Discussion of an Option for Geological Storage of Used Nuclear Fuel Beneath the Williston Basin of Southern Saskatchewan

Brian Brunskill [1]

Brunskill, B. (2006): Discussion of an option for geological storage of used nuclear fuel beneath the Williston Basin of southern Saskatchewan; *in* Summary of Investigations 2006, Volume 1, Saskatchewan Geological Survey, Sask. Industry Resources, Misc. Rep. 2006-4.1, CD-ROM, Paper A-4, 8p.

Abstract

Canada may eventually develop a geological storage site for used nuclear fuel somewhere in the Precambrian Shield. The use of traditional mining methods is currently envisioned for developing rooms at depths in the range of 500 to 1000 m, where long-lived containers housing the used fuel bundles would be placed. Engineered barriers would be designed to retard the rate of contamination into the host rock resulting from any material failure. The stored fuel bundles would be retrievable for some period, then possibly abandoned.

This document suggests that, with proper siting, natural barriers intrinsic to the geological system would provide the greatest degree of isolation and containment in response to the inevitable failure of engineered barriers. If a repository were developed in the Precambrian Shield beneath the Williston Basin in southern Saskatchewan, appropriate hydrogeological characteristics of the basin would likely provide the ultimate safety barriers. Various geological and geomechanical features of the repository site and the significant thickness of the overlying strata (>2.4 km) would provide suitable confinement from the biosphere for a period far longer than the radioactive material is likely to be hazardous, and hydrogeological barriers within the geological container would mitigate contamination due to failure of engineered barriers. The brines currently occupying the basal aquifer above the Precambrian basement are ancient and, in the event of contamination of the storage site, this brine 'slug' could prevent the vertical migration of any contaminated material.

The development of very deep repositories beneath the Williston Basin can be achieved using rotary drilling equipment currently employed in the petroleum industry. Numerous horizontal holes could be drilled to provide storage space for used nuclear fuel bundles.

The concepts presented here require further research. Additional investigation may support the consideration of establishing a used nuclear-fuel repository demonstration site in the Precambrian basement of southern Saskatchewan.

Keywords: *used nuclear fuel, geological storage, natural barriers, contamination, hydrogeology, deep horizontally drilled repository, Precambrian basement, Williston Basin.*

1. Introduction

The concept of using geological repositories to store used nuclear fuel is under investigation in several countries. For example, in Sweden and Finland, research into storage site development in Precambrian rocks is being conducted and, in the USA, repository development in volcanic rocks at Yucca Mountain is being investigated (McCombie, 2003). In Canada, the Nuclear Waste Management Organization (NWMO) has been recently established to conduct research, consult Canadians, and make recommendations to the federal government regarding the long-term management of Canada's used nuclear fuel (NWMO, 2005).

The NWMO findings suggest that it may be appropriate for Canada to develop, within the next 60 or more years, a geological repository somewhere in the crystalline rocks of the Precambrian Shield. Proposed storage facilities would employ traditional mining designs with the development of vertical shafts and storage rooms at a depth in the range of 500 to 1000 m (Figure 1). The stored material would remain accessible for some time and then, if desired, permanently abandoned. In this model, significant emphasis is placed on the reliability of the engineered barriers, which would serve to retard the rate that radioactive material may enter and contaminate the geosphere, and possibly the biosphere. Repository location within unfractured or minimally fractured rocks would also provide

[1] Helix Geological Consultants Ltd., 3634 - 28th Avenue, Regina, SK S4S 2N6; E-mail: brianbrunskill@sasktel.net.

natural barriers in the event of container failure. The proposed storage containers themselves are designed for a 100,000-year life in a water-saturated, anaerobic environment.

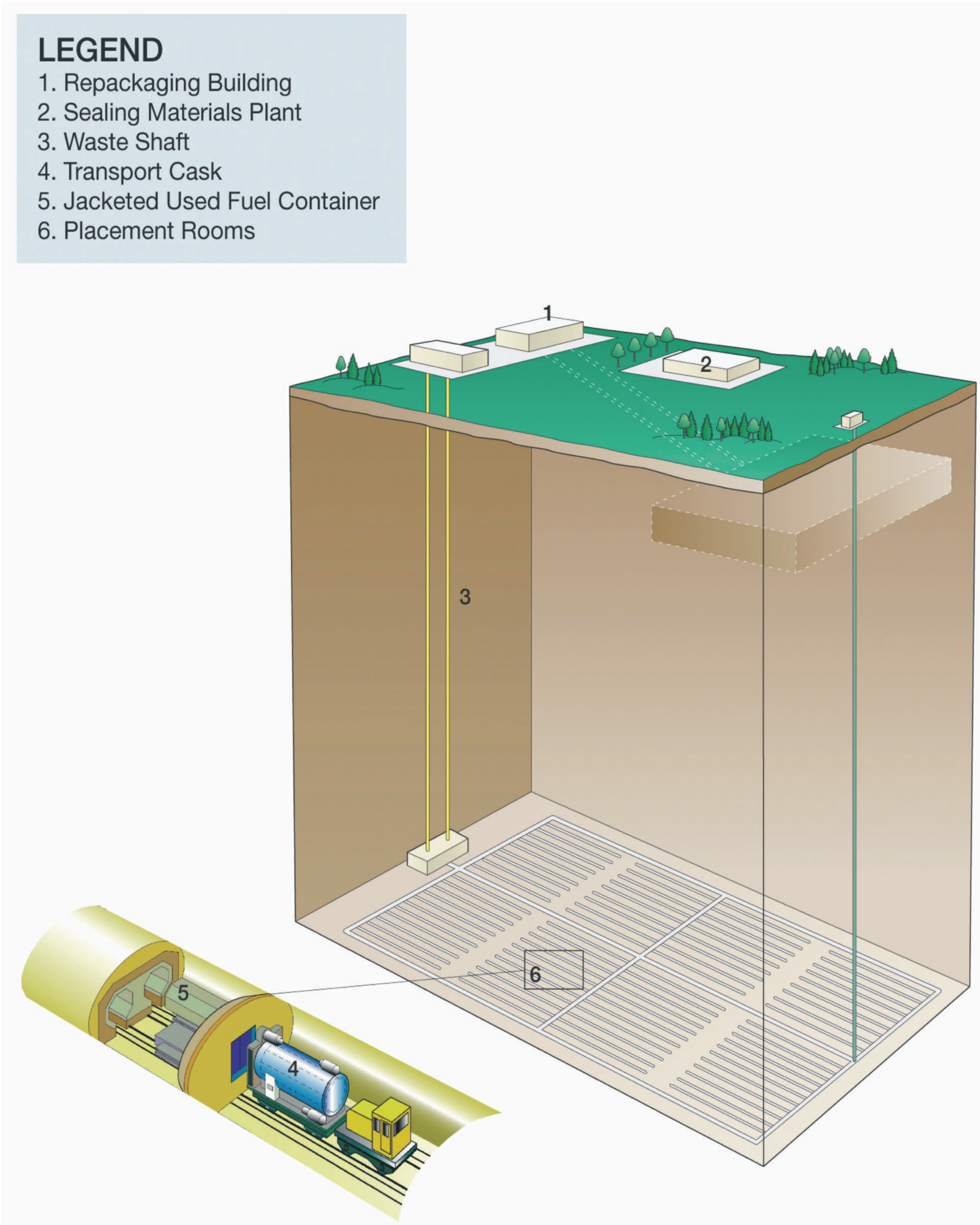

Figure 1 - Conceptual geological repository prepared by the NWMO (2005, p144) (reproduced courtesy of the NWMO).

This discussion paper explores the suitability of developing alternative used nuclear fuel repositories in crystalline Precambrian rocks underlying a thick sedimentary sequence, specifically the Williston Basin, in southern Saskatchewan. Natural systems are emphasized as they ensure permanent isolation and containment of any nuclear material that may escape.

Clearly, the geomechanical stability of the immediate host rock must be suitable for repository development in any environment. The regional geological system, involving thousands of cubic kilometres must, however, also be suitable in order to provide the conditions necessary for ultimate safety. Development of a very deep repository beneath the Williston Basin (>2400 m below surface) would require the utilization of surface-drilling methods and technologies currently used in the petroleum industry.

2. Background

Used nuclear fuel will remain hazardous for hundreds of thousands of years (Hedin, 1997, as cited in McCombie, 2003). The geological container must maintain its integrity through seismic activity and future tectonic/geophysical events that may affect the soundness of the storage site. An earthquake or faulting could compromise or rupture the engineered barriers, potentially resulting in contamination of the geosphere. Although unlikely in the tectonically quiescent Williston Basin, if seismic activity does occur during this time, the geological system must be known to be reliable.

a) Engineered and Natural Barriers

Technical issues integral to the location of a used nuclear-fuel repository include, most importantly, safety and security to humans and the environment. Multiple safety barriers, designed to impede the spread of possible contamination, comprise both engineered and natural barriers. However, the reliability of geological (natural) *versus* engineered barriers for extended periods of time is significant.

It can be assumed that virtually all engineered barriers will eventually fail, possibly within thousands of years, and ensuing contamination of the geosphere could well occur. Similarly, geological barriers may fail, particularly due to tectonic events. The latter risk is, however, relatively small and can be estimated on a geological time scale.

Engineered barriers will retard the rate of contamination over the life span of the barrier materials used. The NWMO (2005) has proposed that used nuclear fuel bundles be packaged in corrosion-resistant containers which would be placed in the excavated rooms. Swelling clay-based materials would be used to backfill and protect the containers and to limit groundwater movement around the containers. In Canada, there will be about 3.6 million bundles to store if all the current reactors complete their life cycle (NWMO, 2005). Given the large volume of material to store, the potential for premature failure of engineered barriers, particularly of some individual storage containers, is significant. To offset this likelihood, great confidence must rest on the integrity of the geological container.

Natural barriers can and will serve to restrict the movement of groundwater that has been contaminated by nuclear leakage. Rock characteristics such as fracture porosity and permeability, the hydrochemistry of ambient fluids and regional hydrogeological characteristics will influence groundwater mobility.

b) Geology of the Precambrian Basement of Southern Saskatchewan and Development of the Williston Basin

The southern two-thirds of Saskatchewan are covered by sediments ranging in age from Cambrian to Recent. The contact at surface between this sedimentary section and the outcropping Precambrian Shield to the north extends roughly northwest-ward from the Saskatchewan-Manitoba border, about 20 km south of Flin Flon, passing close to La Ronge in north-central Saskatchewan. Information provided in this section is taken from work prepared by Kreis *et al*. (2000).

The Precambrian unconformity under this wedge of Phanerozoic strata dips to the southwest over much of southern Saskatchewan. In the southeastern part of the province, it dips more steeply southward into the present day Williston Basin (Figure 2).

Tectonic features described in the exposed Precambrian have been extrapolated southward beneath the sedimentary cover using aeromagnetic and gravity data, which, along with drilling information, have also been used to interpret the sub-Phanerozoic geology. The basement is widely understood to be composed mostly of meta-igneous and meta-sedimentary rocks.

Figure 2 - Location of the Williston Basin.

The Phanerozoic rocks present in southern Saskatchewan are part of the Western Canada Sedimentary Basin. At various times during the Phanerozoic, the Precambrian basement of southeastern Saskatchewan actively subsided, influencing the geometry and sedimentation patterns of the Williston Basin. In the deepest part of the Saskatchewan portion of the basin, south of Estevan near the Canada-USA border, the sedimentary section is about 3.5 km thick.

c) Hydrogeology of the Deeper Williston Basin

Within a succession of sedimentary rocks, strata can be classified into hydrogeological units as aquifers, aquitards or aquicludes, depending primarily upon their permeability. The lowermost or basal aquifer system in the Williston Basin occurs in the Lower Paleozoic rocks that rest directly upon the rocks of the Precambrian basement (Benn and Rostron, 1998; Whittaker *et al.*, 2004). The system is considered to be open because it is exposed at surface in both recharge and discharge areas (Bachu and Hitchon, 1996). Prominent uplifts such as the Black Hills, Bighorn Mountains, and the eastern slopes of the Rocky Mountains provide areas of fresh-water recharge, whereas discharge areas occur to the east and northeast near the Precambrian edge in Manitoba, Saskatchewan, and North Dakota (Downey *et al*., 1987).

Fluid flow is driven primarily by change in basin-scale topography and variations in stratigraphy, lithology, rock permeability, and fluid hydrochemistry in the aquifers (Bachu and Hitchon, 1996). Figure 3 illustrates in cross section, the basin-scale flow of formation waters in the Williston Basin.

Bachu and Hitchon (1996) report that, in southern Saskatchewan, potentiometric surfaces of the basal aquifer system indicate flow trends from basin centre northeast-ward toward the Precambrian Shield outcrop. Hydraulic head values range from nearly 900 m in the deeper part of the basin to 250 m at the shield edge. As well, in the deeper part of the basin, heavy brines with up to 335 000 mg/l total dissolved solids occupy the aquifers, whereas, near the shield edge, these values drop below 50 000 mg/l. The high density (high total dissolved solids) brines appear to have formed a relatively stagnant ‘slug’ in the deep parts of the basin (Benn and Rostron, 1998). Due to density differences, heavy brines in aquifers underlying the sub-Mesozoic unconformity on the northern flank of the basin locally exhibit density-driven flow downdip toward deeper parts of the basin (Whittaker *et al*., 2004).

The brines currently occupying the basal aquifer are ancient, almost certainly being several hundred million years old. If there is a major tectonic event with accompanying significant disruption, it is likely that the stagnant or downward-flow potential of the brines would ensure that contamination due to container failure would remain in the very deep geosphere.

3. Development of Storage Repositories Using Surface Drilling Rigs

In the oil industry, drilling rigs operate surface-based rotary drilling tools to access target strata at great depth. Both directionally and horizontally drilled well bores are created with a very high degree of safety, accuracy, and repeatability and with minimal disturbance to the surrounding geological media. This technology could be used to construct used-fuel repositories.

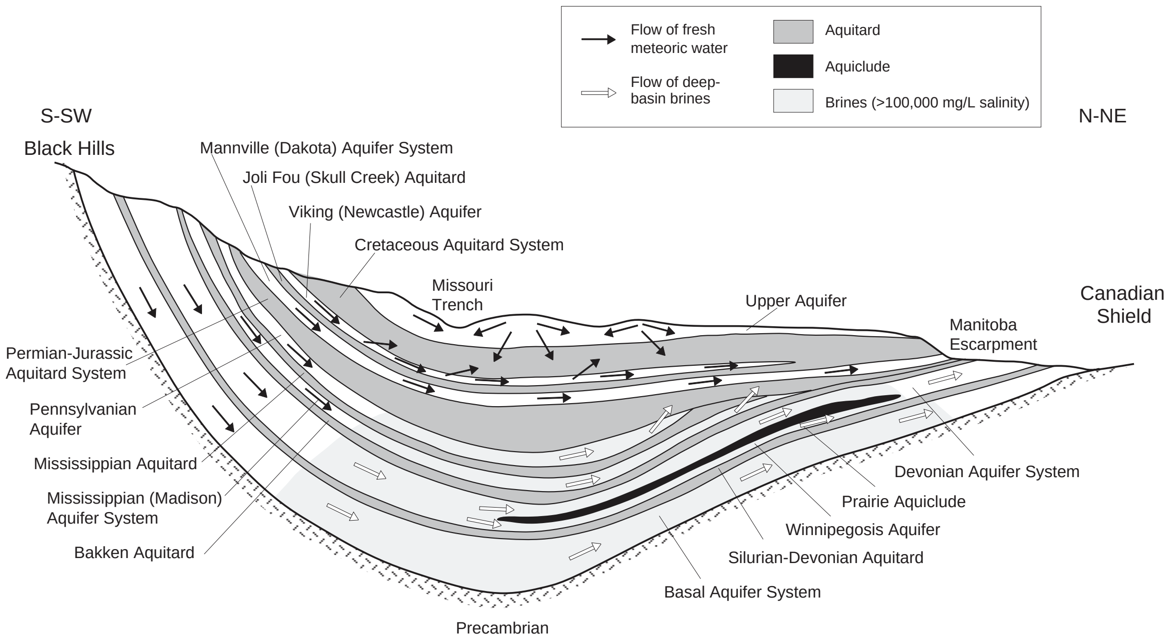

Figure 3 - Diagrammatic cross sectional representation of the northeast-ward basin-scale flow of formation waters in the Williston Basin (from Bachu and Hitchon, 1996; AAPG©[1996] reprinted by permission of the AAPG whose permission is required for further use).

In the southernmost 100 km of Saskatchewan, much of the Precambrian surface is covered by at least 2.4 km of Phanerozoic sedimentary rocks. A hole could be drilled vertically from surface through this sedimentary section into the Precambrian basement and then drilled horizontally for 2 km or more.

The repositories could be developed in the form of numerous, long horizontal holes. The horizontal model is important because it allows for the development of several repositories from a single surface location and the weight of the fuel bundle containers would be supported in the hole. Observation wells could be drilled to monitor groundwater flow for potential contamination.

Each horizontal hole would be lined with metal casing that is cemented in place. The nuclear fuel bundles would be placed in pipe-shaped containers which would then be positioned in the horizontal holes. The wet environment of the repository would be in pressure equilibrium, and in the absence of air, corrosion of materials would likely be limited and minimal.

This design provides for retrievability of the stored bundles for hundreds of years, as long as the integrity of the materials used remains sound. Encasement materials would be monitored and if failure of the casing or bundle containers was anticipated, the containers could be transferred to a new repository. As well as being retrievable, it is important to note that the stored nuclear fuel would also be in an abandonment position if future decision-makers decide to permanently abandon the material.

The NWMO estimates that there will be about 3.6 million fuel bundles produced from Canadian nuclear-energy sources. Assuming that each bundle is approximately 0.5 m in length, if they were stacked end to end they would form a row about 1.8 million metres or 1800 km long. Allowing for additional material necessary for container construction, up to 2000 km of horizontal section would be required to store all the anticipated used nuclear fuel.

a) Single-Leg Horizontal Repository

To illustrate a horizontal repository, the following provides a hypothetical, highly simplistic design based upon the current capabilities of rotary drilling rigs. Many other scenarios could be considered and materials used would be chosen to maximize safety, security, and containment. The diameter of the horizontal holes drilled will determine the size of the containers and the thickness of buffer material encapsulating the fuel bundles. Figure 4 is an illustration of a horizontally drilled repository.

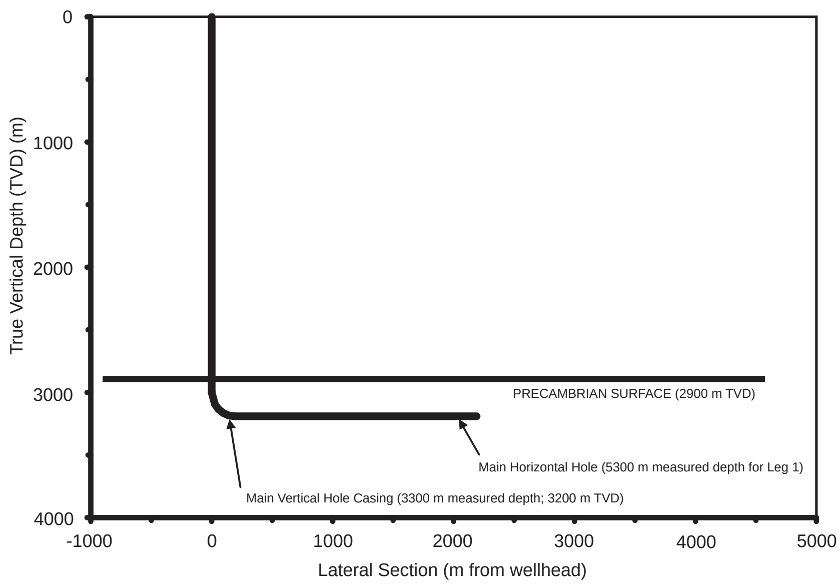

Figure 4 - Sectional view of a horizontal repository constructed by rotary drilling.

For this example, surface casing would first be placed to isolate all potable water-bearing rock formations, to a depth of about 300 m. Assuming the Precambrian surface occurs at a depth of 2900 m, the main hole would be drilled vertically through the sedimentary cover to 3000 m, *i.e.*, 100 m into the basement. Directional drilling tools would be used to drill a gentle curved section to 90 degrees (the "heel") with a measured depth (MD) of 3300 m and true vertical depth (TVD) of 3200 m. The main casing would be cemented in place from the bottom of this hole to the surface.

The horizontal hole would then be drilled laterally 2000 m to the MD of 5300 m. A smaller diameter casing would be cemented in place from the end of this hole to the surface. Once the horizontal section has been drilled, and before the casing is cemented in place, there is an opportunity to inject a suitable grouting compound into any fractures that may transect the hole, thereby potentially reducing fracture permeability.

This horizontal section would be roughly 300 m below the Precambrian surface and provide 2000 m of storage capacity. The tubular containers housing the fuel bundles would be placed in the horizontal section.

Using 2005 petroleum-industry rates, an estimate to drill and case a single, 2000 m horizontal repository would be $4 million and take from 50 to 70 days to complete. It would require about 1000 such repositories to store 2 million metres of material at an estimated cost of $4 billion.

The 2000 m repository design is conservative. Current drilling technologies are quite capable of drilling very deep and very long horizontal holes. For example, British Petroleum has directionally drilled oil wells at the Wytch Farm Oil Field in Dorset, UK with greater than 6.5 km horizontal displacement (British Petroleum, 2006). If each horizontal repository section were 5000 m long then, about 400 repositories would be required. At an estimated cost of $5 million to drill and case each of these repositories, the total cost would be reduced to about $2 billion.

Drilling pads are commonly used to concentrate surface operations. For example, at the Occidental Petroleum–operated Wilmington Oil Field located offshore from Long Beach, California, drilling rigs that are permanently mounted on tracks have directionally drilled over 1200 wells from four small islands totalling 42 acres in size (Occidental Petroleum Corporation, 2006).

A single drilling pad on surface could be used to develop several individual repositories, minimizing the surface area required. Several horizontal planes could be "stacked" one above the other, and other configurations may achieve larger storage capacities. Given the magnitude of this endeavour, economies of scale would reduce costs significantly.

b) Multiple-Leg Horizontal Repository

The multiple-leg repository builds upon the single-leg design by drilling several parallel legs from the main horizontal hole. The resulting plan view of the repository would have a herringbone shape.

There are several technical obstacles to solve using a multi-leg design. When an additional leg (a "side-track") is drilled from the sidewall of the existing hole, the intersection that is formed can create problems for both the casing materials used and the ability of directional tools to re-enter the preferred leg. These technical challenges require further investigation. Figure 5 illustrates the shape of an eleven-leg, herringbone-shaped repository.

In this example, additional legs are 200 m apart and are each drilled to 5300 m MD. Larger diameter drilling tools than those used in the single-leg repository would be required for this design. Once the main horizontal hole is

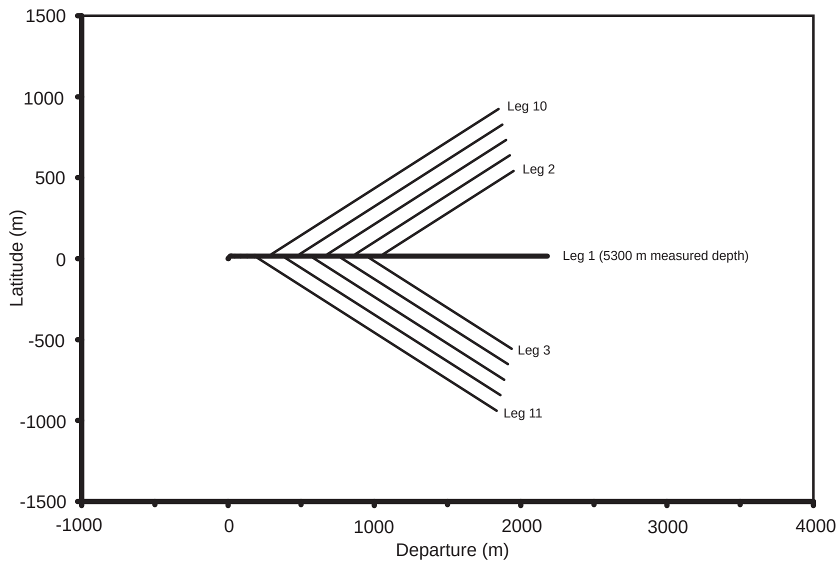

Figure 5 - Plan view of an 11-leg repository.

drilled (Leg 1), the casing would be cemented in place from the end of the hole to surface. At prescribed intervals, this casing would have "windows" milled where the additional legs would be side-tracked. Tubular containers housing the fuel bundles would be placed in the deepest 1000 m of the main hole from 4300 to 5300 m MD.

The directional drilling tools would then be used to mill a hole through the window in the sidewall of the main horizontal casing at 4200 m MD and Leg 2 would be drilled. The casing would be cemented in this new hole and fuel bundle containers would be placed in the casing. This process would be repeated where additional legs would alternate right then left from the main hole, with each new leg being 100 m closer to the heel of the well than the previous leg. As well, each new leg would provide 100 m more storage capacity than the previously drilled leg.

As noted above, drilling and casing a single-leg horizontal repository would cost roughly $4 million. Additional horizontal legs would likely take 10 to 20 days to drill at a cost of about $600,000 per leg. The total anticipated drilling and casing costs would be about $10 million [$4 million + (10 x $0.6 million)] with the storage capacity of 16 500 m of material. About 121 such repositories would be required to store two million metres of fuel bundle containers at a cost of approximately $1.2 billion.

The spacing between the legs of the repository could be reduced further, resulting in increased storage capacity. For a repository comprising 41 legs, the anticipated drilling and casing costs would be roughly $28 million [$4 million + (40 x $0.6 million)]. This repository could potentially contain over 61 000 m of used fuel. Each parallel "row" of material would be 50 m away from the next nearest row. About 33 such repositories would be able to store two million metres of containers at a cost of approximately $924 million. Again, multiple repositories of this type could be drilled from a single surface location.

Direct cost comparisons for the development of a very deep repository using drilling technologies *versus* the cost to develop a mined repository have not been completed. However, a report provided to the NWMO estimates that the costs for design and construction of a mined repository, including surface handling facilities is about $2.4 billion (in 2002 dollars) (CTECH Radioactive Materials Management, 2003).

4. Benefits of a Deep Horizontally Drilled Repository

Development of a repository of this type in the Precambrian basement beneath the Williston Basin of southern Saskatchewan has several benefits which include:

1) a suitable geological environment comprising at least 2.4 km of sedimentary cover plus at least 300 m of Precambrian crystalline cover over the repository, in an area with the tectonic stability generally associated with an interior continental basin;
2) a favourable hydrogeological regime which would isolate and contain any contamination resulting from failure of either engineered barriers through, for example, degradation over time or natural barriers following a significant tectonic event;
3) the possibility for future decision makers to retrieve the stored nuclear fuel if evidence indicates that this method of storage proved to be unsatisfactory or that there may be additional value in the used fuel;
4) the stored material is already positioned for permanent, non-accessible storage and abandonment;
5) minimal disturbance to the surface and geological media during development;
6) elimination of most underground-related mining construction and attendant radiation safety issues;

7) unlikely impact from future disturbances due to climate change or glaciation;
8) high-level security in the event of political instability;
9) the ability to monitor groundwater movement with observation wells;
10) the use of existing surface transportation infrastructure; and
11) a possible significant cost savings compared to current strategies.

5. Conclusions

The development of a very deep geological repository in the Precambrian basement beneath the Williston Basin of southern Saskatchewan appears to be technically and economically feasible. Besides great depth, geological attributes which support development of a repository include the hydrogeological and hydrochemical characteristics which will provide for containment following any contamination that might occur. Current evidence suggests that it is the hydrogeological conditions which will provide the greatest long-term safety from leakage and migration of contaminated material.

Before such a site could be developed, further geological and other research is required. The work conducted in Saskatchewan would provide screening criteria for similar sites that could be developed elsewhere in the world.

6. References

Bachu, S. and Hitchon, B. (1996): Regional-scale flow of formation waters in the Williston Basin; AAPG Bull., v80, no2, p248-264.

Benn, A.A. and Rostron, B.J. (1998): Regional hydrochemistry of Cambrian to Devonian aquifers in the Williston Basin, Canada – U.S.A.; *in* Christopher, J.E., Gilboy, C.F., Paterson, D.F., and Bend, S.L. (eds.), Eighth International Williston Basin Symposium, Sask. Geol. Soc., Spec. Publ. No. 13, p238-246.

British Petroleum (2006): British Petroleum, Wytch Farm Field, Dorset, U.K.; URL <http://www.bp.com/genericarticle.do?categoryId=2012968&contentId=2001682>, accessed 14 Feb 2006.

CTECH Radioactive Materials Management (2003): Cost Estimate for a Deep Geologic Repository for Used Nuclear Fuel, Report of a study carried out for Ontario Power Generation, New Brunswick Power, Hydro-Quebec and Atomic Energy of Canada Limited, Report 1106/MD18085/REP/02, September 2003, URL <http://www.nwmo.ca/adx/asp/adxGetMedia.asp?DocID=613,608,237,199,20,1,Documents&MediaID=2791&Filename=DGR+Cost+Estimate+Report.pdf>, accessed 14 Feb 2006.

Downey, J.S., Busby, J.F., and Dinwiddie, G.A. (1987): Regional aquifers and petroleum in the Williston basin region of the United States; *in* Peterson, J.A., Kent, D.K., Anderson, S.B., Pilatske, R.H., and Longman, M.W. (eds.); Williston Basin: Anatomy of a Cratonic Oil Province, Rky. Mtn. Assoc. Geol., Denver, p299-312.

Kreis, L.K., Ashton, K.E., and Maxeiner, R.O. (2000): Geology of the Precambrian basement and Phanerozoic strata in Saskatchewan; Lower Paleozoic Map Series - Saskatchewan; Sask. Industry Resources, Open File Rep. 2000-2, Sheet 1 of 8.

McCombie, C. (2003): Nuclear Waste Management Organization, Background Paper 6-3: Technical Methods, Status of Geological Repositories for Used Nuclear Fuel, 104p.

Nuclear Waste Management Organization (2005): Choosing a Way Forward, The Future Management of Canada's Used Nuclear Fuel (Final Study), 451p.

Occidental Petroleum Corporation (2006): Occidental Petroleum Corporation, Wilmington Field, Long Beach, California, U.S.A.; URL <http://www.oxy.com/OIL_GAS/world_ops/usa/thums.htm>, accessed 14 Feb 2006.

Whittaker, S., Rostron, B., Khan, D., Hajnal, Z., Qing, H., Penner, L., Maathuis, H., and Goussev, S. (2004): Theme 1: Geological Characterization; *in* Wilson, M. and Monea, M. (eds.), IEA GHG Weyburn CO_2 Monitoring and Storage Project Summary Report 2000-2004, Petrol. Tech. Resear. Centre, Regina, p15-69.