PERMEABILITY OF THE INYAN KARA GROUP IN THE BLACK HILLS AREA AND ITS RELEVANCE TO A PROPOSED IN-SITU LEACH URANIUM MINE

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ABSTRACT

Fluvial sandstone channels in the Cretaceous Inyan Kara Group in western South Dakota have variable thickness and texture, causing variability of the hydraulic conductivity. Pumping tests in two 120-ft thick sandstones at a proposed in-situ leach uranium mine in the Dewey/Burdock area provide hydraulic conductivity data. The hydraulic conductivity in the upper sandstone (Fall River Formation) is approximately 0.45 ft/day and the lower sandstone (Chilson Member of the Lakota Formation) is approximately 1.56 ft/day. These data, along with the prevailing gradient of the potentiometric surface, yield an average groundwater velocity for these two sandstones in the Inyan Kara Group of approximately 66 ft/year.

A groundwater velocity determination of 5,480 ft/year in the Inyan Kara Group near the Dewey/Burdock site was based on 1963 tritium data (Gott et al. 1974). This value seems very high, and contradicts the velocity based on hydraulic conductivity, but if valid, indicates fast groundwater movement through very permeable units or through fractures.

An important environmental consideration following the abandonment of this proposed uranium mine is that the groundwater will migrate down gradient and may contain a high concentration of dissolved uranium (with daughter products radium and radon) and selenium. The rate of movement of these elements would be less than the groundwater velocity because of retardation associated with geochemical reactions related to changes of pH and oxidation/reduction potential.

Keywords

Permeability, groundwater, Inyan Kara Group, uranium mine

INTRODUCTION

This paper contains information about the hydrogeology and permeability of a Cretaceous sandstone aquifer in South Dakota called the Inyan Kara Group. Particular attention is focused on the southwestern Black Hills area where an in-

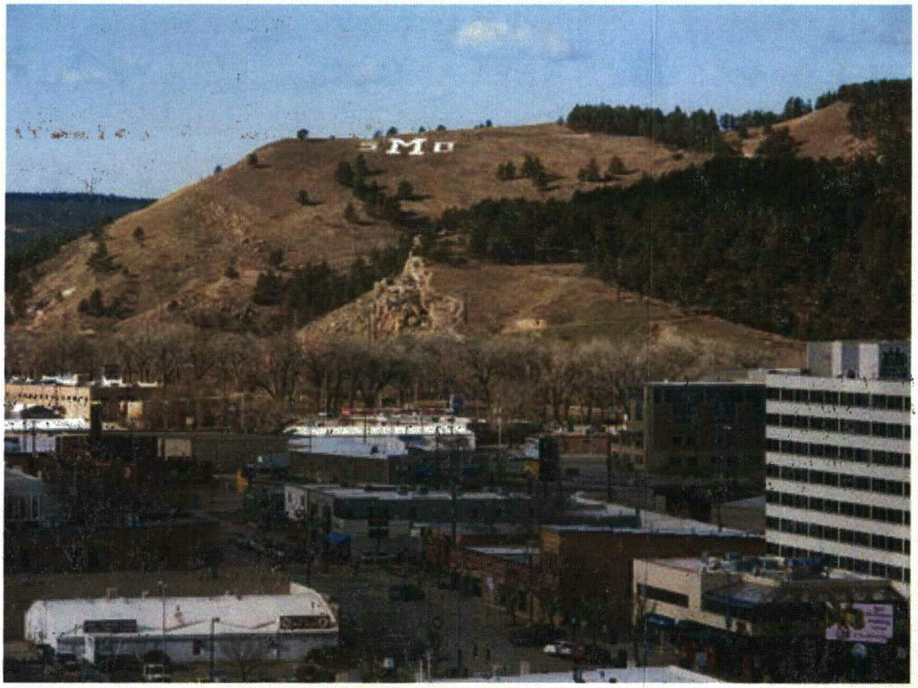

Figure 1. Photograph of the Rapid Creek water gap in Rapid City, as seen from the top of the Alex Johnson hotel. The "M" is on the Chilson Member of the Lakota Formation. The closer sandstone is the Fall River Formation. The two Cretaceous sandstones dip easterly at approximately 20 degrees.

situ leach (ISL) uranium mine is planned. The purpose of this paper is to evaluate the permeability of the Inyan Kara Group and to ascertain the groundwater velocity and potential for contaminant transport from this mine.

The Inyan Kara aquifer, originally called the Dakota aquifer, underlies much of South Dakota and is one of the most famous aquifers in the United States. In the Black Hills area the Inyan Kara Group contains two prominent sandstone strata, the Chilson Member of the Lakota Formation and the overlying Fall River Formation (Figure 1).

Darton (1909) conducted some of the earliest hydrogeologic studies of this aquifer. Gries (1958) developed a stratigraphic model showing that the Dakota Sandstone in eastern South Dakota is roughly equivalent to the Newcastle Formation and the Inyan Kara Group in western South Dakota. Schoon (1971) studied facies within the Inyan Kara Group and showed that the sandstone units, such as the Chilson Member, are fluvial channel units in the Lakota Formation. Keene (1973) studied the Inyan Kara aquifer in Fall River County and found the potentiometric surface in western Fall River County slopes southerly. Strobel et al. (2000) showed the potentiometric surface elevation for the Inyan Kara Group in the southern Black Hills. Bredehoeft et al. (1983) examined alternate theories for regional recharge to this aquifer and concluded that much recharge occurs

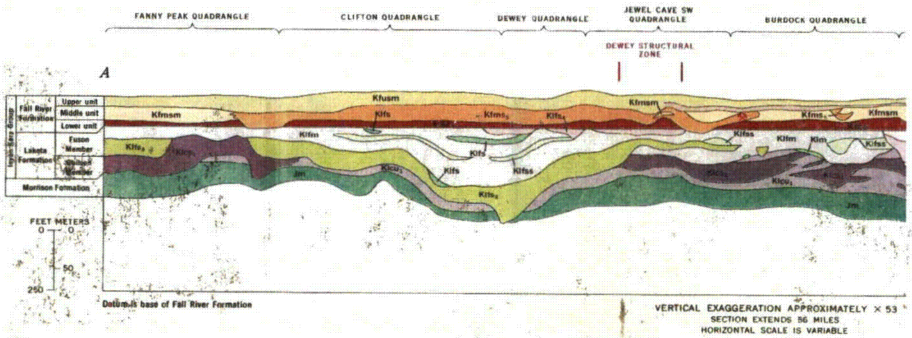

Figure 2. Diagrammatic geologic cross section showing stratigraphy of the Inyan Kara Group in the southern Black Hills (from Gott et al. 1974). The Fall River Sandstone is shown as Kfms$_3$, and the Chilson sandstone member of the Lakota Formation is shown as Klcs$_1$. The two main sandstone units show great variability in thickness from the Wyoming border through the Dewey, Burdock and Edgemont areas.

from leakage from overlying shale. Case (1984) and Carter et al. (2003) showed typical permeability values for the Inyan Kara aquifer.

Detailed geologic mapping in the southern Black Hills was conducted by the U.S. Geological Survey (USGS) in the 1950s and 60s for the purpose of evaluating uranium resources. Figure 2 is a cross section of the Inyan Kara Group in the southwestern flank of the uplift showing stratigraphic facies and the variable thickness of this unit.

HYDRAULIC CONDUCTIVITY DETERMINATION

Several published reports quantitatively document the hydraulic conductivity (K) of the Inyan Kara Group (Table 1). Information concerning the data shown in Table 1 and other studies is given below.

Table 1. Permeability data for the Inyan Kara Group (Driscoll et al. 2002)

	Hydraulic Conductivity (ft/day)	Transmissivity (ft²/day)
Niven (1967)	0 – 100	—
Miller and Rahn (1974)	0.712	178
Gries et al. (1976)	1.26	—
Bredehoeft et al. (1983)	8.3	—
Kyllonen and Peter (1987)	—	0.86 – 6,000

Niven (1967) measured the permeability of cored samples from outcrops in the Black Hills and found the mean hydraulic conductivity of the Lakota Formation is 22.5 ft/day and the Fall River Formation is 4.8 ft/day. Bredehoeft et al.

(1983) pointed out that "one would expect the outcrop to yield higher hydraulic conductivities than exist in the subsurface". Using a best-fit model of western South Dakota, Bredehoeft et al. (1983) determined a horizontal hydraulic conductivity of 8.29 ft/day in the Inyan Kara Group sandstone units.

Based on a recovery test for a 2,300-ft well into the Fall River and Lakota Formations at Box Elder, Miller and Rahn (1974) found the transmissivity (T) to be 1,333 gpd/ft (equivalent to 178 ft^2/day). Because the thickness (b) of the two sandstone units at Box Elder is 250 ft, the hydraulic conductivity (K) is 0.712 ft/day.

Three observation wells were used at Wall, South Dakota, where a pumping test showed anisotropic transmissivity (Rahn 1992). The 3,300-ft deep wells are open to the Lakota Formation, and the sandstone thickness is approximately 200 ft. The transmissivity averages 2,400 gpd/ft (321 ft^2/day) and storativity is 0.000,027. The average hydraulic conductivity is: $K = T/b = 321$ ft^2/day/200 ft = 1.60 ft/day. The principal transmissivity direction was found to be N 35° W, interpreted as the paleodirection of Cretaceous rivers.

An 11-day constant discharge pumping test involving 13 observation wells was conducted in the Lakota aquifer at TVA's proposed underground uranium mine near Dewey, South Dakota (Boggs 1983). In this area the Cretaceous Inyan Kara Group dips approximately 5 degrees towards the west-southwest off the Black Hills uplift and consists of two sandstone aquifers, the Fall River Formation, typically 120 ft of fine-grained sandstone, underlain by the Chilson Member of the Lakota Formation, 120 ft of fine-to-coarse grained sandstone (Boggs and Jenkins 1980; Boggs 1983). Figure 3 shows these two units. The pumping tests indicate the Lakota at this location is exceptionally permeable, having a transmissivity of 4,400 gpd/ft (587 ft^2/day). Boggs (1983) noted that this test site is in an area where the Lakota is composed of a thick, exceptionally coarse-grained sandstone.

A pumping test in the Chilson Member of the Lakota Formation for the proposed Tennessee Valley Authority (TVA) underground mine at Burdock, South Dakota, by Boggs and Jenkins (1980) indicated the transmissivity is approximately 1,400 gpd/ft (187 ft^2/day). A contour map of the drawdown (Boggs and Jenkins, 1980, Figure 19) shows a slight elongation in the northeasterly direction [Note: Boggs and Jenkins (1980) showed this map but mistakenly reported this

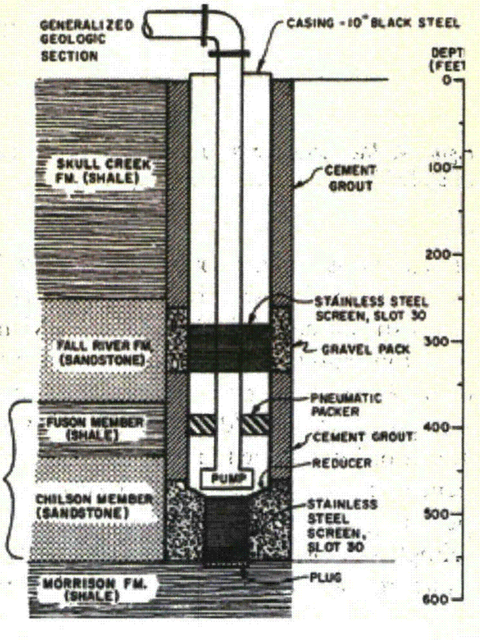

Figure 3. Geologic log of Burdock well (Boggs and Jenkins 1980).

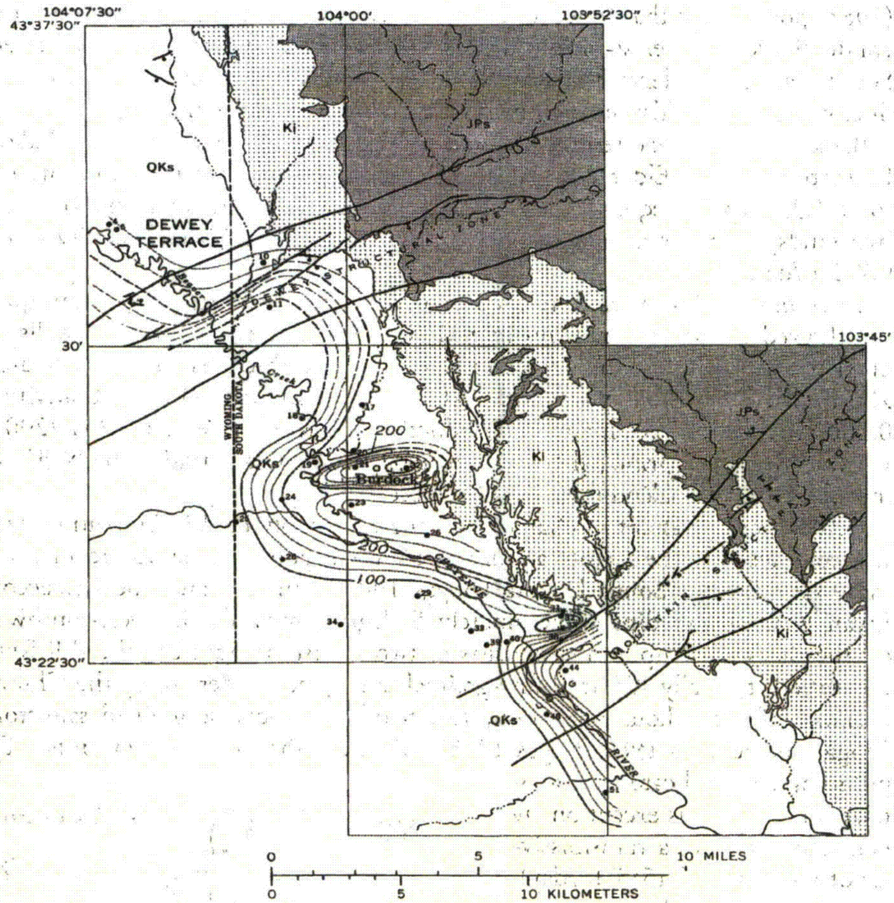

Figure 4. Map showing tritium distribution in groundwater in the Inyan Kara Group (from Gott et al. 1974).

elongation is "…in a northwesterly direction".] The greater permeability in the northeast-southwest direction most likely reflects the orientation of the Cretaceous stream channels. The Chilson Member consists of 120 ft of fine-grained sandstone and siltstone; hence the hydraulic conductivity is 11.7 gpd/ft (1.56 ft/day). A second test on the Fall River Formation found the transmissivity to be 400 gpd/ft (53.5 ft^2/day). The Fall River Formation consists of approximately 120 ft of interbedded fine-grained sandstone, siltstone, and carbonaceous shale; hence the hydraulic conductivity is 3.33 gpd/ft (0.45 ft/day). Subsequent pumping tests for the proposed Powertech ISL mine in the Dewey/Burdock area (Knight-Piesold 2008; Powertech 2009a, 2009b) indicate similar transmissivity values to those determined by the TVA investigations.

TRITIUM

An unusual insight into the permeability and groundwater velocity was provided by Gott et al. (1974) who reported the presence of tritium in groundwater in the Inyan Kara Group near Burdock, South Dakota (Figure 4). The tritium originated from the 1963 Pacific hydrogen bomb fallout. From the location of the tritiated groundwater, Gott et al. (1974) determined that "...near the confluence of Beaver Creek and the Cheyenne River, a flow of 15 feet per day is required to transmit tritium rain-out of the year 1963 from the recharge area at the Inyan Kara outcrop to the positions of the large tritium concentration..." No supporting groundwater velocity calculations were provided by Gott et al. (1974), and this velocity seems quite high. It is possible that there was a tritium sampling error. If, in fact, the true velocity (V_t) is 15 ft/day (equivalent to 5,480 ft/year), two unlikely scenarios would be manifest:

1. **Hydraulic conductivity.** The Darcy velocity (V_d), also called the "specific discharge", through an aquifer is equal to the true velocity (V_t) times the porosity (here assumed to be 10%). Therefore: $V_d = V_t$ (porosity) = 15 ft/day (0.1) = 1.5 ft/day. Near Burdock the potentiometric surface in the Inyan Kara Group slopes south-southwesterly (Boggs and Jenkins 1980). TVA (1979) reported a hydraulic gradient of 9.8 m/km in the Lakota Formation at the Burdock site. The spacing of the equipotential contour lines varies locally, and in the Dewey/Burdock area a head loss from 3700 ft to 3600 ft elevation occurs over a distance of approximately 2.4 miles. Therefore, H/L = 100 ft/12,672 ft = 0.0079. From "Darcy's Law" (Rahn, 1996): $V_d = K\ (H/L)$; therefore the hydraulic conductivity (K) = V_d /H/L = 1.50 ft/day/0.0079 = 190 ft/day. This value seems unrealistically high. For example, Boggs and Jenkins (1980) show the hydraulic conductivity of the Fall River Formation at Burdock is only 0.45 ft/day.
2. **Recharge rate.** Consider the discharge (Q) of groundwater through 1 ft^2 cross section of the Inyan Kara aquifer having V_t = 15 ft/day. With 10% porosity, the effective cross-sectional area is 0.1 ft^2, and the discharge through this cross section would be: $Q = V_t\ A$ = 15 ft/day (0.1 ft^2) = 1.5 ft^3/day. Adequate recharge from precipitation on Inyan Kara outcrops is necessary to sustain this discharge. Brobst (1961) shows the Inyan Kara Group in this area dips approximately 500 ft/mile (equivalent to 5.4 degrees); thus the discharge through a horizontally-oriented recharge area required to service a 1 ft^2 cross section of sandstone = 1.5 ft^3/day (sin 5.4 degrees) = 1.5 (0.09427) = 0.1414 ft^3/day. Sustaining this discharge would require 365 (0.1414) = 51.6 ft of precipitation recharging annually on the outcrops. Obviously this is not possible.

Gott et al. (1974) could have over-estimated the groundwater velocity because they underestimated the distance of transport from the suspected recharge area to the sampling site. Figure 4 shows the locations of wells and springs sampled in 1967 for tritium. The distance to the Inyan Kara outcrops ranges from approximately one to five miles away. Gott et al. (1974) do not show calculations supporting their velocity determination of 15 ft/day, but most likely they assumed a slug flow of tritiated water moved from the recharge area to the sampled well or spring site from rainout that fell in 1963. [Note: tritiated precipitation peaked in 1963 (Freeze and Cherry 1979); Back et al. (1983) show tritiated rain fell in the Black Hills area as early as 1953.] From Figure 4, fifteen feet per day appears to be the maximum velocity.

Another possible explanation for the presence of tritium in the sampled wells is that it entered the aquifer quite close to the sampling locality. It may have leaked downward through overlying shale (from Figure 3 the Fall River Formation is only 250 ft depth). This explanation would support the model by Bredehoeft et al. (1983) suggesting recharge to the Inyan Kara Group occurs through the overlying shale. Another possible explanation is that tritiated water may have leaked down along the casing of the sampled well. However this seems unlikely since many of the sampled sites are artesian wells or springs.

A study by Johnson (2012) shows recent tritium concentration data in this area of up to 15.3 tritium units. Considering that the half-life of tritium is 12.3 years, these data may essentially represent the same water as 1967 except that the tritium has undergone radioactive decay. This indicates the water is not moving through the aquifer at 15 ft/day.

Another possible explanation for the presence of tritium as shown in Figure 4 is that in 1963 it recharged the outcrops as visualized by Gott et al. (1974) but traveled along extremely permeable pathways. These could be fractures in the sandstone (Figure 5) or very permeable conglomerate channels. Gott et al. (1974) point out that cross-bedded sandstone beds contain many intertonging lenses that vary from fine-grained sandstone to conglomerate with pebbles greater than three inches in diameter. The direction of dip of the crossbeds within the sandstones indicates the paleostreams flowed northwesterly. Figure 4 shows the "Dewey Fracture Zone". This zone is shown on geologic maps as the Dewey Fault by Brobst (1961) and the Dewey Fault and Structural Zone by DeWitt et al. (1989). Schnabel (1963) describes well-defined vertical joint systems in the Burdock quadrangle that typically strike N 75-85 degrees E and N 35-45 degrees E. The isograms of tritium content on Figure 4 seem to bend in a manner suggestive that high tritium is associated with the fractures. While the 15 ft/day groundwater velocity posited by Gott et al. (1974) seems enigmatic, a possible explanation is that the tritiated water followed fractures, and did not travel through the sandstone interstices.

Hydrogeologists recognize that at a specific local site groundwater may move faster than the general regional flow. For example, in another Black Hills aquifer, the karstic Madison Limestone, there are diffuse flow components as well as solution-enlarged conduits that transport groundwater very rapidly (Long and Putnam 2004; Long et al. 2007). Back et al. (1983) used ^{14}C to determine the age of groundwater over a large area of western South Dakota. At Midland, for example, they found that the water was recharged 20,100 years ago, and using 10% porosity and the 260-km (162 mile) distance to the recharge area, they determined that the velocity was 12.9 m/yr (42.3 ft/year). The hydraulic gradient

Figure 5. Photograph of "Hangman's Hill" in Rapid City showing the cross-bedded sandstone (Chilson Member of the Lakota Formation) and a pronounced fracture.

in the Midland area is 1.7 X10^{-3}, and the hydraulic conductivity was determined to be 24 X 10^{-6} m/sec (0.63 ft/day). This hydraulic conductivity is close to that determined from pumping tests in Rapid City (Greene and Rahn 1995). Despite these determinations of hydraulic conductivity and velocity, locally there are conduits in the Madison Limestone that permit exceptionally fast movement. For example, dye introduced into sinkholes along Boxelder Creek was traced to Gravel Spring in 68 minutes (Rahn and Gries 1973). The distance is 2,200 ft, so the groundwater traveled at 47,000 ft/day. The dye was traced to City Spring in Rapid City in 34 days (Rahn and Gries 1973; Greene and Rahn 1995). This distance is 7.5 miles, so the groundwater traveled at 1170 ft/day. Unlike the Madison Limestone, the Inyan Kara Group is not a karst aquifer; nevertheless local high groundwater velocity may occur.

In spite of the seemingly enigmatic tritium data, this paper shows a groundwater velocity determination through the two sandstones at the Dewey/Burdock area in the conventional manner using hydraulic conductivity data from pumping tests. These calculations assume that no fractures or extremely permeable conglomerate units are present, and that groundwater flows through the sandstone in a manner predicted by Darcy's Law.

APPLICATION OF PERMEABILITY DATA TO THE PROPOSED DEWEY/BURDOCK MINE

The impact of the withdrawal of groundwater is an important part of any environmental assessment. The South Dakota Department of Environment and

Natural Resources (SD DENR) approved the withdrawals for this ISL mine but is currently involved in litigation over Powertech's proposed withdrawal of 8,500 gallons per minute (gpm) from the Inyan Kara aquifer and 551 gpm from the Madison aquifer. Most of this water is pumped back into the aquifer and is used to introduce oxidizing chemicals necessary for the solution of the uranium minerals. Actual water consumed ("make-up water") is estimated by Powertech to be only 170 gpm. The predicted drawdown from groundwater withdrawals has been discussed in the Water Rights Section of the SD DENR website and is not included in this paper. Rather, the emphasis of this paper is to assess the natural groundwater velocity in this aquifer since this is a critical factor for evaluating the long-term impacts of introducing chemicals ("lixiviants") into this aquifer.

A major concern of ISL uranium mining is the chemistry of the residual groundwater after mining ceases, the rate of groundwater movement downgradient through this aquifer, and the possibility of mixing with water in other aquifers. Studies of existing ISL mines have shown that dissolved uranium and selenium are of particular concern (Borch et al. 2012). In order to assess the environmental impact of residual groundwater following mining at the proposed Dewey/Burdock project area, one can use permeability data to predict the groundwater velocity in the channel sandstones of the Inyan Kara Group.

For the purpose of this paper, pumping test data and the conventional use of hydraulic conductivity with Darcy's Law were applied to determine the groundwater velocity. Table 2 summarizes aquifer parameters that are most relevant to the proposed Dewey/Burdock in-situ leach uranium project. Figure 3 is a geologic section of the Burdock well used in a pumping test by Boggs and Jenkins (1980). The top of the Fall River Formation lies at 250 ft depth and the top of the Chilson Member of the Lakota Formation lies at 430 ft depth. From Table 2, transmissivity averages 365 ft^2/d at the three Lakota Formation (Chilson Sandstone Member) sites. The range of values, from 187 to 587 ft^2/d, is caused, by some degree, to the variable thickness of the sandstone. The coarseness of the sandstone is certainly another reason for transmissivity variability; for example, the largest value, 587 ft^2/d, occurs where coarse-grained sandstone is reportedly present.

Table 2. Relevant aquifer data (modified from Boggs and Jenkins 1980)

Site	Unit studied	Hydr. Cond. (ft/d)	Thickness (ft)	Transmissivity (ft^2/d)
Dewey	Lakota Fm. (Chilson)	4.92	120	587
Burdock	Lakota Fm. (Chilson)	1.56	120	187
Burdock	Fall River Fm.	0.45	120	53.5

Groundwater velocity at the Dewey and Burdock area can be estimated by using the data from Table 2. The natural potentiometric surface slopes approximately WSW at a gradient (H/L) of approximately 0.0079. The effective porosity has been reported at 17% for the sandstones in the Inyan Kara Group (Rahn

1981), but this may be high since hydrogeologists using Darcy Law calculations for other aquifers in the Black Hills area have used 10% effective porosities (Back et al. 1983). For simplicity, in this paper, if one assumes that the effective porosity is 10%, then the groundwater velocity can be determined as follows:

- Dewey area (Lakota Fm): $V_t = V_d/10\% = K\ (H/L)/0.1 = 4.92\ (0.0079)/0.1 = 0.389$ ft/day (equivalent to 142 ft/year).
- Burdock area (Lakota Fm): $V_t = 1.56\ (0.0079)/0.1 = 0.123$ ft/day (equivalent to 44.9 ft/year).
- Burdock area (Fall River Fm): $V_t = 0.45\ (0.0079)/0.1 = 0.0316$ ft/day (equivalent to 11.5 ft/year).

An average groundwater velocity within the Inyan Kara Group at the Dewey/ Burdock area is assumed to be the average of these three velocities, i.e. 0.18 ft/ day (equivalent to 66 ft/year). [Note: this velocity is greater than the "maximum natural groundwater velocity" of approximately 12 ft/year estimated by Powertech (2009a).]

As shown in Figure 2, the Inyan Kara Group in the southern Black Hills has complex stratigraphy and hence has considerable permeability variability. The Inyan Kara Group includes permeable sandstone channels that could carry groundwater faster than an average value of 66 ft/year. At some places the sandstone channels are not present. A crude estimate of the permeability variability can be made by comparing the hydraulic conductivity values from western South Dakota pumping tests described in the above references. These values include: 0.94 (Miller and Rahn 1974); 1.52, 1.47, and 1.85 (Rahn 1992); 1.85, 1.73, 1.70, 1.53, 1.98, 0.17, and 0.17 ft/d (Boggs and Jenkins 1980). Also using 8.3 ft/d (from Bredehoeft et al., 1983) yields twelve values. These values have an approximate log-normal distribution, and hence the largest 10% hydraulic conductivity value would be approximately 9 ft/d. For the velocity determinations of the three sites described above, average hydraulic conductivity is 2.31 ft/d. Therefore, there is a 10% probability that the hydraulic conductivity would be approximately 9/2.31 = 4 times that value. Another factor that plays an important part of any sensitivity analysis is the effective porosity, which in this paper is assumed to be 10%.

RELEVANT HYDROGEOLOGIC CONDITIONS IN FALL RIVER COUNTY

Figure 6 is a geologic cross section near Edgemont, South Dakota, illustrating the typical geology of much of southern Fall River County. At Igloo, for example, the Inyan Kara Group was encountered at 1,085 ft depth and the Madison Limestone was encountered at 3,590 ft. The potentiometric surface of the Madison at the Igloo site is 3,700 ft elevation (Strobel et al. 2000). This is above the land surface, and creates a flowing artesian well. The potentiometric surface of the Inyan Kara, on the other hand, is only 3,250 ft; this elevation is below the land surface. Under these conditions, it is very unlikely that groundwater could

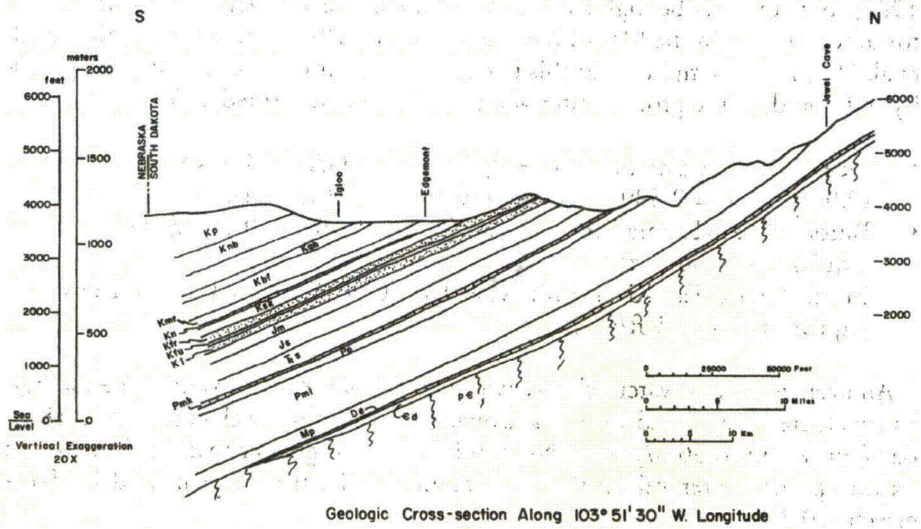

***Figure 6.** Geologic cross section near Edgemont, South Dakota (from Roggenthen et al. 1985). The sedimentary rocks include the Fall River Formation (K_{fr}), the Lakota Formation (K_l) and the Pahasapa Limestone (M_p).*

move from the Inyan Kara aquifer down to the Madison Limestone in most of southern Fall River County.

A relevant groundwater quality issue involves Powertech's plan to drill a waste disposal well into the Minnelusa or Deadwood Formation (Nuclear Regulatory Commission 2012). Rahn and Gries (1973) and Greene (1999) showed that there is a hydraulic connection between the Minnelusa Formation and the Madison Limestone at places. There is the possibility that the Madison aquifer could become contaminated with this waste.

DISSOLVED VS SOLID URANIUM IN A SANDSTONE AQUIFER

The ISL mining process will dissolve solid uranium minerals that occur in the sandstone. A consideration relevant for a pre-mining environmental assessment of an uranium ISL site is a comparison between the amount of uranium that is naturally dissolved in groundwater and the amount of uranium found as solid minerals in the aquifer matrix.

For the purpose of these calculations, a hypothetical uraniferous sandstone aquifer simulating the Dewey/Burdock area in the southwestern Black Hills is used, i.e., the 120 ft (36.6 m) thick Chilson Member of the Lakota Formation. An area underlying 10 acres (4.047 ha) is used for these calculations. The sandstone at this site is nearly horizontal; hence the volume can be approximated as: 36.6 m (4.047×10^4 m^2) = 1.48×10^6 m^3.

Solid uranium

According to the U.S. Senate (1972), as of October 1, 1963, uranium mining in the Black Hills totaled 367,497 tons (3.3339 X 10^8 kg) of ore; this ore contained 1,352,000 lbs (6.1327 X 10^5 kg) of U_3O_8. The actual amount of uranium within U_3O_8 ("yellowcake") can be determined from the atomic weights of uranium (238) and oxygen (16) as follows: 3 (238)/3 (238) + 8 (16) = 0.848 = 84.8%. Therefore, from the historic mining data, the amount of uranium mined in the southern Black Hills is 84.8% (6.1327 X 10^5 kg) = 5.2039 X 10^5 kg.

TVA (1979) reported that at the Dewey/Burdock area "...the ore minerals coat sand grains and fill interstices of complexly cross-stratified sandstone along solution fronts similar to 'roll' type deposits..." For this paper, the proportion of uranium in the sandstone at the Dewey/Burdock site is assumed to be the same as the uranium in the ore historically mined in the southern Black Hills. This proportion equals 5.2039 X 10^5 kg/ 3.3339 X 10^8 kg = 0.0015609 = 0.1561%. Assuming the sandstone weighs 2.20 gm/cm^3, the mass of the sandstone at the Dewey/Burdock site would be 2.2 X 10^4 kg/m^3 (1.480 X 10^6 m^3) = 3.257 X 10^{10} kg. Assuming the ore is distributed throughout the sandstone, the mass of uranium in solid form within this sandstone is 0.00156 (3.257 X 10^{10} kg) = 5.080 X 10^7 kg. [Interestingly, this is equivalent to approximately 15% of all the uranium historically mined in the southern Black Hills. Also of interest is that at the Dewey and Burdock site Powertech Uranium Corporation (2010) estimates the total amount of U_3O_8 to be 10,813,000 lb (4.905 X 10^6 kg.]

Dissolved uranium

Williamson and Carter (2001) showed data on dissolved uranium in groundwater in the Black Hills. In the Edgemont area, the highest concentration is approximately 30 micrograms per liter (μg/L), the same as U.S. Environmental Protection Agency's maximum permissible concentration for drinking water. In the southern Black Hills, Oak Ridge Gaseous Diffusion Plant (1980) showed uranium concentrations in groundwater; 340 samples averaged approximately 10 μg/L, although values up to 200 μg/L were found. Groundwater in Cretaceous rocks typically had high values. TVA (1979) reported that in 1977 the Burdock Well #1 had dissolved uranium ranging from 0.10 to 9.50 μg/L and dissolved ^{224}Ra ranging from 111.4 to 230.1 ρCi/L. For this paper it is assumed that dissolved uranium in the groundwater at this site has a concentration of 30 μg/L (equivalent to 3 X 10^{-5} kg/m^3). Assuming 10% porosity, the ten-acre sandstone unit used for these calculations contains 0.10 (1.48 X 10^6 m^3) = 1.480 X 10^5 m^3 of groundwater. Therefore the amount of dissolved uranium at this site is 1.48 X 10^6 m^3 (3 X 10^{-5} kg/m^3) = 44.4 kg.

Comparison

From above, the mass of the solid uranium under the ten acre site is 50.8 X 10^6 kg, and the mass of the liquid uranium under this site is 44.4 kg. The ratio is 1.14 X 10^6 : 1. Solid uranium (in the form of minerals such as carnotite, coffinite, uraninite, etc.) vastly exceeds the uranium dissolved in groundwater. This indicates that ISL uranium mining has the potential to dissolve vast amounts of uranium from its natural solid form.

The originally proposed method of mining by TVA at the Dewey/Burdock site was to be a conventional underground mining method (TVA, 1979). The proposed method of mining by Powertech (2009a, 2009b) is "solution mining", known as "in-situ leach", also called "in-situ recovery". This method will utilize chemicals pumped into the sandstone that dissolve the solid uranium minerals. Given the vast quantities of solid uranium that could be dissolved at this site, after mining ceases there will most likely still be a high concentration of dissolved uranium (as well as other elements) in the groundwater. The Nuclear Regulatory Commission (2012) notes "at the end of the uranium recovery process, constituents that were mobilized by the lixivients remain in the production aquifer. The NRC requires that groundwater quality be restored to a concentration limit established by the NRC." This water will migrate down gradient. Dissolved uranium generally precipitates in fully reduced zones, but uranium sorption also depends on the presence of iron hydroxides (Johnson and Tutu 2013, who concluded "…the resulting uncertainty of uranium sorption is quite high."). Although chemicals could be introduced to mitigate high concentrations of dissolved uranium, its ultimate concentration is unknown.

ENVIRONMENTAL IMPACTS FROM ISL URANIUM MINES

A major concern of conventional or ISL uranium mines is the fate of radioactive elements that remain in the area after mining ceases. Environmental impacts from conventional uranium mines in the Edgemont area are described by Rahn and Hall (1982).

A draft Environmental Impact Statement (DEIS) for the proposed Dewey/Burdock ISL uranium mine was prepared by the Nuclear Regulatory Commission (2012). [The NRC refers to the in-situ-leach (ISL) method of solution mining as in-situ recovery (ISR) method.] The DEIS, available "on line", contains a wealth of background environmental data but has no post-mining groundwater velocity determination such as given in this paper. Rather, the impacts envisioned by this project are discussed in terms of tables showing "ratings". For instance, NRC states the overall groundwater impact will be "small to moderate" and the "proposed mitigation measures will eliminate or substantially lessen potential adverse environmental impacts."

Following mining, the residual fluids in the project area will begin migrating through the aquifer. A major concern about ISL uranium mines is that no dissolved minerals or chemicals introduced into the mined zone should escape the project area. Mining companies assure the public that this will not happen because, during operation, recovery wells surround the injection wells. Presently there are six active in-situ leach (ISL) uranium recovery mines in the U.S. (Borch et al. 2012). Hall (2009) studied two ISL uranium mines in Texas and found that dissolved uranium and selenium are the two elements most likely to be above restoration objectives following termination of ISL operations.

In nearby Crawford, Nebraska, the Crow Butte ISL uranium mine has been in operation by Cameco Resources for 21 years. Coatings of coffinite, carnotite, and uraninite occur in basal Chadron conglomerate beds 65 -135 m (213 – 443 ft) below the ground surface (Spalding et al. 1984). The Crow Butte mine includes a system of 4,500 wells that use a solution of water, oxygen, and bicarbonate to dissolve uranium minerals and bring the liquid to a processing plant on the surface. A system of monitoring wells on the perimeter of the mined area is used to detect any excursions from the mine area. Dave Carlson, retired from the Nebraska Department of Environmental Quality, commented that the project has not negatively affected the surrounding aquifers (Woster 2012). A website for the SD DENR states that the most commonly reported problems at the Crow Butte mine are spills from production fluids and leaks in pond liners. They also report that "other problems include excursions for process fluids beyond the limits of the production zone".

Commenting on efforts to restore groundwater at an ISL mine at the Christensen Ranch area near Pumpkin Buttes, Wyoming, Lustgarten (2012) stated that a Nuclear Regulatory Commission report "… concluded that restoring water to baseline levels was 'not attainable' for many of the contaminants, including uranium".

SUMMARY

The chemistry of groundwater at an abandoned ISL uranium mine will be changed from its pre-mine condition. The amount of chemical change and the groundwater velocity downgradient from the mined site are important for any environmental assessment. The chemistry of this water will be greatly altered. Elements such as uranium, radium, and selenium will be dissolved by chemicals during the mining operation. These elements originally were bound up within the Inyan Kara aquifer as solid minerals. Solution mining will set them free as dissolved constituents in the groundwater. Their concentration and mobility within the aquifer is uncertain.

The ultimate fate of groundwater contaminants from an ISL uranium mine depends on the groundwater velocity and the natural attenuation that could immobilize contaminants such as uranium and selenium. In this paper, the natural groundwater velocity through the Inyan Kara aquifer in the Dewey/Burdock area is determined to be approximately 66 ft/year. If this relatively slow rate is representative, the average migration of contaminants from the proposed Dewey/Burdock ISL uranium mine would not appear to be a great concern to landowners who live miles away. The 1963 tritium data showing much faster velocity is an unresolved issue. It is not known if the data are accurate; but if they are, there could be fractures or permeable conglomerate channels that transmit groundwater much faster than the velocity calculated by traditional Darcy Law as presented in this paper.

Future research should include detailed hydrogeologic study of the permeability of fractures and the coarse-grained facies of the Inyan Kara Group as well as quantification of the chemical changes that could retard contaminant transport in groundwater from an ISL uranium mine.

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