SITE CHARACTERIZATION FOR A SHALLOW LAND BURIAL FACILITY AT CRNL

J.S. Devgun and R.W.D. Killey
Atomic Energy of Canada Limited
Chalk River Nuclear Laboratories
CHALK RIVER, Ontario, Canada
KOJ 1J0

ABSTRACT

A prototype intrusion-resistant shallow land burial facility (designated SLB-P1) for low- and intermediate-level radioactive wastes is planned at CRNL. Siting studies for SLB-P1 have been in progress for some time. This paper examines the disposal options available based on the type of CRNL terrain, describes the site selection and characterization strategy, summarizes the main characteristics of the site selected for SLB-P1 and outlines the direction of future efforts.

INTRODUCTION

Chalk River Nuclear Laboratories (CRNL) have maintained storage facilities for radioactive wastes since 1946. Only about 5% of the wastes are high-level; the bulk of the wastes are low-level (80%) and intermediate-level (15%). Approximately 3,000 m^3 of largely low- and intermediate-level (LIL) wastes are generated annually at present, with the waste currently in storage approaching a consolidated volume of about 50,000 m^3. About 60% of the wastes originate on-site from the operation of the research reactors, laboratories and hot cell facilities, from radioisotope production and from the associated activities such as decontamination and dismantling. Off-site sources, such as hospitals, universities, industrial producers and users of radioisotopes, nuclear fuel fabricators and one small power reactor account for the rest. Program planning at CRNL calls for a change from current storage practices to permanent disposal of these wastes[1]. A program called Waste Disposal Project (WDP) has been established to direct the transition from storage to disposal. The prototype intrusion-resistant shallow land burial facility (SLB-P1) is the first disposal facility being built and siting studies have been in progress for some time. This paper examines the disposal options available based on the type of CRNL terrain, describes the strategy of site selection and characterization, summarizes the main characteristics of the site selected for SLB-P1 and outlines the direction of future investigations.

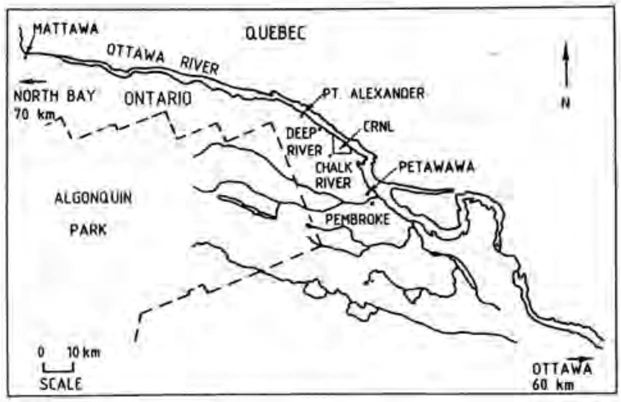
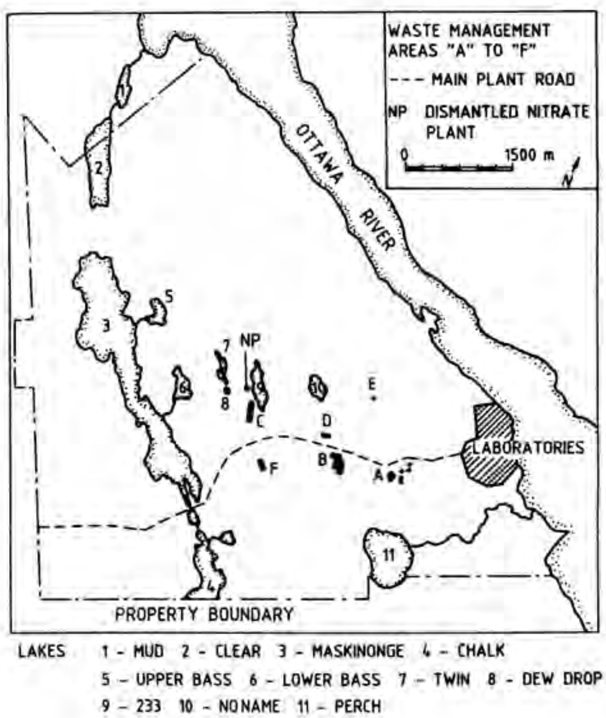


Fig. 1. CRNL Location.



LAKES 1 - MUD 2 - CLEAR 3 - MASKINONGE 4 - CHALK
5 - UPPER BASS 6 - LOWER BASS 7 - TWIN 8 - DEW DROP
9 - 233 10 - NONAME 11 - PERCH

Fig. 2. CRNL Property.

CRNL SITE AND DISPOSAL OPTIONS

General

CRNL is located on the south bank of the Ottawa River about 150 km upstream from the city of Ottawa. Figure 1 shows the CRNL location and the surrounding areas. The CRNL property covers an area of 37 km^2. Figure 2 provides a general description of the property.

The area around CRNL is sparsely populated with an average population density of only 15 people/km^2 within a radius of 20 km. The closest population center downstream which uses the Ottawa River water is the Canadian Forces Base and the township of Petawawa (population about 20,000), 20 km from CRNL. Marginal agriculture and dairy farming have existed in the area for the past century, but most of the land is covered with forest of small commercial value. Climate is that of cold snow-forest classification with a warm summer and no distinct dry season. Mean air temperatures range from -12°C in January to 19°C in July. Night temperatures in midwinter, however, occasionally fall to <-30°C. Average annual precipitation (equivalent rain) amounts to 730 mm. The winds are generally light and are oriented by the topography. Predominant wind direction is from the northwest or the southeast and most frequent wind speeds are between 10 to 18 km/h.

Site Capability and Disposal Options

A major requirement in the WDP is that disposal facilities be located on the CRNL property. This limits the terrain types available. About 5% of the property area consists of exposed bedrock, with the remainder being covered by thin (up to 30 m) unconsolidated sediments of late glacial and post-glacial origin. Figure 3 (prepared from previously published information[2,3]) summarizes the surficial geology of the CRNL property. The areas shown as bedrock in this figure include the exposed bedrock, but also fairly large areas where bedrock is covered by less than about a metre and a half of unconsolidated sediments. Precambrian bedrock that underlies the area consists primarily of granitic gneiss.

The unconsolidated sediments fall in two major classes: (i) very bouldery sandy glacial till, and (ii) aeolian and fluvial sands with minor gravels. There are no significant deposits of low-permeability sediments. Because of a temperate humid climate, water tables lie within a few metres of ground surface everywhere except beneath the stabilized sand dunes that are prominent topographic features on the site. Water tables beneath the dunes are up to 15 m below ground surface.

Given the nature of the site, there are at least four options for solid waste disposal facilities. These are disposal facilities located:

- above the water table in sand
- below the water table in unconsolidated sediments
- below the water table in bedrock, and
- in bedrock with engineered drainage to maintain unsaturated conditions within the waste.

Based on considerations of the site's capability, the nature of the wastes, regulatory concerns and other technical and socio-economic factors, three concepts were chosen for development at CRNL[1,4]. These concepts - Improved Sand Trench (IST), intrusion-resistant Shallow Land Burial (SLB) and Shallow Rock Cavity (SRC) are being matched to three groups of waste categorized on the basis of hazardous lifetime[a] (<150 years, <500 years and >500 years, respectively).

[a] The hazardous lifetime here means the period of time over which the radioactive wastes present a potential radiation hazard to humans under conditions of disposal.

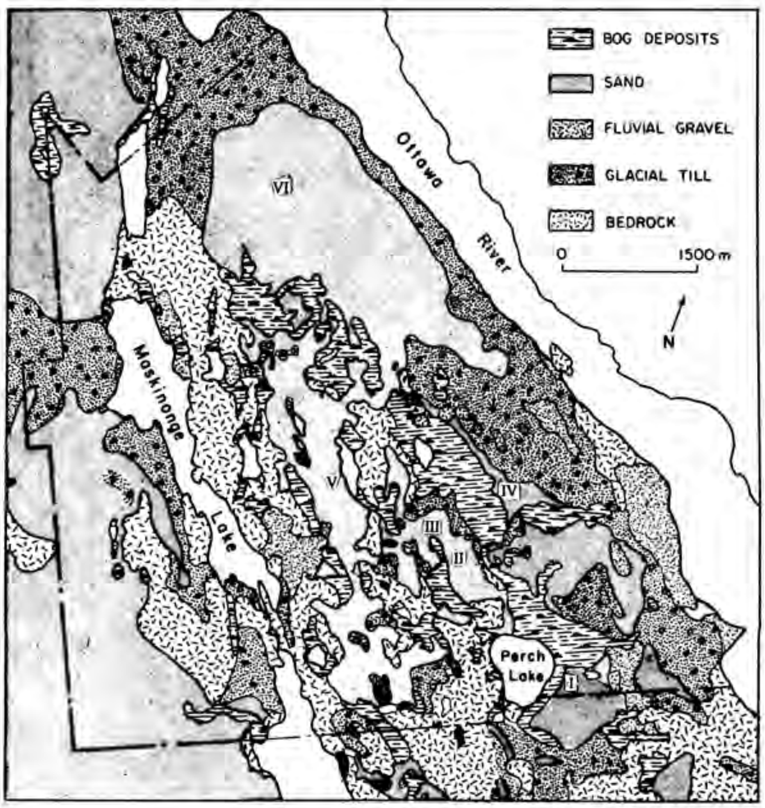


Fig. 3. Surficial Geology of CRNL Property.

SLB-PI

Since most of the wastes at CRNL are believed to have hazardous lifetime <500 years, the SLB concept is being given priority. SLB-P1, a forerunner of possible similar SLB facilities, is being built to develop and demonstrate the relevant technology, to perform the necessary R&D for safety assessments and to gain operational experience. The concept adopted is that of a facility in free-draining unconsolidated sediments above the water table. The proposed structure will consist of a concrete-walled and -roofed trench approximately 100 m long x 20 m wide x 8 m deep with a usable depth of at least 6 m. The facility will contain a minimum of 7,000 m^3 of waste, the remainder being filled with buffer and backfill. The facility design incorporates engineered barriers to radionuclide migration in the form of infiltration control, leach-resistant waste forms, waste packaging and the use of buffer and backfill materials having good radionuclide sorption characteristics. Besides the intrusion-resistant concrete cap, the facility may be covered with other water-shedding barriers and the surface drainage at the site may be engineered. An example of a possible preliminary design is shown in the cross-section depicted in Fig. 4.

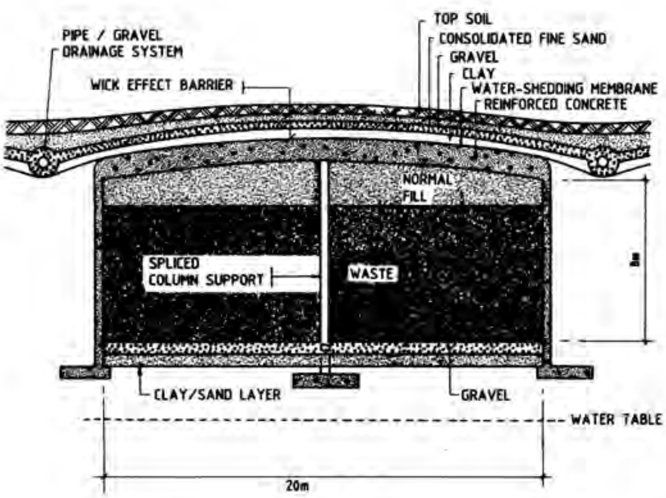


Fig. 4. Schematic Cross-section of SLB-P1.

SITE SELECTION STRATEGY

The strategy adopted for selecting and characterizing a site for SLB-P1 is summarized in Fig. 5. Details of the site selection and characterization process are being reported elsewhere[5].

Based on the existing extensive geoscientific information and using the process described in Fig. 5, out of the six candidate sites (marked I to VI on Fig. 3), site V was chosen as the SLB-P1 site; the remaining areas were ranked as alternate sites. Preliminary site analysis and safety assessment studies have found the SLB-P1 site acceptable for an engineered SLB facility. Site characterization studies in detail have focused on this site.

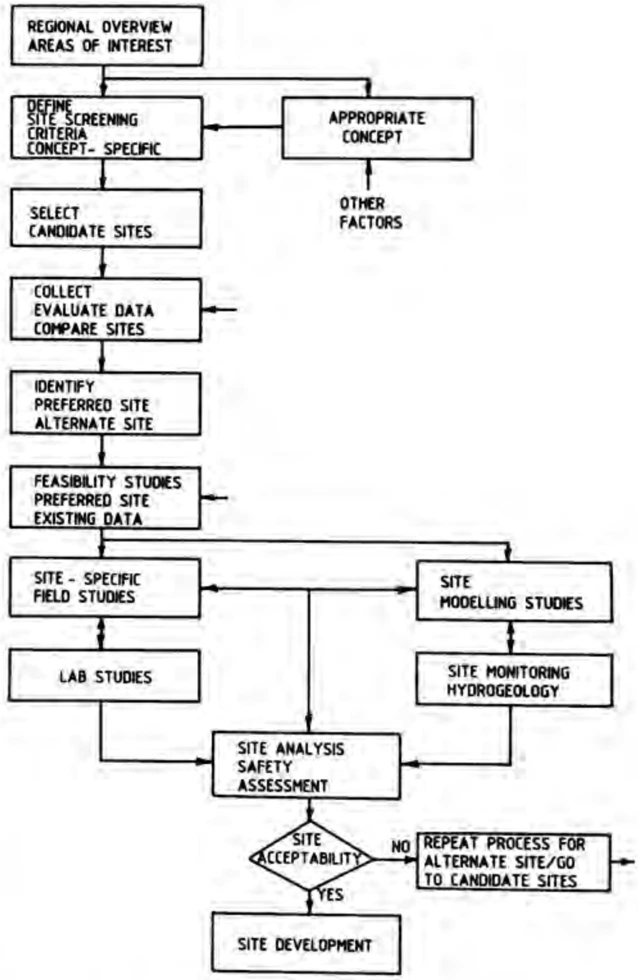


Fig. 5. Strategy of Site Selection and Characterization.

SITE CHARACTERIZATION

The characterization program for the SLB-P1 site has been divided into three phases:

Phase 1: Studies on undisturbed site before excavation begins.
Phase 2: Studies on excavated site during construction of the facility.
Phase 3: Monitoring studies during operation, closure and post-closure periods of the facility.

Present site characterization efforts are part of Phase 1 studies. Some sixty considerations, technical as well as socio-economic, were initially tabulated for complete characterization of the site. Technical factors which have high significance for the CRNL area and for the SLB-P1 facility have received priority effort. These factors are listed in Table I. Work on the other tabulated factors and the compilation of relevant information is expected to continue through the other phases of the program.

TABLE I

SLB-P1 Site Characterization - High Significance Factors

1. Geology	i	seismicity (e.g. liquefaction potential of soil)
	ii	surficial geology, stratigraphy, topography
	iii	characterization of sediments
2. Hydrogeology	i	water table information
	ii	groundwater-surface water interaction
	iii	hydraulic conductivity, hydraulic gradients, porosity, dispersivity
	iv	radionuclide transport pathways, modelling and safety assessment
3. Geochemistry	i	groundwater chemistry
	ii	sorption characteristics of soil for SLB wastes
	iii	background levels of radionuclides

BRIEF DESCRIPTION OF SITE CHARACTERISTICS

Geology

CRNL lies in the Ontario gneiss belt in the Grenville Province of the Canadian Shield. Bedrock of the area is a complex of Precambrian rocks that are extensively faulted, folded and fractured. The major rock types are paragneiss, monzonite and gabbro with pegmatite, a relatively minor rock type, occurring as dykes within other rock units. Hydrogeologic studies of the fractured rock have been conducted at CRNL during the past several years[6-8].

Unconsolidated sediments of late and post-glacial age mantle much of the bedrock at CRNL. Two units of bouldery silty sand till of late-Wisconsin age lie at the base of the overburden sequence over most of the area[3,9]. Thin deposits of sands and brackish-water clays, attributed to a brief incursion of the Champlain Sea, are occasionally encountered between the two tills. In areas with elevations below 150 m (Above mean Sea Level, ASL), fluvial sands and some gravels often overlie the bedrock or till. Immediately after ice retreat, precursors of the Upper Great Lakes drained through the Ottawa River, leaving extensive braided-stream deposits[10].

Water levels in the Ottawa River dropped abruptly approximately 9,500 years ago[11]. A brief episode of aeolian reworking of some of the fluvial sands led to the development of dune ridges and sheet deposits of sand; these have since been stabilized by vegetation. Wetlands on site are currently accumulating organic sediments.

SLB-P1 Site

Setting, Surficial Geology and Hydrogeology

The site selected for SLB-P1 is located on a sand dune which already hosts two waste management areas (Fig. 6). The dismantled Nitrate Plant (NP), which was briefly used in the early 1950s for decomposition of ammonium nitrate solutions containing mixed fission products, lies just northwest of the SLB-P1 site. It released activity to an infiltration pit and the subsurface radioactivity plume has been extensively monitored over the past 30 years. Waste Management Area "C", to the southeast of SLB-P1 site, is currently used for the burial of low-level solid waste in unlined trenches. It has released tritium (as tritiated water) and traces of Co-60 to the underlying aquifer. The sand dune extends approximately in the northwest-southeast direction with the areas described above lying on the northwestern part of the dune. The northeastern face of the dune is relatively steep and forms one margin of a small seasonal lake known as 233 Lake which is empty part of the year. Drainage from a 1.7 km^2 basin (northeast of the lake) flows into 233 Lake, which in turn drains by recharging approximately half a million cubic metres of water per year to the aquifer underlying the dune. Recharge from the lake, plus direct infiltration of precipitation on the dune, flow southwest through the unconfined sand aquifer to a series of springs and seepages in a perennial wetland about 450 m from the dune ridge. The wetland drains via two streams to Maskinonge Lake; the water then passes through Chalk Lake and eventually enters the Ottawa River. Average flow in the Ottawa River at CRNL amounts to about 65 million cubic metres per day.

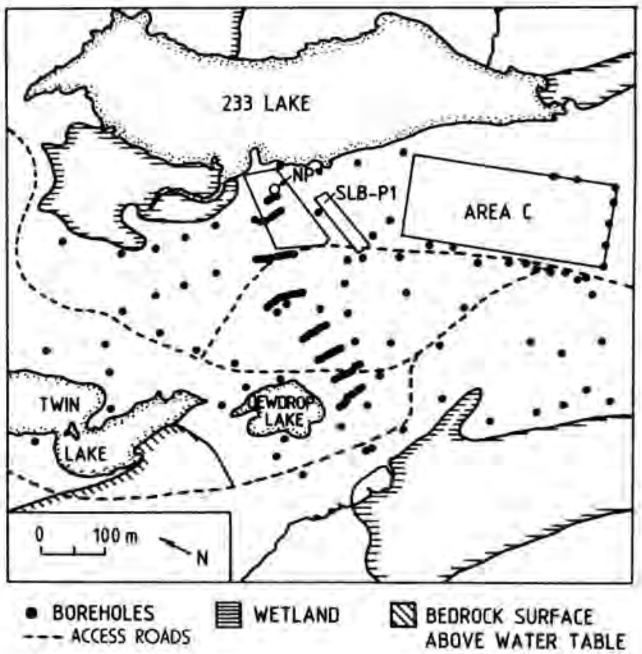


Fig. 6. SLB-P1 Site and Environs.

Figure 7 is a stratigraphic section based on continuous coring of boreholes along a groundwater flowline just northwest of the SLB-P1 site. At the base of the overburden is patchy bouldery till, overlain by a fining-upward sequence of fluvial sands ranging from medium sands to interstratified very fine sands and minor silts. Aeolian sands overlying the fluvial sediments form the dune ridge and gradually thin to the southwest. All of the sediments have a granitic mineralogy with about 30% quartz, 55 to 60% feldspars, and 8 to 12% ferromagnesian minerals. Dry bulk density of the sands is 1.7 to 1.8 g/cm^3 with higher values in the more compact fluvial sediments.

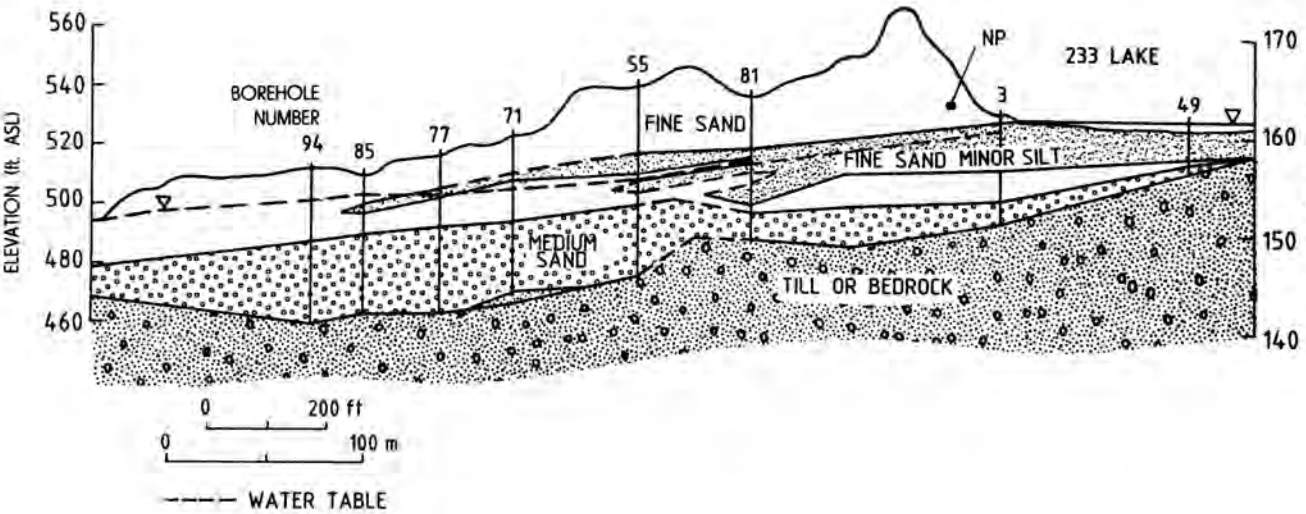


Fig. 7. A Geologic Cross-section Near the SLB-P1 Site (Southwest-Northeast).

Porosities in undisturbed samples of aquifer sands range from 0.38 to 0.42. From approximately 300 measurements (using a variety of techniques), horizontal (K_h) and vertical (K_v) hydraulic conductivities of the sands were found to be lognormally distributed. Mean values of K_h for the various sands range from 0.0063 to 0.015 cm/s; vertical hydraulic conductivities are on average lower by a factor of two to three. The K_h for the sand and silt unit is estimated to be between 0.003 to 0.005 cm/s; measured K_v values average 0.0002 cm/s. For the underlying till, mean value of K_h is 0.00035 cm/s and, for all practical purposes, the till forms the lower boundary of the aquifer.

Most of the boreholes in the area southwest of 233 Lake are instrumented with multiple piezometers, and at present the network for monitoring hydraulic head consists of approximately 600 piezometers in 148 boreholes. The network has increased gradually over the past six years - hydraulic heads are monitored at most locations on a monthly to bi-monthly basis. Mapping of vertical head distributions has shown downward hydraulic gradients beneath and immediately adjacent to 233 Lake and lateral flow over almost all of the rest of the aquifer. Upward flow is present only beneath and immediately adjacent to the wetland receiving the groundwater discharge. Mean groundwater velocity calculated from average hydraulic conductivity, porosity and gradient data is 0.45 m per day, in good agreement with an average velocity of 0.38 m per day determined in 18 borehole dilution tests along the SLB-P1 flowpath.

Two sets of field experimental studies of hydrodynamic dispersion have been performed at CRNL[12-14]. Over distances of 7 to 40 m, whole-aquifer longitudinal dispersivities of several 10s of cm were measured. Results indicated that over the subsurface flowpath from the SLB-P1 site to the groundwater discharge area, whole-aquifer longitudinal dispersivities between 1 and 10 m are probable. The experiments showed that transverse dispersivities are one to two orders of magnitude smaller than longitudinal values.

Three numerical simulations of groundwater flow in 233 Lake area have been performed to date. In 1984/85, the three-dimensional finite difference numerical code SWIFT (version 2.80.FW) employing 1664 elements was applied[15] to an area covering 610 m by 1093 m. Good agreement between calculated and observed hydraulic head distributions gives strong support to the conceptual hydrogeologic model. Good agreements between observed and computed hydraulic heads were also found in two 2-dimensional finite element simulations, one in vertical section down-gradient of the NP and one in plan view of the 233 Lake area. Hydrogeologic modelling for simulating groundwater movement at the site forms an integral part of the safety assessment studies to determine the radiological consequences of radionuclides leached and transported by groundwater from SLB-P1 to the human environment.

Hydrogeochemistry

Groundwater residence time between the SLB-P1 site and the discharge area is about three years. Without chemical reactions between radionuclides and solid phases in the aquifer matrix, only extremely short-lived isotopes that might be leached from the facility would undergo substantial attenuation by decay. Considering the limitations of the site, substantial reliance is placed on the engineered barriers (to radionuclide release and migration) of the facility.

Baseline aquifer geochemistry at the site has been established. Groundwater samples have been analyzed for pH, E_h, Ca^{2+}, Mg^{2+}, Na^+, K^+, Fe_t (total iron), Cl^-, SO_4^{2-}, HCO_3^-, F^-, NO_3^-, PO_4^{3-}. The pH typically lies between five and six. With increased residence time in the aquifer the groundwater pHs rise to between seven to eight. The E_h values are neutral to slightly oxidizing. The waters are dominated by Ca^{2+} and HCO_3^-; total dissolved solids are, however, low (<200 ppm). The waters are saturated only with respect to quartz and iron oxyhydroxides. Information is being gathered on the background levels of radionuclides in the 233 Lake area.

Extensive data on the long-term behaviour of Sr-90 and Cs-137 in the aquifer of interest are available from studies of the contaminant plume from the NP[16,17]. These and other local studies[18,19] have shown that Cs-137 has been nearly immobile, while most of the Sr-90 is migrating at <5% of groundwater velocity. Both ion exchange and kinetically slow chemisorption by iron oxyhydroxide coatings on the sand grains are involved in retardation of Sr-90.

Nonradioactive components in waste leachate may influence the movement of radionuclides. Local evidence of this is the migration of very low levels of Co-60 from Waste Management Area "C" with little or no sorption by sediments. Experiments are currently under way[20] to test the mobility of radionuclides (initially of Co, Sr and Cs) under field conditions in the presence of leachate from waste forms proposed for the SLB-P1.

Siting Advantages

The SLB-P1 site has many advantages that are common to the CRNL property as a whole, including low population density and low projected population growth in the area, no significant natural resources such as minerals and no anticipated major future economic developments, no known ecological uniqueness concerns, availability of long-term institutional control (being government-owned land), availability of road and rail links and a balanced public perception of nuclear matters. The discussion in the previous sections points to some geotechnical characteristics that contribute to site suitability. These can be summarized as follows:

(1) The site is located in an upland groundwater recharge area of the property free of flooding and ponding concerns.

(2) Sand deposits at the site offer sufficient depth to water table to allow locating the facility within the unsaturated zone.

(3) Site engineering can be implemented at relatively low cost and surface recontouring of the site to enhance topographic stability can be achieved with relative ease.

(4) Because of the areal extent of the sand dune, future expansion at the site is feasible.

(5) Extensive hydrogeologic and geochemical data bases already exist on the site and its environs from previous studies of nearby contaminant plumes. Water table at the site is well mapped and monitored. These available data allow preliminary assessment of the site and are of use in current and future safety analyses.

(6) Hydrogeologic conditions at the site are relatively simple which allow inexpensive and reliable definition and modelling of the groundwater flow system.

Seismic Concerns

It was recognized early in the program that, considering the regional seismicity of the area, long-term stability of the facility under a seismic event must be assessed. A review of the regional seismicity and the concerns related to the SLB-P1 is available elsewhere[21]. The frequency of seismic activity is relatively high in the area, even though the magnitude of earthquakes has historically been ≤4 (Richter) near the CRNL area. The possibility of soil liquefaction in the event of water table rise accompanied by a strong earthquake was identified as an important concern.

To address the soil liquefaction concerns, CRNL requested assistance from the National Research Council of Canada (NRCC). NRCC (Division of Building Research) carried out Cone Penetration Testing (CPT) at the proposed SLB-P1 site using piezo cone probes and cyclic triaxial tests on the sand specimens from the SLB-P1 site in the laboratory. The results indicated that the sand to a depth of about 8.5 m was dry and loose with a relative density between 40 to 50%. The sand below 10.5 m, which is fully saturated, had relative density in the range of 75 to 90%. Between 8.5 m and 10.5 m (the position of water table at the time of CPT in 1984 November), the sand was partially saturated due to capillary rise and the seasonal water table fluctuations. It is also believed to be the transition zone between the aeolian and fluvial sands. Some loose layers were detected in the transition zone and there are some concerns that if fully saturated and if no pore pressure dissipation is considered during the build-up, these layers could liquefy for peak ground acceleration of 0.25*g* or more. As the site would be excavated to about 8 m depth, in accordance with the NRCC suggestions, the density of these layers will be increased by compaction to ensure resistance to liquefaction under anticipated ground motions.

FUTURE PLANS

The proposed schedule for the SLB-P1 facility calls for excavation to begin in 1987. The construction of the facility is likely to be completed in 1989/90. The facility will then be operated for about five years with closure completed shortly thereafter.

In the site characterization program plan, the near-term aim is to fully characterize the sediments and continue collecting hydrogeologic data on the undisturbed site until the start of excavation. To date, physical hydrogeology of the study area has been well defined. An additional 19 boreholes in the area of the SLB-P1 site were drilled in 1985 October and instrumented with multiple piezometers. Further permeameter tests on undisturbed samples are planned to determine K_v values. Borehole dilution techniques are being used to measure profiles of groundwater velocity vs. depth.

Influence of nonradioactive contaminants on radionuclide migration can be very significant. Column tests are currently underway using aquifer sediments under field geochemical conditions to evaluate the influence of leachate from sample SLB-P1 waste forms on the movement of Cs, Sr and Co. The data gathered during Phase 1 are expected to improve the ability to predict contaminant transport from the site and to calibrate models of the flow system.

During Phase 2 of the program, additional boreholes will be drilled immediately adjacent to the SLB-P1 structure and hydrogeologic and geochemical data gathering will continue. Work is also expected to continue on collecting and documenting the data on the tabulated list of factors mentioned earlier.

The collection of the relevant data and the monitoring of the site during Phase 3 are expected to provide a sufficiently large information base on the site area to make decisions as to whether the construction of future standard SLB units should proceed.

CONCLUSION

Although yet unconventional in the planning for shallow disposal of LIL wastes, selecting sites in sand in humid climates can offer several advantages. Open-bottom facility designs above the water table in free-draining sediments also ensure that infiltrating precipitation (through cracks in the cap, for example) will not pond and drench waste for long periods of time and lead to the "bathtub effect". At CRNL, however, there are two other main reasons for selecting sands to host the SLB-P1 facility. Firstly, on the CRNL property, there are no extensive surficial deposits of low permeability sediments. Secondly, most existing LIL waste management facilities are located in sand and over the past 40 years, an extensive base of hydrogeologic and radionuclide migration data has been established. The selected site for SLB-P1 lies between two existing waste management areas and the existing information on the site supplemented with detailed drilling, soil sampling and hydrogeologic testing has allowed confirmation of the site.

SLB-P1, being a prototype facility, is expected to provide the relevant R&D, the short-term operational performance assessment and the methodology for the long-term safety predictions of such facilities at CRNL. The site characterization program accordingly extends through all phases of the facility up to and including the post-closure monitoring period.

REFERENCES

1. D.F. DIXON (Editor), "A Program Plan for Evolution from Storage to Disposal of Radioactive Wastes at CRNL", AECL-7083, Atomic Energy of Canada Limited (1985).

2. N.R. GADD, "Surficial Geology of Waste Disposal Areas - AECL Project, Chalk River, Ontario", Topical Report #6, Geological Survey of Canada (1959).

3. N.R. GADD, "Surficial Geology, Chalk River, Ontario-Québec", Map 1132A, Geological Survey of Canada (1962).

4. D.G. HARDY and D.F. DIXON, "The Transition from Storage to Permanent Disposal of Low- and Intermediate-Level Wastes at the Chalk River Nuclear Laboratories", Proc. Waste Management '85, Tucson, Arizona, March 24-28, 1985, Vol. 2, 35 (1985).

5. J.S. DEVGUN, Atomic Energy of Canada Limited report, in preparation (1986).

6. K.G. RAVEN, "Studies in Fracture Hydrology at Chalk River Nuclear Laboratories: 1977/78/79", TR-113[b], Atomic Energy of Canada Limited (1980).

7. C.C. DAVISON, "Physical Hydrogeologic Measurements in Fractured Crystalline Rock - Summary of 1979 Research Programs at WNRE and CRNL", TR-161, Atomic Energy of Canada Limited (1981).

8. K.G. RAVEN, K.S. NOVAKOWSKI and D.J. BOTTOMLEY, "Hydrogeologic Research at the Chalk River Research Area", Proc. of Sixteenth Information Mtg. of the Nuclear Fuel Waste Management Program, Winnipeg, September 26-27, 1983, TR-218, Atomic Energy of Canada Limited (1984).

9. N.R. CATTO, R.J. PATTERSON and W.A. GORMAN, "The Late Quaternary Geology of the Chalk River Region, Ontario and Québec", Can. J. of Earth Sci., 19, 1218 (1982).

10. R.W.D. KILLEY and J.H. MUNCH, "Geology and Hydrogeology of the Twin Lake Tracer Test Site", AECL-8262, Atomic Energy of Canada Limited (1986).

11. M. BOYKO-DIAKONOW and J. TERASMAE, "Palynology of Holocene Sediments in Perch Lake, Chalk River, Ontario" in Hydrological Studies on a Small Basin on the Canadian Shield (P.J. Barry, ed.), AECL-5041/I, Atomic Energy of Canada Limited (1975).

12. J.F. PICKENS and G.E. GRISAK, "Scale-Dependent Dispersion in a Stratified Granular Aquifer", Water Resources Res., 17(4), 1191 (1981).

13. G.L. MOLTYANER and R.W.D. KILLEY, "Hydrodynamic Dispersion in a 20-Metre Natural Gradient Tracer Test" in Proc. of Fifteenth Information Mtg. of the Nuclear Fuel Waste Management Program, Toronto, April 12-13, 1983, TR-216, Atomic Energy of Canada Limited (1983).

14. G.L. MOLTYANER and C. PANICONI, "Migration of Radionuclides in Porous Media: Analysis of Experimental Data", AECL-8254, Atomic Energy of Canada Limited (1984).

15. D.W. LaFLEUR, J.F. PICKENS and R.W.D. KILLEY, "Hydrogeologic Assessment of the 233 Lake Area: Calibration of a Three-Dimensional Groundwater Model", TR-257, Atomic Energy of Canada Limited (1985).

16. P.J. PARSONS, "Migration from a Disposal of Radioactive Liquid in Sands", Health Phys., 9, 333 (1963).

17. R.W.D. KILLEY, "Long Term Strontium-90 Behaviour in a Sand Aquifer", Proc. of Int. Symp. on Migration in the Terrestrial Environment of Long-Lived Radionuclides from the Nuclear Fuel Cycle, Knoxville, July 27-31, 1981, IAEA-SM-257 (1981).

18. R.E. JACKSON and K.J. INCH, "Hydrogeochemical Processes Affecting the Migration of Radionuclides in a Fluvial Sand Aquifer at the Chalk River Nuclear Laboratories", NHRI Paper No. 7, Scientific Series No. 104, National Hydrology Research Institute, Environment Canada, Ottawa (1980).

19. K.E. LYON and R.J. PATTERSON, "Evidence of Non-Equilibrium Adsorption of Sr-90 from Groundwater", Water Pollution Res. J. Canada, 19(2), 23 (1984).

20. L.P. BUCKLEY, "Waste Packages and Engineered Barriers for the Chalk River Nuclear Laboratories' Disposal Program", AECL-8853, Atomic Energy of Canada Limited (1985).

21. J.S. DEVGUN, "Preliminary Analysis of Seismic Concerns for the Siting of a Shallow Land Burial Facility at CRNL", TR-314, Atomic Energy of Canada Limited (1985).

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[b] Reports in TR series are unpublished reports available from Atomic Energy of Canada Limited, Chalk River, Ontario, K0J 1J0.