THE GEOLOGICAL DISPOSAL OF SPENT NUCLEAR FUEL BENEATH SEDIMENTARY BASINS

B. Brunskill
Helix Geological Consultants Ltd.,
Regina/Sk., Canada

M. Wilson
Petroleum Technology Research Centre,
Regina/Sk., Canada

ABSTRACT

The risk of contamination of the geosphere surrounding any relatively shallow (less than 1000 m) used nuclear fuel repository increases with time due to the eventual degradation of engineered materials used to contain the waste. The potential for the vertical movement of this contaminated material further in the geosphere, and possibly into the biosphere, will be largely dependent upon the vertical mobility of the contaminated groundwater in the fractures in the host-rock surrounding the repository. The primary emphasis for absolute containment, therefore, should be on the selection of a geological environment that provides great vertical separation from the biosphere accompanied with a hydrogeological environment that would, due to significant resident-fluid density stratification, contain water that is geologically ancient, having been in-place for millions of years. Rocks beneath some deep sedimentary basins could potentially provide this environment. In appropriate locations, repositories could be developed using drilling methods such as those currently used to develop oil and gas resources throughout the world.

1. INTRODUCTION

Several countries are evaluating various methods of disposing their spent nuclear fuel in geological repositories. Some proposed storage facilities would employ traditional mined designs with the development of vertical shafts or ramps and storage rooms at depths up to several hundred metres. Waste materials would be packaged in highly resistant containers and entombed in these storage rooms. The option of also having the materials retrievable may be attractive since the fissile isotopes may be useable in future energy systems.

The expectations for developing a repository in this scenario include isolation from the biosphere, confinement of the radioactive waste in the geosphere in the near-term (~10,000 years) and, due to the timely degeneration and failure of the barrier materials used, mitigated release to the geosphere in the long-term [1]. Significant emphasis is placed on the reliability of the engineered barriers, which would serve to retard the rate of contamination of radioactive material that may escape into the geosphere and, possibly, the biosphere. The risk of escape of nuclear material increases with time due to the natural degradation of the engineered barriers. Geological barriers are also subject to failure (fracturing and faulting), due particularly to tectonic events.

It is likely, therefore, that any repository will eventually experience leakage and nuclear material will escape into the surrounding rocks. Since fractures in the rocks surrounding any geological repository provide conduits, contaminated groundwater moving in these fractures could potentially communicate vertically with the biosphere. To prevent this potential migration, it would be highly beneficial to locate the repository where the groundwater surrounding the repository is not vertically mobile. The ultimate reliability in the disposal method used must, therefore, rely on the integrity of the ***geological container*** that hosts the repository. Under the appropriate conditions, disposal sites could be developed where the natural environment provides reliability for geological periods of time (*i.e*., for millions of years).

Conditions under the deeper portions of some sedimentary basins may provide this environment. In some cases, the hydrogeological environment of deep basins develops, with increasing depth, a significant salinity gradient, and becomes more strongly density-stratified. In deep parts of these basins, brines may have been chemically and physically isolated for millions of years and, due to density stratification, flow that may occur tends to be lateral rather than vertical. When the engineered containment barriers fail and contamination of this water occurs, it is extremely unlikely that this contaminated water would communicate vertically with the biosphere. In granitoid rocks forming a basement beneath these basins, dense brines would also likely occupy any interconnected porosity. Very low hydraulic conductivity in these basement rocks would significantly limit even the lateral migration of the resident fluids.

Technology currently being utilized by the oil and gas drilling industry could be used to develop very deep borehole repositories in a number of geological environments. Reports prepared by Sandia National Laboratories [2] and the Nautilus Institute [3] suggest that the placement of High-Level Waste (HLW) and Spent Nuclear Fuel (SNF) in deep boreholes under suitable geological conditions will provide effective, long-term isolation.

Using the model described in this paper, deep borehole disposal repositories developed under sedimentary basins are expected to provide:

1) permanent isolation and containment of the radioactive material;
2) retrievability of the material for a considerable time (in the order of 100 years); *and*
3) the ability to monitor the containment system indefinitely.

2. MODEL BASIN: THE WILLISTON BASIN

The example basin presented here is the Willison Basin, where a repository could be developed in the Precambrian Shield *beneath* the basin. The Williston Basin is generally located in southern

Saskatchewan and southwestern Manitoba in Canada, and northeastern Montana and parts of both North and South Dakota in the USA (Figures 1 and 2). Section A–A' in Figure 2 provides a cross-sectional view through the basin, from the Black Hills Uplift to the Manitoba Escarpment. This cross section is illustrated in Figure 3 (Figure 1 courtesy the United States Geological Survey; Figure 2, Iampen).

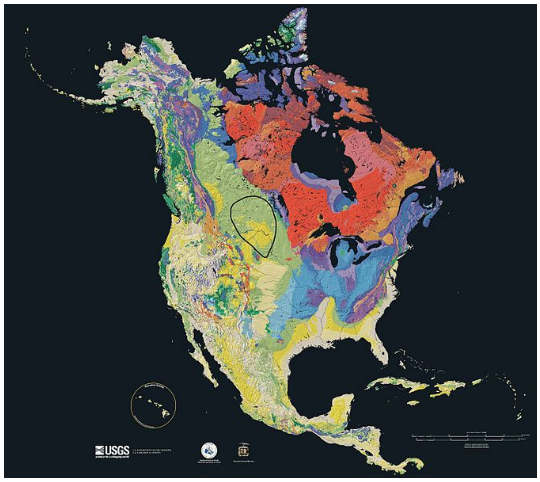

Figure 1. Location of the Williston Basin in North America.

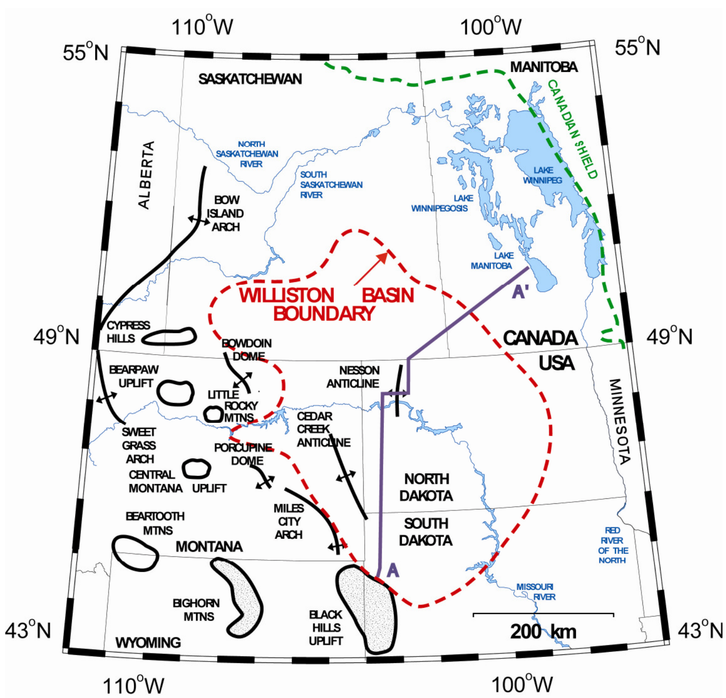

Figure 2. Location of the Williston Basin in southern Saskatchewan, North and South Dakota, and Montana.

The cross-sectional view in Figure 3 crosses through the deepest part of the basin and illustrates the distribution of low-mobility, heavy brines that occupy aquifers near its base (figure modified from, and courtesy of Iampen). These fluids can contain from 250 to 350 g/l Total Dissolved Solids [4]. Hydrogeological evidence suggests that this *brine slug* may be geologically ancient, being millions, or possibly hundreds of millions of years old, covering an area of thousands of square kms. If, therefore, a repository were to be developed beneath the Williston Basin, it would not only be situated at great depth (2,500 to 4,000 m), but the stagnant, dense brines would potentially provide complete isolation of any leakage for a period of time far longer than any nuclear material would be harmful. Even following a significant tectonic event or periods of glacial loading and rebound, contamination would likely remain in the very deep geosphere.

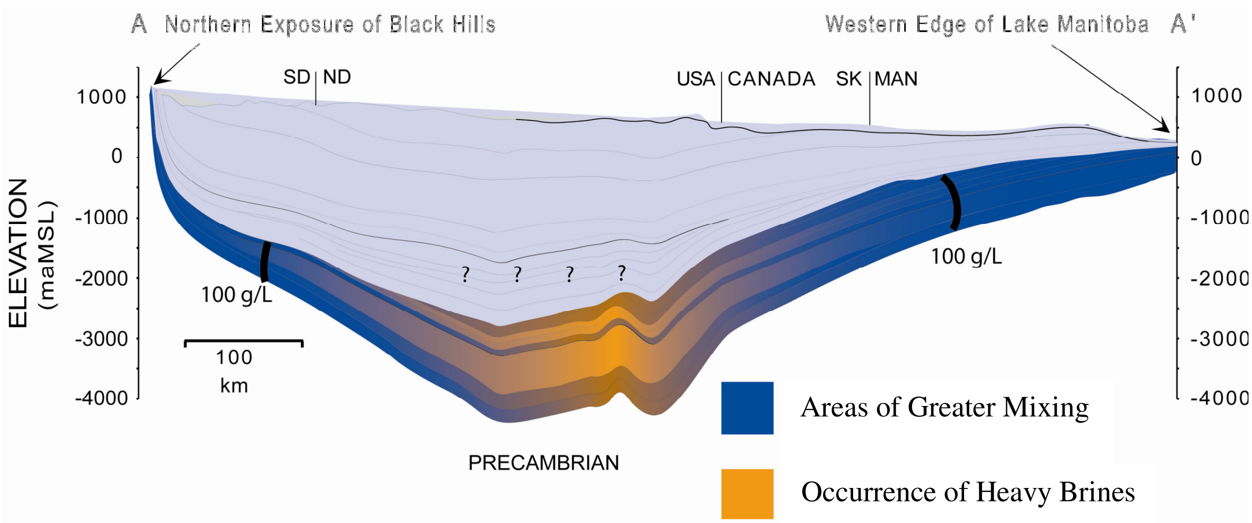

Figure 3. Cross-sectional view of the Williston Basin.

In many deep basins worldwide, including the Williston Basin, there is exploration drilling for hydrocarbons and geothermal energy. The development of a nuclear waste repository would be limited to non resource-prone areas that would remain restricted from any future drilling activity.

3. DEVELOPMENT OF THE VERY DEEP BOREHOLE REPOSITORY

The development of these repositories is technically possible today, and may be economically feasible if, for example, surface-drilling methods currently utilized in the petroleum industry are used [5]. The space for the spent fuel would be developed by drilling long, sub-horizontal, small-diameter "rooms" that are lined with continuous metal casing. The sub-horizontal model is important because the weight of the fuel-bundle containers will be supported in the hole, eliminating any damage caused to the containers by the weight of overlying canisters that would occur in a vertical stacking scenario.

Figure 4 provides a sectional view of a model waste-disposal unit developed under the Williston Basin. In this scenario, a large-diameter hole (444 mm) is drilled vertically from the surface to the depth of 400 m. Surface casing (339.7 mm) is cemented in place from 400 m to the surface, thereby isolating drilling activities from all near-surface aquifers. A smaller-diameter hole (311 mm) would be drilled from within this surface casing, through the sedimentary section of rocks into the Precambrian basement at a depth of, say, 2500 m. Intermediate casing (244.5 mm) would be cemented in place from 2500 m to the surface. A smaller-diameter hole (222 mm) would then be drilled from within this intermediate casing, around the curved section, then laterally to a maximum reach of approximately 6700 m. Disposal casing (177.8 mm) would then be cemented in place from 6700 m to the surface. The deepest section of the hole from 2700 to 6700 m would provide 4000 m of disposal space. The corresponding true vertical depth from surface would be from approximately 2660 to 4350 m respectively. Tubular containers, like sections of pipe, would be used to house the spent fuel bundles. These tubular containers would be lowered into the disposal section end-to-end using a wireline tool. The estimated temperature of the rocks at these depths ranges from 80 to 130 °C.

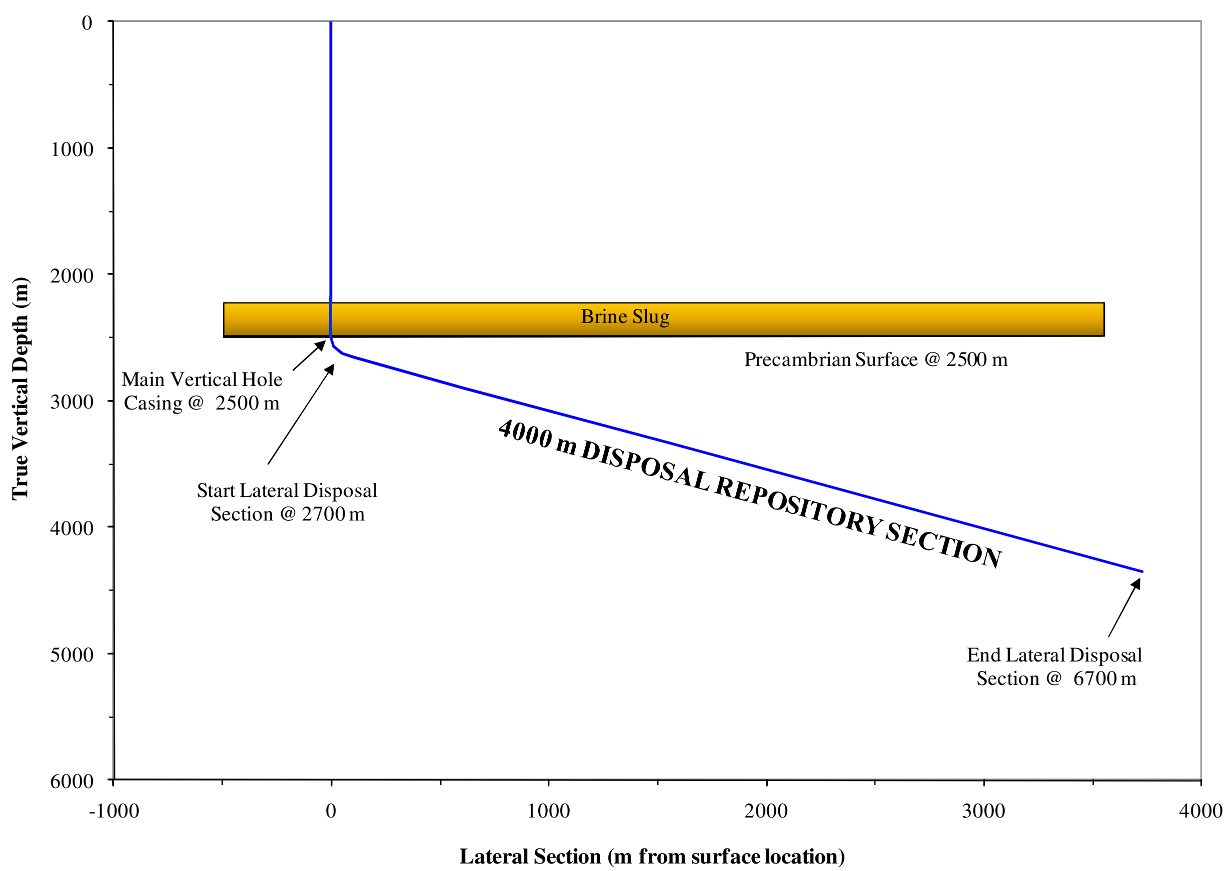

Figure 4. Sectional view of a 4000 m long disposal repository developed in the Precambrian basement underlying the Williston Basin.

3.1 Development Costs

Using 2011 petroleum industry rates, an estimate to drill and case a single, 6700 m repository would be from CDN $12.0 to 13.4 million and take from 120 to 140 days to complete. A large-scale drilling project would benefit significantly from economies of scale.

In Canada, one estimate of the total anticipated spent fuel from the current reactor fleet will be approximately 3.6 million bundles [6]. This value represents the reference case, with each of the existing reactors completing its fully-planned life-cycle. Each fuel bundle is approximately 0.5 m (19.7") in length and 102 mm (4") in diameter. Placed end-to-end, there would be roughly 1.8 million m of material to dispose of, assuming the fuel bundles are placed intact, without any pre-consolidation. Including an additional 5% for canister hardware, etc. the total length required would be approximately 1.9 million m. Each 4000 m unit would contain approximately 7,580 bundles or 152 tonnes of Heavy Metal (assuming each bundle contains 20 kg of heavy metal). About 475 holes, like this model, would be needed to dispose of all of Canada's anticipated waste. If the base cost of each unit is assumed to be CDN $12.5 million to develop, not including emplacement, operation, management and licensing costs, then the total cost would be approximately $5.94 billion or $82,200 per tonne of Heavy Metal.

The same model can be applied to the disposal of inventories in other countries. Hole and tubular sizes would be adjusted to accommodate the size of the waste canisters.

3.2 Repository Footprint Size and Model Drilling Parameters

Drilling "pads" would be used to concentrate surface operations. For example, unit heads (entry point at surface) could be located 10 m apart in 500 m long rows (50 units per row). Eleven rows, each 50 m apart, would accommodate up to 550 units. In this arrangement, the grid size at surface would be approximately 500 m x 550 m, covering an area of about 27.5 ha.

The accommodation size in the subsurface would be significantly larger than at surface. Using the general configuration above, the overall footprint would be approximately 500 m x 4.4 km or 218 ha. The individual rows of used fuel canisters would be at least 10 m distant from each other. There would be, however, significant flexibility in the orientation of each unit. Units could be staggered and drilled at a number of different angles and elevations to minimize thermal overlap and the total area required. Precision drilling methods would make it highly unlikely that boreholes would intersect.

Table 1 provides the hole-drilling dimentions, and casing sizes and weights used in this model.

Table 1. Unit drilling and completion parameters

Casing	Depth	Bit Size	Casing Size OD/ ID	Casing Weight
Surface	400 m	444 mm	339.7/ 320.4 mm	81.1 kg/m
	1,312 ft	17.5 in	13.4/ 12.6 in	54.4 lb/ft
Intermediate	2,500 m	311 mm	244.5/ 224.4 mm	59.5 kg/m
	8,202 ft	12.25 in	9.6/ 8.8 in	40 lb/ft
Disposal	6,700 m	222 mm	177.8/ 154.8 mm	56.6 kg/m
	21,982 ft	8.75 in	7.0/ 6.1 in	38 lb/ft

4. RETRIEVABILITY OF THE USED NUCLEAR FUEL

Although nuclear material placed in the disposal section of the hole would be in the abandonment position, the containers could potentially be retrieved and inspected as deemed necessary, particularly in response to currently unforeseen conditions. If material failure is observed or anticipated the waste containers could be transferred to a new repository unit. With this option of being readily retrievable for some time, future decision-makers would have greater flexibility as new knowledge, experience, concerns and technologies arise. Current drilling and completion designs could likely ensure retrievability for up to 100 years (*i.e.,* for as long as the encasement materials maintain their integrity). Casing materials would serve only to provide a means to place the radioactive waste in the deep subsurface and to provide for inspection and retrieval for a short period of time relative to the entire anticipated containment period. It is expected that the geological and hydrogeological conditions alone will provide for long-term material containment.

If the option of retrievability was not desirable, the repositories could be abandoned using methods that would make retrieval very difficult and extremely expensive.

5. DISPOSAL WITHOUT THE OPTION OF RETRIEVABILITY

If it is deemed unnecessary to have the option of retrieving the stored material, there are simple modifications to the design of the repository that could significantly reduce development costs. A multiple-leg disposal unit could be developed from the single-leg model described above. In this scenario, a hole is drilled vertically from the surface into the basement at a depth of, say, 2500 m. Casing would be cemented in place from 2500 m to the surface. A smaller diameter hole would be drilled from within this casing around the curved section, then laterally to its maximum reach of approximately 6700 m. This section of the hole would remain uncased. From the side of this primary hole, additional holes ("legs") would be drilled off to the side (a "side-track") alternating left then right, with each subsequent leg being 100 m closer to the curved portion of the hole (the "heel"). This orientation would result in a "herringbone" shape where 23 legs, for example, would provide approximately 64,000 m of disposal space. The rows of waste material would be at least 100 m distant from each other. About 30 holes, like this model, would be needed to dispose of all of Canada's anticipated waste. Figure 5 illustrates an 11-leg disposal repository.

This model may also be appropriate for the permanent disposal of depleted uranium and lower-level radioactive waste.

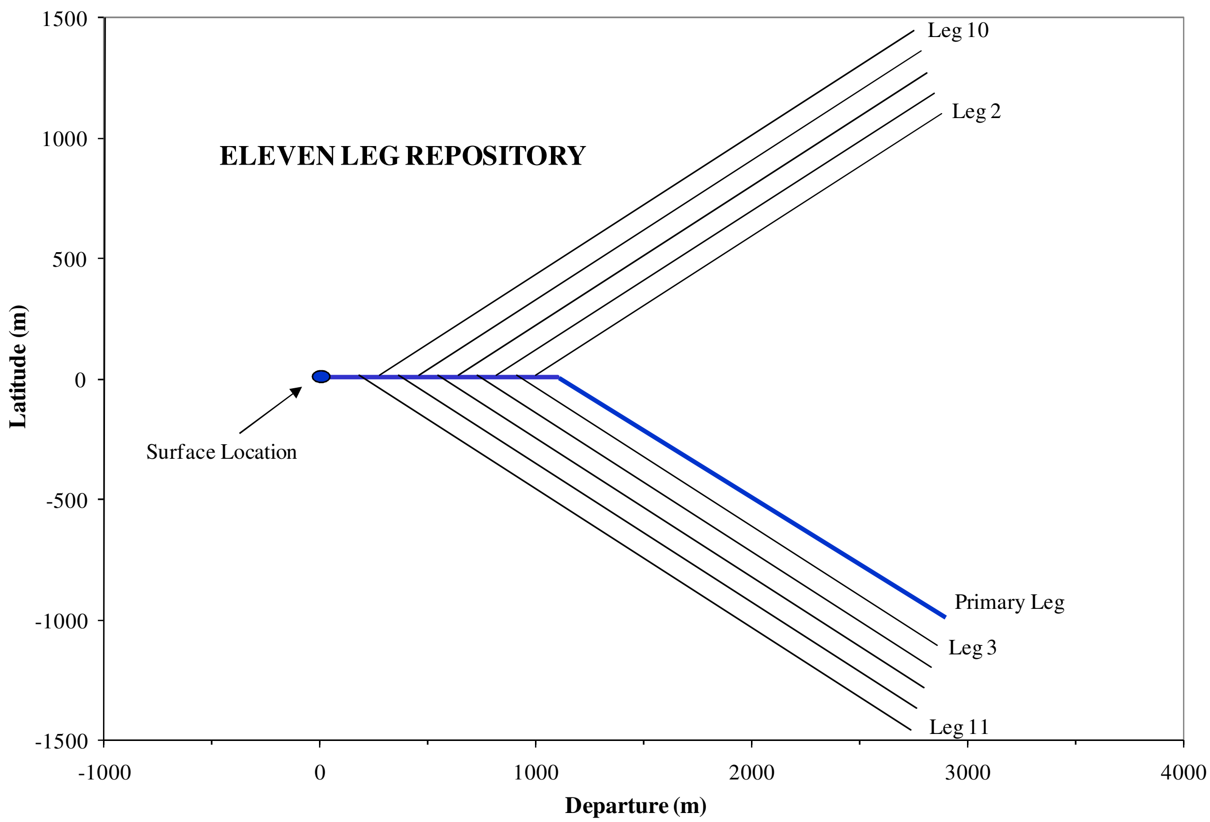

Figure 5. Plan View of an 11 leg, 31,900 m, Multiple-Leg Disposal Repository.

6. NON-INVASIVE REPOSITORY MONITORING

Effective monitoring methods are necessary to verify both the safety of the disposed materials and the reliability of the methods used under present and future conditions. Being able to monitor the repository indefinitely without compromising the integrity of the containment barriers is also critical to long-term public acceptance.

In the Williston Basin example, the presence of an aquifer at the base of the sedimentary section provides a means to conduct reliable and timely monitoring of the repository site without compromising the integrity of the geological container. Observation wells can be placed strategically in and around the disposal site area and be used to circulate native brines from the overlying aquifer across the repository area to the surface where any radionuclides can be detected (Figure 6). If deemed appropriate, remedial action, appropriate for the time, could be taken. To access the material, say, 500 years from now, re-mining would likely be required.

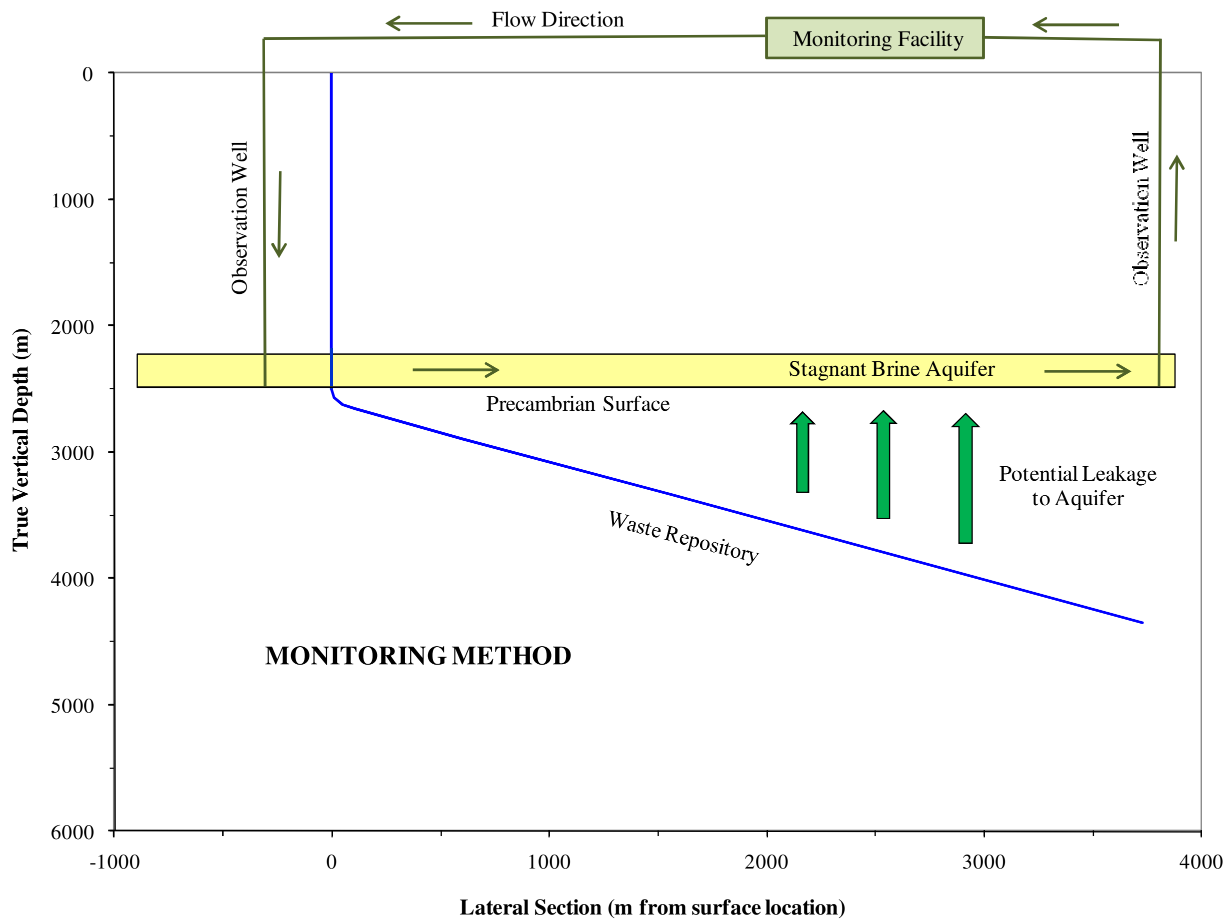

Figure 6. Observation wells circulate brines across the repository field to detect radionuclides that have escaped into the overlying aquifer.

7. SUMMARY AND CONCLUSIONS

Development of a deep borehole repository of this type in the Precambrian basement underlying the Williston Basin of Saskatchewan, Montana and North Dakota, and potentially many other basins worldwide, has several benefits which include:

1. a suitable geological environment comprising 2.5 km, or more, of sedimentary rock cover plus at least 150 m, or more, of Precambrian crystalline rock cover over the disposal 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 engineered barriers due to their degradation over time or of natural lithological barriers due to tectonic or climate-change related (*e.g.*, a period of glaciation) events;

3. the possibility for future decision-makers to retrieve the radioactive waste for about 100 years;

4. the ability to monitor indefinitely for contamination using non-intrusive observation wells;

5. minimal disturbance to the rocks in the subsurface during development and the elimination of most underground-related construction and attendant safety issues;

6. the possibility for the development of several modular, decentralized repository locations, and

7. potentially significant cost savings compared to current strategies.

It is appropriate to find site locations where it is the *natural* character of the site that provides safety for millions of years, without any reliance upon engineered barriers. Performance assessments of human-made containment systems can be expected to be predictable for only a relatively short period of time because of uncertainties in forecasting the reliability of engineered materials into the distant future. Events in 2011 at the Fukushima Dai-ichi nuclear power plant in Japan remind us of the potential consequences of our reliance upon engineered barriers that fail due to unforeseen circumstances.

8. RECOMMENDATIONS FOR ADDITIONAL WORK

1. Age-dating deep brine samples will indicate the resident time that these waters have been in place and how stagnant or immobile they have been over geological periods of time. In areas of interest, brine samples could possibly be extracted from oil and gas production operations or from newly drilled wells.

2. More consideration is required for the design and performance assessment of borehole materials and procedures specific to site development in the very deep subsurface.

The deep borehole model presented herein, and other models, may provide for greater safety than current mined strategies at a significantly reduced cost to develop. Including the assessment of deep borehole disposal methods equally with current strategies would be, therefore, in the greater public interest.

Ultimately, a full-scale demonstration project could be undertaken to gain direct experience and to assess the viability of this deep borehole model. An international, deep borehole facility could be located in a host country with the appropriate geological setting. Radioactive waste could be substituted by an alternative material. The costs, benefits and challenges could be assessed, and this experience could lead to the international standardization of procedures and materials used. We recognize that there are several social and political challenges that must also be addressed before the use of deep borehole disposal methods could become a reality.

9. REFERENCES

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