SAFETY ASSESSMENT FOR A DOUBLE-BARRIER IN-GROUND CONTAINER FOR WASTE STORAGE

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ABSTRACT

The worst credible accident scenario was identified as ground water contacting the stored waste through a failure of an in-ground container, leaching radioactivity from the waste, travelling down to the lower aquifer, and reaching a well.

The maximum dose to a member of the critical group, who lives on a farm that derives its potable and irrigation water from a public well at about 2 km from the storage site, is approximately 7.9×10^{-4} Sv/a. The maximum dose to a local worker who drinks water on the job from a well within the property boundary, located about 700 m from the storage site, is approximately 2.9×10^{-4} Sv/a. The likelihood of such an accident is shown to be very small.

INTRODUCTION

Many designs of storage facilities are being used for storage of radioactive wastes on various North American sites. Earlier designs, used at Ontario Hydro's Radioactive Waste Operations Site 2, had been concrete or concrete and steel cylinders built on pads in an excavation.

Double-barrier in-ground containers are the latest storage structures designed for the storage of medium level, solid, radioactive waste. The principles and designs employed are simple, and provide a multiple barrier-detection system between the radioactive wastes and the environment. These containers are an improvement over the existing in-ground designs because they eliminate the need for a subsurface drainage system, and the massive excavation and backfilling operations.

A design accident analysis evaluates the safety of using the in-ground containers for radioactive waste storage. This paper describes the worst credible accident scenario and the results of the safety assessment for the in-ground containers.

LOCATION OF ONTARIO HYDRO'S REACTOR WASTE MANAGEMENT FACILITIES

The Radioactive Waste Operations Site 2 (Site 2) has been constructed to provide storage for radioactive wastes at the Bruce Nuclear Power Development (BNPD) which is located on the shore of Lake Huron approximately 250 km northwest of Toronto (Figure 1).

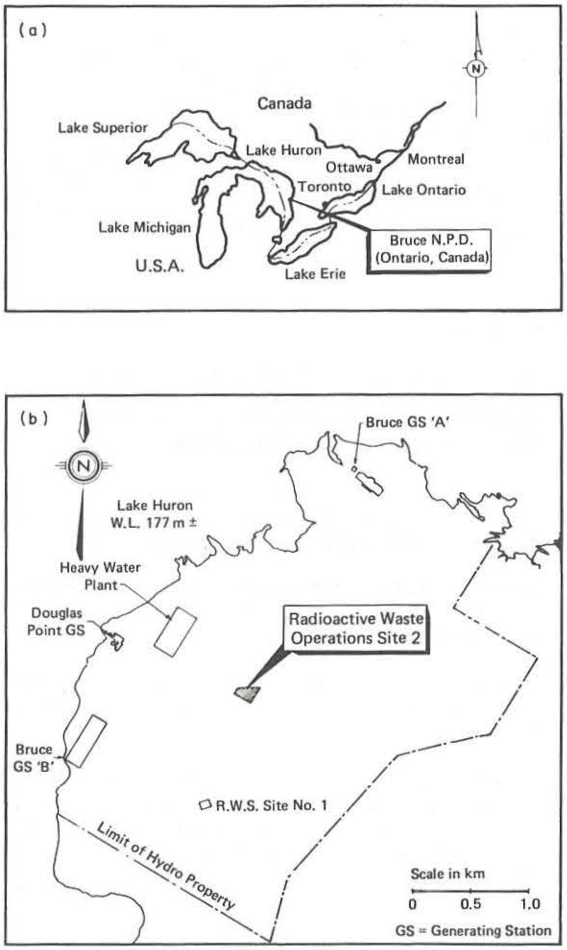
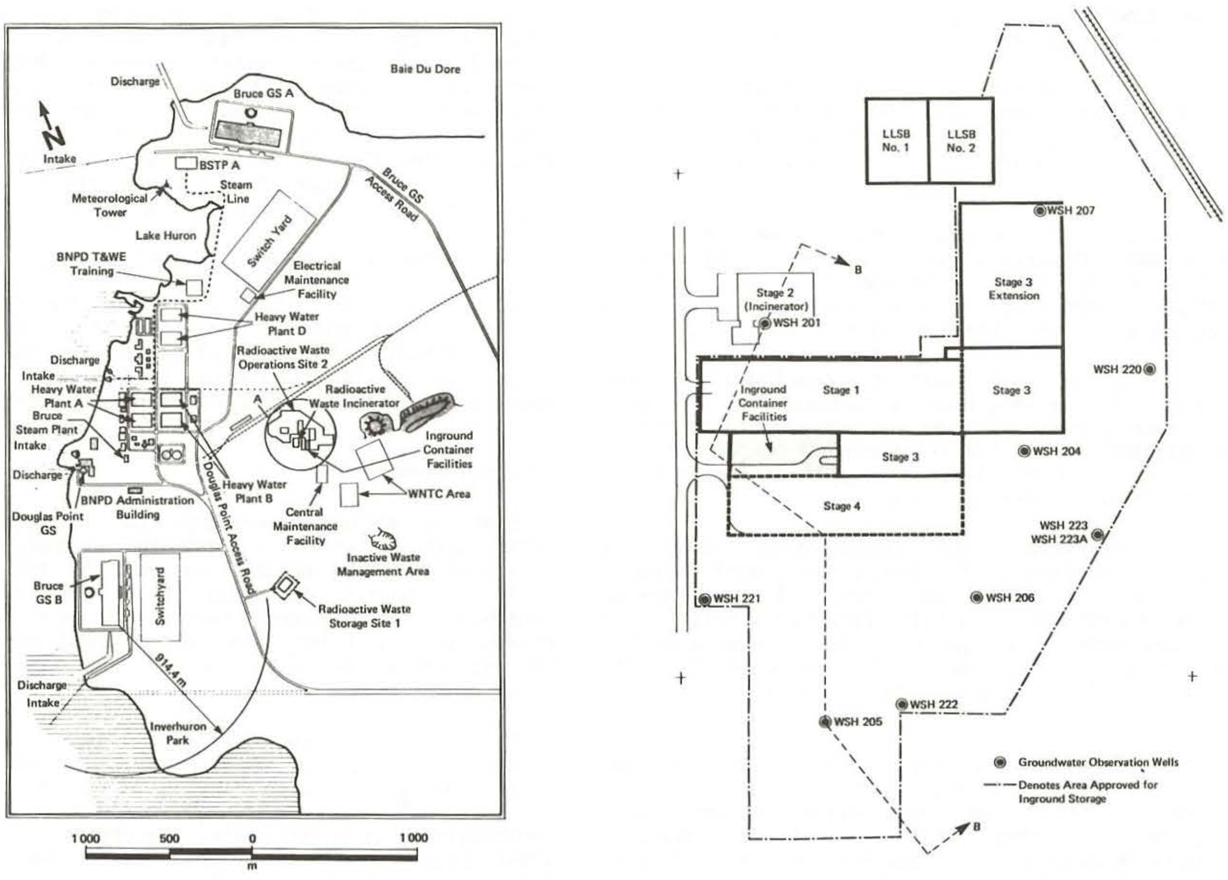


FIGURE 1
LOCATION OF ONTARIO HYDRO'S REACTOR WASTE MANAGEMENT FACILITIES

Site 2 occupies about 7.7 ha of land and is partially developed. At present, the storage facilities at Site 2 include in-ground, steel containers, concrete trenches and tileholes; and above-ground, concrete quadricells and low level storage buildings. The in-ground containers facility is located within Site 2 adjacent to the existing Stage 3 facilities and east of Stage 1 (Figure 2).



(A) BNPD SITE LAYOUT

(B) A-RADIOACTIVE WASTE OPERATIONS SITE 2

FIGURE 2
BNPD SITE LAYOUT AND LOCATION OF IN-GROUND
CONTAINERS FACILITY

BRIEF DESCRIPTION OF THE DESIGN AND CONSTRUCTION OF AN IN-GROUND CONTAINER

The in-ground container is constructed of two concentric, 0.95 cm (3/8 in) thick steel pipes with a welded steel bottom and bolted steel lid. Each container is 61 cm (24 in) in diameter and about 7.6 m (25 ft) deep. Nominal storage capacity is 2 m^3 of radioactive waste (Figure 3).

The outer pipe has a welded, gasketted flange which prevents surface water ingress. The bolted cover plate has a leaktight pipe plug assembly connected to a sampling pipe. This sampling pipe is attached to the exterior of the inner pipe and is used for periodic sampling of the interspace.

The pipes are placed in a cylindrical hole constructed by vertical augering of the soil. The annular space between the augered hole and outer pipe is backfilled with concrete, when levelling of the structure is complete.

A drained asphalt surface allows for runoff of surface water away from the facility. A paraplastic sealant, applied to the joints between the container and the asphalt course, prevents seepage. These measures minimize the likelihood of surface water becoming a pathway for radioactivity in the waste reaching man.

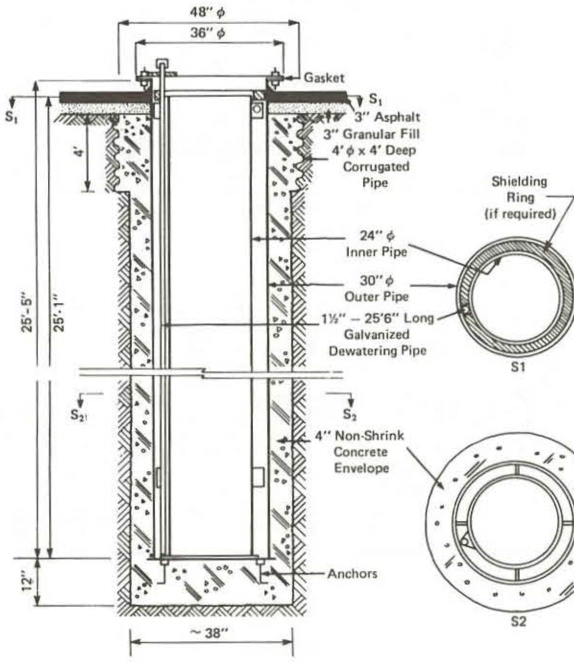


FIGURE 3:
A SKETCH OF AN IN-GROUND CONTAINER

HYDROGEOLOGICAL CONDITIONS IN THE VICINITY OF IN-GROUND CONTAINERS FACILITY

Quaternary deposits, in the vicinity of the in-ground containers facility (Figure 4) may be divided into three units: surficial sand and gravel unit, a silty glacial till unit and a basal sand and gravel unit.

Overlying the Quaternary deposits may be varying thicknesses of fill material placed during various phases of the Site 2 development. Underlying the Quaternary deposits is fractured carbonate rock, more permeable than the glacial till material.

The glacial till unit is continuous in the vicinity of the in-ground containers facility, with occasional pockets of sand and gravel interbedded in the glacial till. The thickness of glacial till in this area is 12 to 14 m. The upper 2 to 5 m of the glacial till deposit is brown.

The weathered till (unsaturated zone) is generally as deep as 5 m below the ground surface. Weathering process has produced wide-spaced fracturing of the brown till, observed a metre or so into the unweathered glacial till (saturated zone). The ground water flow in the unweathered till, however, is not influenced by fracturing at greater depths.

The water table at the proposed site for the in-ground containers facility is 1 to 2 m below ground. However, the construction of the nearby in-ground facilities and the associated subsurface drainage systems may have lowered the water table in parts of the proposed site (Figure 4).

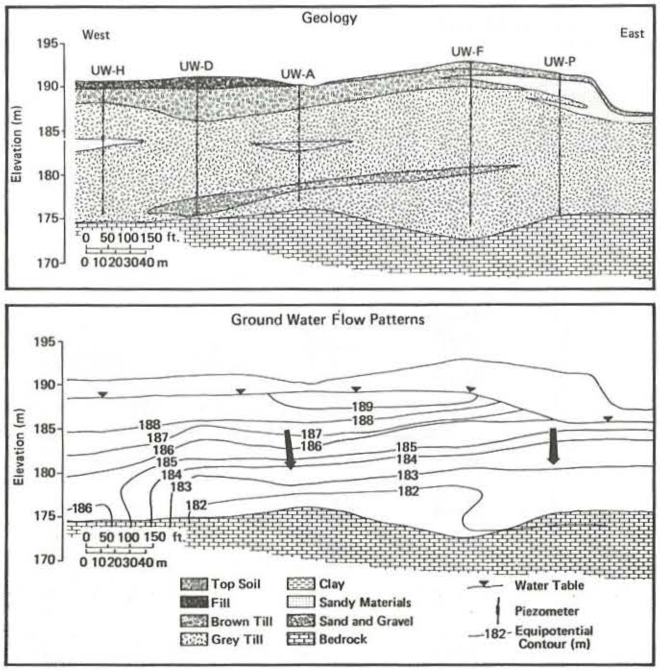


FIGURE 4
WATER-TABLE POSITION AND DISTRIBUTION OF HYDRAULIC HEAD IN THE VICINITY OF THE IN-GROUND CONTAINERS FACILITY (SECTION B-B OF FIGURE 2)

The three-dimensional distribution of hydraulic head in the glacial till indicates that the direction of ground water movement through the unweathered glacial till is downward toward the fractured bedrock (Figure 4). The vertically downward hydraulic gradients is 0.75. The weathered zone of the glacial till deposit may have a more active ground water flow system than does the underlying unweathered glacial till.

The hydraulic conductivity and porosity for the unweathered glacial till are 5×10^{-10} m/s and 0.19, and for the bedrock aquifer are 1.10×10^{-5} m/s and 0.35, respectively. Using the Darcy Equation, the estimated ground water velocities in the unweathered glacial till and the bedrock aquifer are 6 cm/a and 40 cm/a respectively.

ACCIDENT SCENARIO

Risk of radiation exposure to the public can exist only if water contacts the wastes, leaches radioactivity, and reaches the public. The process includes ingress of water into the structure, contamination of ground water by contacting the stored wastes, leakage of contaminated water from the structure and migration of the contaminated water to the public.

The worst credible accident scenario has been identified as ground water contacting the stored waste through a failure of the two containment barriers of the in-ground container, leaching radioactivity from the waste, travelling down to the lower aquifer, and reaching a well. No response from the structure monitoring program or from the BNPD perimeter monitoring system is assumed for a period of one year.

Case 1 - Hypothetical Public Well

A hypothetical public well is assumed to be located at the nearest publicly accessible location which is at or near the north or northeast property boundary. The well is therefore located about 2 km from the storage site.

Case 2 - Well Within Property Boundary

A well located within the property boundary, nearest to the storage site, is about 700 m in the northern direction.

ACTIVITY ESTIMATION

(A) Assumptions

(1) The in-ground container is loaded with moderator ion exchange resin.

(2) The ground water is in continuous contact with the stored waste which becomes saturated rapidly and radioactivity is leached at a constant rate.

(3) The leach rates for the radionuclides are assumed to remain constant at 1 percent per year.

(4) Activity is assumed to be released from a failed in-ground container for one (1) year only because remedial action is assumed to prevent further release.

(B) Activity Content

The major radionuclides in the stored wastes are tritium, carbon-14 and gross beta-gamma activity. Tritium and carbon-14 are the most mobile of these radionuclides in ground water. The gross beta-gamma activity, primarily Cobalt-60, Strontium-90 and Cesium-137, are less mobile in ground water because of their retardation factors but have a much higher specific radio-toxicity. Other radionuclides including Chromium-51, Cobalt-58, Zinc-65, Zirconium-95, Niobium-95, Ruthenium-106, Cesium-134 and Cerium-144 are contributors to the radioactivity. They are not significant, however, for consideration in long-term storage because of their short half-lives, or in short-term storage because of their long migration times through the geomedia.

With the aforementioned assumptions and the estimated specific activities of radionuclides for moderator resin, the estimation of the activity content of an in-ground container can be summarized as follows:

Radionuclides	Half-Life (yrs)	Estimated Activity (with no decay)	
		Bq	Ci
H-3	12.3	1.20E+12	32.5
C-14	5730.0	5.00E+12	135.0
Co-60	5.3	9.25E+10	2.5
Sr-90	28.9	2.35E+07	6.35E-4
Cs-137	30.2	1.67E+08	4.50E-3

ASSUMPTIONS FOR GROUND WATER MIGRATION OF RADIONUCLIDES

(1) The water table is within a meter or two from the ground surface, so the till surrounding the in-ground containers will be saturated.

(2) The radioactivity leached from the wastes is assumed to originate from a point source in the till.

(3) Ground water travels vertically downward in the glacial till to the aquifer on the limestone bedrock and then flows horizontally with the aquifer.

(4) The radionuclides H-3 and C-14 are assumed to travel through the subsurface environment at a speed equal to that of the ground water.

(5) Other Radionuclides such as Co-60, Sr-90, and Cs-137 are assumed to have retarded velocities with the distribution coefficients of 50, 4.3 and 950 respectively, because of chemical interactions with the clays and other soils in the geomedia.

ANALYSIS METHOD

(A) Introduction

In the design accident analysis, the migration of radionuclides leached from radioactive wastes in an in-ground container to a well down-gradient from the storage site has been simulated, using the computer model Subsurface Transport (SST) and PATHWAY-II(1). This model was originally developed by Dames and Moore(2), then subsequently modified and expanded by the Technology for Energy Corporation(3) and finally rewritten to simplify the calculations and incorporate the ICRP26(4) methodology for calculating the dose to man from exposure to radionuclides in the environment.

The following sections briefly outline the principle equations and concepts used in the radioactivity transport model. The exposure scenario and the pathway analysis for the two cases are described.

(B) Outline of the Principal Equations Used in the Transport Model

(1) Source Term

$$Jo = RATIO * Tc * Lr * Co \quad (Bq/a)$$

where RATIO = rate of water leaving an in-ground container to rate of water entering an in-ground container

Tc = contact leachate time fraction (day/a)

Lr = fraction of radioactivity leached per day (day^{-1})

Co = initial radionuclide inventory (Bq)

(2) Source Depletion Time

$$T = (1/h) \ln (1 + h * Co/Jo)$$

where h = radionuclide decay constant (a^{-1})

Co = initial radionuclide activity (Bq)

Jo = source term (Bq/a)

(3) The Dispersion-Advection Equation

As the leached radioactivity travels in the subsurface environment, its concentration in ground water is reduced by both diffusion and mechanical dispersion (due to microscopic variations with the ground water velocity and path length). The dispersion-advection equation which governs the radionuclide concentration at various points in the ground water is given by:

$$\frac{D}{R}\frac{d^2C}{dS^2} + \frac{D_t}{R}\frac{d^2C}{dS_t^2} - \frac{V}{R}\frac{dC}{dS} - hC = \frac{dC}{dt}$$

where C = radionuclide concentration in ground water (Bq/m^3)

D = longitudinal dispersion coefficient (m^2/a)

D_t = transverse dispersion coefficient (m^2/a)

V = ground water velocity (m/a)

S = distance along ground water flowline (m)

S_t = distance transverse to ground water flowline (m)

h = radionuclide decay constant (a^{-1})

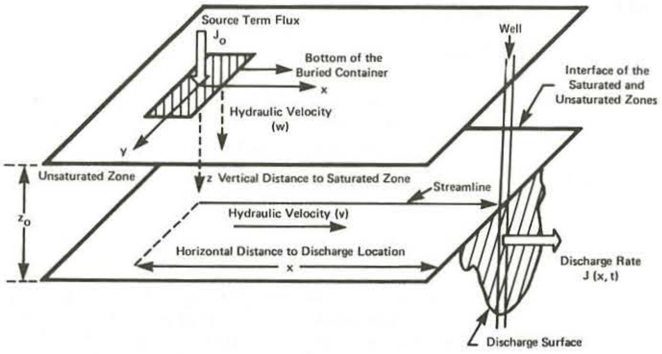
R = Retardation factor for a given radionuclide

$$= 1 + \frac{Pb}{n} * Kd$$

where Pb = bulk density of the media (g/ml)
n = porosity of the media
Kd = radionuclide distribution coefficient (ml/g)

The solution of the dispersion-advection equation, given the initial and boundary conditions of the failed in-ground container scenario and hydrogeologic variables at the storage site, yields the ground water radionuclide concentration down-gradient from the site.

The geometry of the mass transport problem is illustrated in the following:



GEOMETRY OF THE MASS TRANSPORT PROBLEM
(TAKEN FROM REFERENCE 1)

(4) Dose Rate Calculation

(a) Exposure Scenario for Public

A hypothetical critical group is assumed to live on a farm that derives all of its potable and irrigation water from a well located directly along the flow of the contaminated aquifer. Well water is used for drinking, irrigation of vegetables and watering of livestock. The well is assumed to be located at about 2 km from the storage site and has a depth of 15 m and a pumping rate of 5 m^3/day.

Pathway Analysis

The radiological pathway analysis in the SST model is based on the methodology of Wong(5) and others(6-17). A generalized pathway analysis diagram is shown in Figure 5a.

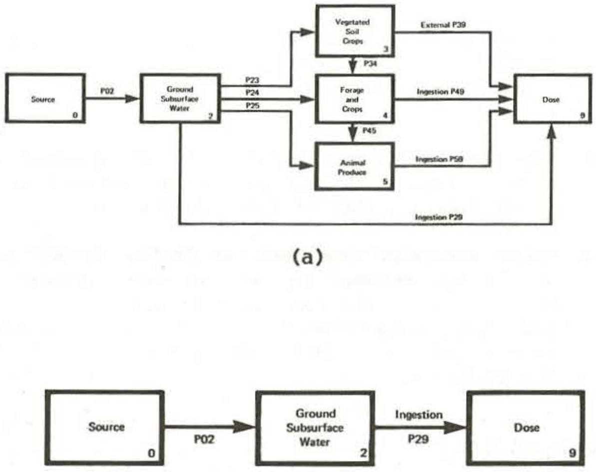
The dose rate from water ingestion, vegetable consumption and animal produce consumption can be written as:

Dose (water) = C * P29I (Sv/a)

Dose (veg) = C * (P24 + P23 * P34) * VC * P49 (Sv/a)

Dose (animal) = C * P25 * PC * P59 (Sv/a)

Where C = radionuclide concentration in well water ($Bq.L^{-1}$)
P29I = water ingestion dose conversion factor ($Sv.a^{-1}.Bq^{-1}.L$)
VC = vegetable consumption rate (kg/a^{-1})
P23 = water to soil transfer parameter ($L.m^{-2}$)
P24 = water to vegetation transfer parameter ($L.kg^{-1}$)
P34 = soil to vegetation transfer parameter ($m^2.kg^{-1}$)
P49 = ingestion does conversion factor ($Sv.Bq^{-1}$)
PC = produce consumption rate ($kg.a^{-1}$)
P25 = water to animal produce transfer parameter ($L.kg^{-1}$)
P59 = ingestion dose conversion factor ($Sv.Bq^{-1}$)



(a)

(b)

FIGURE 5
ENVIRONMENTAL TRANSFER MODEL

(b) Exposure Scenario for Workers

There are a number of wells located within the property boundary. The nearest well is located about 700 m north of the storage site. In the analysis, a worker is assumed to drink water on the job from this well, which is directly along the flow of the aquifer. The well is assumed to have a depth of 15 m and a pumping rate of 5 m^3/day.

Pathway Analysis

As in (a), the radiological pathway has been analyzed by using the SST model. A generalized pathway analysis diagram is shown in Figure 5b. The dose rate from water ingestion can be written as:

Dose (water) = C * P29I (Sv/a)

where C = radionuclide concentration in well water ($Bq.L^{-1}$)

P29I = water ingestion dose conversion factor ($Sv.a^{-1}.Bq^{-1}.L$)

RESULTS

ACTIVITY MIGRATION TIME

The time required for ground water to travel vertically in the glacial till from the in-ground container down to the lower aquifer (bedrock) piezometric surface is approximately 72 years. The time required for ground water to travel horizontally in the lower aquifer from the storage site to a hypothetical public well located at about 2 km away and to a well, located at about 700 m, within the property boundary would be approximately 52 years and 18 years, respectively.

The minimum time for the radionuclides to migrate down to the lower aquifer and travel to the nearest well (700 m away) from a failed in-ground container is estimated to be about a century. The low velocities result in long travel times allowing significant radioactive decay of the radionuclides during travel. C-14, which has a long half-life of 5730 years, is the predominant radionuclide contributing to potential radiation dose.

Case 1 - Hypothetical Public Well

The committed effective dose equivalent to an adult via the three aforementioned pathways for a failed in-ground container was approximately 7.9×10^{-4} Sv/a (79 mrem/a). This dose would be expected to occur approximately 120 years after the in-ground container failed and would be the maximum dose to a member of the critical group. The critical radionuclide is C-14 and the critical pathway is well water ingestion. The period of exposure would depend upon the spread of the contaminant in the ground water and how quickly the release was detected.

Case 2 - Well Within Property Boundary

The maximum dose that a local worker would receive by drinking water on the job from the nearest well, under the above accident scenario, was approximately 2.9×10^{-4} Sv/a (29 mrem/a) from a failed in-ground container. This dose would be expected to occur approximately 90 years after the in-ground container failed and would be the maximum dose to the local worker. The critical radionuclide is C-14 and the period of exposure would depend upon the spread of the contaminant in the ground water and how quickly the release was detected.

DISCUSSION

In practice, a routine quarterly monitoring program to check for the presence of water during the storage phase is instituted by Operations. Should an in-ground container fail, the maximum period that a leak could remain undetected is three months.

If the only remedial action taken after detection was the removal of the failed container, the maximum dosage that an adult in the public and a local worker would receive via the aforementioned pathways are 2.0×10^{-4} Sv (20 mrem) and 7.0×10^{-5} Sv (7 mrem), respectively. These doses are small and are equivalent to about one-tenth of the dose that one would receive annually from the natural background.

If the contaminated soil surrounding the failed container was also removed after detection, no radioactivity would reach any of the wells. Hence, there would be no radiation hazard to the public or to local workers.

CONCLUSION

There are many conservative assumptions used in the analysis, including a high leach rate for radioactivity and continuing activity releases without remedial action. In addition, a number of failures must occur before a leak from a failed structure remains undetected. These failures are:

1. A failure of the two barriers of the in-ground container structure,
2. A failure of the structure sampling system, and
3. A failure of the site perimeter well monitoring system.

Ingress of ground water due to failure of a double-barrier in-ground container structure is unlikely. It would be improbable that the interspace between the inner and outer pipes would "flood" during the storage period and persist for more than, say, a few weeks until corrective action was undertaken. The probability of this "pooled" subsurface water penetrating the inner steel pipe and contacting the encased wastes, leaching significant quantities of radioactivity, and escaping undetected into the surrounding till during a short time period is very low. The likelihood of this sequence of events going undetected by the interspace monitoring program, and the Site 2 monitoring wells, is even lower.

A routine monitoring program to check for the presence of water during the storage phase is instituted by Operations. Water, if detected, would be removed via the sampling pipe located in each in-ground container. Further actions would also be carried out to investigate the source of water.

Given the many conservative assumptions used in the analysis and the very low probability of an undetected leak resulting from a number of failures, it is concluded that the risk (product of all probabilities of failure time consequences) due to the long-term use of the in-ground containers is extremely low.

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