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Surveillance and Monitoring of Near Surface Disposal Facilities for Radioactive Waste

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SURVEILLANCE AND MONITORING OF NEAR SURFACE DISPOSAL FACILITIES FOR RADIOACTIVE WASTE

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FOREWORD

The safety of near surface disposal facilities for radioactive waste is provided for by containment of the waste in a matrix material, such as concrete, and a surrounding container, by engineered containment features around the waste and engineered covers over the facilities and by controlling the inventory of waste placed in the facility. The host geology in the lithosphere provides a barrier to the movement of any radionuclides that migrate through these containment barriers. Human intrusion into facilities is generally prevented by institutional controls, both active and passive. During construction, operation and closure, those aspects important to safety are assured by active control measures exercised at the disposal site and quality management programmes. These activities involve exercising surveillance over a number of parameters including monitoring various radiological and other parameters.

Surveillance programmes, including monitoring, are important elements in ensuring the safety of operating and closed near surface waste disposal facilities. In view of the extensive surveillance and monitoring experience gained by Member States in the development and operation of near surface disposal facilities, the IAEA concluded that a review of current practices should be carried out and documented. In 1998, the [Radioactive] Waste Safety Standards [Advisory] Committee (WASSC) supported the preparation of a Safety Report on surveillance and monitoring that would include practical guidance on the design and implementation of such programmes during the pre-operational, operational and post-operational phases of a near surface disposal facility.

This Safety Report discusses the objectives of surveillance and monitoring during each of the three phases and provides advice on good practice in the operation of such programmes, based on the experience of Member States. The emphasis in the report is on surveillance and monitoring at facilities designed to meet current safety standards and examples are provided of such practices. The changes to monitoring programmes that may be needed if the disposal facility is not found to be performing to current standards are also addressed. The type of monitoring programme that might be needed for an existing facility designed to previous standards is also outlined. The focus of the report is on those facilities having disposal units close to the ground surface, but the majority of the topics discussed are also relevant to disposal units sited at greater depths.

The principal IAEA officers responsible for the development of the report were R. Dayal and K.W. Han of the Division of Nuclear Fuel Cycle and Waste Technology, and P. Metcalf and I. Vovk of the Division of Radiation and Waste Safety.

EDITORIAL NOTE

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1. INTRODUCTION

1.1. BACKGROUND

Many Member States of the IAEA have now had experience with the disposal of certain types of solid or solidified radioactive waste in disposal facilities situated near the ground surface. In general, the waste suitable for disposal in this way is that which contains short lived radionuclides and low concentrations of long lived radionuclides [1]. The method has been found to provide an effective means of safely isolating such waste and thereby protecting human health and the environment.

A surveillance and monitoring programme is an important element in ensuring that a disposal facility provides the required level of containment, isolation and protection during its operational and post-closure phases. The philosophical and technical bases for requirements on radioactive waste management are established in the IAEA Safety Fundamentals publication The Principles of Radioactive Waste Management [2]. Relevant requirements are set out in the publication entitled Near Surface Disposal of Radioactive Waste [3] which, in particular, includes a requirement that responsible organizations implement surveillance and monitoring programmes with such facilities.

For the purposes of the present Safety Report:

Surveillance is periodic inspection and testing to verify that structures, systems and components continue to function or are in a state of readiness to perform their functions.

Monitoring is the measurement of dose or contamination for reasons related to the assessment or control of exposure to radiation or radioactive substances, and the interpretation of the results [4].

In relation to near surface disposal facilities, surveillance is taken to mean the periodic inspection and testing of disposal facility structures and of any systems and components on which the safety of the disposal facility depends. Such surveillance to ascertain whether these items are functioning correctly, by definition, includes monitoring of appropriate parameters both at and around the disposal facility. Monitoring for radiation safety purposes at near surface disposal facilities will also need to include measurement of meteorological and hydrological variables that may be needed in interpreting any activity measurements. In this Safety Report, those aspects of surveillance that do not directly involve radiological (or related meteorological or hydrological) monitoring are referred to generally as surveillance and are discussed separately from radiological monitoring as such. The results of both surveillance and monitoring can point to deficiencies in the disposal facility structures, systems and components that may need remedial action. Both surveillance and monitoring will be subject to the requirements of the quality assurance (QA) programme defined for the disposal facility.

General guidance on strategies for monitoring radionuclides in the environment is being developed as part of the Safety Standards Series. This Safety Report focuses on the requirements and guidance relevant to surveillance and monitoring for near surface disposal facilities. It is a companion publication to the Safety Standards Series publications addressing monitoring and surveillance for mining and milling facilities [5]. It is also related to the Standards on siting [6] and safety assessment [7] of near surface repositories, and draws on the earlier advice of the International Commission on Radiological Protection (ICRP) [8].

There are various kinds of near surface disposal facility, including simple earth trenches a few metres deep, engineered concrete vaults on or near the surface, or rock caverns several tens of metres below the ground surface. ‘Disposal’ in these cases means the emplacement of waste in approved, specified facilities, without there being any specific intention to retrieve the waste.

There are three distinct phases associated with the lifetime of a near surface disposal facility: pre-operational, operational and post-closure. The pre-operational phase includes the necessary siting and design studies and the period of construction of the disposal facility. The operational phase includes the period of operation of the disposal facility and its closure. The post-closure phase is the period that follows closure. Different requirements are placed on the surveillance and monitoring programme in each of the three phases.

Surveillance and monitoring provide the means to obtain the assurance that the active control measures used during the operation of a disposal facility and the passive measures, such as restrictions on land use after closure, are effective in providing for the protection of human health and the environment.

1.2. OBJECTIVE

The objective of this Safety Report is to provide Member States with advice and examples of good practice in relation to surveillance and monitoring programmes for near surface disposal facilities for radioactive waste.

1.3. SCOPE

The Safety Report covers surveillance and monitoring during pre-operational, operational and post-closure phases. It includes discussion of the general criteria needing to be met by a surveillance and monitoring programme intended to ensure radiological safety and the specific criteria for each of the three phases of the near surface disposal facility. Guidance is provided on how to implement such a programme. A distinction is made between the monitoring programmes described here and those programmes put in place for radiological protection purposes at operational facilities associated with the disposal facility where there may be controlled discharge of effluent streams to the environment.

The assumption is made in the Safety Report that the disposal facility is designed, operated and closed in accordance with the requirements for safety detailed in the various Safety Fundamentals, Safety Requirements and Safety Guides noted above. The design of the surveillance and monitoring programme described here is, therefore, different from one that might need to be implemented at facilities that have been built, in the distant past, to different standards. Such a programme is discussed in a separate section.

The content of this Safety Report is generally applicable to all those facilities that can be termed 'near surface'. It is not intended for surveillance and monitoring at deep geological repositories nor at surface accumulations of waste derived from processes such as mining, milling and environmental restoration. Although the same general considerations apply, surveillance and monitoring at these other facilities are covered explicitly in other IAEA publications [5, 9].

1.4. STRUCTURE

The responsibilities for surveillance and monitoring at near surface disposal facilities are described in Section 2. Criteria for, and a general description of, the surveillance and monitoring programmes are provided in Section 3. Guidance specific to pre-operational, operational and post-closure phases is given in Sections 4, 5 and 6, respectively. Section 7 provides guidance on the monitoring programme that may be needed if unanticipated migration of radionuclides from a near surface disposal facility is observed or if a monitoring programme is being implemented at an existing facility that was not designed to current IAEA standards.

The Annexes contain descriptions of the surveillance and monitoring programmes implemented at some existing near surface facilities developed and operated in Member States.

2. RESPONSIBILITIES FOR NEAR SURFACE DISPOSAL AND QA

2.1. RESPONSIBILITIES FOR SURVEILLANCE AND MONITORING

Provision of the rules, regulations, guidelines and criteria needed in the licensing process for near surface disposal is the responsibility of the regulatory body [3]. These rules, regulations, guidelines and criteria provide the guidance necessary for the disposal facility operator or responsible organization to establish a surveillance and monitoring programme in all phases of the disposal process.

The operator of the disposal facility is responsible for ensuring that the required surveillance and monitoring programme is designed and implemented throughout the pre-operational, operational and closure phases of the disposal facility and that it meets the requirements as established by national authorities [3]. The organization responsible for the post-closure phase also has to take measures to ensure that a surveillance and monitoring programme continues in the post-closure phase in a manner that meets national regulatory requirements and policies [3].

2.2. QA PROGRAMMES

The surveillance and monitoring programmes will be subject to the QA programmes established for each of the phases of the disposal process and will reflect the elements of such QA programmes as those defined for nuclear facilities [10] and for some aspects of waste management [11]. In particular, the programme elements will cover management, performance and appraisal.

The QA elements relating to management will include definitions of:

(a) Managerial responsibilities for developing, implementing and maintaining the QA programme;
(b) Functional responsibilities;

(c) Levels of authority and interfaces for those managing, performing and assessing the adequacy of the surveillance and monitoring programme;
(d) Criteria for training and qualifications of those carrying out the surveillance and monitoring programme;
(e) Procedures to be followed when items, services or processes associated with the surveillance and monitoring programme do not meet specified criteria;
(f) Requirements for record keeping and reporting.

The QA elements relating to performance will include criteria for ensuring that:

(a) All surveillance and monitoring be performed according to established codes, standards, specifications, practices and administrative controls;
(b) All surveillance and monitoring equipment items be identified, handled and controlled so as to ensure their proper use without damage;
(c) All monitoring and surveillance equipment be of the appropriate type and be capable of obtaining data with the required accuracy and precision;
(d) Evidence, including the results of inspection with appropriate administrative controls, be obtained that all items of equipment procured for surveillance and monitoring meet the programme requirements;
(e) The design and modification of the surveillance and monitoring programme be in accordance with established standards and that the adequacy of the programme be verified by independent individuals or group.

The QA elements relating to assessment will include criteria for:

(a) Self-assessment by management of the effectiveness of the surveillance and monitoring programme;
(b) Independent assessment of the management and adequacy of the surveillance and monitoring programme.

3. GENERAL CRITERIA FOR SURVEILLANCE AND MONITORING

3.1. GENERAL OBJECTIVES OF SURVEILLANCE AND MONITORING

The general objectives of surveillance and monitoring programmes are to provide direct evidence of the measurable presence or non-detectability of radionuclides and radiation in the environment that could be attributable to the disposal facility [3]. The design of the programme will be closely linked to the findings of the safety assessment so that the results of the monitoring can be applied to confirm the assumptions made in the safety assessment [3]. The monitoring data obtained form part of the information set supporting demonstration of compliance with regulatory and legal requirements for the protection of human health and the environment. The monitoring data also serve to indicate when investigation of an actual or potential inadequacy in the safety of the disposal facility is warranted during or after operations, and when remedial or protective action may be needed [3].

The surveillance and monitoring programmes that are the subject of this Safety Report need to be distinguished from those surveillance and monitoring programmes that have different objectives. One kind of monitoring that falls into this category is that associated with radiation protection programmes in what may be regarded as operating nuclear facilities. During the operation of the disposal facility, such programmes will be in place for the protection of the workforce and for the protection of the public against controlled or accidental effluent releases from facilities at the site. There may also be other nuclear facilities associated with the disposal facility and these are also included within the scope of these operational programmes. Such programmes have different bases and objectives from the programmes established specifically for surveillance of near surface disposal facilities which focus on confirmation of the integrity of the disposal facility and the level of containment it provides. The principles underlying those programmes more associated with operational radiation protection are defined in the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources [1]. Guidance on the design and implementation of monitoring programmes associated with protection of the workforce in operating nuclear facilities and programmes associated with the control of effluent discharges from operating nuclear facilities are provided in a series of Safety Guides [12–15] and ICRP publications [8, 16]. These programmes are not included within the scope of the surveillance and monitoring programmes that are the subject of this Safety Report.

Another distinct programme is one that may need to be implemented to track radioactive material migrating from a disposal facility that was not built to the standards assumed in this Safety Report. Such monitoring would be aimed at determining the extent of contamination with a view to undertaking remediation and retrospective safety assessment. The design and implementation of this kind of monitoring is outlined in Section 7.

A programme for monitoring the presence of toxic chemicals will be subject to different national regulations and requirements than will a programme for radiological purposes. Such a programme is not addressed in this Safety Report. However, operators and other responsible organizations may find it convenient to combine the programmes.

The effort expended on surveillance and monitoring needs to be commensurate with the potential hazards that may arise in the disposal facility and the time-frames over which potential problems could arise. Monitoring in excess of that needed to protect human health and the environment incurs unnecessary expenditure and can generate an impression of hazards that may not be warranted. The programmes provided by way of example in the Annexes represent the extent of surveillance and monitoring deemed to be reasonable and adequate.

3.2. RELATIONSHIP TO SAFETY ASSESSMENT

The safety assessment for a near surface disposal facility is the procedure for evaluating the performance of the disposal facility and, in particular, its potential radiological impact on human health and the environment [7]. In the safety assessment, pathways along which radionuclides might migrate into the accessible environment are defined and the potential health impact estimated.

Monitoring before operations start provides a baseline for determining any additional increments in environmental levels that can be associated with releases from the disposal facility. Monitoring during operations and after closure of the disposal facility is intended to show that the actual measurements in the environment do not invalidate the assumptions and predictions of the safety assessment [7].

Surveillance during operation and after closure of the disposal facility is intended to show that the structural integrity of the disposal facility remains as assumed in the safety assessment. If monitoring of site parameters such as hydrological flow or groundwater chemistry indicates changes or invalid assumptions in the safety assessment, then the safety assessment should be revised accordingly. Similarly, revision would be needed if surveillance of the structure or systems of the disposal facility indicates that there are invalid assumptions in the safety assessment. The design of the surveillance and monitoring programme therefore needs to be based on the assumptions, modelling and findings of the safety assessment. For example, it is necessary that monitoring locations be related to the potential migration pathways, and that the frequencies of sampling and measurement take into consideration the rates at which the quantities of interest might change. It should always be possible to relate the results obtained from the programme during operation and after closure of the disposal facility to the predictions of the safety assessment.

3.3. APPLICATION OF THE RESULTS OF SURVEILLANCE AND MONITORING

3.3.1. Demonstration of compliance with safety standards

For a near surface disposal facility, regulatory acceptability of the facility design and demonstration of compliance after operations start are based on the comparison of the results of the safety assessment with the regulatory standards applicable to the disposal facility [7]. The monitoring data obtained therefore provide support for the assumptions made in the assessment and its results. The expectation is that there will be not be any significant migration of radioactive material from the disposal facility, at least during its operating phase and into the post-closure phase. However, the support from monitoring will be through the non-detectability of some contaminants and the absence of statistically significant changes in the levels of others that are not unique to the disposal facility at that location. The monitoring is designed so that the result ‘less than a given activity or concentration’ is sufficient to support the safety assessment. Similarly, the surveillance programme is designed such that deterioration of the disposal facility structures and systems to an extent that could compromise the validity of the safety assessment could not occur without being detected.

3.3.2. Prompting of investigations and corrective action

The monitoring data serve to indicate when investigation of an actual or potential inadequacy in the performance of the disposal facility in respect of its safety is warranted during or after operations, and when corrective action may be needed. This would be apparent from the detection of the unanticipated presence of, or increase in the concentration of, radionuclides of concern outside the disposal facility. If monitoring during operations were to indicate such changes, or to indicate changes in the site parameters that affect the safety assessment, then, in addition to any corrective actions being taken, the safety assessment needs to be revised accordingly and the adequacy of the monitoring programme reviewed [7]. Similarly, if surveillance of the disposal facility structures or systems indicates that the assumptions of the safety assessment may not be valid, then the assessment has to be reappraised.

3.4. FEATURES OF SURVEILLANCE AND MONITORING PROGRAMMES

The details of a surveillance and monitoring programme will depend on the phase of the disposal facility, whether pre-operational, operational or post-closure. The programme that evolves throughout these phases follows from the objectives of (a) providing direct evidence of the measurable presence or non-detectability of radionuclides and radiation in the environment attributable to the disposal facility, (b) providing support for the assumptions, choice of parameters and findings of the safety assessment, and (c) providing information to support demonstration of compliance (see Section 3.1). The details of a surveillance and monitoring programme will also depend on the specifics of the particular disposal facility.

The Annexes provide descriptions of surveillance and monitoring programmes that have been implemented at a variety of disposal facilities. The evolution of disposal facility technology over the last 50 years is apparent from these descriptions. Annexes I and II describe the programmes at a modern (1986) engineered facility and an older (1969) engineered facility, respectively. Annex III describes a set of rock cavity repositories dating from the 1960s. Annexes IV and V describe the programmes in place at very old trench, pit and vault facilities dating from the 1940s.

As noted above, the emphasis in this Safety Report is on the surveillance and monitoring programme that needs to be designed and implemented at a modern facility, and designed and operated to current IAEA standards. It is desirable that a surveillance and monitoring programme for such a facility have the following features:

(a) The capability to detect changes in the engineered structures and systems of the disposal facility that might affect the radiological performance of the facility;
(b) The capability to detect radioactive contaminants of concern;

(c) Sampling protocols that reflect the possible varying radioactive, physical and chemical characteristics of radioactive contaminants that could migrate from the facility;
(d) A sufficient number of monitoring locations to allow any significant migration of contaminants to groundwater to be detected;
(e) A sufficient number of monitoring locations to allow any significant migration of contaminants to the atmosphere to be detected;
(f) A sufficient number of monitoring locations to allow any transport of contaminants in surface waters near the disposal facility to be detected;
(g) Provision for monitoring ambient radiation levels;
(h) Provision for monitoring biota and surface waters in the general environment of the disposal facility primarily for the purpose of public reassurance;
(i) Documented procedures;
(j) Provision for retention and statistical analysis of monitoring data.

These features are discussed below.

3.4.1. Surveillance to detect deterioration in the engineered structures and systems of the disposal facility

The engineered barriers comprise all the materials placed around the waste to isolate it from the environment, including any low permeability or intrusion resistant covers placed over the disposal facility close to the ground surface. Vegetation is often planted on the disposal facility cover to act as absorbents and decrease the potential for water permeation into the disposal facility. The state of these engineered barriers needs to be ascertained through the surveillance programme. Reference documents on the techniques for surveillance are available [17–24].

Changes in the structural stability of a near surface disposal facility may occur as a result of natural processes and human activity. Processes that can compromise barrier performance include erosion, landslides, flooding, changes of flow paths in both vadose and saturated zones, degradation of covers due to shrinkage, subsidence, intrusion by vegetation or animals, and rock deformation [7]. Continuing surveillance of the surrounding area is needed to assess its stability and to detect any movement of the disposal facility structure or the surrounding host rock.

It is necessary that the integrity of the disposal facility covers be ascertained in the surveillance programme, in particular verifying that erosion, cracking, subsidence, deflation, burrowing animals or any other processes have not led to sufficient deterioration of the cover that the assumptions and predictions of the safety assessment are invalidated. Techniques such as visual inspections and movement of survey markers are useful for detecting small changes to the disposal facility cover. If the changes are visible, keeping a photographic record is helpful. Appropriate measurements are to be made of the characteristics and state of the cover to allow any less obvious changes to be determined, such as increases in water content or permeability. The covers and any water channels conveying water away from the disposal facility need to be examined regularly.

Erosion is usually a slow or sporadic process but erosion of barriers or the land in which the disposal facility is located may decrease the effectiveness of the waste isolation system over the long term. The surveillance programme therefore has to be able to verify that any erosion is at a rate that does not invalidate any safety assessment assumptions. Remedial action would be needed if the erosion processes are determined to be greater than acceptable. Surveillance to detect these changes is more important for earth trenches or engineered concrete vaults than for disposal facilities sited in rock cavities.

Depending on the topographic conditions of the site and the geomechanical properties of the rocks, assessments of structural stability may be required. For disposal facilities close to the ground surface, the main purpose of this kind of measurement is likely to be for the assessment of slope stability, as creep or collapse movements of the surface materials have the potential to disrupt the waste isolation system. [1]

3.4.2. Detection of radioactive contaminants of concern

The radioactive contaminants of concern that are included in the monitoring programme depend on the disposal facility. The radioactive contaminants may include fission products, activation products, fissile materials and naturally occurring radionuclides. For some disposal facilities, the presence of heavy metals, organics and other materials disposed of in the facility may have implications for the potential radiological hazard and may be included within the radiological monitoring programme.

Information on these potential contaminants will become available as the safety assessment proceeds and this should help in defining the scope of the monitoring programme. Waste acceptance criteria are usually developed, and these list the conditions under which radioactive and non-radioactive

[1] For repositories sited in rock cavities, the main purpose of geomechanical measurements would be to allow assessment of the stability of underground openings and operational safety, rather than to address radiological aspects which are the focus of this Safety Report.

substances can be accepted for disposal. Some waste acceptance criteria are generic (e.g. the exclusion of complexing agents and pyrophoric materials) while others are site specific. Since the waste acceptance criteria indicate the constituents expected to be in the waste, as well as those that should not be present, they provide the basis for defining the suite of radionuclides for which monitoring is needed.

The expectation for a well-designed disposal facility is that there will be no significant migration of radionuclides from it; certainly for the operational phase and into the post-closure phase. Hence, values will generally be reported as being below the limits of detection. The monitoring and detection methods adopted should be such that the limits of detection are low enough for there to be an assurance that the reported maximum values are not indicating that the safety assessment predictions are in error and that there is no incipient hazard to the public.

Analytical techniques for measurement of radionuclides in water and other environmental media are described in a number of documents [25, 26].

3.4.3. Sampling protocols that reflect radiological, physical and chemical characteristics of potential contaminants

Variables that need to be taken into account include: various radioactive decay rates and the ingrowth of radioactive progeny; the possibility of chemical transformations of the materials (e.g. biodegradation, redox reactions) carrying radionuclides of concern; different migration rates of contaminants in different chemical forms; and changes in the chemical characteristics of radioactive contaminants owing to the influence of waste form and disposal facility materials. Examples of possible variables include the interchange of ^{3}H in a disposal facility between tritiated water, tritiated hydrogen gas and organically bound ^{3}H, and the influence of the alkalinity (caused by cementitious disposal facility components) on the chemical analysis of groundwater samples.

The monitoring protocols also need to take into account the different times at which different radionuclides might be expected to appear, were the disposal facility not to behave as designed. For example, some contaminants in a near surface disposal facility may be volatile and subject to migration in the gas phase. Examples of volatile substances include chlorinated solvents, tritiated water vapour, radon and ^{14}C. In general, the rates of contaminant migration in soil gas and the atmosphere are much higher than in the aqueous phase. Hence, if the disposal facility contains appreciable quantities of volatile contaminants and if there is a pathway for their migration, the volatile contaminants can be the first species that would be detected by environmental monitoring. Under these circumstances, soil gas sampling is needed in the early phases of a monitoring programme.

Depending on the water flow rates, non-volatile contaminants migrate through aqueous media as a result of advection and diffusion. These contaminants, were they to escape from the disposal facility, could record a wide range of migration rates owing to their differing interactions with soil and sediment matrices or because of incorporation into insoluble phases. For example, long lived anionic species of ^{14}C, ^{36}Cl and ^{129}I can migrate at or near groundwater velocity. Actinide species, in contrast, may migrate at rates that are four or five orders of magnitude lower than the groundwater velocity owing to strong interactions with soil and sediment matrices. If the actinides were to be associated with colloids, then the migration rates could be much higher. It is desirable that all these factors be taken into consideration in the safety assessment and that the monitoring programme be designed accordingly.

Techniques for monitoring in the various media are outlined below.

3.4.4. Monitoring of ambient radiation levels

Ambient radiation levels are monitored at and around the disposal facility in the pre-operational and operational phases and in the initial period following closure.

3.4.5. Monitoring for migration of contaminants in groundwater

Pathways to be monitored for radionuclides are those by which any leachate from the disposal facility may be transported. Such transport may be by diffusion or advection through water filled pores. The pathways can continue through the vadose and saturated zones, with the radionuclides eventually reaching the accessible environment where they could enter the food chain, contaminating foodstuffs, surface waters and biota.

The collection of hydrological, hydrogeological and geochemical data (see Section 4) that are needed for the safety assessment and which are therefore important for the design of the monitoring programme and the interpretation of its results need to be part of the monitoring of contaminant transport in groundwater.

3.4.5.1. Leachate monitoring

It is important that any leachate be analysed for contaminants, which if present require the derivation of flow rates from the measured discharges as a function of time. The disposal facility design may also include an underdrain

(French drain) with or without a water collection sump. Such a drainage system should be monitored for water flow rate and for concentrations of dissolved or suspended materials. If radionuclides are detected, their presence should be suspected in the vadose and saturated zones. The results of monitoring in these zones (see below) have to be reviewed in the context of the safety assessment to ascertain whether the assessment remains valid or whether reassessment or remediation of the engineered barriers is needed.

Surveillance of the geological materials immediately around and beneath the waste needs to be undertaken to determine changes in, for example, moisture content, pressure head or gas and solute concentrations, which will provide an early indication of the potential for releases beyond the engineered barriers.

Measurement of flow rates through the engineered barriers can provide information on the potential for mobilization and release of contaminants. Engineered barriers should be designed to permit access for sampling of liquid leachate and gas. Since these samples are close to the source, their analysis will provide information on container stability and assist in the determination of release mechanisms. The actual measurement technique will depend on the construction of the engineered barrier outflow [22–24]. Simple techniques, such as measuring the accumulation of fluid in a sump, are generally the most suitable. The measurement frequency should be adequate to allow determination of seasonal variations in water accumulation.

3.4.5.2. Vadose zone monitoring

The vadose zone is the zone between the land surface and the permanent water table. Although often referred to as the unsaturated zone, the term vadose zone is more accurate, since parts of this zone may actually be saturated, at least temporarily. In the vadose zone, the pores are normally partly filled with water, which is held in place primarily by capillary forces. Water moves mainly vertically, but there may be significant lateral flow if the geological profile contains materials of variable permeability, which allow the formation of perched water bodies. In arid regions or areas where transport of water from the surface to the underlying aquifer is very slow, any contaminants migrating from the disposal facility may not be detectable in groundwater for a long time. Monitoring of the vadose zone provides a possibility for earlier detection of any deterioration of the disposal facility’s integrity and should be part of the programme.

Although the main objective of vadose zone monitoring is to provide an early indication of any contaminant release from the disposal facility, it is also used in the development of the safety assessment to determine how environmental conditions affect the movement of soil water, to provide estimates of the in situ hydraulic properties and soil water retention profiles, and to provide field data sets to support vadose zone modelling.

Contaminant migration through the vadose zone depends mainly on four variables. Three of these, contaminant concentration, water content and pore water pressure, are directly observable and should be monitored. The fourth variable, the soil water flux, is not directly observable but can be estimated from changes in water content and in pore water pressure gradients.

Increases in the concentration of contaminants in the vadose zone water can be caused by permeation of surface water through the disposal facility cover and by the lateral flow of perched water into the waste. If the water leaving the disposal facility moves under saturated conditions, it is collected in drains, sumps, or outflows. Its flow rate and composition can be used to determine the hydraulic performance of the cover, the status of containment and the leachability of the waste.

The water content in the vadose zone generally varies the most in the first few metres below the surface and can be used to estimate losses to evapotranspiration (the water used by vegetative growth) or the downward movement of water. Water content can be measured either by direct or indirect techniques. The former include soil sampling followed by gravimetric analysis and the latter include time domain reflectometry, water content reflectometry, and the use of capacitance sensors and neutron probes [27].

As noted above, although water mainly moves vertically within the vadose layer there may be significant lateral flow if the geological profile allows formation of perched water. The dynamics of soil water movement will generally be fast if the precipitation rate is high, vegetation cover is low and shallow depressions exist over the land surface. Directing runoff water into unlined drainage channels will enhance water ingress and the formation of perched water. Such surface conditions should be taken into account when interpreting data from measurements made in the vadose zone.

Water movement can be assessed by placing tensiometers or moisture sensors that can measure pore water pressure at several depths throughout the vadose zone to determine the direction of flow and to measure the wetting front velocity. Correlating the wetting front data to the weather and to site management practices can assist in developing an understanding of the general behaviour of the soil water around the disposal units. A steel tape or a pressure transducer/data logger can be used to measure water levels. The pore water pressure data provided by tensiometers can be used to estimate the in situ hydraulic properties of the geological medium and derive water retention profiles for the unsaturated materials.

Pore fluids can be sampled with porous cup-suction lysimeters when the soils or sediments are unsaturated but moist enough to collect water [26, 28], and pan lysimeters [24, 26] if the soils or sediments are wet. If perched water is detected above the water table, a borehole should be sunk to measure the level of the water table and to obtain water samples. Measurements of water level are needed to estimate in situ water recharge rates, travel times and the permeability of the local lithology responsible for perching.

Dry boreholes may be driven or casing installed below and adjacent to the engineered structures of the disposal facility to allow monitoring with geophysical instrumentation. Horizontal casing can be installed for geophysical logging beneath the waste disposal facility, and this is less expensive if carried out at the time of disposal facility construction. Neutron logging will provide data on the status of the moisture content of the soil, sediments or rock surrounding the tubing.

In heterogeneous media, where fracturing or stratigraphic variability is present, water samples should be taken from locations where the water is actually flowing. These preferential flow paths may record faster flow rates than in the surrounding materials. Techniques for vadose zone monitoring in fractured media are discussed in Ref. [29].

If a possibility exists that gaseous radionuclides may be present as contaminants (e.g. ^{3}H, radon, ^{129}I, and ^{14}C), the gas sampling ports should be installed in the vadose zone. These can be located in separate boreholes sunk specifically for gas sampling or in the groundwater monitoring boreholes (see below) [25, 29].

Although the hydraulic properties of rock cavern disposal facilities are different from those around facilities utilizing engineered concrete structures, the above techniques can also be used, with appropriate modification, for monitoring and surveillance of the vadose zones of these types of facility. Further and more detailed guidance on monitoring and sampling in the vadose zone is available in a variety of publications [17, 21, 25, 27].

3.4.5.3. Saturated zone monitoring

The two parameters that have to be monitored in the saturated groundwater zone near a disposal facility are water level and contaminant concentration. Groundwater monitoring is normally carried out in addition to the vadose zone monitoring described above. Information on groundwater monitoring and sampling is available in a variety of publications [17, 19, 21, 25, 28, 30, 31].

Water levels are measured to identify the direction of groundwater flow. They can be measured directly with calibrated tapes or with electronic pressure sensors and data loggers [32]. Initial information (e.g. for the safety assessment) on the hydraulic characteristics of the site soils can be obtained by measuring water levels while subjecting the aquifer to stress by pumping or injection.

Boreholes are sunk upstream and downstream of the disposal facility to measure water levels and to allow water samples to be taken. Groundwater models or particle tracking models can assist in identifying the optimum siting of the boreholes and are used in conjunction with the pre-operational siting studies and characterization results to plan the groundwater monitoring programme.

The optimum downstream borehole locations are those which intercept the flow paths of contaminants. In unconfined aquifers, this is generally downstream of the disposal facility and in the upper portion of the aquifer [28]. Some boreholes need to be located close to the disposal facility to provide early warning of an inadequacy in an engineered barrier. Some also need to be located further away to provide additional spatial coverage and assurance. The actual number of boreholes will vary with each disposal facility. If the geological materials are homogeneous and the hydrogeological conditions relatively simple, a small number of boreholes may suffice. If the hydrogeological conditions are more complex, more boreholes will probably be required. Detailed guidance on the construction and monitoring of boreholes is available in a variety of publications [19, 25, 28, 30, 32–34].

Water samples can be extracted from monitoring boreholes using devices such as bailers and dedicated or portable pumps. The sampling technique needs to allow collection of groundwater samples that are representative of the specific parameters being measured. Detailed guidance is provided in a variety of publications on how to analyse and interpret the results [17, 35–41].

3.4.6. Monitoring for migration of contaminants to the atmosphere

Potential migration of contaminants to the atmosphere from the disposal facility could be in the form of gases (e.g. waste degradation products, volatile radioactive materials) or as particulate material (e.g. contaminated soil particles). Examples of potentially airborne radionuclides are ^{3}H, ^{14}C and radioiodines. Dispersion of airborne material in the environment surrounding the disposal facility depends on the environmental conditions, the chemical and physical forms of the contaminants and the location of the disposal facility. If dispersed, the radioactive material could contaminate foodstuffs, surface waters and biota. Monitoring of the atmosphere for airborne contaminants around the disposal facility therefore needs to be included in the surveillance and monitoring programme.

The collection of meteorological data is also part of monitoring dispersion pathways through the atmosphere. As a minimum this includes the measurement of wind speed and direction and in some stages of the programme (see Section 4) also includes measurement of precipitation, evaporation rate and temperature.

There are two types of sampling for airborne contaminants — passive and active. Passive sampling involves exposing collection devices or sorbent materials to the atmosphere, whereas active sampling consists of passing a known volume of air through a filter or sorbent. The former technique is generally less quantitative than the latter but is often preferred for 'scoping' studies and for long term monitoring. Examples of these techniques as applied to sampling for ^{3}H, ^{14}C and particulates are given below.

Tritium as water vapour in the atmosphere or in soil gas can be sampled by pumping the air through traps to collect the tritiated water vapour. Active samplers include freeze traps, desiccants [42] (e.g. silica gel, molecular sieve) and bubblers containing water. The usual detection technique used with such samples is liquid scintillation counting. The technique of ^{3}H mass spectrometry provides the greatest sensitivity although at considerable cost [37]. Passive samplers that are reasonably quantitative for tritiated water vapour may also be used [43].

Sampling for ^{14}C in the CO_2 present in soil gas can be carried out by pumping the air through bubblers containing sodium hydroxide solution, thus trapping the carbon dioxide as sodium carbonate. The ^{14}C specific activity is determined after separation and weighing of the sodium carbonate and measurement (e.g. by liquid scintillation counting) of the ^{14}C.

Particulate material in air can be sampled using collectors or filters [42, 44, 45] or by making use of deposits on environmental samples (e.g. vegetation). Passive samplers such as dry cloth collectors collect the particulates onto frame mounted cloths. Filters placed in air samplers or in deposit gauges can also collect particulate material. The detailed location of the samplers can be affected by nearby surfaces such as walls, buildings and trees, since these may affect both the airflow pattern and may themselves act as collection surfaces for particulate material. Assay of collected material is desirable with standard radioanalytical methods such as those described in Ref. [46].

3.4.7. Monitoring for transport of contaminants in surface waters at the disposal facility

Should conditions be such that there is water flow on the surface close to a disposal facility, the water and downstream sediments need to be sampled to ascertain whether there is any migration of radioactive contaminants from the disposal facility into the surface water. Detailed guidance on sampling surface water and sediments is provided in Refs [45, 47, 48]. Samples need to be collected and analysed regularly, the frequency of which depends not only on the phase of the disposal facility (see Sections 4–6) but also on the occurrence of any high flow events in case such conditions cause any migration of material that was not anticipated in the safety assessment.

When sampling sediments, representative samples need to be obtained. This can be accomplished by taking a core sample instead of a grab sample [49].

3.4.8. General environmental monitoring

Monitoring of biota, such as fish and vegetation, and surface waters and sediments is usually referred to as environmental monitoring. Whereas groundwater and atmospheric monitoring provide warning of any migrations from the disposal facility, general environmental monitoring should be undertaken to provide additional assurance that exposure pathways have not been overlooked. Included in this category may be the monitoring of biota that selectively accumulate radionuclides and which may, therefore, be regarded as indicators of change. Possible examples are aquatic plants and freshwater mussels. Selection of these indicators is based on availability, ease of sampling and analysis, analysis costs and the time over which monitoring of these substances will provide information on the performance of the disposal facility.

3.4.9. Documented procedures

The procedures to be followed in surveillance and monitoring have to be documented and controlled as part of the QA programme (see Section 2.2). The documentation details the scope and extent of surveillance and monitoring during each disposal facility phase and should define who is responsible for each aspect of the surveillance and monitoring programme. The procedures are developed in consultation with the regulators and specify the regulatory requirements on the monitoring, e.g. the number and nature of the measurements.

3.4.10. Retention and statistical analysis of monitoring data

Generally, the approach used in monitoring is to accumulate data for the derivation of statistical information such as mean values, ranges, distributions and trends. For a near surface disposal facility, all monitoring data have to be retained for the duration over which regulatory control is maintained over the facility [50]. Given the expected absence of detectable levels of many of the radionuclides likely to be of concern, statistical analysis of the levels of those radionuclides that are not already in the environment is likely to be inappropriate. However, if the scope of the monitoring does include monitoring for radionuclides that are already present in the environment at generally detectable levels (e.g. ^{3}H, ^{14}C, ^{137}Cs), then such analysis is important and needs to be carried out. Similarly, ambient radiation levels should be analysed statistically to obtain mean values, ranges, and seasonal and geographical distributions and trends.

Meteorological, hydrological, hydrogeological and geochemical data, which are obtained for the purposes of the safety assessment and are therefore important for the design of the monitoring programme, should also be analysed to obtain mean values, ranges, distributions and trends.

Monitoring data that are inconsistent, either with observed trends or with related measurements, need to be checked for accuracy. This will involve reviewing the relevant procedures and, if possible, repeating the measurements or observations.

4. PRE-OPERATIONAL SURVEILLANCE AND MONITORING

4.1. SPECIFIC OBJECTIVES OF PRE-OPERATIONAL SURVEILLANCE AND MONITORING

The specific objectives of the surveillance and monitoring programme during the pre-operational phase are to:

(a) Provide input data needed for the safety assessment,
(b) Assist in the characterization of pathways along which any radionuclides migrating from the disposal facility would travel,
(c) Define baseline radiological conditions for comparison with later monitoring results,
(d) Collect samples of environmental media for archival purposes,
(e) Design the operational surveillance and monitoring programme.

The general nature of these activities was described in Section 3. Aspects specific to the pre-operational phase of the disposal facility are described below.

4.2. SUPPORT OF THE SAFETY ASSESSMENT

The work undertaken during the pre-operational phase includes initial consideration of sites and final site selection, site characterization, design and construction, commissioning and licensing. Safety assessment plays a central role in the development of a disposal facility. It is used iteratively throughout the period of design and provides a basis for obtaining regulatory approval and public acceptance of the disposal facility [7] as well as establishing the necessary controls and limitations on design, construction, operation and closure. Pre-operational monitoring in the area surrounding the planned disposal facility site should include collection of the site specific radiological, hydrological, geochemical, meteorological and biological data needed for the safety assessment [51].

4.3. PATHWAY CHARACTERIZATION

4.3.1. General

The pre-operational monitoring programme starts as soon as the decision has been made to investigate a particular site. Details of the parameters to be measured, the frequency of measurement and the required precision and accuracy of the measurements will be based on the aims of the safety assessment and will be specific to the particular site and facility. In this phase, the frequency of sampling and measurement has to be sufficient to allow for seasonal variations in site parameters to be adequately addressed and for spatial heterogeneities in hydrological and hydrogeological characteristics to be determined on a scale commensurate with the modelling requirements for the safety assessment.

4.3.2. Groundwater pathways

The hydrogeological and geochemical characteristics of the disposal facility site needed for the definition of the monitoring programme (as well as for the safety assessment) are obtained in the pre-operational phase. The hydrogeological and geochemical characteristics are as follows:

(a) *Hydrogeological conditions.* These should include details of infiltration and evapotranspiration, permanent and temporary springs, depth and oscillation of water table, preferential flow pathways, direction and rate of groundwater flow in both unsaturated and saturated zones, travel times to existing and potential outflow and extraction points;

(b) *Geochemical conditions.* These should include details on the retention of natural radionuclides by soil and geological materials.

As noted in Section 3.4.5, these measurements will involve drilling boreholes at the site. These need to be constructed in such a way that they can be used in the future as monitoring boreholes.

4.3.3. Atmospheric pathways

The meteorological characteristics of the disposal facility site needed for the definition of the monitoring programme (as well as for the safety assessment) have to be ascertained in the pre-operational phase. Mean values and temporal distributions are obtained for precipitation, temperature, wind vectors and evaporation rates.

4.3.4. General environment

The surface hydrological characteristics of the disposal facility site needed for the definition of the monitoring programme (as well as for the safety assessment) are defined in the pre-operational phase. Data that are needed include details of surface runoff and the flow characteristics of existing water streams (including an assessment of the potential for flooding), lakes and wetlands.

The flora and fauna are characterized in the pre-operational phase so as to provide a basis for selection of possible indicators of change (see Section 3.4.6).

4.4. BASELINE RADIOLOGICAL CONDITIONS

Radionuclides that will be of concern for the disposal facility (see Section 3.4.1) are monitored for in the general environment of the disposal facility during the pre-operational phase. For those that are detectable (likely examples are ^{3}H, ^{14}C, ^{137}Cs), their concentrations in the various environmental media at likely monitoring locations have to be measured. For groundwater and surface waters, these locations should be sited both up-gradient and down-gradient of the disposal facility site. Mean values, ranges, distributions and trends have to be obtained. Similarly, ambient radiation dose rates at and around the disposal facility site have to be measured. Mean values, ranges, distributions and trends have to be obtained and, in particular, any anomalous values (e.g. local ‘hot spots’ perhaps due to natural radionuclides) noted.

This baseline information is documented in such a manner that meaningful comparisons can be made with data that will be collected in the future. As regards archiving of samples, consideration should be given to storage of representative materials, recovered from sampling activities, which could be of use at a later date.

4.5. DESIGN OF THE SURVEILLANCE AND MONITORING PROGRAMME FOR THE OPERATIONAL PHASE

The programme to be followed when operation of the disposal facility begins should be defined towards the end of the pre-operational phase. It needs to be based on the safety assessment; the controls and limitations imposed as conditions of authorization, including waste acceptance criteria (see Section 3.4.2); the information obtained in the pathway characterization (Section 4.3) and the information derived from baseline monitoring (Section 4.4). All the features of a surveillance and monitoring programme (see Section 3.4) have to be included.

The detection and monitoring methods have to be specified for all the radionuclides of concern; guidance is provided in Ref. [37]. The detection of the more mobile contaminants (e.g. ^{3}H) that would be expected to be the forerunners of any migration from disposal facilities needs to be emphasized. Locations for groundwater, atmospheric and ambient radiation monitoring are defined, together with the required frequencies of sampling and measurement. The general principle that guides the selection of sampling frequencies and the extensiveness of sampling and measurement locations is the unlikelihood of any appreciable change in the quantity of interest having occurred in the interval between sampling or conducting successive measurements. For example, a potential migration of radionuclides in groundwater might be expected from pre-operational monitoring to be at a rate of less than a few metres per year. Sampling for such migration need only be undertaken once or twice a year. If radionuclides were to be released by some unforeseen circumstance to the atmosphere, then the transport of such a plume could be rapid and more frequent sampling would be warranted. Similarly, the design of the programme for sampling and measuring potential radioactive contaminants in leachate or water in underdrains should reflect the fact that these measurements provide an early warning of unanticipated migration and their frequency has to be accordingly higher than for groundwater.

For groundwater monitoring, the protocols to be followed should be specified, taking into account the particular geochemical characteristics of each location. The protocols to be followed for general environmental monitoring, including the sampling of biota and surface waters, should be specified. All the definitions and protocols need to be documented and subsequently controlled within the disposal facility QA programme.

Depending on the final design of the disposal facility, there may be engineered water drains collecting leachates or engineered channels redirecting water flows around the facility. Any such streams existing outside the engineered structure have to be included in the radiological surveillance and monitoring programme.

If the disposal facility is brought into operation in stages — for example, a set of engineered disposal structures that are constructed, brought into operation and closed in sequence — then the transition from the pre-operational to operational monitoring programme may be a gradual one with the actual operational monitoring programme being revised in the light of experience as successive disposal structures are brought into operation. Advantage is taken of this staging to refine the surveillance and monitoring programme.

5. SURVEILLANCE AND MONITORING DURING OPERATIONS

5.1. OBJECTIVES OF SURVEILLANCE AND MONITORING DURING OPERATIONS

The objectives of the surveillance and monitoring programme during the operational phase are to provide:

(a) Data against which to test the predictions of the safety assessment and which support demonstration of compliance with regulatory and legal requirements for the protection of human health and the environment,
(b) Information to allow the surveillance and monitoring programme in the post-closure phase to be developed.

5.2. SUPPORT OF THE SAFETY ASSESSMENT AND DEMONSTRATION OF COMPLIANCE

The surveillance and monitoring programme designed in the pre-operational phase is to be implemented as soon as waste is delivered to the disposal facility. As noted in Section 3.1, the programme that is the subject of this report does not include the monitoring that is associated with operational radiological protection programmes in what may be regarded as operating nuclear facilities. Compliance with respect to both occupational and public protection during the operating phase will be covered by the regulations pertaining to operating nuclear facilities.

For the near surface disposal facility as such, the safety assessment plays the central role during operations, setting the basis for ensuring compliance with regulations pertaining to the performance of the disposal facility. Accordingly, the programme, designed as described in Section 4.5 and possessing the features described in Section 3.4, has the distinct role of providing the data against which the validity of the safety assessment results may be judged. As noted in Section 3.4, if the disposal facility is performing as designed, there should be virtually no migration of contaminants through the engineered barriers and most if not all of the monitoring results will be providing only upper bounds to possible contaminant transport.

The potential exists for changes to occur to the local environment as the result of construction and operation of the disposal facility, specifically from modifications to site features, which affect the assumptions made in the safety assessment. An example is increased water penetration due to disturbance of the ground surface, elimination of native vegetation over the disposal units, drilling of boreholes, or channelling of runoff water. Another example is the possible generation of preferential pathways for the migration of groundwater (and any migrated radionuclides if disposal facility failure occurs) such as those provided by excavation work related to the construction of rock cavity repositories. The implications of such changes in site hydrogeological and geochemical parameters, detected by the surveillance and monitoring programme, need to be reviewed, the safety assessment revised and the programme adjusted accordingly.

Environmental contamination that may occur during the operational phase from waste handling during emplacement could affect the capability to detect the migration of any radionuclides from the engineered disposal facility. The operator has to be alert to this possibility and should adjust the surveillance and monitoring programme accordingly.

If the results of monitoring indicate that the current or long term performance of the disposal facility may not be compliant with regulations then the reasons need to be investigated and any protective action undertaken.

5.3. DESIGN OF THE SURVEILLANCE AND MONITORING PROGRAMME FOR THE POST-CLOSURE PHASE

The programme to be followed when operation of the disposal facility ceases and the facility is closed is defined towards the end of the operational phase. This programme needs to be based on the safety assessment, data on the emplaced waste and information obtained in conducting the pathway characterization (Section 4.3), and supplemented by the results of, and experience gained with, the surveillance and monitoring programme through the operating phase. All the features of the programme (see Section 3.4) need to be included.

The detection and monitoring methods need to be specified for all the radionuclides of concern; guidance is provided in Ref. [37]. The detection of the longer lived radionuclides of concern is important. Locations for groundwater, atmospheric and ambient radiation monitoring are defined, together with the required frequencies of sampling and measurement. For groundwater monitoring, the protocols to be followed are specified, taking into account the particular geochemical characteristics of each location. Reference concentrations of radionuclides in the various environmental media, which would indicate migrations from the disposal facility in excess of predictions of the safety assessment, need to be defined. The key hydrological, hydrogeological and geochemical assumptions on which the safety assessment is based need to be kept for reference in the post-closure phase.

The protocols to be followed for general environmental monitoring, including the sampling of biota and surface waters, have to be specified. All the definitions and protocols need to be documented and subsequently controlled within the disposal facility QA programme.

If the disposal facility is an assembly of disposal units that are filled and closed in sequence, it may be possible to change to the post-closure monitoring programme for some locations before the disposal facility as such is completely closed. This approach would provide for some evaluation of the design of the post-closure programme before a commitment to the post-closure phase is made.

6. SURVEILLANCE AND MONITORING AFTER CLOSURE OF THE DISPOSAL FACILITY

6.1. OBJECTIVES OF SURVEILLANCE AND MONITORING AFTER CLOSURE OF THE DISPOSAL FACILITY

The objectives of the surveillance and monitoring programme after closure of the disposal facility are to provide:

(a) Data against which to test and demonstrate compliance with regulatory and legal requirements for the protection of human health and the environment,
(b) Information that will help the development of a schedule for the withdrawal of active controls.

6.2. DEMONSTRATION OF COMPLIANCE

The programme for the post-closure phase, which was designed during the operational phase (see Section 4.5), is implemented as soon as all operations have ceased, the disposal facility has been designated by the appropriate authorities as closed and the organization responsible for the post-closure phase has taken charge.

In addition, during the post-closure phase, the protective elements of the disposal facility will be inspected periodically as part of the surveillance programme. This will include inspection of the disposal facility cover and any drains and leachate collection systems, examination of the integrity of fences and warning signs, and verification of the maintenance of restrictions on land use. If any observation during such inspections indicates that the evolving disposal facility may be causing changes to the local hydrology, hydrogeology or geochemistry, then the appropriateness of the current radiological monitoring programme has to be re-evaluated.

If the results of monitoring indicate that concentrations of radionuclides of interest are greater than the reference values set as discussed in Section 5.3, then an investigation has to be undertaken to determine the reason for the unanticipated values. This may involve repeated or more extensive sampling and possibly extension to include other potential contaminants. The investigation needs to be continued until an explanation is obtained that is satisfactory to both the responsible organization and the regulatory body. If the results of monitoring indicate that the current or long term performance of the disposal facility may not be as anticipated and therefore not compliant with regulations, consideration may have to be given to taking remedial action. This will involve reference to the safety assessment and may require reappraisal and revision of the assessment or possibly a new safety assessment. If necessary, the monitoring programme should be revised (see Section 7). The potential exists for changes to occur in the long term to the local environment as a result of climatic changes. Monitoring of the site's hydrological, hydrogeological and geochemical characteristics needs to be undertaken periodically, every few years, to ascertain whether the assumptions underlying the design of the monitoring programme remain appropriate. The implications of any observed changes should be reviewed and the surveillance and monitoring programme adjusted accordingly.

The adequacy and appropriateness of the sampling and measurement protocols also need to be surveyed periodically, again every few years. Monitoring and detection technologies continue to evolve and improve in sensitivity, efficiency and reliability. It is important that the responsible organization be alert to possible improvements in the effectiveness of monitoring available as a result of technological advances. The intention here is to maintain a monitoring effort that is consistent with the measurement requirements and is as efficient and effective as reasonably achievable.

6.3. SUPPORT FOR SCHEDULING THE WITHDRAWAL OF ACTIVE CONTROLS

As noted in Ref. [3], as far as is reasonable, and in accordance with the principle of not imposing undue burdens on future generations, the safety of a closed disposal facility shall not rely on institutional controls that necessitate extensive and continuing active measures. The surveillance and monitoring programme that is the subject of this Safety Report is an example of an active control measure. Other measures such as land use control are passive. It is expected that both active and passive controls will be in place initially in the post-closure phase with the intention that, eventually, active controls and some passive controls will be able to be safely discontinued.

The authority responsible for a disposal facility has to make a case showing that, in the period after any withdrawal of controls over the disposal facility, the radiological consequences of events that could affect the isolation and containment capability of the facility would not cause safety requirements to be exceeded [3]. The results of monitoring have to provide support for such a case.

7. MONITORING WHEN DISPOSAL FACILITY PERFORMANCE IS NOT CONSISTENT WITH THE ASSUMPTIONS OF A SAFETY ASSESSMENT

There are two distinctive circumstances in which the monitoring programme described in the previous sections may not be adequate. One is when the performance of a disposal facility, supposedly designed, constructed and operated to current standards has, in practice, been shown through the surveillance and monitoring programme to be failing to provide a level of protection consistent with the predictions of the safety assessment. The other circumstance concerns an old disposal facility that was not designed, constructed or operated to current standards, and from which radionuclides are migrating. A safety assessment may or may not exist. In both circumstances, the radiological consequences of unanticipated or poorly defined radionuclide migration need to be determined.

The objectives of the surveillance and monitoring programme in the circumstances described above are, therefore, to:

(a) Characterize the pathways along which radionuclides migrating from the disposal facility will travel,
(b) Obtain data to allow the characteristics of the migrating radionuclide plumes to be defined,
(c) Obtain information on the sources of radionuclide migration and their long term behaviour,
(d) Support the development of a new or revised safety assessment,
(e) Support an assessment of the need for intervention and the nature of any remedial action,
(f) Provide continuing data against which to test the predictions of the revised safety assessment,
(g) Provide information that will help the development of a schedule for the withdrawal of active controls.

A surveillance and monitoring programme described in the earlier sections would serve to meet some of these objectives but the delineation of the extent of the migrating plumes of radionuclides and the assessment of their radiological consequences will require more extensive and frequent sampling and monitoring. The surveillance and monitoring programme described in Annex V illustrates how extensive a plume tracking and assessment programme might be and provides some guidance on the frequency of which samples should be collected. For example, samples of surface water drainage are collected weekly and monitored weekly, monthly or quarterly for radionuclides, depending on the location. The facilities are visually inspected quarterly. Groundwater from an extensive suite of boreholes is sampled semiannually. Ambient radiation fields are measured annually.

The actual frequency and location of sampling will depend on the specifics of the particular disposal facility, its environment and the extent of the radionuclide migration. The guiding consideration is that in the interval between sampling or successive measurements a significant change in the quantity of interest is unlikely to have occurred. For example, a radioactive plume that is migrating only a few metres per year need only be sampled once or twice a year. If radionuclides are being transported by surface water, then more frequent (possibly even continuous) monitoring is needed.

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Annex I

SPAIN: ENGINEERED DISPOSAL FACILITY AT EL CABRIL

I–1. INTRODUCTION

The El Cabril facility has been operated by ENRESA, the national radioactive waste management company, since January 1986. It is located in the northeast of the province of Córdoba, at a distance of about 130 km from the capital. The layout of the facility is shown in Fig. I–1.

This site has been equipped with temporary storage facilities for low and intermediate level wastes, comprising three industrial bays. Each bay has a covered surface area of 1800 m^2 and a storage capacity of 5000 220-L drums. In December 1989, ENRESA started work on enlarging the El Cabril facilities. The design of the new facilities is based on a system of shallow disposal and engineered barriers, similar to the French model.

The waste drums, most with a capacity of 220 L, are placed inside concrete containers, producing concrete blocks that weigh 24 t. The containers are placed within the 28 platform structures, each of which has a capacity of 320

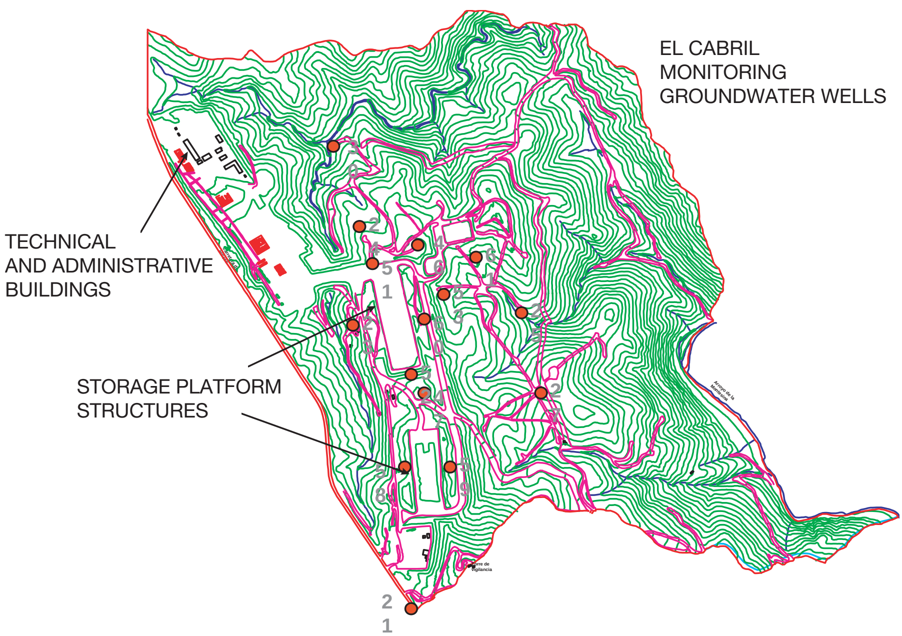

FIG. I–1 Layout of the El Cabril repository showing locations of monitoring boreholes.

containers. When a platform is full, an upper, sealing, slab is installed, followed by a waterproof cover made from synthetic material.

The lower slab of the platform collects any water that may have seeped in through the cover, channelling it to the seepage control system. This system allows the structure from which the seepage has occurred to be identified, so that the defective cover can be repaired.

In addition to the waste emplacement areas, there are various buildings dedicated to technical and administrative controls and services. These include the conditioning building and the radioactive characterization laboratory building. The conditioning process produces radioactive gaseous effluents from the ventilation system and the incinerator. These effluents are released to the environment after filtration.

Any liquid effluents generated by the different processes are re-used to make the concrete that is subsequently used to fill the concrete containers.

The activity inventory authorized for the end of the operating life of the facility comprises about 28 000 TBq of beta/gamma emitters, and 27 TBq of alpha emitters. The authorized radionuclides are mainly beta/gamma emitters with a half-life of less than 30 years. Specific limits are established for ^{3}H, ^{14}C, ^{59}Ni, ^{63}Ni, ^{60}Co, ^{90}Sr, ^{94}Nb, ^{99}Tc, ^{129}I, ^{137}Cs and ^{241}Pu.

Up to the end of 1998, some 53 000 drums had been emplaced in 2181 containers, located inside the platform structures.

I–2. PRE-OPERATIONAL MONITORING AND SURVEILLANCE ACTIVITIES

A new monitoring and surveillance programme had to be implemented to meet the specific requirements of the expanded facility. Similar to other nuclear and radioactive installations, the first stage included planning of a pre-operational monitoring programme to define natural background levels and baseline data. This pre-operational programme included studies to obtain detailed information on the site where the facilities were to be located. These included:

(a) *Geological surveys.* Erosion was identified as the major foreseeable risk. Surveys would be carried out during the operational phase and suitable engineering techniques applied to prevent it.
(b) *Hydrogeological surveys.* These have provided information on the hydrogeological performance of the site. This has made it possible to locate the waste emplacement structures well above the highest level reached by the

water table and to optimize the locations of the boreholes required to monitor the repository.

(c) *Geotechnical surveys.* These have provided information on the load bearing capacity of the ground, the potential presence of sediment, the stability of slopes and other data useful for the design of the facility.
(d) *Geochemical surveys.* These have allowed the conclusion to be drawn that the El Cabril formation has adequate capacity as a barrier against the migration of radionuclides.
(e) *Seismotectonic surveys.* These have indicated that no tectonic activity within a 25 km radius of the site has taken place within the past 500 000 years.
(f) *Meteorological studies.* These have provided data which were used, inter alia, to select the sampling points for the monitoring of gaseous effluents during the operational phase.

The radiological monitoring programme is based on the previous monitoring programme established when the site was a temporary storage facility. It has been extended to cover the new operations and types of facility, taking into account the results of the studies described above.

I–3. OPERATIONAL MONITORING AND SURVEILLANCE

The current operational monitoring and surveillance programme is based on the results of the pre-operational programme. Some hydrological and geological surveys are being continued, albeit with a lower frequency than during the pre-operational phase.

The radiological monitoring programme is broadly similar to the pre-operational programme, but sampling frequencies are generally reduced and only those radionuclides known to be present in the facility are measured.

All liquid effluents are monitored prior to discharge. Their chemical and radiological contents are measured to ensure compliance with the discharge limits.

Gaseous effluents are continuously sampled and analysed for gross alpha and beta activities. Filters are analysed by gamma spectrometry to determine the presence of specific radionuclides and additional samples are taken and analysed in the laboratories for ^{3}H and ^{14}C.

Groundwater direction and velocity are periodically reassessed to incorporate any changes which might have occurred as a result of variations in precipitation rates, water usage, pumping and other factors.

The meteorological station is still being used, since wind direction measurements are necessary to determine the movement of any released airborne materials. For example, precipitation data are required to determine the amounts of water available for surface runoff and penetration. Temperature is measured because it has an impact on a number of processes, including the rate of evapotranspiration.

I–4. ENVIRONMENTAL MONITORING

I–4.1. Air

Air monitoring is carried out to determine the extent of contamination from airborne effluents. Monitoring is carried out at the following locations:

(a) At four points on the site boundaries,
(b) At one point at the nearest down-wind residence,
(c) At one control point at a location remote from the site.

Samples are collected on a continuous basis using an air sampler. The filter is replaced weekly and analysed to measure gross beta activity. A composite sample is measured quarterly to determine the presence of gamma emitters (spectroscopic analysis) and ^{90}Sr (radiochemical analysis).

At the same points, samples are collected for the measurement of ^{3}H and ^{14}C on a quarterly composite sample. The ^{3}H samples are collected by adsorption of air on silica gel and the ^{14}C samples by bubbling air through barium hydroxide.

During the pre-operational phase, samples were also analysed for natural radionuclides, such as ^{226}Ra and uranium; measurements of alpha gross activity were also carried out. This has been discontinued.

I–4.2. Water

I–4.2.1. Groundwater

Groundwater monitoring was established to assess the chemical and radiological quality of the water and to detect potential leaching from the repository. The locations of the monitoring boreholes are shown in Fig. I–1.

Samples are collected from boreholes located mainly around the disposal area, at representative points on the hydrological groundwater flow paths between the disposal structures and the water outflows. There are a further 12 sampling points on the El Cabril site. A borehole located upstream of the disposal area is used as a control point. In addition, an old well, located upstream of the site, is used to confirm the historical background data.

Sampling is performed quarterly and the samples are analysed for gross beta activity, gamma emitters, ^{90}Sr, ^{3}H, ^{14}C, ^{129}I and ^{99}Tc.

The additional measurements carried out on these samples include pH, Eh, chloride, zinc, phosphorus, copper, chemical oxygen demand and specific conductance. During the pre-operational phase, gross alpha activity, ^{226}Ra and uranium were also measured, but this is no longer the case.

I–4.2.2. Surface water

Surface water monitoring may provide information on the presence of radionuclides derived from the waste in the form of liquid effluents. The sampling points are as follows:

(a) Five points in areas where permanent water exists and where surface waters pass through or off the site, and which may be subject to direct surface drainage from potentially contaminated areas or from discharge of liquid effluents;
(b) One upstream control point.

The sampling frequency and the types of analysis performed are similar to those used for groundwater samples.

I–4.3. Vegetation, food and fish

Vegetation samples of the dominant species in the area are collected periodically at off-site locations representing both potentially impacted areas and background conditions.

Eight of the vegetation sampling points are at the same locations as where air is sampled; four additional points are at locations where it is not possible to install electric air samplers. One additional point at a remote location is used as a control point. Samples are collected annually and analysed for gamma emitters, ^{90}Sr, ^{3}H and ^{14}C. The sampling frequency has been reduced from every six months in the pre-operational phase to annually during the operational phase.

Samples of food are collected annually and analysed for gamma emitters. These food samples are representative of local production and include lamb from the nearest farm, honey from nearby beehives, and lamb and honey from a remote control location.

Highly specific to this site are samples of fish and game. These are collected annually and the edible parts and bones analysed for gamma emitters and ^{90}Sr, respectively.

During the pre-operational phase, the content of natural radionuclides in vegetation and other edible products was also measured, but this has been discontinued.

I–4.4. Soils and sediments

Soil and sediment samples may contain radioactive materials released from the facility. Soil samples are expected to reflect airborne transport of radionuclides and sediment samples are related to the emission of liquid effluents.

Soils samples are taken annually at four points on the site boundary, at one point in the middle of the disposal structures and at the same eight locations that the vegetation and air samples are taken. One additional sampling station has been established as a remote control point. Gamma emitters and ^{90}Sr are measured for each sample.

Sediment sampling is carried out at the same locations at which surface water is sampled. The sampling frequency is currently annual and each sample is analysed for gamma emitters and gross beta activity. During the pre-operational phase, the sampling of soils and sediments was carried out every three months.

I–4.5. Direct gamma radiation

Direct gamma radiation is associated with the transport of radioactive wastes, contamination of air and temporary storage in the old facilities.

External gamma radiation measurement is carried out along the site boundary, at the 12 points at which air, surface water and vegetation samples are taken, and at 12 additional points around the bays.

I–5. PLANS FOR POST-OPERATIONAL MONITORING

At present, the post-operational monitoring requirements are not well defined. Eventually, they will be specified by the regulatory body with due consideration being given to the physical, biological and geochemical features of the disposal site and the surrounding area.

Post-operational monitoring and surveillance programmes may include:

(a) Inspection of surface conditions and drainage systems,
(b) Cover maintenance,
(c) Intrusion surveillance,
(d) Monitoring of groundwater.

Annex II

FRANCE: ENGINEERED DISPOSAL FACILITY AT CENTRE DE LA MANCHE

II–1. INTRODUCTION

The French radioactive waste management agency (ANDRA) owns two near surface disposal facilities: (1) Centre de l'Aube, which has been in operation since 1992, and (2) Centre de la Manche, which started operating in 1969 and which closed in 1994.

This Annex discusses the Centre de la Manche monitoring and surveillance programme.

II–1.1. Background

The Centre de la Manche was the first near surface radioactive waste disposal facility in France. It is located near the COGEMA fuel reprocessing plant in northwestern France (average annual rainfall amounts to approximately 1000 mm).

Some 500 000 m^3 of packaged low level waste was disposed of at the site; the activity inventory comprises 46 500 TBq of beta and gamma emitters (mainly ^{60}Co, ^{137}Cs, ^{90}Sr and ^{241}Pu) and 430 TBq of alpha emitters (mainly ^{226}Ra, ^{239}Pu, ^{241}Am).

It was covered between 1991 and 1997 in three different stages, with a multilayer cover comprising layers of compacted coarse grained materials and a drainage layer of fine grained sand on both sides of a bituminous geomembrane.

There are four different drainage systems that were designed and built for different purposes:

(1) *Runoff water collection system.* This consists of a network of gutters and pipes situated on and around the cover and connected to 20 collection sumps.

(2) *Cover drainage system.* Water that may flow through the earth layer down onto the bituminous membrane and eventually through the membrane is drained via 20 drainage sumps into a main collection chamber.

(3) *Vault drainage system.* Leachate from each individual disposal unit or group of units is directed into sumps connected to a separate collection system. The leachate is then allowed to run by gravity into a set of holding

tanks. This system is accessible via a gallery for inspection and intervention.

(4) *Complementary drainage system.* This consists of drains located along the base of the supporting walls and galleries.

II–1.2. Monitoring programme strategy

A new monitoring programme was set up in 1998 to meet the specific requirements of the 'intensive surveillance phase' recommended in 1996 by the Evaluation Commission.

Safety assessments had previously shown that a radiological impact could be caused by two major events:

(1) Abnormal degradation of the bituminous membrane which would increase the permeability of the cover,

(2) Premature release of radionuclides from any part of the disposal facility owing to degradation of waste packages/engineered barriers' properties or to a sudden increase in the level of the water table.

The new programme was established taking into account the 25 years of monitoring and surveillance experience gained at Centre de la Manche. During this new phase, studies of the behaviour of the cover will be undertaken, as well as routine monitoring to identify potential releases of contaminants into the environment and groundwater, and control of effluent discharges.

II–2. MONITORING THE INTEGRITY OF THE COVER

Several techniques are employed in monitoring the integrity of the cover:

(a) Visual inspections are performed, including:
   (i) External inspections of the cover surface, including vegetation, cracking and subsidence of the ground surface layer and evidence of intrusion by burrowing animals;
   (ii) Internal inspections in the vault drainage system gallery;
   (iii) Video camera inspection of the cover drainage system.

(b) Topographic controls are made by monitoring the displacement of a set of markers placed on the cover.

(c) Sampling of the bituminous membrane and subsequent laboratory analysis to check for membrane ageing and changes in membrane properties such as porosity, thickness and diffusion coefficient in comparison with a reference sample.

(d) Hydraulic controls that make use of the drainage system situated beneath the bituminous membrane to detect an increase in permeability. This system is equipped with meters that can detect a sudden increase in water flow rate.

(e) Radiological and chemical monitoring of leachate collected in the vault drainage system and of groundwater may provide an indication of degradation in cover performance. More details are given in Section 3.1.

II–3. MONITORING FOR RELEASES

Monitoring for releases is performed at three different levels:

(1) Leachate drainage system;
(2) Aquifer, with particular emphasis on major streamlines outflow;
(3) Streams down-gradient from the facility.

II–3.1. Monitoring the leachate

Monitoring fluids that collect in the vault drainage system allows changes in the integrity of the cover and any abnormal degradation of engineered barriers to be detected.

The leachate tanks are sampled continuously prior to discharge into the sea, to determine the total activity released every week. Determinations are made for gross alpha and beta activities, ^{3}H, pH and potassium content on water samples and for gross beta activity on suspended materials.

More comprehensive monitoring is performed every six months. A detailed radioisotopic analysis (e.g. for ^{60}Co, ^{90}Sr, ^{239}Pu) is conducted on a representative sample. Valuable information on the nature of the contamination can be obtained by comparing results from acidified and non-acidified samples, since addition of acid solubilizes contamination on suspended particles. Measurements are made on the leachate to identify the principal radionuclides, toxic substances and chemicals in the disposed waste (e.g. lead, cadmium, boron, arsenic and mercury).

These measurements allow determination of the activity and quantity of chemicals released on a weekly, monthly and annual basis. If an abnormal trend is observed, individual collection sumps (~150 exist) would be investigated.

II–3.1.1. Deep drainage system

As regards the deep drainage system, monitoring and sampling are carried out weekly and the samples analysed for gross alpha and beta activities, ^{3}H, pH and gross beta activity on suspended matter. Monitoring this drainage system can help detect any rise in the water table; any such rise would flood these drains before reaching the disposal units.

II–3.2. Groundwater monitoring

Groundwater monitoring is carried out to:

(a) Determine the concentrations of radioactivity and toxic substances,
(b) Derive groundwater gradients and flow directions,
(c) Monitor the position of the water table relative to that of the vaults.

The groundwater monitoring regime was established on the basis of experience gained with operational monitoring, through observation of trends and experimental work, and from the results of hydrogeological modelling.

II–3.2.1. Boreholes sited inside the ANDRA site

The boreholes sited inside the ANDRA site were drilled during the operational phase. The first set of 12 boreholes (Set No. 1), sited on the groundwater flow paths between the disposal units and the three outflows, are monitored every month. The second set of 17 boreholes (Set No. 2), which do not intercept the main groundwater flow paths, is monitored every two months. The third set of 10 boreholes (Set No. 3), sited upstream, on the southern limit of the disposal facility, is monitored every six months. Samples from these boreholes are analysed for gross alpha and beta activities, ^{3}H, pH, potassium, toxic substances and other physical parameters. Seven boreholes from Set No. 1 and seven boreholes from Set Nos 2 and 3 are monitored every six months.

II–3.2.2. Boreholes sited outside the ANDRA site

The two main reasons for monitoring the groundwater levels are to confirm that the water level is well below the bottom of the lowest disposal unit (hence no flooding of the disposal units can have occurred) and to confirm the direction of water flow paths.

A set of 19 boreholes was drilled between the disposal facility and the outflows situated downstream of the repository. Sampling and radiological monitoring are carried out on a monthly basis and in a manner similar to that employed for the on-site boreholes. Continuous monitoring of water levels is performed in four of these boreholes, which are equipped with detection alarm sensors. Six-monthly campaigns are conducted on all boreholes, both within and outside the disposal facility, at times of maximum and minimum water level.

II–3.3. River water monitoring

The aquifer, which could contain released contaminants from the disposal facility, is connected to two rivers. Runoff water from the disposal facility is discharged into one of these rivers.

Monitoring of the river flow rate is performed at the discharge point and downstream of it. Radiological monitoring and sampling (for gross alpha and beta activities and ^{3}H) is carried out weekly at different points along these rivers. Every year, a comprehensive radioisotopic analysis is performed on water samples and suspended materials taken downstream of the confluence of the two rivers. Monitoring for chemicals is performed every six months at different locations along the two rivers. Monitoring of river sediments for several important radionuclides is performed every month at three locations and every year for a wider range of radionuclides.

II–4. MONITORING OF DISCHARGES

Monitoring is performed on effluents prior to discharge into the river, to demonstrate compliance with the discharge authorizations. The monitoring performed includes:

(a) Continuous volume monitoring.
(b) Radiological monitoring:
   (i) Continuous beta/gamma activity monitoring;
   (ii) Gross alpha and beta activities, ^{3}H and potassium in water samples and gross beta activity on suspended materials every three days;
   (iii) Radioisotopic (e.g. ^{14}C, ^{99}Tc, ^{226}Ra, ^{241}Am) analysis every six months;
   (iv) Gamma and alpha spectrometry on sediments deposited in the collection sump every year.

(c) Monitoring for toxic substances (e.g. mercury, nickel, arsenic, cadmium) and for other parameters such as temperature, conductivity and carbon monoxide every six months.

II–5. ADDITIONAL MONITORING

In addition to those described above, the following procedures are carried out:

(a) Rainfall measurement (daily);
(b) Radiological monitoring of rainwater for gross alpha and beta activities and for ^{3}H (weekly);
(c) Radiological monitoring of air for gross alpha and beta activities (daily) and for ^{3}H (weekly);
(d) Monitoring of grass on the cover by gamma spectrometry (weekly);
(e) Dose measurement using thermoluminescent dosimeters placed on fences around the site;
(f) Continuous monitoring of gamma dose rate;
(g) Radon concentration measurement of the air at two locations.

Annex III

CZECH REPUBLIC: ROCK CAVITY REPOSITORIES AT HOSTÍM, LITOMĚŘICE AND BRATRSTVÍ

III–1. INTRODUCTION

The disposal of radioactive wastes in rock cavity repositories started in 1959, when the first repository, located near Hostím in the Beroun District, was put into operation. The operational period of this repository ended in 1963, and the repository was closed in 1965.

At present, there are two rock cavity repositories in operation. The Richard II repository is used for disposal of wastes containing artificial radionuclides and the Bratrství repository for disposal of natural radionuclides.

During the period 1991–1998, several safety studies for the individual disposal sites were carried out. The main objectives of these studies were the evaluation of the condition of the disposed wastes, the technical state of the repositories, the qualities of the natural and engineered barriers and the possible impact of the disposed wastes on the environment.

III–2. GENERAL CHARACTERISTICS OF THE DISPOSAL FACILITIES

In the rock cavity disposal facilities, the requirement for isolation of the waste from the environment is realized through a system of multiple barriers. The first barrier is the immobilized waste. The second barrier is provided by the packaging of the wastes inside two drums and encasing them in concrete. The geological formation hosting the disposal facility, owing to its isolation characteristics, constitutes the third and most important barrier from the viewpoint of long term safety. Repository operations require monitoring to determine if any contamination of the site and drinking water sources has occurred.

III–2.1. The Hostím disposal facility (closed)

The Hostím disposal facility was put into operation in 1959. The repository is situated in the galleries of an abandoned limestone mine. The repository was closed in 1965. Before the facility was closed, waste packages containing substantial activities were transferred to the Richard II disposal facility. The predominant radionuclides are ^{3}H, ^{14}C, ^{60}Co, ^{90}Sr and ^{137}Cs.

The basis of the radiation monitoring system is the long term sampling of water from four monitoring boreholes located around the disposal site, from two small rivers near the disposal site and from two boreholes in the nearby village. The beta activity of the samples is measured by liquid scintillation counting and the activities of other radionuclides such as ^{137}Cs, ^{60}Co, ^{222}Rn, ^{214}Bi and ^{40}K are measured by gamma spectroscopy. Radiation monitoring of the site and surroundings indicates no deviation from natural background levels.

Geodetic monitoring of the region, capable of identifying very small rock movement, has so far not identified any movement.

Water level measurements and pumping tests are carried out to provide data on water ingress into the boreholes and on water migration in the region.

III–2.2. The Richard II disposal facility for artificial radionuclides (in operation)

The Richard II disposal facility, near Litoměřice, has been in operation since 1964. It was built as a relatively large capacity repository for low and intermediate level wastes and spent sealed sources in the abandoned Richard II limestone mine. During the Second World War, an underground military factory was situated in this mine. Only a part of the mine is used for the repository. The total volume of the radioactive wastes disposed of so far is about 2700 m^3.

The water table lies approximately 50 m below the disposal modules, in a sandstone layer, and the repository is continuously monitored for possible contamination of water, land and air.

Tritium is one of the most important radionuclides from the radiological point of view, especially because of its high content in the waste, its volatility and the difficulty involved in its immobilization. Other critical nuclides are ^{241}Am, ^{239}Pu, ^{137}Cs, ^{14}C and ^{90}Sr. The total disposed activity is estimated at roughly 10^{15} Bq.

Recent hydrological studies indicate that the isolation characteristics of this site are adequate. The underlying geological bed of the site is formed partly of marl. Small amounts of mine water (several litres per day) flow from the mine throughout the year. The hydrological, geotechnical and radiological monitoring systems of the facility are under continual improvement. The waste packages are in relatively good condition. An isolated central retention basin for the accumulation of mine water has been built. Recent studies indicate that there is no real threat to the surrounding environment. It has been necessary, however, to take the following measures to enhance safety:

(a) Undertaking continuous inspection and repair, as necessary, of the concrete structures in the repository;
(b) Undertaking continuous inspection and repair of the drainage system;
(c) Undertaking systematic monitoring of the air and mine water inside and outside the facility;
(d) Completing the deep monitoring system as called for by hydrogeological and geological safety studies;
(e) Supplying the disposal facility with modern equipment for the safe handling of tile waste.

Safety studies proceed continuously; their results are used to enhance radiation safety in the radioactive waste disposal facility.

The monitoring system consists of:

(a) Measuring the basic climatological parameters (precipitation, atmospheric humidity, temperature).
(b) Measuring the quantity of the mine water effluents.
(c) Conducting chemical and radiological analysis on water samples (twice per year) taken from 8 boreholes and from 15 other places. Positive ^{3}H values (which are well below the legislative levels) have been measured but no significant levels of other radionuclides have been found.
(d) Undertaking periodic geotechnical monitoring of the underground system to confirm the stability of the facility. This involves taking convergence and dilatometric measurements and using pressure pads and surface inclinometers to carry out checks for structural deformation.

The geotechnical monitoring results (carried out between 1993 and 1997) indicate that the rock mass is stable. Any manifestation of instability is limited only to the spalling of small rocks in non-operational places.

Part of the monitoring system is also devoted to the control of the waste packages, including surface contamination, and radiological control of working places in the disposal facility. The purpose of this monitoring is to fulfil the requirements of the decree on radiation protection, whereby:

(a) Control of the air in underground operating spaces is achieved by measurement of the concentration of ^{222}Rn and ^{3}H progeny. The allowable limits are not exceeded.
(b) Personal monitoring is provided by film and personal thermoluminescent dosimeters and by measurement of the radionuclide content of urine.

(c) Neutron activation analysis and gamma spectroscopic measurements have shown that there is no connection between the radionuclides disposed of in the repository and its environment.

On the basis of the results gained from the monitoring system and the results of former measurements (geophysical, pumping tests, water table determinations, long term tracer techniques), no preferential pathway for the migration of contaminants, in the case of a postulated accident, was identified.

The post-operational monitoring programme will be based on the present monitoring system and will be modified according to the final waste inventory, mode of filling the disposal space, results of post-operational safety assessment and requirements of regulatory bodies. Further points on water and soil sampling, frequency of sampling, measurement techniques and how to use monitoring results are still to be determined.

III–2.3. The Bratrství disposal facility for natural radionuclides (in operation)

The Bratrství disposal facility, near Jáchymov, has been in operation since 1974. It was built in the gallery of an abandoned uranium mine and has five disposal chambers. It is used for wastes containing natural radionuclides, predominantly ^{226}Ra, ^{210}Po and ^{210}Pb, and isotopes of uranium and thorium. The wastes also contain spent sealed sources and neutron sources. The predominant isotopes are ^{226}Ra, ^{232}Th and ^{210}Po. The main reason for the separation of these wastes from other wastes is radon emanation, which would cause serious problems in the Richard II disposal facility.

The following provisions for increasing the safety of the facility are being made:

(a) Tracer examination of groundwater movement using artificial radionuclides;
(b) Hydrochemical determination of the mine waters, mineral waters and surface waters;
(c) Estimation of the engineering and geological stability of the site;
(d) Continuous geotechnical works and maintenance to improve the stability of the galleries and the drainage system.

The monitoring system takes measurements of the following components:

(a) Radiation exposure of workers,
(b) Radon-222 concentration in the workplace air,

(c) Surface contamination on waste packages,
(d) Effective dose rate equivalents on the surface of the waste package,
(e) Surface contamination in most working areas of the facility,
(f) Activity in the mine water effluents,
(g) Instability or damage of the facility (regular measurement using inclinometers),
(h) Seismicity (measured using microseismic profile techniques).

As regards item (h), microseismic profile measurements are taken because the facility is situated in a zone of weak seismicity. Such measurements show only weak rock mass deformation and as such indicate that the facility is stable.

Annex IV

UNITED STATES OF AMERICA: TRENCHES, PITS AND VAULTS AT THE IDAHO NATIONAL ENGINEERING AND ENVIRONMENTAL LABORATORY (INEEL)

IV–1. INTRODUCTION

This Annex summarizes the monitoring and surveillance activities of the Environmental Monitoring Program at the Radioactive Waste Management Complex (RWMC) of the INEEL [IV–1]. The INEEL is owned by the US Department of Energy (USDOE). The USDOE established the INEEL as the National Reactor Testing Station in 1949 to conduct research and further the development of peaceful uses of atomic energy. The purpose of the monitoring programme is to monitor effluents and environmental media in order to meet applicable permits, rules and regulations, to assess the impact of INEEL operations on the environment and to protect public health. Media sampled include drinking water, liquid effluents, groundwater, ambient air, surface water, soils and vegetation.

Early monitoring activities focused on pathways along which radioactive contaminants from INEEL operations could be released and where exposure of the general public in southeast Idaho could occur. Because the INEEL was heavily involved in testing nuclear facilities, radionuclides were the major contaminants of concern. However, this has since been expanded to include selected hazardous constituents.

IV–1.1. Regional physical setting

The INEEL is located in the north–central part of the Eastern Snake River Plain of Idaho. The average elevation is about 1500 m above mean sea level. The surface of the RWMC comprises about 0–8 m of loam type surficial sediment which is underlain by basalt. The INEEL occupies a substantial part of a closed topographic basin.

The INEEL is approximately 63 km long in a north–south direction and 58 km wide at its widest point covering an area of approximately 2300 km^2. The climate is characteristically warm and dry in the summer and cold in the winter. The relatively dry air and infrequent low clouds permit intense solar heating of the surface during the day and rapid cooling at night. Meteorological data have been collected at over 45 locations on and near the INEEL site since 1949. Thirty meteorological stations are currently operating. The average annual precipitation at the Central Facilities Area, located about 10 km northeast of the RWMC, is 220 mm. The average annual snowfall recorded is 700 mm, and the water content of melted snow contributes between one-quarter and one-third of the annual precipitation [IV–2].

The long term average daily air temperature ranges from -12°C during early January to 21°C during the second half of July. The average annual temperature at the INEEL gradually increases over seven months beginning with the first week in January and continuing through the third week in July. The temperature then decreases over the course of five months until the minimum average temperature is again reached in January. A winter thaw has occurred in late January on several occasions. This thaw has often been followed by more cold weather until the spring thaw.

Various solid and liquid radioactive and chemical wastes, including transuranic wastes, have been disposed of at the RWMC. The RWMC is a 40 ha facility containing pits, trenches and vaults where radioactive and organic wastes were disposed of below-grade, as well as above-grade, and covered on a large pad. Shallow land disposal practices have historically been employed to deal with the waste. The sediment has been removed to the basalt surface, 0.7 m of sediment placed on the basalt, then the waste placed in the excavation and the sediment placed over the waste up to the level of the land surface. Waste is currently disposed of in a large excavation where the sediment and basalt were removed to a depth of 9.1 m, 1 m of sediment and gravel placed over the basalt and then the waste stacked in containers. The waste is then covered by sediment up to the level of the land surface.

IV–1.2. Surface water hydrology

Three surface waters terminate within the INEEL boundary. The Big Lost River, Little Lost River and Birch Creek drain mountain watersheds located to the north and west of the INEEL.

For more than 100 years, flows from the Little Lost River and Birch Creek have been diverted for irrigation. Birch Creek terminates at a playa near the north end of the INEEL and the Little Lost River terminates at a playa just north of the central northwestern boundary of the INEEL.

The Big Lost River flows onto the INEEL near the RWMC and flows northeastward to the Big Lost River playas. During peak river flows, water is diverted to the INEEL, spreading to areas located 1.6 km west of the RWMC. The RWMC experienced flooding caused by local basin runoff in 1962, 1969 and 1982. These events were caused by rapid snowmelt combined with heavy rains and were often compounded by frozen soil conditions.

IV–1.3. Groundwater hydrology

The Snake River Plan Aquifer is a vast groundwater reservoir that may contain more than 1200 km^3 of water. The flow of groundwater in the aquifer is chiefly to the south–southwest at velocities that range from 1.5 m/d to 6 m/d. The aquifer is composed of basaltic lava flows and interbedded sedimentary deposits. Water is contained in, and moves through, pores, fractures, cavities, interstitial voids, interflow zones and lava tubes. Openings in the rock units and their degree of interconnection complicate the movement of groundwater in the aquifer.

Most of the groundwater is recharged in the uplands to the northeast of the INEEL. It then moves southwestward through the aquifer and is discharged from springs along the Snake River near Hagerman, 250 km southwest of the RWMC. Lesser amounts of water are derived from local precipitation on the plain. Part of the precipitation evaporates, but some infiltrates the ground surface and percolates downward to the aquifer. At the INEEL, significant recharge is derived from the intermittent flows of the Big Lost River.

IV–2. ENVIRONMENTAL MONITORING

Environmental monitoring is conducted in and around waste management facilities to ensure compliance with USDOE Order 5820.2A. During normal operations at INEEL facilities, some radioactive and non-radioactive materials are released to the environment. Various environmental processes may transport these materials from the INEEL site to nearby populations. Environmental transport through the atmosphere directly results in exposure of people off-site. Exposure may also occur indirectly as a result of radionuclides deposited in soil or taken up by plants or animals.

Transport pathways are ranked in terms of relative importance according to the following four criteria: (1) mechanism of transport, which is considered to be either direct or indirect in terms of transporting contaminants to a human receptor; (2) amount of contaminant that could potentially be transported; (3) rate at which the contaminant could be transported to the receptor point; and (4) duration of exposure to the contaminant by each transport pathway.

Air is the most important transport pathway. It is considered more important than the groundwater pathway because it has the potential to transport a large amount of activity to the receptor in a short period. Groundwater can also transmit large amounts of radioactivity, but over a much longer period. This longer period allows more time in which to implement corrective action to minimize doses from contaminated groundwater. At the RWMC, the water table is located approximately 180 m below the ground surface.

The biota pathway is ranked higher than the surface water pathway because there is seldom any surface water in the INEEL area that could transport contaminants to off-site receptors. The biota and surface water pathways are both seasonal and intermittent, and neither is considered to be a significant transport pathway to on-site or off-site receptors.

Soils are also sampled to determine if long term deposition of airborne materials released from the INEEL has resulted in a buildup of radionuclides in the environment. Food chain surveillance and off-site air and soil measurements are conducted which provide additional information on dose.

IV–2.1. Air

The surveillance programme collects particulate material on ~10 cm diameter membrane filters using two types of air monitor: the PM_{10} monitor for particulate matter and the SP monitor for suspended particulate. While the PM_{10} monitors are designed to admit only those particles less than 10 μm in diameter, the SP air monitors are designed to admit larger particles. The PM_{10} monitors sample particulates considered to constitute the respirable fraction, which is also the range of particle sizes that can be transported to off-site locations by wind. The filters are collected and analysed every two weeks (semi-monthly) for gross alpha and gross beta activities, and monthly composites for each location are analysed quantitatively for gamma emitting radionuclides. Filters are also bulked quarterly by location and analysed for specific alpha and beta emitting radionuclides.

Filters are collected from a network of low volume air monitors on a weekly basis. Each low volume air monitor maintains an average airflow of about 57 L/min through a set of filters consisting of a 5 cm diameter 1.2 nm pore membrane filter followed by a charcoal cartridge.

These filters are analysed weekly for gross alpha and gross beta activities, then bulked quarterly by location. They are then analysed using gamma spectrometry and specific alpha and beta analytical techniques. In addition to the particulate filter, charcoal cartridges are collected and analysed weekly by gamma spectrometry. Dust burden is monitored using low volume filters to collect the radioactive particulate samples.

The gross alpha activity results are used as a criterion to screen samples for further radiochemical analysis of specific alpha emitters. The results of gross beta activity analysis of the air filters are evaluated to determine any significant increases in the radioactivity that may require more immediate or more in-depth analysis by gamma spectrometry or radiochemistry. Gross beta activity results are evaluated by comparison with historical and background data and used to identify trends using a log concentration-versus-time plot. Each plot is compared with control concentrations, detection limits and alert levels. Warning (or alert) levels are set at 25% of the most restrictive Derived Concentration Guides for the public. Comparisons are made between stations and control monitors using statistical analysis methods. Concentrations are compared with applicable Derived Concentration Guides for the public.

IV–2.2. Surface water runoff

Surface water runoff is collected to determine if radionuclide concentrations exceed alert levels or if concentrations have increased significantly compared with historical data.

Surface water runoff occurs at the subsurface disposal area only during periods of rapid snowmelt or heavy precipitation. At these times, water may be pumped out of the subsurface disposal area into a drainage canal. Water also runs off the asphalt pads around the Transuranic Storage Area and into drainage culverts and the drainage canal, which direct the flow outside the RWMC. The canal also carries outside runoff water that has been diverted around the RWMC. Ponding of the runoff in a few low areas may increase subsurface saturation, enhancing subsurface migration.

Two control locations 2.0 km north of the RWMC are also sampled.

IV–2.3. Soil

Soil is sampled both at waste management facilities and at site surveillance locations. Samples are collected at each location and combined to form a single composite sample. These samples are analysed by gamma spectrometry and selected samples submitted for radiochemical analysis.

IV–2.4. Biota

Crested wheat grass is collected in odd number years and clipped at ground level within a 90 cm × 90 cm frame. Russian thistle is collected in even number years and the entire plant pulled up within a 90 cm × 90 cm frame. Either rabbitbrush or sagebrush is collected in odd number years by clipping 20% of the branches from the designated plants.

Thus, the same plant can be sampled biennially. Russian thistle samples were scheduled to be collected in 1998 from the RWMC. However, not enough

Russian thistle was found at the RWMC to provide an adequate sample and therefore no samples were collected.

IV–2.5. Direct radiation

Thermoluminescent dosimeters (TLDs) measure cumulative exposure to ambient ionizing radiation. The TLDs detect changes in ambient exposures attributed to the handling, processing, transport, or disposal of radioactive waste. TLDs are sensitive to beta energies greater than 200 keV and to gamma energies greater than 10 keV. The TLD packets contain five lithium fluoride chips and are placed about 0.9 m above the ground at specified locations. The five chips provide replicate measurements at each location. The TLD packets are replaced in May and November of each year. The sampling periods for 1998 ran from November 1997 through May 1998 (spring) and from May through November 1998 (autumn).

IV–3. COMPLIANCE MONITORING PROGRAMMES

Compliance monitoring programmes contain the requirement to sample drinking water, liquid effluents, storm water runoff and groundwater to show compliance with federal and state regulations and permits. The Drinking Water Program contains the requirement to conduct monitoring to ensure that drinking water is safe for consumption. This is achieved by demonstrating that the water quality meets federal and state regulations, that is, maximum contaminant levels (MCLs) are not exceeded. The Safe Drinking Water Act establishes the overall requirements for the Drinking Water Program.

IV–3.1. Groundwater monitoring

The Drinking Water Program requires that the Environmental Protection Agency (EPA) approved analytical methods (and no others) be used to analyse drinking water in compliance with IDAPA 16.01.08 and 40 Code of Federal Regulation (CFR) 141.28. Parameters with primary MCLs are required to be monitored at least once every compliance period, which is three years. Parameters with secondary MCLs are monitored every three years on the recommendation of the EPA. Many parameters require more frequent sampling during an initial period to establish a baseline, and subsequent monitoring frequencies are determined from the baseline.

The Drinking Water Program requires more frequent monitoring than that carried out at the RWMC to meet the minimum regulatory requirements.

This is because of known contaminant plumes. Thus, the Drinking Water Program requires that samples be taken more frequently than quarterly because of historical problems with bacteriological contaminants.

During an INEEL-wide characterization programme conducted by the United States Geological Survey (USGS), carbon tetrachloride and other volatile organic compounds (VOCs) were detected in groundwater at the RWMC. Review of waste disposal records indicated that an estimated 335 000 L of organic chemical wastes were disposed of at the RWMC prior to 1970, including carbon tetrachloride; trichloroethylene; tetrachloroethylene; toluene; benzene; 1,1,1-trichloroethane and lubricating oil. High vapour phase concentrations (up to 2700 parts per million by volume) of VOCs were measured in the unsaturated zone above the water table. Groundwater models predict that VOC concentrations will continue to increase in the groundwater at the RWMC.

The RWMC production well is sampled at the wellhead and at the point of entry to the distribution system, which is the point of compliance. Since monitoring began at the RWMC in 1988, there has been an upward trend in recorded levels of carbon tetrachloride. In October 1995, the level of carbon tetrachloride increased to 5.48 mg/L at the well. This was the first time that the level in the well exceeded the MCL of 5.0 mg/L. The levels at the well are used for comparison purposes only because no MCL has been exceeded at the distribution system (WMF-604), which is the compliance point. The distribution system represents the point from which water is first consumed at the RWMC. Technologies are being considered for treatment of the carbon tetrachloride to ensure the water is safe for potable usage (e.g. drinking, eye washes, showers).

IV–3.2. Storm water sampling

Samples are collected from snowmelt or storms that produce at least 2.5 mm of precipitation and which are preceded by a period of at least 72 hours without measurable precipitation. This mode of sampling allows pollutants to build up and then be flushed from the drainage basin. Because sampling occurs in response to specific meteorological conditions, advance sampling schedules cannot be developed. For meteorological reasons, it may not be possible for all sites to be sampled every year. The outflow is tested for a range of materials and properties including metals, total and dissolved magnesium, inorganics, toxic materials and radiological content.

Variables, including storm duration, quantity of precipitation and time period between the storm event sampled and the end of the previous storm are recorded for all precipitation events. Storm water monitoring results are compared with a number of criteria to evaluate the quality of storm water discharges. Concern arises when the concentration of material reaches a level at which a storm water discharge could potentially impair or contribute to impairing water quality or affect human health through ingestion of water or fish.

IV–3.3. Active waste monitoring

Monitoring is planned within the Active Waste Management Area Pit at the subsurface disposal area. The Active Waste Management Area is an excavation which penetrates the surficial sediment and into basalt to a depth of 9.1 m. It has been backfilled with 0.7 m of sediment and 0.3 m of gravel. The overall size of the area is 200 m × 100 m. The waste is stacked in this area and then covered with sediment.

Monitoring instruments have been placed adjacent to the waste containers. As waste is added to this area it will surround or cover these instruments. The monitoring instruments include access tubes, gas sampling ports and suction lysimeters.

The access tubes are sunk vertically from the ground surface into the underlying sediments, allowing moisture determination using a neutron probe or sediment monitoring (beneath the waste) using instruments such as portable tensiometers [IV–3]. Soil gas will be collected from the underlying sediments and at locations adjacent to the waste. The samples may be analysed for ^{3}H, ^{14}C and ^{129}I. Soil water sampling will be conducted using suction lysimeters installed within the sediments beneath the waste.

Monitoring will commence after the instruments have been surrounded by waste and the cover materials added above the waste at these locations.

IV–3.4. Groundwater sampling

The USGS monitors approximately 178 boreholes at the INEEL on a regular basis. The groundwater samples are analysed for a variety of radionuclides, including ^{3}H, ^{90}Sr, ^{241}Am, ^{238}Pu, ^{239}Pu and ^{240}Pu. The samples are also analysed for other species and properties, including chloride, nitrate, sulphate, sodium and chromium ions.

IV–4. QUALITY ASSURANCE/QUALITY CONTROL

To ensure that the monitoring programme is effective, quality assurance and quality control programmes are implemented.

The quality assurance programme ensures that the sampling methods produce representative samples of the media being monitored, confirms that laboratory analyses are reliable and verifies that the quality of reported results is sufficient to support decisions based on the environmental monitoring data. The quality assurance plan includes programme plans; technical procedures for sampling, conduct of field work and analysis; corrective action plans; chains of custody; instrument calibration records; data verification/validation; internal/external inspection reports; personnel qualification/training records; records/logbooks; analytical reports/data packages; and statements of work and purchasing. Quality control samples are used to measure and document uncertainties in the analytical data.

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Annex V

CANADA: TRENCHES, PITS AND VAULTS AT THE CHALK RIVER LABORATORIES (CRL)

V–1. INTRODUCTION

This Annex summarizes the monitoring and surveillance activities undertaken at CRL's Waste Management Areas (WMAs). The facilities described in this Annex are radioactive waste storage facilities; there are no facilities for radioactive waste disposal in Canada. Many of the storage facilities at CRL have buried wastes, hence, monitoring and surveillance requirements for these facilities will be similar to those of disposal facilities.

CRL is a nuclear research facility that was established in 1944 by Atomic Energy of Canada Limited (AECL), a corporation that is owned by the Government of Canada. Operations at the CRL site began in the autumn of 1944. Over the years, CRL has served the needs of basic research, radioisotope production, and research and development in support of AECL's CANDU heavy water reactor. The facilities provide storage for radioactive wastes arising from the operation of research and development facilities at CRL, isotope processing operations, prototype CANDU reactors, hospitals, universities and industries across Canada.

Monitoring and surveillance of the WMAs is one component of the overall AECL Environmental Protection Program. Comprehensive environmental and effluent monitoring programmes for the CRL site are summarized in a series of annual reports [V–1, V–2]. The environmental monitoring programme reports on radioactivity levels for the site and its surroundings in media such as surface water, soils, air, precipitation, fish, game animals, milk and vegetables. The effluent monitoring programme reports on airborne and effluent releases from various installations on the CRL site.

V–2. PHYSICAL SETTING

CRL is located in the Province of Ontario on the southern shore of the Ottawa River, 160 km northwest of Ottawa (Fig. V–1). The CRL site is typical of its immediate surroundings, being a mixture of exposed bedrock, glacial till, fluvial sand and gravel, small lakes and marshes. Elevations vary between 80 m and 120 m above the level of the Ottawa River, which is the dominant drainage feature in the area. Flow in the Ottawa River, measured at the des Joachims dam (35 km upstream of CRL), averaged 2.56×10^{10} m^3/a between 1960 and 1988. The CRL site contains numerous small lakes, streams and wetlands, and is characterized by a forest cover consisting of pine, birch, hemlock, spruce, beech, maple, oak and poplar.

V–2.1. Climate and weather

The climate of the area is classified as humid continental, with warm summers, cold winters and no distinct dry season. In quantitative terms, based on data collected at CRL since 1963, the salient meteorological features are as follows:

(a) Daily mean air temperature ranges from -12ºC in January to 19ºC in July, with historic minima and maxima of -39ºC and +39ºC, respectively.

(b) Distribution of wind velocities and direction has been found to vary little from year to year. Prevailing winds are from the west–northwest (parallel to the Ottawa River valley) with velocities being most frequently between 4 m/s and 5 m/s (14–18 km/h) and exceeding 10 m/s (36 km/h) 2.5% of the time.

(c) Annual precipitation has ranged from 570 mm to 1080 mm of water equivalent, with an average of 820 mm. Sixty per cent of the annual precipitation is lost by evapotranspiration; the remaining 40% either runs

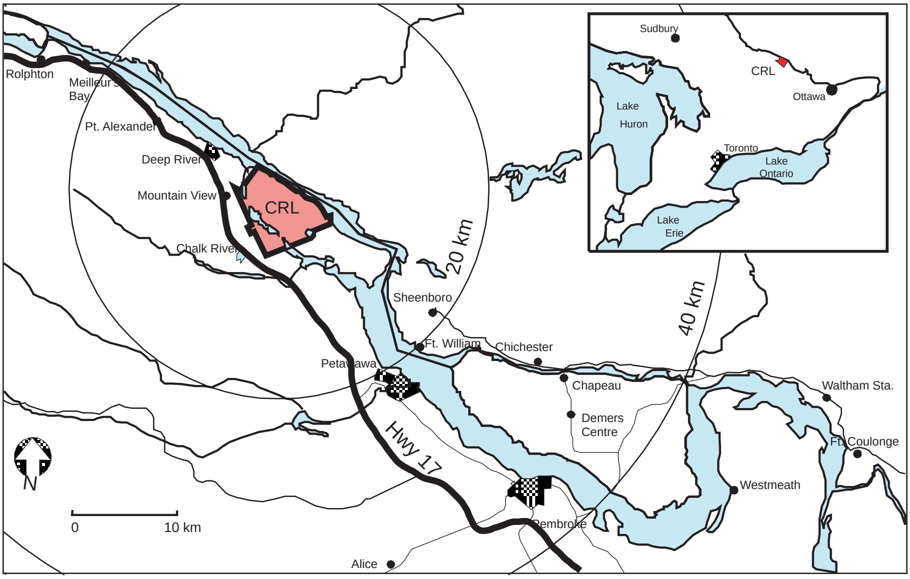

FIG. V–1. Location of CRL.

off directly to local surface water bodies or infiltrates the ground to recharge groundwater flow systems. Approximately 20% of the annual precipitation falls as snow.

V–2.2. Surface hydrology

Several drainage basins are defined within the CRL site, all of which drain, directly or indirectly, to the Ottawa River. The two basins of significance for the WMAs are:

(1) *Perch Lake Basin*. Perch Lake lies within a natural basin (2 km × 7 km) of bedrock and drains to the Ottawa River by way of Perch Creek (average discharge: 1.8×10^6 m^3/a).
(2) *Maskinonge Lake Basin*. Maskinonge Lake has a volume of 11.8×10^6 m^3 and an annual flow through of 5.8×10^6 m^3. It discharges to Chalk Lake (average flow: 4.7×10^6 m^3/a), which, in turn, drains into the Ottawa River near the town of Petawawa.

V–3. WMAS

The information below provides a brief description of the larger WMAs with radiological inventories on the CRL site. More detailed descriptions of these facilities can be found in Ref. [V–3]. WMAs designated as A, B, D, G, the Waste Tank Farm, and the Liquid Dispersal Area (LDA) are located within the Perch Lake Basin; WMAs C and F are in the Maskinonge Lake Basin (Fig. V–2).

WMA 'A'. The first emplacement of radioactive waste at CRL took place in 1946 into what is now referred to as WMA 'A'. These emplacements took the form of direct disposal of solids and liquids in trenches excavated in the sand overburden.

LDA. This contains seepage pits that went into operation in 1953 to receive active liquids from various laboratories and facilities associated with reactor operations. The seepage pits (Reactor Pits 1 and 2, and the Chemical Pit) are located on a small dune, in an area bounded on the east and south by wetlands and by WMA 'A' to the west.

WMA 'B'. This was established in 1953 to succeed WMA 'A' as the site for solid waste management. It contains a wide variety of waste burial structures, such as unlined sand trenches, concrete monoliths containing solidified liquid wastes, asphalt lined trenches, concrete bunkers and tile holes for high level

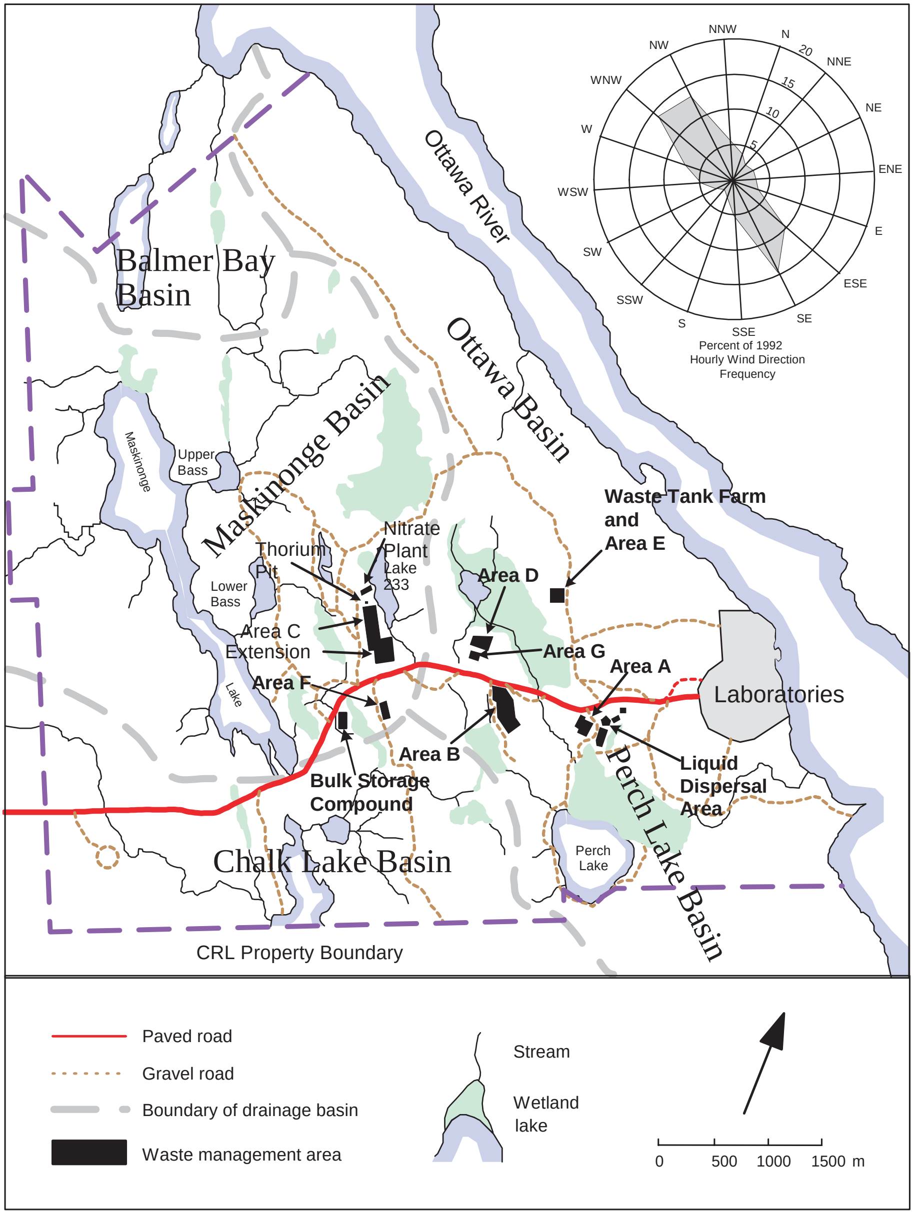

FIG. V–2. The CRL site showing the location of the WMAs.

wastes. Tile holes are below-grade concrete pipes set vertically on a poured concrete base; some of the tile holes have a steel lining.

Waste Tank Farm. This was built to store high and intermediate level liquid wastes in tanks that are housed in stainless steel lined concrete bunkers. Water level sensors in the concrete bunkers, which are tested periodically, are wired to alarms at response centres in the inner area.

WMA 'C'. This is a sand trench facility that went into service in 1963 to receive low level wastes having hazardous lifetimes of less than 150 years and wastes that cannot be confirmed as being uncontaminated. Some of the older trenches at WMA 'C' have been covered with an impermeable membrane of high density polyethylene.

WMA 'D'. This is used to store obsolete or surplus equipment and components that are known to be or suspected of being contaminated but which do not require enclosure (pipes, vessels, heat exchangers, etc.), plus closed marine containers containing drums of contaminated oils and liquid scintillation 'cocktails'.

WMA 'F'. This was established in 1976 to store contaminated soils and slags containing low levels of ^{226}Ra, uranium and arsenic. Emplacement was completed in 1979 and the site is now considered closed.

WMA 'G'. This facility was established in 1988 to store the entire inventory of irradiated fuel from the Nuclear Power Demonstration prototype CANDU power reactor in above ground concrete canisters.

Non-engineered waste management facilities at CRL have permitted some radiological and chemical contamination to escape from their boundaries, primarily via subsurface and surface groundwater transport. This has led to the generation of several plumes of contamination which are the subject of characterization and surveillance programmes (the plumes are mapped at approximately five-yearly intervals). The plumes originating from WMA 'A' and the LDA, for example, are illustrated in Fig. V–3. In general, these plumes do not represent a direct external exposure hazard to operating personnel or to the public. However, some surface waters are contaminated as a result of contaminant migration in these plumes.

V–4. MONITORING AND SURVEILLANCE

Monitoring and surveillance of the WMAs largely comprises periodic surveillance activities and semi-annual groundwater sampling programmes. Periodic surveillance activities include visual inspection of facilities and measurement of radiation fields. The containment status of below-grade waste storage facilities is confirmed by an Operational Control Monitoring (OCM)

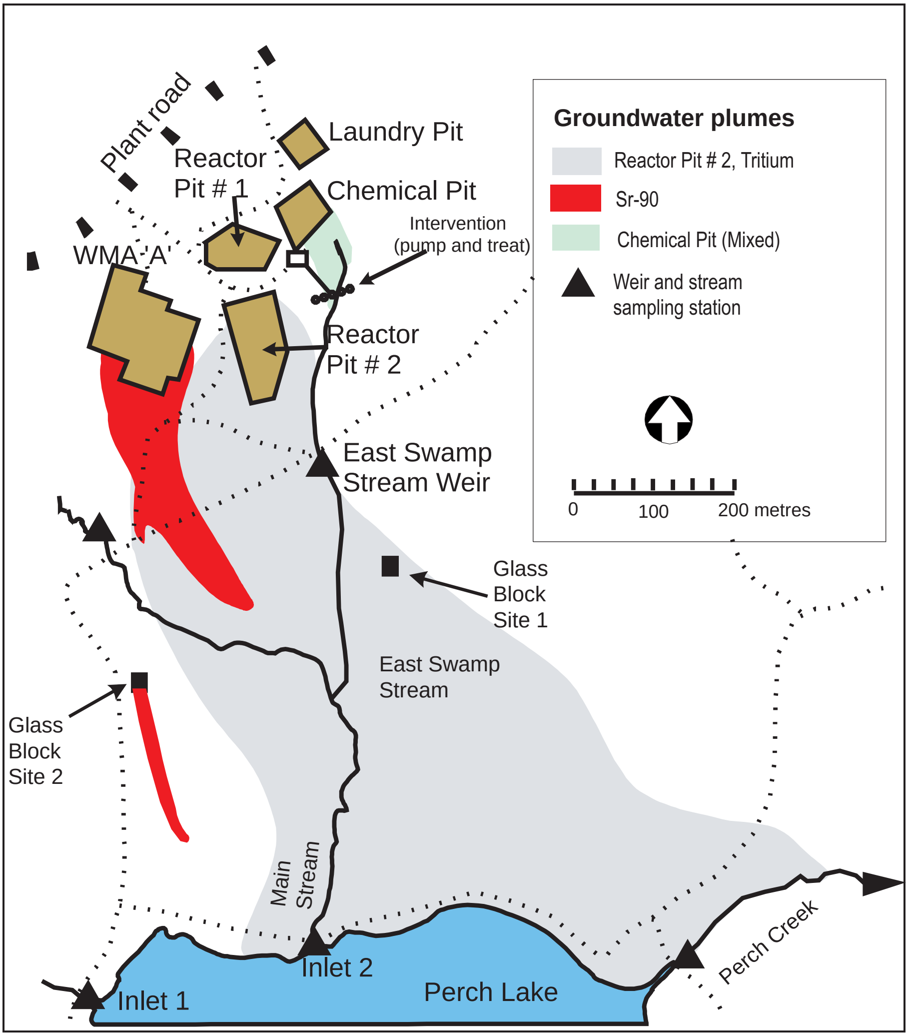

FIG. V–3. Subsurface plumes originating from WMA 'A' and the LDA.

programme. This programme concentrates on monitoring radiological and non-radiological contaminants in groundwater in the vicinity of the storage facilities.

V–4.1. Periodic surveillance activities

Quarterly surveillance activities include:

(a) Visual inspection of each WMA for evidence of erosion, subsidence, fence penetration or any other abnormal condition;
(b) Monitoring the gamma radiation fields of all the waste storage facilities that are built or which project above ground;
(c) Visual inspection of the above-grade portion of waste storage facilities for evidence of deterioration (e.g. cracking or spallation of concrete);
(d) Radiation field monitoring at thermoluminescent dosimetry stations.

Annual surveillance activities include:

(a) Radiation monitoring of perimeter fences,
(b) Measurement of gamma radiation fields above areas containing buried wastes,
(c) Sampling to detect water ingress in solid waste storage facilities equipped with detection systems.

Surface water samples are collected weekly at a number of sampling points within the Perch Lake and Maskinonge Lake basins. Samples are monitored for gross alpha and beta activities, ^{3}H and gamma emitters, on a weekly, monthly or quarterly basis, depending on the location. Continuous air monitoring is carried out and periodic air sampling for the presence of radon is also undertaken at some of the WMAs.

External radiation hazards presented during operation of the WMAs are described and addressed in annual reports [V–4]. General radiation fields at the perimeters and within the WMAs, as recorded by periodic surveys, are consistently less than 10 μGy/a. There are a few locations where higher radiation fields are recorded and these are segregated and signposted accordingly. Annual whole body and surface doses accumulated by operating staff have consistently been below 10 mSv.

V–4.2. Groundwater monitoring

Groundwater concentrations of a large suite of radiological and non-radiological contaminants are reported for samples collected from monitoring boreholes located at the perimeter, and in some cases within the WMAs [V–5]. Groundwater was, and still is, considered to be the most significant agent for mobilizing contaminants from the WMAs.

Between 60 and 90 monitoring boreholes are sampled semi-annually. Sampling boreholes are constructed of pre-cleaned PVC having threaded joint connections that incorporate bevelled seals. Most of the OCM boreholes are 5 cm internal diameter, with 1.5 m borehole screens. Studies of radionuclide migration at the site have shown that the highest levels of contamination are, in most cases, either found at the water table along site perimeters or would be expected to be most abundant at the water table. As a result, most of the boreholes used for OCM sampling are screened at or near the water table.

The following four broad categories of items are investigated:

(1) Inorganic and dissolved organic species and physicochemical parameters (e.g. pH, dissolved organic carbon, major anions and cations, heavy metals);
(2) Volatile organic compounds (e.g. benzene, toluene, halogenated solvents such as carbon tetrachloride, chloroform, methylene chloride);
(3) Extractable organic compounds (e.g. polyaromatics, phenols, dioxins, furans, PCBs);
(4) Radiological content (gamma emitters, ^{3}H, ^{14}C, total alpha and total beta activities).

Borehole head measurements of temperature, electrical conductance, pH, Eh (redox potential) and dissolved oxygen are made during sample collection.

In accordance with drinking water quality guidelines, the groundwater sampled contains little contamination associated with either inorganic or extractable organic contaminants. Volatile organic compounds and chlorinated solvents in particular are the only categories of organic contaminants that exhibit measurable groundwater contamination.

The radionuclides that are common in the low level radioactive waste at CRL reflect the site's waste sources. For the most part, the radionuclides that appear in groundwater samples are those expected in the early releases associated with these WMA facilities, i.e. ^{3}H, ^{90}Sr, ^{14}C and occasionally small amounts of ^{60}Co and ^{137}Cs. Concentrations of alpha emitters were found to be elevated at some of the WMAs. After ^{3}H, the dominant radioisotope to have exhibited appreciable migration is ^{90}Sr. Under the geochemical conditions prevalent in shallow aquifers at CRL, strontium interacts with aquifer solids, but only to a degree that reduces ^{90}Sr transport velocities to a few per cent of those of the groundwater itself. Complexing of a fraction of ^{60}Co that has been released from waste management facilities with naturally occurring groundwater organics has led to appreciable mobility of this isotope. Similar complexing reactions, or the formation of mobile colloids, have been suggested as the mechanism for the migration of much smaller amounts of actinide elements. Many of the waste radionuclides, with ^{137}Cs being a notable example, have undergone very little subsurface migration over the CRL site's operating history.

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