8.5 POSTCLOSURE ASSESSMENT AS A DESIGN TOOL FOR WASTE DISPOSAL SYSTEMS


Introduction

AECL Research and Ontario Hydro share the responsibility to evaluate the feasibility and safety of the concept for the disposal of Canada's nuclear fuel waste. The concept involves deep underground disposal in crystalline rock on the Canadian Shield (CNFWMP 1978, 1981). AECL Research is currently preparing an Environmental Impact Statement (EIS) for review by a federal Environmental Assessment Review Panel.

The EIS is supported by several detailed technical documents known as primary references. One of these primary references is the postclosure assessment (Goodwin et al. 1994) which describes the long-term performance and behaviour of the disposal system. The time frame of concern for the postclosure assessment starts when all shafts, tunnels and boreholes have been sealed and the facility closed, and extends more than 10,000 years into the future. Over this time scale, an evaluation of the performance of a disposal system cannot be based on actual observations. Instead we must use scientific arguments, including simulations with mathematical models, to infer the long-term behaviour of the disposal system and to estimate its potential effects.

In this paper, we present an example of how simulations performed for the postclosure assessment could influence the design and layout of the engineered system with respect to the structural features of its host rock formation.

Characteristics of the Reference Disposal System

The main features of the concept for disposal of Canada's nuclear fuel waste involve the placement of nuclear fuel waste in protective containers, and the burial of these containers in a disposal vault at a depth of 500 to 1000 metres in crystalline rock of the Canadian Shield. For the postclosure assessment, we have evaluated a hypothetical implementation of the concept. This implementation, called the "reference disposal system", contains a number of specific choices for the design of the engineered system, the characteristics of the exposed human population and the location of the vault within the host rock. For example, we assume that:

- the nuclear fuel waste consists of used fuel bundles (irradiated UO₂ fuel and Zircaloy sheaths) from CANDU™ nuclear generating stations (Johnson et al. 1994);

- the containers are relatively long and narrow and constructed of thin-wall titanium (with glass beads providing internal mechanical support) (Johnson et al. 1994);

- the containers are emplaced in boreholes in the floor of rooms of the vault (Johnson et al. 1994);
the vault is located in a granite pluton at a nominal depth of 500 metres (Davison et al. 1994); and

- the individuals exposed to the greatest risk (called the critical group) spend all their lives in the vicinity of the site of the disposal vault and they obtain all their food, water, fuel and building materials from local sources (Davis et al. 1993).

Another important category of assumptions bears on the site characteristics of the reference disposal system. Many hundreds of plutons in the Canadian Shield region are potentially suitable sites, with a wide range of possible characteristics. For the postclosure assessment, we assume that the site characteristics correspond to the characteristics of the Whiteshell Research Area (WRA) near AECL's Whiteshell Laboratories in Manitoba. The WRA has been intensively studied for more than a decade so that a consistent set of physical, chemical and geological data is available.

Some site-specific characteristics of the reference disposal system that are important to the postclosure assessment are the following (Davison et al. 1994):

- A relatively small volume of rock would be contaminated by the radionuclides and chemically toxic elements that escape from the disposal vault. The simulations of the geosphere in the postclosure assessment involve five layers of rock, from the lower rock zone surrounding the disposal vault to layers of overburden and sediment at the surface. In general, the bounds of the contaminant plume from the disposal vault is limited to a depth of about 500 m and to an areal extent about 1 km by 2 km on the surface above the disposal vault.

- The rock contains a number of fracture zones and discrete fractures. The simulations of the geosphere assume the presence of several low-dipping fracture zones which extend from the surface to a depth of 1 km, and several vertical fractures which extend downwards to 4 km.

- These fractures and fracture zones tend to be highly permeable and, together with the topography, control the direction and volume of groundwater movement in the geosphere and the vicinity of the vault. Based on detailed studies of groundwater flow in the WRA, we assume groundwaters that have flowed through the vault reach the surface environment at four discharge zones: three to topographical lows and the fourth to a well.

Figure 1 shows an important feature simulated in the geosphere model. We assumed one of the fracture zones, called LD1 (for Low Dipping fracture zone 1), passes through the plane of the reference disposal vault. In addition, we assumed LD1 is connected at depth to a vertical fracture (not shown in Figure 1) and the hydrological conditions allow for rapid groundwater movement towards the surface. (These assumptions were based on information available in 1985; current observations at the WRA (Davison et al. 1994) show that LD1 does not, in fact, extend to the depth of the hypothetical vault.) The overall tendency of groundwater movement is downward to LD1 on the right hand side of the figure, and upward along LD1.
to the surface on the left hand side. There is no significant groundwater movement in the rock below LD1, so that contaminant transport in this region is dominated by diffusion. In the rock above LD1, and in LD1 itself, contaminant transport occurs by diffusion and advection.

Fracture zones are thought to be common features on the Canadian Shield, and we included the presence of nearby fracture zone LD1 so that we could examine its influence on the long-term performance. A key parameter for the reference disposal system, called the waste exclusion distance, represents the length of low-permeability sparsely fractured rock that isolates the containers in those vault rooms nearest to fracture zone LD1. Since LD1 dips at a shallow angle of about 18°, the shortest distance between LD1 and any container is given by the perpendicular shown in Figure 1.

Development of a Design Constraint

The waste exclusion distance can be regarded as a design parameter which, in an actual implementation, could be realized through an observational engineering approach. We used preliminary studies of the reference disposal system to study how its value affects estimated impacts. These studies indicated that a waste exclusion distance of about 50 metres would provide a wide margin of safety with respect to long-term impacts. This distance is also called a "design constraint" because it is an imposed restriction on the layout of the disposal system that derives from consideration of long-term performance and geotechnical feasibility, and not directly from a prescribed regulatory criteria.

We considered several different options in the vault layout to achieve different waste exclusion distances. Larger distances could be achieved by moving the vault further away from LD1, by changing the vault dimensions to a rectangular arrangement so that rooms on the sides next to LD1 are relocated to the sides away from LD1, and by eliminating all or parts of some vault rooms nearest LD1. For the study of the reference disposal system, we chose the first option because it makes the best use of information available from the geological studies (Davison et al. 1994). In addition, however, we chose to eliminate those vault rooms above LD1 where groundwater flows downward towards LD1. The elimination of these rooms leads to slightly smaller inventory of nuclear fuel waste than that originally specified.

Estimated annual doses are strongly dependent on the magnitude of the waste exclusion distance. Figure 2 summarizes some sensitivity analyses that illustrate this dependence. The five curves in Figure 2a show estimated annual doses attributed to $^{129}$I for five different waste exclusion distances; Figure 2b shows doses due to $^{14}$C. The horizontal lines at $5 \times 10^{-5}$ Sv/a and $3 \times 10^{-3}$ Sv/a show, respectively, the annual dose associated with the AECB radiological risk criterion (AECB 1987) and a typical annual dose due to natural background.

Our analysis shows that a larger waste exclusion distance within the low-permeability sparsely fracture rock leads to much smaller estimated annual doses, primarily because of the larger transport time of contaminants. Transport in this rock is dominated by diffusion, and diffusive transport times vary (approximately) as the square of the transport distance. The
results in Figure 2 indicate that longer waste exclusion distances delay
the arrival of contaminants and lead to smaller maxima in estimated annual
doses, and that the differences are more pronounced at earlier times.

As shown in Figure 2b, estimated doses from $^{14}$C are more strongly affected
than doses from $^{129}$I. The difference occurs because of radioactive decay:
the half-life of $^{14}$C is $5.7 \times 10^3$ a compared with $1.6 \times 10^7$ a for $^{129}$I.
Since $^{129}$I is the major contributor to dose estimates, the curves in Figure
2a also represent the dependence of total dose (from all radionuclides) on
the waste exclusion distance.

We also examined vault configurations where there are vault rooms on both
sides of LD1 for various waste exclusion distances. These latter
configurations produced estimated doses that were several orders of
magnitude larger than the corresponding cases with no vault rooms above
LD1. For example, the estimated annual dose is six orders of magnitude
larger at $10^4$ a, and two orders of magnitude at $10^5$ a, for a waste
exclusion distance of 50 m (Goodwin et al. 1994). Removing vault rooms
above LD1 corresponds to decreasing the dimensions of the vault and the
total inventory of contaminants because of the way in which we have chosen
to change the vault layout. In general, however, the inventory change is
less than 15% while the estimated doses change by orders of magnitude.
Thus inventory differences are relatively unimportant. The large increases
in estimated dose that occur when there are vault rooms above LD1 arise
because:

- Groundwater flow velocities above LD1 are more than ten times
  faster than flow velocities below LD1, leading to much faster
  transport of contaminants.

- More importantly, groundwater flow velocities above LD1 are
directed downwards, so that contaminants leaving the buffer from
rooms above LD1 would pass directly into the rock, without passing
through any part of the backfill (see Figure 1). Our analysis
indicates the backfill is an important barrier for $^{129}$I, and is
effective in delaying and attenuating releases of $^{129}$I to the
surrounding rock.

From our scoping calculations, we concluded that a waste exclusion distance
of about 50 m and the absence of vault rooms above fracture zone LD1 would
provide a large safety factor. Using this design constraint, the vault for
the reference disposal system is approximately 1700 m by 1900 m. Assuming
the same number of containers per vault room as in the conceptual vault
design (Simmons and Baumgartner 1994), the inventory for the reference
disposal system is then reduced from about 191 000 to 162 000 Mg U. The
postclosure assessment case study pertains to this reference disposal
system.

It must be noted that the constraint described here is very dependent on
the particular geological conditions specified for the reference disposal
system. Thus the constraint should not be interpreted as having general
applicability. On the other hand, the analysis and specification of the
constraint demonstrate how the postclosure assessment can be used to
influence the details of the design of a disposal system, and to ensure
that the facility design results in estimated risks that are as low as
reasonably achievable. In an actual implementation, social and economic factors would also be taken into account.

The analysis and specification of the design constraint also illustrate that the vault design process should be flexible. The process should allow for modifications that may arise to accommodate new information that becomes known as the implementation proceeds. For the duration of the project, an iterative procedure of model calibration, evaluation and prediction would be followed to take into account new information on the subsurface geology and hydrogeology, and to provide increased confidence in model predictions.

**Other Studies from the Postclosure Assessment**

The postclosure assessment (Goodwin et al. 1994) includes sensitivity analyses to examine other design constraints and to evaluate their potential to improve the safety performance of the reference disposal system. Examples include the use of more durable container materials and thicker layers of buffer and backfill.

Studies like these are based on information that would be available during the early stages of implementation of the concept. They would contribute to a decision on whether to proceed with more detailed study at a candidate disposal site.

The value of the postclosure assessment extends beyond these early stages, and in fact the postclosure assessment would be an integral part of all stages of implementation of a disposal facility: siting, construction, operation, extended monitoring, decommissioning and closure. Each of these stages would include a decision point on whether work should proceed to the next stage, and a series of postclosure assessments would provide information for the decision makers. In addition, postclosure assessments would be used in refining the facility design to help:

- improve long-term performance through modifications to the vault orientation and layout (as described above for the waste exclusion distance);
- examine the effects of different vault geometries, including the in-room and borehole options for container emplacement;
- optimize the cost-benefit ratio, achieved from studies of the relationships between cost and performance of different engineered options;
- choose an option for extended monitoring that would not compromise long-term performance; and
- evaluate the effects of changes in regulatory policies and practices.
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References


FIGURE 1: Illustration of the Waste Exclusion Distance

- Vault
- Fracture Zone LD1
- Vault Rooms Above LD1
- Groundwater Flow
- Waste Exclusion Distance

FIGURE 2: Dose-Time Curves for Different Waste Exclusion Distances