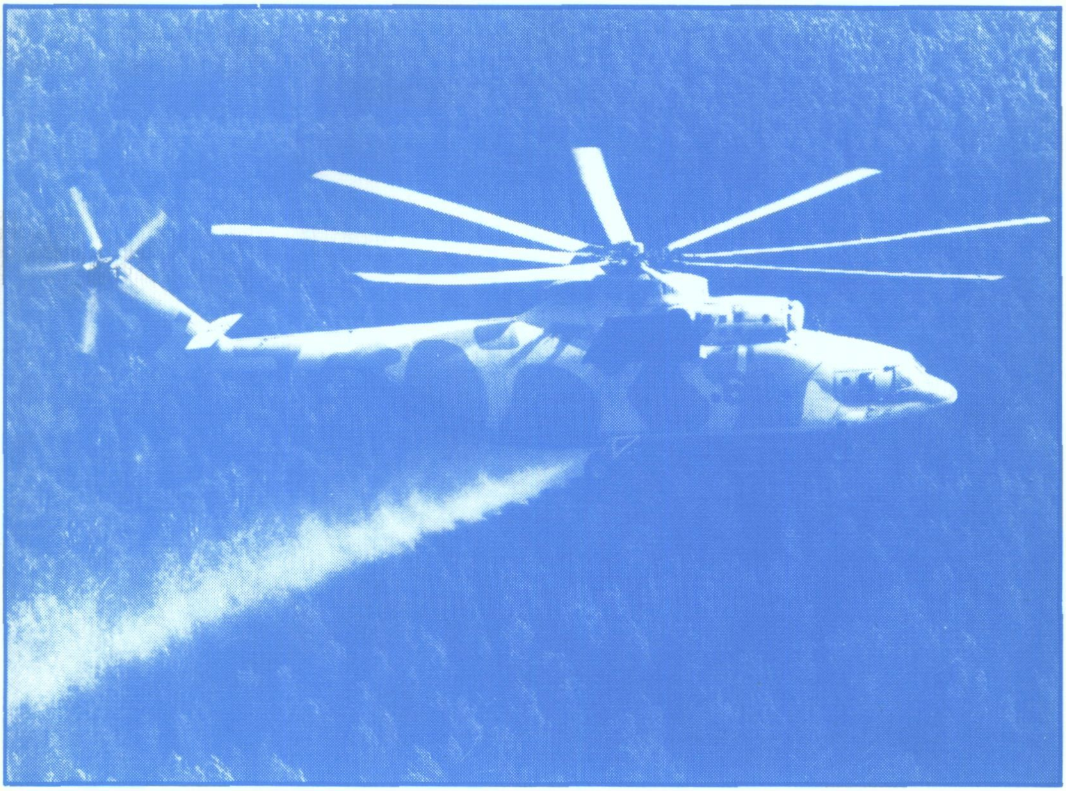

TECHNICAL REPORTS SERIES No. **330**

Disposal of Waste from the Cleanup of Large Areas Contaminated as a Result of a Nuclear Accident

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1992

DISPOSAL OF WASTE FROM THE CLEANUP OF LARGE AREAS CONTAMINATED AS A RESULT OF A NUCLEAR ACCIDENT

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FOREWORD

In more than thirty years of nuclear power experience there has been only one accident at a power reactor with major consequences for public health. The record of more than 6000 reactor-years confirms that radiation exposure due to nuclear power production remains less than 0.1% of that due to natural background radiation.

Despite this experience, a higher level of safety has been required and implemented recently. Although the risk of a severe accident has further been minimized by various improvements in operating nuclear power plants and in plants under construction, a general consensus prevails that severe accidents cannot be excluded from safety considerations.

In this context, a special concern is the problem of ground contamination. This has led several countries to collect and evaluate information on planning and management of safe transportation and disposal of large volumes of contaminated materials, with the objective of minimizing the consequences of such an accident.

This report is the last of a series of three dealing with the cleanup of large areas contaminated as a result of a nuclear accident. It is closely linked to the first report (Cleanup of Large Areas Contaminated as a Result of a Nuclear Accident, Technical Reports Series No. 300, 1989), which gives an integrated overview of the methods and equipment available to characterize the radioactive fallout, clean up contaminated urban, rural and forested areas and stabilize the deposited radioactive contamination. The second report (Planning for Cleanup of Large Areas Contaminated as a Result of a Nuclear Accident, Technical Reports Series No. 327, 1991) is mainly a planning and management document, which outlines the broad strategic and tactical approach to the cleanup, as well as the management structure and other key requirements to ensure that cleanup can be performed safely and efficiently under adverse conditions.

The present report was drafted by a group of consultants in June 1988 in Vienna and reviewed in February–March 1989 at a Technical Committee Meeting attended by 13 experts from 12 Member States. The document was revised accordingly after the meeting by M. Feraday of the IAEA's Division of Nuclear Fuel Cycle and Waste Management, who acted as Scientific Secretary at both of the above mentioned meetings; Z. Dlouhy was the IAEA officer responsible for finalizing the document. The IAEA would like to acknowledge the assistance of H. Köhler in the development of the mathematics for Appendix B.

CONTENTS

1. INTRODUCTION

All nuclear facilities are sited, designed, constructed and operated according to strict requirements and regulations to protect the environment and ensure the safety of the workers and the public. Although the probability of occurrence of an accident which results in the release of unacceptable amounts of radioactive material or unacceptable exposures is very low, the possibility of such an accident cannot be excluded.

In certain cases, the long term effects of the radioactive material deposited on the ground from such an accident can represent a greater hazard than the short term effects of the accident if the contaminated areas are not cleaned up. Therefore, it would seem reasonable that some preliminary planning be done for the cleanup of large areas in countries having nuclear facilities which could release unacceptable amounts of radioactive material in the event of an accident.

The term 'cleanup' includes processes which will reduce the potential doses to people. These processes include decontamination, stabilization or isolation of contamination, and transportation and disposal of the wastes arising from the cleanup.

The cleanup of contaminated areas could be implemented at an intermediate phase (days to weeks) following the accident, or later (weeks to years). The immediate objective of a post-accident cleanup is to decrease the risks to acceptable levels in the short term, and the longer term objective might be to return an area to either restricted or unrestricted use.

The IAEA has published general guidance and recommendations on emergency planning and preparedness for situations where an accident at a nuclear facility may involve the need for off-site remedial actions and the implementation of protective measures [1–3]. In the event of an accident at a nuclear facility which results in the release of significant amounts of radioactive material, the protective measures may range from sheltering or evacuating people to decontaminating lands and buildings. The implementation of these protective measures involves cost, inconvenience and risk to the public, so the hazard or social cost associated with a remedial measure must be justified by the resulting reduction in risk [4–6]. Remedial actions are appropriate only if their total costs, in terms of radiation detriment and socioeconomic considerations, are expected to be less than corresponding costs in the absence of such remedial programmes. Appendix A presents the derived radiological criteria required to implement the cleanup of large areas radioactively contaminated after a nuclear accident. Appendix B describes a generic method for estimating costs for loading, transporting and disposing of wastes originating from such a cleanup.

The cleanup of large contaminated areas could cost hundreds of millions of dollars and create risks and inconvenience to the public. If the resulting detriment to health and social life of this kind of intervention would be less than that resulting from further exposures, all reasonable means should be used to minimize the costs and detriment to humans of such a cleanup. The best way of doing this is to ensure that proper planning, co-ordination and management are enforced for all activities associated with cleanup.

The costs of loading, transporting and disposing of the wastes arising from such a cleanup will be a significant fraction of the total cost of the remedial actions. These operations must be done correctly so that the cost, the occupational exposure and the future dose to humans will be optimized. Information available from past experience in Canada, the United States of America and the former Union of Soviet Socialist Republics is presented in Appendices C, D and E respectively.

An IAEA report has been published [7] which provides an overview of the important technological aspects related to the cleanup of large areas contaminated as a result of a nuclear accident. The report includes information on the methods and equipment available to characterize the radioactive fallout, stabilize the contamination and clean up contaminated urban, rural and forested areas, but also contains brief sections on the transport and disposal of the wastes. A companion report [8] provides information on the operational planning and management considerations for such a cleanup.

2. PURPOSE

The purpose of this report is to give guidance to Member States on the means for safe loading, transport and disposal of large volumes of contaminated material which could arise from the cleanup of areas contaminated as a result of a serious accident at a nuclear facility.

3. SCOPE

The report provides an overview of the methodology and technology available to load, transport and dispose of large volumes of contaminated material arising from the cleanup of areas after a nuclear accident and includes data on the planning, implementation, management and costing of such activities. To demonstrate the use of this information, three cleanup and disposal scenarios are examined, ranging from disposal in many small mounds or trenches within the contaminated area to disposal in a large facility away from the plant. As in the two companion reports [7, 8], it is assumed that the population has been evacuated from the affected area.

The report reviews the generic types of low level radioactive waste which are likely to arise from such a cleanup.

The report does not deal with the recovery and disposal of intermediate and high level radioactive material on or near the plant site. This material will have to be recovered, packaged, transported and stored on-site or disposed of at an appropriate facility. These operations should be done by specialist teams using shielded or remotely operated equipment.

Also not included are methods of in situ stabilization of contamination, for example ploughing to bury the top contaminated layer at a suitable depth. These techniques, which are likely to be widely used in part of the evacuated area, are discussed in Ref. [7].

4. WASTE CHARACTERISTICS AND QUANTITIES

The characteristics and volumes of the wastes arising from the cleanup of an area contaminated as a result of a serious accident at a nuclear facility will depend on many factors. These may be subdivided into two groups.

(1) *Factors affecting the radiological characteristics of the waste*

The factors which would determine, directly or indirectly, the radiological characteristics of the waste include:

(a) The inventory and quantity of radionuclides present in the facility at the time of the accident;
(b) The design of the facility;
(c) The specific accident scenario;
(d) Meteorological conditions during and subsequent to the accident;
(e) Selective deposition of radionuclides;
(f) Decay or in-growth of radionuclides after the accident;
(g) The manner in which the cleanup is effected.

By the time the cleanup of an area starts, the major radionuclides of concern following an accident would probably be ^{134}Cs, ^{137}Cs and ^{90}Sr. The major radionuclides from a safety viewpoint are ^{137}Cs and ^{90}Sr, each with a half-life of about 30 years, but long lived radionuclides may also have to be considered.

(2) *Factors affecting the quantity of waste*

Factors affecting the quantity of contaminated waste arising from the cleanup of the affected area include:

(a) The extent, depth and nature of the contamination;
(b) The characteristics of the environment (prairie, desert, forest, urban, agricultural, etc.);
(c) The decision on handling the affected area, i.e. stabilization of radionuclides in place, interdiction or cleanup;

(d) The methods used for cleanup;

(e) The cleanup criteria applied, i.e. the volume of waste generated would be directly proportional to the stringency of the criteria, so that the volume will increase as the required level of residual activity decreases.

4.1. WASTES ARISING FROM THE CLEANUP OF DIFFERENT TYPES OF AREAS

4.1.1. Rural areas

Rural areas would include agricultural lands for crops, pasture, orchards, etc., wooded and non-productive grassy areas and a relatively small number of buildings and roads. The waste types would include soil, organic material (sod, crops, grass, small trees, etc.), vehicles, building contents, equipment, etc., and limited amounts of building and road material. Wastes arising from road cleanup could include a layer of material removed from the surface [7] or soil adjacent to the road that is contaminated after flushing.

The actual volume of waste will depend on the type of area and the cleanup process used. For example, if a 5 cm layer of soil and sod were removed, about 50 000 m^3 of waste could arise from each square kilometre. However, the volume (but not the weight) to be transported will be greater than this owing to a reduction in the density of the removed material during handling. Furthermore, additional organic waste would be produced, the volume of which will depend on the types of crop being grown. It is estimated that, in certain cases, an additional 50 000 m^3 of organic waste could be generated per square kilometre; however, the volume of the organic waste would reduce sharply as the plant material decomposed.

4.1.2. Urban areas

Urban areas could include single- and multi-family residences, commercial and industrial buildings, roads, parking areas, parks, vacant land and vehicles. The waste types arising from the cleanup could include those mentioned in Section 4.1.1. Other major waste types which must be considered include decontamination liquids from the cleanup of buildings, equipment and roads and the residues, sediments and sludges arising from the treatment of contaminated water and decontamination solutions. The ratio of the volumes of soil to building or road material would be less in urban than in rural areas.

In Ref. [7], it was estimated that up to 20 m^3 of soil waste and an equal volume of vegetation, fences, etc., could be generated from the cleanup of a garden area of 200 m^2 if a 10 cm layer of soil were removed.

4.1.3. Forests

The types and volumes of waste arising from a contaminated forest could vary from little waste if the area were interdicted to large volumes of organic material if the forest were defoliated (by natural or artificial means) and the undergrowth cleaned up. Trees and stumps may also have to be removed to allow equipment access for cleanup [7].

4.1.4. Water systems

It is unlikely that attempts would be made to decontaminate large water systems. However, in selected cases, dredging of parts of a river bed which are near to the facility and have become seriously contaminated could be carried out. Thus it is possible that limited volumes of soil or organic material (weeds, swamp plants, etc.) could arise from the cleanup of water systems.

The volume of waste arising from the cleanup of water systems would probably be small in comparison with other wastes and would be very site specific.

5. TREATMENT OF WASTES

The requirements for the treatment of wastes will be determined by the nature of the wastes. These can be divided into those which do not require treatment before being transported and/or disposed of, and those which require treatment for various reasons. Wastes requiring treatment before transport and/or disposal may include liquids and certain types of solids.

5.1. LIQUID WASTES

The volumes of contaminated liquids arising from the decontamination of buildings, roads and equipment will be very large. Since most of the liquids will have low concentrations of radioactivity and chemical additives and will be produced in many different areas, they probably will be directed into roadside ditches during the flushing of roads, or into special holding areas, or merely allowed to flow off a building into the surrounding earth. The contaminated soils resulting from these practices would be collected later for disposal.

However, other liquids may require treatment to satisfy safety regulations for transportation and disposal. For example, contaminated chemicals such as oils or wash solutions from vehicle decontamination centres may be treated to remove the radioactive materials for separate disposal.

5.2. SOLID WASTES

Much of the solid waste arising from cleanup, for example contaminated soil or concrete, will not require any treatment before transportation or disposal since it is relatively stable.

From an economic viewpoint it may be desirable to reduce the volume of certain compactible wastes, for example building materials or discarded furniture from demolished buildings, before they are transported for disposal. In some cases, crushing by a bulldozer may be an effective way of reducing the volume of some items.

From a disposal viewpoint, it may be desirable to reduce the volume so that the wastes are stable and will not lead to significant settling and slumping of the cap over the disposal unit. The wastes could include crops, garden plants, underbrush and small trees. Low concentrations, for example up to 5 vol.%, of organic material mixed with inert soils or concrete should not result in significant settling of the disposal mound if the wastes are compacted as they are placed in the disposal facility.

Whether or not such pretreatment is performed on organic wastes in a real accident situation would depend on many factors. For example, if it were decided to dispose of waste in a valley or in mounds, the waste could be temporarily covered with plastic until most decomposition and settling had occurred. The final cover could then be installed and any further settling could be accommodated by remedial maintenance as required. If the organic material is deposited in thin, relatively uniform layers and compacted, uneven settling may only be a minor problem.

For higher concentrations of organic material, segregation and/or temporary storage to allow chemical and biological processes to decompose the organics would be desirable.

6. SCENARIOS FOR THE TRANSPORTATION AND DISPOSAL OF WASTES

During routine emergency preparedness exercises, the Cleanup Director and associated team should examine some possible scenarios for the transportation and disposal of large volumes of waste. A wide variety of scenarios could be postulated for different situations, and some typical scenarios are examined in this report. The selection of the actual scenario will be site specific and result from the evaluation at the time of the accident of a variety of conflicting factors and possible options, including radiation protection and safety, availability and location of disposal sites, type of disposal facility, availability of suitable equipment and transport routes, unit transport costs, location and characteristics of the waste, and required cleanup criteria to allow reuse of the area.

In cases where a disposal facility is not yet available, it may be desirable to move the contaminated material into piles and cover it for temporary storage rather

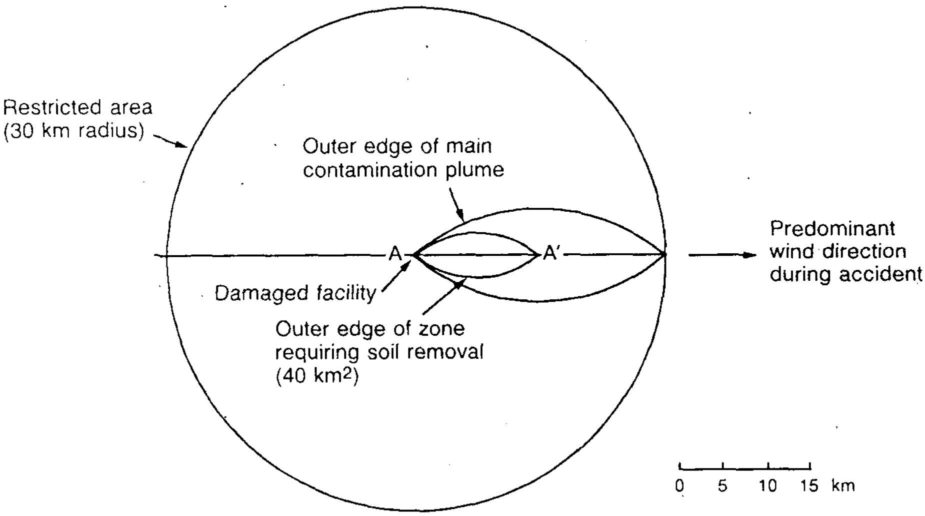


FIG. 1. Assumed shape of the contamination plume within which extensive cleanup is required after a serious accident at a nuclear facility. The restricted area is assumed to be mainly rural. The most heavily contaminated 40 km^2 require removal of soil. Other cleanup methods, e.g. ploughing, are used on the rest of the plume area and the remainder of the restricted area as required.

than leaving the contamination dispersed over large areas, where it could be leached into the ground or dispersed to clean areas by the wind.

For the purpose of this report, it is assumed that a large area has been contaminated as a result of a serious accident and containment failure at a nuclear facility. Although the accident may affect an area up to some 30 km from the facility, only 40 km^2 will need to have contaminated material removed (Fig. 1).

It is further assumed that the cleanup of the 40 km^2 zone produces about 2×10^6 m^3 of low level radioactive waste which must be transported and disposed of. This waste includes soil, concrete, asphalt, building materials, crops, underbrush, sod, vehicles, equipment, and sludge or ion exchange resins arising from the treatment of decontamination solutions or contaminated water.

Three disposal scenarios are postulated and examined. Two scenarios assume disposal facilities in the affected area, and the other scenario assumes disposal at a facility located outside this area.

Scenario 1 assumes that the contaminated waste is carried from small piles using belly scrapers or bulldozers and disposed of at 40 sites (one per square kilometre) in large piles or natural depressions located close to the points of highest contamination. This method could require a considerable fraction of the affected area for disposal.

Scenario 2 assumes a limited number of larger disposal facilities located within the affected area. Two cases are examined, one assuming one large disposal facility (Scenario 2a) and a second assuming four facilities of 500 000 m^3 each (Scenario 2b). The waste would be moved into piles using graders, loaded onto vehicles and transported to the sites. Since the transportation is done in a controlled manner over designated routes, the controlling regulations would not need to be as stringent as in the IAEA's Regulations for the Safe Transport of Radioactive Material [9]. In addition, if disposal in a suitable valley or large depression is assumed, the repository in Scenario 2 would take less of the land area than that required in Scenario 1.

Scenario 3 assumes that a large repository suitable for this type of waste is available off-site and at a reasonable distance. Since transportation would be over uncontrolled roads in the public domain, the IAEA transport regulations [9] would apply (Section 7).

In a real situation, the volumes arising could be less or greater than 2×10^6 m^3, depending on factors such as distribution of activity and the cleanup criteria which are set. In certain cases a combination of scenarios may have to be used. For example, if a large town or city is located within the 40 km^2 cleanup zone, Scenario 1 could not be used for the city since the cleanup waste would probably be removed from the city boundaries. However, the remainder of the area could be cleaned up using the Scenario 1 approach.

7. LOADING AND TRANSPORTATION OF LARGE VOLUMES OF WASTE

Once the disposal strategy for an actual accident has been defined by the Cleanup Control Centre [8], the detailed transportation plan for moving wastes to the disposal site can be developed. This section briefly reviews some of the methods and techniques which have been used to transport large volumes of low level radioactive waste in a safe, controlled and economical manner.

The loading and moving of large volumes of soil is a time consuming and relatively expensive practice commonly used worldwide. For example, during the construction of large earth dams, millions of cubic metres of soil have to be loaded and moved. At uranium mining and milling facilities, it is common to load and move large volumes of radioactive ore, tailings and waste rock.

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

7.1. LOADING TECHNIQUES

The loading of contaminated soil could be accomplished by using [7]:

(a) Equipment such as wheeled or tracked loaders with capacities of 30 m^3 or more. The material would first be moved into piles using conventional scrapers, bulldozers or graders with wide blades before being loaded onto trucks.

(b) A force feed loader with 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) 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.

7.2. TRANSPORTATION ARRANGEMENTS

Requirements for transportation of radioactive material are specified in the IAEA transport regulations [9].

Since most of the wastes arising from the cleanup would probably be classifiable as low specific activity wastes, they would normally have to be shipped in industrial packages in accordance with Ref. [9]. Should industrial packages capable of holding large volumes of contaminated soil not be available, or should their use not be cost effective, the transport regulations [9, 10] provide for the possibility of conducting the transport as a special arrangement. The use of a special arrangement can constitute an effective way of addressing the problem of moving 2×10^6 m^3 of bulk wastes.

The regulations stipulate that the approval of shipments under special arrangements shall depend on the approving competent authority being satisfied that the overall level of safety is at least equivalent to that which would be provided if all the normally applicable regulatory requirements had been met. The level of safety necessary in special arrangement shipments is normally achieved by imposing operational controls to compensate for any deficiencies in the package or the shipment procedures [10]. Operational controls which could effectively be employed include exclusive use of vehicles, escort of shipments, control of the timing and routing of shipments, limited vehicle speed and specific emergency response provisions.

If the Emergency Director [8] decided that the low level wastes arising from cleanup are to be shipped to a repository outside the restricted area, such shipments would probably not occur for some time after the start of the cleanup. This time would permit the competent authorities to define the special transport strategy, methods, routing, etc., and assess the risks associated with the special procedures to ensure that such risks are acceptable [11].

The type of special transport selected would also have to comply with external radiation requirements based on suitable radiation protection measures [9].

7.2.1. Means of transportation

Contaminated materials could be transported using one or more of the following techniques:

(a) Moving the layer of contaminated soil directly into natural depressions or specially excavated trenches using scrapers, bulldozers or graders; the soil can be moved 100–150 m without reloading or stopping [7].
(b) Transporting the soil to the disposal site by dump trucks; rear dumping trucks are available with capacities of up to 250 t.
(c) Transporting the soil to the disposal site by rail.

The choice of rail transport depends on the availability of rail lines in the vicinity of the cleanup and disposal sites. Canadian analyses suggest that if double or triple handling of material is required, as in a truck–rail–truck transportation system, rail transport is less expensive for distances greater than a few hundred kilometres. However, more important than this economic consideration may be the fact that rail transport results in less radiation exposure to transportation workers and involves less interaction with the public than does truck transport if it is over public roads.

7.2.2. Transportation routes

Well defined and controlled transportation routes between the cleanup areas and the disposal sites should be established.

During routine emergency preparedness planning, in the area around a particular nuclear facility, potential disposal sites and transportation routes can be assessed for different accident scenarios. However, the final selection cannot occur until after the accident, when the extent and location of the contaminated area are better defined. As the cleanup proceeds, the transportation routes could change, depending on the strategy used for cleanup.

During the cleanup, the transportation routes within the restricted area should be kept as contamination free as possible. If the waste is transported out of the restricted area, the selected routes to the disposal site should be as short as possible, avoid high traffic areas, schools, hospitals, etc., and be closely controlled and monitored.

7.2.3. Management and control of shipments

Once the disposal strategy has been defined (Section 6), effective management and control systems will be required to ensure that the waste is loaded, moved and disposed of in a safe and efficient manner, and that good records are kept, especially if the waste is transported out of the restricted area.

The safe and effective movement of large volumes of waste requires a management and control system which includes:

(a) A modified waybill control system used in conjunction with the data handling system to control the loading, transport and disposal of waste;
(b) Well defined transportation routes and truck control points to ensure compliance with the routing plan;
(c) Truck cleanup areas and monitoring points between the contaminated and clean areas;
(d) An emergency response plan to be implemented in the event of a transportation accident.

Road control systems such as TRUSYSTEM [12] have been developed and are being used with computers and telemetry to keep track of trucks, waste and manpower in large scale cleanup operations. The information recorded in road control systems should include: volume and description of waste, including radionuclide content and characteristics and where the waste comes from, time required to load the truck, number of trucks and crews, length of route, departure time, number of stops, arrival time at disposal site, and route taken.

If such road control systems are used in the cleanup of large areas, they would probably require modifications to adapt them to site specific needs. The level of sophistication of such programs would probably differ for transport of waste within the restricted area and for shipments to a disposal site outside this area.

Whether the waste is transported to a location within or outside the restricted area, trip tickets or waybills are required to ensure that the waste is handled in the authorized manner from the remedial action site to the disposal area and that records are kept.

The trip ticket usually contains three copies. At the waste loading site, the radiation inspector would record the required information on the ticket and retain one copy. The other two copies would be given to the driver. The inspectors at each transition zone or checkpoint on the transport route and at the disposal area would enter the time of arrival. The final location of the waste would also be recorded. One copy would be returned to the driver and the disposal area inspector would keep the last copy for reconciliation with the copy held by the inspector at the point of origin [13]. For large scale operations, the reconciliation could be done using a computerized network. The repository disposal records should agree with the transport records.

Before leaving the loading site, trucks should undergo a thorough radiation check, loose contamination should be removed and the trucks should be closed to prevent the loss of material during movement. The extent of the truck monitoring and decontamination operations would vary, depending on the circumstances at the time of loading and whether or not the shipment would leave the restricted area. For example, at the start of the cleanup, the movement of trucks to the disposal site may be through areas which are still very contaminated. In that case, intensive decontamination and monitoring procedures before leaving the loading site would not be justified. However, as the cleanup proceeds, and particularly if the trucks are moving through a clean zone or out of the restricted area, then intensive decontamination of the trucks would become necessary.

Procedures should be established to ensure that containment during transport will be maintained. These include regular inspection of tailgate control and locking mechanisms to ensure positive operation during dumping and secure closure.

7.2.4. Accidents during transportation

In the event of an accident involving a vehicle hauling contaminated material in which no spillage has occurred, the driver should contact the security control or other competent authority for assistance [11]. Trained personnel should be sent to the scene as soon as possible to render medical and technical assistance and confirm that no spillage has occurred.

In the case of an accident involving spillage of contaminated material, the responsible authorities should cordon off the area and redirect traffic if necessary. Radiation technicians and cleanup teams should be sent to the area as soon as possible, especially if the spillage occurred outside the restricted area.

Details of all accidents should be recorded on the trip ticket, including the final disposal of any spilled or unloaded material. No unloading of waste should be permitted without prior authorization.

7.3. COSTS

The costs of loading, transporting and unloading large volumes of contaminated waste will depend on many site- and country-specific factors, including:

(a) The type of area being cleaned up; for example, the loading of waste onto trucks in an urban or forest area would probably be more time consuming and costly than in a rural area.

(b) Availability and type of equipment, trained personnel, etc.
(c) Method of transport: bulldozer, truck, rail, etc.
(d) Financial considerations: salaries, price of fuel, insurance costs, repair costs, etc.
(e) Transportation distances.
(f) The types of waste and regulations covering the safe transportation of wastes (including decontamination of means of transport).

Information on costs for transporting large volumes of contaminated wastes is becoming available from the Uranium Mill Tailings Remedial Action (UMTRA) Project in the United States of America and for the movement of such wastes in other countries (Section 10).

Figure 2 shows a plot of the relative cost of loading, transporting and unloading waste against the distance travelled as derived from cleanup experience in the UMTRA Project [14]. The waste is disposed of in large disposal facilities. The cost is given per unit volume and unit distance travelled. Initially, up to about 10–15 km, the loading and unloading costs dominate the total cost. However, as the distance increases the cost of transport per unit volume and unit distance decreases. For example, at 3 km, the relative cost would be about 2 as compared with 0.25 at 50–100 km.

Figure 3 shows some data from Japan on the cost of loading, transporting and unloading waste in relation to the distance travelled [15]. The cost per unit volume depends on the type of waste. The maximum load is usually limited by weight rather than by volume.

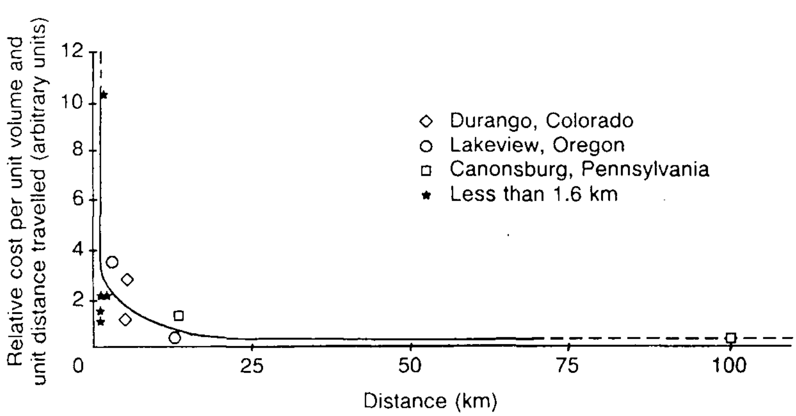


FIG. 2. Data from the UMTRA Project on the relative cost of loading, transporting and unloading waste as a function of distance travelled.

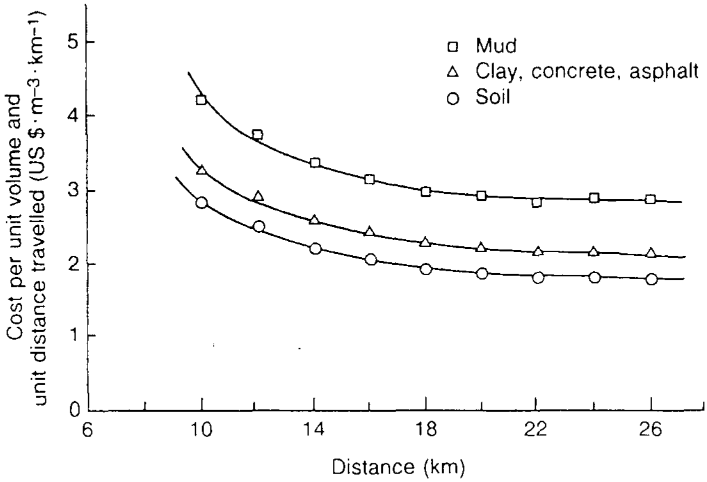


FIG. 3. Data from Japan on the cost of loading, transporting and unloading waste as a function of distance travelled. Volume of waste loaded per 10 t truck: mud, 3.2 m^3; clay, etc., 5.0 m^3; soil, 6.7 m^3. Cost of loading and unloading: US \$13·m^{-3}.

Appendix B gives an example of a generic method for estimating the total relative costs for loading, transporting and disposing of wastes for the three scenarios described in Section 6.

8. DISPOSAL OF LARGE VOLUMES OF WASTE

The objective of disposing of any radioactive waste is to contain it in such a way that it does not represent an unacceptable risk to the environment or the public at any time. Thus, a disposal facility should fulfil two important and related functions in this regard:

(a) Limit the dispersion, via water and air pathways, of the radionuclides contained in the waste;
(b) Isolate the disposed waste from the environment and humans by discouraging inadvertent intrusion by humans, or preventing exposure of the waste as a consequence of processes such as erosion, burrowing by animals or penetration by vegetation [16–18].

The radionuclides of longer term concern after an accident at a nuclear facility are ^{90}Sr and ^{137}Cs, both with a half-life of about 30 years. The average concentration of these radionuclides in the waste transported to a disposal facility would be considerably less than on the surface of the contaminated area after the accident.

During cleanup it is usually not possible to remove just the thin contaminated layer. Considerable amounts of clean soil would also be removed and mixed with the contamination and thus reduce the average radionuclide concentration.

However, in a serious accident even mixed soil can have relatively high concentrations of radionuclides. For example, the inner 900 km^2 zone around the Chernobyl nuclear power plant had about 220 PBq of surface activity two months after the accident. Assuming that 5 cm of soil are removed along with the contamination, then the average radionuclide concentration in the waste sent for disposal would be about 5 $GBq \cdot m^{-3}$. Assuming that ^{90}Sr and ^{137}Cs are the main radionuclides present, after about 300 years these would have decayed to about 5 $MBq \cdot m^{-3}$. Therefore, a disposal facility with a design life of a few hundred years would probably be required to meet regulatory criteria in Member States.

A wide variety of generic designs of facilities for the storage or disposal of large volumes of low level radioactive waste (LLW) are available. Some of the more common designs and the engineering features available to improve the integrity of such repositories are discussed below.

8.1. SELECTION OF A DISPOSAL FACILITY DESIGN

8.1.1. Basic factors

The basic factors which should be considered in an integrated manner to achieve a suitable disposal facility for LLW are [19]:

(a) The nature and quantity of the waste;
(b) The site characteristics and the engineered features which should be incorporated into the generic designs (Section 8.1.2) to make them suitable for available sites;
(c) The requirements for support services (Section 8.1.3), operational monitoring and institutional control, including post-operational monitoring and the length of control (Section 8.3).

All of these factors are evaluated in the safety assessment (Section 8.4) to ensure that the potential impact of the disposal system will not exceed the established regulatory and environmental protection requirements.

8.1.2. Design options

A variety of generic designs of facilities are available for the disposal of the large volumes of contaminated soil and other bulk materials arising from the cleanup after a nuclear accident. These make use of features such as natural depressions, specially dug trenches, surface mounds, existing excavations, abandoned mines, caverns or rock cavities, and above and below ground concrete vaults.

8.1.2.1. Natural depressions

Natural depressions, such as valleys or basins, have been used to store uranium mill tailings [16] and LLW. Such features if available might be suitable for the disposal of large volumes of LLW arising from a post-accident cleanup. The containment characteristics of features such as valleys can be enhanced by construction of an embankment at the downstream end to form an impoundment basin. Other engineered features such as an impermeable lining or cover, and flow diversion

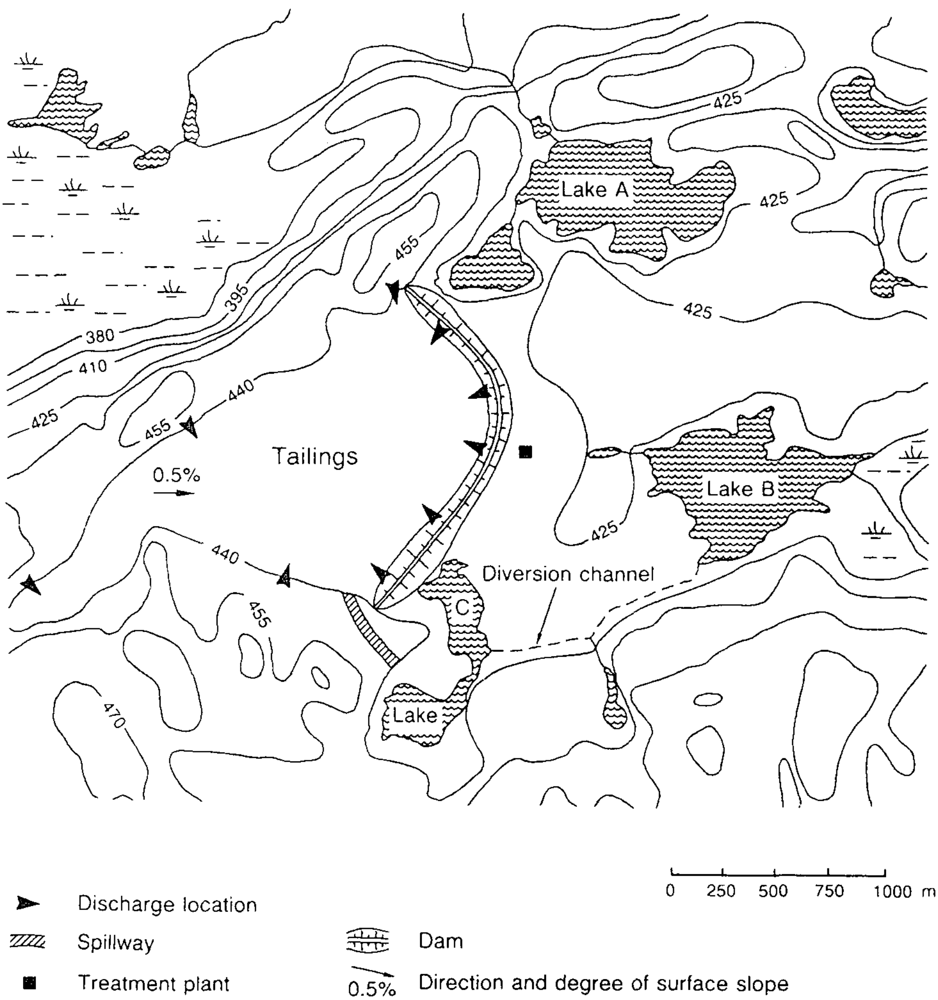


FIG. 4. Alluvial valley tailings site. (Contours in metres above sea level; contour interval, 15 m.)

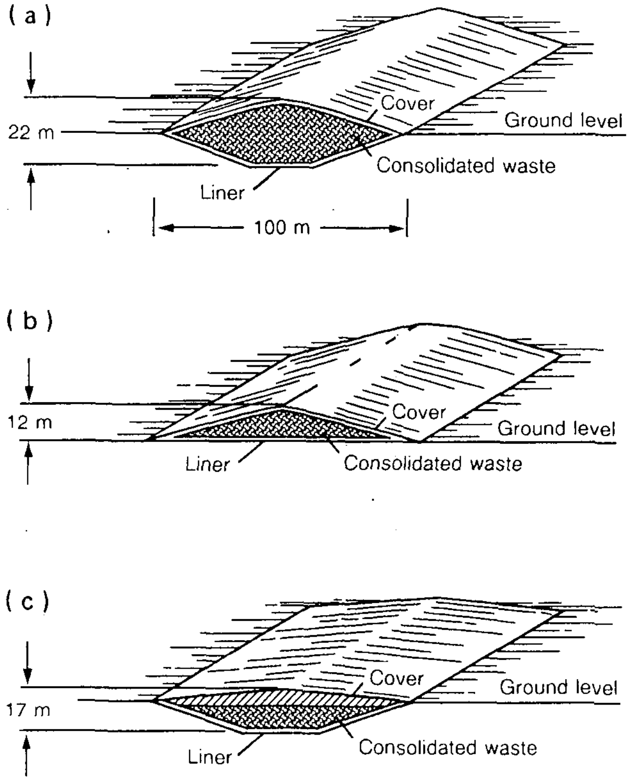


FIG. 5. Types of engineered landfill: (a) conventional landfill, (b) above ground landfill, (c) shallow entombed landfill.

channels around the facility to drain rainwater and to control erosion and long term seepage, can be added as required. Figure 4 shows a typical configuration of a dammed valley used for the storage of uranium mill tailings [16, 20]. The requirements for impoundment facilities for uranium mill tailings may be more severe than for wastes contaminated with ^{90}Sr and ^{137}Cs because of the long half-life (1600 a) of ^{226}Ra, the radionuclide of major concern in mill tailings.

8.1.2.2. Excavated trenches

Various sizes and designs of excavated trenches or pits have been or are being used in many countries for the near surface disposal of very large volumes of municipal waste, radioactive or toxic chemical waste or uranium mill tailings. The most common approach consists of excavating a trench, placing the waste in the trench up to a prescribed level which is often below the original ground surface, and covering or capping the waste with excavated clean material.

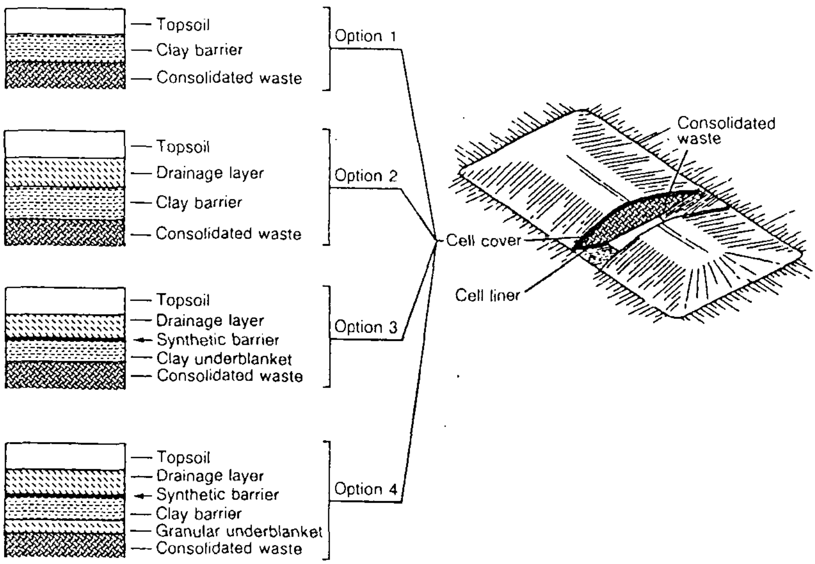


FIG. 6. Engineered landfill cover options. (Not to scale; total thickness of cover varies from approximately 0.6 to 2.0 m.)

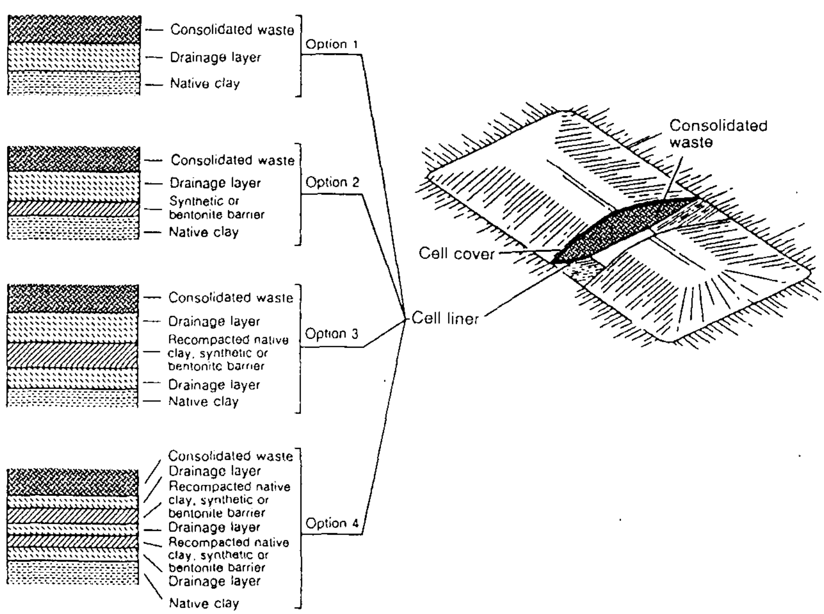


FIG. 7. Engineered landfill liner options. (Not to scale; total thickness of liner varies from approximately 0.5 to 3.0 m.)

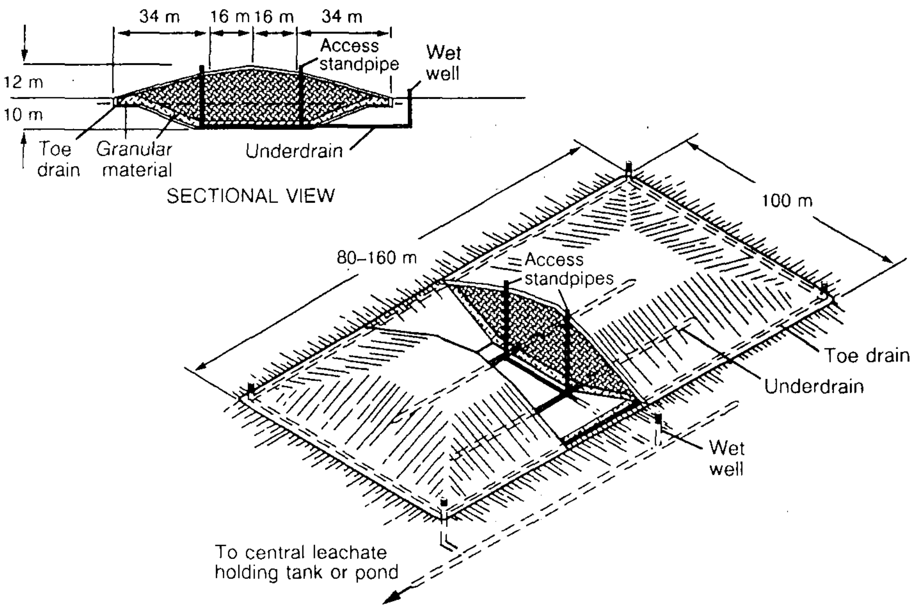


FIG. 8. Leachate collection concepts: conventional landfill. (Initial design would probably include only underdrain system.)

The isolation capability of such a trench relies mainly on the properties of the excavated overburden and the geological and hydrogeological characteristics of the site. Various engineered barriers can be added to the simple trenches to compensate for deficiencies in the site and improve the safety of such facilities. The objective is to limit the release rates of radionuclides to levels which, at any time, would not significantly affect health, safety or environment.

The most widely used design of this general type of facility is the conventional design employed for the disposal of municipal waste (Fig. 5(a)). Other conventional variations of landfill designs include the above ground landfill or mound design (Fig. 5(b)) and the shallow entombed landfill (Fig. 5(c)). Each of these designs can incorporate, as required by specific circumstances, engineered covers, liners and leachate collection systems such as those shown in Figs 6–8 [21]. In addition, barriers can be added to make intrusion by humans, animals and plants more difficult. In general, the more dangerous or long lived the waste, the greater will be the protective barriers which are added to the simple facility or the longer the institutional control required. This type of facility could be suitable for the disposal of large volumes of LLW arising from the cleanup of large areas provided that suitable engineered barriers are added where warranted.

Variations of these simple, near surface facilities have been used for the disposal of LLW for years in many countries [18].

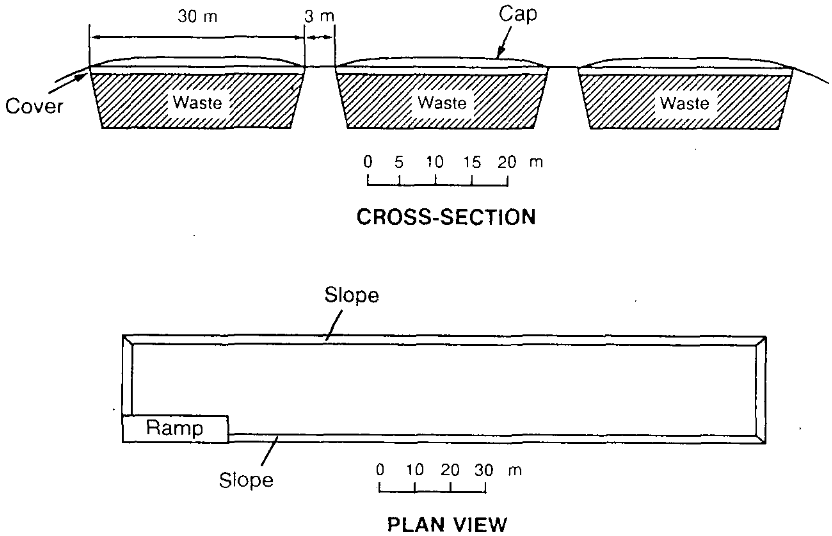


FIG. 9. Typical trenches used for disposal of low level waste from nuclear facilities in the USA.

The disposal facilities for LLW in the USA employ shallow land burial trenches similar to those shown in Fig. 9. Wastes having higher radiation levels or higher radionuclide concentrations are placed at the bottom of the trench or covered with some type of intrusion barrier such as a thicker cover of fill or concrete.

The slope of the side walls of shallow land burial trenches for LLW can vary from about 45° for sand to about 90° for clay and tuff [22]. Facilities to accommodate 20 000 to 40 000 m^3 of waste have been built.

If suitable transportation is not available, it may be necessary to dig many smaller pits or trenches and bulldoze the waste into these. Earth moving machines such as bulldozers or graders can be used to efficiently remove layers and transport the soil distances of 150 m without reloading or stopping. The clean material from the trench could be used as a cover and/or to raise the trench walls above the normal ground level. However, with small trenches it may be more difficult to delineate the outer perimeter of the trench and keep track of the many facilities. In addition, small trenches do not use land efficiently.

8.1.2.3. Surface mounds

Surface mounds of various designs have been used for the storage or disposal of radioactive waste, municipal waste and uranium mill tailings. Typical above ground landfill designs for municipal waste are shown in Figs 5(b) and 10.

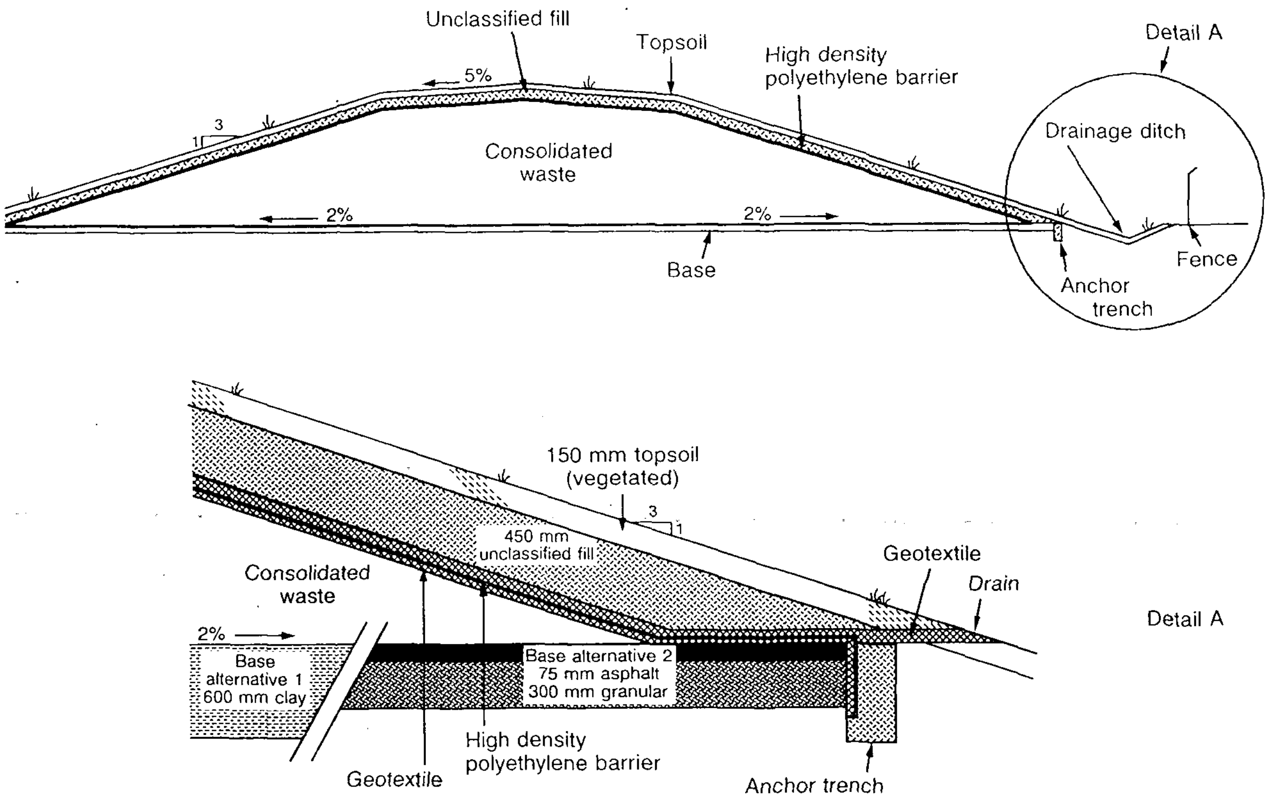


FIG. 10. Typical landfill disposal facility (top) and details of construction (bottom).

Any of these generic designs could be modified by the addition of more engineered barriers to make them acceptable for the disposal of large volumes of LLW arising from a serious nuclear accident.

The advantage of a surface mound is that it can be sited on virtually any relatively flat area and, with appropriate engineering features or provisions for institutional controls, can be expected to satisfy regulatory requirements in most Member States.

8.1.2.4. Existing excavations

Existing excavations such as mined out quarries or open pit mines could be used for the disposal of large volumes of LLW.

The acceptability of old quarries or open pit mines for disposal of LLW depends to a great extent on a number of site specific factors such as the climatic, geological and hydrogeological conditions, but also on susceptibility to flooding, etc. If a particular quarry is considered especially desirable, some natural limitations can be compensated for by using engineered features such as a water diversion or interception system, linings and impermeable covers.

8.1.2.5. Mined caverns or cavities

Caverns or cavities are being used or proposed for low and intermediate level radioactive waste disposal [23–26].

The usefulness of underground mines is difficult to characterize at short notice and any deficiencies may be more difficult to compensate for through engineering. Their usefulness depends on many factors, including groundwater depth and movement through the mine, susceptibility to ingress of water via ventilation raises, boreholes, etc., and the practicality of placing waste in the mine.

In Canada, large caverns (85 000 m^3) excavated in massive competent limestone formations about 100 m below the ground surface have been studied for the disposal of 1×10^6 m^3 of waste contaminated with low concentrations of ^{226}Ra. Geomechanical constraints limit the size of each cavern to a width of 15 m and a height of 50 m.

The major difficulty with using this approach for the disposal of waste arising from a serious nuclear accident is the time required to identify and characterize a suitable site and build the facility. It is most unlikely that such a facility could be used for an emergency unless it was already constructed.

The lead time and the cost associated with constructing such a facility could be greater than those of surface mounds or engineered shallow land burial facilities. However, mined caverns or cavities may result in lower longer term costs for post-operational monitoring and institutional control, and would require less surface land to be removed from future alternative use, such as agriculture.

8.1.2.6. Concrete vaults

Above and below ground concrete vaults or buildings could be used for the disposal of large volumes of LLW. These vaults are large reinforced concrete structures in which access is usually from the top. The vault is usually divided into separate compartments, although this is not necessary except for structural considerations. The compartments are sealed after filling, usually by a concrete cover.

An above ground vault does not have any earthen cover system and relies principally on its structure to isolate the waste.

A below ground vault could be of similar design except that the concrete cover would probably be covered eventually with an earthen cap. Although it would be possible to do maintenance on the cap (before final covering with earth) and on the sides, it would be more difficult to do repairs on the bottom of the facility.

As for specially mined caverns, it would be difficult to justify the expense of building this type of facility for disposal of large volumes of LLW in an emergency if simpler and less expensive alternatives could be shown to be acceptable.

8.1.2.7. Engineered features

The word 'engineered' in this context refers to the fact that features and materials have been added to accomplish, or improve, certain functions such as containment. It should be possible to add engineered barriers to most of the facilities described above to make them suitable for wastes containing radioisotopes such as ^{90}Sr and ^{137}Cs.

Basically, the engineered features to improve the safety of these disposal facilities fall into the following categories:

(a) Barriers to make the intrusion of humans, animals or plants more difficult. These include: greater depth of earth cover, riprap and reinforced concrete. Intrusion barriers would not be required if the facility were under institutional control until the waste had decayed to an acceptable level.

(b) Barriers to prevent the ingress of groundwater, surface water or precipitation. These include: clay covers, manufactured impermeable barriers, and hydraulic bypasses around the facility.

(c) Barriers or mechanisms to prevent the egress of radionuclides from the facility. These include: impermeable clay or man-made barriers, and buffers which let water out but retard radionuclide migration.

The reader is referred to documents such as Refs [16, 20, 27] for further information.

8.1.3. Support facilities

If the disposal facilities of the various designs described above are to operate efficiently, administrative and support facilities would be required to ensure smooth operations, keep records, provide monitoring and maintenance services, etc. Figures 11 and 12 give examples of the layout of administrative and operational areas for a large LLW disposal facility for reactor wastes and the wastes from medical, industrial and other applications [17]. Not all of these features may be exactly suitable for the disposal of large volumes of LLW arising from the cleanup of large contaminated areas.

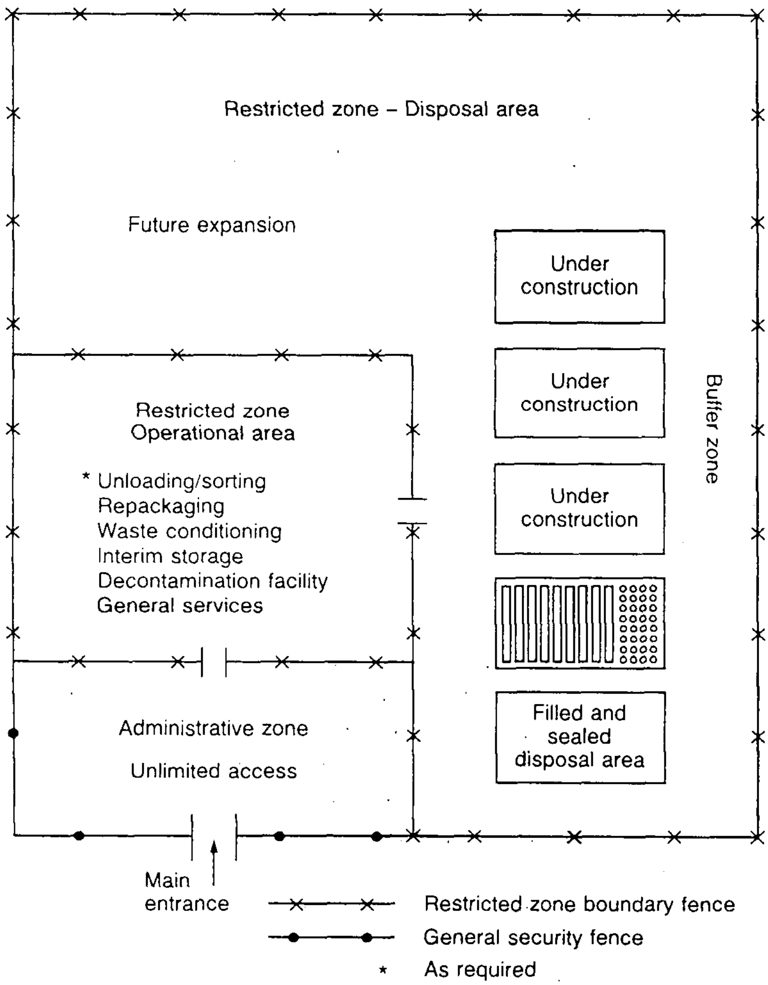
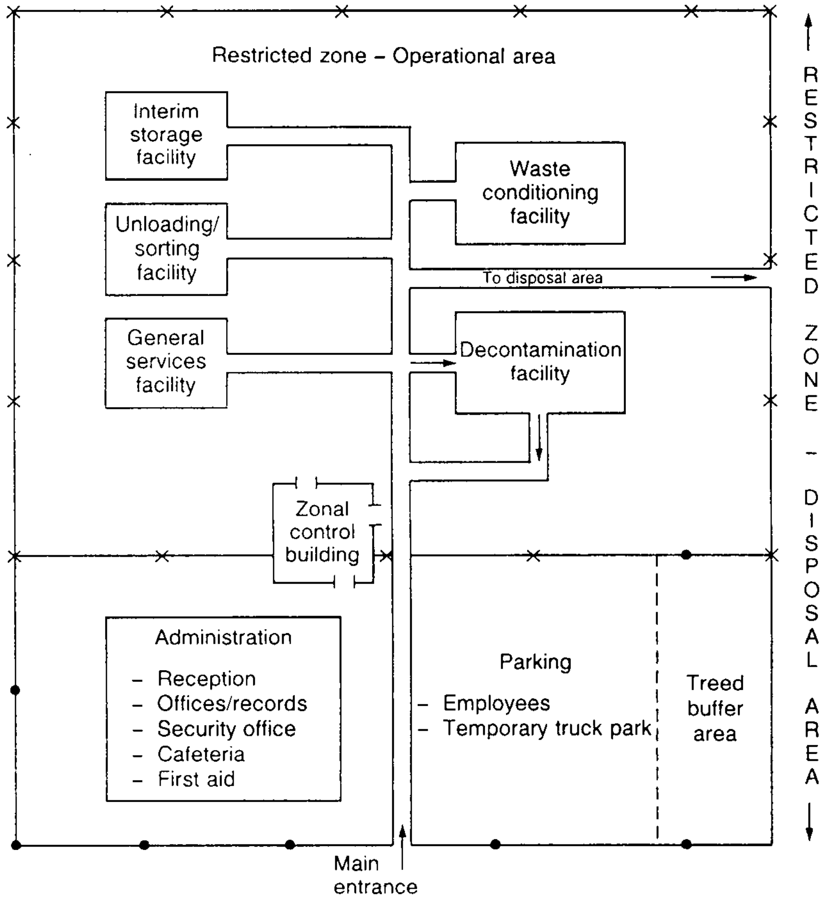


FIG. 11. Example of layout of a shallow ground disposal site for low and intermediate level wastes (see also Fig. 12).



Zonal control building

- Operators' changing/shower rooms
- Portal monitoring: personnel and equipment
- Security control
- Health physics and environmental protection laboratory
- Personnel decontamination

General services facility

- Equipment maintenance and storage
- Laboratories
- Utilities substation (water, power, fire fighting)

Unloading/sorting facility *

- Checking dose rate, contamination, damage, etc.
- Validating information on documents
- Sorting packages (radioactivity, size, etc.)
- Shipping packages to conditioning facility, storage or disposal

Waste conditioning facility *

- Volume reduction (incineration, compaction)
- Repacking, overpacking
- Treatment of wastes from the site

Decontamination facility

- Decontamination of trucks, equipment, etc.
- Contamination monitoring of equipment

* As required

FIG. 12. Example of layout of administrative and operational areas.

8.2. SITE SELECTION

The choice of location, like the method of disposal, will be dictated by many factors, including radiological impact, availability of equipment, the radionuclides involved, climate, future land use, availability and characteristics of disposal sites and requirements for institutional controls. The cost of loading and transporting the large volumes of waste from contaminated land can significantly influence the choice of location of disposal site(s). Societal and political implications can also have an effect on the choice of disposal site.

The idealized sequence of investigation for the selection of any waste disposal site has four general phases [19]:

- Planning and general studies
- Area survey
- Preliminary site selection
- Site confirmation.

During routine emergency preparedness planning, a review of potential sites for the disposal of large volumes of contaminated waste could be done using available data or with new data if funding is available. However, since even the selection of potential sites could be a very sensitive issue, it may only be possible to do this study in a generic manner and match up repository designs with generic sites in the area. The final selection of the site or sites would take place if an accident occurred.

The weighting placed on the factors involved in siting a disposal facility in a zone seriously contaminated by a nuclear accident will be different from that required for the siting of a normal disposal facility under non-emergency conditions.

The reader is referred to other IAEA publications, such as Refs [16, 19, 28, 29], which deal with siting in more detail.

8.3. INSTITUTIONAL CONTROL

Following closure of the waste disposal facility, a period of surveillance will be necessary to determine whether the facility is performing as predicted, in compliance with established regulatory requirements. This surveillance could include water and air sampling and monitoring of cover stability. Once it has been demonstrated that the facility is behaving as designed, a further period of institutional control may be required, depending on the design of the facility, country requirements, etc. For example, in some countries, if it can be demonstrated that the facility has been built to prevent intrusion by humans, animals or plants and if release levels are likely to stay within safe limits until the waste decays to innocuous levels, then further institutional control may not be required. This institutional control period after closure is usually specified in regulations and for near surface disposal/storage facilities is usually many tens of years, for example 100 years in the USA [30] and between 200 and 300 years in France [18]. The control may be active (monitoring, surveillance, remedial work) or passive (land use control).

The selection of the length of the institutional control period will be based on the types and concentrations of major radionuclides present in the waste, the repository design, whether or not intrusion barriers are used, regulatory criteria related to concentrations which are below regulatory concern, etc.

8.4. SAFETY ASSESSMENT OF DISPOSAL FACILITIES

As for any facility being designed for the disposal of radioactive waste, the proposed design of a facility for the disposal of large volumes of LLW must be shown to be safe. The main objective of the safety assessment is to ensure that the public and the repository workers would not be exposed to radiation exceeding prescribed limits during the operational and post-operational phases of the facility.

The safety assessment requires that all relevant pathways by which radionuclides could enter and be transported through the environment to humans should be identified. A quantitative analysis then provides an evaluation of the potential individual radiation dose and collective dose commitment likely to arise from the disposed waste. The results are then compared with the criteria established by national regulatory authorities to ensure that the disposal facility does not represent an unacceptable risk to humans at any time.

In designing and siting a disposal facility and assessing its safety, many interrelated factors must be considered. Figure 13 summarizes some of the important factors and shows the various stages of the life cycle of a disposal facility which should be considered in the safety analysis. Regulatory input and review should be available at all stages.

Figure 14 shows the safety assessment components and their interactions [29].

Safety assessments should be made at various steps in the disposal facility development in consultation with the regulatory authorities to ensure that the design will be adequate for disposal of the waste specified for the site.

At the conceptual design stage, a general safety analysis should be performed. The necessary information for this analysis is general data on geological, demographic and environmental characteristics of the site (which may be obtained from the site reconnaissance), on the likely form of the waste and on the means of transport. These, together with the design concept, give the first estimate of the feasibility of the system.

As design activities proceed, a more detailed safety analysis is required. Detailed information about the site geology and hydrogeology is necessary. Waste characteristics should be determined and the transport system well defined. Engineering studies of the disposal concept should be carried out. On the basis of

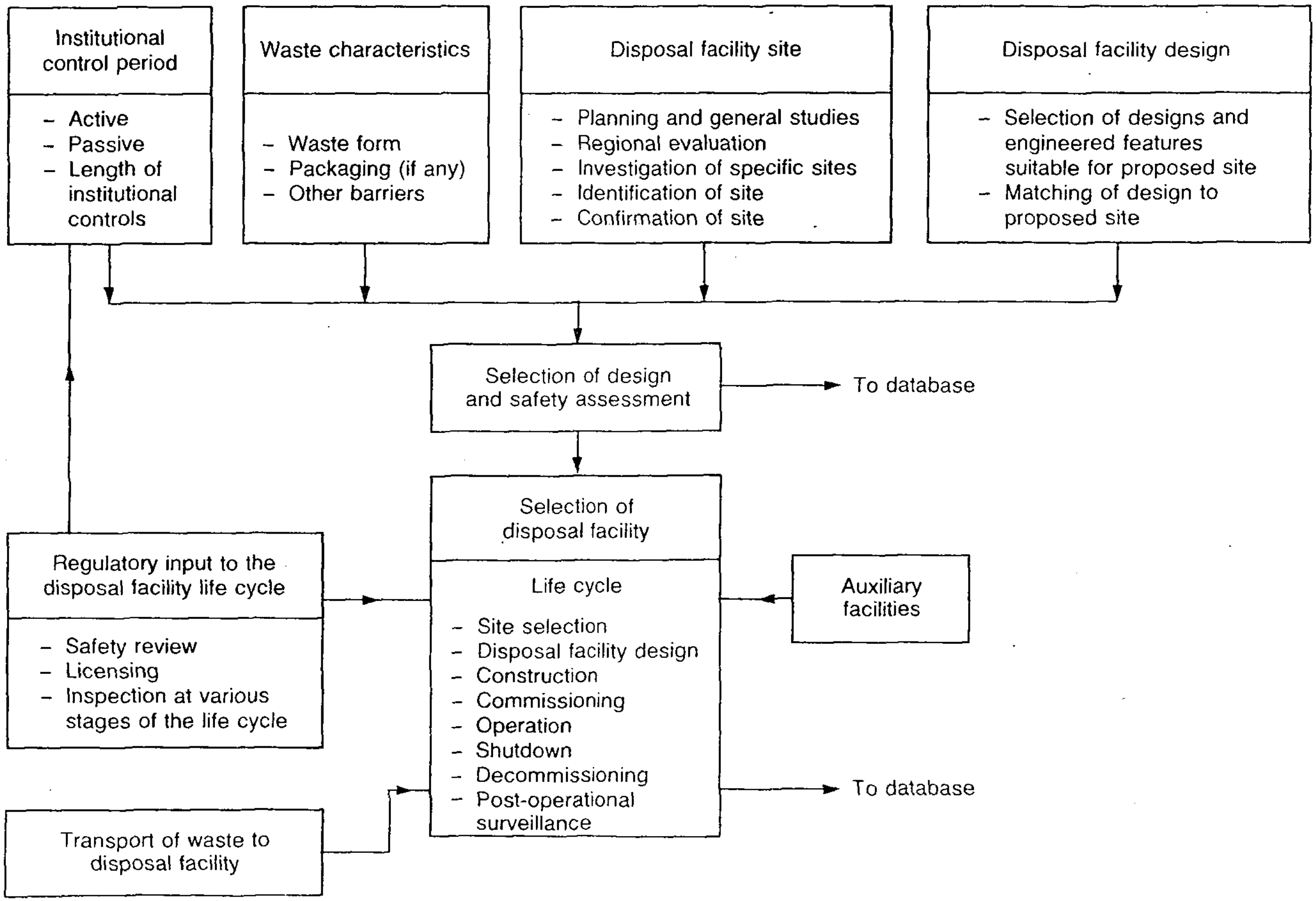


FIG. 13. Basic interrelated factors for the design of any waste disposal facility.

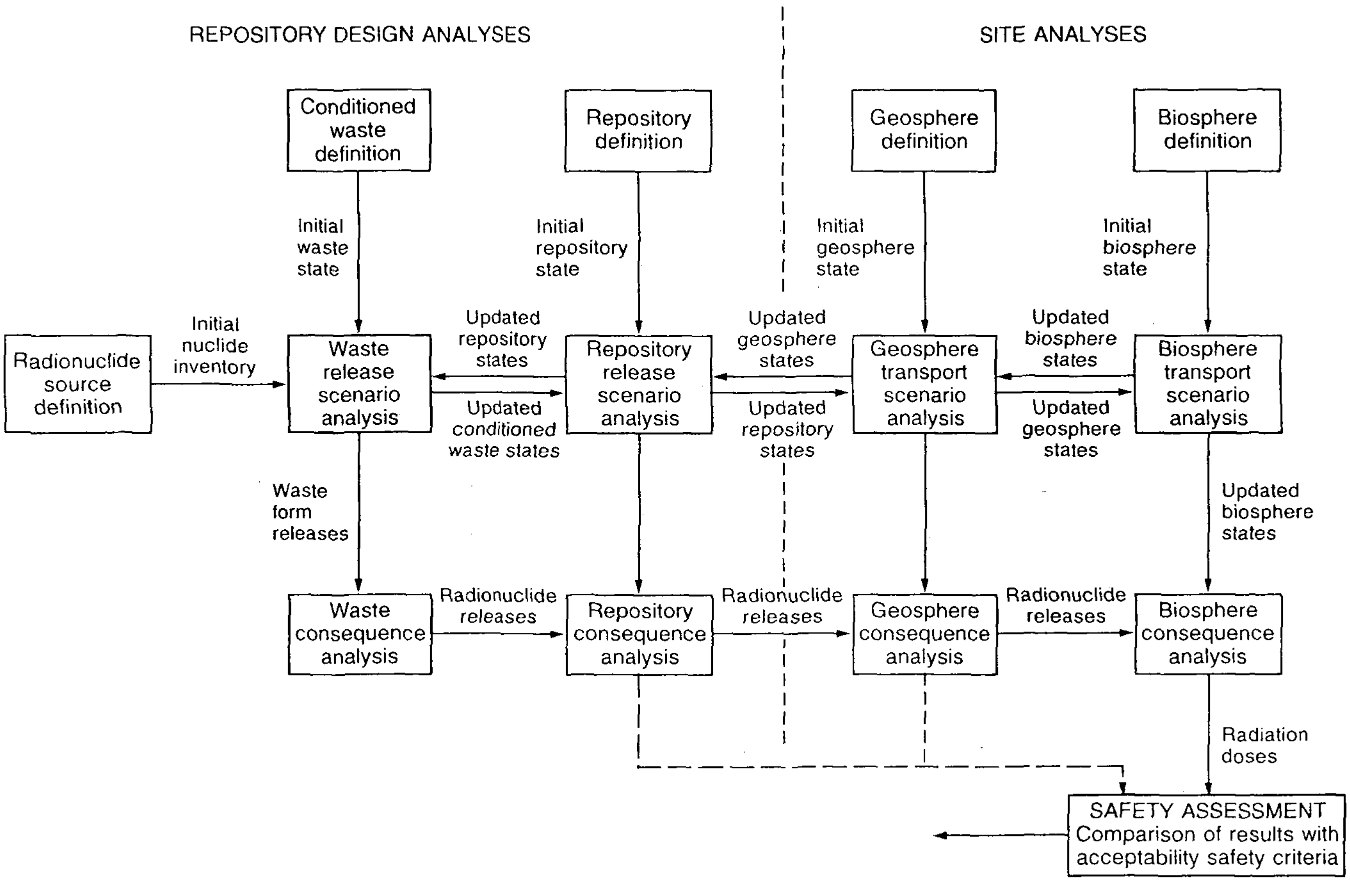


FIG. 14. *Safety assessment components and their interactions.*

this more detailed safety analysis, a decision can be made to proceed with further development of the design or, if results are negative, on how to revise the design or select another site.

For the final safety analysis, which must be approved by the licensing authority, detailed information based on the waste form, transport system and final disposal design, supplemented by thorough site investigation, is necessary. The results of this analysis should be a basis on which to start licensing and construction activities. If results are unacceptable, the whole system should be revised and the disposal concept changed until a full accord with prescribed requirements is reached.

The reader is referred to other IAEA publications, such as Refs [16, 19, 28–30], for more information on the methods and techniques available in a safety assessment of disposal facilities and to Ref. [31] for regulatory input to the facility life cycle.

8.5. DISPOSAL COSTS

Section 7.3 reviewed available information on the costs of loading, transporting and unloading waste arising from the cleanup of large areas. This section discusses costs associated with the construction, operation and closure of the disposal facility, i.e. disposal costs. These include costs for site evaluation and acquisition, site improvement and facility construction, operational and material costs for items such as waste emplacement, administration and monitoring, and post-operational costs for decommissioning, surveillance and institutional control.

The total costs will also be strongly affected by the construction, operation, closure and post-closure licensing conditions set down by the regulatory authorities. Other factors which could influence the disposal costs in a particular country include labour costs, land costs and sociopolitical considerations.

A method for evaluating the costs of disposal of large volumes of bulk waste is given in Appendix B, while Refs [32, 33] and Appendices C and D provide information on cost data for waste disposal in particular countries. These data cannot be extrapolated directly to other situations without detailed consideration of the differences from country to country in the factors incorporated into the costs, for example labour costs, regulatory requirements and available equipment. However, the information should be useful in outlining which factors should be considered in a methodology to estimate these costs.

8.6. PREFERRED OPTION

It is beyond the scope of this report to define the best disposal facility designs for a particular situation. However, this section briefly discusses some of the factors affecting the final choice.

The preferred option regarding a site for disposal of large volumes of radioactive material arising from the cleanup of large contaminated areas can be obtained from an evaluation of available site–facility design combinations. The final choice will depend on many site-, country- and accident-specific parameters and the strategy selected for cleanup and disposal of waste. As a general guideline, the simplest facility should be selected which:

- Will contain the waste safely for the required time in compliance with the applicable regulatory requirements,
- Can be sited and constructed within a suitable time frame.

For this assessment it is assumed that the disposal facility will be sited, designed, constructed, operated and closed so that retrieval of the waste is not anticipated.

8.6.1. Factors affecting final choice

Some of the factors which will influence the preferred option for waste disposal are listed below:

(a) *Short and long term safety* of the workers, the public and the environment.

(b) *Availability of suitable disposal sites:* Disposal concepts for which there are a larger number of acceptable sites might be preferable to concepts for which fewer sites are available. This would increase the probability of finding a site or sites which are also acceptable on social and political grounds, although these factors may not be as important in an emergency as during normal site selection processes. If there are a number of acceptable sites, this provides greater flexibility in designing the overall waste management system, for example in optimizing transportation.

(c) *Availability of equipment, resources and personnel* to construct and operate the selected facility.

(d) *Time required to characterize the site and construct the facility:* From this viewpoint, an accident situation such as that which arose at Chernobyl would probably rule out concepts requiring long lead times, e.g. specially mined caverns, unless the site had been characterized before the accident.

(e) *Long term predictability:* Since some facilities may have to function effectively for several hundreds of years or longer, it is important that their future performance within the applicable regulatory requirements can be predicted with assurance.

(f) *Requirements for institutional control of the facility after closure:* These requirements should be evaluated. Facilities which do not require institutional control after closure may be preferable to those which do. When evaluating disposal options, the need for post-operational monitoring programmes must be taken into account.

(g) *Consequence of failure:* The probability of occurrence and the consequence of a serious failure in the integrity of the disposal facility must be assessed, particularly beyond the period of institutional control.

(h) *Land area:* It may be desirable to limit land loss by optimizing the design.

(i) *Cost:* Since disposal costs could be a large part of the total cleanup costs, the least expensive means of doing the job consistent with safety and radiation protection principles should be selected.

(j) *Public acceptance:* This is an important factor which has a variety of technical, social and economic components. Siting might be facilitated by using already licensed areas or locating the facility in the restricted area.

In selecting the most suitable disposal facility for a particular site, all these factors should be considered. The evaluation will be country-, site- and accident-specific since the weighting of each factor could differ from case to case.

8.6.2. Discussion of scenarios

Scenario 1 (Section 6) would avoid loading and transportation costs but would have higher scraping/bulldozing and disposal costs.

For Scenario 2, the relative cost per unit volume and distance travelled (using Fig. 2) would be slightly higher than for Scenario 3 but the distances travelled to the repository would be considerably less, so overall loading and transportation costs would be less. Scenario 2a with one disposal site should have the same loading costs as Scenario 2b (four disposal sites) but higher transportation costs.

If Scenario 1 is to be used, the control of factors such as the location of individual loads of waste in the disposal site will be much less comprehensive than for Scenarios 2 and 3. However, an attempt should be made to fit the grid into which the affected area is divided to the disposal sites where the waste is deposited. Since the radionuclide characteristics and volumes would be reasonably well defined, an estimate of the total radioactivity in each of the 40 disposal sites would be known.

With Scenario 2, for the type of waste described in this report, a simple design of a disposal facility seems the most preferred option. Strict adherence to the IAEA transport regulations [9] would not be required since the loading, movement and disposal of all radioactive wastes would be within the restricted area, from which the public is excluded. However, the control teams should develop clear and concise transportation procedures to ensure protection of the workers, minimize secondary spread of waste, ensure that the waste is deposited in the correct place and keep a record of shipments.

If Scenario 3 is to be used, a relatively simple design of bulk repository combined with good barriers and institutional control is an attractive concept. The movement of wastes outside the restricted area should comply with the IAEA transport regulations [9, 10] or national regulations based on these documents.

8.6.3. Constraints

The selection of a site for a facility to be used for the emergency disposal of large volumes of LLW arising from a serious nuclear accident has constraints not normally present in the development of a repository for normal disposal.

The major constraint is time. For a normal LLW repository, the site evaluation could take months or years, depending on regulations, public opinion, etc. In an accident situation, the time available for such evaluations would probably be quite short. However, as part of routine emergency preparedness planning, some preliminary site evaluations could be carried out unless the issue is very sensitive politically or with the public. Such preliminary work could significantly reduce the time needed to site, design and construct repositories under emergency conditions and would probably result in a better facility.

9. DISPOSAL FACILITY OPERATION, CLOSURE AND SURVEILLANCE

The major steps that are usually involved in the operation, shutdown and surveillance of a shallow ground disposal facility are outlined in several IAEA publications [17, 18, 28] and will only be briefly reviewed here. These publications also mention the types of responsibilities that may be made mandatory for the facility operator and the implementing organization.

In addition to normal operational requirements, the operator should have an approved plan of actions to meet with contingencies arising from abnormal situations or remedial actions required to arrest the accidental release of radionuclides outside the confines of the facility.

As for any nuclear facility, the operator should have procedures to ensure that the disposal facility is operated in such a manner that the radiation exposure to the operating staff is maintained within acceptable limits and that non-radiological safety on site is maintained at proper levels.

The major functions in disposal facility operations include:

(a) *Receipt of waste:* Relevant data about the waste shipment should be confirmed by physical verification, including radiological measurements.
(b) *Waste handling and interim storage:* Equipment suitable for unloading the waste and placing it in the facility must be available. For the waste types considered in this report, interim storage would normally not be required except possibly for contaminated equipment or to allow organic wastes to decay before emplacement in the facility.

(c) *Waste conditioning:* Some of the wastes arriving at the disposal facility could require conditioning, e.g. volume reduction. However, such operations should ideally be done at the cleanup point to reduce transportation costs.
(d) *Documentation:* Adequate documentation of disposal operations must be maintained by the operator. For bulk disposal of large volumes of waste, a record of the exact locations of truck shipments will be more difficult to maintain than at a normal disposal facility. Permanent markers identifying the boundaries of each disposal unit should be provided and their locations and the locations of special shipments should be recorded on maps. The details of the waybill (Section 7.2.3) and receipt verification should be recorded on permanent files.
(e) *On-site monitoring:* Confirmation of radionuclide confinement and personnel protection require on-site monitoring of surface contamination, groundwater, soil, vegetation and air samples, and ambient radiation levels.
(f) *Off-site surveillance:* Off-site surveillance may also be required during operation and after shutdown to determine how well the facility's barriers are retaining the radionuclides. Prior to shutdown of the disposal facility, any requirements for post-operational controls or surveillance should be identified.
(g) *Radiation protection:* Disposal facilities should be subject to normal radiation protection programmes.

The reader is referred to Refs [17, 18, 28] for further information. Although these publications deal with the disposal of wastes under normal conditions, with some modification they also should be applicable to the operation and closure of facilities to be used for the disposal of large volumes of waste arising from an emergency.

10. REVIEW OF OPERATIONAL EXPERIENCE

Additional information on the procedures, techniques, equipment and facilities used to safely load, transport and dispose of large quantities of soil containing low concentrations of radioactivity can be found in the literature.

For example, in Canada 70 000 m^3 of soil and debris contaminated with ^{226}Ra (2 $Bq \cdot g^{-1}$) were gathered from the town of Port Hope, loaded into 20 m^3 dump trucks and transported to a storage site about 350 km away at the Chalk River Nuclear Laboratories without any major incidents. About 3000 truckloads of contaminated soil and demolition debris were hauled from Port Hope to Chalk River between 1976 and 1979 (Appendix C).

In the USA, remedial actions have been completed to clean up a 51 ha uranium mill site in Utah and move 2.6×10^6 t of contaminated material by train to a new location about 140 km away. The total cost of the remedial actions required was US $61 million (Appendix D).

In the former USSR after the Chernobyl accident, about 500 000 m^3 of LLW soil and debris were bulldozed into piles, loaded onto trucks and transported to central disposal sites (Appendix E).

11. RADIATION PROTECTION AND SAFETY PLAN

Planning and implementation for the radiation protection and safety of workers are inherent parts of all nuclear activities and are especially important in activities such as the cleanup of large contaminated areas.

During the last few decades, considerable work has been done on the development of the principles of radiation protection and on techniques and procedures to implement these principles for controlled situations [34–38]. To ensure that the techniques are correctly applied, a wide variety of instruments are available for personnel monitoring, air monitoring and the detection and measurement of all types of radioactivity from very low to very high levels. The application of radiation protection principles and techniques is demonstrated daily at nuclear facilities around the world and they have also been applied successfully to small and large cleanup tasks. The cleanup tasks include the decommissioning of nuclear facilities for unrestricted use, the rehabilitation of damaged reactors, the cleanup of contaminated sites and large areas and the transport of large volumes of contaminated material.

This section briefly reviews the methods which could be used to improve the radiation protection and safety of workers involved in transportation and disposal of large volumes of radioactive waste. Radiological criteria required to implement the cleanup of large areas are given in Appendix A.

11.1. FORMULATION

As part of routine emergency response planning, a preliminary radiation protection and safety plan should be formulated with the assistance of radiological experts. If an accident resulting in environmental contamination should occur, this plan should be tailored to meet the specific accident situation [8].

The radiation protection and safety plan should include a comprehensive radiation monitoring and data management programme [34, 38] which provides for the measurement, evaluation and recording of all exposures incurred by individuals through different pathways. The plan should also deal with practical aspects related to the implementation of this programme, including training and qualification of personnel, duties and responsibilities of various groups in all aspects of cleanup (e.g. handling, transport and disposal), use of protective clothing and respirators [34] and other means of reducing occupational exposures.

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

A major consideration in planning for radiation protection in any cleanup operation is the radiation exposure which the workers would be allowed. The limits should be set by national authorities on the basis of the recommendations of the International Commission on Radiological Protection (ICRP) and the IAEA [35, 37] and taking into consideration the accident situation.

Means of minimizing occupational exposures during the performance of all tasks should be clearly outlined in procedures. In general, lower occupational exposures during operational tasks can be achieved by reducing radioactive sources, e.g. by decontamination, and dose rates by shielding and distance or by minimizing the time workers spend in radiation zones, as well as by using protective clothing and respirators.

11.2. IMPLEMENTATION

During the implementation of the cleanup operations many activities should be controlled or initiated to ensure that radiation protection and safety are maintained, including [38]:

(a) Safety and radiation protection procedures;
(b) Specification of the type and extent of monitoring to be done;
(c) Selection, testing, calibration, maintenance and issue of suitable dosimeters and other instruments;
(d) Monitoring and sample collection;
(e) Processing and interpretation of individual and area monitoring data;
(f) Maintenance of adequate records and provision of the means to report such records;
(g) Quality assurance programme;
(h) Provision of trained staff for the above activities;
(i) Provision of materials and supplies to protect workers, including respirators, disposable clothing and airpacks;
(j) Provision for decontamination of workers and transport vehicles;
(k) Provision of first aid teams and other medical support;
(l) Control of non-radiological health problems within the cleanup zone, e.g. sanitation or decaying foodstuff or garbage.

Occupational exposures can be reduced by means of adequate procedures and techniques such as the use of shielding on trucks and of remotely operated equipment to load and unload wastes. During the cleanup of the most highly contaminated areas at Chernobyl, heavily shielded bulldozers and a variety of remotely operated vehicles were used [7]. The cabs of the operator driven vehicles also had clean-air supply systems.

An important way of reducing occupational exposures is to minimize the time workers remain in radiation fields, especially high level fields. Thus, any technique that allows the loading and transport workers to perform duties more efficiently or in a shorter time should reduce exposures.

12. CONCLUSIONS

It is concluded that:

(1) A great deal of information is available regarding the transportation and safe disposal of large volumes of waste. Much of the technology could be used directly in an emergency situation. However, the cost data cannot usually be used alone but should be considered together with relevant country- and site-specific factors.

(2) Disposal of wastes at a greater distance may be acceptable if a suitable disposal facility is already available to compensate for the higher transportation costs.

(3) The type of disposal facility selected will depend on many factors, including the availability of sites, transportation possibilities and the length of time before the facility is required.

(4) In an emergency situation involving large volumes of waste of the types described in this report, the use of a relatively simple design of bulk repository combined with good barriers and institutional control could be a safe and attractive concept.

To assist Member States in their emergency preparedness activities and to gather the new information which is becoming available on various cleanup programmes worldwide, this topic should receive further attention, including the preparation of manuals related to the practical application and costing of large cleanups, especially in urban areas.

Appendix A

RADIOLOGICAL CRITERIA REQUIRED TO IMPLEMENT THE CLEANUP OF LARGE AREAS AFTER AN ACCIDENT AT A NUCLEAR FACILITY

The following radiological criteria are required for implementing the recovery of areas contaminated as a result of a nuclear accident:

(a) Derived intervention levels (DILs), which the Emergency Director uses in deciding when to implement various measures to protect the public;
(b) Cleanup criteria, which are needed by remedial action teams to decide whether their cleanup activities at a particular site meet requirements;
(c) Criteria for the final release of all or part of the affected area for restricted or unrestricted use.

A variety of measures to protect the public in the case of an accident at a nuclear facility have been identified [5, 6]; they range from sheltering or evacuation of people to cleanup and decontamination of areas. The principles which apply in setting intervention levels at which measures for the protection of the public should be taken are outlined in Ref. [5]. This guidance is expressed in terms of dose ranges corresponding to each protective measure. However, decision making during an emergency would be more rapid and effective if the intervention levels were expressed in terms of the radionuclide concentrations in materials. Therefore the IAEA has published information on the principles for setting DILs, environmental pathways and concentration ranges of radionuclides of potential radiological significance, and procedures for evaluation [6]. These DILs are the practical expression of the intervention dose level, for example in $Bq \cdot m^{-3}$ or $mSv \cdot h^{-1}$. The reader is referred to Refs [5] and [6] for detailed discussion on the development and use of DILs and ILs.

Before the cleanup is implemented, the cleanup criteria must be available to determine the maximum specific radionuclide concentration or gamma exposure level to be achieved by workers doing the remedial actions. In practice, different cleanup criteria may be set for different zones or situations [7]. For example, higher residual activity levels may be acceptable for remote, forest or desert areas and for buildings with good shielding properties or low occupancy.

Criteria must also be available for the final release of all or part of the restricted area for restricted or unrestricted use to permit the evacuated population to return safely to their jobs and/or homes. The actual values of these re-entry criteria will be based on many factors, including health related effects which are likely to arise as a result of the set criteria, property value losses, the cost of decontamination, transportation and disposal, and radiological surveying and monitoring costs.

The criteria should be based on acceptable risk levels translated into acceptable dose limits. Concentration limits for radionuclides in soil, water, air and food or acceptable radiation levels can be derived using suitable pathway analysis and, where possible, realistic site specific parameters. Means must also be available to ensure that the cleanup is in compliance with such criteria [7, 8].

Appendix B

A GENERIC METHOD FOR ESTIMATING COSTS OF WASTE LOADING, TRANSPORTATION AND DISPOSAL

B.1. INTRODUCTION

A great many factors would have to be considered in determining which of the three scenarios (Section 6) for the loading, transportation and disposal of wastes would be preferred in any particular situation.

During preliminary planning for a particular facility, it may be possible to determine which options seem to be preferable on the basis of a knowledge of the area, the equipment that is readily available, suitable disposal sites, etc. However, the final selection of the preferred option could not be done until full details of the accident, plume direction and size, contamination levels, disposal site locations, etc., were known.

Since the cost of transportation for Scenarios 2 and 3 would be a major part of the loading–transport–unloading costs, it is important that the total haulage distance for all loads of wastes delivered to the repository be known.

Disposal costs will vary primarily with the type of disposal facility. For example, facilities with extensive engineered barriers can cost several times as much, per unit volume of waste, as those relying only on the waste characteristics and the containment capabilities of the surrounding geological media. Disposal costs per unit volume will also vary somewhat with the scale of the operation. Fixed costs will change by relatively small amounts with the total volume of waste at a major disposal site. Examples of such costs are the costs for support facilities (administration and maintenance buildings, truck decontamination facility, etc.), site services and infrastructure, and long term monitoring. Other costs will vary almost in direct proportion with the total volume of waste. Examples of such 'variable costs' are the costs of building disposal facilities, emplacing the wastes and closing the facilities. Even here, though, some increase in efficiency with scale would be expected.

If there is only one disposal site possible, then the calculation of transportation costs would only need to be done to determine overall cleanup costs, and not to optimize locations and amounts of waste disposed of at the locations.

An example is presented below of an approach which could be used to determine which of various scenarios would have the lowest total comparative cost for loading and transporting to the disposal site and for disposal facility construction, waste emplacement and facility closure. The location(s) of the disposal site(s) may be determined by other factors (Section 8).

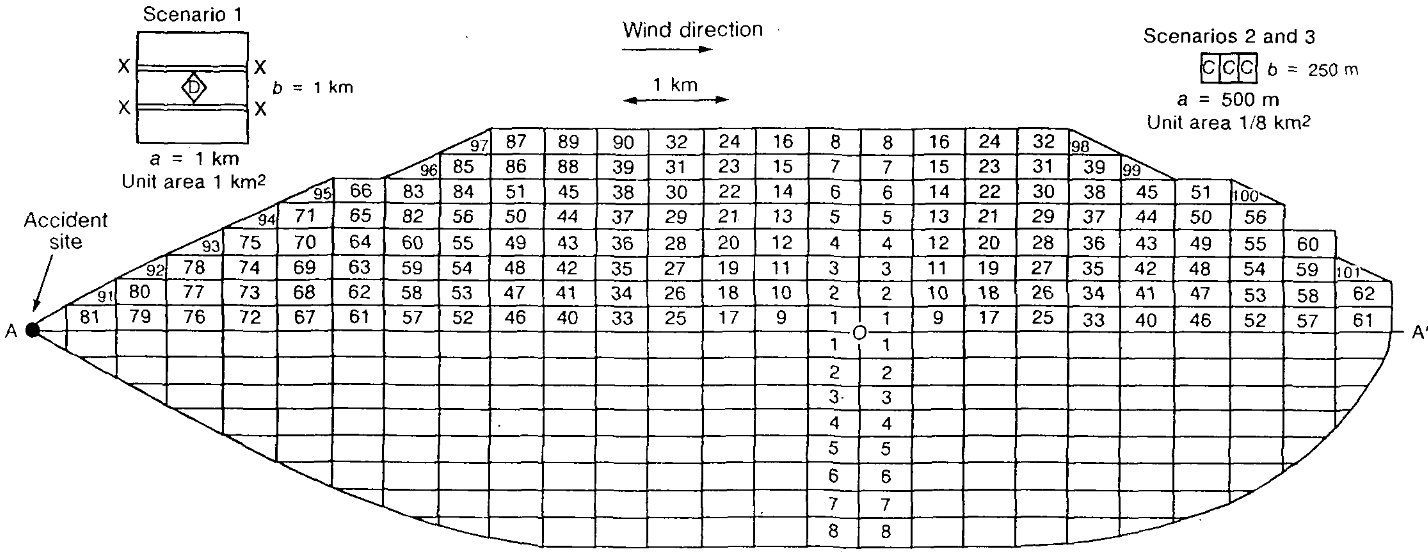


FIG. 15. The inner plume (Fig. 1) showing the 40 km² from which soil must be removed. For analysis the shape of the plume has been modified slightly, as shown above line AA', and divided into unit areas of 1 km × 1 km for Scenario 1 and 250 m × 500 m for Scenarios 2 and 3. The part below AA' would also be changed but it has been left as it was so that the extent of the changes is clear. In the scenario shown, the disposal site is located at point O. The whole plume consists of four symmetrical groups of 62 unit areas, two symmetrical groups of 28 unit areas (63–90) and two symmetrical groups of 11 half-unit areas for Scenarios 2 and 3, and 40 unit areas for Scenario 1.

The following assumptions are made to illustrate the method:

(a) The cleanup or decontamination operations have been completed and the waste has been collected into piles suitable for moving it to the disposal site(s).

(b) For Scenario 1, the waste is moved by graders into two windrows (XX, Fig. 15) and then moved directly by belly scrapers an average distance of 300 m to a pyramidal disposal site (D, Fig. 15; height 12 m; square base with sides of 112 m) at the centre of each unit area.

(c) For Scenarios 2 and 3, the waste is moved to three collection points in each unit area (C, Fig. 15), loaded into 25 m^3 trucks, transported to a central disposal site via a direct route and unloaded by dumping.

(d) Although the methodology described below is applicable to any contaminated area, the simplest case has been selected here for illustration purposes, i.e. a rural area in which the release occurred during relatively constant weather conditions (no rainfall, fairly constant wind direction, fairly short time of release, etc.) (Fig. 1).

(e) Only the inner 40 km^2 of the plume (Fig. 1) require removal of soil (5 cm) to clean it up. The remainder of the plume would be cleaned up by ploughing and other means [7].

(f) For costing purposes, the inner plume is divided into unit areas of 1 km $\times$ 1 km (Scenario 1) or 250 m $\times$ 500 m (Scenarios 2 and 3), as shown in Fig. 15.

(g) The belly scraper cost is P per cubic metre moved and kilometre travelled.

(h) The cost to load waste into trucks is Q per cubic metre.

(i) The transportation of waste in a 25 m^3 truck costs R per kilometre travelled.

(j) F_{50}, F_{500} and F_{2000} are the fixed costs associated with setting up a disposal facility for 50 000, 500 000 and 2 000 000 m^3 of contaminated soil respectively. An allowance for long term monitoring and maintenance is also included. That is, the total fixed cost for Scenario 1 will be $40F_{50}$, and for Scenario 2a, F_{2000}.

(k) V_{50}, V_{500} and V_{2000} are the variable costs per unit volume of contaminated soil disposed of at facilities for 50 000, 500 000 and 2 000 000 m^3 respectively. That is, the total variable cost for Scenario 1 will be $40 \times 50\,000V_{50}$, and for Scenario 2a, $2 \times 10^6V_{2000}$.

B.2. SCENARIO 1

(a) The cost of transporting 50 000 m^3 of waste from unit area (1 km^2) to a disposal site 300 m away is:

$$50\,000 \times 0.3P = 15\,000P$$

The total cost of transporting the contaminated soil from 40 km^2 to the disposal areas is:

$40 \times 15\,000P = 600\,000P$

(b) The total cost of disposing of the contaminated soil from unit area is:

$F_{50} + 50\,000V_{50}$

The total disposal cost for 40 km^2 is:

$40F_{50} + 2 \times 10^6 V_{50}$

(c) Therefore, the total cost of transporting and disposing of the waste in Scenario 1 is:

$600\,000P + 40F_{50} + 2 \times 10^6 V_{50}$

B.3. SCENARIO 2a (ONE DISPOSAL FACILITY)

(a) The loading cost is:

$2 \times 10^6 Q$

(b) The cost of transporting the 6250 m^3 of waste from one unit area (0.125 km^2) to the central disposal site (O in Fig. 15) in 25 m^3 trucks is:

$$2 \times \frac{6250}{25} Rd_i = 500Rd_i$$

where d_i is the distance from the centre of unit area i to the disposal site and is calculated using the formula given in Fig. 16. The cost of transporting the waste from all the unit areas is:

$$\sum_i 500Rd_i$$

(c) The disposal cost is:

$F_{2000} + 2 \times 10^6 V_{2000}$

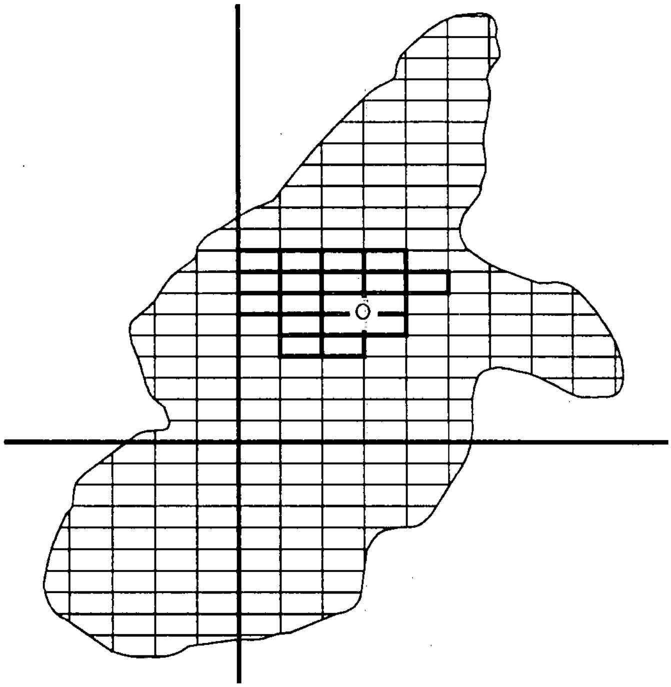


FIG. 16. Area from which contaminated material must be cleared and sent for disposal. Each unit area is ab m^2. *For a unit area whose centre is at position* (a/2 + ia, b/2 + jb), *the distance from the disposal site at O is given by* $[(a/2 + ia)^2 + (b/2 + jb)^2]^{1/2}$ (i, j = 1, ...n).

(d) Therefore, the total cost of loading, transporting and disposing of the waste in Scenario 2a is:

$$2 \times 10^6 Q + \sum_i 500Rd_i + F_{2000} + 2 \times 10^6 V_{2000}$$

B.4. SCENARIO 2b (FOUR DISPOSAL FACILITIES)

(a) The loading cost is:

$$2 \times 10^6 Q$$

(b) The cost of transporting the waste in 25 m^3 trucks to the four repositories is:

$$\sum_{j=1}^{4} \left(\sum_i 500Rd_i \right)_j$$

(c) The disposal cost is:

$$4F_{500} + 2 \times 10^6 V_{500}$$

(d) Therefore, the total cost of loading, transporting and disposing of the waste in Scenario 2b is:

$$2 \times 10^6 Q + \sum_{j=1}^{4} \left(\sum_{i} 500 R d_i \right)_j + 4F_{500} + 2 \times 10^6 V_{500}$$

B.5. SCENARIO 3

The cost of moving the contaminated waste to one disposal site located outside the restricted area can be estimated using the same formulas as for Scenario 2a. The disposal cost could either be the same as for Scenario 2a, or be different for a different type of disposal facility or for one where support facilities and other required infrastructure already exist.

If the trucks leave the inner plume (40 km^2) area by means of one exit, e.g. point A$'$ in Fig. 15, the total cost could be calculated using the formula given in Section B.3 except that the distance d_i would be calculated using point A$'$ as the origin instead of O. To these values must be added twice the distance from A$'$ to the external repository, which should be the same distance for each truckload.

Appendix C

EXPERIENCE IN CANADA WITH THE TRANSPORTATION AND LONG TERM MANAGEMENT OF RADIOACTIVELY CONTAMINATED SOILS

C.1. BACKGROUND

During the period from the early 1930s to 1953, ores were processed in the town of Port Hope, Ontario, to extract radium and uranium. Waste management practices, although acceptable at the time, do not conform to current standards and practice. Also, a substantial volume of soil has been contaminated owing to the spread of contaminants by wind, surface water and groundwater and the inappropriate use of contaminated material for construction fill.

In the 1970s, remedial actions were carried out on the contaminated properties, and the resulting wastes were transported to a storage site at the Chalk River Nuclear Laboratories (CRNL) of Atomic Energy of Canada Limited (AECL). However, substantial volumes of contaminated soils, processing residues and other contaminated materials still remain at two waste management sites which no longer receive wastes, and at a number of other locations within Port Hope. The Low Level Radioactive Waste Management Office of AECL is responsible for remedial action for the latter sites. Depending on the options selected for further work, up to 800 000 m^3 of material may be transported to a new site for long term management.

C.2. CONCEPTUAL DESIGN AND COST STUDIES

In preparation for the removal of this large volume of waste, conceptual design and costing studies have been carried out [26, 39–41].

To resolve significant differences between the present and past cost estimates, the Low Level Radioactive Waste Management Office commissioned a study to develop comparative cost estimates. The work involved updating previous conceptual studies on the basis of common design and costing assumptions with little effort made to optimize design concepts. The objective was to develop comparative estimates reflecting the differences in material handling methods between concepts and the costs of additional engineered barriers around the waste.

There will be some variation in unit cost with volume of waste. For example, if costs associated with site administration and infrastructure represent 5% of the total cost for a facility with a capacity of 800 000 m^3, then the unit cost for a facility with a capacity of 200 000 m^3 would be:

$$\frac{0.05 + 0.25 \times 0.95}{0.25} = 1.15 \text{ times the unit cost for the larger facility}$$

TABLE I. COMPARISON OF UNIT DISPOSAL COSTS[a] FOR FOUR TYPES OF DISPOSAL FACILITY AND TWO DISPOSAL VOLUMES

Volume of contaminated soil for disposal (m^3)	Shallow land burial in unlined trenches	Above ground concrete vault	Below ground concrete vault	Intermediate depth cavern in rock
2 000 000	1.00	3.09	4.24	2.29
500 000	1.48	3.80	5.09	2.95

[a] Normalized to unit cost for disposal of 2 000 000 m^3 by shallow land burial in unlined trenches.

Table I shows estimates for disposal of 500 000 and 2 000 000 m^3 of waste in four kinds of facility described in Ref. [41].

C.3. CASE STUDY ON THE TRANSPORTATION OF 70 000 m^3 OF RADIUM CONTAMINATED WASTE TO A SITE 350 km AWAY

Approximately 70 000 m^3 of waste contaminated with radium (2 $Bq \cdot g^{-1}$) and arsenic were recovered in Port Hope, loaded into 20 m^3 trucks and transported without incident to a specially prepared site within the controlled perimeter of the CRNL 350 km away. The waste was shipped between October 1976 and August 1979.

C.3.1. Loading and transportation of waste

A weighing facility for trucks was built close to the areas being cleaned up to determine the weight of waste being shipped per truckload.

Before loading, a polyethylene sealer was placed over the tailgate to prevent leakage of the waste. The waste was then loaded, the truck decontaminated and a tarpaulin placed over the load to prevent the loss of waste during transportation on public routes. The transportation routes were monitored regularly but no significant waste spills were discovered.

C.3.2. Waste disposal facility

A special unloading and decontamination area was prepared at the disposal site. On arrival, the tarpaulin was removed from the truck, the load was monitored

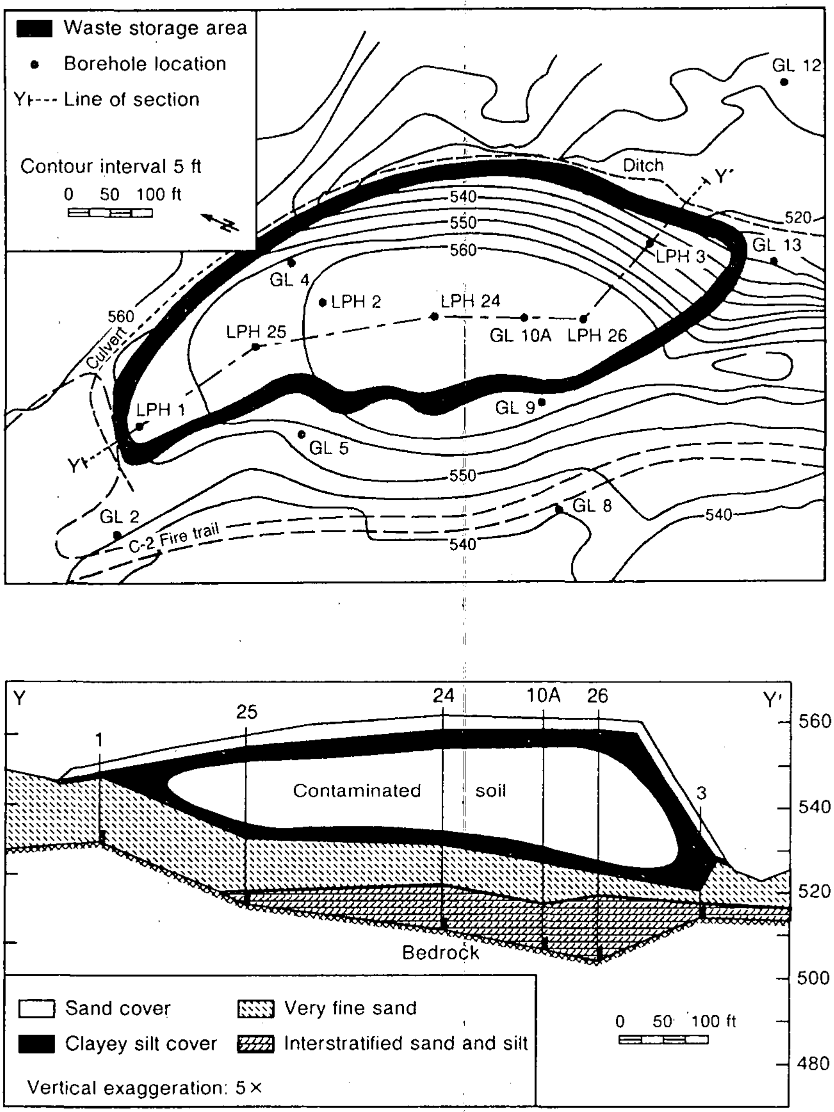


FIG. 17. Plan view (top) of waste management area used for disposal of 70 000 m^3 of radium contaminated waste at CRNL, showing topography, borehole positions and location of stratigraphic cross-section YY' through repository (bottom) (1 ft = 0.3048 m).

and representative bulk samples were taken. Before unloading, the front end of the dump truck was connected to a tractor shovel to give it stability during dumping. Before leaving the site the truck was decontaminated at a special decontamination facility and monitored to ensure that the residual contamination did not exceed acceptable levels. The decontamination facility consisted of a temporary water storage tank and a special drainage area with concrete kerbs to collect the contaminated water.

The waste was placed in a well characterized area between a large ridge of soil and bedrock ridges. The portion of the valley floor designated for waste storage was characterized (Fig. 17) and all slash was removed prior to waste soil emplacement. The contaminated soil was dumped at the head of the valley; bulldozers were used to spread and compact the soil into layers about 0.7 m thick. The eastern edge of the fill area was defined as the 1 m sand isopach (i.e. the contour defining a 1 m thickness of sand over bedrock). On the western side of the valley, waste was placed directly against the face of a sand dune. The waste surface was brought up to within 1 m of the elevation of the dune ridge, and sloped to the east and south. The maximum final thickness of the waste is approximately 12 m; the plan view area covered by the waste is approximately 1.5 ha. In addition to the contaminated soil, waste from Port Hope also contained considerable quantities of debris such as concrete sidewalk slabs, logs and tree roots.

When waste placement was complete, measures to minimize infiltration of water were undertaken. A ditch was constructed to the north and east of the fill area and down the floor of the valley to divert any runoff from the bedrock side of the valley before it could come into contact with the waste. Measures were also undertaken to minimize infiltration from direct precipitation. The selected design includes 30 cm of local clayey silt placed directly on the contaminated soil, overlain by 70 cm of sand and 15 cm of sandy topsoil. The clayey silt was intended to provide a low permeability cover over the contaminated soil and divert any infiltration to the ditch or into the adjacent sand dune. The 70 cm of overlying sand were intended to prevent erosion of the clayey silt by runoff and to reduce the possibility of root penetration of the low permeability layer. Topsoil was fertilized and seeded with a mixture of bird's-foot trefoil and rye. Final contours of the site, the areal extent of the waste and the runoff collection ditch are shown in Fig. 17. Work on the final cover was completed in autumn 1979.

Studies in 1980 and 1983 showed that the cover had not been effective in reducing infiltration. Although the radium remained immobile, some arsenic was transported by infiltration to unsaturated sands beneath the repository. Iron oxide coatings on the sand grains sorbed the arsenic. The arsenic concentration in the pore water in the sands is at natural background level [42].

Appendix D

EXPERIENCE IN THE USA WITH THE TRANSPORTATION AND DISPOSAL OF RADIUM CONTAMINATED WASTE

D.1. BACKGROUND

This appendix describes experience with the transportation of 2.16×10^6 m^3 of radium contaminated waste from the Vitro Chemical Plant Site in Salt Lake City to South Clive, Utah, and its disposal.

The Vitro Chemical Plant Site had a long history of chemical processing of uranium and other compounds. The 51 ha site was covered with 2.64×10^6 t (dry weight) of radium contaminated (20.7 Bq$\cdot$g^{-1}) material, mainly in the form of sand or wet sludge. The site was designated for remedial action under the Uranium Mill Tailings Control Act of 1978 since the processing plant was abandoned and was surrounded by non-nuclear commercial, industrial and residential areas in a growing urban setting [43–45]. At Vitro, a very large amount of radioactive material was presenting a hazard to the population living or working in an area of economically important real estate.

Three alternative remedial actions were considered in the Final Environmental Impact Statement (FEIS): no action, stabilization in place, and removal of the contaminated material to another area followed by cleanup of the Vitro site. The State of Utah and the people of Utah with the concurrence of the US Department of Energy decided to clean the site.

The technical and managerial strategies required to handle the cleanup of the site are similar to those required to handle the cleanup of an area contaminated as a result of an accident at a nuclear facility, except for the urgency of cleanup and size of the task. The procedures and equipment used at Vitro for monitoring, cleanup, quality control, loading, transportation and disposal of the wastes and for verifying that the site was suitable for unrestricted use could all be applied to any large area cleanup.

D.2. DISPOSAL SITE

A variety of potential disposal sites were screened and one known as South Clive was selected. The site, which is located in a semiarid area (124 mm of rainfall per annum), is adjacent to both a rail line and an interstate highway and is about 140 km by road from the Vitro site. The South Clive site, which is isolated from any population centre, was selected after an evaluation based on climate, air quality, precipitation, surface and subsurface features, hydrology, ecosystems, radiation

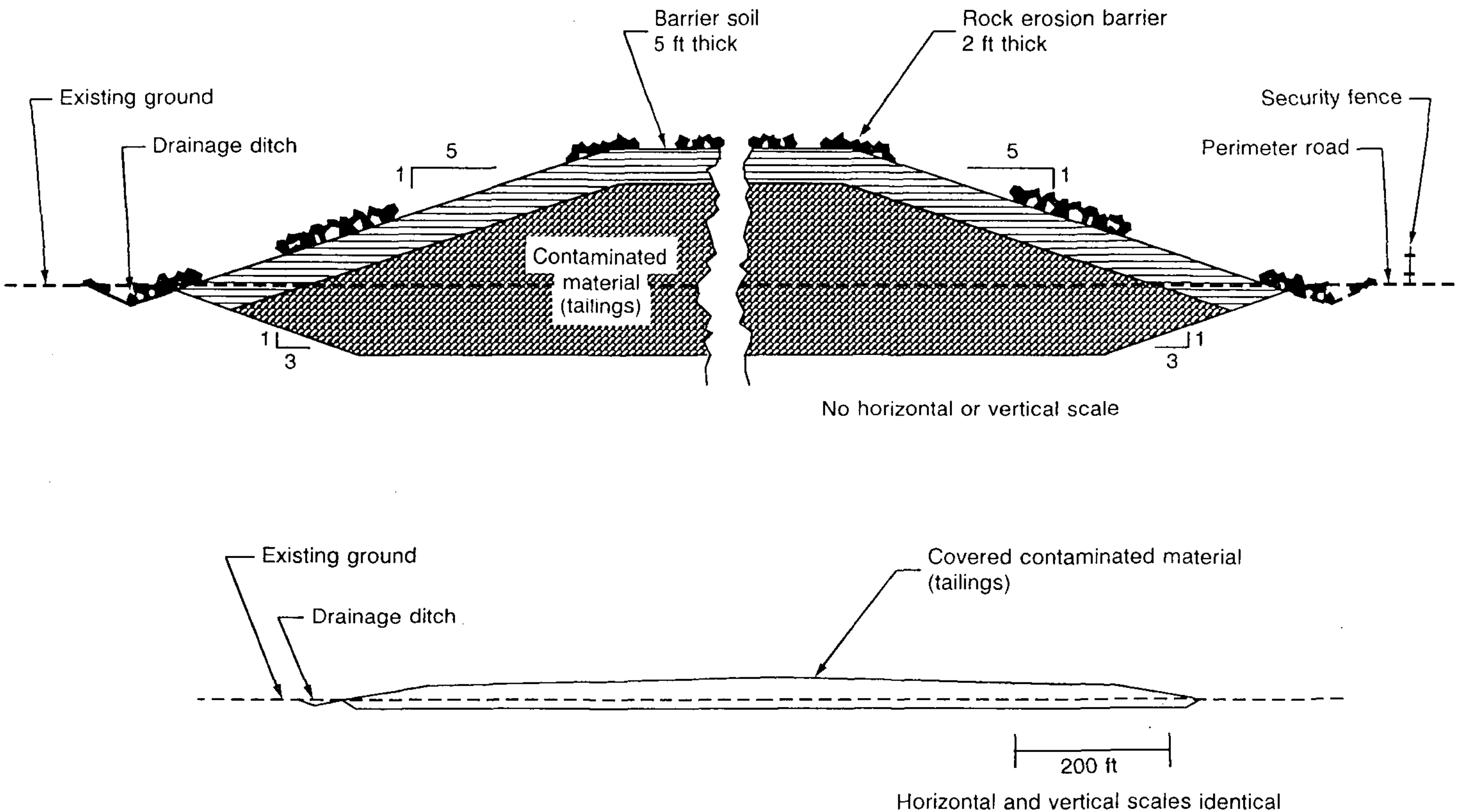


FIG. 18. Typical section of embankment at South Clive site (1 ft = 0.3048 m).

levels, land use, ambient sound levels, historical and cultural resources and socioeconomic considerations.

To prepare the disposal site, the surface material was scraped away and stored for later use as a cap over the pile of contaminated soil.

D.3. LOADING, TRANSPORTATION AND DISPOSAL OF WASTE

The waste could have been transported by: railroad cars, which would require spur tracks and unloading facilities; or trucks, which would require improved or new roads at the South Clive end. A decision to use railroad cars was based on both economics and the public desire to limit potential congestion and contamination on the highway.

Two 50 car trains were used, with one being loaded with contaminated material at Vitro while the other was being unloaded at South Clive. Each site had decontamination facilities. The waste in the cars was sprayed with polymer surfactants and the loads were covered with tarpaulins to prevent the spread of contamination during the trip.

Contaminated material was unloaded from the train and spread and compacted to the designed depth and contour. The disposal embankment pile grew as the project proceeded. Each new section was completed with a stabilizing cover of compacted clean soil and an erosion barrier of rock (Fig. 18). One large embankment pile containing 2.16×10^6 m^3 of waste was constructed. The disposal mound was designed to contain the waste for at least 1000 years.

The zonal concept for area and contamination control was used for both the Vitro and South Clive sites. Access to the Vitro site was controlled with security barriers and guards 24 hours a day. Radiation protection personnel controlled the movement of equipment and workers between contaminated and clean zones by means of transition zones. This ensured that contaminated items were not inadvertently removed from the site and that radioactive material, e.g. tailings, was moved from the controlled active area through clean areas in a controlled manner.

To protect the public and the workers from unnecessary radiation during the operational phase, water control impoundments, radiation monitoring, dust abatement, decontamination and access control were used at the Vitro site.

The US Environmental Protection Agency (EPA) set the following limits to release the Vitro site for unrestricted use:

— < 185 mBq of ^{226}Ra per gram of soil averaged over 100 m^2 in the first 15 cm layer of soil,
— < 555 $mBq \cdot g^{-1}$ below the first 15 cm,
— < 200 $nGy \cdot h^{-1}$ gamma radiation above background in the area.

TABLE II. PERSONNEL REQUIREMENTS AND POTENTIAL DURATION OF EXPOSURE FOR RELOCATION OF CONTAMINATED SOIL TO SOUTH CLIVE, UTAH (TRANSPORTATION BY RAIL)

	Number of working days[a]	Limited exposure[b]		On-site exposure[c]		Exposure during haulage[d]		Total	
		Number of people	Exposure time (10^3 person·h)	Number of people	Exposure time (10^3 person·h)	Number of people	Exposure time (10^3 person·h)	Number of people	Exposure time (10^3 person·h)
Site preparation: Vitro									
Equipment operators	35			11	3				
Truck drivers	35	32	9						
Maintenance personnel	35			2	1				
Miscellaneous personnel	20			22	4				
Supervisor/Foreman	35			7	2				
Total personnel		32		42				74	
Total exposure time (10^3 person·h)			9		10				19
Site preparation: South Clive									
Equipment operators	35	9	3						
Truck drivers	35	8	2						
Maintenance personnel	35	2	1						
Miscellaneous personnel	20	28	4						
Supervisor/Foreman	35	8	2						
Total personnel		55						55	
Total exposure time (10^3 person·h)			12						12

Tailings relocation: Vitro									
Equipment operators	635			9	46	5			
Equipment operators	30			1			25		
Truck drivers	635			3	25				
Maintenance personnel	635			2	10				
Miscellaneous personnel	635			11	36				
Supervisor/Foreman	635			4	30				
Total personnel				30		5		35	
Total exposure time (10^3 person·h)					147		25		172
Embankment construction: South Clive									
Equipment operators	640			13	67				
Truck drivers	640	3	15	1	5				
Maintenance personnel	640			2	10				
Miscellaneous personnel	640			8	41				
Supervisor/Foreman	640			4	20				
Total personnel		3		28				31	
Total exposure time (10^3 person·h)			15		143				158
Site restoration: Vitro									
Equipment operators	625			4	20				
Truck drivers	625	17	85						
Maintenance personnel	625			1	5				
Miscellaneous personnel	625								
Supervisor/Foreman	625			2	10				
Total personnel		17		7				24	
Total exposure time (10^3 person·h)			85		35				120
Overall exposure time (10^3 person·h)			121		335		25		481

[a] With 8 h per working day. [b] Limited exposure to remedial action workers transporting uncontaminated fill. [c] Exposure to remedial action workers on the site. [d] Exposure to remedial action workers transporting mill tailings.

TABLE III. SITE COST ESTIMATE FOR RELOCATION OF CONTAMINATED SOIL TO SOUTH CLIVE, UTAH (TRANSPORTATION BY RAIL)

	Cost (10^3 US $ (1983))
Site acquisition	
Mineral value	0
Land value	80
Total, site acquisition	80
Remedial action	
Work at Salt Lake City:	
Site preparation	2 520
Decontamination	350
Relocation	33 400
Site restoration	5 270
Supervisory and field services	3 980
	45 520
Work at South Clive:	
Site preparation	2 820
Cover installation	1 250
Erosion protection	1 430
Decontamination	330
Relocation	6 460
Fencing	90
Supervisory and field services	3 020
	15 400
Total, remedial action	60 920
Engineering/Construction management	
Engineering	1 150
Construction management	1 560
Total, engineering/construction management	2 710
Maintenance and surveillance	90
Total cost estimate	63 800

TABLE IV. LOGISTIC DATA FOR FOUR REMEDIAL PROJECTS IN THE USA

	Canonsburg, Pennsylvania	Shiprock, New Mexico	Lakeview, Oregon	Durango, Colorado
Remedial action carried out	Stabilization in place	Stabilization in place	Relocation of pile	Relocation of pile
Site area (ha)	16	39	61	21
Job duration (months)	23	17	29	46
Equipment used (number of units used at site)				
Scraper (17–34 m^3)	2	11	4	5
Bulldozer (150–300 kW)	4	7	2	8
Front end loader (2–6 m^3)	2	2	2	6
Water truck (800–2600 L)	1	3	1	2
Haulage truck (8–28 m^3)	10	12	16	13
Compactor/Roller	5	3	2	3
Motor grader (95–135 kW)	1	3	1	3
Backhoe (0.4–1.5 m^3)	1	1	2	1
Quantities hauled (10^3 m^3)				
Tailings	162	814	510	1 155
Radon barrier/liner	36	590	59	341
Erosion protection material	40	180	34	143
Haulage distances (km)				
Tailings	[a]	[a]	11	4
Radon barrier/liner	11	[a]	[a]	[a]
Erosion protection material	96	[a]	4 (rock) 15 (bedding)	5.6
Costs per m^3 per km transported[b,c] ($)				
Tailings	—	—	0.6	1.3
Radon barrier/liner	1.6	—	—	—
Erosion protection material	0.4	—	2.8	2.3
Costs per m^3 transported[b,c] ($)				
Tailings	6.0	2.9	—	—
Radon barrier/liner	—	2.2	1.7	2.8
Erosion protection material	—	15.1	—	—

TABLE IV. (cont.)

	Canonsburg, Pennsylvania	Shiprock, New Mexico	Lakeview, Oregon	Durango, Colorado
Number of personnel				
Contractor:				
Site manager	1	1	1	1
Site engineer	1	1	1	1
Construction engineer	3	—	3	3
QC supervisor	1	1	1	1
QC staff	2	2	6[d]	1
Construction superintendent	—	—	1	1
Secretary	1	1	1	1
Health physics personnel:				
Management	1	1	1	1
Staff	8	5	28[d]	12
Subcontractor personnel:				
Management	3	2	8	4
Staff	28	58	33	54
Average total personnel	49	72	84	80
Field management costs ($)				
Contractor	908 000	677 000	783 000	1 299 000
Health physics personnel	685 000	306 000	1 044 000	1 550 000
Health physics costs[e] ($)				
Health physics costs	248 435	100 762	346 722	249 478
Excavation control/verification costs	497 616	201 524	693 444	498 957
Total costs per ha	46 050	7 700	17 120	34 870

[a] Haulage distances less than 1.6 km (quantities for Canonsburg and Shiprock are actual; those for Lakeview and Durango are based on bids).

[b] Includes placement cost.

[c] Haulage distances greater than 1.6 km.

[d] More staff required because of extended working week (seven 12 h days).

[e] Include salaries, travel, payroll, taxes, employee benefits, relocation, safety supplies and physical examinations.

Upon completion, the Vitro site was certified and released for unrestricted use. The South Clive site was surrounded by a fence and locked gates and identified with permanent markers; the site will be monitored regularly and there will be periodic inspections and maintenance as required. The radon release from the pile had to be less than 740 $mBq \cdot m^{-2} \cdot s^{-1}$ to meet EPA standards.

D.4. LOGISTICS AND COSTS

The personnel requirements and potential durations of exposure (Table II), as well as site cost estimates and transportation costs (Table III), were evaluated during preparation of the FEIS and were important factors in making the final selection of site and transport method.

The FEIS total estimated cost for loading, transportation and unloading of 2.16×10^6 m^3 of contaminated soil, closure of the disposal facility and decontamination of the Vitro site was about US \$61 million, or $\$17 \cdot m^{-3}$. The actual cost is expected to be about \$55 million, or $\$15 \cdot m^{-3}$ [46].

Table IV summarizes logistic data for four other remedial action projects in the USA: at Canonsburg, Pennsylvania; Shiprock, New Mexico; Lakeview, Oregon; and Durango, Colorado.

Appendix E

TRANSPORTATION AND DISPOSAL OF LARGE VOLUMES OF CONTAMINATED MATERIAL ARISING FROM CLEANUP AFTER THE CHERNOBYL ACCIDENT

E.1. BACKGROUND

As a result of the accident at the Chernobyl nuclear power plant some radionuclides from the reactor of Unit 4 were released into the atmosphere. The radioactive cloud containing fission gas and aerosol products contaminated nearby and remote zones with radioactive fallout. The data on the activity releases and contamination following the accident were given in a paper presented at an IAEA experts' meeting in August 1986 [47, 48].

According to the specialists' estimates the amount of active products in the nearby zone was 400 PBq while the total amount throughout the former USSR was 1150 PBq [49]. As a result of this fallout, the environment outside the reactor site became significantly contaminated.

E.2. CLEANUP AND TRANSPORTATION OF CONTAMINATED MATERIAL

Immediately after the accident, decontamination was started to clean buildings, other structures and areas. The area within a 30 km radius of the destroyed reactor was divided into three zones according to the contamination level [47]. For each zone special decontamination operations were determined by the priority of the various tasks required for the fast elimination of the accident consequences.

Thus, in the zone immediately adjacent to the plant, the main task was to decontaminate the site, buildings and other structures so that a sarcophagus could be built around the damaged reactor to permit the future operation of Units 1 and 2. The decontamination was implemented by piling up refuse and the debris from buildings and other structures, and removing the contaminated upper layer of soil (5–10 cm). Owing to the very high activity in this zone, the decontamination was accomplished remotely with robots and other special devices. More detailed information on the machinery used is contained in Ref. [50]. The active materials from this zone were put in metallic containers which could be mechanically loaded and transported to the disposal site.

The main task of the decontamination of other regions within the 30 km controlled zone was to clean up towns and villages, for example the towns of Pripyat and Chernobyl, to allow the possible re-entry of the population. More than six hundred populated areas were decontaminated [48]. The adjacent territory was decontaminated simultaneously. The general principle in cleaning the contaminated areas was to divide them into plots according to their contamination level and to successively clean them, proceeding from more to less contaminated plots. This practice prevented recontamination and reduced considerably the amount of work. The sequence of operations to remove large amounts of contaminated soil was as follows.

The upper 5–10 cm soil layer was removed using different road building machines (bulldozers, scrapers, graders, etc.) and moved into piles within 50–100 m of the centre of the cleaned area. Then with wheeled or tracked loaders, the removed soil was loaded into dump trucks and other transport vehicles. Conventional road building machines with wide blades could not be employed to decontaminate the territory inside the city blocks and dwelling areas in the countryside owing to the density of building and the small size of some areas. Because of the absence of special devices suitable for soil removal from small areas, the operations were chiefly carried out manually.

To prevent the spread of activity within the decontaminated zones measures were taken for the safe transportation of active material. Prior to loading, the boxes of dump trucks and other transport vehicles were lined with polyethylene sheet. When a box was full, it was covered with polyethylene sheet and then with a tarpaulin. These measures prevented the spread of active soil during its transportation to a disposal site.

All loading and transportation operations were constantly monitored.

Transport vehicles crossing the boundaries of zones having different contamination levels were decontaminated at special treatment points to prevent the spread of the contamination to areas of lower activity.

E.3. DISPOSAL OF CONTAMINATED MATERIAL

To clean up the badly contaminated areas, it was necessary to remove the contaminated material and send it for disposal. The large scale of the accident and the short time granted to eliminate its consequences did not allow the use of the traditional approach for the solution of the problem and showed the need for engineering solutions.

The waste disposal method adopted at that time was based on the following:

(a) Safe isolation of active waste for the time that the waste is a potential danger,

(b) Use of readily available materials and designs to build disposal facilities,

(c) Use of engineered barriers in the construction of disposal facilities to prevent radionuclide migration in dangerous amounts,

(d) Modular design of disposal facilities for waste of any activity level to permit their construction in quantities defined by the rate of solid active waste arising from decontamination,

(e) A single special centre for extended storage of solid low and intermediate level wastes.

E.3.1. High level waste

The highest activity solid wastes arising from the decontamination of the site close to the damaged facility were buried in Unit 4 by building the sarcophagus. For the disposal of the remaining high level waste the use was made of simple above ground concrete vaults of modular design. In the vaults metallic containers were stacked in two layers; each layer was filled with concrete. The concrete was covered with asphalt and the vault was covered with soil. The vault base was hydraulically sealed with reinforced concrete plates and concrete blocks.

E.3.2. Low and intermediate level wastes

E.3.2.1. Interim storage facilities

The experience gained from the decontamination of the nearby and outer zones showed that the low and intermediate level wastes have some characteristic features. The decontamination of large territories, particularly in the countryside, produced large amounts of low level solid waste consisting of removed soil and large quantities of organic materials (grass, turf, thatch, shrubbery, plants, organic fertilizers, etc.). Owing to the absence of long term storage facilities immediately after the accident, the large amount of waste and the need for its quick removal, it was decided to store the waste in surface mounds that were made near many settlements. The surface mounds are simple in their design and permitted the quick storage of active waste. The disposal site was selected far from open reservoirs and water distribution systems and had the engineered features that met the safety requirements for disposal. The base of the surface mound was lined to prevent the escape of liquids. After transportation of waste to a disposal site, soil and organic materials were moved with a bulldozer into large piles and when the whole site was filled the piles were covered first with polyethylene sheet and then with pure topsoil. The repository was enclosed, precautionary signs were set in place and drainage lines were dug around the site.

It is expected that this practice of interim storage of low level waste will adequately repay itself since it permits a quick decrease of contamination levels in populated areas. The storage of organic materials together with soil results in a reduction of the total waste volume due to organic material decomposition. Besides, the specific activity of waste in such repositories falls quickly through the natural decay of radionuclides. One year after the accident the total amount of gamma active products in the nearby zone had decreased significantly [48] and it was found that many of the repositories of this type could be classed as 'inactive' as the dose rates of the alpha radiation near the repositories were not above the gamma background. Because of this, today most of the interim storage facilities have been eliminated and higher level waste has been transferred to extended storage facilities.

E.3.2.2. Extended storage facilities

For long term storage of low and intermediate level wastes, trench type facilities of modular design and having a large capacity ($> 10\,000$ m^3) were used.

The bottom and the slopes of the trench are impermeable barriers of compacted clay. After the trench is filled with waste, it is covered first with a layer of local soil (0.6 m) and then with an upper clay barrier (0.5 m). The clay barriers are covered with a layer of local soil (1.0 m) to protect them from damage. The thickness of the bottom clay barrier is 1.0 m.

Barriers of bentonite clay to sorb radionuclides and inhibit the ingress of water are expected to fully eliminate radionuclide migration into the open hydrogeological system.

The engineered features of a repository involve access roads, parking areas, decontamination and monitoring points at the entry to a repository site, hydraulic bypasses around each facility, sampling wells around each disposal facility and the repository as a whole, and enclosure and lighting for the repository site.

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