Vienna (1988).
[39] UNITED STATES DEPARTMENT OF ENERGY, Proc. 1987 International Decommissioning Symp., Pittsburgh, October 1987; Rep. Symp. CONF-871018.
[40] BENGAL, P.R., MASON, R.C., "Results of the gross decontamination experiment and implications for future decontamination activity", paper presented at ANS/CNA Conf. on Decontamination of Nuclear Facilities, Niagara Falls, September 1982.
[41] LEWIS, W.B., The Accident to the NRX Reactor on December 12, 1952, Rep. AECL-232, Atomic Energy of Canada Ltd, Ontario (1953).
[42] TVETEN, U., "Deposition and natural decontamination of caesium on urban surfaces — the Nordic programme", Methods for Assessing the Off-site Radiological Consequences of Nuclear Accidents, Rep. EUR-10397, Commission of the European Communities, Luxembourg (April 1985).
[43] SANDALLS, F.J., Retention of radiocaesium on urban surfaces, five months after Chernobyl, Radiat. Prot. Dosim. **21** 1/3 (1987) 65–68.
[44] GALE, H., HUMPHRIES, D.L.O., FISHER, E.M., Weathering of caesium-137 in soil, Nature (London) **201** (1964) 257–259.
[45] JACOBS, R., MECHBACH, T., MILLER, H., Reduction of external exposures from deposited radionuclides by run-off, weathering, street cleaning and migration in the soil, Radiat. Prot. Dosim. **21** 1/3 (1987) 51–57.
[46] ROED, J., "Runoff from roofing material", paper presented at 4th Nordic Radioecology Seminar, February–March 1985, Gol, Norway.
[47] WARMING, L., Weathering and Decontamination of Radioactivity Deposited on Asphalt Surfaces, Rep. RISO-M-2273, Roskilde, Denmark (1982).
[48] WARMING, L., Weathering and Decontamination of Radioactivity Deposited on Concrete Surfaces, Rep. RISO-M-2473, Roskilde, Denmark (1984).

[49] SANDALLS, F.J., Removal of Radiocaesium from Urban Surfaces Contaminated as the Result of a Nuclear Accident, Rep. AERE-R-12355, Harwell, UK (1987).

[50] SARTOR, J.D., BOYD, G.B., AGARDY, F.J., Water pollution aspects of street surface contaminants, J. of Water Pollut. (January 1974) 456–467.

[51] CALVERT, S., BRATTIN, H., BHUTRA, S., Improved Street Sweepers for Controlling Urban Inhalable Particulate Matter, Rep. EPA-600/7-84-021, US Environmental Protection Agency, Washington, DC (1980).

[52] WILTSHIRE, L.L., OWEN, W.L., Removal of Simulated Fallout from Asphalt Street by Fire-Hosing Techniques, Rep. AD-641480, US Radiological Defense Laboratory, San Francisco, CA (1965).

[53] WILTSHIRE, L.L., OWEN, W.L., Three Tests of Firehosing Technique and Equipment for the Removal of Fallout Simulant from Asphalt Street and Roofing Materials, Rep. USNRDL-TR-1048, US Radiological Defense Laboratory, San Francisco, CA (1966).

[54] DICK, J.L., BAKER, T.S., Monitoring and Decontamination Techniques for Plutonium Fallout on Large-area Surfaces, Rep. WT-1512, Air Force Special Weapons Centre, Kirkland AFB, CA (1966)

[55] PICK, M.E., et al., Decontamination techniques developed in the UK for reactor application, paper presented at Spectrum-86 Conf., Niagara Falls, September 1986.

[56] MEIGS, R.A., "Use of foam chemicals for decontamination", (Proc. Decon. Symp. Pittsburgh, 1987), Vol. 2, Westinghouse Hanford Co., Richland, WA (1987) IV.23.

[57] BOND, R.D., et al., The Decontamination of a Pressurized Suit Area at AEE Winfrith, Rep. AEEW-R-1742, Winfrith, UK (1984).

[58] HARRIS, J.M., et al., "A foam process for application of decontamination agents", paper presented at ANS/CNA Conf. on Decontamination of Nuclear Facilities, Niagara Falls, September 1982.

[59] ROBEV, S.K., et al., "A method of decontaminating radioactively contaminated surfaces by film", Practices in the Treatment of Low- and Intermediate-Level Radioactive Wastes (Proc. Symp. Vienna, 1985), IAEA, Vienna (1966) 751.

[60] RISLEY NUCLEAR POWER DEVELOPMENT ESTABLISHMENT (UKAEA), Radioactive Decontamination — Code of Practice, Rep. AECP-1057, Risley, UK (1983).

[61] HORTON, J.H., ALBENESIUS, E.L., Volume reduction of plutonium contaminated soil, Nucl. Technol. **30** (1) (1976) 86–88.

[62] LEVESQUE, R., "Soil Decontamination", paper presented at ASME-EPRI Radwaste Workshop, Charlotte, NC, January 1983.

[63] GARNETT, J.L., MITCHELL, D.L., PACCINI, P., Initial Testing of Pilot Scale Equipment for Soil Decontamination, Rep. RFP-3022, Rockwell International, Richland, WA (1980).

[64] MILLER, R.L., DOWNS, W.F., FLINN, J.E., Preliminary Assessment for Decontamination of Idaho National Engineering Laboratory Radioactive Soils Using Chemical Extraction Processes, Rep. RE-M-79-012, EG&G, Idaho Falls, ID (1979).

[65] POLYAKOV, Yu.A., Radioecology and Decontamination of Soils, Rep. OLS-79-101; abstract reported in Rep. ORNL/EIS-199, Oak Ridge Natl Lab., Oak Ridge, TN (1982).

[66] SUNDERLAND, N.R., Volume Reduction Research and Development Project (VORRP) Utilizing the TRU Clean Process, Rep. HN-10476-1141, USDOE, Las Vegas, NV (September 1987).
[67] MENZEL, R.G., JAMES, P.E., Treatments for Farmland Contaminated with Radioactive Material, United States Department of Agriculture Handbook No. 395, Washington, DC (1971).
[68] JAMES, P.E., MENZEL, R.G., Research on Removing Radioactive Fallout from Farmland, US Department of Agriculture Technical Bulletin No. 1469 (1973).
[69] LONSJO, H., HAAK, E., Effects of Deep Placement and Potassium Fertilization on the Crop Uptake of Caesium and Strontium, Rep. SLU-REK-60, Swedish University of Agriculture, Uppsala (1986).
[70] WINTERINGHAM, F.P.W., Radioactive Fallout in Food and Agriculture, IAEA-TECDOC-494, IAEA, Vienna (1989).
[71] DORP, F. von, ELEVELD, R., FRISSEL, M.J., Agricultural Measures to Reduce Radiation Doses to Man Caused by Severe Nuclear Accidents, Commission of the European Communities, Rep. EUR-7370 EN, Luxembourg (1979).
[72] UNITED STATES ATOMIC ENERGY COMMISSION, Enewetak Radiological Survey, Rep. NVO-140, Vol. II, Las Vegas, NV (1973).
[73] DUNNING, G.M., "Protective and remedial measures taken during three incidents of fallout", paper presented at Symp. on Radiological Protection of the Public in a Nuclear Mass Disaster, Interlaken, Switzerland, May–June 1968.
[74] BARBIER, M.M., "Machine Technology: A survey", paper presented at Workshop on Environmental Contamination, Oak Ridge, TN, December 1979; Rep. CONF-791234 (1981).
[75] CHAPIN, J.A., COOPER, C.S., Feasibility of Using Plants to Decontaminate Radioactive Soils, Rep. TREE-1366, EG&G, Idaho Falls, ID (1979).
[76] JAYARAMAN, A.P., PRABHAKAR, S., "The water hyacinth's uptake of ^{137}Cs and ^{90}Sr and its decontamination potential as an approach to the zero-release concept", Environmental Migration of Long-Lived Radionuclides (Proc. Symp. Knoxville, July 1981), IAEA, Vienna (1982) 557.
[77] NISHITA, H., et al., Release of strontium-90 and cesium-137 from vina loam upon prolonged cropping, Soil Sci. **86** (1958) 195–201.
[78] BACK, D.A., "Tailings disposal to-day", paper presented at First Int. Tailing Symp. Tucson, 1972; abstract reported in Rep. ORNL/EIS-199, Oak Ridge Natl. Lab., Oak Ridge, TN (1982).
[79] BENGSON, S.A., "Irrigation techniques for tailing revegetation in the arid southwest", paper presented at Second Int. Tailing Symp. Denver, 1978; abstract reported in Rep. ORNL/EIS-199, Oak Ridge Natl. Lab., Oak Ridge, TN (1982).
[80] REITEMEIER, R.F., JAMES, P.E., MENZEL, R.G., "Reclamation of agricultural land following accidental radioactive contamination", paper presented at Conf. on Protection of the Public in the Event of Radiation Accidents, Geneva, 1963; abstract reported in Rep. ORNL/EIS-199, Oak Ridge Natl. Lab., Oak Ridge, TN (1982).
[81] ROBISON, W.L., et al., An Updated Radiological Dose Assessment of Bikini and Eneu Islands at Bikini Atoll, Rep. UCRL-53225, Lawrence Livermore Labs, Berkeley, CA (1982).

[82] FRONDEL, G., Geochemical scavenging of strontium, Science **128** (December 1958) 1623-1624.
[83] HAGHIRI, F., Decontamination of Soils Containing Fission Products, Rep. COO-414-18, Ohio Agricultural Research and Development Centre, Wooster, OH (1972).
[84] SCHUFTE, J.A., Soil stripping for removal of strontium-90, Texas J. Sci. **13** (1) (March 1961) 3-6.
[85] ALEKSAKHIN, R.M., TIKHOMIROV, F.A., Radionuclide Migration in Forest Biogeocenoses in Radioecology (KLECHKOVSKII, V.M., et al., Eds) (translation published by Wiley, New York (1971)).
[86] PRITCHETT, W.L., Properties and Management of Forest Soils, Wiley, New York (1979).
[87] MATTSSON, L., Long-term Effects of N Fertilizer on Crops and Soils, Swedish University of Agricultural Science, Uppsala, Sweden (1987).
[88] MELIN, J., Turnover and Distribution of Fertilizer Nitrogen in Three Coniferous Ecosystems in Central Sweden, Swedish University of Agricultural Sciences, Uppsala, Sweden (1986).
[89] EDGINGTON, D.N., ROBBINS, J.A., "The behaviour of plutonium and other long-lived radionuclides in Lake Michigan", Impacts of Nuclear Releases into the Aquatic Environment (Proc. Symp. Otarieni, 1975), IAEA, Vienna (1975).
[90] CARLSSON, S., A model for the movement and loss of ^{137}Cs in a small watershed, Health Phys. **34** (1978) 33-37.
[91] TRUSOV, A.G., et al., "The behaviour of ^{90}Sr and ^{137}Cs in the waters of the Baltic Sea", Impacts of Nuclear Releases into the Aquatic Environment (Proc. Symp. Otarieni, 1975), IAEA, Vienna (1979) 133.
[92] PILLAI, K.C., DEY, N.N., KOTHARI, M.B.U., "Behaviour of discharged radionuclides from fuel reprocessing operations in the aquatic environment of Bombay Harbour Bay", Impacts of Nuclear Releases into the Aquatic Environment (Proc. Symp. Otaniemi, 1975), IAEA, Vienna (1975) 277.
[93] FOWLER, S.W., et al., Rapid removal of Chernobyl fallout from Mediterranean surface waters by biological activity, Nature (London) **329** (1987) 56-58.
[94] MOFFETT, D., personal communication, Eldorado Resources Limited, Ottawa, Canada.
[95] UNITED STATES DEPARTMENT OF ENERGY, Uranium Mill Tailings Project, Remedial Actions at the Former Vitro Chemical Company Site, Final Environmental Impact Statement, Rep. DOE/E1S-0099 Volume 1, Salt Lake City, UT (July 1984).
[96] INTERNATIONAL ATOMIC ENERGY AGENCY, Design, Construction, Operation, Shutdown and Surveillance of Repositories for Solid Radioactive Wastes in Shallow Ground, Safety Series No. 63, IAEA, Vienna (1984).
[97] JOHNSON, T.M., et al., A Study of Trench Covers to Minimize Infiltration at Waste Disposal Sites, Rep. NUREG/CR-2478, Illinois State Geological Survey, Urbana, IL (1982).

[98] UNITED STATES DEPARTMENT OF ENERGY, Remedial Action Plan and Site Conceptual Design for Stabilization of the Inactive Uranium Mill Tailings Site at Shiprock, New Mexico, Rep. UMTRA-DOE/AL-050504.0039, USDOE, Washington, DC (1985).

[99] UNITED STATES DEPARTMENT OF ENERGY, Remedial Action Plan for Stabilization of the Inactive Uranium Mill Tailings Site at Canonsburg, Pennsylvania, Rep. UMTRA-DOE/AL-140, USDOE (October 1983).

[100] UNITED STATES DEPARTMENT OF ENERGY, unpublished data, 1987.

[101] INTERNATIONAL ATOMIC ENERGY AGENCY, Investigation for Repositories for Solid Radioactive Waste in Shallow Ground, Technical Reports Series No. 216, IAEA, Vienna (1982).

[102] INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Protection Procedures, Safety Series No. 38, IAEA, Vienna (1973).

[103] INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Protection During Operation of Nuclear Power Plants, Safety Series No. 50-SG-O5, IAEA, Vienna (1983).

[104] INTERNATIONAL ATOMIC ENERGY AGENCY, Basic Safety Standards for Radiation Protection: 1982 Edition, Safety Series No. 9, IAEA, Vienna (1982).

[105] INTERNATIONAL ATOMIC ENERGY AGENCY, Basic Requirements for Personnel Monitoring: 1980 Edition, Safety Series No. 14, IAEA, Vienna (1980).

[106] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Publication 26, Pergamon Press, Oxford and New York (1977).

[107] INTERNATIONAL ATOMIC ENERGY AGENCY, Basic Principles for Occupational Radiation Monitoring, Safety Series No. 84, IAEA, Vienna (1987).

[108] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Limits for Intakes of Radionuclides by Workers, Publication 3, Pergamon Press, Oxford and New York (1979–82).

[109] INTERNATIONAL ATOMIC ENERGY AGENCY, Summary Report on the Post-Accident Meeting on the Chernobyl Accident, Safety Series No. 75-INSAG-1, IAEA, Vienna (1986).

[110] USSR STATE COMMITTEE ON THE UTILIZATION OF ATOMIC ENERGY, The Accident at the Chernobyl Nuclear Power Plant and its Consequences, Working documents for the post-accident review meeting held in Vienna, August 1986, Parts 1 and 2.

[111] IL'IN, L.A., PAVLOVSKIJ, O.A., "Radiological consequences of the Chernobyl accident in the Soviet Union and measures taken to mitigate their impact", Nuclear Power Performance and Safety (Proc. Conf. Vienna, 1987), Vol. 3, IAEA, Vienna (1988) 149.

[112] ASMOLOV, V.G., et al., "The accident at the Chernobyl nuclear power plant: One year after", Nuclear Power Performance and Safety (Proc. Conf. Vienna, 1987), Vol. 3, IAEA, Vienna (1988) 103.

[113] VARLEY, J., Report from Chernobyl, Nucl. Eng. Int. (March 1988) 18–22.

[114] ARKHYPOV, M., Interview in News from Ukraine, No. 19 (May 1987) 955.

[115] YURCHENKO, Yu.F., "Assessment of the effectiveness of mechanical decontamination technologies and technical devices used at the damaged unit of the Chernobyl nuclear power plant", Nuclear Power Performance and Safety (Proc. Conf. Vienna, 1987), Vol. 5, IAEA, Vienna (1988) 161.

[116] ADAMOV, Yc.O., et al., "Development of robotic systems for nuclear applications including emergencies", paper presented at American Nucl. Soc., Int. Mtg on Remote Systems and Robotics in Hostile Environments, Pasco, WA, March–April 1987.

[117] YURCHENKO, Yu.F., "The use of robotic machinery with atomic-energy installations under extreme conditions", ibid.

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