Transactions of the 15th International Conference on
Structural Mechanics in Reactor Technology (SMiRT-15)
Seoul, Korea, August 15-20, 1999

Intrusion Resistant Underground Structure (IRUS) Facility for Disposal of Low-Level Radioactive Waste.

Ravi P. Jategaonkar

Atomic Energy of Canada Limited, Canada

ABSTRACT

For the long-term management of low-level radioactive wastes, Atomic Energy of Canada Limited (AECL) has proposed to build a permanent low-level radioactive waste disposal facility called the Intrusion Resistant Underground Structure (IRUS) at Chalk River, Ontario, Canada. IRUS will be a below ground vault consisting of an engineered permeable floor and reinforced concrete structure. The vault structure is required to meet the defined functional requirements for 500 years until the radioactivity in the waste has decayed to acceptable levels.

INTRODUCTION

Low-level radioactive wastes (LLRW) generated from the operations at Chalk River Laboratories (CRL) and from off-site waste generators, such as isotope producers and users (e.g. hospitals, universities) are currently managed at the CRL site by storage in a variety of structures. As part of a waste management strategy to move from storage to disposal, AECL proposes to develop the IRUS facility at CRL. In one of the early papers on this subject, the essential features of the IRUS design were discussed [1]. In this paper, special issues and design considerations which arise due to longevity requirements are discussed in detail.

FUNCTIONAL OBJECTIVES

The IRUS disposal facility is designed to meet the following functional requirements[2]:

(i) minimize contact of water with the waste;
(ii) ensure long-term structural integrity;
(iii) prevent inadvertent intrusion into the waste;
(iv) restrict the loss of radionuclides from the vault; and
(v) minimize the need for long-term maintenance.

IRUS FACILITY

The IRUS facility is to be located at the AECL CRL property, approximately 180 km northwest of Ottawa, Canada (Figure 1). The facility will consist of a near-surface, below-ground, concrete structure placed 1 m above the maximum recorded water table in a large thick sand dune deposit. The geology of the area consists primarily of a granitic gneiss bedrock unit overlain by compacted sandy glacial till, which in turn is overlain by a range of unconsolidated sand, generally ranging from very fine to medium in grain size.

IRUS will be a concrete vault (approximate dimensions 30 m x 20 m x 8 m) that contains waste packages and a sorbing backfill (Figures 2 and 3). The vault will accept about 1900 m^3 of waste packages and an equal volume of backfill. The outer walls are arch-shaped in plan view to resist the external soil pressure by inducing direct compressive stresses in the concrete. During operations the waste emplacement procedures will take place within the weathershield building designed to protect the vault and waste packages from precipitation. After the vault has been filled with waste, it will be covered by a concrete roof and earthen cover (Figure 4).

The vault roof will consist of a 1 m thick reinforced-concrete slab designed to resist infiltration of water as well as to deter inadvertent intruders. This roof slab will be overlaid by a multi-layer earthen cover engineered to limit infiltration down to the roof, and to isolate the roof and vault structure from freeze-thaw cycles. The roof slab will be poured in place on top of the vault walls such that the reinforcing steel continues from the exterior walls into the roof, making the walls and roof one integral structure. To monitor the performance of the stored waste material, an access will be provided in the form of a vertical shaft to an underground monitoring room located adjacent to the IRUS base. The floor of the vault is constructed of two separate layers of sorbing buffer and is intended to allow the vault to be free-draining.

The long service life of IRUS requires particular attention to be paid to the following issues:

a. an external hazard such as a seismic event that could seriously affect the structural integrity of IRUS, and also the overall stability of the IRUS facility; and
b. the durability of concrete over the period of the intended IRUS service life.

These aspects of the project are discussed in the following sections.

SEISMIC DESIGN OF IRUS

Geotechnical Considerations

IRUS will be located in a sand ridge (Figure 5). Slope stability of this ridge during a seismic event is an important consideration. Cyclic loading from an earthquake can cause saturated sandy soil to lose its shear strength and load-bearing capacity. This phenomenon, known as liquefaction, can be followed by subsidence of soil possibly causing a significant ground movement. To investigate the liquefaction potential of the area, a program of Standard Penetration Test (SPT) borings and Dilatometer tests was carried out. This study indicated that the IRUS site is located over essentially very stable sand-textured soils. However, some potential for liquefaction exists in the bottom portion of Zone 3 that lies below the water table; and in the lower loose fine sand which forms a part of Zone 5 near the lake. A study was carried out to determine the probable ground configuration during and subsequent to the postulated seismic events as described in the next section. A number of slip surfaces were considered as possible sources of instability and the stability calculations were made using the GSLOPE computer program to assess the factor of safety against the failure of the slope. A key factor in assessing post liquefaction behavior of a soil mass is the residual strength of the soil involved. The earthquake induced displacement was estimated using the model proposed by Byrne[3].

The assessment indicated that the ground located on the east side of the IRUS facility, between IRUS and Lake 233, would be subject to movement due to a seismic event. For example, an earthquake of peak horizontal acceleration (PHA) 0.30 g would probably result in flattening of the slope from 30 to approximately 20 degrees, due to the possible liquefaction of the lower sand layer. IRUS is located 75 m west of the shoreline and this movement will not affect the stability of IRUS. The ground on the west side of the IRUS facility was found to be stable with PHA of 0.30 g at the centre of gravity of the soil mass. Ground movements due to such an event are expected to be less than 0.7 m laterally and less than 0.20 m vertically. Such movements will have no significant impact on the stability of the site during subsequent seismic events. Since IRUS and the surrounding soil mass will move as a unit, the movement will have a minimal impact on the structural integrity of the concrete structure.

Seismic Analysis of the Structure

A soil-structure interaction study was carried out to determine the structural integrity and stability of IRUS during a seismic event. The design for IRUS is based on the Design Basis earthquake (DBE) having the probability of exceedance 1×10^{-3} per annum (p.a.). The parameters for such an event at CRL are as follows[2]:

At bedrock level Peak Horizontal Acceleration (PHA) = 0.24 g and
Peak Horizontal Velocity (PHV) = 0.130 m/sec.

However, structural consequences of an earthquake that have a probability less than 1×10^{-3} p.a. were investigated as part of the design review process. A site-specific study for Chalk River, Ontario, was done using local seismicity data, and ground motion relations for Eastern North America (ENA) earthquakes[4]. The results were expressed in terms of uniform hazard spectra (UHS) for Chalk River corresponding to various levels of probability 5×10^{-4}, 2×10^{-4}, 1×10^{-4} p.a. for 5% damping.

Two time-histories corresponding to each seismic event (i.e., total four time-histories) were generated as shown below:

Probability	High-frequency event	Low-frequency event
1×10^{-4} p.a.	M6 at distance 12 km	M7 at distance 30 km

Where M denotes the moment magnitude scale used as a logarithmic measure of ground motion.

Soil-structure interaction analysis was carried out using the FLUSH software [5]. The software is based on the finite-element technique incorporating non-linear material properties of soil and simulating transmitting boundary conditions. The results indicate that the maximum acceleration experienced by IRUS (during a seismic event having probability level of 1×10^{-4} p.a.) is of the order of 0.45 g at the roof level and about 0.36 g level at the foundation level with the walls experiencing about 0.28 g acceleration.

The FLUSH analysis also gives the horizontal dynamic soil pressure experienced by IRUS due to the soil-structure interaction (SSI) during the postulated seismic event. These dynamic pressures computed by Flush compare reasonably well with the average dynamic pressures calculated using the Mononobe-Okabe Formula (Coulomb's Theory)[6].

The forces and moments in the IRUS structure were evaluated using the finite-element software, ANSYS [7], in which the seismic loads were applied in a pseudo-static manner.

The inertial loads as indicated above were applied to the concrete wall elements and the dynamic soil pressure. This dynamic soil pressure was conservatively assumed to be in the form of an inverted triangle. The assessment indicates that the structural integrity of IRUS will be maintained.

DURABILITY

Crack Control

Ingress of water into the vault from outside will be influenced by the extent of cracking and crack width in the vault roof and walls. This in turn will also affect durability of concrete. Therefore, special crack control measures will be taken, including construction pouring sequence, and incorporation of construction joints, isolation joints and expansion joints. Crack width calculations formed part of the design process, to ensure that the crack widths in the structure will remain less than the maximum acceptable value of 0.33 mm.

The crack width due to drying shrinkage was estimated as 0.03 mm at the end of 5 years, with very little increase after that period; and the crack width due to sustained load was computed using the following formula which forms the basis for crack control parameters given by CSA Standard A23.3[8]:

$$W = 11 f_s (d_c/A)^{1/3} (h_2/h_1) \times 10^{-6} \qquad (1)$$

where : W = Crack width at tensile face (mm)
f_s = Calculated stress in reinforcement (MPa)
h_2 = overall depth of member (mm)
h_1 = distance from extreme compression fibres to centroid of tension reinforcement (mm)
d_c = distance from centroid of tension reinforcement to the extreme tension fibre of concrete (mm)
A = Effective tension area of concrete surrounding the reinforcement bar (mm^2)

ACI Manual of concrete practice [9] provides a state-of the-art report on cracks in concrete structures and discusses in detail crack width and increase in crack width over a long term. Based on this report, a crack width factor of 2 was applied for sustained loading condition, and a factor of 1 was applied for seismic and thermal loading conditions. Using these factors, the maximum total long term crack width under the worst combination of loading including seismic loading was estimated to be 0.29 mm in the roof slab, 0.24 mm in the external wall and 0.38 mm in the footings.

Concrete Durability

As part of the IRUS licensing support effort, in 1987 AECL initiated a research program on concrete durability. The objective of the program was to develop a method for designing a concrete mix that would have a long service life. The experimental work in this program was performed by the National Research Council (NRC) under contract to AECL. Durability and qualities of a wide variety of concrete types were evaluated under a range of environmental exposure conditions [10].

The "service life" of a concrete structure is defined by the failure criterion adopted. After examining various processes which might affect IRUS concrete, the time to failure of IRUS concrete was defined as the time taken for chloride ions to diffuse through the 75 mm of concrete that will cover the reinforcing steel. Chloride was chosen as a marker for ionic ingress because it is a mobile, nonsorbing species and is a major cause of reinforcing steel rods corrosion. A value of 0.3% chloride was used to determine the position of the reaction front (i.e., penetration depth). This criterion is conservative since it assumes that the chemical conditions are conducive to the chemical reaction involved (e.g., attack by chloride requires the presence of greater than threshold quantities of moisture and oxygen).

In view of the above considerations, the main focus of the NRC experimental work was diffusion studies designed to set a lower bound on the time required for corrosion of reinforcing steel, the process that is expected to limit the lifetime of IRUS structural concrete elements. Measurements were also made on other degradation mechanisms (e.g., carbonation, sulphate attack, and freeze-thaw cycling). The recommended concrete mix consists of blended cements with 75 % slag. This mix yielded the lowest diffusivity, about 25 times lower than the equivalent mix obtained with ordinary (Type 10) Portland cement.

UNIQUE ASPECTS OF THE CONSTRUCTION

Trial Batching for Concrete Mix

A trial batching program will be carried out prior to the start of concrete construction. The aim of this program will be to ensure that the contractor can produce concrete of desired quality consistently in the field using a large batch plant. The stringent quality control procedures will be in place during the trial batching and also during production. The field concrete samples will be tested by the NRC or an independent testing agency to ensure that the concrete produced meets the defined durability specifications and requirements.

External Backfill

The facility is designed to minimize the contact between the infiltrating water and the concrete structure. The earthen cover that will be placed over the roof during the repository closure phase of IRUS will be an engineered earthen cover, highly permeable to divert the infiltrating water away from the concrete structure (Figure 4). The external backfill that will surround the IRUS will also be of free-draining type, well-graded material that will prevent any accumulation of water outside the concrete structure. Special care and quality control will be exercised during backfill placement to retain the necessary free-draining quality over the required long period of time. Furthermore, any undue movement of the structure during construction caused by an imbalance of the lateral soil pressure will be avoided. The construction procedure will require that the backfill is placed evenly to ensure that the maximum difference in soil height on opposite sides of the IRUS vault will not exceed 1.0 m.

Construction Plan

The sequence of major construction activities is shown in the form of flowchart in Figure 6. The construction of IRUS shall be carried out in accordance with CSA Standard N286.3 [11]. This compliance will ensure that the IRUS facility, when completed and turned over for operation, shall meet specified technical and safety requirements, and operational objectives. The IRUS Construction Plan is under preparation. This document provides the strategic plan and associated processes, including the quality assurance level requirements needed for the construction of the IRUS facility. A detailed construction flowchart will be included in the construction plan document.

The project organization for the construction of IRUS shall include the project Quality Control (QC) team and a Project Quality Assurance (QA) manager. The QA manager shall be responsible for monitoring the implementation and effectiveness of the IRUS Project QA

Plan. The project construction QC team will be responsible for verifying and demonstrating the compliance of the quality of field construction with the specifications.

ACKNOWLDGEMENT

Geotechnical investigations including the slope stability and ground movement assessment were done by J. Hayes, Site Investigation Services Ltd., Peterborough, Ontario, Canada. The site- specific study to determine seismic parameters corresponding to low probabilities was carried out by G. M. Atkinson, Ottawa, Ontario, Canada. The seismic analysis of IRUS and crack width calculations were implemented as part of the overall design review by R. Dawson, D. Curtis and I . Shaw of ACRES International Ltd., Niagara falls, Ontario, Canada. This work was initiated and managed under separate contracts with AECL. The author would like to thank these individuals and organizations for their assistance.

REFERENCES

1. Mok, J.S., Shah, P.J. and Philipose, K.E., "Concrete Facility for Long-term Disposal of Low Level Radioactive Waste," *Supplement to the Transactions of the Eleventh International Conference on Structural Mechanics in Reactor Technology*, Vol. SD1-15/4, pp 29-42, Tokyo, Japan, August 1991.
2. G. M. Dolinar, et al, "Preliminary Safety Analysis Report (PSAR) for the Intrusion Resistant Underground Structure (IRUS)", *AECL-MISC-295 (Rev.4)*, October 1996.
3. Byrne, P.M., "A Model for Predicting Liquefaction Induced Displacements," *Soil Mechanics Series # 147,* Department of Civil Engineering, University of British Columbia, Canada, 1990.
4. Atkinson, G. and Boore D., "Ground Motion Relations for Eastern North America,"*Bulletin of Seismological Society of America*, Vol. 85, pp 17-30, 1995.
5. Lysmer, J. et al, "FLUSH-A Computer Program for Approximate 3-D Analysis of Soil-Structure Interaction Problems," *Report No. EERC 75-30*, University of California, Berkeley, CA, USA, 1979.
6. ASCE, "Structural Analysis and Design of Nuclear Plant Facilities," *American Society of Civil Engineers, Manual # 58*, pp. 444-453, 1980.
7. ANSYS Linear Plus - version 5.3, Swanson Analysis Systems, Inc., Houston, Pennsylvania, USA, 1996.
8. CSA/CAN3-A23.3-M90, "Code for Design of Concrete Structures for Buildings," Canadian Standards Association, Toronto, Canada, 1990.
9. ACI Committee 224.1R-93, "Causes, Evaluation of Cracks in Concrete Structures," *ACI Manual of Concrete Practice: Part 3,* American Concrete Institute, Detroit, Mi., USA, 1996.
10. Tumidajski, P. J. 1995. "Critical Examination of Concrete for Nuclear Waste Repositories," *National Research Council of Canada Report No.A-2406.1*, Ottawa, June 1995 .
11. CSA/CAN3 - N286.3-83. "Construction Quality Assurance Program for Nuclear Power Plants," Canadian Standards Association, Toronto, Canada, 1983.

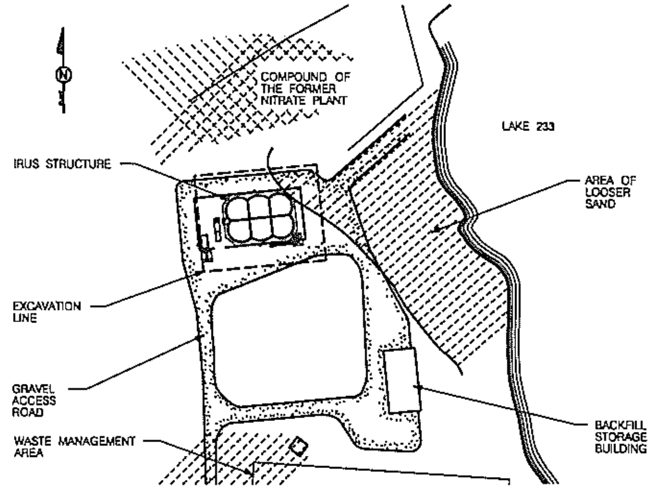

FIG. 1 LAYOUT OF IRUS SITE

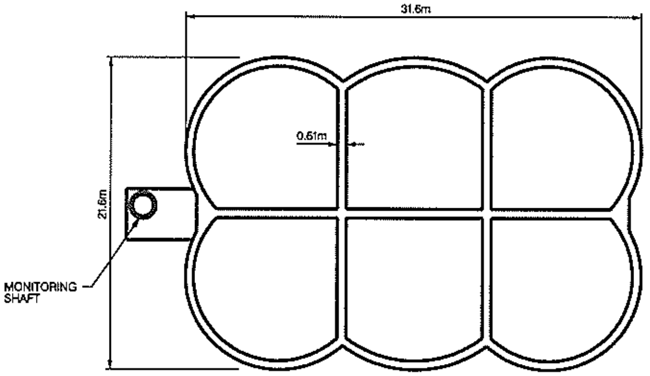

FIG. 2 IRUS STRUCTURE - PLAN

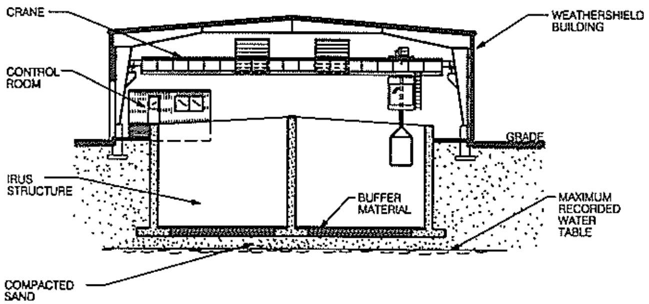

FIG. 3 OPERATION STAGE

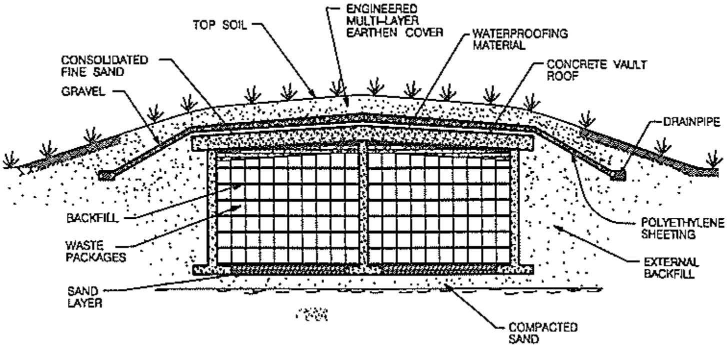

FIG. 4 POSTCLOSURE STAGE – IRUS FACILITY

MATERIAL	SOIL ZONE	UNIT WT kN/m3	C kPa	PHI DEG	PIEZO. SURF.	RU
FILL	1	19.2	0	40	0	0
FINE SAND COMP.	2	18.9	0	40	0	0
FINE SAND LOOSE	3	18.8	0	32	1	0
FINE SAND/SILT	4	19.2	0	37	1	0
FINE SAND	5	16.8	0	33	1	0
SAND TILL	6	FIRM STRATA				

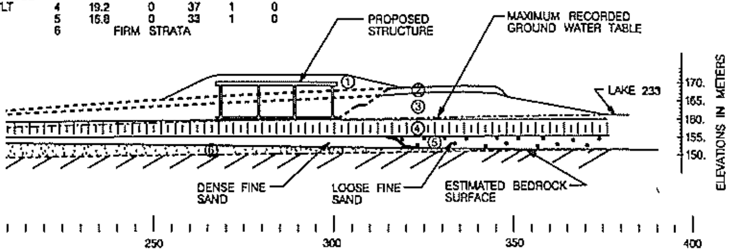

FIG. 5 GEOTECHNICAL DATA – IRUS SITE

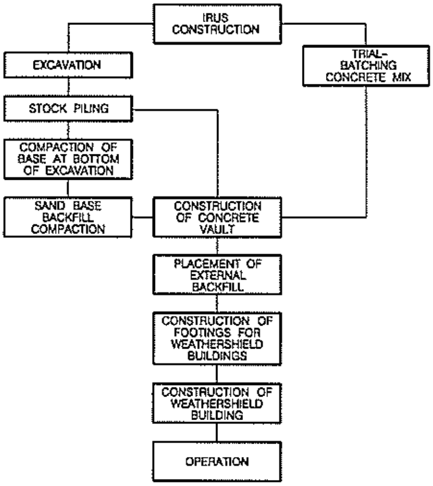

FIG. 6 IRUS CONSTRUCTION FLOW CHART