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Technologies for remediation of radioactively contaminated sites

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FOREWORD

In response to the needs of its Member States in dealing with the problems of radioactive contamination in the environment, the International Atomic Energy Agency (IAEA) has established an Environmental Restoration Project. The principal aspects of current IAEA efforts in this area include (1) gathering information and data, performing analyses, and publishing technical summaries, guides, reports and documents on key technical aspects of environmental restoration; (2) conducting a Co-ordinated Research Project in Environmental Restoration; and (3) contributing expert assistance and co-ordinating technical activities for the IAEA's technical co-operation projects for the rehabilitation of radioactively contaminated sites. Included in the information and data gathering effort is a survey of radioactively contaminated sites in the current membership of the IAEA (127 Member States) and development of an international registry.

This TECDOC focuses on the available technologies for cleanup and remediation of radioactively contaminated sites. In parallel to this effort, the IAEA has conducted activities in related areas which have been reported in companion reports dealing with (1) the characterization of radioactively contaminated sites for remediation purposes and (2) important factors to be considered in formulating a strategy for environmental restoration. Additionally, complementary activities are nearing completion in two other areas, namely, planning and management options for cleanup of contaminated groundwater, and post-restoration monitoring of decommissioned sites to ensure compliance with cleanup criteria.

The focus of this report is on radioactive contamination of soils, waters, structures and biota that may have a hazard potential for people. It is hoped that this report will serve as an important source of information on technologies that can be usefully applied to contaminated sites for environmental cleanup and remediation purposes, including evaluations of efficiency, under what conditions and how the technologies are used, scale of the problems, states of development of individual techniques, and representative experiences in various Member States.

The initial draft of this report was prepared in May 1995 with the assistance of experts from Belgium, the Russian Federation and the United Kingdom. A Technical Committee Meeting (TCM) was convened in Vienna in March 1996 to review and revise the initial draft report. Representatives of fourteen Member States participated in this TCM. A final consultants meeting was held in Vienna in November 1996 to prepare a final revision and recommendations for this task. Experts from Australia, Canada, the Russian Federation, the United Kingdom and the United States of America participated in this meeting. The Scientific Secretary responsible for the two consultants meetings and the TCM was D.E. Clark, Division of Nuclear Fuel Cycle and Waste Technology. The report was finalized for publication by D. Stritzke from the same Division.

CONTENTS

1. INTRODUCTION

1.1. GENERAL

To address the growing concerns for the environmental restoration of radioactively contaminated sites, the IAEA has initiated an Environmental Restoration Project with the objective to collect and disseminate information on, and to support development of:

(a) management techniques for planning and implementing environmental restoration activities; and
(b) review of available technologies for remediation of radioactively contaminated sites.

In the near term (until 2000), these objectives will be met through performing the following tasks:

- Gathering information and data on key technical aspects of environmental restoration.
- Publishing technical reports on factors for formulating a strategy for environmental restoration; characterization/monitoring of radioactively contaminated sites, and remediation technologies for radioactively contaminated sites (including treatment methodologies for soil and groundwater).
- Conducting a co-ordinated research programme focusing on site characterization techniques.
- Performing technical co-operation activities with Member States to assist in the remediation of radioactively contaminated sites.
- Developing an international directory of radioactively contaminated sites.

Based on the International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources [1], the IAEA published a report on application of radiation protection principles to the cleanup of radioactively contaminated areas [2], which aims to establish an approach to developing radiological criteria for cleanup and recommends ranges of generally applicable numerical values.

Within a technical co-operation project on planning for environmental restoration of radioactively contaminated sites in central and eastern Europe, a discussion was held on characterization, technologies and planning for environmental restoration of sites in the former USSR and in some east European countries [3]. A subsequent report expands on environmental restoration of uranium mining and milling sites in eastern Europe [4]. A TECDOC on Characterization of Radioactively Contaminated Sites for Remediation Purposes discusses various approaches used to determine the extent of contamination to support remediation activities [5].

1.2. OBJECTIVES

The objectives of this report are to provide Member States with guidance on criteria for selecting technologies, with information about commercially available technologies, trends in technology developments, and case examples of environmental characterization and remediation. Early in the 1990s it was recognized that environmental restoration technologies should be viewed as a stimulus, rather than an obstacle, to economic revitalization, and that preventing environmental degradation is fundamental to sustainable development [6–10].

The present report is to be consulted in reference to other reports published by the IAEA or other organizations, institutes, programmes, and so on. The report is intended to assist Member

States in planning and implementing the control and remediation of radioactively contaminated environments through systematic presentation of the data on the world experience and ideas in environmental restoration technologies. Specifically, it should serve all those involved in planning, management and decision making on radioactively contaminated sites requiring some remediation action, but also regulatory authorities responsible for licensing of remediation activities and releasing remediated sites. Governmental organizations may benefit from the report in their policy-making decisions. It is assumed that the public will have an interest in available technologies for remediation purposes.

1.3. SCOPE

This report presents particulars on environmental restoration technologies (control and treatment) which can be applied to land based, radioactively contaminated sites. The media considered include soils, groundwater, surface water, sediments, air, and terrestrial and aquatic vegetation. Beyond the scope is the marine environment radioactively contaminated as a result of nuclear testing, accidents, and former sea dumping practices. Moreover, this report does not specifically address environmental contamination from uranium mining and milling tailings.

The technologies addressed in this report can be categorized as follows:

(1) self-attenuation (natural restoration),
(2) in situ treatment,
(3) removal of contamination,
(4) ex situ treatment, and
(5) transportation and final disposal.

It is also important to recognize that many of the in situ treatment processes are used in conjunction with subsurface access technologies, and therefore, descriptions of these technologies are provided as necessary.

Although technologies related to site characterization and monitoring are integral to site remediation, descriptions of such techniques and technologies can be found elsewhere in the abundant published literature on environmental restoration (see, for example Refs [5, 8]).

1.4. STRUCTURE

The present report is divided into 11 Sections. Section 2 provides background information about, and a general approach to remediation of radioactively contaminated sites. Discussion on technology evaluation is presented in Section 3, and basic information on the natural restoration process is contained in Section 4.

The following sections provide detailed information on in situ remediation technologies (Section 5), removal technologies (Section 6), and ex situ treatment (Section 7). Transportation and disposal issues are dealt with in Section 8. Sections 9 and 10 describe development trends in remediation technologies and in human resources. The report is completed with a summary and conclusions (Section 11).

The appendix provides some guidance for the selection of a preferred remediation technology. Attached are also two annexes giving examples of remediation experience in Australia and Canada.

2. GENERAL APPROACH TO THE REMEDIATION OF RADIOACTIVELY CONTAMINATED SITES

2.1. BACKGROUND INFORMATION

There is a common understanding by governments and communities, of the urgency, complexity and social significance of the problems associated with radioactively contaminated sites. Although the actual magnitude of these problems may be relatively minor compared with other worldwide issues, care must be taken to ensure that the sensitivity and importance placed on these problems by the public are not ignored. A great effort is required to organize the remediation work to best utilize available resources and to give greatest advantage to technology research and development.

Considerable contamination of air, soils, water, vegetation, and structures (e.g., buildings, roads, etc.) has occurred due to:

(1) The fabrication and testing of nuclear weapons (see Annex I);
(2) Extraction and processing of ores;
(3) Old practices in the use of radionuclides and in waste management (see Annex II); and
(4) Accidents involving radionuclides.

The principal contaminants of concern are those of the naturally occurring uranium and thorium series and man-made radionuclides (e.g., ^{60}Co, ^{137}Cs, ^{90}Sr, ^{239}Pu, ^{241}Am, and others). The primary public health threats from these radioactive elements are through inhalation, external whole body exposure to gamma radiation; and ingestion of radionuclides through consumption of food and water.

As a result of such contamination, several countries have initiated programmes to assess and remediate radioactively-contaminated sites. Significant resources are being expended worldwide for the purpose of identifying and managing the problem, and assisting necessary remediation.

In connection with technologies applicable for remediation of radioactively contaminated sites, much experience has been gained over the past several years in the use of control and treatment technologies, applied to different configurations and types of contaminated sites. The USA and the Russian Federation (former USSR) have conducted environmental restoration activities for several decades and a great deal of experience has accrued in the use of various technologies. Based on this experience, it is possible to provide Member States with information on technologies currently in use in actual restoration projects.

Although in many cases available technologies are adequate for cleanup, it has been recognized that many techniques and technologies, applied before in a routine weapons production or nuclear fuel cycle practices for decontamination purposes, may be too costly to implement on a large scale and/or may be inadequate to address the magnitude and combinations of contamination problems. The present report contains information on applicable technologies, including those which are innovative, and technologies which may be important for use in the future.

2.2. CONTAMINATION SOURCES

Radioactive contamination can result from various sources. Examples are:

2.2.1. Fabrication and testing of nuclear weapons

Operations and disposal practices associated with nuclear weapons materials production since the 1940s have resulted in considerable contamination of soils, water, and other media [11]. For example, radioactive liquid wastes, sometimes mixed with other chemicals, were commonly disposed directly to the ground or into surface water bodies. Liquid waste was sometimes placed in containers (e.g., metal drums) and subsequently buried, resulting in leakage into the soils. Radioactive solid wastes (e.g., contaminated machinery, clothing, etc.) were commonly buried directly in trenches. These disposal practices led to serious environmental problems which require urgent and well grounded remediation measures.

Radionuclides produced by nuclear weapons testing comprise a large source of man-made radioactivity dispersed into the Earth's environment. Nuclear explosives have been detonated above the ground, on the surface, and below ground for military and quasi-industrial purposes. Examples of resulting contamination from this type of activity can be found, associated with test locations in the South Pacific at the Atolls of Mururoa and Fangataufa (French Polynesia); Novaya Zemlya (Russia); Semipalatinsk [12, 13] (Republic of Kazakhstan); Maralinga (Australia, see Annex I); and the Nevada Test Site (USA).

2.2.2. Extraction and processing of ores

Residues from the production of phosphoric acid and various phosphates may also cause contamination to the environment. Derived from naturally-occurring phosphate bearing ores, the residue can contain Ra and Th and their daughters. In some cases, the residues from the processing of such ores have been used in foundations for roadways and buildings or have just been dumped into spoil heaps. The dumping of phosphogypsum on the near surface, as well as the direct discharge of phosphogypsum into rivers, estuaries, and coastal waters, are sources of increased concentration of naturally occurring radionuclides in the affected areas.

Mining and processing activities may also result in radioactive contamination of areas accessible to the public. For example, uranium-bearing waste from the Bulgarian copper mine "Rosen" was dumped into the Black Sea resulting in contamination of the Bay of Vromos near Burgas [14]. Another example can be found associated with copper mining in Germany, which has caused environmental contamination with ^{210}Po and ^{210}Pb [15]. Wastes from ore mines may also inadvertently be used as road and building materials.

Elevated levels of ^{226}Ra have been found in wastewater from coal mining and oil extraction activities but until recently, these levels have been ignored. Upon its release from the mine, this wastewater is usually discharged into streams or sedimentation ponds. Once released into a stream or river, the ^{226}Ra may quickly dilute, but precautions must be made if public access is available an area directly after the release before adequate dilution occurs. Within sedimentation ponds, ^{226}Ra may precipitate out and may be found in sediments and along the banks of outlet channels.

The combustion of coal for electricity generation, smelting processes, and residential and area heating may lead to the release and dispersion of radium in the environment. Of the amount of ^{226}Ra found in coal (a few tens kBq/kg), most of this will be contained in the ash (fly and bottom ash) and disposed of or used in construction; the remainder will be released as atmospheric emissions, as gases or very fine particles.

2.2.3. Old practices in the use of radionuclides and in waste management

Contamination of the environment has resulted from manufacturing processes associated with former luminising workshops, which primarily used ^{226}Ra to make luminous dials for aircraft and military vehicle instruments, as well as clocks. Residual contamination has also been found within the immediate environment (e.g., in unregistered burial sites) of luminising workshops, at military establishments, and scrap yards. Some contamination has also resulted at facilities using ^{3}H as the luminising source.

Contamination of the environment may also be caused as a result of the collection, processing, storage and disposal of wastes associated with the use of radioactive isotopes for industrial, research and medical applications [16]. In some cases medical or research activities may generate biological radioactive wastes which can lead to potential contamination of the environment [17]. This can include solid, liquid or gaseous wastes.

2.2.4. Accidents involving radionuclides

There have been several major accidents resulting in significant dispersion of radioactive substances. Examples are the 1957 waste tank explosion at Chelyabinsk in Russia [18]; the 1957 Windscale event in the United Kingdom; and the more recent 1986 Chernobyl event in the Ukraine [19]. Other examples of accidental releases include those associated with military exercises such as air plane crashes, as the 1966 incident in Palomares, Spain [20] or in Greenland in 1968 [21], or nuclear submarine incidents like the 1985 accidental release during refueling in Chazhma Bay, Russia [22].

Further types of accidental releases include leaks from tanks, process piping and active waste storage facilities. In addition, localized contamination associated with the loss of radioactive materials during transportation (e.g., along railroad tracks) has been found in many places in the Ukraine [23].

Another example of accidental release is where radiation sources have been lost, stolen or discarded. Since 1962, reported accidents with sealed radiation sources have resulted in 21 fatalities among members of the general public. Moreover, significant expenditure has been involved for the monitoring and cleanup costs associated with the accidents (e.g., 1987 accident in Goiânia, Brazil, involving a ^{137}Cs radiotherapy source [24]).

2.3. MAJOR STEPS IN REMEDIATION PROGRAMME MANAGEMENT

This report deals with technologies used in environmental remediation programmes, not with emergency responses to the release of radioactive materials. In contrast to pre-existing situations of environmental contamination, emergency responses have a different character. Immediately after occurrence of emergency conditions, attention is paid first to the safety of the affected population and to the actions needed to control the accident. Implementation of remediation should be based on sound principles of project management and the ALARA (*as low as reasonably achievable*) radiation protection principles formulated in the IAEA Basic Safety Standards [1]. Only following the completion of all necessary measures, a remediation programme can be considered.

Major steps in the management of a remediation programme are outlined below.

2.3.1. Planning for remediation

Environmental remediation should commence with a planning stage. Matters which should be considered first, i.e., at the very beginning of the planning stage, should include the following:

- potential human health and ecological impacts;
- likely permanence of adverse effect of contamination;
- potential for spread of contamination;
- public perception and response to the problem;
- established radiological and other criteria;
- potential for transboundary effects;
- availability of technological solutions and resources, and
- financial capability.

The preparation of a programme plan is linked to a number of other activities. The general elements of an actual environmental restoration programme are as follows:

- preparing the programme plan;
- conducting site characterization;
- establishing remediation criteria;
- selecting remediation approach;
- implementing remediation activities;
- conducting post-restoration activities;
- considering special aspects.

Each of these elements requires pre-planning. It is helpful to prepare reports which detail all the supporting activities related to these elements before significant levels of funds and efforts are committed. The preparation of this programme plan will usually require several iterations. A number of preliminary choices or strategic decisions will be taken as the plan is developing. Each supporting element is discussed in the sections below.

2.3.2. Site characterization

Site characterization is needed to provide sufficient data to take early strategic decisions on the likely environmental remediation activities. An environmental baseline and a profile of the contamination will consider the following aspects:

- characteristics, distribution, and extent of radioactive constituents or contamination sources, as well as the potential for future releases of constituents;
- risks associated with exposure of humans and the environment to the radioactive constituents, and
- where appropriate, transport of radioactive constituents in groundwater and hydraulically-connected surface water, as well as any other pathways which may lead to exposure of workers and the population.

The source characterization should include both waste characterization and facility or site characterization, and should provide reliable estimates of the release rates of radioactive constituents as well as constituent distribution. For rural zones, the transport of the constituents from the soil into the vegetation should also be measured or estimated. An IAEA-TECDOC [25] provides general information on the characterization of radioactively contaminated sites for remediation purposes.

2.3.3. Remediation criteria

A remediation programme should have clearly expressed objectives. If the remediation is justified and any cleanup action optimized, criteria are needed to target remediation activities, to assess performance as the work proceeds, and to verify that the remediation has been achieved at its conclusion. These criteria may be expressed in terms of the residual dose, i.e., the projected dose from the future use of the remediated site, or in terms of concentration limits from which the residual dose, through a pathway analysis, can be calculated. Where necessary, re-entry criteria may be established by which it can be decided whether to allow the return of the population and/or reuse of the land for agriculture, and so on.

It is beyond the scope of this report to give detailed guidance on the development of such criteria and for more detailed information, the reader is referred to a recent IAEA publication dealing with this specialized task [2].

2.3.4. Remediation strategy

During or after the preliminary site characterization, an engineering study should be conducted to develop remediation options which address the specific contaminant problem and are aimed to reduce radiological and chemical exposure. Options will include engineering approaches and associated technologies. A preliminary selection of options may be made based on several factors including future land use, technical and institutional considerations, public acceptability, cost, regulatory requirements, etc. The choice of a particular technology over others is discussed in Section 3.

A further focused investigation of one or more particular method(s) may also be conducted; this may include, for example, conducting a bench scale and pilot scale tests of a specific technology. These tests would be designed to collect sufficient information to develop, procure, and operate a full-scale system. Final decision to adopt the preferred remediation action would be made by the appropriate authority. At the national level, the decision making process for environmental restoration may be driven by a number of factors [26].

Once the cleanup criteria are confirmed, the preferred alternative should be selected, taking into account future land use constraints, if any, and the need for institutional control.

2.3.5. Implementing remediation actions

The implementation of remediation actions includes: procurement of the selected technology; preparation of the site; development of a health and safety plan; development of operations procedures; staff selection and training; completion of site cleanup; verification; waste disposal; and release of the site for any future use.

At the completion of remediation activities, the site will meet the remediation objectives set at the outset as demonstrated in final verification activities. Long term monitoring may be necessary. Quality assurance protocols will have been applied to all programme activities.

2.3.6. Conducting post-remediation activities

Once remediation activities have been completed and verified, the remediated site can be released for restricted or unrestricted use. However, in most cases it is necessary to impose certain post-remediation activities on the area of concern. These activities will vary in comprehensiveness and duration according to the degree of remediation that has been achieved.

If institutional control has been seen as necessary, then post remedial activities will occur in a controlled context and, normally, will include the following:

- monitoring the long term stability and performance of barriers which isolate or contain residual radioactively contaminated materials;
- monitoring environmental indicators within and down gradient of the remediated site;
- maintenance of barriers and other protection systems;
- prevention of intrusion;
- adherence to licensing conditions that may have been imposed;
- regulation and administration of administrative controls, and
- assembly, distribution, and safekeeping of all project and post-remediation period data, analyses, and records.

2.4. SPECIAL CONSIDERATIONS

The general approach to remediation of radioactively contaminated sites may require special adaptation to address sites covering very large surface areas, or those which are deep and difficult to access. Small localized sites may benefit from removal or isolation approaches which are not feasible for very large sites. In addition, rigorous quality assurance techniques may be very important to demonstrating success of these projects as remediation criteria approach environmental background values. Each of these special considerations is addressed in the sections below.

2.4.1. Remediation of areas of extensive surface contamination

Radioactive contamination of the environment, such as caused by nuclear explosives testing, or nuclear accidents resulting in environmental dispersion, can cover surface areas of hundreds of square kilometers. These areas may include urban areas (roofs, walls, streets, yards), agricultural and open areas (crop lands, grasslands, parks) and forested regions (undeveloped, forest product areas).

For example, in 1967, 160 km/h winds dispersed radioactive silts from the dried up Lake Karachai at Mayak, Russia over a region of approximately 3000 km^2 (measured: 1000 km^2 at contamination level >7.4×10^{10} Bq $^{90}Sr/km^2$ and 2000 km^2 at contamination level >3.7×10^9 Bq $^{90}Sr/km^2$) [18]. It is estimated that approximately 2×10^{13} Bq of radionuclides (principally ^{90}Sr and ^{137}Cs) were spread over a distance of 75 km during this event. Also, years after the Chernobyl reactor accident, deposited radionuclides remain in the top 3 or 4 cm of the soil of fields in a wide zone around this site.

Although contamination for such events is largely spread over a large area, the radionuclides can be redistributed both laterally and vertically with time. For example, rainfall may assist in moving the contaminants into deeper sections of the soil and potentially into the groundwater. Runoff or flooding can also redistribute the contaminants thus contaminating river flood plains, or causing accumulation of radionuclides behind engineered structures such as dams. Wind may also spread contamination.

The cleanup associated with this type of contamination can itself result in secondary radioactive waste streams which may be difficult or impractical to recover and process further. For example, the following waste types requiring further management and disposal may be generated during remediation or by other activities occurring in the contaminated zone:

radioactively contaminated municipal sanitary wastes; sludge arising from waste water treatment; radioactively contaminated ash from domestic heating facilities that use radioactively contaminated firewood and peat; and radioactively contaminated dredged soils.

The selection of the methods to be used to clean up an area must consider 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 may be required. The methods selected should prevent contaminants from entering the food chain and should 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 large areas and the subsequent need to dispose of the wastes.

2.4.1.1. Agricultural and forested zones

For radioactively contaminated agricultural areas, selected technology must provide in situ, effective and economical remediation, as well as ecological safety and respect of the environment. In some cases, they must allow the utilization of the remediated areas for agricultural production. Some technologies such as in situ bioremediation and land farming have already been demonstrated but need further development and improvements for optimal application. Past experience in remediation of forests includes the decontamination of wood cuttings, as well as measures to preserve the forest while radionuclide decay occurs (e.g. protecting the forests from pests and diseases; improving fire-protection capabilities; and so on).

Past experience in the remediation of agricultural areas, such as found in Belarus, Russia and the Ukraine, has included the implementation of the following activities:

- institutional controls (i.e. restricting living and economic activities of the inhabitants;
- self-cleaning processes;
- containing runoff from radioactively contaminated flood plains;
- deep plowing arable lands to remove contamination from the surface and the root zone;
- promoting natural or introduced vegetation;
- using potassium and phosphorous fertilizers;
- selectively separating the radionuclides from the soil matrix;
- removing the vegetation and/or top layer of soil containing most of the contaminants;
- using uncontaminated feed for cattle and poultry, and
- adding natural sorbents or substances to animals diets in order to bind ^{137}Cs so, when eaten, the radionuclide will not be absorbed into animal flesh.

A range of techniques have also been tested after the Chernobyl accident under an international decontamination programme [27, 28].

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 radioactively contaminated soils and vegetation is an important factor in selecting the proper method. For example, if the disposal area is at a long distance from the wastes, transportation costs could exceed all other costs if the layer removal technique was used.

2.4.1.2. Urban zones

In urban zones, consideration must be given to people occupying the areas as well as to their personal health and safety. The nature of land uses, structures and utility systems present are also considerations.

A large variety of decontamination techniques and chemical mixtures have been developed over the years to assist in removing contamination from various surfaces. These were developed in association with nuclear facility decommissioning or for facilities used in support of environmental remediation. A decontamination process must be selected on the basis of site specific considerations taking into account a wide variety of parameters such as the following:

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

Other factors which are important in selecting the method and equipment, include the following:

- 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; and
- the amount of work involved and the difficulty in decontaminating the equipment used for the cleanup if it is to be reused.

Cleaning of radioactively contaminated roads and pavements can be done using fairly simple techniques such as motorized and vacuum sweeping, road planing and grinding, as well as application of decontaminating coatings. These techniques are in general readily available even in less developed countries. The choice on what technique will/should be used depends on the time between the accident and the cleanup operation, the way the material is deposited (wet or dry), the particle size, and so on.

Motorized sweeping and vacuum sweeping

Motorized road sweepers and vacuum sweepers are used for cleaning roads and parking areas; hence such equipment should be readily available. Measures should be taken to avoid the generation of secondary contamination by re-suspension of the original contamination. Vacuum sweeping is the more efficacious procedure since it not only cleans the surface but also picks up the displaced contamination more effectively. However, the removal efficiency for small radioactively contaminated particles, typical of those from a reactor accident, is likely to be low for these types of equipment.

Even if cleanup efficiencies are low, 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. 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). One should be aware that collecting dust containing a very large concentration of plutonium may cause a criticality problem.

Road planing/grinding

The removal of a fairly precise defined layer, typically 1-3 cm from the surface of asphalt or concrete roads, using commercial equipment is a common procedure during road resurfacing. Both cold planing for asphalt and concrete and hot planing for asphalt are used. The planers cut the surface with hard bits at speeds up to 4.5 km/h 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 radioactively contaminated material from a road surface has not been reported, it is likely that very effective decontamination could be achieved. Costs for cleaning radioactively contaminated pavements would be higher than for normal road work since measures to keep radioactively contaminated dust from spreading would be required (e.g., wetting surfaces and spraying the rubble). Decontamination of the equipment would also add to the overall project cost.

Road planers or general road bed graders, using different types of cutters and direct loading into trucks, can also be applied in areas with fairly flat surfaces for the removal of layers of earth (see Sections 5.4.2 and 7.2).

A large number of hand held and large commercial grinders are available for removing thin layers of radioactively contaminated material from the surface of concrete. Some of the technology employed is an extension of highway grinding processes used in many countries since the 1970s.

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 due to the magnitude of the problem.

Decontaminating coatings

Decontaminating clayey coatings (DCC) on the base of natural clay and clayey minerals are effective and cheap sorbents. They can be applied easily and quickly to large areas and require minimum equipment and personnel. The major advantage of DCCs is that their removal is performed by the standard equipment and do not require manual labor. The mechanism of decontamination involved adhesion, sorption and ion exchange processes. These unique properties of DCCs, or composition based on natural clinoptilolite, allow to remove contaminants from the cracks, clearances, junctions and even from macro pores. The decontamination factor depends on the properties of surface and contaminants, and ranges from 2 to 5.

2.4.2. Remediation of areas of localized contamination

Localized accidental spills and intentional dumping, have resulted in contamination in soils to extensive depths, in groundwater, and within surface waters. Waste forms can be in both liquid (surface and groundwater) and solid (solid wastes and radioactively contaminated soils) form. For example, in the past, liquid radioactive effluent has been directly disposed to the soil, injected directly into the groundwater, or disposed to natural surface drainage. Some holding tanks for high-level radioactive wastes have leaked into the soil. Solid wastes from nuclear weapons processing or medical applications were commonly buried directly into soil trenches, without sufficient packaging. Moving plumes of contamination underground, which may be many metres below the surface, are difficult to detect, monitor and access, in order to conduct remedial operations.

When contamination is due to leakage of tanks or incidents related to confined storage, the radionuclide concentration is high but the contaminated zone is generally relatively limited. In some cases, however, transport to and by groundwater led to large volumes of radioactively contaminated soils and undergroundwaters.

When contamination is due to intentional dumping and injection, both contaminated volumes and contamination levels can be very extensive. In some cases, the natural water flow pattern has been destroyed by other activities, leading to short-circuiting of the channel and an accelerated dispersion of the contaminants. The Techa River, Russia [29] is a typical example. Another example is the TOMSK 7 incident in Sibiria [30].

Although the remediation of these sites is probably more complicated and more expensive on a per unit volume basis than for the sites considered previously in this chapter, the approach and the process leading to a decision are not fundamentally different. Nevertheless, one must consider the importance of the cost factor during the evaluation of the necessity for remediation.

2.4.3. Remediation of radioactively contaminated sites from extraction and processing of ores

Another potentially significant area of radioactive remediation activities is found in the mining field [31, 32]. Natural radionuclides may be contained in non-radioactive ores and, depending on the chemical and physical properties of the elements in the ore, may be enriched during the smelting process and later found in products or in residues (slag and other). In these residues, the radionuclides of the decay chain are frequently not in radioactive equilibrium, because the daughter products have shorter half-lives relative to the parent products. Also, flue dust and other air-borne smelting residues found in exhaust air can contain decay products like ^{210}Po and ^{210}Pb.

Site remediation at mining and associated nuclear materials sites include the mines themselves, on-site plants and structures, tailings impoundments, and facilities where mine products are processed, stored or used. The scale of such remedial projects can be large. The methods and technologies used in the remediation and decommissioning of uranium mining and related facilities are dealt with in detail in the relevant IAEA reports [33–35].

2.5. QUALITY ASSURANCE

Ensuring that areas, buildings, materials or equipment being released for reuse comply with release criteria can be very important to the overall remediation effort. Of course, all of this rests on accurate data and analysis. Therefore, an adequate quality assurance of sampling, analysis and remedial practices is of vital importance.

Depending on factors such as future land use, population density, soil type, uniformity of contamination, type of topography and accessibility, and equipment availability, the number of environmental measurements required for verification may vary to a great extent.

Since the number of samples taken during the cleanup operations may be very large, statistical sampling plans are normally developed for various zones to minimize the number of samples required and increase the probability that unacceptable levels of contamination are not missed. Such a sampling plan should be integrated with an appropriate quality control programme. For measurement sets having a large number of samples, the quality control programme, measurement validation function, type of measurement, etc., would be strongly influenced by costs.

Depending on the intended use of a specific type of measurement, differing quality control requirements may be appropriate. For example, less stringent quality control need be applied to initial aerial survey data, since (for various reasons) interpretation of such measurements is difficult and measurements are generally used either for preliminary direction of cleanup or for final checks of cleanup effectiveness on a broad scale only. On the other hand, quality control for final surveys and for sample and laboratory analyses, including sample preparation, are more stringent, since the instruments are capable of good accuracy and the results could be critical for release of sites.

The selection of the appropriate quality control criteria should be performed in advance, based on an evaluation of such factors as the following:

- variation of the parameters being monitored;
- purpose of the particular data set, for example: for final dose estimates or preliminary gamma exposure estimates, and
- the costs of sampling and the funding available.

To control costs and maintain adequate accuracy when quality control for a large number of individual measurements is required, a logical sequence of measurement quality control should be considered in advance. In general, quality control is performed only on a small fraction using expensive laboratory chemical separation analysis. This level of quality control is used only as a final check on the absolute accuracy of well designed field analytical systems, which in turn are used to regularly corroborate inexpensive scan type systems that produce the vast majority of the cleanup measurements.

3. TECHNOLOGY EVALUATION

3.1. GENERAL

The selection of preferred technologies to solve or mitigate an environmental contamination problem requires the consideration of several factors. The selection process for available technologies can follow various routes. This section identifies and discusses factors commonly considered. An example approach to the selection of a preferred restoration technology is provided in the Appendix.

In order to make defensible decisions regarding the selection of the preferred technology, the technology evaluation factors should be treated in an integrated manner. Their consideration in isolation from each other will not address mutually conflicting requirements. For example, increased reduction of the risk posed by a given problem to the health and safety of the public may require considerable expenditures of resources.

The factors to be taken into account include the following:

- the ability of the technology to reduce or avert risk to the health and safety of the public and to the environment (i.e., *performance*);
- the *reliability and maintenance* requirements for the technology;
- the associated *cost* of implementing the technology;
- the *infrastructure* available to support the technology;
- the ease of accessing the technology and associated services (i.e., *availability*);
- the *risk to workers and public safety* during the implementation of the technology;
- the *environmental impacts* of the technology;
- the ability of the technology to meet *regulatory acceptance,* and
- the obtaining of *community acceptance.*

An overview of factors important to the selection of a preferred technology is presented in the following text.

3.2. FACTORS FOR TECHNOLOGY SELECTION

3.2.1. Performance

Several aspects of performance should be reviewed prior to making a selection of the remediation technology. The problems to be solved prior to selection include the following:

Ideally, through the use of the selected technology the required degree of restoration should be achieved. However, in selecting the preferred option, consideration should also be given to the compatibility of the selected technology with other elements of the system and to the likely need for decontamination or decommissioning of the equipment after the end of the remediation work. Another important consideration is the likely generation of a secondary waste stream which may require additional treatment and disposal.

Finally, the time required to complete the cleanup with the technology under consideration should also be evaluated. If it is technology under development, the time until it is available for commercial use should also be taken into account, keeping in mind that, as the development matures, so will cost and schedule estimates.

3.2.2. Reliability and maintenance

Prior to its use in a remediation project, an evaluation of the technology's reliability and versatility should be performed. The frequency and ease of maintaining the equipment and its energy requirements should also be considered. Technologies can vary in their complexity and so can vary the level of skill or training required for operation and maintenance. Another area of concern is whether the technology will function as designed when it is scaled-up.

3.2.3. Cost

When evaluating the potential use of a technology, it is necessary to assess its cost; this should be weighed against the benefits derived from using the technology. For an innovative technology, it may also be necessary to evaluate the developmental costs, including procurement, construction, and licensing. At the completion of the project, it may be necessary to budget for decommissioning costs and legal liability.

3.2.4. Infrastructure

The availability of the infrastructure necessary to support a technology is a key consideration in the evaluation of the usefulness of a technology. Infrastructure includes both the necessary trained labour to operate and control the technology, and the supporting commercial businesses which provide materials and supplies required by the technology. Physical resources and systems such as electric power, access roadways, rail access and disposal or storage facilities, also form part of the infrastructure. When the use of a technology requires the development of supporting infrastructure, this adds to the total costs of the remediation project.

3.2.5. Availability

The commercial availability of the technology should be taken into account. Ideally, the technology is procured 'off the shelf'; however, for some particular reasons, the appropriate technology should be developed first; then the companies which can design, construct, operate and maintain the technology should be contacted.

3.2.6. Risk to workers and public safety

An issue that should receive attention because it could be significant in the selection of particular technologies, is the potential risk to workers applying the technologies.

Consider, for example, the problem of digging up buried waste. An effective and inexpensive risk reduction techniques would be to use standard earth-moving equipment, perhaps with shielding added, rather than hand digging, to exhume the waste. In certain circumstances, even this approach could expose the worker to unacceptable risks. On occasion, the addition of worker safety precautions, such as dust inhalation protection, may serve to increase the relative cost and reduce efficiency of some technologies.

Technology should be evaluated both for its effects on the safety of the onsite worker and the public residing in the vicinity of the radioactively contaminated site. Equipment safety measures (such as automatic shutdown devices) may be needed and should be in place to protect workers and the public. In addition, the potential for worker exposure to hazardous materials and contaminants should be assessed. Information whether the use of the technology has a history of accidents, or routinely releases contaminants should be part of the evaluation.

3.2.7. Environmental impacts

Potential impact of the technology on the various ecosystems (i.e., wildlife, vegetation, air, soil, water or people) should be evaluated. In some cases, more damage may be done from the remediation than from the original status quo. There may also be aesthetic impacts of the technology (i.e., visual impacts, noise) which should be included in the evaluation.

3.2.8. Regulatory acceptance

Technologies must be capable of achieving the objectives of the remediation and must comply with all applicable regulations (i.e. off gas emissions, waste acceptance criteria, etc.). A knowledge of all relevant regulatory requirements is absolutely necessary to complete the evaluation of a given technology.

3.2.9. Community acceptance

The social dimensions of environmental remediation are generally of crucial importance for resolution of these problems. Therefore it is important to achieve public support. This requires an early public input already in the planning phase, adequate information of the public on the technology selection, as well as public endorsement of the selected remediation approach. Technologies and approaches which enhance the likelihood of public acceptance are preferred.

To create an atmosphere conducive to public acceptance the following actions can be considered:

- communication with the public in a deliberate, sincere, and effective manner;
- identification and proposal of areas where restoration measures will yield the greatest public benefit for the money expended;
- undertaking a comparative risk and benefit analysis if available data permits;
- approaching the planning of the restoration programme as a partnership involving all of the affected parties, and
- encouraging members of the public to participate in development of regulatory reports to ensure that their concerns are well understood and addressed at an initial stage.

4. NATURAL REMEDIATION

4.1. GENERAL

The following advice is useful to keep in mind when developing a working strategy for environmental restoration: before recommending a large-scale application of any rehabilitation technique, it is important to know the medium- and long-term intensity of self-restoration for most of the radioactively contaminated territories; it is indeed essential to forecast the radiological situation in the absence of intervention [27].

Natural remediation is the 'zero intervention' option. This only depends on the natural processes of retention (sorption), retardation (physical, chemical and biological), and radioactive decay. Consideration of this option requires modelling and evaluation of contaminant degradation rates and pathways to demonstrate that natural processes will reduce contaminant concentrations below regulatory standards before exposure through various pathways can occur. Sampling should be conducted throughout the process.

'Natural remediation' ought to be considered initially, before any intervention based remediation methods are considered. Natural remediation is the reference base case against which other options (Sections 5 through 7 of this report) should be evaluated.

As stated above, following radioactive contamination of an area, the level of contamination present begins to vary as a result of natural processes. Radioactive decay of radionuclides will diminish the contaminant loading. Calculations show that a noticeable decrease in soil contamination due to decay occurs in about 5–10 years after contamination from fission products. For long lived isotopes such as ^{239}Pu, however, there would not be any significant decrease in activity even after 500 years.

But decay is not the only process occurring in the environment. The self-restoration of sites contaminated with stable compounds (e.g., mining sites) is also well-known. Certain soil types can naturally retain radionuclides, thereby holding them in place while they decay. Weathering, and microbial action transform the chemical state of the radioactive contaminants and modify their solubility and thus their mobility. The lithology of soil forming deposits and the vegetation cover also influence the capability of natural ecosystems to contain the radionuclides.

Not all natural processes result in a diminution of the contaminant(s), however. After the radioactive releases at Chernobyl, the affected soils themselves became an accumulation medium, where both accumulation and prolonged storage of long-lived radionuclides could take place. After the accident, therefore, the radioactively contaminated soil became a secondary source of contaminants. These secondary sources resulted in a further supply of radionuclides to different components of the biosphere, and contaminant levels were found to be rising after an initial fall in level.

It is therefore necessary to have an understanding of the effects of natural remediation processes on the radioactively contaminated site. Observational data and modelling are necessary to determine what likely effects natural remediation will have. As stated previously, these models can then be used to determine if an intervention based technology is more beneficial overall.

4.2. INSTITUTIONAL CONTROLS

Even though remediation technology is not applied directly to the contaminants, there may be a need for certain responses to the presence of contamination. Representative examples of such responses are discussed below.

4.2.1. Notification of the local community

This would have the aim of increasing public awareness of the radioactively contaminated areas, so as to avoid involuntary dose uptake. It is most beneficial in areas where public access is generally limited (e.g., remote region), and where the local population is predisposed towards compliance.

4.2.2. Fencing and/or securing the site

This is the next stage beyond notification. Securing the site aims to minimize dose uptake by preventing intrusion onto the site, whether involuntary or not.

4.2.3. Restricted use of area or goods

This limits the use of the area to certain prescribed activities, whilst preventing activities with a greater potential for dose uptake. For example, use of a site for industrial purposes rather than agricultural, where the main dose pathway is via ingestion of radioactively contaminated foodstuffs. Similarly, goods from the radioactively contaminated zone may be subject to restrictions or institutional controls.

4.2.4. Monitored natural assimilation

In this case the site remains under institutional control. The assimilation of radionuclides is monitored as it progresses, until a point is reached when one of the earlier mentioned forms of control is sufficient.

4.2.5. Delayed (or timed) future intervention

This is a variant of monitored natural assimilation. The difference in this case is that site release is not possible until an intervention based technology has also been used. The future intervention, however, occurs when is more beneficial than at the present. Generally, the need and timing of such future intervention is planned before this variant is adopted.

4.2.6. Mixed strategies

This covers intervention based technologies working in conjunction with on-site natural remediation. These generally operate in tandem over different areas of the site and/or timescales.

With mixed strategies, it should be noted that partial use of natural remediation may have additional benefits. For example, the use of groundwater flows after removal of the contamination source to self-clean a plume of activity comes into this category. The aim of such self cleaning would be to permit the contaminant to be moved to a location where removal is facilitated, and avoid the societal impact associated with more intrusive methods of removal. Finally, having completed a more extensive decontamination of a site, a point is reached where the remaining contamination will be self-cleaning, due to hold-up and attenuation of the remaining contaminants. Natural Remediation therefore provides the final polishing stage of the overall remediation plan..

4.3. SOCIETAL CONSEQUENCES

Because the above responses may be necessary, the use of natural remediation processes is not necessarily an easy or cheap option to employ, as its societal cost may be high. The lost opportunity cost for using site for things such as recreation and agriculture and the cost of long-term monitoring and notification, etc., must be accounted for when choosing this method of cleanup.

The option should be retained when the selection process (see Appendix A) concludes there is no net benefit from technological interventions. The natural restoration option also requires an implementation plan, just as other remediation options (characterization of the site, monitoring during and after remediation phase, confirmation of remedy, and so on).

5. IN SITU REMEDIATION TECHNOLOGIES

In situ remediation technologies for control or treatment of soils and groundwater are increasingly being investigated because they offer the potential for:

- significant cost reduction of cleanup by eliminating or minimizing excavation, transportation, and disposal of wastes;
- reduction of health impacts on workers and the public by minimizing exposure to wastes during excavation and processing;
- significant reduction in ecological impacts, and
- remediation of inaccessible sites, including deep subsurfaces and in, under, and around buildings.

In situ remediation technologies either prevent waste migration through containment, immobilize or fix waste in place, or enhance waste mobility for extraction and treatment.

In situ technologies can be categorized or subdivided into three major groups:

(1) Containment technologies;
(2) Stabilization/immobilization technologies, and
(3) Treatment technologies.

5.1. CONTAINMENT TECHNOLOGIES

Containment technologies aim to prevent exposures by isolating contaminants at the site and obstructing migration to surrounding soils and groundwater. Containment technologies are considered when contaminated materials are to be permanently disposed at a site or as a temporary control measure to prevent the spread of contamination. Containment options are considered when extensive subsurface contamination precludes treatment or excavation of the waste. In general, containment technologies are applicable to all forms and types of waste. Surface caps, cutoff walls, and bottom barriers are the primary forms of containment technologies [36].

5.1.1. Surface caps

Surface caps are essentially horizontal barriers that are placed over a waste site to isolate the waste from water infiltration and natural erosive processes [37, 38]. Capping is part of a closure process in which buried waste, or residual contamination remaining after remedial action has been taken, is isolated to avoid direct contact with receptors and to avoid surface water infiltration, thereby minimizing the generation of leachate [39]. Capping may also be used to control the emission of gases, reduce erosion, attenuate radiation and improve aesthetics. In situations when waste is entirely above the zone of groundwater saturation, a properly designed cap can prevent the entry of water to underlying contaminated materials. Capping is considered to be a standard construction practice and is often performed in conjunction with treatment technologies, groundwater extraction or other containment technologies such as physical or hydraulic barriers. The selection of the cap design and materials depends on the nature of the waste to be covered, the function of the cap, the local climate and hydrogeology, the availability of materials, and the intended use of the capped area. Surface cap designs and materials frequently considered include:

Multilayered caps

Multilayered caps generally consist of an upper vegetative layer, a protective layer to prevent erosion and animal burrowing, a drainage layer, and a barrier or low permeability layer. The layer thicknesses, layer permeabilities, and materials can be varied to meet individual site requirements and performance objectives [40].

Soil/clay caps

Soil and clay caps are constructed by spreading soil/clay over the contaminated area and then compacting the soil/clay layer to achieve a specified permeability [40-43]. The low permeability layer is typically composed of fine-grained natural soils (silts and/or clay) that can achieve a minimum in-place permeability of 1×10^{-7} cm/s. To achieve this design permeability, the soil/clay admixture may be modified with bentonite, lime, cement, or other material. Although the costs of soil/clay covers are relatively low, their long-term effectiveness is limited because of their susceptibility to weathering and breaching by animals and plants. They are also susceptible to cracking in arid climates.

Asphalt and concrete caps

Asphalt caps are single-layered caps composed of bituminous asphalt. Concrete caps are also single layered, and consist of aggregate and cement material mixtures [40, 41]. The design of these caps depends on consideration of settling and weathering effects, and they must be sloped for runoff to minimize infiltration into the contaminated soils below. These caps are expected to be effective in the short-term, but periodic long-term maintenance is required to reduce and/or repair the effects of weathering, cracking, and, in the case of concrete caps, subsidence.

Synthetic membranes

Synthetic membranes, also called flexible membrane liners, are used for capping to reduce or eliminate infiltration of surface water, prevent contaminated soil erosion, and reduce or control odors and dust [43]. Materials typically used for capping operations are polyvinyl chloride, high density polyethylene, very-low-density polyethylene, and hypalon. Different membranes vary with respect to thickness, flexibility, and durability. Selection of the membrane must be based on compatibility of the membrane with specific site conditions, including steepness of slopes, climate, and settlement or subsidence. This technology is well developed, readily available, and considered effective in the short term. However, long term maintenance is difficult, and deterioration is likely to require replacement of the membrane.

Surface sealants/stabilizers

Surface sealants/stabilizers are used to stabilize or cover waste deposits to control erosion, prevent surface water infiltration, provide dust and vapour control and contain contaminated wastes. Bituminous or sulfur membranes can be spray-applied to the site surface to form an impermeable barrier. Soil additives can be used to increase stability and strength, reduce permeability and/or reduce shrinking and swelling behaviour of the soil. Additives include chemical stabilizers and dispersants (e.g., latex emulsions, plastic films), cement, lime and bentonite. These technologies are effective only as short term measures.

5.1.2. Cutoff walls

Cutoff walls are vertical subsurface impermeable barriers designed to direct groundwater flow [44]. They can be used to direct groundwater away from a contaminated site and thus reduce the potential for waste migration, or they can be used to channel waste to a collection or treatment zone. Cutoff walls are effective for preventing lateral migration of contaminants but not downward flow to groundwater. Implementation of cutoff walls is highly dependent on the physical characteristics of the soil (e.g., uniformity, permeability, porosity) and the depth required to control groundwater and contaminant migration (i.e., depth to the confining layer or hydraulically calculated depth based on the depth of contamination). The use of cutoff walls is a standard industry practice. Examples of the different types of cutoff walls used or in development are summarized below.

Bentonite slurry walls

Slurry walls are the most common form of vertical subsurface barrier. Slurry walls are formed by excavation of a vertical trench using the slurry as a drilling fluid and to shore the trench to prevent collapse. The slurry reduces fluid loss into surrounding soils through formation of a filter cake on the trench walls [44]. Slurry walls are often used with capping technologies to fully confine a waste area and to prevent clean water from leaching through the waste. Materials used to construct slurry walls include soil-bentonite and cement-bentonite mixes. Soil-bentonite slurry walls have a wider range of chemical compatibility and lower permeability than cement-bentonite slurry walls, but are less strong and more elastic.

Cement based grout curtains

Cement based grout curtains are vertical barriers formed by pressure injection of grout through pipes or augers that are inserted into the ground with a crane and hammer or drill rig [41, 42]. Grout curtains are generally not as effective in controlling migration flow as slurry walls because gaps may form in the curtain as a result of grout shrinkage during setting. This technology should be avoided in the presence of organic contamination since the organics will inhibit the solidification of the grout.

Sheet piling walls

Sheet piling cutoff walls can be made from a variety of materials including wood, precast concrete, or steel. Steel is most commonly used because wood deteriorates and concrete is more bulky and costly. Sheet pilings are constructed by driving individual sections of interlocking steel sheets into the ground with impact or vibratory hammers to form a thin impermeable barrier. Sheet piling is considered a less permanent measure than slurry walls because of unpredictable wall integrity but may be installed quickly and at lower cost. Sheet piling is a developed technology that could be effective as a short-term measure to enhance containment. Installation is favoured in soil but can be very difficult if not impossible in rocky environments (e.g., old river beds).

Polymer based grout walls

Polymer based grout wall technology involves the development of advanced polymer based materials for tile placement of impermeable, highly durable subsurface cutoff walls. The US Department of Energy is developing and testing superplastified grouts and soil cements that have improved mechanical, physical, and durability properties over those of conventional formulations. The permeabilities of polymer grout walls are two to three orders of magnitude less than soil-bentonite and cement-bentonite slurries. Therefore, the thickness of the barriers can be reduced. Polymer based material grout walls are considered developmental.

Soil freezing

A vertical cryogenic wall is constructed by freezing interstitial water within the soil, forming a barrier to lateral contaminant migration. The soil is frozen by installing steel pipes uniformly along a freeze line. A smaller diameter pipe placed within the steel pipe is used for coolant circulation. The outer pipe serves as a return line. Under arid conditions, performance may be affected by the need to first create full saturation (i.e., near zero porosity) and then maintain this condition under the frozen state. Soil freezing in arid environments is considered an innovative technology [45].

Biological barriers

Bacteria inherently possess a surface layer that serves to aggregate individual microbes into large masses. A vertical subsurface impermeable barrier could be achieved by continuously introducing microbial nutrients into wells that surround the contaminated area. Extensive biomass accumulation is thus encouraged to reduce local hydraulic conductivity. Biological barriers are considered an immature technology [41].

Synthetic membranes

Polymeric geomembranes are primarily semicrystalline plastics and thermoplastics that have a very low permeability to gases, vapours, and liquids. Examples include high-density polyethylene, polyvinyl chloride, and hypalon. The polymeric material should be selected based on its chemical compatibility with the wastes in containment, as well as on design factors such as facility configuration and adjacent components of the containment system. The use of synthetic membranes as vertical impermeable barriers is not a well developed technology [43].

5.1.3. Bottom barriers

Bottom barriers are horizontal subsurface barriers that prevent vertical migration by providing a "floor" of impermeable material beneath the waste [46–48]. Although the concepts are well developed, reliable installation methods have yet to be developed. Installation methods are strongly influence by the physical characteristics of the soil (e.g., uniformity, permeability, porosity) and the depth of contamination. Although the majority of the barrier materials discussed in the previous subsection could be adapted as bottom barriers, some specific examples of bottom barriers are given below.

Grout injection

Grout injection involves introducing an impermeable barrier composed of some kind of grouting material below the contamination, thereby preventing downward movement (Fig. 1). Two emplacement methods are being tested: (1) permeation grouting that uses a slight pressure to inject the grout and takes advantage of the natural porosity of the soil by letting it flow into the soil [49], and (2) jet grouting by mixing that uses a drill and rotates while injecting the grout. This latter method intentionally fractures the soil and intermixes it with the grout. In both of these methods, boreholes are drilled at regular intervals around the waste to a specified depth beneath the contaminated zone. Horizontal drilling techniques are then required for grout injection without disturbing the site. Grout materials that have been tested include ultra fine cements, wax/bentonite mixtures, and a sodium silicate grout. Grout injection is an innovative technology which, although tested, has not been implemented on a large scale.

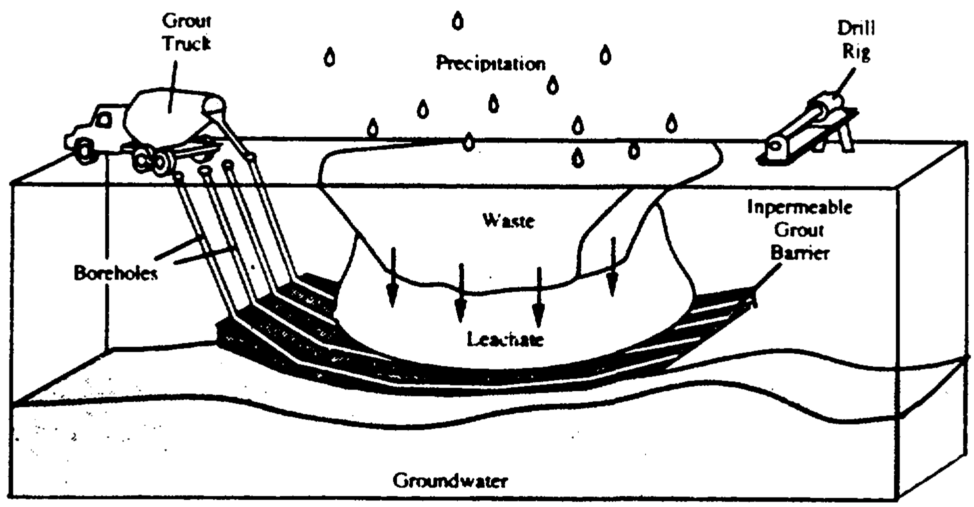

FIG. 1. Containment and stabilization of buried waste (source: DOE/EM-0128P).

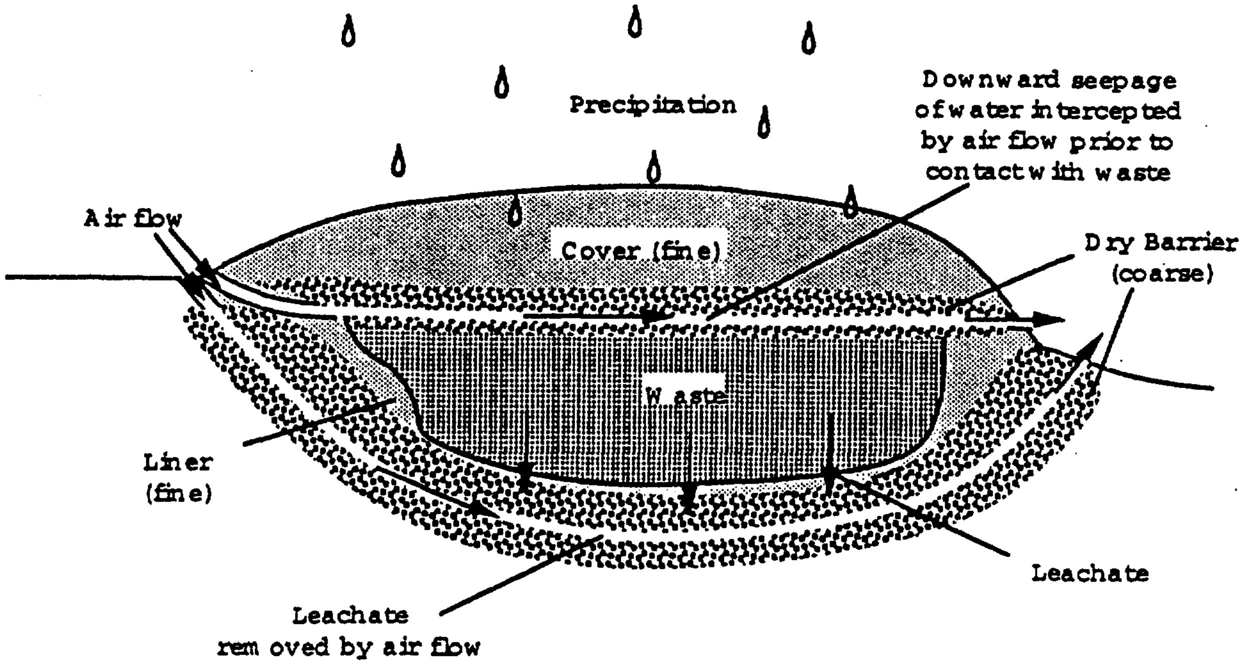

FIG. 2. Dry barriers (source: DOE/EM-0128P).

Dry barriers

Dry barriers can be used in engineered liner systems (1) in which the air-dried layer would be used as a final barrier to prevent leachate movement beyond the zone of contamination and (2) to strip denser-than-air gas-phase constituents as they migrate downward. Air flow through the dry barrier layer beneath the site can be induced with vertical or directional holes to supply and remove air. This technology does not rely on an engineered liner but uses existing heterogeneous soil beneath the site. Dry barriers are considered an immature technology applicable only to arid environments.

Liners

A liner is a layer of material placed beneath a landfill, a liquid impoundment, a plume (of contaminated groundwater), or a surface that prevents waste constituents from migrating out of the waste unit into other areas, particularly groundwater (Fig. 2). A liner is typically designed as one component of a lining system. The different components of a lining system include two or more liners, a leachate collection and removal system (LCRS) between the liners, and, in the case of a landfill, an LCRS above the liners. Design life of liners depends on chemical compatibility with the waste, on physical stability of the constructed facility, biological and environmental stresses, and continued maintenance. Research is lacking on many aspects of liner durability. The most common liner materials are low-permeability soils and polymeric geo-membranes. Low permeability soils include re-compacted native clay and bentonite-amended sands and silts, which inhibit flow by swelling to absorb water or dilute leachate. Polymeric geo-membranes are primarily semicrystalline plastics and thermoplastics that have a very low permeability to gases, vapours and liquids. Examples are high-density polyethylene, polyvinyl chloride, and hypalon. Liner systems are considered to be developed technologies that are effective in preventing vertical migration. The relative costs of these systems are considered to be moderate because of the need for long term maintenance.

Injectable polymeric barriers

This technology involves injecting a latex emulsion and a reactant/coagulant solution through a series of wells into an aquifer [50]. The injected polymer solutions will tend to migrate along preferential flow and highest permeability zones within subsurface formations. Groundwater systems will facilitate mixing of the emulsion and reactant solutions, and the solid coagulant formed from the reaction will effectively block the highly transmissive pathways. This barrier technique is novel because it uses newly formulated barrier material in conjunction with the existing soil structure to form a barrier. It can potentially place a barrier under a site without disturbing the site or generating hazardous air emissions. This technology has not been tested in the field and is considered an extremely immature technology.

5.1.4. Hydraulic control measures

Hydraulic control measures are designed to prevent the spread of contamination by changing hydraulic gradients [49]. The general methods applied to accomplish this include the withdrawal of groundwater through wells (extraction wells) if contamination is deep or through ditches and drains if groundwater is near surface. Cutoff walls as previously noted are also used effectively for groundwater control where contamination and groundwater are near surface. Application of groundwater pumping through extraction wells requires a good understanding of the regional hydrogeologic flow patterns to ensure effective well placement and pumping rates which will be required for effective control. In general, the application of ditch and drain or cutoff wall technologies will be used as a first choice. Where hydraulic control requires extraction of contaminated groundwater, storage and/or treatment of this material maybe required. Applicable treatment technologies are discussed in the following section of this report. These control measures are generally well developed conventional technologies applicable to the containment of all waste forms and types.

Pumping systems

Pumping systems involve groundwater extraction wells and injection wells. Extraction wells are used to withdraw or isolate contaminated groundwater by manipulation of the hydraulic gradient. They are generally used when the contamination is too deep to be reached by ditches and drains or if property ownership or land use and utilities preclude ditch/drain construction. The extraction system design may include a single well for the control of isolated contamination or multiple wells to control a larger more dispersed area of contamination.

Ditches/drains

Ditches and drains include any type of buried conduit equipped with pumps, or below grade trench used to direct and collect contaminated shallow groundwater by gravity flow. Ditches/drains can be used as barriers to prevent contamination or to intercept a contamination plume down-gradient from a source [49]. These technologies are well developed but generally limited to shallow contamination. The cost of installation is expected to be high relative to other subsurface flow control technologies.

5.2. STABILIZATION TECHNOLOGIES

Stabilization technologies reduce the mobility of hazardous substances and contaminants in the environment by trapping them within their host medium or in a stabilized mass. In general, these technologies are designed to do one or more of the following: improve the handling and physical characteristics of the waste, decrease the surface area of the waste mass across which transfer or loss of contaminants can occur, and limit the solubility of the contamination. Considerations important for the selection, design, implementation, and performance of processes and products include waste and site characteristics, management objectives (e.g., leave in place, landfill, or store), regulatory requirements, and economics. Stabilization technologies can generally be group into two major categories which include in situ encapsulation and compaction. Stabilization technologies do not apply to contaminated groundwater.

5.2.1. In situ encapsulation

In situ encapsulation technologies trap or immobilize contaminants by fully encasing the waste in a monolithic structure through the injection of grout or polymers. The target analyse groups for in situ encapsulation technologies are metals and radionuclides. If the waste contains moderate to high concentrations of organics, polymers would need to be used because the organics will inhibit the solidification of grout materials. These technologies are generally well developed.

Grout or polymer injection

Grout or polymer injection is an in situ stabilization/solidification technique involving the injection of grout or polymer into a contaminated zone. The end product of this process is a monolithic block of contaminated material encapsulated in grout. Grout injection is applicable to soils and buried wastes contaminated with heavy metals, semivolatile organic compounds (SVOC), and radionuclides. The technology is well developed and readily available at low cost.

Cement based deep soil mixing

This process mixes soil with a slurry forming a cement-like matrix that immobilizes contaminated soil, increases soil strength, decreases soil permeability, and provides many other geo-technical improvements without having to excavate contaminated soils. Deep-soil mixing uses standard construction equipment with some specialized attachments, consisting of hollow stemmed augers and mixing paddles. During penetration a slurry containing cement based stabilizing agents is injected into the soil through the auger and is blended with the soil. The target contaminant group is inorganics. It also has limited effectiveness against volatile organic compounds (VOCs), SVOCs and pesticides. This technology is well developed and readily available at low cost.

5.2.2. In situ compaction

In situ (or dynamic) compaction is used to consolidate soils, sludges, and bulk waste. The effect of compaction is to provide a more dense and impenetrable waste form which offers less surface area exposure to natural processes that will otherwise tend to cause contaminant migration. Compaction can be accomplished by dropping a steel or concrete weight from a predetermined height onto the area to be compacted. The impact of the weight causes shock waves within the underlying media, thereby consolidating the materials. Dynamic compaction is a well developed, inexpensive, readily available technology. This technology is available for all waste types and analyse groups.

5.3. IN SITU TREATMENT TECHNOLOGIES

Treatment technologies are source control technologies that reduce the toxicity and/or volume of the waste by destroying or removing polluting constituents. Treatment technologies are capable of permanently reducing the overall risk posed by wastes.

In situ treatment technologies allow soil or groundwater to be treated without being excavated and transported, resulting in potentially significant cost savings. However, in situ treatment generally requires longer time periods than ex situ treatment, and there is less certainty about uniformity of treatment because of the variability in soil and aquifer characteristics and because the effectiveness of the process is more difficult to verify. The major categories of in situ treatment processes are biological, physical/chemical, and thermal treatment. In situ treatment technologies are generally not applicable to bulk waste.

5.3.1. Biological treatment

Biological treatment processes take advantage of natural organisms such as bacteria, fungi, and plants to destroy or remove pollutants, or to mineralize metal contaminants and the associated radioactive contamination, thus immobilizing them in place. Clear benefits of bioremediation processes are that they are often less expensive than more aggressive interventions and they generally create little to no residual waste requiring treatment. However, these processes require time, and it is difficult to confirm effectiveness. Although not all organic compounds are amenable to biodegradation, bioremediation techniques have been successfully used to remediate soils, sludges, and groundwater contaminated by petroleum hydrocarbons, solvents, pesticides, wood preservatives, and other organic chemicals. Figure 3 shows a field test on a DOE site. Bioremediation of inorganic materials is less well developed than the application to organic contaminates. Bioremediation methods generally fall into two categories, viz., biodegradation or transformation and vegetation enhanced remediation.

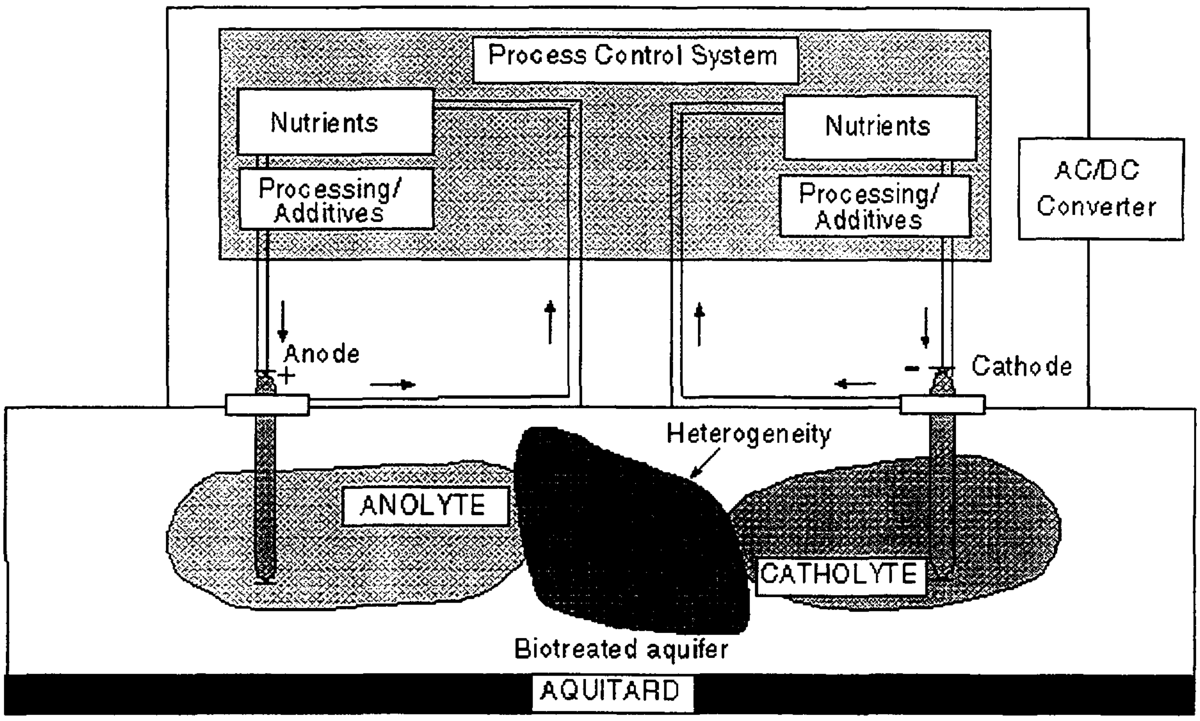

FIG. 3. In situ bioremediation (source: DOE/EM-0248).

Biodegradation

Biodegradation is generally applied to remediate radioactive contamination in soils and groundwater where the associated organics are functioning as chelating agents which enhance contaminant mobility [36, 51, 52]. Destruction of the organics serves to reduce transport rates which provides the time for the radioactive materials to decay to innocuous levels. Indigenous or inoculated microorganisms degrade organic contaminants in soil and/or groundwater under either aerobic or anaerobic conditions. The in situ bioremediation of soil typically involves the percolation or injection of groundwater or uncontaminated water mixed with nutrients and saturated with dissolved oxygen. In some cases microorganisms and/or a source of oxygen are also introduced. Bioremediation techniques have been successfully used to remediate soils, sludges, and groundwater containing a wide variety of organic pollutants including petroleum hydrocarbons, solvents, pesticides, and wood preservatives. Biodegradation is also effective in the remediation of chemicals used to make explosives. There are several different approaches and or methods that can be applied including the following: (1) bioventing, (2) biosparging, (3) co-metabolism, and (4) nutrient addition.

Bioventing

Subsurface soils are subjected to relatively low-flow aeration to enhance the bioremediation of organic contaminants. The process is based on the concept that naturally occurring soil microbes are ubiquitous in the subsurface and capable of degrading organic contaminants if sufficient oxygen is supplied. Bioventing maximizes biodegradation while minimizing contaminant volatilization. Bioventing is effective for VOCs, SVOCs, fuels, and pesticides. Bioventing is usually implemented with air injection wells but vacuum extraction wells may also be used depending on site conditions. Bioslurping is a variation of bioventing in which floating free product is recovered at the same time that biological activity in the vadose zone is enhanced. This technology is well developed and readily available.

Biosparging

Naturally occurring soil microbes degrade organic groundwater contaminants in the presence of sufficient oxygen provided by pressurized air injected below the water table [53]. Nutrients are added to increase the rate of biodegradation. Groundwater is extracted by submersible pumps for further treatment or discharge. Biosparging employs the same concept as bioventing, and is most effective for treating non-halogenated volatile organic compounds (VOCs), semivolatile organic compounds (SVOCs), and fuels.

Co-metabolism

Co-metabolism is one form of secondary substrate transformation in which enzymes produced for primary substrate oxidation are capable of degrading the secondary substrate fortuitously, even though the secondary substrates do not afford sufficient energy to sustain the microbial population. Target contaminants are VOCs and SVOCs in groundwater. The process may also have some effectiveness for treating fuels and pesticides. Injection of water containing dissolved methane and oxygen enhances methanotrophic biological degradation. This class of microorganisms can degrade chlorinated solvents such as vinyl chloride and trichloroethylene (TCE), by co-metabolism. This technology is relative new but results are promising.

Nutrient addition

The addition of nutrients enhances degradation by stimulating growth of indigenous bacteria. The process involves injection of a nutrients or cultured bacteria directly into the groundwater. Residual products are then extracted for surface treatment or recirculation into the site. Biological denitrification is an anaerobic process where microbial metabolic action reduces nitrates to nitrogen gas after the injection of oxygen and nutrient sources directly into the groundwater. Nutrient enhanced bioremediation is a developed technology that is considered moderately effective when variables such as bacterial and nutrient concentration, temperature, and oxygen availability are controlled.

Biomass remediation

Metal-tolerant plants including native species of trees, legumes, or small grains are planted on heavy metal or radionuclide-contaminated soils. The plants naturally take up and concentrate the metals or radionuclides in their biomass through absorption [54]. The plants are eventually harvested for disposal and/or processing.

Vegetation enhanced remediation

Indigenous microorganisms are stimulated to degrade trichloroethylene (TCE), tetrachloroethylene (PCE), and their daughter products in soils and groundwater by planting and cultivating specific types of trees and other plants. The bacteria and fungi associated with the roots of these plants fortuitously degrade contaminants in the soil. The stimulation of these microbes by roots of the plants provides a solar nutrient source. Methanothrophic organisms have been demonstrated to degrade TCE through metabolic processes completely to carbon dioxide and chloride. Vegetation is not harmed by TCE and PCE, even in high concentrations because the root systems do not absorb the contaminant and because the contaminates are not toxic to the vegetation. This technology is innovative.

5.3.2. Physical/chemical treatment

Physical/chemical treatment takes advantage of the physical properties of the contaminants or contaminated medium in destroying (i.e., chemically converting), separating, or containing the contamination. Physical/chemical treatment is typically cost effective and can be completed within short time periods (in comparison with biological treatment). Treatment residuals from separation techniques require treatment or disposal, which adds to total project costs and may require permits. Certain in situ physical/chemical treatment technologies are sensitive to certain soil and aquifer parameters. In situ physical/chemical treatment is used only for the treatment of soils, sludges, sediments, and groundwater and does not apply to bulk wastes.

Soil flushing

In situ soil flushing is the extraction of contaminants from the soil with water or other aqueous solutions. It is accomplished by passing the extraction fluid through in-place soils using either infiltration or injection. Extraction fluids must generally be recovered from the underlying aquifer. The process is most applicable to inorganic contaminants, including radionuclides, but may be applied to organic contamination [55–57]. Surfactants may be added to the extraction fluid to increase the solubility of organic compounds and of nonaqueous phase liquids. This technology is readily available through vendors.

Soil leaching

In situ soil leaching enhances the natural leaching processes to a deep underground layer by applying enhanced irrigation of the soil. The leaching is done with weak solutions of fertilizers which do not destroy the structure and fertility of the soil layer. The method is applicable in cases where there is a sufficiently thick aeration zone with deep (3–5 m) subterranean water level and the presence of an underground layer with good adsorption properties for the radionuclide concerned. Good leaching rates are obtained for ^{90}Sr and ^{137}Cs with an ammonium bicarbonate solution of 25–50 g/L.

Electrokinetic remediation

Electrokinetic remediation is a relatively new remediation technology that uses low-level direct current between electrodes placed in the ground in an open flow arrangement [50, 55]. This arrangement allows processing or pore fluid to flow into or out of the porous medium. The low level direct current results in physiochemical and hydrological changes in the soil mass, leading to species transport by coupled and uncoupled conduction phenomena. The principles of the process are demonstrated in Fig. 4.

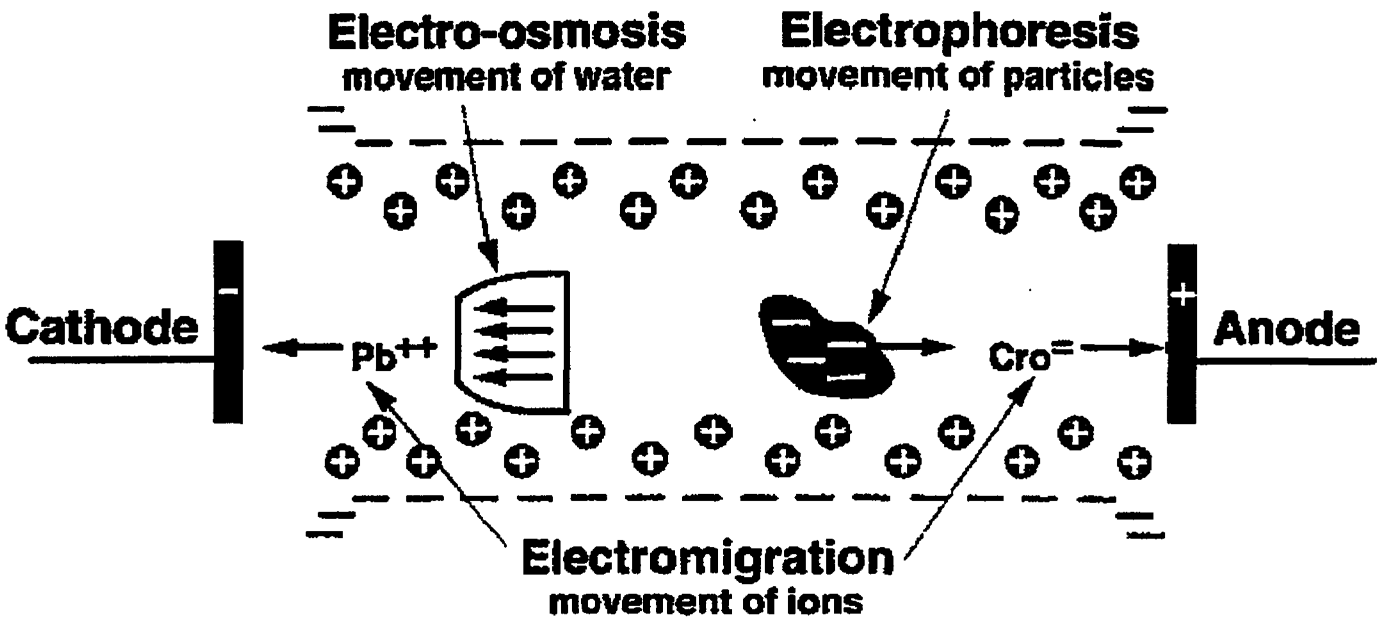

FIG. 4. Contaminant transport process induced by applying direct current between buried electrodes (source: DOE/EM-0248).

In situ chromate reduction and heavy metal fixation

In situ chromate reduction is an innovative technology. The approach consists of in situ reduction of chromates with a ferrous salt, and fixation of the metals using a destabilized aqueous sodium silicate solution. The silica treatment serves two purposes: it reacts with the metal and metal hydroxides to reduce metal solubility, and it lowers the soil permeability thereby reducing the leaching rate of the treated soils [55]. The primary objective of this technology is to remediate heavy metal contamination in soil. An example of this technology is shown in Fig. 5.

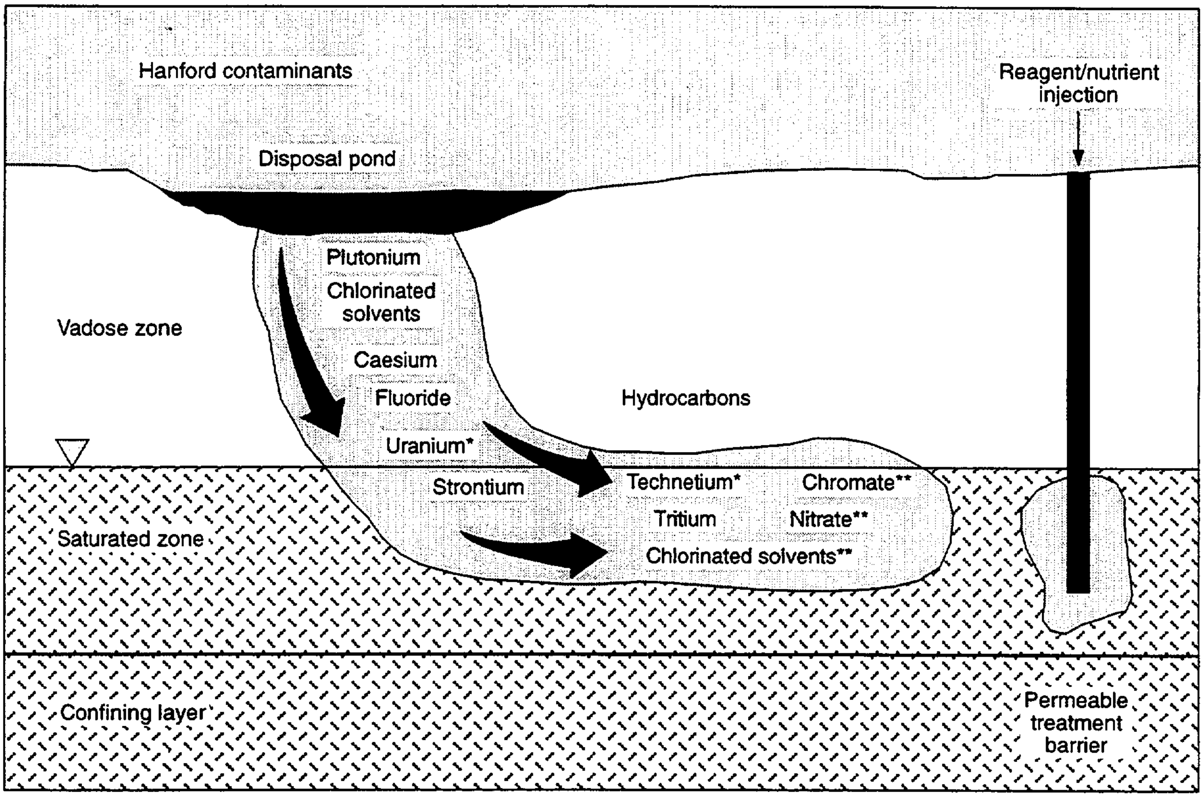

FIG. 5. Permeable treatment barrier concept (source:DOE/EM-0248).

Chemical oxidation/reduction

Chemical and/or microbial reducing agents can be injected into contaminated soil or unconfined aquifers to create a subsurface treatment barrier to immobilize or destroy target contaminants [56]. Then water containing the reaction by-products and any remaining reagent is pumped back out. The treatment barrier is a zone of favourable redox potential. The goal is to effectively transform dissolved metals and radionuclides to less soluble forms, and to promote the destruction of organics, especially chlorinated hydrocarbons. This innovative technology allows in situ treatment of groundwater contaminants and avoids disposal costs, since metals and radionuclides are immobilized in place. The technology offers great promise and is undergoing pilot scale studies but is not currently available.

Reactive gas injection

Feasibility studies for treating unsaturated soils by injection of reactive gases are being tested. Dilute mixtures of hydrogen sulfide in air or nitrogen are being used to treat soils contaminated with heavy metals, while chromate or uranium-contaminated soils are being treated with hydrogen sulfide and sulfur dioxide gas mixtures diluted by inert gases [56, 57]. Reactive gas injection is an innovative technology still under experimentation.

Soil vapour extraction

A vacuum is applied through extraction wells to create a pressure/concentration gradient that induces gas-phase volatiles to diffuse through soil to extraction wells [51]. The process includes a system for handling off-gases. Target contaminant groups for soil vapour extraction are VOCs and some fuels. This technology would be beneficially applied for remediation of radioactive materials if destruction of the organics to eliminate chelation effects serves to slow transport rates for the radioactive materials. This technology is well developed and readily available.

Sparging

Air sparging is a technology in which air is bubbled through a contaminated aquifer creating an underground stripper that removes contaminants by volatilization [58]. The air bubbles carry the contaminants to a vapour extraction system. Air sparging operates at high flow rates to maintain increased contact between ground water and soil. Target contaminants are VOCs and fuels.

A variation of the technology is to pull a vacuum on a ground water well, lifting contaminated ground water up into the well. Some of the VOCs in the contaminated ground water are transferred to air bubbles which rise and are collected at the top of the well by vapour extraction. The partially treated ground water is never brought to the surface. It is forced into the saturated zone, and the process is repeated. As ground water is circulated through the treatment system in situ, contaminant concentrations are gradually reduced.

5.3.3. Thermal treatment

Thermal treatment processes range from low to extremely high temperatures to remove or completely destroy polluting constituents in wastes. There are basically two classes of in situ thermal treatment systems. The most extreme is in situ vitrification which serves to destroy the waste and immobilize radioactive contaminants in a glass mass that forms as a result of soil melting. At the other end are thermal enhancements designed to drive off organics and thus reduce radioactive transport by eliminating chelation effects. Thermal treatment offers quick cleanup times but are typically the most costly. Cost is generally driven by energy and equipment costs and is both capital and operation- and maintenance-intensive. In situ thermal treatment is typically used for the treatment of soils, sludges, sediments and ground water and does not apply to bulk wastes.

In situ vitrification

In situ vitrification (ISV) [59, 60] is a thermal treatment process that involves the electric melting of radioactively contaminated soils, sludges, or other earthen materials by forming a melt between four electrodes at temperatures of approximately 1600–2000°C and is illustrated in Fig. 6. The melt starts at the surface and grows deeper and wider, typically processing 3–6 tonnes per hour. The process usually requires 0.7 to 0.8 kW·h per kg and a full size melt, which can be up to 7 m deep and 15 m wide, requires 3.2 to 4 MW. After power is removed the molten mass solidifies slowly into a vitreous monolith with physical, chemical, and weathering properties which result in an extremely durable and highly leach resistant material. Heavy metals and radionuclides in the melt are permanently immobilized by incorporation into the vitreous product and organics are destroyed by pyrolysis. The vitreous product generally consists of high concentrations of silica (50–80%) and low levels of alkali oxides (1–5%). Most soil types (sands, silts, clays, etc.) can be treated if the concentration of glass formers and alkali oxides (less than 1 wt%) provide adequate electrical conductivity or if additives are used. Sludges and soils with high moisture content (less than 70 wt %), can only be treated provided de-watering or watering diversion techniques are used.

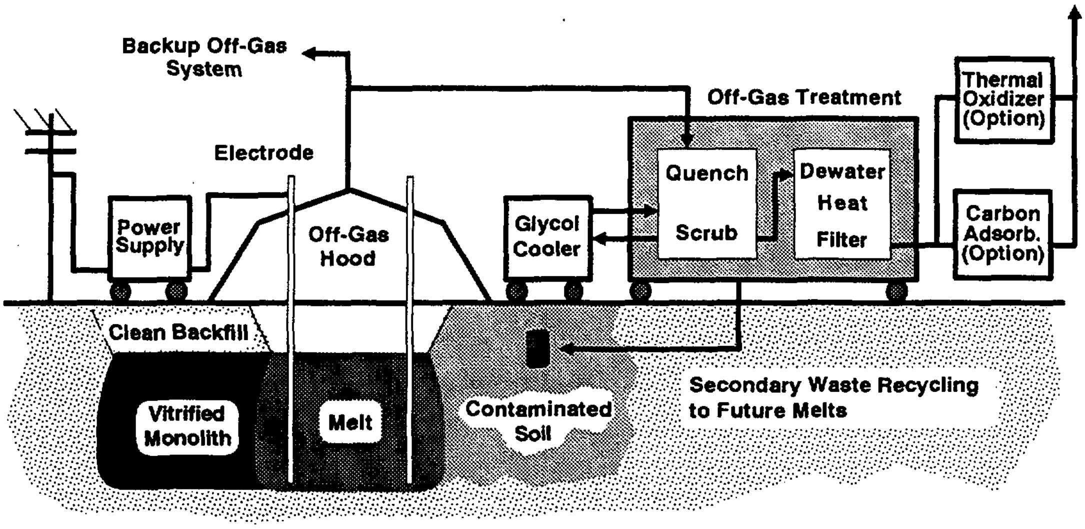

FIG. 6. Overview of joule heated in situ vitrification process (Credit: Geosafe Corp.).

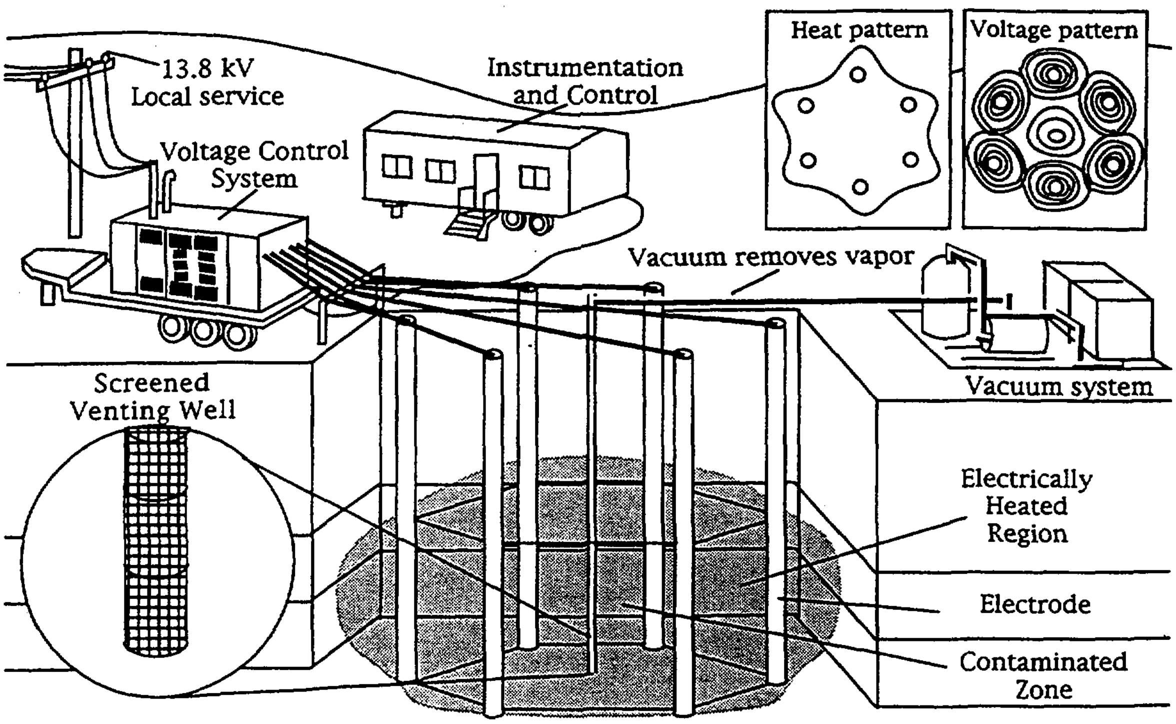

FIG. 7. Six-phase soil heating.

Dynamic underground stripping

Dynamic underground stripping is a technology integration of vacuum extraction and direct electric heating or steam injection (depending on the substrate) [61]. Cyclic steam injection combined with vacuum extraction has been successfully demonstrated for sandy soils, whereas the integration of electrical heating and vacuum extraction has been demonstrated for clay soils.

Radiofrequency heating

Radiofrequency (RF) heating involves the use of RF energy to heat vadose zone sediments through a dielectric heating mechanism in which the application of an electromagnetic field physically distorts the molecular structure of the material. The physical distortion is transferred into mechanical and then into thermal energy which serves to drive off organics.

Thermally enhanced soil vapour extraction

Thermally enhanced soil vapour extraction (Fig. 7) is a full-scale technology that uses steam/air injection to increase the volatility of SVOCs and facilitate extraction [62]. The system is designed to treat SVOCs but will treat VOCs. Thermally enhanced soil vapour extraction technologies are also effective in treating some pesticides and fuels, depending on the temperatures achieved by the system. This technology is developed and available.

Steam flushing

Steam is forced into an aquifer through injection wells to vaporize volatile and semivolatile contaminants. Vaporized components rise to the unsaturated (vadose) zone where they are removed by vacuum extraction and then treated. In situ biological treatment may follow the displacement, and is continued until contaminant release levels are reached. The target contaminants for this technology are SVOCs and fuels. VOCs can be treated but the methodology is not effective.

5.4. AGRICULTURAL METHODS

There is no 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.

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

- eventual reduction in residual activity levels in the soil by natural means;
- decontamination of the land followed by reclamation measures such as fertilization;
- deep or shallow ploughing in combination with the addition of chemicals or adsorbents to reduce the uptake of residual radionuclides in plants; and
- using the land to grow non-food/feed crops.

5.4.1. Soil inversion techniques

Plant plowing and deep plowing have been applied to reduce external gamma radiation. The objective is to uniformly mix contamination over a larger volume of soil and reduce concentrations through dilutions. This practice maybe pragmatic for certain contamination problems but in general is not advised in part because the result may simply be to increase the size and complexity of a future remediation. Cleanup of the Maralinga site in Australia (see Annex I) serves as an excellent case study. A secondary disadvantage is that deep plowing may significantly reduce the fertility of the soil. New methods have been tested that address these concerns to a limited extent.

Skim and burial plowing

A tractor drawn trenching plow is used to lift a thick layer of soil, 30–40 cm, skimming off the active top 10 cm of soil. This material is placed into the bottom of a trench. The deeper clean level will then be placed on top of the active level in the trench in its original stratification [63]. In theory, this method would place the major part of the activity well below the lower boundary of the roots of the crop while still keeping some of the fertile topsoil in the root zone. The effect of this mixing has been investigated to some extent, but large scale tests need to be conducted to determine impact on soil fertility and productivity. The impact of deep plowing is influenced by the type of soil and the crops grown.

Triple digging

Triple digging is the manual version of skim and burial plowing. It is a labour intensive process applicable in areas not accessible by machinery. A reduction by factors of 5 to 15 in external dose rate have been achieved.

5.4.2. Revegetation

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. Most of these studies address revegetation to stabilize soils rather than to increase direct beneficial use. This is an acceptable approach since, 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.

5.4.3. Soil additives

Several practices have been explored that may be effective in returning land to productive use by reducing the uptake and retention in plants of radionuclides following a contamination incident. Increased availability of beneficial isotopic or chemically related elements can reduce the soil-plant transfer of radioactive isotopes. The use of lime to increase 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.

To obtain a reliable estimate of the usefulness of such techniques to assist in the reclamation of contaminated land, the chemical nature of the added chemicals and contaminants, their interaction with plants, and nature of the soil types must be kept in mind. Adding fertilizers or chemical analogues creates a competition with the radionuclide in the plant root absorbing zone and results in a lower contamination level in the plant should be expected. However, a similar competition may also occur at the soil adsorbing sites of the plant, resulting in an increase in bioavailability and higher levels of contamination in the plant. Therefore, depending on the chemical nature of the added chemical and 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 adsorption has to be obtained before these methods can reliably be applied to reclaim land.

Because of the lack of suitable complexing agents, selective removal of ^{137}Cs from soil poses a more difficult problem. Although compounds such as crown ethers will complex caesium, they are quite toxic and very expensive; therefore, they would not be suitable for a large scale agricultural application. 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 will need careful consideration.

5.4.4. Crop selection

Even if there is some residual contamination, land may be reclaimed and used for productive purposes, by the judicious selection of crops. For example, the cultivation of non-food/feed crops such as cotton, flax and timber could be considered for an area if food crops would contain unacceptable concentrations of radionuclides. Plants with low mineral contents, such as corn, would be safe to grow on radioactively contaminated land.

Since most of the radioactivity in the refined products would be removed during processing, sugar and oil producing crops could be used to restore land to a productive use. 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 has 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 from natural processes such as rainwater infiltration.

5.4.5. Animal production methods

A range of methods have been investigated for reducing the radionuclide content in animal products. Three methods have found use after the Chernobyl accident.

Use of bolus

A bolus containing caesium absorbers is administered orally to cows every three months. This reduces the caesium uptake by the animal and the caesium content in milk by a factor 2–3.

Clean fodder

Caesium-137 has limited residence time in the body. By feeding the animal clean fodder harvested outside the radioactively contaminated area during the two to three months before slaughter the ^{137}Cs content in the meat is reduced by a factor 2 to 3.

Salt licks

Cows have been given salt licks containing Preussian Blue to reduce the animals' caesium uptake. Reductions by a factor of 2 to 3 can be obtained.

6. MATERIALS REMOVAL TECHNOLOGIES

Contaminated material can be removed and transported elsewhere to permit treatment and/or disposal, either locally or off site. Although excavation and off-site disposal alleviates the contaminant problem at the site, it does not treat contaminants. Some treatment of the radioactively contaminated media may still be required in order to meet land disposal restrictions. The following factors may limit the applicability and effectiveness of the process:

- generation of fugitive emissions may be a problem during operations;
- the hauling distance from the radioactively contaminated site to the nearest disposal facility will affect cost and may affect community acceptability;
- depth and composition of the media requiring excavation must be considered; and
- consideration must be given to what is going to be done with the removed material.

Where the radioactively contaminated areas are small, conventional decontamination and excavation techniques, appropriately modified to reflect likely radiological protection issues, can be adopted. In all cases involving excavation, monitoring of both the excavated material and the adjacent remaining soil will need to be conducted in parallel to ensure that all contaminated material is removed. Since under certain conditions vegetation can intercept almost all of the fallout, its removal could be an effective method of decontaminating certain areas.

In the case of large radioactively contaminated areas careful ecological and other studies must be undertaken to determine nature and extent of the contamination.

Since in the case of large areas it is impossible to do everything at once, some priorities must be set. Priorities should be based on climate, vegetation and soil character as well as environmental and population risks posed by the contaminants.

Infrastructure may need to be modified or must be created to remove large volumes of contaminants. In some cases, planning for local waste disposal and corresponding network of roads is required. All conventional technologies for the excavation and transport of material should be taken into account and assessed for their effectiveness in removing radioactively contaminated soil to the required depth, their flexibility and reliability, the radiological and conventional safety and the cost of operation.

It should be kept in mind that the remediation is expected to produce a net positive benefit. Equipment must be selected to suit a particular area and accident situation. There is no method which is best for all circumstances. There may be special large scale industrial equipment that could be modified to cleanup areas contaminated with radioactive and toxic pollutants. In addition the climatic conditions at the site and the end use to which the site is to be put will affect the way in which the removal is performed.

6.1. REMOVAL OF VEGETATION

The removal of radioactively contaminated vegetation may be appropriate for three situations:

(1) As a method to remove the radioactivity directly intercepted by the biomass. This occurs when dry radioactively contaminated settles out of the atmosphere onto vegetation. In this case it will be possible to eliminate up to 70% of the activity deposited by unit of area, depending on the density of the vegetation and if it had been precipitated on, thus effectively washing the contamination off.

(2) To remove vegetation to simplify the removal of surface soils. Here, the object of decontamination is the soil not the vegetation.

(3) Where vegetation is used principally as a mechanism for removing radioactively contaminated soil attached to the roots [64–66].

For large areas, brush and small trees can be removed using cabling or anchor chaining, depending on the size of vegetation. 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 chain is dragged by two tractors to break or uproot vegetation including small trees. Anchoring disturbs the soil to a greater degree than does cabling.

For small areas, removal by hand of large shrubs with chain saws, hedge trimmers and shears is an option and has an advantage in not disturbing the soil.

Another option is the burning the vegetation in situ, however, this may cause resuspension of contamination and spread of activity and there is the potential to create a general fire control problem.

More conventional types of harvesting equipment such as flail-type forage harvesters, direct-cut forage harvesters and mowers, followed by side-delivers rake and windrow pick-up baler to collect the vegetation can be useful.

Using bulldozers with the blade set above the soil surface level and piling the vegetation to the side to be picked up by front end loaders is an option, however, large equipment such as this with tractor treads can cause significant disturbance of the contaminated soil.

With appropriate grappling equipment small bushes can be lifted from the soil.

When vegetation is defoliated and allowed to dry, 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 stabilized or dampened.

Ten years after the Chernobyl accident the majority of deposited radionuclides remains in the 3 or 4 cm of the topsoil of abandoned fields in the Chernobyl zone. Harvesting vegetation with a turf harvester allows removal of a layer of few centimetres of the topsoil. The removal efficiency observed at Chernobyl was 97% for ^{137}Cs and ^{90}Sr. After scraping the soil with the turf harvester, the bare soil must be covered and re-grown in order to prevent wind erosion of the sandy soil. This technique seems promising but is limited by soil type, climate and growing season. A trial spraying of polyacrylamide on the soil, which binds the soil and aids revegetation, was carried out.

6.2. REMOVAL OF SURFACE SOIL

Shallow earth removal studies and decontamination projects in the former USSR, the USA and other countries show that many common types of earth moving equipment such as graders, bulldozers, front end loaders, excavators 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 [67]. The contaminated earth is either moved into piles and hauled away or buried directly in a depression or specially excavated trenches.

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, presence of rock, 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. If the surface is coarse grained or gravel, the contamination may have seeped to considerable depth, making this type of decontamination less effective. Figures 8–11 show examples of machines currently used to remove surface soil.

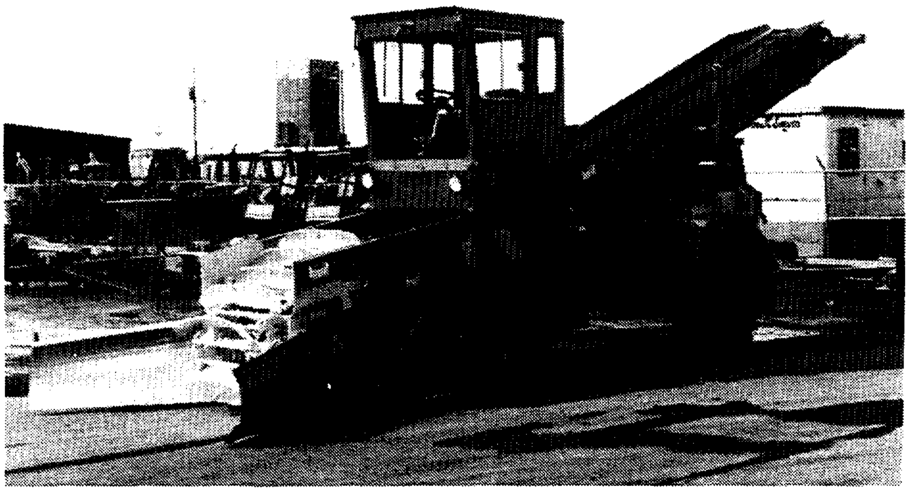

FIG. 8. Force feed loader with ~8 m main conveyer. The moldboard is adjustable and tapered. (Credit: Athey Products Corp.)

FIG. 9. High capacity scraper used in the coal industry (26 m^3). (Credit: TEREX).

FIG. 10. High capacity loader. (Credit: Dresser).

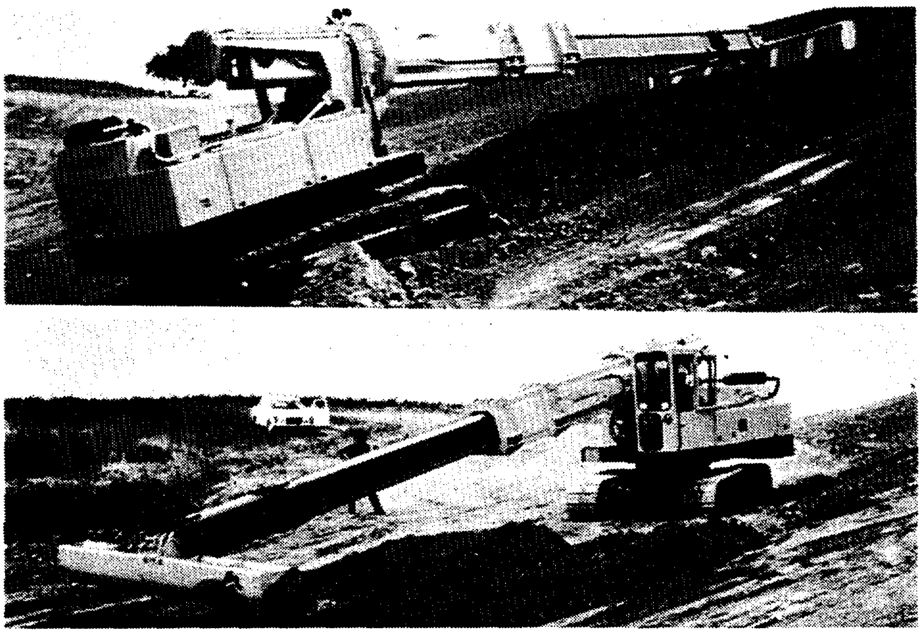

FIG. 11. Machine for removing a layer of soil from steep slopes. (Credit: Wieger Maschinenbau GmbH).

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 which dries and glues the soil components together for removal of the layers. In selecting these alternatives, the future management of the removed material must be taken into account.

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 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.

6.2.1. Standard excavation

A range of mechanical excavators are available in the civil construction and mining industries which is suitable for the removal of surface soil over large areas. Excavation equipment must be chosen with consideration to its suitability for the terrain and soil type. A rocky uneven terrain will require the use of equipment such as a bulldozer or front end loader where as for smooth flat surfaces it would be possible to use graders and scrapers. This would enable a more precise cut thereby reducing the volume of material requiring treatment or disposal.

For transport over short distances of several hundred metres, scrapers which load material directly into a storage compartment can be useful because double handling of material is avoided. For transport over larger distances it will be necessary to load material into trucks or containers. If suitable containers are chosen it is often possible for material to remain in these for disposal.

Equipment suitable for excavation includes:

Graders

Machine with a blade located between the wheels and suitable for removing relatively thin layers of material accurately from smooth surfaces. Requires another machine such as a front end loader to pick up material which has been graded into piles to the side of the machine. Its advantages include the accuracy of removal and little cross contamination due to the continuous forward motion and leaving a clean side of the work face. Its disadvantages are that it requires other plant to load and remove excavated material and it can only remove thin layers.

Scraper

The scraper is a combination of an excavator, loader and transport vehicle and will excavate up to approximately 300 mm in depth of material. It has an angled blade which places material directly into a hopper for transporting soil short distances from the removal site. Its advantages are that excavation and storage of material takes place close to ground level and the material is contained in a hopper minimizing dust and cross-contamination. It also combines excavation and transportation into one operation avoiding double handling and enabling material to be deposited and spread at the disposal site. It is capable of reasonable accuracy in excavation. Its disadvantages are that it may require a bulldozer to push it for additional traction in difficult terrain and is not suitable on uneven rocky surfaces or heavily vegetated areas. Material may be left on each side of the cut. It is only suitable for transporting material a few hundred metres.

Bulldozer

Machine with a blade in front, which is more suited to heavy excavation work with short distances of material movement as it is only able to push material forward. Requires another equipment such as a front end loader to pick up soil for loading into a truck for transport and dumping. Unless there is considerable overlap of excavation or the blade is angled material may be left either side of the blade.

Front end loaders

Machine with a scoop on the front for picking up material from heaps or windrows. Suitable for taking material from small areas or from rocky or uneven terrain and for moving piles of soil. Not very accurate for taking fine cuts but has advantages of mobility and versatility. Its disadvantages are the it requires multiple movements to operate and that it drops material from a height both of which increase dust generation.

Excavators

This machine is a backhoe which comprises an excavation bucket on the end of an arm. It has a relatively small capacity for material movement and is not suitable for large scale operations. Its long reach does give it some advantages when removing small areas of high contamination in difficult places such as exhuming burial pits. It is very effective in combination with bulldozers and graders.

6.2.2. Remote excavation

Remote excavation is undertaken when the radiation levels are too high for sustained operator exposure, even if the mechanical device is shielded. Generally, remote excavation is undertaken by teleoperated versions of the 'standard' excavation equipment. In some instances, however, (e.g. retrieval of waste from temporary storage), a remotely guided crane with multiple attachments may be used.

6.2.3. Cryogenic retrieval

Cryogenic freezing is used as a temporary measure in civil engineering, either to prevent the spread of a liquid plume, or to shore up ground to permit repairs to structures or foundations. For cryogenic removal, this is taken a stage further, and the ground is hard-frozen prior to removal. This would be most beneficial for areas such as marshland or peat bogs, where there is no stable surface from which to use more conventional excavation equipment.

6.2.4. Dust control

Removal of radioactively contaminated soils can lead to the resuspension of large quantities of soil as dust. Depending on the radionuclides in the contamination this may lead to an inhalation hazard for workers and for others in the vicinity. Two aspects of dust control are important: firstly the protection of equipment operators, which uses standard industrial techniques, and secondly the prevention of further widespread dispersion of contamination. Climatic factors are important and proper selection of the time of operation may lead to natural dust suppression by rainfall or dust dispersion by strong wind. Climatic conditions strongly influence costs and effectiveness. The general rule of cleaning the area down the wind direction is obvious. In many cases spraying with water or emulsions may be necessary but may increase costs.

Equipment such as scrapers are preferred as the material is loaded directly into a storage compartment, reducing the amount of handling and therefore, the amount of dust created. Graders and bulldozers require three separate operations before the material is placed in a truck or container.

Dust may be suppressed by wetting or spraying with binding agents, however, care should be taken as this may lead to contamination of expensive equipment which may be hard to remove. Spraying with water may also increase costs. If there is a particularly acute inhalation hazard then spraying with water alone may not be sufficient to reduce this to acceptable levels. Inhalation controls may still need to be applied.

For small scale operations it may be sufficient for operators to wear face masks such as half face or full face respirators. In extreme circumstances full air supply suits may be required. For large sale operations it may be more efficient for workers to work in sealed cabins which are fed with highly filtered air.

6.2.5. Other methods

The main 'other method' not covered above is the use of manual excavation tools or small scale excavators (e.g. minidozer or backhoe). These are most suitable where the area of contamination is well characterized, and either small or difficult to reach with conventional equipment.

Wet methods may be used (water jetting, directed water jetting, water lance) to locally convert the soil into a slurry, which is pumped away for treatment. By definition, this technology will result in a secondary effluent which will require treatment. However, the control of such liquid based excavation is sufficiently precise to permit removal of known hot-spots prior to further excavation by another (less expensive) method.

In some cases, promotion of natural erosion processes may be useful. In the case of mountainous areas, water erosion is the most important factor and in the case of flat areas wind erosion may be significant. In case of water erosion, the transport direction and final sedimentation site may be predicted whereas in the case of wind erosion such predictions are more difficult.

6.3. REMOVING CONTAMINATION FROM HARD OR ROCKY SURFACES

Where hard or rocky surfaces are radioactively contaminated many of the techniques described in Section 6.2 are applicable. These include manual or mechanical brushing, vacuuming, abrasive jet cleaning using abrasives such as sand, and glass or metallic beads, high pressure water jetting and scarifiers, which hammer surfaces of rock with hard bits to spall of thin layers of contamination.

7. EX SITU TREATMENT TECHNOLOGIES

Ex situ treatment is the maximum intervention option. These technologies rely on bringing the waste or radioactively contaminated material to the remediation technology, rather than the other way around (by definition, some form of excavation or recovery of the radioactively contaminated material is required). The aims of ex situ processing are to ensure a more consistent standard of clean up, and avoid the difficulties inherent with in situ techniques. Such techniques may not be suitable for the very low concentrations of activity likely for widespread contamination problems, due to small concentration gradients.

Ex situ treatments of materials radioactively contaminated by non-radioactive substances such as oil, solvents, heavy metals and other chemicals have been applied on an industrial scale. The technologies adopted include soil washing, solidification, biological treatment and incineration.

In principle, these technologies may be suitably adapted so they may be applied to the treatment of radioactivity. However, the experience gained with radioactive contamination has not been extensive and a programme of research and development would be required to ensure the efficiency of any proposed treatment for any specific waste.

Ex situ processes are also used for the remediation of radioactively contaminated surface and groundwaters. It is normally impractical to obtain sufficient data to characterize the radioactively contaminated aquifer fully and to accurately predict its response to any cleanup system. Technologies to clean up ground and surface waters contaminated with hazardous waste usually rely on pumping followed by ex situ above ground treatment. The technologies applied closely resemble traditional water treatment technologies used to treat industrial and municipal wastewater.

If the waste is not diluted in the water, these ex situ technologies are based on the effectiveness of the pumping system in capturing the wastes and bringing them to the surface with the groundwater for treatment. If pumping cannot remove the particles with the adsorbed contaminants from the aquifer, the ex situ treatment technologies do not have an opportunity to treat them.

Enhancements to traditional pump and treat technologies include pulsed pumping, reinjection, and chemical extraction. These enhancements promote more efficient removal/treatment of less mobile contaminants in less homogeneous, less permeable aquifers.

Extraction of radioactively contaminated groundwater for treatment can be achieved by extraction wells or trenches. The regulatory authorities normally set criteria that must be met before the treated groundwater can be released or reinjected into the environment. The residual wastes from a groundwater treatment system may be radioactive enough to require disposal. If natural flushing is the appropriate procedure for aquifer restoration, the groundwater cleanup period may be shortened using gradient manipulation to direct the flow, injection wells to increase the flow rate, and limited extraction, treatment and re-infection.

Overall, ex situ techniques are just a potential component in an overall waste/remediation strategy. Even if they are not applied directly to the waste, as in the groundwater examples above, they are of benefit for the treatment of secondary wastes generated by other treatment techniques. (An example is the use of solidification for conditioning of ion exchange resins used in the treatment of groundwater.)

The main ex situ treatment technologies for all wastes fall into three categories: physical, chemical and biological.

7.1. PHYSICAL PROCESSES

These technologies rely on the physical properties of the materials to achieve separation or to fix the contamination to prevent the spread of activity. 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 soil conditioners such as fertilizers will be necessary to restore land fertility after the remedial activity.

Physical separation may be used with chemical extraction to produce fractions with higher concentration of contaminants in smaller volumes. The physical separation technologies may also be suitable for removing radionuclides which have been deposited as solid particulate in the soil.

7.1.1. Physical retrieval

Physical retrieval is the simplest form of physical process, known generally as 'dig and tip', or 'muck and truck'. The waste or contaminated material is excavated, and then placed in a disposal area or engineered facility. There is little if any additional treatment.

Methods of physical excavation are detailed in Section 6.2, but is should be noted that excavation could be undertaken using a'remote excavator', if the direct radiation dose is too high to permit the use of standard excavators (even modified for use in higher radiation fields).

7.1.2. Overpacking/repackaging/redrumming

This is the next stage along from physical retrieval. The aim of overpacking or Redrumming is to transfer the radioactively contaminated material into a container which meets current Regulatory disposal limits. After the radioactively contaminated material has been excavated, it is placed into engineered disposal packages prior to emplacement in an engineered disposal facility. If the remediated material is held in containers (e.g. drums), then this operation is known as Repackaging or Redrumming depending on the final waste container.

7.1.3. Screening

This uses the physical size difference between the contaminated and less contaminated components to effect a separation. For example: Plutonium contamination from nuclear tests in 1962 is present at Johnston Atoll in soil throughout a 10-ha site. A pilot plant was built using a mineral jig to concentrate heavier plutonium particles from lighter soil particles. It uses water to move soil over a screen, loaded with shot and soil sorters. Sorters preceding the jigs would prevent unnecessary cleaning of clean soil.

7.1.4. Soil washing

The most common industrial treatment of non-radioactively contaminated soils is that of soil washing, which uses wet particle size separation. The underlying principle employed is the fact that contaminants have greatest affinity for particles with the highest surface area/volume ratios, i.e., very fine particles of silts and clays. The separation of larger particles by washing forms the basis of a volume reduction step and the separation achieved is dependent on the composition of the soil size fractions.

The process steps are multiple but straightforward. They normally involve some or all of the following: Screening, attrition scrubbing, hydro cyclone separation, gravity settling, dissolved air flotation and mechanical dewatering. The basic process is normally modified to address site-specific contaminants and the contaminated media.

The final stage of soil washing processes is the secondary treatment of the wash water. While the aim is generally to recycle the water, is it normally inevitable that some discharge to the environment is made. All efforts should be made to enclose the process to minimize accidental discharges and to treat and properly dispose of the waste water too dirty to return to the process.

Generally, soil washing is enhanced by the addition of chemical treatment steps. These are detailed in Sections 7.2.3 and 7.2.4.

7.1.5. High gradient magnetic separation

High gradient magnetic separation (HGMS) is a physical process that segregates materials based on their magnetic susceptibility. This results from the paramagnetic properties of plutonium and uranium and many fission product components. Such paramagnetic properties permit differential separation of such materials.

Using the very high magnetic fields (8 tesla) of superconducting magnets, useful separations have been achieved on small particles (<50 μm). This means of separation could be used after soil washing to achieve further volume reductions. The work is still at an experimental stage but shows promise as a useful method of reducing volumes of contaminated material. However, as the method relies on the removal of smaller particles from larger ones, the particle size distribution may have an adverse effect on the overall removal of contamination.

7.1.6. Solidification

Solidification in a number of forms provides a suitable treatment for both non-radioactive and radioactive wastes. An inert matrix is used at low temperatures to fix the activity into a form where it cannot readily be dispersed.

Examples of such matrices include:

- cements;
- polymer modified cements;
- organic polymers;
- inorganic fixing agents such as Chemfix (solid silica polymer).

Since these processes normally increase the volume of waste requiring disposal, they are of less value where there are large volumes of material requiring treatment. There is also a potential conflict between high organic contents and certain matrices. This is also true for retardant inorganic materials such as borate with cements.

Solidification can also be used in conjunction with dewatering to convert liquid wastes into a disposable solid form. This is not advisable if the incorporation levels of dissolved materials are low in the chosen matrix.

7.1.7. Vitrification/ceramics

Vitrification is the high temperature equivalent of solidification [68–70]. The waste is converted into a glass or ceramic material. Generally glass formers (such as silica) are added, though some wastes may contain sufficient silica to be vitrified without further addition. The resulting waste form is a relatively insoluble glass or ceramic in which the contaminants are incorporated. Vitrification is a high cost energy intensive process, and is more suitable for high activity, low volume contaminated material, and/or where the contaminants are long-lived species such as transuranics.

7.1.8. Incineration

Another treatment used for non-radioactive contamination is that of thermal treatment of contaminated materials in an incinerator. A number of companies now market portable equipment to assist in the remediation of chemically contaminated sites.

The process essentially involves passing quantities of soil or waste through an incinerator and recovering the ash/clinker/residue for immobilization or direct disposal. The incinerator off gas needs treatment by appropriate filtering and scrubbing. The 'burnt clay' resulting from incineration is poorer at supporting soil fertility and mechanical load bearing than the unburnt soil. The technology is mainly applicable to solvent and organic chemical contaminated materials, hence, is probably not likely to be of value for most radioactive contamination.

Incineration is also potentially useful for the volume reduction of inflammable liquids and materials such as biomass. Care should be taken, however, to ensure that the incineration process results in the contaminant radionuclides being retained in the ash residue, rather than released with the off gas.

7.1.9. Filtration/ultrafiltration

These techniques are applicable to liquid wastes only. The aim is to remove suspended solids holding the contaminants. Ultrafiltration is the application of filtration to particles of the order of a few microns in size, whereas standard filtration aims to remove coarser particulate material.

7.1.10. Reverse osmosis/membrane processes

These techniques are also only applicable to liquid wastes. The aim of these technologies to remove dissolved contaminants from the liquid stream. Reverse osmosis and some membrane processes act to concentrate the contaminants into a retained stream, permitting the cleaned water to be returned to source. The remaining membrane processes use selectively permeable membranes to remove individual contaminants from the water.

7.1.11. Solar evaporation

This uses natural solar evaporation to dewater the contaminated waters, in a manner similar to the production of sea salt. The aim is to reduce the volume of material requiring further treatment. It is usable when the form of the contamination prevents its re-suspension during the evaporation process. Solar evaporation of contaminated water has been proposed for the Straz deposit (Czech Republic).

7.2. CHEMICAL PROCESSES

These technologies are generally derived from the minerals processing industries. For solids, they rely on the chemical properties of the materials and/or extractants to either selectively remove the contamination, or to enhance physical separation. For liquids, the aim is to reduce the volume of material to be handled by selective removal of contaminants.

7.2.1. Chemical/solvent extraction

This method uses a chemical extractant to remove the contamination from the waste, with the aim of concentrating the activity into a separate liquid stream, which can then be treated/disposed separately. The conditions for chemical extraction (temperature, contact time, etc.) will have a significant affect on the efficiency of extraction. The various applicable chemical extraction techniques for solids include extraction with:

(1) Water;
(2) Inorganic salts;
(3) Mineral acids, and
(4) Complexing agents.

For liquids, solvent extraction is more usual, where a solvent is used to selectively remove the contaminant from the wastewater stream. Solvent extraction is viable when there is a high concentration of contaminant to be removed

However, care must be taken in the selection of the solvent; firstly so that regeneration of the solvent is possible by stripping out the contaminant (to avoid creation of an additional waste), and secondly that the residual solvent in the cleaned wastewater will not result in adverse effects (e.g. non-radioactive pollution of the aquifer or enhanced mobilization of residual activity).

7.2.2. Heap leaching

The contaminated material (generally soil) is excavated and placed (heaped) on an impermeable pad on the surface of the ground. The pad is sloped towards a sump at the bottom edge of the heap. The selected leaching reagent(s) are pumped to the top of the heap and distributed with a drip irrigation system or aerial sprayers. The reagent travels down through the soil, solubilizing and mobilizing the contaminants. The leachate is collected from the sump and pumped to a leachate treatment and regeneration system.

7.2.3. Enhanced soil washing

This method combines the physical separation of soil washing with chemical extraction. The net result is a concentration of the waste material into the fines fraction, and reduced loadings of contaminants in the coarse fractions. The enhancement of standard soil washing improves the decontamination of the cleaned material for return to site.

Additional processes may be added to the basic soil washing process (e.g. crushing, froth flotation, activated carbon addition) and the wash medium may operate with chemical additives to enhance performance, e.g. pH adjusters, detergent addition, coagulants/flocculants, etc.

7.2.4. Enhanced soil leaching

This method combines soil washing and chemical extraction differently than that used for enhanced soil washing. (An example is the UK's EXCEL*CR process, which uses chemical extraction of the contaminant from the fines fraction obtained by standard soil washing.) The net result is the activity is concentrated into the liquid extraction medium, and can be treated separately. The fines are returned to the soil, reducing the loss in fertility. The extractant is normally treated to precipitate the activity and return the (normally expensive) leaching reagents to the process.

Laboratory scale demonstrations have shown the removal of 90% of plutonium in a relatively small clay fraction is possible. Other work has shown the value of chemical decontamination in association with soil washing but concluded that the reagent usage would limit its application to small areas or require efficient recycling of the chemical decontaminants.

7.2.5. Chemical precipitation

This is used to remove soluble activity from liquid, both as a volume reduction method and to permit it to be disposed of separately. This also includes related techniques such as coagulation and floc precipitation. Because of concentration effects and solubility limits, these techniques are more effective for high concentrations of contaminants.

In the specific case of radium contamination, barytes ($BaSO_4$) can be used to co-precipitate radium from the water, as radium can substitute for barium in the mineral structure. Attempts have been made to clean radium contamination from mining waters. In addition, barytes is a desired admixture in any radioactively contaminated materials due to its effective attenuation of gamma radiation.

7.2.6. Ion exchange

Ion exchange is the complement to chemical removal. This removes soluble activity from liquid wastes and concentrates it onto a solid ion exchange material. The ion exchange materials function at lower concentrations of activity than chemical removal. Selection of the correct ion exchange material is important. Certain materials are used to hold the activity for disposal, others can be regenerated using an eluting agent (normally a mineral acid or similar). In the latter case, the concentrated eluant may then be treated by chemical methods.

Examples of ion exchange materials and pseudo-ion exchange materials include:

- natural zeolites (e.g. clinoptilolite);
- synthetic zeolites;
- natural phosphates (apatite);
- supported liquid membrane;
- bone char;
- ferrocyanides.

7.2.7. Electrodialysis

These use semi-permeable membranes in conjunction with an applied electric field to selectively remove the contaminants

Remediation of tritium contaminated groundwater is currently achieved by natural decay of the 12.3 year half-life time of tritium and long times for migration of water through geologic formation. Processes for removing tritiated water are viable (e.g., combined electrolysis-catalytic exchange). However, these processes require extensive capital or energy expenditures.

7.2.8. Adsorption

This uses adsorption of the contaminant by various media, such as Granular Activated Carbon, which is a common medium for drinking water treatment; activated alumina, which can be used for the treatment of some radioactive compounds; and selective complexes, which essentially complex the contaminant and are not regenerable. It is therefore similar to the use of ion exchange.

Adsorption can also be used for radon if decontamination of slowly released gas is required. Polyethylene coated activated carbon is used to adsorb the radon gas, as the polyethylene coating is permeable for radon diffusion but can stop any other gas or vapours which can reduce the adsorption quality of carbon.

Similarly, naturally occurring systems can be used or emulated. For example, the Cretaceous sandstones with kaolinite matrix of the Sudety area (Poland) is an efficient natural adsorbing system combining high permeability with adsorption.

7.2.9. Aeration

Aeration, is used to remove volatile compounds from wastewater. Generally, this is to remove organic compounds with the potential to complex radionuclides. In the context of radioactively contaminated waste waters, aeration can be used to sparge out radon, which can then be treated by other means (see Section 8.2.8). In addition, aeration can be used to alter the redox potential of the wastewater prior to subsequent chemical treatment, to facilitate removal of certain radionuclides (e.g. uranium).

7.3. BIOLOGICAL PROCESSES

These use the same generic processes as for in situ treatment (see Section 5.3.1). Unlike the in situ processes, however, for ex situ treatment the contaminated material, micro-organisms and nutrients are added to a suitable mixing vessel. Conditions are then optimized to degrade the contaminants. Most biological treatment is aimed at degradation of organic materials, and so will have value with mixed (hazardous/radioactive) contamination. Its value for radioactive contamination has not been demonstrated.

The use of mobilizing micro organisms (siderophores, bio mimetic analogues, etc.) is also feasible. These use biochemistry to convert the radionuclides to a soluble form. The process results in a leach solution that is treated to remove and concentrate the contaminants. The treated leach solution is then recycled to minimize costs and secondary wastes.

A difficulty with the use of biological methods is their viability, both in terms of maintaining a viable bioculture (nutrient supply, temperature variations, absence of biocides in the material to be treated), and with the low tolerance of certain micro organisms to high radiation fields.

Simulation of naturally occurring adsorbing systems may be useful in some cases. An example of this is the Bukhovo (Bulgaria) uranium mine [14] where an artificial peat bog with dispersed iron is used to adsorb and accumulate uranium from mining waters.

8. TRANSPORTATION AND DISPOSAL OF WASTE

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 than that used on the site in major civil engineering and mineral extraction projects could be used.

Large volumes of contaminated soil, concrete, asphalt, equipment, vegetation, etc. could arise from the cleanup of a large contaminated area. 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.

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 graders/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. On flat surfaces it may be possible to use a modified road planer;

(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 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.

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 manifest/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.

The objective of disposing of radioactive wastes is to confine the radionuclides within the repository site until they no longer represent an unacceptable risk to the environment and the public. A repository should fulfill two important and related functions in this regard: (1) to limit dispersion of the radionuclides contained in the wastes by waterborne and airborne pathways and (2) to protect the waste from surface and near surface deteriorating processes such as erosion or intrusion by humans, burrowing animals or deep-rooted vegetation.

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 immediately 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. It is likely that for transport of large quantities of material haulage cost will be the largest component of the overall cost.

Conditions are combined in the safety assessment 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.

8.1. METHODS FOR STORING/DISPOSING OF LARGE VOLUMES OF WASTE

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 remediation of a large contaminated site. These designs include:

(a) **Natural basins or valleys**. For a valley, an embankment may be required at the downstream end to form a run-off retention 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) **Underground caverns**. Naturally occurring underground caverns could be used and their use would be governed by consideration of many factors but most importantly the groundwater depth and the movement of groundwater through the cavern. Long term hydro-geological studies would be required to characterize the site.

(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-rap/earthen 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 similar factors to underground cavern above, including groundwater depth and movement through the mine and susceptibility to flooding. These aspects could be difficult to characterize without long-term hydro-geologic studies.

(e) **Specially dug trenches**. If suitable transportation is not available or is prohibitively expensive, it may be necessary to dig many smaller trenches near the site and place the wastes into these. The clean fill removed from the trench could be stockpiled and be used as a cover and/or to raise the trench walls above the normal ground level. A large number of small trenches may be more difficult to delineate and keep track of and do not use land efficiently. The use of specially engineered large trenches or specially dug pits should be considered to eliminate the risks associated with possible embankment failures in other facility designs. Large trenches or pits using sound engineering technology such as that used for well engineered municipal disposal areas could be constructed for the disposal of large volumes of contaminated soil.

(f) **Specially dug underground vaults or disposal cells**. Again the flow of groundwater and hydro-geology of the site would need to be well characterized. Many of these vaults or cells will be constructed so as to retain contaminated material.

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

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 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.

Impoundment facilities are currently in use which hold very large volumes of uranium mill tailings during the operational phase of the mill. Tailings are pumped as a slurry into the impoundments. The latest facilities are designed 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 rehabilitation site will not be in the same form as slurries from mill tailings, much of the generic information on the design and construction of mill tailing impoundment facilities would be of great use in designing and building disposal sites for contaminated soils.

Some highly radioactively contaminated materials may require special handling and disposal depending on the type and activity of radionuclides present and the radiological hazard they pose. If long lived actinides are present in significant concentrations, the wastes may be required to be disposed of in special disposal areas. Care should be taken in the characterization of the waste so that correct assessments are made and high level waste material is not inadvertently categorized as low level waste.

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

8.2. SITE SELECTION

The method of disposal and the selection of the disposal site are determined by many factors. The first requirement is an accurate assessment of the radionuclides involved, their activities and the physical and chemical nature of the material in which they are incorporated. As many disposal sites will be expected to retain the material buried for periods up to 300 or 500 years, site selection criteria require detailed knowledge of site characteristics including the geology and climate of the site. In addition any current or future land use requirements or proposals for the area need to be taken into consideration as well as any other societal concerns. In selecting the method of disposal the availability of expertise and equipment as well as the cost of any proposals should be carefully assessed. The cost of packaging, loading and transporting large volumes of contaminated materials can be the most significant costs associated with the operation and can significantly influence the choice of disposal site.

The sequence of events in the selection of a disposal site and disposal methodology are as follows:

- preliminary planning and detailed assessment of the remediation problem;
- gathering together of existing information on proposed disposal sites and an assessment of any information which is not available but which is required to make an informed selection;
- selection of one or more suitable sites and the development of a programme to get the required information in order to enable site selection;
- selection of the site and further studies to enable detailed planning of the project.

Detailed planning of the methodology to be used and studies of the proposed disposal are essential prior to commencement of operations, as any changes during the work can be very expensive. This will be particularly so if the scale of the operation which has been proposed in not adequate to cope with the size of the problem at hand. It is also possible that the proposed methodology is not suitable for the nature of the contaminated material or for the site or that the site itself has problems which were unrealized but which would become apparent in the future.

9. TECHNOLOGY DEVELOPMENT TRENDS

Existing technologies in many cases are adequate, in principle, for dealing with radioactively contaminated sites. However, not all of them meet such obvious and practically important criteria as "best available technology not entailing excessive cost" and "best practicable environmental option". More efficient, cost effective and safer methods are still needed. It should be noted that many of the currently available methods for cleanup of the residual contamination are very expensive or ineffective in given situations. Moreover, in some cases, there are no known methods for clean up.

The most obvious intervention is the simple removal of contaminated material. However, this may lead to a high cost of contaminant removal and treatment and storage of removed material. The challenge is to find reliable methods which minimize the amount of contaminated material to be removed or to allow the contaminated material to remain on-site, without major impact on the planned land use. The most efficient strategy to minimize or avoid site restoration costs is to identify potential sources of residual environmental contamination and take preventative measures. Thus, the environmental remediation challenge must focus on the source of the material and on restoring and preventing contamination of the waters under and around facilities. Confining contamination, removing the source of contamination, and restoring water containing, as usual, low concentrations of a broad spectrum of contaminants pose problems of enormous magnitude.

Contaminant migration to areas surrounding a pollution source is a major environmental concern and methods are needed to control the spreading of pollution. These technologies could provide short-term containment while the source plume is being remediated or long-term containment for sites presenting no immediate danger or requiring development of new remediation methods.

High priority is placed on treating plumes in situ, so that potential worker and public exposure is eliminated. In situ methods minimize waste material and reduce costs. Innovative treatment technologies, in conjunction with improved subsurface access techniques such as horizontal wells, are encouraged. Biological remediation systems are important. By utilizing the natural ability of plants or microbes to metabolize, sorb, oxidize, or reduce radioactive compounds, significant cost savings can be achieved.

New technology for gaining access to the subsurface for delivering in situ remediation process is needed. Improved methods of constructing impermeable barriers at depths greater than fifteen metres and new methods of installing containment barriers are necessary to reduce construction costs and increase their depth of application. The ability to install horizontal barriers without disturbing surface conditions or structures is needed. New methods to simplify maintenance of reactive and temporary barriers are desirable.

Further investigations should be conducted on selection of technologies, once further information is gathered on Member State environmental problems and technology needs. In many cases, countries will not have the appropriate infrastructure or sufficient funds to conduct remediation using already existing technologies. This is the more so, because no single technology would work for all sites, or even for a single contaminant, and the most remediation technologies must be considered in the form of technology train. Therefore, it is recommended that a further effort be made to promote the establishment of (1) more inexpensive characterization/monitoring field screening tools, (2) more passive, simple techniques for containing contaminants, (3) more universal combinations of methods allowing to cleanup environments from various toxins (radionuclides, chemicals, heavy metals) simultaneously or in consecutive order, and (4) more environmental friendly means and techniques.

The effort will require the use of present resources and the development of new resources to address and solve the problems resulting from the past disposal practices. Very pragmatic and transparent commercial considerations would become effective driving forces for such activities. Already today commercialization of environmental restoration technologies gives to the more developed countries an advantage of significant opportunities abroad — opportunities to test environmental technologies; opportunities to buy or license foreign technologies, and opportunities to market their environmental technologies and expertise in other countries. In turn, the countries with limited resources obtain, in principle, an opportunity to sell technologies and know-how, or to lease an experimental range for technological trials, and by this way, to improve both economic and environmental conditions. If this new tendency (commercialization) will develop steadily, environmental restoration activity can obtain a powerful impetus and, in turn, it can stimulate noticeable progress in legislation, education and science both on the national and international levels.

Currently, research and development work is being pursued in the following areas:

- development and application of appropriate technologies to rehabilitate arable lands. This will preserve and improve the soil fertility and significantly increase ecologically clean (uncontaminated) crop yields;
- reduction of the exposure doses for the remediation personnel, by application of simple and modern technologies;
- application of the technologies decontaminating agricultural semi-finished goods for use in the manufacture of clean products;
- development of practical measures for cleanup of areas affected by settling particulates.

10. HUMAN RESOURCES DEVELOPMENT

Trained staff working at various levels of remediation action is of vital importance for the success of operation. Possible groups are as follows:

- programme managers and designers;
- supervising staff;
- health physics and health protection personnel;
- equipment operators;
- labour force.

Because of its complexity, workers on a remedial action need a wide range of skills and experience. Labourers should be able to critically analyse the situation for both individual safety and the general success of the operation. Equipment operators should be empowered to make decisions about the depth of excavation etc. Supervising staff must be able to modify the plan according to changing conditions (e.g. weather). Project designers and managers should be able to prepare a holistic approach to the problem, including technical, legal, economic and natural science issues. They also need to determine the education level required from their staff.

Formal recognition of qualifications is a problem. The existing trend is to create international levels of professionals recognition, promoted in most cases, by professional organizations. In some countries a special exam after years of practice is required to confirm the qualifications. It is suggested that the following measures are undertaken:

- development of training courses for environmental restoration designers and managers;
- national educational activities oriented toward supervising staff and equipment operators with possible international recognition;
- preparation of educational books, films and user-friendly computer programs These activities are also important from the point of view of pubic relations and preliminary education of staff. Widespread radioecological knowledge is especially important in the case of large contaminated areas where even individual farmers may be involved in decontamination activity. In this case the national educational (consulting) networks for farmers or farmers associations can be used. Radioecological information and education should be also offered to green ecological clubs and movements.

11. SUMMARY AND CONCLUSIONS

The variety of technologies and related research and development programmes presented in this report are intended to provide the reader with information on international activities in practical and engineering issues in environmental restoration activities. These materials may be called upon to promote corresponding programmes both on national and international levels, and to focus the efforts on the actual issues within environmental restoration.

A great deal of information has been presented in this report. Some of these techniques are readily available and relatively inexpensive to employ, while others still require further refinement and development. A great effort must be given to organizing the remediation work to best utilize available resources and give greatest advantage to technology research and development.

Technology is not a separate part of environmental remediation activities, and complete cleanup of contaminated sites should never be considered as the end in itself. The primary and, perhaps, the only aim of environmental restoration is reduction or elimination of the risk to human health including ethical, social, psychological and economic impacts.

This report has also highlighted areas needing further research and development. They can be summarized as follows:

- minimizing hazardous and radioactive waste increasing effectiveness of environmental restoration projects through systematic approaches and careful justification of the necessity of environmental intervention;
- eliminating the probability of recontamination; and
- introducing low cost, low waste, safe and productive cleanup technologies and techniques.

Active research and development in many countries can offer, in principle, potentially effective and inexpensive techniques to effect remediation. However, there is no single generic solution to site remediation. Thus the effort will require the use of present resources and the development of new resources to address and solve the problems resulting from the past practices.

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Appendix

SELECTION OF PREFERRED TECHNOLOGIES

This appendix is intended to provide some guidance for the selection of preferred technologies for remediation. A methodology applicable to the selection process is briefly described.

Technology evaluation factors can be developed for use in a structured approach to the selection of appropriate technologies. In order to make defensible decisions, the technology evaluation factors should be assessed in an integrated manner. Their consideration in isolation will address mutually conflicting requirements. For example, increased reduction of the risk posed by a given problem to the health and safety of the public may require considerable expenditures of resources.

Table A.1 lists the technology evaluation factors presented in the text above and also provides a subjective ranking scale for each factor. The scale offers three categories which can be classified as exemplary, acceptable, and unacceptable. A technology assigned as unacceptable would be disqualified from further consideration.

Table A.2 presents an evaluation matrix in which evaluations of all the factors for a particular technology can be presented together. No attempt is made to produce a single "score" or "grade". However, this is often found to be a useful next step when comparing options.

Table A.3 illustrates an evaluation of three hypothetical technologies. The application of this approach is left to the reader.

TABLE A.1. TECHNOLOGY EVALUATION FACTORS

EVALUATION	RANGE		
FACTOR	**EXEMPLARY**	**ACCEPTABLE**	**UNACCEPTABLE**
	6 | 5 | 4	**3 | 2 | 1**	**0 | Fail**
Performance	Near 100% removal	Removes contaminants to desired limit	Mobilized or additional contaminant
Reliability	Near 100% reliable	Available without excessive down time	Unreliable
Maintenance Required	Minimal	Occasional	Spares/suppliers unavailable or at great cost and delay
Cost	Costs recoverable against credits (energy, usable products, etc.)	Cost within acceptable levels	Excessive cost
Infrastructure available to support technology	Not needed or fully available and already in place	Available	Unavailable or requires significant expense to provide
Availability	Well proven and 'off the shelf''	Demonstrated and available in short time frame	Unproven/early in development
Risk to public and operators	No risk to public or operators	Risk to public or operators within regulatory guidelines	More risk than if nothing done
Impact on environment	Clean and green	Little effect on overall ecosystem	Significant pollution/damage
Regulatory acceptance	Exceeds regulatory standards	Meets rgulatory standards	Fails regulatory standards
Community acceptance	Wholehearted acceptance without reservation	Acceptance with two-way dialogue	Unacceptable

TABLE A.2. TECHNOLOGY EVALUATION MATRIX

TECHNOLOGY NAME:									
EVALUATION	**RANGE**								
FACTOR	**EXEMPLARY**			**ACCEPTABLE**			**UNACCEPTABLE**		
	6	**5**	**4**	**3**	**2**	**1**	**0**		**Fail**
Performance									
Reliability									
Maintenance required									
Cost									
Infrastructure available to support									
Availability									
Risk to public and operators									
Impact on environment									
Regulatory acceptance									
Community acceptance									
DESCRIPTIVE EVALUATION:									

TABLE A.3. EXAMPLE TECHNOLOGY COMPARISON (A vs B vs C)

TECHNOLOGY NAME: Technology A

FACTOR	**EVALUATION SCORES**								
	EXEMPLARY			**ACCEPTABLE**			**UNACCEPTABLE**		
	6	**5**	**4**	**3**	**2**	**1**	**0**		**Fail**
Performance			X						
Reliability			X						
Maintenance required				X					
Cost					X				
Infrastructure available				X					
Availability		X							
Risk to public and operators				X					
Impact on environment				X					
Regulatory acceptance				X					
Community acceptance			X						

DESCRIPTIVE EVALUATION:
- all factors are evaluated as “Acceptable” or better
- exceeds Technology B on “Availability” and “Community acceptance”
- exceeds Technology C on “Cost” but is slightly less attractive in “Community acceptance”
- overall, exceeds Technology B and C

TABLE A.3. (cont.)

TECHNOLOGY NAME: Technology B

FACTOR	**EVALUATION SCORES**								
	EXEMPLARY			**ACCEPTABLE**			**UNACCEPTABLE**		
	6	**5**	**4**	**3**	**2**	**1**	**0**		**Fail**
Performance			X						
Reliability			X						
Maintenance required				X					
Cost					X				
Infrastructure available				X					
Availability		X							
Risk to public and operators				X					
Impact on environment				X					
Regulatory acceptance				X					
Community acceptance							X		

DESCRIPTIVE EVALUATION:
- fails evaluation on "Community acceptance"
- this technology not considered
- overall, should consider Technology A or C

TABLE A.3. (cont.)

TECHNOLOGY NAME: Technology C

FACTOR	EVALUATION SCORES								
	EXEMPLARY			ACCEPTABLE			UNACCEPTABLE		
	6	5	4	3	2	1	0		Fail
Performance			X						
Reliability			X						
Maintenance required				X					
Cost							X		
Infrastructure available				X					
Availability		X							
Risk to public and operators				X					
Impact on environment				X					
Regulatory acceptance				X					
Community acceptance		X							

DESCRIPTIVE EVALUATION:
- all but “cost” factor are “acceptable” or better
- if “cost” can be improved, this could be a viable technology
- preferred somewhat by public over Technology A
- overall, Technology A seems a better choice

Annex I

AUSTRALIA – EXAMPLE OF REMEDIATION EXPERIENCE AT A NUCLEAR WEAPONS TESTING SITE

I-1. INTRODUCTION

The Maralinga and Emu sites are located in the state of South Australia in the region south of the Great Victoria Desert and north of the Nullarbor Plain (Fig. I-1). Maralinga is 270 km north west of Ceduna. Emu Field is about 190 km northeast of Maralinga.

Between 1953 and 1963, the United Kingdom conducted several programs of nuclear warhead development trials at Maralinga and Emu [I-1]. Nine major nuclear trials involving atomic explosions, and several hundred smaller scale experiments ('minor trials') which dispersed radioactive materials, were carried out. In addition three major trials were carried out on the Monte Bello Islands off the northwest coast of Australia. A cleanup of the Maralinga and Emu sites (Operation Brumby) was undertaken by the United Kingdom in 1967 [I-2].

The nine atomic explosions deposited fission products in the form of radioactive fallout downwind of the ground zeros and induced some radioactivity in the soil [I-3]. Some explosions, particularly those on low towers, fused sand into 'glazing'. Today the radiological hazard at these sites is minimal and, because of the relatively short half-life of the fission and activation products, within 30 to 50 years these sites will be suitable for unrestricted occupancy.

The situation at some of the so called 'minor trial' sites is not so acceptable. Five minor trials at Emu and several hundred at Maralinga involved the dispersal by burning and explosion of radioactive materials including uranium and plutonium. About 22 kg of plutonium was dispersed explosively in narrow plumes in the Vixen B trials at Taranaki. The residual plutonium in surface layers exists as a finely divided dust, as small sub-millimetre particles, and as surface contamination on larger fragments of debris. In the central area at Taranaki, the surface soil was mixed by ploughing to a depth of 15–25 cm (Operation Brumby) in an attempt to reduce surface contamination [I-4].

Contaminated debris, soil and general rubbish, was buried in pits in the forward area at Maralinga. Those pits known to contain radioactivity were recorded and numbered. Twenty one numbered burial pits at Taranaki are believed to contain greater than 2 kg of plutonium associated with an estimated 830 tonnes of debris and 1120 tonnes of soil from the Vixen B trials. These pits are capped with about 65 cm of reinforced concrete. Four numbered pits outside of Taranaki contain about 90 g of plutonium and small quantities of other radioactive and toxic material. Up to seven tonnes of uranium are contained in pits at Kuli. Some plutonium has been detected in five out of eighty three unnumbered pits in the Maralinga area. The crater formed by the Marcoo event (a major trial) was used to bury a considerable quantity and variety of debris and soil including some contaminated with plutonium.

Surface contamination levels at Maralinga and Emu were measured in an aerial radiological survey covering 1550 km² which included the major and the minor trial sites. Detailed ground measurements have been made in limited areas of Maralinga and Emu. A total of approximately 100 km² of land is contaminated to a level for which estimated doses exceed 5 mSv per year.

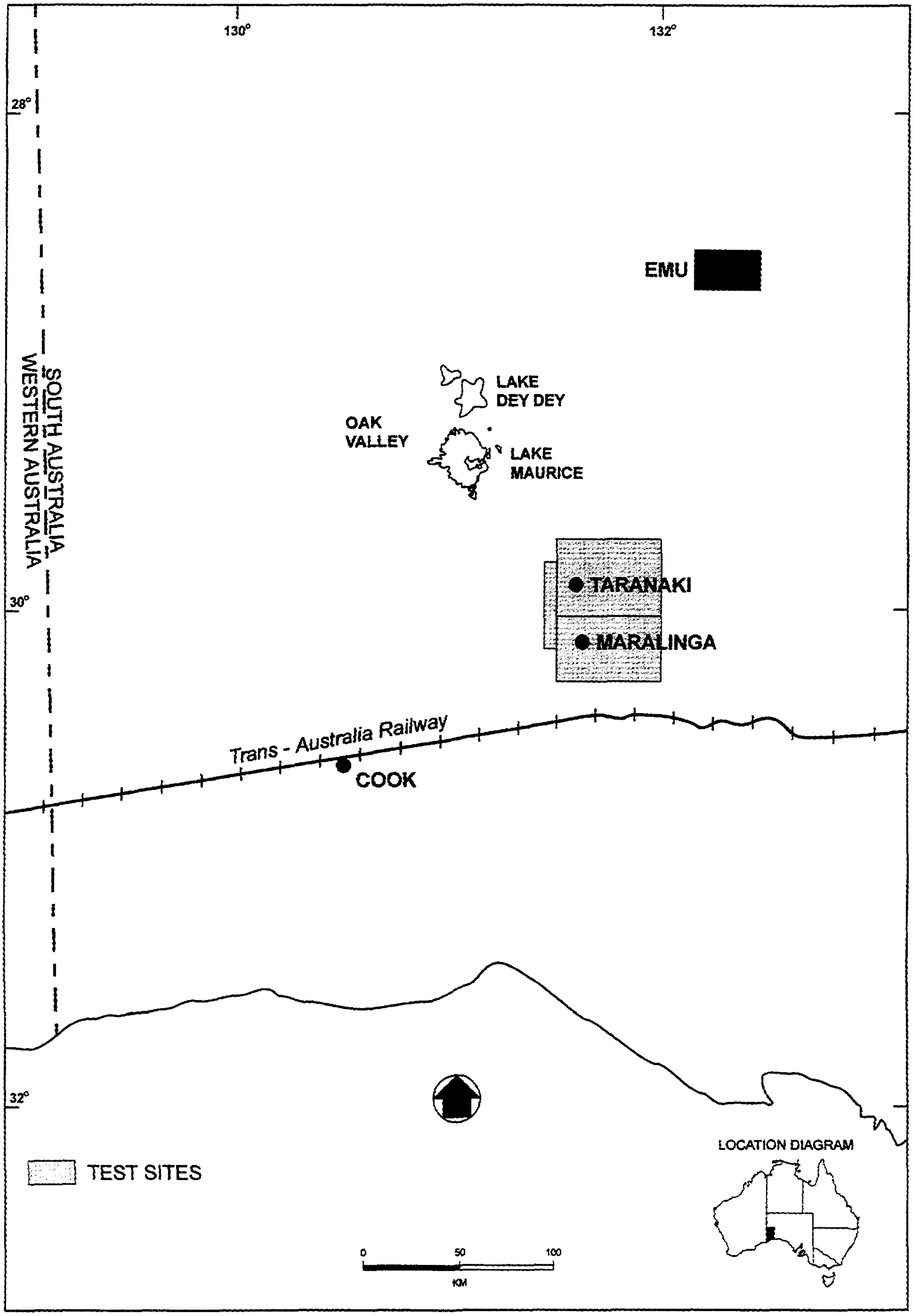

FIG. I-1. Location of Maralinga and Emu.

I-2. MARALINGA REHABILITATION STUDIES

In February 1986, the Australian Government established a Technical Assessment Group (TAG) to report in detail on options, and associated costs, for the decontamination and rehabilitation of the Maralinga site [I-5].

Studies were commissioned by TAG to provide the necessary input data to develop clearance criteria, engineering options and costs. The first five studies established the base data needed to determine a level of acceptable contamination for each of the land use options considered. These studies were in the following areas:

- anthropology;
- radioecology;
- bioavailability;
- inhalation hazard assessment;
- radiochemical and chemical analysis.

In addition, an aerial radiological survey provided contamination contours for the major areas at Maralinga and Emu, and a dosimetric modelling study brought together the data from the other five studies and assessed the range of potential annual radiological doses from 100 per cent occupancy of the areas.

In considering options for the cleanup of the sites it was assumed that possible human access would cover the range from:

(i) fully unrestricted habitation by Aboriginals including the case of high dependence on local plants and animals for food; to
(ii) casual access assuming retained or, if necessary, extended fences.

The TAG studies showed that residual plutonium contamination of soil from the minor tests is the predominant contributor to potential radiation dose at the former nuclear test sites. At four sites plutonium was explosively dispersed and it is at these sites that potential doses are the highest and remediation is required. The sites of concern are:

Wewak **(Vixen A trials)** – where two plutonium burnings involving a total of 410 g of plutonium and four explosive dispersals of a total of about 570 g of plutonium took place;

TM100 and TM101 – where explosive dispersals of plutonium (about 600 g at each site) took place at both of these locations; and

Taranaki – where in 12 Vixen B trials, conducted between 1960 and 1963, 22 kg of Pu-239 along with a similar amount of U-235 was explosively dispersed, carrying plutonium contaminated debris many kilometres downwind.

The plutonium contamination at Taranaki is the most widespread and occurs mainly in three forms – as a fine dust, as sub-millimetre particles, and as surface contamination on larger fragments of debris. The fine dust was dispersed for many kilometres in narrow plumes while the remaining contamination stayed within several hundred metres of the firing pads. The central area at Taranaki was ploughed during Operation Brumby, mixing the surface contamination to depths of 15–25 cm. This area still contains many thousands of contaminated fragments which are large enough to attract attention as souvenirs and are active enough to constitute a significant radiation hazard.

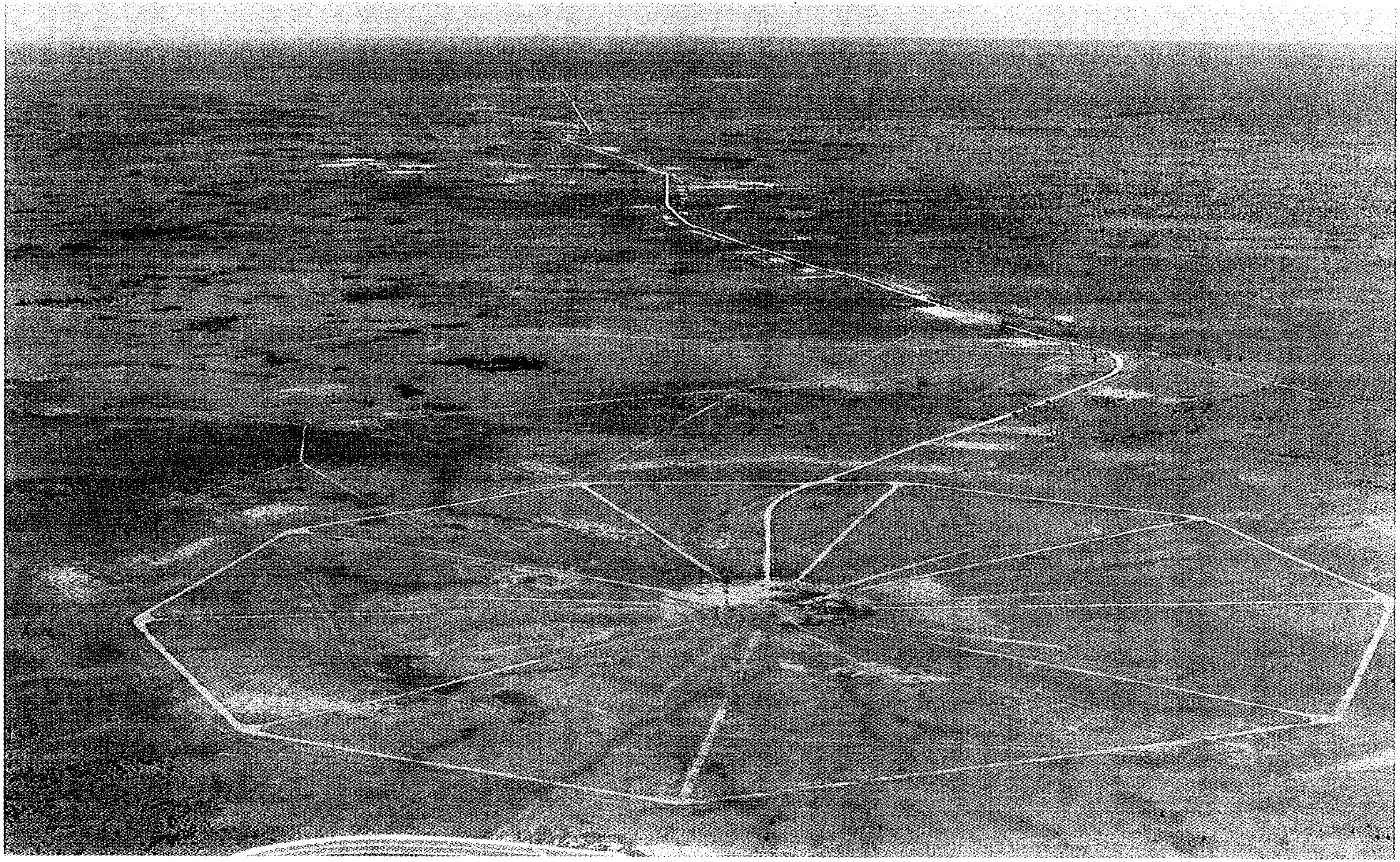

FIG. I-2. Taranaki test site where 12 Vixen B trials took place. (Photograph courtesy of Geosafe Australia).

TAG assessed the level at which risks became unacceptable considering social, economic and scientific factors. It was considered that the contour corresponding to an annual committed dose of 5 mSv, based on 100% occupancy, was the border-line between acceptability and unacceptability of risk [I-6]. In recommending this cleanup contour, corresponding to an annual committed dose of 5 mSv per year based upon an average soil concentration of plutonium and americium, it was recognized that a few discrete, highly radioactive particles may remain, but that because the probability of contamination of an individual is low, averaging the soil concentration is an adequate approach.

The options to reduce dose which were assessed included the following:

- restricting access by fencing;
- removing and burying contaminated soil in a specially constructed trench;
- mixing soil in areas of low contamination to reduce the average concentration of activity;
- processing the contaminated soil to concentrate the radioactivity into a smaller volume which would then be buried and the major portion of uncontaminated soil returned to the site;
- treating burial pits to immobilize the pit contents; and
- exhuming burial pits and burying the exposed debris in either a sub-trench in the specially constructed trench referred to above, or in a specially constructed borehole.

Following the recommendations of TAG, a remediation program was developed which involved treating the contamination on the surface by restricting access by means of fencing or warning signs in areas of low concentration, and by soil removal in areas of high concentration. It was also decided that the contents of the active burial pits would be immobilized by a process of in situ vitrification (ISV), which involves passing an electric current through electrodes in the ground to melt and vitrify the contents of a pit.

I-3. CLEANUP CRITERIA

The plutonium used in the minor trials at Maralinga comprised ^{239}Pu, ^{240}Pu and ^{241}Pu. The ^{241}Pu has a half-life of 14.4 years and has since decayed to ^{241}Am, which emits a gamma ray and is a useful means of detecting plutonium in the field. The ratio of ^{239}Pu/^{241}Am has been determined for each site [I-7] and clearance levels have been calculated in terms the activity of ^{241}Am per square metre, averaged over an area of 3 km^2. At Taranaki, access to areas with contamination levels greater than 3 kBq/m^2 is to be restricted and soil is to be removed from areas with greater than 40 kBq/m^2. Soil will be removed to achieve levels less than 3 kBq/m^2, determined experimentally as an average over an area of 1 hectare.

At the Wewak, TM100 and TM101 sites, soil will be removed up to achieve the levels given in Table I-1, which also gives the areas to be treated.

TABLE I-1. TARGET LEVELS FOR SOIL REMOVAL AT WEWAK

Trial site	^{241}Am surface concentration (kBq/m^2)	Area (km^2)
Taranaki	3. 0	1. 50
TM100	1. 8	n.a.
TM101	4. 0	0. 46
Wewak	1. 8	0. 31

The cleanup criteria also included the requirement that no observable fragments contaminated with ^{241}Am nor particles with activity greater than 100 kBq, should remain after the cleanup, and there should be no more than an average of one fragment or discrete particle of activity greater than 20 kBq per 10 m^2. Where fragments are found to lie beyond the soil removal contour, adjustments to the contour may be necessary or the fragments may be removed individually in a separate operation. After verification of the effectiveness in removing the contaminated soil, fragments and particles, the sites will be reinstated with clean soil to aid revegetation.

I-4. REHABILITATION METHODOLOGY

The recommended strategy of TAG included the removal of contaminated soil from the areas most contaminated with plutonium, the burial of this soil in one or more burial trenches, and the reinstatement of these areas with fresh soil to promote revegetation. In identifying the available options for these soil-removal operations, the following criteria were considered:

(i) effectiveness in removing the contaminated soil to the required depths;
(ii) the radiological and conventional safety of the operations;
(iii) minimization of the overall cost of the program;
(iv) flexibility of the selected plant within the overall program;
(v) reliability of equipment and methodology and minimization of complexity;
(vi) compatibility of processing rates with other program objectives; and
(vii) reasonableness of demands on workers in terms of their working environment, training needs, work precision requirements, etc.

I-4. 1. Dust control

In recognition that airborne dust presents the major hazard in the removal of contaminated soils, there was considerable investigation of ways to minimize dust levels. From previous studies and the soil characteristics at Maralinga it was apparent that generated dust presents potential radiological health risks to operators in the field during remediation activities and that the risk of spreading contamination from contaminated areas onto clean or cleaned areas during soil removal and transportation activities had to be considered. Two main dust control strategies, dry and wet, were considered. The dry approach involves the minimization of dust formation by reducing the rates at which energy is transferred to soils thorough shearing and dropping operations, etc, and by enclosing dust-generating areas to the maximum possible extent and using local vacuum dust extraction systems on equipment. The wet approach involves the thorough soaking of soil prior to removal. Between these options are variants which use portable dust extraction systems or water sprays to suppress and remove formed dust.

It was concluded on the basis of the available data and experience of previous cleanups, both at Maralinga and elsewhere, that both the wet and dry approaches for soil removal can be successfully engineered to achieve the desired rehabilitation. Both options have advantages and disadvantages.

The major uncertainties with the dry approach relate to the maximum amount of recontamination which could be expected from spreading dust and whether adequate personnel protection could be achieved. An assessment of the recontamination scenario showed that even for dust from the most contaminated area and with the worst-case spreading characteristics, the maximum extent of recontamination would only be to half the cleanup limit and for all reasonable scenarios would be very much less. The approach to ensure personnel protection involves all operations being carried out from within plant with sealed and pressurized cabs with personnel only being on the ground after potential dust-raising operations have ceased.

The studies concluded that, although the application of water is the most practical dust control method available, it alone could not eliminate the problem to the extent that no other form of protection was required, and that the balance of advantages resides with the dry approach, which offers the simpler, faster and cheaper approach. The application of water for dust suppression would also lead to problems with additional contamination of plant, etc. This led to the decision to favour drier operations and to build HEPA, filtered air protection systems into the operator cabins of all equipment operating in areas where there is contaminated soil and debris.

In order to reduce the impacts of any spillages or dust spreading, soil will be removed from the most distant areas first, working towards the burial trench. This has the advantage that the bulk of the soil transport operations will take place within contaminated areas and will be by a system of haul roads which can be incrementally removed as an integral part of the soil-removal operation.

I-4.2. Burial trenches

Assessing the options for the location of the burial trenches and for the disposal of contaminated material involved consideration of a number of factors including local geology, proximity to the soil removal areas, contamination levels at the trench location, and haulage distances. A major outcome of these studies was that haulage costs are a significant component of the soil-removal costs, while bulk excavation costs are relatively cheap. Consequently, excavation of burial trenches at each of the three soil removal locations, Taranaki, Wewak and TM 100/101, would be the most economical option unless geological conditions were very unsuitable. The additional costs for blasting rock are not such that economies would be made by moving the trench any significant distance to minimize the amount of blasting required.

Trench excavations are to be located in areas which are essentially free of contamination in order to simplify operations. This will enable the excavation of the trench to be carried out with only the minimum of health physics controls and without the need to modify plant.

The areas in which the trenches may be excavated were of sufficient size to allow for a range of trench plan shapes to enable contractors to select a shape best suited to their working methods. The same basic requirements for depth of burial and cover over the contaminated materials will be maintained for all proposed trench designs.

Excavation of the trenches will be by traditional earthmoving methods such as scrapers, bulldozers, front end loaders and trucks to remove and stock-pile the surface soil. The calcrete and dolomite cap requires blasting while geotechnical investigations indicate that the underlying sandstone is rippable. The ripped and blasted rock will be transported to individual stockpiles located close to the trenches to minimize haulage costs and facilitate backfilling of the trenches.

The different types of material from the excavation will be stock-piled separately. The topsoil, claystone and sandstone require special management in the stock-piles. Topsoil is recommended to be placed in stockpiles not exceeding 2 m in height and should be seeded with a cereal rye in conjunction with a synthetic surface stabilizer to stabilize the surface. Claystone requires stockpiling in such a manner that prevents the loss of moisture, as it will be very difficult to increase the moisture content once the material dries. Salinity tests on the borehole material show that the salinity increases with depth. Therefore, the material should be stockpiled such that the deeper and more saline sandstone from the bottom of the excavation is used first when backfilling the trench.

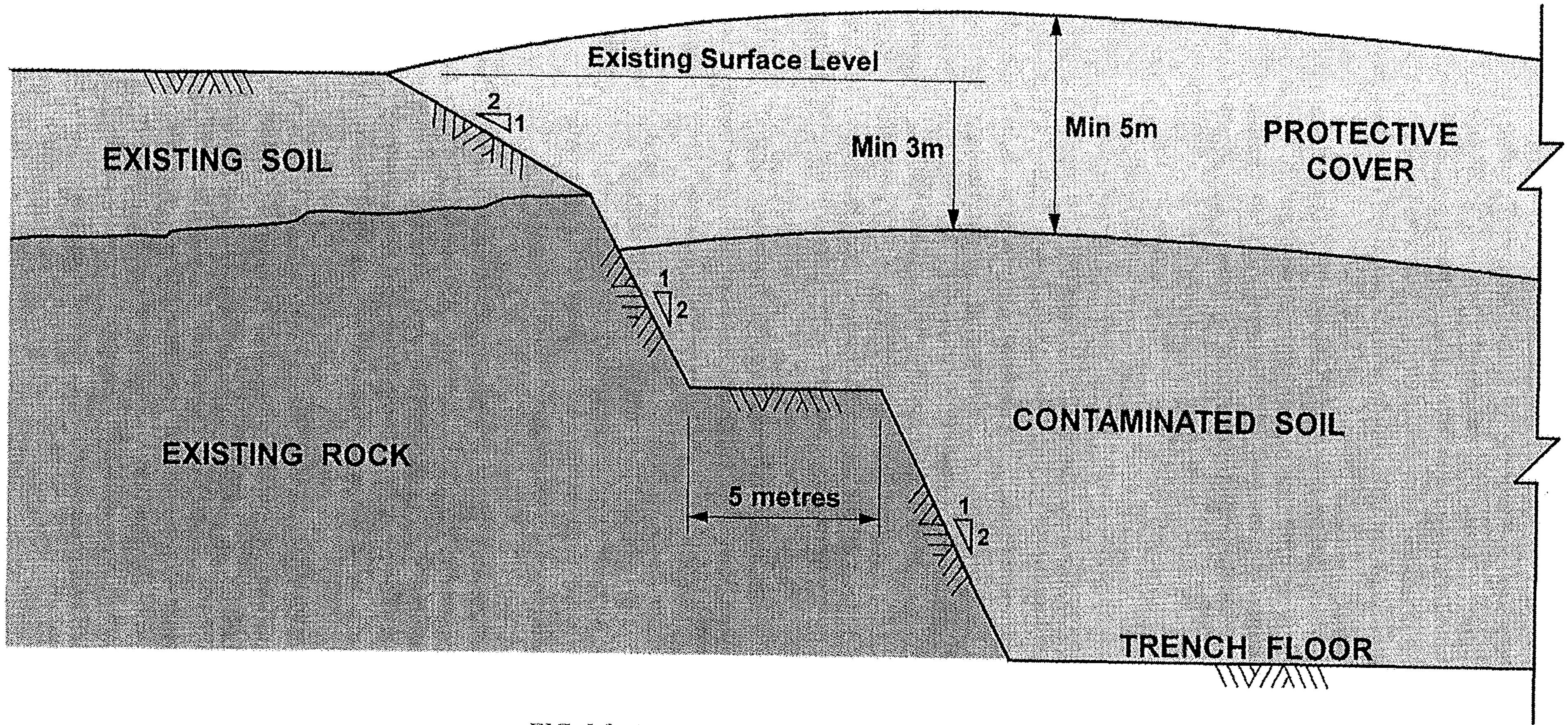

FIG. I-3. Cross-section of typical burial trench.

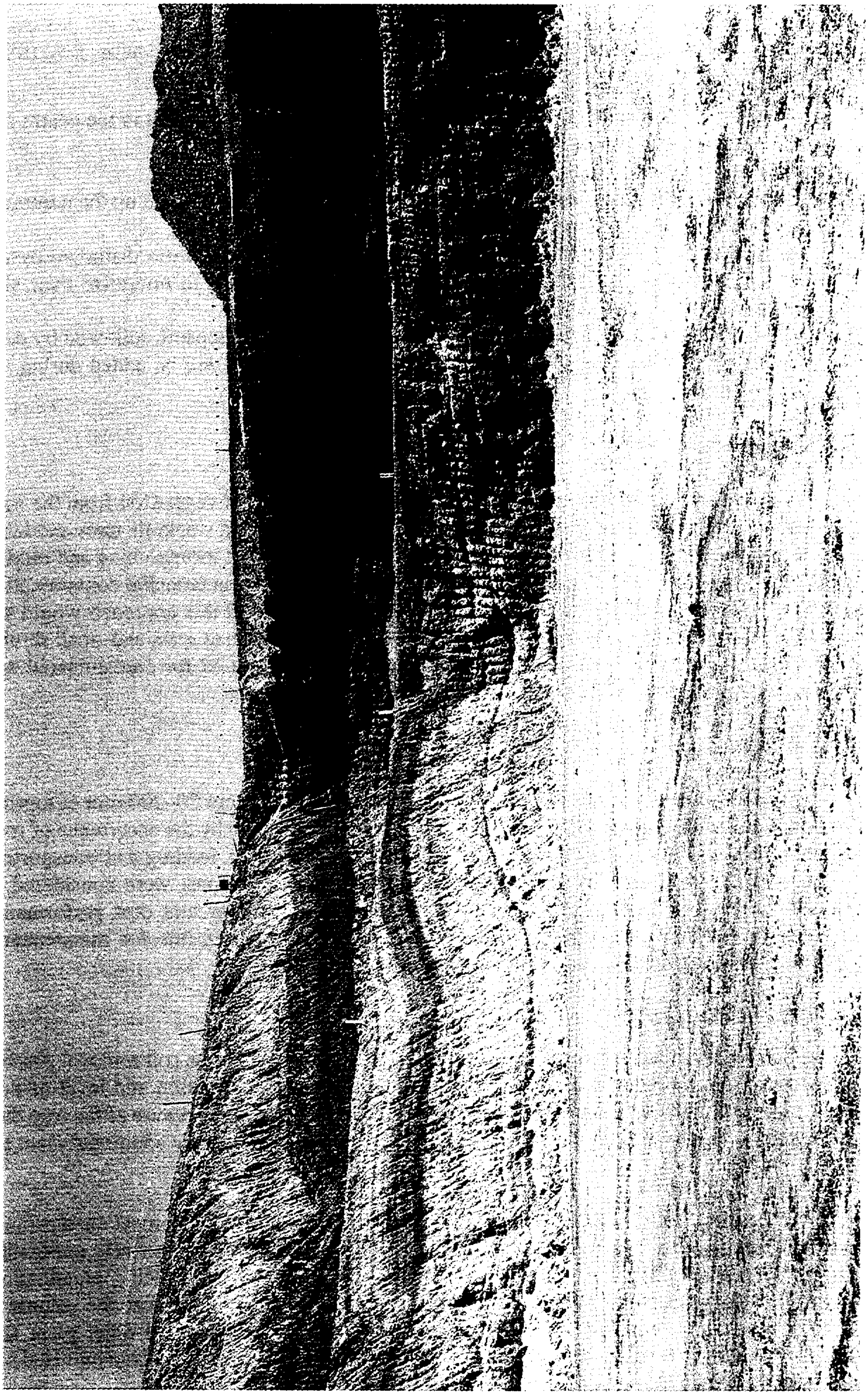

FIG. I-4. The burial trench at Taranaki. (Photograph courtesy of Geosafe Australia).

Once the contaminated soils and debris have been placed in the trench, the process of backfilling with uncontaminated materials is a straightforward earthmoving operation. Backfilling will be undertaken in the following order:

(i) backfill with sandstone to just above the natural surface with a mound in the centre and using the more saline sandstone first;
(ii) place any claystone material in a layer over the sandstone backfill;
(iii) place at least 1 m of the less saline sandstone over the claystone to build up the minimum cover of 5 m over the contaminated soil in the trench;
(iv) spread the topsoil from the stockpile over the trench and other areas disturbed by the trench excavation with the remaining stockpiles to be shaped to minimize their side slopes;
(v) place a 300 mm layer of calcrete and dolomite rock over the topsoil, followed by deep ripping to mix the rock with the topsoil. Fertilizer and seed will be added during the ripping process.

I-4.3. Vegetation removal

The first step in the process will be to remove any significant vegetation from the soil-removal areas. The preferred vegetation removal method is to grub and stockpile trees and large shrubs using machines, followed by burning. Collecting the vegetation for mulching and mixing with the topsoil to aid revegetation was considered to present significant potential contamination problems. Also, the volume of mulch obtained would be small and this approach would not warrant the effort and health risks involved. Low level vegetation, such as grass and small shrubs, which will not affect the performance of the earthmoving plant used for contaminated soil removal, will be removed as part of that process.

I-4.4. Soil removal

The soil-removal process requires the removal of between about 50–200 mm of topsoil. In some areas, such as central Taranaki, the removal depth is restricted by the occurrence of rock near to the surface. Possible equipment and techniques for excavating, loading and transporting the contaminated soil were identified and compared. These techniques were considered in combinations and then ranked using criteria which included risks to operators, cost, performance effectiveness and dust-generating characteristics, as well as requirements for maintenance, monitoring, decontamination and operator training and control.

I-4.4.1. Earthmoving plant

Features considered when assessing the suitability of plant for the soil removal process were accuracy in removing thin layers of soil, speed of topsoil excavation and level of dust generation. Some plant are susceptible to producing cross-contamination because of the way they handled soil, or because they collect soil in piles which requires handling by additional plant for removal.

At Taranaki soil decontamination factors up to 1000 are necessary to meet the clearance limit. This limit will be very difficult to achieve with wheeled plant and effectively impossible to meet with tracked plant due to their tendency to mix surface soil, and hence contamination, with deeper layers. Because of this mixing, the use of tracked plant will increase the volume of soil to be removed compared to rubber-tyred plant. Front-end loaders and other plant that generally drop the material when unloading are also less preferred for handling contaminated soil because of their higher potential to raise contaminated dust.

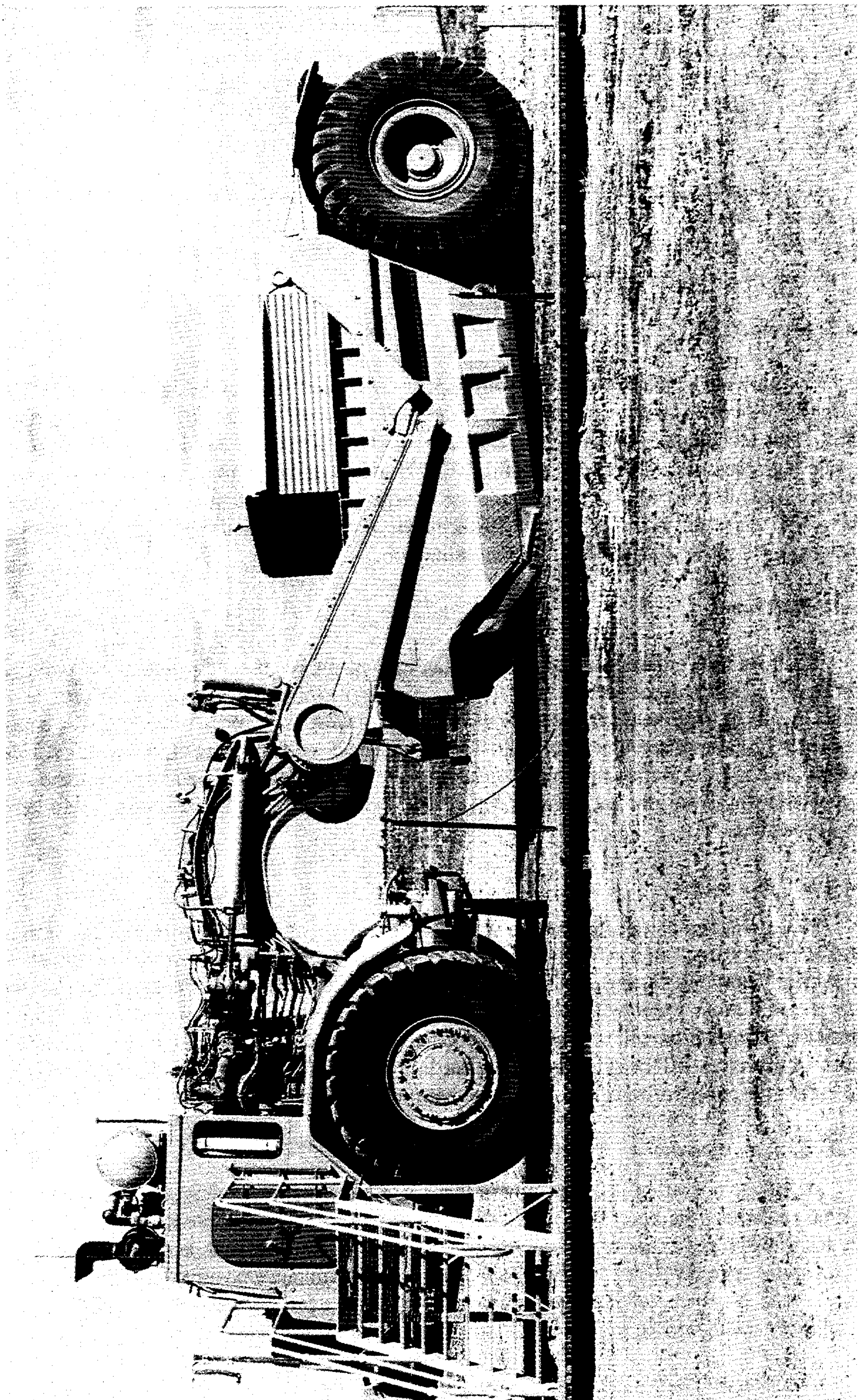

FIG. I-5. Modified scraper used for soil removal showing sealed cabin with HEPA filtered air intake. (Photograph courtesy of Geosafe Australia).

Equipment considered includes scrapers, bulldozers, excavators, front-end loaders, graders, road planers and soil skimmers. Loading options considered include front-end loaders, excavators, force feed loaders with conveyors, backhoes and scrapers, while for soil transport they also include quarry and articulated dumper trucks, conveyor belts, bucket trains and fluid conveyors.

These studies identified the auger scraper as offering the greatest overall efficiency, taking into consideration all aspects associated with the process, i. e. being capable of soil removal, transport and effective deposition of soil in the trench. However, it was acknowledged that the same ends could be achieved using a variety of plant.

I-4.4.2. Exposed rock

It is anticipated that soil removal will expose significant areas of the calcrete layer, which is close to the surface, and it may be necessary to clean the rock surface to meet the acceptance criteria. The techniques evaluated for this duty include brushing, vacuuming, abrasive jet cleaning, high pressure water jetting and the use of scarifiers and road planers. The methodology developed for soil removal recommends the use of road sweeper-type plant to clean the surface of rock. The use of air jets to clean rock surfaces will not be permitted due to the possibility of resuspension of significant amounts of contamination.

I-4.4.3. Haul roads

The haul routes that the subcontractor may use will be based on the general requirement that soil collection commences at the furthest point from the burial trench in the area to be cleaned. It is likely that the haul roads will be constructed with main roads running up the centre of each major plume of contamination with a series of finger roads running off to the sides. Haul roads will be confined to the soil-removal areas except for the sections of haul road from the soil-removal area to the burial trench and to the Forward Area facilities. These sections will be as short as practical.

I-4.4.4. Soil placement

Placement and compaction of the pre-wetted surface soil will be performed as a normal earthmoving activity. Soil will be dumped from trucks and spread in loose layers of approximately 200 mm depth or unloaded in similar layers from scrapers. If the soil is relatively dry on arrival, more water will need to be added using a water tanker or sprinklers prior to compaction. Compaction will be undertaken soon after placement to ensure that soil moisture is not lost. Compaction will be achieved by the earthmoving plant running over the surface, as the requirement for compaction is to be such that earthmoving plant can operate in the trench.

I-4.4.5. Plant modifications

All plant operating in zones where there is a hazard from contaminated dust will be modified to protect the operators, who will work within a sealed and pressurized cabin, with filtered air intakes and extracts, without the need to wear special personal protection equipment. The protective system will supply absolute filtered air and maintain a positive pressure within the cabins. The filter system will incorporate a primary cyclone, a pre-filter and double HEPA filters. Air inside the cabin will be sampled and monitored for alpha particle emitting radionuclides.

The scraper bowls will be enclosed and vacuum extraction systems installed to cover dust generating areas.

I-4.6. Revegetation

Areas left denuded of vegetation by the proposed works will be revegetated to the extent practicable. There are a number of factors in the Maralinga area which limit the success of revegetation works. These include low and unreliable rainfall, shallow soils with low fertility, rabbits which could graze out young seedlings, and very saline groundwater which is unsuitable for irrigating plants.

The general approach to revegetation of the soil-removal areas is to use surface soil from the surrounding area and place small amounts at regular spacing over the rehabilitation areas. This imported soil will contain seed, organic matter and fungi which assist plant growth. Additional seed will also be added. Calcrete and dolomite rubble from the trench excavation will be placed around the imported soil and act as traps for wind blown soil.

Seed for the revegetation will be locally collected from native species. Seed will be collected from outside the contaminated areas and within 100 km of the site. The direct seeding method using machinery is preferred over the more traditional method of raising and planting seedlings. Direct seeding is less expensive, does not require a follow-up watering program and has been used successfully in environments similar to Maralinga.

I-5. TREATMENT OF BURIAL PITS

In situ vitrification (ISV) is being deployed to treat a series of 21 burial pits containing soil and debris primarily contaminated with plutonium and uranium at Taranaki. Three options were considered for stabilization of the pits: exhumation and re-burial of the pit contents, stabilization by concrete grouting, and stabilization by ISV. The ISV technology was selected because it appeared to have advantages of improved occupational, public, and environmental safety together with superior containment of the radioactive materials in the vitreous product, which would be substantially more durable compared to alternative stabilization methods.

I-5.1. The in situ vitrification process

In situ vitrification is a thermal treatment process that involves the electric melting of contaminated soils, sludges, or other earthen materials for the purposes of permanently destroying, removing, and/or immobilizing hazardous and radioactive contaminants. The ISV process is illustrated in Figs I-6 to I-9 and involves forming a melt at the surface of a treatment zone between an array of four electrodes, at temperatures between 1600–2000°C. The typical process rate is three to six tonnes per hour and melts up to 7 m deep and 15 m in diameter are possible [I-8].

I-5.1.1. Vitrified product characteristics

When electrical power is shut off, the molten mass solidifies into a vitreous monolith with excellent physical, chemical, and weathering properties. The vitreous product generally consists of high concentrations of silica (50–80%) and low levels of alkali oxides (1–5%), and is extremely durable and highly leach resistant. Leach test results indicate that the vitreous product is typically 5 to 100 times more durable than borosilicate glasses used to immobilize high level nuclear wastes.

A subsidence volume usually occurs above the vitreous monolith because of volume reduction. The monolith is most often left in the ground but can be removed with conventional heavy equipment.

FIG. I-6. The melt surface between four carbon electrodes during ISV trial. (Photograph courtesy of Geosafe Australia.)

FIG. I-7. Plutonium contaminated steel plate being positioned for an intermediate scale ISV trial. (Photograph courtesy of Geosafe Australia.)

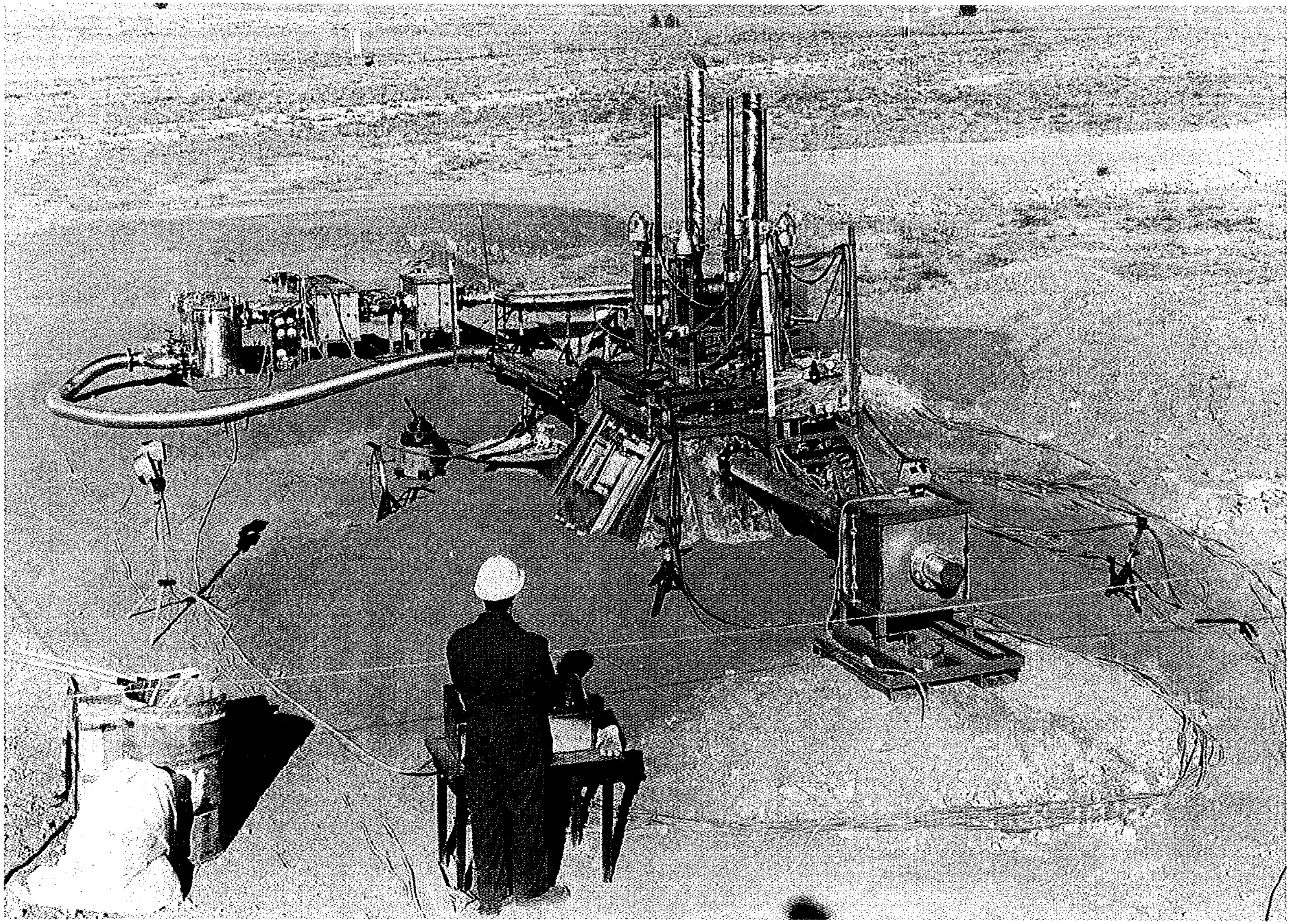

FIG. I-8. Off-gas hood and filtration system for intermediate scale ISV trial. (Photograph courtesy of Geosafe Australia.)

FIG. I-9. Vitrified monolith from ISV trial being fractured for sampling. (Photograph courtesy of Geosafe Australia.)

Heavy metals and radionuclides are physically and chemically incorporated into the vitreous product, which results in permanent immobilization. Most species of metals and radionuclides are uniformly incorporated into the vitreous product as stable oxides. The percentages of these species that are normally retained in the melts are summarized in Table I-2:

TABLE I.2. PERCENTAGE OF RADIONUCLIDES AND HEAVY METALS RETAINED IN THE MELT

Non-volatiles (Pu, Am, Sr, Ba, Cr)	99. 99% – > 99. 9999%
Semi-volatiles (Co, Cs, Pb, Cd)	90% – 99. 99%
Volatiles (As, Hg)	0% – 90%

Ferrous metals (e. g., scrap metals, piping, drums) do not have a strong affinity for oxygen in an ISV melt and remain in a reduced state, sinking to the bottom of the melt pool where they are encapsulated by the vitreous product.

The process destroys organics by pyrolysis within the soil closely adjacent to the melt due to the temperatures involved. The typical destruction and removal efficiencies for all organic species are greater than 99. 9999%.

The ISV process is capable of tolerating significant amounts of debris within the treatment zone such as scrap metal, steel drums, concrete, asphalt, wood, plastic, paper, protective clothing, HEPA filters, activated carbon filters, automobile tires, and general construction demolition debris.

I-5.1.2. Required characteristics of media to be treated

The ISV process can be used to treat all soil types (sands, silts, clays, etc.) provided there is a sufficient concentration of glass formers and alkali oxides (>1 wt%) to provide adequate electrical conductivity in the molten soil. If necessary, additives can be used to allow treatment of otherwise unacceptable media.

Sludges and soils that have a high moisture content (>70 wt%), including soils in the water table, have been successfully treated with the process. De-watering or water diversion techniques have been used during commercial ISV operations to facilitate the treatment of sites where the water recharge rate is excessive (>1×10^{-4} cm/s).

I-5.2. Process equipment description

The equipment generally consists of an electrical transformer to convert three-phase power into two-phase power for soil melting, an off-gas treatment system, and a steel containment hood that is positioned over the melt to capture off-gases. The ISV process equipment is all trailer mounted except for the off-gas hood, which is assembled on site, and typically requires 0. 7 to 0.8 kW·h per kg of material vitrified, or 3.2 to 4 MW for a full-sized melt. Heavy equipment necessary to support the operation includes a fork lift, together with 30 tonne and 130 tonne capacity cranes. The process requires a set-up area for equipment that is a minimum of 30 m in length and 12 m in width directly adjacent to the area to be treated.

The off-gases are processed by an off-gas treatment system designed to ensure all emissions are within regulatory limits. The standard off-gas treatment system consists of quenching, two stages of high efficiency scrubbing, de-watering, heating and one or two stages of high efficiency particulate air filtration. A stainless steel sheet metal hood, maintained at a slight vacuum, collects off-gases that evolve from the treatment zone and are then piped to the off-gas treatment system.

I-5.3. Intermediate scale tests

A four phase ISV project was initiated in 1993. The project is now in the third phase which involves the design and construction of a full-scale ISV treatment plant. The design and construction of the plant will be completed in mid to late 1997. Melting operations, Phase 4, will occur during 1998.

During Phase 2, a series of on-site tests and demonstrations were conducted, including two intermediate-scale demonstrations involving radioactive materials. The two radioactive demonstrations involved the treatment of scaled pits filled with soil, 37 wt% steel debris, and other debris including bitumen-stabilized soil, lead, plastic, electrical cable and baryte bricks. One kilogram of uranium oxide was buried in each pit to serve as a surrogate for plutonium. For each demonstration melt, the uranium oxide was contained in a plastic bag and located in the centre of the pit to serve as a highly localized area of contamination. The second radioactive demonstration included a steel plate, originating from the weapons tests, that was contaminated with approximately 0.5 gram of plutonium oxide (predominantly ^{239}Pu with about 3% being ^{241}Pu). About 90% of the ^{241}Pu originally on the plate had decayed to ^{241}Am.

Following the two demonstrations, the resulting vitreous monoliths were excavated for examination, weighing, and sampling. The mass of each monolith was approximately 4000 kg. Results indicate that all demonstration objectives were met and that the process could tolerate the types and amounts of debris present in the pits. Health physics surveys of the equipment established that the insides of the off-gas containment hood and off-gas piping were free of detectable contamination above background levels (<0.25 Bq alpha and beta combined per 100 cm^2). Consequently, decontamination of the equipment was not required. Based on isokinetic off-gas sampling, it was determined that 99. 99997% of the plutonium and 99. 9998% of the uranium were retained in the melts. Radiochemistry analyses showed that the radioactive materials were uniformly distributed through the vitreous products (due to the convective mixing currents that exist in ISV melts). Leach tests of the vitrified product using the Product Consistency Test procedure at 7 and 28 day leaching intervals indicated that the normalized leach rates are extremely low (<0. 1 g/m^2) for all oxide species. The metal phase at the base of each melt was determined to be free of plutonium and uranium based on qualitative analyses.

NOTE: Geosafe Corporation is the sole licensed provider of ISV remedial services and is the sole owner of Geosafe Australia Pty. Ltd, a subsidiary company established to carry out the ISV project at Maralinga.

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Annex II

CANADA – EXPERIENCE WITH THE REMEDIATION OF RADIOACTIVELY CONTAMINATED CIVILIAN SITES

II-1. INTRODUCTION

This annex, which describes remediation experience in Canada, is intended to illustrate the application of environmental restoration technologies at radioactively contaminated civilian sites. Canada participates internationally in environmental restoration activities through committee and expert panel work with NATO, IAEA and other organizations, and undertakes projects related to radioactive contamination resulting from civilian activities at home [II-1].

II-2. RADIOACTIVE CONTAMINATION IN CANADA

As in other countries, the initial use of radioactive materials in Canada was limited to naturally occurring materials such as thorium and radium, used for gas mantles, luminous paint, etc. With the advent of nuclear power and the use of radioisotopes, the range of materials and applications and the scale of use has increased dramatically. Canada has a substantial civil nuclear power program supported by uranium mining and refining within the country. It has no nuclear weapons program. As a consequence, it has several major sites where nuclear materials are handled, used and stored. In addition, many small to medium sized sites contaminated with "historic low-level radioactive waste" can be found in Canada.

In the early years of use of radioactive materials, just as in other countries, the quality of controls and waste management practices was of a considerably lower standard than is acceptable today. A number of sites became contaminated to varying degrees. Most of these sites were small in size and linked to either thorium/radium operations or research use. Disposal of radium and thorium contaminated materials was generally by local burial. Any contamination has been from inadequate long-term waste storage practices or uncontrolled distribution of contaminated soil. At the more recently developed nuclear power sites, the control of radioactive materials has generally been much better.

Historic low-level radioactive (LLR) wastes date back to 1933 in Canada, when a radium refinery began operation in Port Hope, Ontario. Ores were mined at Port Radium on Great Bear Lake in the Northwest Territories and transported 5000 km to the refinery. Refining of uranium began at this site in 1942. The problem of contaminated buildings and soils in the community surrounding the plant site, resulted from accepted practices in the early years of radium and uranium production. Off-site contamination was only recognized in the mid-1970s. Immediately a radiation reduction program was initiated in Port Hope and extended to the mining communities of Elliot Lake and Bancroft in Ontario, and Uranium City, Saskatchewan.

Additional historic waste sites have subsequently been identified at other communities in Canada including: Surrey, British Columbia; Scarborough, Ontario; Fort McMurray, Alberta; and, along the water transportation route from the original mine sites in the Northwest Territories. This contamination has been found in buildings or soils where spills of ores or concentrates have occurred during transport, or where processing residues have been spilled or dumped, where salvaged refinery plant materials have been used as building materials in private homes, or where radium paints or other products have been manufactured, used, stored or disposed. It was common for processing residues and other contaminated wastes from the refinery to be used either as fill materials during construction, or to be sent to early landfill sites. Contamination was further spread by wind and water transport from these sites.

Canada

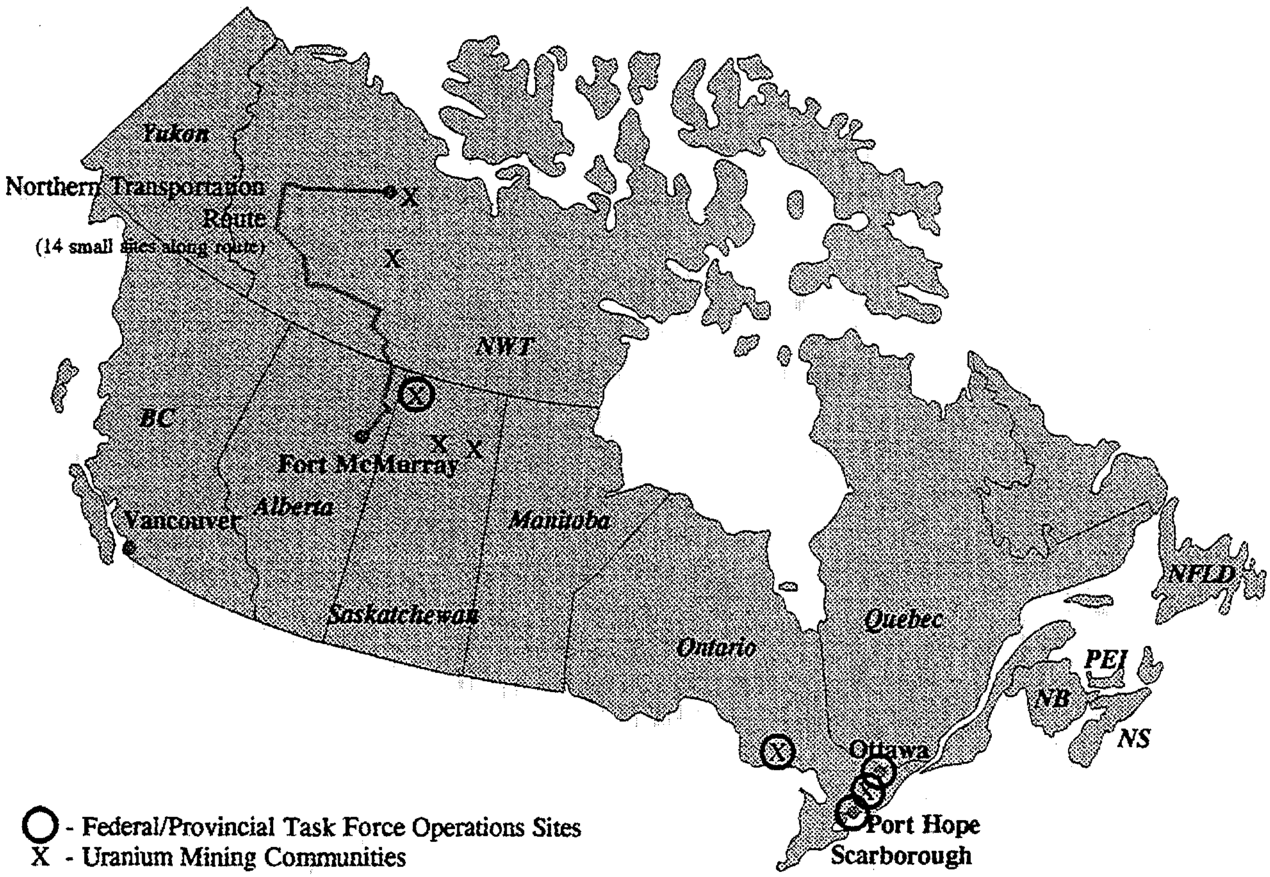

FIG. II-1. Location of the sites.

In Canada, "low-level radioactive wastes" are defined as all radioactive wastes other than nuclear fuel wastes and uranium mill tailings. The forecast amount of all LLR wastes to the year 2025 is in the range of 1.6 to 1.8 million cubic metres. "Historic wastes" are those LLR wastes for which the original producer can no longer reasonably be held responsible, which are managed in a manner no longer considered acceptable, and which are accepted as a federal responsibility. The only increases expected to add to the volume of historic LLR waste will come from discovery of new sites or improved delineation and characterization of present sites. There are approximately 1 000 000 m^3 of historic LLR waste in Canada, mostly located in the Port Hope area. Over 600 000 m^3 is in licensed storage facilities. Slightly over 200 000 m^3 is found in large and small scale sites in the Town of Port Hope. Almost 100 000 m^3 is estimated to be at all other historic waste sites in Canada. For comparison, the current annual production rate of ongoing LLR waste in Canada from the nuclear fuel cycle, the production of electricity by nuclear reactors and the use of radioisotopes is about 6000 m^3.

There are substantive differences in radiological, chemical and physical characteristics between historic wastes and LLR waste produced today from nuclear power production and radioisotope use. The contaminants in historic wastes are natural uranium and other radionuclides and heavy metals present in the original ores. Arsenic is the most significant of the heavy metals in terms of amount, mobility and toxicity. At many of the old sites, for every cubic meter of waste that was originally produced, there is now about 10 m^3 of contaminated soil, which has become part of the overall problem.

II-3. GENERAL APPROACH TO REMEDIATING A SITE IN CANADA

Remediation work in Canada has been on a relatively small scale. Compared with other countries, sites are smaller and fewer in number. The degree of contamination found at most sites is less than at major sites elsewhere in the world. Sites have been cleaned up or partially restored by removal of the contaminated soil and other material to cleanup criteria levels. Recently, segregation of soils by activity concentrations, has been used to advantage to optimize storage and disposal opportunities. Below criteria contaminated soils have been disposed at industrial landfills. Above criteria soils and waste are dealt with as required in regulations and as mutually agreed in advance by stakeholders. Disposal and storage are discussed in Section II-7 below.

The conventional approach to remediating a site begins with building a consensus among affected parties and regulators and then uses detailed pre-engineering of remediation plans followed by rigorous project management. This ensures that both the technical and community objectives of the remediation program are fully met.

All interested and affected parties must be identified to begin a consultative process. Often group participation, public meetings, and reporting obligations are undertaken by a community committee once stakeholders are known.

Extensive consultations are undertaken with the various regulatory bodies. In Canada, these include federal, provincial and municipal government agencies. Often, a joint regulatory review process is conducted. The agencies commonly involved include: the Atomic Energy Control Board, Health Canada, Department of Labour, Transport Canada, and Environment Canada (all federal government agencies); the provincial Ministry of the Environment, the Municipal Council and Medical Officer of Health. These agencies have statutory responsibilities for the protection of workers, the public and the environment.

The technical approach includes (but is not limited to) the following:

(a) *Detailed characterization of the contaminated site to determine the nature and extent of the contamination.*
Delineation studies obtain radiological and chemical data and interpret the location and configuration of contamination. Characterization of the contamination includes investigations of the physical and chemical nature of the contaminants and the concentration in the host material.

(b) *Assessment of the risks to workers, the public and the environment from the contamination and from potential remediation options.*
Dose impacts and exposure scenarios are forecast in advance of remedial activities. The environment and the workplace are monitored as work proceeds.

(c) *Selection of the preferred remediation strategy and approval of that strategy by the regulatory bodies and community.*
Such selection is usually based on an overall cost benefit, and is affected by the location of the site and potential receptors, and the proposed end use after remediation.

(d) *Design of selected processes and implementation of the selected strategy.*
Although this is mainly an engineering activity, alternatives and objectives are often developed with input from stakeholders.

(e) *Verification of achievement of agreed cleanup targets by monitoring, sampling, and so on.*
Usually a formal verification plan is prepared in advance of remedial activities for approval by the regulatory authorities.

In practice, for most sites, the preferred strategy is excavation and removal. Where the wastes/soil have been excavated and removed, they must be stored for future disposal because Canada has no disposal facility for these materials. Often, on-site storage or "consolidation" of waste in a smaller managed area on-site is practical.

Excavation has generally been carried out using conventional earth moving equipment, or using hand tools if the areas are very limited. Such excavations are performed under a strict health physics control regime. Migration of contaminants from project sites is minimized by control of dust, surface and groundwater flow, as well as vehicle tracking, etc. As the wastes are removed they are carefully monitored using methods appropriate to the volumes removed. Staff are supplied with protective clothing and respiratory protection appropriate to the level of risk posed, and personal and areal air sampling regimes are often employed.

II-4. SITE CHARACTERISATION

For the remediation of historic low level radioactive waste contaminated sites, the LLRWMO develops appropriate characterization approaches on a site-by-site basis matching technology to the demands of the project. In the last few years, the LLRWMO has refined its capabilities in the delineation and characterization of contaminated sites. The aspects which have advanced include the technology for collecting data, data analysis techniques, and calibration techniques.

The primary method used by the LLRWMO for surface characterization is the Large Area Gamma Survey (LAGS) System that has been developed by the LLRWMO. It consists of a mobile or portable scintillometer bank and continuous reading analysis software which records data automatically during a survey [II-2]. Location data are recorded along with gamma radiation data. Manual (dead reckoning), ultrasonic, and Global Positioning System (GPS) data collection techniques have all been used, depending on the application.

Analytical techniques [II-3] developed to complement the LAGS hardware system have greatly improved the ability to detect and delineate areas contaminated with low levels of radioactivity, and have routinely detected localized contamination containing 7400 Bq (0.2 μCi) ^{226}Ra (in equilibrium with its progeny) or less, and distributed contamination with concentrations of approximately 74 mBq/g (2 pCi/g) ^{226}Ra or less.

The system was extensively used in Fort McMurray and in Scarborough to determine cleanup boundaries prior to excavation and to verify whether criteria were met following cleanups [II-4]. The LAGS System is continually being improved to meet present and future requirements.

The LLRWMO has also used subsurface and other remote detection approaches. Borehole data logging for total count, count and spectral analysis is used wherever practical using techniques developed jointly by the LLRWMO and the Geological Survey of Canada [II-5]. Large amounts of data can be gathered compared with sampling and analysis for the same cost.

To interpret the large amount of total count scintillometer data of near background areas that is gathered by modern LLRWMO surveys, a calibration method has been developed [II-6]. It is based on a method used to calibrate field spectrometers [II-7], and has several advantages over the traditional point-source approach. Radiological measurements are taken on pads with known concentrations of potassium, uranium, and thorium, and the sensitivities to these naturally occurring sources of gamma radiation are determined. Measurements can then be converted into radionuclide concentration or exposure rates.

II-5. DECONTAMINATION OF SITES

Refurbishment and decommissioning of existing nuclear facilities, or the post operational clean out of redundant facilities is expected to require decontamination of structures and disposal of wastes over the next 20 years. However, to date decontamination work has only occurred at nuclear demonstration sites and some nuclear power facilities in Canada as well as at some early laboratory sites. Most decontamination activities have occurred under Canada's historic waste program. Structures, roadways and contaminated lands in private ownership and the public domain have been remediated.

Many historic waste cleanups have been accomplished in Canada. Over 500 small scale sites had been cleaned up in the communities of Port Hope, Elliot Lake, Bancroft and Uranium City. This completed the work sites identified in a survey of over 7000 properties in the 1970s based upon the cleanup criteria, which were developed in 1977 by a Federal-Provincial Task Force. These criteria are still in effect today.

In the Town of Port Hope, 9 large scale on-land sites and the harbour had been identified and characterized (200 000 m^3). Two in situ consolidations of just under 40 000 m^3 have been completed on major sites. Four licensed storage sites exist in the Town (40 000 m^3). A program to monitor and assist with safe handling of contaminated soil found at construction sites is in place and has operated since 1989; it has diverted 6000 m^3 of radium contaminated soil to temporary storage. An estimated 30 000 m^3 of contaminated soil at small scale sites, remains to be removed. In nearby municipalities in the Port Hope area, two major licensed storage facilities (600 000 m^3) also await decommissioning and potential waste removal operations.

In Scarborough, the McClure Crescent and the McLevin Avenue sites, 68 residential properties and 3 land development sites were cleaned up. Approximately 16 600 m^3 of radium contaminated soil were excavated, and underwent mechanical sorting and segregation. Approximately 50 m^3 of licensable material (soil with 3.7 kBq/kg ^{226}Ra) were recovered and transferred to an LLRWMO interim storage warehouse at Chalk River Laboratories of Atomic Energy of Canada Limited. Separation of clean soil, interspersed throughout the excavated material, then reduced the original volume by about half. The remaining mildly contaminated soil was placed in an engineered storage mound at the sorting site, in an undeveloped part of an industrial area. It will be removed when a permanent disposal facility is available. This project resolved the long-standing problem of contaminated properties in this community and provided a demonstration of a new soil sorting technique.

In Fort McMurray, eight of the nine identified contaminated properties were cleaned up in the period 1992–1996. About 31 000 m^3 of an estimated 40 000 m^3 of contaminated soil have been excavated. Selective excavation has enabled the segregation of 85 m^3 of licensable material ($\leq$500 ppm uranium). The portion not requiring a license has been moved to a purpose built cell in the local municipal landfill site and is regulated as industrial waste now in final disposal.

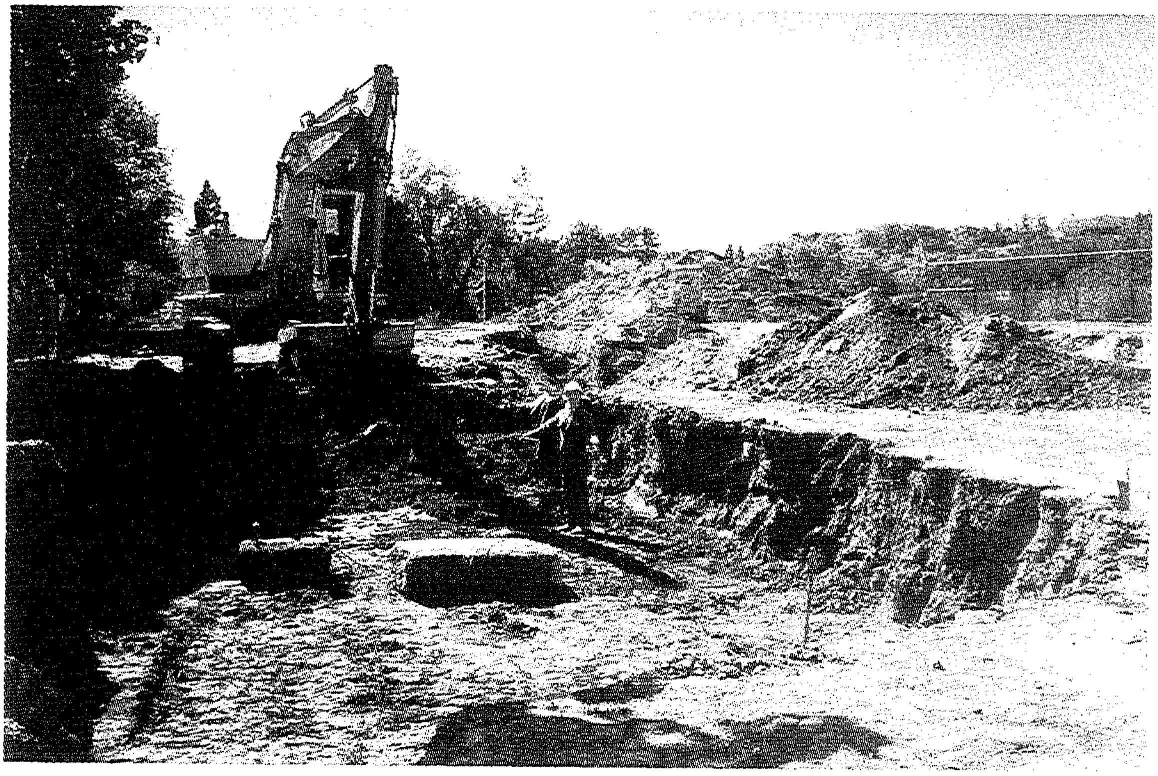

FIG. II-2. Supervised excavation of contaminated soil (Carolyn Street Park), Port Hope, Ontario, Canada.

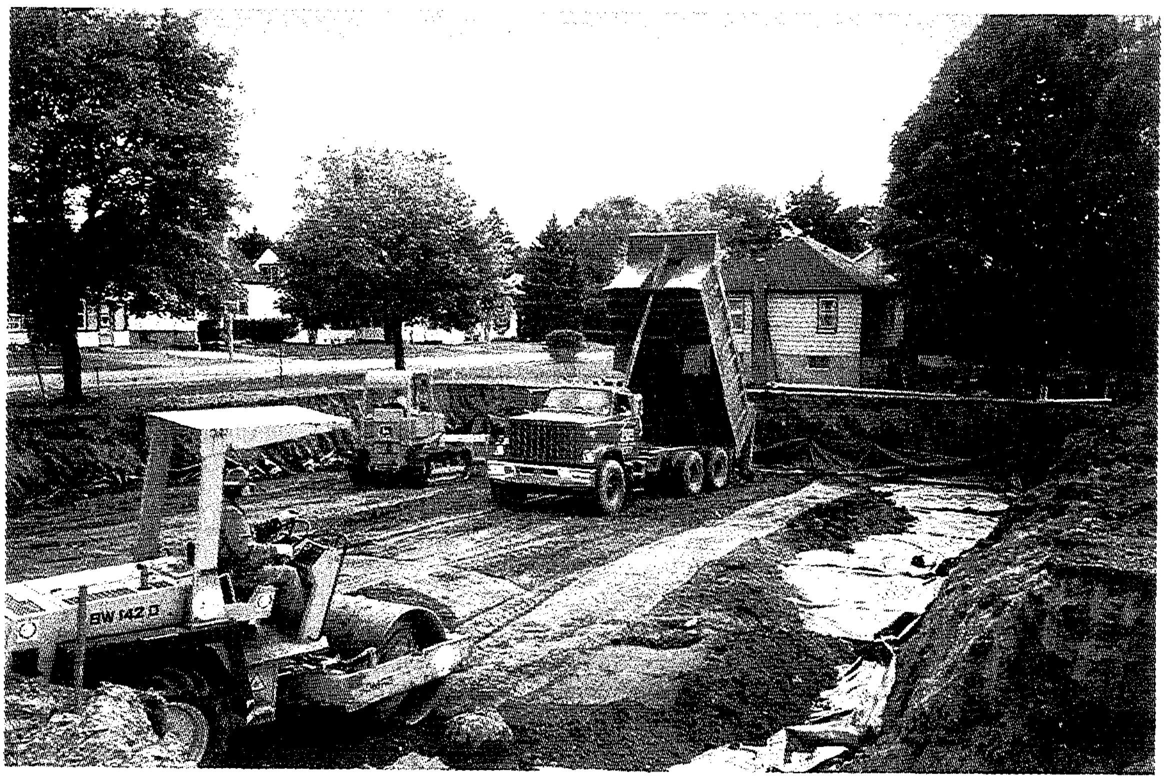

FIG. II-3. Placement of contaminated soil in enginneered in situ consolidation cell (Carolyn Street Park), Port Hope, Ontario, Canada.

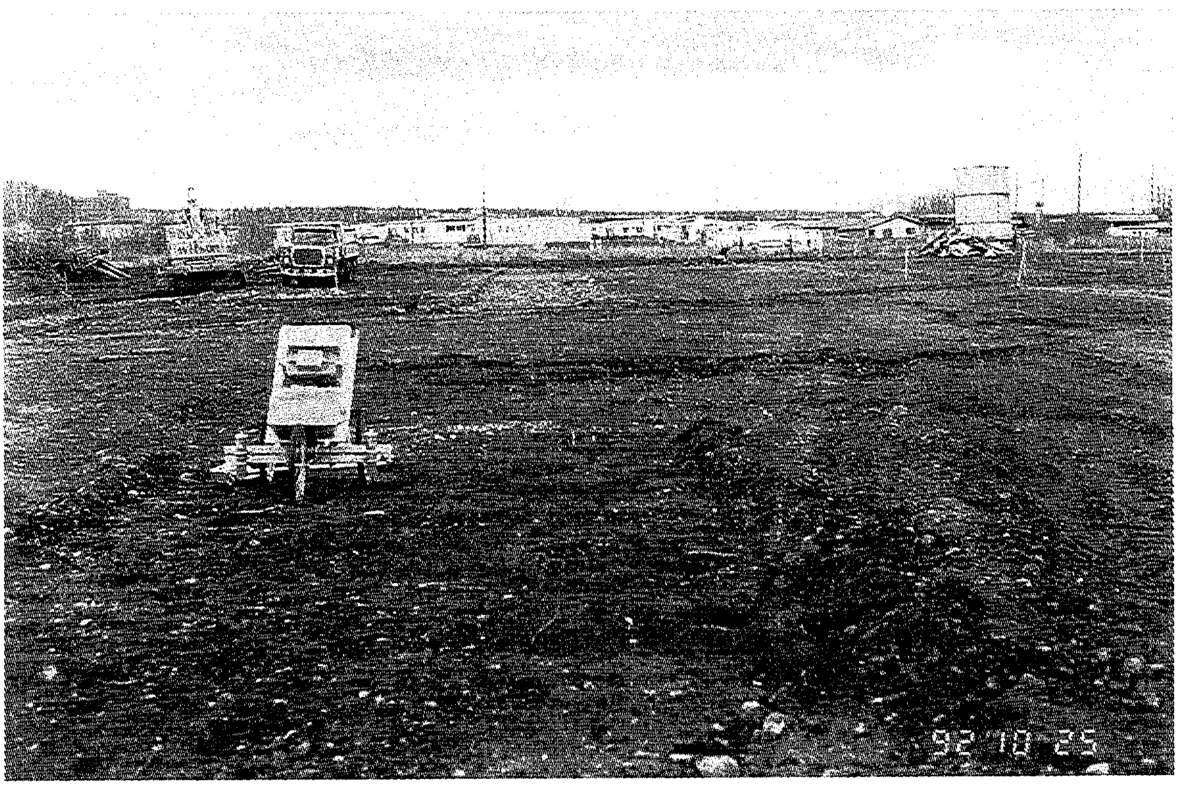

FIG. II-4. Large area gamma survey (LAGS) system in use to verify shallow waste removal excavation, Fort McMurray, Alberta, Canada.

FIG. II-5. LAGS technology in use to survey surface soil after removal of thin layer, Fort McMurray, Alberta, Canada.

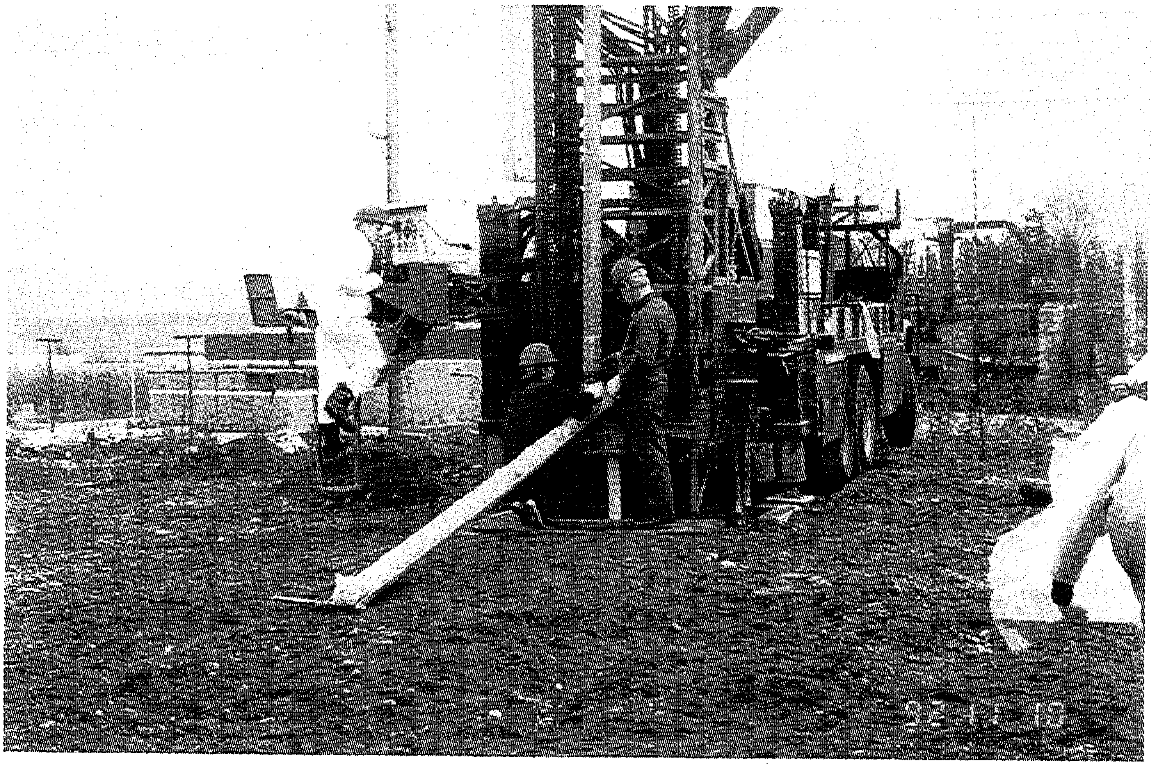

FIG. II-6. Borehole sampling of stored waste, Surrey, British Columbia, Canada.

FIG. II-7. Gamma scan of recovered core prior to gamma probe & logging of borehole, Surrey, British Columbia, Canada.

Along the Northern Transportation Route (NTR), 14 contaminated sites have been identified. The NTR extends from the Port Radium Mine site on Great Bear Lake, via a 2100 kilometre system of lakes and rivers (including Great Bear and Great Slave Lakes, and the MacKenzie, Slave, and Athabaska Rivers) south to Fort McMurray, Alberta. Initial surveys in 1991 of transfer points have been complemented by further investigations each year until 1996. Small quantities of waste (200 m^3) have been removed from 2 sites where people were living in close proximity to the waste. Further cleanup work will be required at both these sites. It is estimated that 20 000 m^3 and 14 sites await further work.

Across Canada, scattered radium dial painting operations and instrument repair shops have resulted in 15 cleanup projects generating about 1000 barrels of waste. Potentially, there are hundreds of sites and thousands of artifacts from the radium industry that will require future consideration. Throughout the 1990s a cooperative program between the Atomic Energy Control Board (AECB) and the LLRWMO to find and remove radium from former radium dial painting operations and instrument repair shops across the country has evolved. The AECB locates operations that are known to have utilized radium and determines whether a radium inventory or radium contaminated materials are likely present. Suspected contaminated sites are referred to the LLRWMO for survey and cleanup. The LLRWMO has visited over 50 sites and conducted cleanups at 15. Hundreds of properties will be visited over the next few years and cleanups will be conducted where necessary to remove radium from the public domain.

II-6. IN SITU REMEDIATION TECHNOLOGIES

In situ approaches are important in Canada because permanent disposal facilities are not yet available and storage space is limited. The LLRWMO experience in consolidation and storage projects has shown a number of additional advantages of this approach. Containment of the waste prevents further spread of contamination thereby limiting the problem and future remedial costs. Barriers applied over the waste protect potential intruders from any hazards and also lessen the probability that unsuspecting parties will relocate and further spread the problem. Covering the waste affords physical shielding to eliminate gamma fields and a barrier against radon emanation. In fact, the act of excavating and stockpiling waste provides self-shielding layers. An accurate understanding of the characteristics and volume of the waste requiring further long term management is obtained when the materials are delineated and excavated for interim consolidation.

Consideration of storage technologies is important in planning and executing remedial actions. The LLRWMO has used a number of in situ storage approaches including: ravine fills, small mounds, concrete block walled bunkers, and drummed storage within a fenced area. These have occurred at sites in Ontario and British Columbia. Such storage sites have held as little as 50 and as many as 30 000 cubic meter of contaminated soil but it is most likely that this approach will typically apply to inventories of a few thousand cubic metres.

The LLRWMO operates several storage facilities. These include two engineered mound sites (36 000 m^3; 2500 m^3) and two temporary storage sites in Port Hope, Ontario (6000 m^3; 2000 m^3); one concrete bunker site in Surrey, BC (4000 m^3); and two metal storage buildings at Chalk River, Ontario for packaged waste. All except the bunker are held under a licence by the AECB.

Recent work at Scarborough, Ontario has added another engineered mound (9100 m^3, of waste). The Fort McMurray work has added a purpose build landfill cell (31 000 m^3). Two in situ containment areas have been constructed at Port Hope sites since 1993 at a municipal park (320 m^3) and at a roadway project (1400 m^3). Because waste segregation techniques are now applied wherever practical, small amounts of licensable material were taken to the warehouse at Chalk River, and therefore none of these recent sites require a licence for storage.

II-7. EX SITU TREATMENT TECHNOLOGIES

The LLRWMO has found that a significant fraction of the radionuclide inventory is often found in a disproportionately small fraction of the volume of the "waste" at a remedial site. Appropriate segregation and categorization of materials have lead to significantly reduced interim storage and final disposal costs. Each category of material can be treated in a manner appropriate to its potential hazard.

For example, the Scarborough (Malvern) material was segregated into three categories: Low-Level Radioactive Waste (LLRW), Mildly Contaminated, and Clean. The small volume of LLRW, roughly 50 m^3, may eventually be disposed of in a packaged LLRW or nuclear fuel cycle waste disposal facility; a fairly expensive option. The remaining 16 600 m^3 of material divided approximately equally into Mildly Contaminated and Clean fractions. The Mildly Contaminated material may be disposed of in a bulk LLRW facility, or as non-hazardous industrial waste. The Clean material, which was unavoidably excavated in the process of removing the contaminated materials, may be released for use as clean fill or landfill cover.

Two approaches have been used to segregate the various waste fractions. These are "selective excavation" and "mechanical sorting". They can be used individually or in combination.

"Selective excavation" was employed at Fort McMurray project sites. The cleanup was conducted such that the inventory of material exceeding a uranium concentration of 500 ppm was separated during excavation from the inventory of material with less than 500 ppm uranium. This was accomplished by excavating the contaminated material in 15 cm lifts. Prior to excavation of each lift, a radiation survey was conducted of the area. Based on the in situ gamma radiation measurements, the inventory with a uranium concentration greater than 500 ppm was placed in 210 litre drums and the remaining inventory was placed in a dump truck. Confirmatory measurements were then made on both the drums and the trucks before the material was sent for disposal. This technique resulted in 31 000 m^3 of material with a mean uranium concentration of approximately 10 ppm being taken to the disposal cell at the landfill and 85 m^3 of material with a mean uranium concentration exceeding 1000 ppm being taken to Chalk River Laboratories for storage and future disposal.

"Mechanical sorting" was the basis for the success of the Scarborough (Malvern) project [II-8]. The Soil Sorting Conveyor System (SSCS), which was initially developed by the LLRWMO in 1990, was redesigned and rebuilt on a larger scale and, with enhanced detection capabilities, for use during the Malvern Remedial Project in 1995 [II-9]. The task included a major quality assurance component to ensure the successful operation of the system. The system operates by passing a stream of soil on a conveyor past sensitive radiation detectors, the output of which is monitored by a computer. The computer triggers a gate to segregate the material based on its gamma radiation. Soil samples are automatically collected for analysis to confirm soil classification. The SSCS processed more than fourteen thousand cubic metres of soil at the Malvern Remedial Project. The LLRWMO now has a complete system available for other projects, as required.

II-8. TRANSPORTATION AND DISPOSAL OF WASTE

There are no existing waste repositories in Canada for the disposal of LLR waste materials. Storage facilities exist in several locations for the various types of LLR waste materials. Near nuclear power stations LLR wastes are stored in various modes. Near the refinery site at Port Hope, two closed storage areas contain production waste. At several remedial work project sites in eastern and western Canada, consolidated LLR waste rests in temporary engineered storage cells. Small quantities of packaged waste can be stored at facilities operated for the LLRWMO by the Chalk River Laboratory, of AECL. A low-level waste repository for certain wastes including the Port Hope area historic LLR wastes, has been the subject of a siting initiative over the past few years and shows potential to solve the disposal siting issue.

Transportation of radioactive material or dangerous waste must comply with federal regulations administered by the Atomic Energy Control Board and Transport Canada. Packaging, labelling, placarding and reporting are regulated. Industrial and other wastes often also fall subject to regulation by lower levels of governments.

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GLOSSARY

(The definitions are intended for use in this report)

Adsorption. A process somewhat similar to ion exchange whereby molecular contaminants are immobilized onto a solid matrix (sorbed onto the solid surface).

Available (or existing) technology. A technology that is fully proven in routine commercial use and for which sufficient performance and cost information are available.

Bio-barrier. A low permeability barrier which employs the growth of bacteria to block the pores in a geological formation, thereby retarding fluid flow.

Cleanup. Measures carried out to reduce the exposure from existing contamination; these can be related to the contamination of itself (the source) and to the exposure pathways to humans. For example, cleanup includes stabilization of a source at a site. The sources considered for cleanup include contaminated land areas, structures, rivers, lakes an sear areas.

Cut-off wall. A vertical barrier installed to prevent the horizontal migration of groundwater.

Displacement barrier. A barrier constructed by forcing the barrier material into the ground without any associated excavation.

Electrokinetics. The use of an electrical field to remove contaminants from the groundwater or from soil.

Emerging technology. Those technologies that require additional laboratory or pilot-scale testing to document the technical viability of the process.

Ex situ technology. A process applied external to the contaminated region, above ground.

Excavated barrier. A barrier constructed by removing soil material and replacing it with the a desired barrier material.

Extraction. Removal (extraction) of groundwater via pumping.

Hydraulic containment. Containment achieved through the manipulation by hydraulic means of the groundwater flow around a particular region of contamination in order to prevent further migration or movement of the contaminants.

In situ technology. A process applied in place (within the ground or contaminated region).

Innovative technology. A treatment technology for which cost or performance information is incomplete, thus hindering routine use at hazardous waste sites. An innovative technology may require additional full-scale field testing before it is considered proven and ready for commercialization and routine use.

Intervention. Any action intended to reduce or avert exposure or the likelihood of exposure to sources which are not part of a controlled practice or which are out of control as a consequence of an accident.

Mixed wastes. Wastes containing both radioactive materials and other hazardous agents.

Remediation. Measures taken, including stabilization or isolation of the contamination in situ, to reduce human exposure or environmental damage from already contaminated land or water.

Restoration. Measures taken to return the environment in to approximately the same state in which it previously existed or to a state that is in agreement with future land use scenarios and all publically accepted agreements.

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Consultants Meetings
Vienna, 22–26 May 1995
Vienna, 11–15 November 1996

Technical Committee Meeting
Vienna, 25–29 March 1996