Hydrogeological and hydrogeochemical evaluation of a proposed flue gas cleanup dry waste disposal pit near Beulah, North Dakota

Nathan T. Hunke

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HYDROGEOLOGICAL AND HYDROGEOCHEMICAL EVALUATION
OF A PROPOSED FLUE GAS CLEANUP DRY WASTE DISPOSAL PIT
NEAR BEULAH, NORTH DAKOTA

by
Nathan T. Hunke
Bachelor of Science, Bemidji State University, 1986

A Thesis
Submitted to the Graduate Faculty
of the
University of North Dakota
in partial fulfillment of the requirements
for the degree of
Master of Science

Grand Forks, North Dakota
August
1989
This thesis, submitted by Nathan T. Hunke in partial fulfillment of the requirements for the degree of Master of Science from the University of North Dakota, is hereby approved by the Faculty Advisory Committee, under whom the work has been done.

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(Member at Large)

This thesis meets the standards for appearance and conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

Dean of the Graduate School
Title: Hydrogeological and hydrogeochemical evaluation of a proposed flue gas cleanup dry waste disposal pit near Beulah, North Dakota

Department: Geology and Geological Engineering

Degree: Master of Science

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ABSTRACT

The Coyote I electrical operating station of the Montana Dakota Utilities Company (MDU) is located near Beulah, North Dakota. Flue gas cleanup (FGC) dry waste is generated by the facility in the conversion of coal to electricity. MDU submitted a permit application to the North Dakota State Department of Health (NDSDH) to dispose of FGC dry waste in a strip-mined area 1.6 kilometres northeast of the plant.

Two disposal pits were proposed by MDU, a Phase I and Phase II pit. The objectives of the investigation were to determine the hydrogeological and hydrogeochemical suitability of the site for FGC waste disposal and to develop a groundwater level and quality monitoring program for the landfill. These objectives were attained through installation of 18 monitoring wells and 3 test holes at the site.

Based on groundwater level information, groundwater was found to flow to the west-northwest. Two hydrogeologic units exist, a bedrock flow system and a glacial fill local flow system superimposed on the bedrock system. Water levels range from about 590 to 565 metres msl in the bedrock sediments and from 600 to 575 metres msl in the glacial fill sediments.

Background water quality was determined through a sampling procedure that focused upon groundwater at several
stratigraphic horizons beneath the site. Chemical analysis indicates a brackish background water quality with total dissolved solids (TDS) concentrations ranging from 1200 to 5000 milligrams per litre (mg/L) and averaging 2515 mg/L. A significantly higher TDS concentration was detected in Coyote-ash leachate generated during Extraction Procedure (EP) toxicity testing (greater than 32,000 mg/L).

The proposed Phase I pit lies from 12 to 18 metres above the local bedrock water table and is the site recommended for ash disposal. The proposed Phase II pit is not recommended for ash disposal as it lies, in part, within saturated low-permeability materials of the glacially-filled valley.

Strategically located monitoring wells which penetrate high-permeability lignite units at different stratigraphic levels were chosen to document the effects of waste disposal on the hydrogeology of the site. The groundwater quality monitoring plan should focus upon the uppermost bedrock aquifer. Two background water-quality and three down-gradient detection wells are recommended.

The base of the proposed FGC dry waste disposal pit should be maintained above the water table and constructed with a scarified and recompacted layer of in situ sediment. A gently-sloped compacted cap over the disposal setting will minimize infiltration and prevent leachate formation. This setting should provide long-term ash disposal success.
INTRODUCTION

Problem

Coyote Station Unit I is a 410 megawatt electrical power generating facility that began commercial operation in May 1981, four years after construction of the facility began. The coal-fired power plant is jointly owned by Montana-Dakota Utilities Co. (MDU) and several other power companies of the Dakotas and Minnesota. The facility burns North Dakota lignite that is mined from open-pit strip-mines located in upland areas surrounding the plant. The lignite is provided to the mine-mouth plant at a rate of about 19,732 metric tons per week or about 947,000 metric tons per year (Montana-Dakota Utilities Company). This is roughly 23,000 railroad cars of coal consumption each year.

Coyote Station is ideally located for electrical power generation, lying in close proximity to: (1) vast lignite reserves of the near-surface Beulah-Zap lignite bed, which are required to fuel the plant's massive generator; and (2) abundant water, supplied by the Missouri River several miles north of the plant.

The lignite is burned to produce high pressure steam which rotates the plant's large turbine to generate electricity. The by-product of electrical power generation is approximately 115,000 cubic metres of Flue Gas Cleanup (FGC) dry waste each year (Montana-Dakota Utilities Co., 1988). In the facility's environmental control systems,
sodium carbonate (Na₂CO₃) is reacted with sulfur dioxide gas (SO₂) to form sodium sulfate (Na₂SO₄). FGC dry waste, a mixture of fly ash, Na₂SO₄ and unreacted Na₂CO₃, accumulates in the plant's anti-pollution devices. The waste is then transferred to an intermediate storage silo and is ultimately hauled to an abandoned strip-mine for permanent disposition. The present abandoned strip-mine storage facility is scheduled to reach capacity by early 1989 (Verwey, 1988) and a search for a new disposal facility is underway. On June 15, 1987, Montana-Dakota Utilities Company submitted a permit application to the North Dakota State Department of Health (NDSDH) for authorization to dispose of FGC dry waste in a strip-mined area known as the Black Pit. The submittal was reviewed and an evaluation summary was prepared by the North Dakota State Health Department (NDSDH) on August 10, 1987. Several questions about the hydrogeologic suitability of the proposed disposal site were raised. The need for further characterization of the hydrogeologic regime of the proposed disposal site was recognized, and led to the present supplemental investigation by the North Dakota Mining and Mineral Resources Research Institute (NDMMRRI).

Objectives

The objectives of the present investigation were to determine the hydrogeologic suitability of the Black Pit site for disposal of FGC dry waste and to develop associated
groundwater monitoring programs for the landfill by further defining the physical and hydrogeologic characteristics of the setting.

Specific objectives of the groundwater investigation were to:

1. Define the hydrogeologic conditions of a glacially-filled valley in the northern and eastern portions of the study site.
2. Characterize the nature, extent, and temporal variability of perched water table conditions in near-surface lignite units of the bedrock part of the study site.
3. Develop a groundwater level and quality monitoring program for the landfill.
4. Determine the background chemical composition of the groundwater at the study site.

The specific objectives defined above were met, in part, by supplementing results from previous investigations (Montana-Dakota Utilities Co., 1987) and by studying previously undefined aspects of the site.

Location

The proposed Coyote I FGC dry waste disposal area lies in the northwest, southeast, and southwest quarters of Section 11, T 143N, R 88W, in eastern Mercer County of west-central North Dakota, approximately 3.2 kilometres south-southwest of Beulah (Figure 1). The Montana-Dakota
Figure 1. Study Site Location
(In Section 11, T 143N, R 88W)
Utilities Coyote Station is located near the proposed ash-disposal site (Figure 2). The strip-mined area known as the Green Pit lies northeast and is the active disposal site for FGC dry waste (Figure 2). The proposed waste disposal site, also shown on the "Test Hole, Piezometer, and Pit Boundary Location Map" (Plate 1), consists of a Phase I and Phase II pit with bottom elevations of 588 metres and 582 metres msl, respectively (Figure 3). A geologic interpretation of the site is also included on Plate 1.

Physiography and Topography

The local setting contains two major physiographic features: (1) rolling-to-hummocky upland areas and (2), the Knife River which is incised into the uplands (Figure 4). The Knife River, an underfit stream occupying a large, alluvial-filled floodplain, is the master stream of the area, flowing northeasterly to its confluence with the Missouri River approximately 20 kilometres from the study site (Montana Dakota Utilities Co., 1987). The gently-rolling-to-hummocky upland areas are dissected by intermittent tributaries of the Knife River (Figure 4).

The topography of the Knife River Basin, which lies mostly within the glaciated portion of the Missouri Plateau, is characterized by integrated drainage. Maximum relief in the area is approximately 91 metres. The effects of glacia-tion on the topography are minimal, as nearly all of the glacial materials have been removed from the uplands
Figure 2. Coyote I FGC Waste Disposal Site Location
(Top Half of Figure 1)
MDU Coyote Station and Knife River Coal Mining Co

MDU Black Pit

EXPLANATION

--- Ephemeral Tributary of The Knife River

--- Railroad

--- Glacially-Filled Valley Boundary

300 m
1000 ft

Section Line

N

MDU Green Pit

Co
Figure 3. Proposed Phase I And Phase II FGC Dry Waste Disposal Pits
EXPLANATION

- Ephemeral Tributary
- Glacially-Filled Valley

Proposed Phase II Pit (582m)
Proposed Phase I Pit (588m)

300 m
1000 ft
Figure 4. Topographic Map Of The Study Site And Surrounding Area
by erosion; typically, only lag deposits of boulders remain on the surface, but large glacial valley fills occur in diversion trenches and preglacial channels and valleys. Missouri River diversion trenches, which exist near the towns of Beulah, Hazen, and Underwood, trend northeast-southwest and are incised as much as 122 metres below the surrounding highlands (Groenewold, et al., 1979). The topography of the area is described as glacially-modified bedrock topography, the mantle of drift generally following the preglacial topography (Carlson, 1973).

The study site is characterized by a steeply sloping upland area where the mining activities of the Black Pit have greatly modified the preexisting topography (Plate 1). The upland is dissected to the west by steep-sided draws containing ephemeral streams which drain into a deeply-incised, unnamed tributary to the Knife River bordering the site to the south and west. A glacially-filled valley occupies the northern and eastern portions of the study area (Plate 1).

**Climate**

The west-central region of North Dakota is dominated by a semi-arid continental climate (Montana-Dakota Utilities Co., 1987). The continental characteristics of the climate are reinforced by the Rocky Mountains which modify the temperature and moisture characteristics of the easterly flow of air. Monotonous weather systems are typically not
encountered in North Dakota due to the various source regions of the air masses that converge upon the state (Jensen, 1972).

Yearly temperature fluctuations are extreme. The coldest month is January with a daily minimum of roughly -17°C, and daily maximum temperatures near -5°C, while July is the hottest month, with low temperatures averaging 13°C and daily highs averaging 29°C (Montana-Dakota Utilities Co., 1987).

Precipitation amounts vary widely. An average of 410 millimetres of precipitation falls upon the region each year with less than 25 millimetres of precipitation typically occurring during the winter months (Montana-Dakota Utilities Co., 1987). The largest amount of precipitation falls upon west-central North Dakota during the spring and early summer. The majority of the groundwater recharge also occurs at this time, as the effects of evapotranspiration are small and precipitation that has accumulated during the previous 4 to 5 winter months is available for infiltration and can pass below the root zone, unimpeded by the effects of evapotranspiration (Rehm, et al., 1982).

The average length of the growing season is about 120 days but varies drastically from year-to-year (Montana-Dakota Utilities Co., 1987).

Previous Work

The lignite deposits of North Dakota have been estimat-
ed to occupy 72,520 square kilometres (Leonard, Babcock, and Dove, 1925). The extent and thickness of individual beds were described and the Beulah-Zap bed was recognized and named in that reconnaissance study of the prospecting and development of lignite deposits in North Dakota.

The geology of Mercer and Oliver counties was studied in 1966, 1967, and 1968 (Carlson, 1973), in which previous geologic investigations were compiled and a complete geological survey of the two-county area was developed.

Relatively few hydrogeologic investigations of the area can be found in the literature prior to the 1970's; one of the first was conducted near Beulah, North Dakota to locate an alternative source of water to groundwater of the Knife River valley aquifer (Bradley and Jensen, 1962). A few years later, several pump tests were conducted on wells penetrating the Fox Hills, Hell Creek, and Bullion Creek Formations of Oliver and Mercer counties in order to define particular aquifer parameters and evaluate the potential of these sediments to produce groundwater (Croft and Wesolowski, 1970). Valuable groundwater basic data for the area was compiled by Croft (1970), followed by a comprehensive groundwater study to determine the quantity and quality of groundwater available for municipal, domestic, livestock, industrial, and irrigation use in Mercer and Oliver counties (Croft, 1973).

Various hydrogeologic and hydrogeochemical investi-
investigations have been conducted in the Knife River Basin area associated with the rapidly expanding use of lignite as a fuel to generate electrical energy. This has resulted in several reports of investigations by the North Dakota Geological Survey (Moran et al., 1978a, 1978b; Groenewold et al., 1979, 1983) and several unpublished Master's theses (Gilman, 1975; Morin, 1979; Winbourn, 1986). Several of these investigations led to the development of a hydrogeochemical model which describes the evolution of shallow subsurface groundwater of undisturbed and disturbed settings in western North Dakota (Moran et al., 1978a, 1978b; Groenewold, et al., 1983). Similar investigations have focused upon strip-mined areas other than the Knife River Basin (Van Voast and Hedges, 1975; Houghton, et al., 1984).

As a result of coal-fired electrical power production, \(2 \times 10^9\) kg (2,000,000 metric tons) of coal conversion solid wastes are generated annually in North Dakota (Beaver, 1986, p. 2). Much of the waste is disposed in reclaimed strip-mine areas adjacent to mine-mouth electrical power plants. A major concern is the effect of ash disposal on groundwater quality, as leachate generated from the waste deposit is typically highly-mineralized, has high concentrations of several major ions and several toxic trace elements, and is highly alkaline (Groenewold and Manz, 1982; Groenewold, et al., 1985; Beaver, 1986). The possible deleterious effects of ash disposal have prompted several investigations direct-
ly related to disposal of ash in western North Dakota. For a discussion of the regulatory history of groundwater contamination control of hazardous solid wastes, see Beaver (1986).

Two types of disposal settings were studied at the Center mine south of Center, North Dakota: (1) pit-bottom, disposal of ash at the base of a strip-mined pit, generally below the post-mining water table; and (2) vee-notch, ash disposal between spoil ridges, typically above the post-mining water table and the base of the spoils (Groenewold and Manz, 1982). That study concluded that ash disposal below the post-mining water table promotes dissolution, leaching, and migration of various constituents, generating a water characterized by high TDS concentrations, whereas disposal above the post-closure water table is the most suitable ash disposal setting, as the waste material is mostly dry with little or no leaching.

The capacity of western North Dakota overburden sediments to neutralize alkaline leachate generated from ash disposal was investigated by Koob and Groenewold (1984). All sediments tested illustrated an ability to neutralize alkaline solutions in the laboratory. Several possible mechanisms of hydroxyl anion consumption were discussed, including base neutralization by bicarbonate anions, neutralization by cation exchange, base induced hydrolysis of aluminosilicate matrix or organics, and anion exchange.
An investigation of the effects of saturated and unsaturated fly ash disposal on groundwater quality and the capacity of western North Dakota overburden to attenuate and neutralize chemical constituents was also conducted (Groenewold, et al., 1985, Hassett and Groenewold, 1986). That study was complemented by earlier works (Groenewold and Manz, 1982; Koob and Groenewold, 1984). The pozzolanic processes that harden fly-ash after disposal and produce a much less reactive mass of solid waste were also discussed.

Hassett and Groenewold (1986) conducted laboratory attenuation experiments in order to determine the specific processes involved in the immobilization of several major and trace elements that concentrate in fly ash and flue gas desulfurization (FGD) waste. Several types were gathered from western and central North Dakota overburden and specific attenuation processes determined. The results show that immobilization is approximately 100% for iron and cadmium, 50-95% for arsenic, 0-90% for selenium, and virtually 0% for molybdenum. It was concluded that western North Dakota overburden sediments have a strong tendency to attenuate iron (as iron hydroxide), cadmium, during hydroxide carbonate precipitation, and arsenic and selenium through pH dependency, immobilization increasing as pH decreases.

A long-term field investigation of the hydrogeologic and hydrogeochemical effects of fly-ash and FGD waste disposal was summarized (Beaver, 1986). The chemical char-
acteristics of undisturbed, disturbed, FGD waste disposal, and fly-ash disposal settings were compared and concentrations versus time plots for the various species common to ash-originated leachate were constructed. That study showed that sodium, sulfate, calcium, magnesium, barium, and molybdenum are relatively mobile while arsenic, selenium, lead, chromium, and iron are effectively attenuated once outside the waste deposit. The results indicate clay-rich native sediments, iron hydroxide precipitation, and carbonate and sulfate precipitation, impart rapid attenuation of most ash-leached trace elements and rapid buffering of pH of any waste-originated leachate. These findings are similar to the results of experiments conducted in the laboratory (Koob and Groenewold, 1984; Groenewold, et al., 1985; Hassett and Groenewold, 1986).

The results of these investigations of the effects of ash disposal on shallow subsurface groundwater in western North Dakota were applied to a particular ash-disposal setting near Mandan, North Dakota (Ronnei, 1987). The effect of fly-ash disposal varies, dependent upon microclimate and geology. Compare, for example, Kean and Cherkauer, 1980; and Ripp and Villaume, 1985.
Regional Geology

The North Dakota stratigraphic column is presented in Figure 5. The sedimentary and tectonic history of the Williston basin has been described by Carlson and Anderson (1970) and the regional geology of Mercer and Oliver Counties by Carlson (1973). The following discussion is largely from these two studies.

Mercer and Oliver counties lie on the southeastern flank of the Williston structural basin with Precambrian basement rock at depths of 3810 to 3962 metres beneath the surface. The Paleozoic and Mesozoic geologic record makes up approximately 2559 to 3688 metres of this total thickness.

During late Mesozoic time, marine conditions led to the deposition of the Pierre Formation (Figure 5), a thick sequence of shale that forms the base of the freshwater-bearing units beneath Mercer and Oliver counties (Croft, 1973, p. 17). The following discussion is restricted to those units above the Pierre, as the underlying formations are largely irrelevant to this investigation.

The Fox Hills and Hell Creek Formations directly overlie the Pierre Formation and were deposited during late Cretaceous time (Figure 5). The Fox Hills Formation ranges from 61 to 99 metres in thickness and records the last phase of marine Cretaceous deposition. An upper unit of fine-to
Figure 5. North Dakota Stratigraphic Column
(From Groenewold, et al., 1979, p.4)
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<tr>
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<th>SYSTEM</th>
<th>SEQUENCE</th>
<th>GROUP</th>
<th>FORMATION</th>
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medium-grained sandstone lies beneath the study area and is the probable equivalent of the Colgate member of surface stratigraphic studies (Carlson, 1973). The Hell Creek Formation was deposited during predominantly non-marine conditions and consists of a series of siltstones, claystones, and sandstones, lignitic in part. The formation ranges in thickness from 56 to 104 metres.

The Ludlow, Cannonball, Slope, Bullion Creek, and Sentinel Butte Formations are all part of the Fort Union Group, deposited during the Paleocene epoch of the Tertiary (Figure 5). Nomenclature changes led to the removal of the Tongue River Formation and the addition of the Slope and Bullion Creek Formations to the North Dakota stratigraphic column (Clayton, et al., 1977). Predominantly non-marine conditions continued from the late Cretaceous through early Paleocene times, depositing the Ludlow and Slope Formations which consist of sandstone, siltstone and lignite. The marine lateral equivalent of the Ludlow and Slope Formations, the Cannonball Formation, consists of marine shale, silt, and sand deposited by the last marine invasion in this area. The Bullion Creek and Sentinel Butte Formations of the upper Fort Union Group represent non-marine deposition and consist of sand, silt, clay, and interbedded shale, lignite and limestone. These sediments were deposited in a deltaic plain environment which terminated at the shorelines of an inland sea (Jacob, 1976) or in a swamp and fluvial-
lacustrine environment on a broad alluvial plain (Daly, et al., 1985). The Upper Fort Union Group sediments range in thickness from 290 to 428 metres.

The overlying nonmarine Golden Valley Formation was deposited during Paleocene to Eocene time and consists of sand, silt, and clay, roughly 50 metres in thickness (Figure 5).

Deposits of the Coleharbor Group and Oahe Formation veneer the landscape, marking the effects of glaciation, wind and water, during Pleistocene to Holocene geologic time. Though these sediments are generally thin, nearly 90 metres of Pleistocene and Holocene fill occurs in meltwater diversion trenches in the area.

Regional Hydrogeology

The Pierre shale forms an extensive, regional aquitard (Groenewold, et al., 1979). Therefore, discussion of the regional hydrogeology is limited to the sediments above the Pierre Formation (Figure 5).

Three distinct aquifers are delineated in the subsurface beneath the study area: (1) the upper Fox Hills-basal Hell Creek aquifer, which includes the upper Fox Hills sandstone (the Colgate Member of the Fox Hills Formation) and a fine-to medium-grained sandstone of the Hell Creek Formation; (2) the upper Hell Creek and lower Cannonball-Ludlow aquifer, fine-to medium-grained sandstone of the base of the Upper Hell Creek Formation and fine-grained sandstone of the base of the
Ludlow-Cannonball Formation, undifferentiated; and (3) the lower Bullion Creek aquifer, fine-to medium-grained sandstone at the base of the Bullion Creek Formation (Croft, 1973). The stratigraphic units that contain these aquifers are shown in Figure 5.

The upper Fox Hills-basal Hell Creek aquifer ranges from 46 to 113 metres in thickness. Several pump tests conducted on the aquifer yielded transmissivities averaging $7.3 \times 10^5$ m$^2$/s, and a mean hydraulic conductivity of $7.4 \times 10^4$ m/s. Storage coefficients range from $10^{-4}$ to $10^{-5}$ and an average specific capacity of 17.6 m$^3$/day was calculated for the aquifer (Croft, 1973). The water is a sodium-bicarbonate type with total dissolved solids (TDS) concentration ranging from 1230 to 1990 parts per million (ppm) (Croft, 1973). Water movement through the aquifer is from west to east.

The upper Hell Creek and lower Cannonball-Ludlow aquifer underlies all of Mercer and Oliver counties at depths ranging from 152 to 396 metres. Transmissivities range from $2.6 \times 10^5$ to $6.0 \times 10^4$ m$^2$/s and expected yields range from 0.3 to 6.3 L/s. The water produced from this aquifer is a sodium-bicarbonate type with a TDS concentration between 1510 and 1890 ppm (Croft, 1973).

The lower Bullion Creek aquifer zone lies between 30 and 152 metres beneath the land surface and underlies the southwest corner of Mercer County and most of Oliver County.
A hydraulic conductivity of $2.8 \times 10^3$ to $4.6 \times 10^3$ m/s was calculated from three core samples. Wells tapping the aquifer yield from 0.3 to 3.2 L/s (Croft, 1973). Water movement through the lower Bullion Creek aquifer zone is from south-southwest to the north-northeast.

Head differences indicate that water movement is upward from the upper Fox Hills-basal Hell Creek aquifer to the upper Hell Creek-lower Cannonball-Ludlow aquifer and downward from the lower Bullion Creek aquifer to the upper Hell Creek-lower Cannonball-Ludlow aquifer indicating that the upper Hell Creek-lower Cannonball-Ludlow aquifer is a regional groundwater sink (Croft, 1973 and Figure 5).

Lignite aquifers of the Bullion Creek and Sentinel Butte Formations are generally less than 90 metres below land surface and generally yield between 4.0 and 38 L/min (Croft, 1973). Lignite aquifers of the Northern Great Plains region of the United States, southern Saskatchewan, and Alberta average $3.0 \times 10^4$ m/s. Sand and sandstone aquifers associated with lignite deposits exhibit a similar average ($1.0 \times 10^4$ m/s), but the frequency distribution of hydraulic conductivities of sandy sediments are more strongly skewed toward low conductivity due to the general presence of other fine particles in these sediments (Rehm, et al., 1980).

Glacial drift and alluvial sediments occupy glacial meltwater trenches and form several important aquifers in
the vicinity. Hydraulic conductivities for Pleistocene sand and gravel deposits of the Northern Great Plains typically average $5.0 \times 10^3$ m/s (Rehm, et al., 1980).
METHODOLOGY

Selection of Additional Groundwater Monitoring Well and Test Hole Locations

A review was made of both the FGC dry waste special use permit application (Montana-Dakota Utilities Co., 1987), and an evaluation summary of the permit application, prepared by the NDSDH (Tillotson, 1987). The preexisting monitoring wells and test holes are shown on Plate 1. A series of test holes and groundwater instrumentation (1700-1721) installed during this investigation are shown on Figure 6 (and Plate 1). Two additional areas where monitoring wells and test holes were needed are: (1) the bedrock part of the study site, represented by a very hummocky surface where the mining activities of the Black Pit have greatly modified the preexisting topography, and (2) the northern and eastern portions of the study site where a glacially-filled valley occupies the subsurface (Plate 1). The selection of monitoring well and test hole sites is based upon several site-specific deficiencies recognized by the NDSDH (Tillotson, 1987).

In the bedrock part of the proposed ash disposal site, anomalous, possibly perched, water table conditions were identified in several wells during the previous investigation (Montana-Dakota Utilities Co., 1987). Perched water table conditions were recognized in the upper Beulah-Zap, lower Beulah-Zap, and Spaer lignites of the Sentinel
Figure 6. Location Of Additional Groundwater Monitoring Wells And Test Holes Installed During This Investigation
Butte Formation (Figure 5 and Plates 2 and 3). Specifically, perched water at an elevation of 588 metres was measured in monitoring well BP4-U, screened in the upper Beulah-Zap lignite, 0.2 metres above the elevation of the base of the proposed Phase I pit (Plate 1). Perched water was also identified at elevations of 585 and 583 metres msl in monitoring wells BP2-A, and BP5, respectively, screened in the lower Beulah-Zap lignite which lies 1-2 metres below the base of the upper Beulah-Zap lignite. These water table elevations lie between 2.4 and 4.9 metres beneath the proposed Phase I pit bottom. Possible saturated conditions for the upper Spaer lignite were identified during drilling of bore hole 1469. Monitoring wells 1463 and 806 (Plate 1), screened in the Spaer silty sand, recorded saturated conditions at elevations of 577 and 578 metres respectively, approximately 10 metres beneath the proposed Phase I pit.

Along the western edge of the proposed Phase I pit, adequate hydrologic control was lacking, as the wells in that area of the study site were either too deep or too shallow. A water level elevation of 573 metres was noted for monitoring well 810, screened in the Spaer silty clay, well below the proposed Phase I and II pit bottoms. Monitoring wells TA2 and BP1, which lie in and around the proposed Phase II pit (Plate 1), fail to reach a sufficient depth to allow for determination of the lithologic and hydrologic characteristics of the sediments. Monitoring wells TA2 and
BP1 are also shallow, reaching only the upper Beulah-Zap and lower Beulah-Zap lignites, respectively.

Consequently, additional groundwater monitoring instrumentation, screened in the upper and lower Beulah-Zap lignites and possibly the Spaer lignite, was needed to further characterize the near-surface hydrologic regime in the bedrock portion of the study area.

The next area identified for installation of additional groundwater monitoring wells and test holes was the northern and eastern part of the study area where a glaciofluvial channel was identified in the subsurface during previous investigations (Montana Dakota Utilities Co., 1987). In this area, saturated conditions were detected in a Coleharbor sand at monitoring well 820 (Plate 1), at an elevation of 580 metres above sea level and approximately 2 metres below the proposed Phase II pit boundary. The extension of Coleharbor sand into the Black Pit was confirmed by exposures of glaciofluvial sediment in the highwall of the Black Pit. A transect of borings across the northern and eastern parts of the study area was proposed to further characterize the saturated conditions of the so-called paleo-channel and to define the thickness and extent of the glacial sediment.

Thus, further characterization of the groundwater flow regime in several areas of the study site was required. The selection of additional water table monitoring wells and
test hole locations was made. New information was gathered during the drilling procedure which provided additional insight to the hydrogeologic conditions at the study site. As a result, well locations changed as drilling proceeded.

**Drilling and Descriptive Logging**

The exploratory holes and monitoring wells were drilled with a 13.3-centimetre bit using an air mist rotary drilling rig, with fluid injection upon circulation loss. Circulation loss most often occurred when a lignite unit was penetrated and air loss resulted due to the highly fractured lignite. This made sample collection difficult. Water circulation did not greatly improve the situation, as the lignite units do not greatly restrict the flow of water, either. Drilling was difficult in glacial pebble-loam sediment due to its agglomeritic and plastic characteristics. Soap was used to alleviate penetration problems in that sediment. Every attempt was made to minimize drilling fluid injection.

Samples were bagged and lithologic descriptions made at 1.5-metre intervals as drilling proceeded. The samples were then placed in plastic "zip-lock" bags for laboratory analysis to aid in well log descriptions. The sample bags were labeled according to well number, date, and depth of penetration.

**Monitoring Well Construction and Installation**

Monitoring wells were constructed on site, using 2-inch
(5.1-cm) schedule 40 PVC pipe and screen. With one exception, the screened interval consisted of a 6.1-metre section for water table observation wells and a 1.5-metre section for piezometers; piezometer 1711 has a screened interval of 3.0-metres, as the presence of saturated conditions in either seam of the Spaer lignite split (separated by about 3.0 metres of silty clay) was anticipated. A 25-millimetre slot size was used. The piezometers and water table observation wells were then installed. Shallow wells were constructed at the surface while deeper well construction consisted of in-hole installation, section-by-section. Silica sand was tremied to approximately 0.3 to 0.6 metres above the screen to form a sand pack surrounding the screen and the remaining space was filled with grout cement to form a seal and to prevent groundwater cross-contamination between wells. A grout pad approximately 0.5-metres in radius was then poured around each monitoring well. Well numbers were placed on each monitoring well to enable easy field identification and the wells were capped with a 5.1-centimetre male adaptor to prevent contaminants from entering the well. The piezometers were installed in nests of 2 to 3, with the depth of penetration dependent upon the lithologic unit of interest beneath a particular location.

Typical piezometer construction is shown in Figure 7A. Typical water table observation well construction is shown
Figure 7. Schematic Representation Of Typical Monitoring Well Construction (Modified From Ronnei, 1987)
A = Typical Piezometer Construction
B = Typical Water Table Observation Well Construction
A 5.1 cm Threaded End Cap/Male Adaptor

Ground Surface

5.1 cm PVC Schedule 40 Pipe

Grout Seal

Water level

5.1 cm Slotted PVC Schedule 40 Pipe
25 mm x 0.25 mm Slots

1.5 m Screen Interval

(Not To Scale) Plezometer
\( \psi > 0 \)

B

5.1 cm Slotted PVC Schedule 40 Pipe (25 mm x 0.25 mm Slots)

Sand Pack

Water level

~6.1 m Screen Interval

(Not To Scale) Water Table
Observation Well
\( \psi = 0 \)

\( \psi \) - Pressure Head
in Figure 7B. The symbol beneath each well type denotes pressure head.

Well Development

A large metal slug and a PVC bailer were used to develop the wells. The slug was used to surge the well and draw the fines out of the surrounding geologic unit to form a tight sand pack. The water was then brought to the surface using a bailer. Each well was bailed until about three well volumes of water were removed or until the well was bailed nearly dry. About 2 weeks were then allowed for the water levels to reach equilibrium before water level measurements were made.

Water Level Measurements

An electric water level tape was used to obtain water level measurements. The level was measured from the top of the casing for each well. The surveyed elevation of the top of the pipe was used to determine the water level elevation. Water level measurements were obtained for new and previously existing groundwater monitoring instrumentation. These were made on a monthly basis by Paul Nelson, the Coyote Station grounds engineer, after the initial survey of levels was made.

Geophysical Logging

The deepest well of each piezometer nest, as well as each exploratory test hole, was geophysically logged immediately following completion of the hole. The survey
included gamma ray, density, neutron, and resistivity logs. A lithologic column was constructed adjacent to the geophysical log with the aid of lithologic descriptions from the drilling operation. This information was then combined to construct well log descriptions. The gamma ray logging device is especially useful for lithologic interpretations in coal bearing strata when used in combination with the other surveys. Gamma rays are electromagnetic radiation produced by nuclear decay of certain naturally occurring unstable isotopes. Clay strata show the greatest amount of radiation, the amount decreasing through siltstone and dirty sandstone. Clean sandstone and lignite typically exhibit the lowest response and must be differentiated using other geophysical tools (Hoffman, et al., 1982). The vertical resolution of the gamma ray response was poor and so the other logs were used to define the vertical contacts more accurately. These data were then combined with water level measurements to construct four hydrostratigraphic cross sections (Plates 2 and 3). Existing subsurface data collected from previous studies were also used.

Chemistry Sampling Procedure

The groundwater sampling procedure was conducted in accordance with the detailed methods used by the Wisconsin Department of Natural Resources (Lindorff, et al., 1987). Several wells at different stratigraphic intervals were monitored for background water quality at the study site.
Well purging was carried out using a PVC bailer attached to approximately 30 metres of nylon cord. Well purging is important as the water quality of water standing in a well prior to sampling is affected by:

1. Leaching or adsorption of certain constituents from or onto the well casing or screen.
2. Depletion of heavy metal species precipitated by sulfide which is produced by sulfate-reducing bacteria common to stored water.
3. Precipitation of certain metals due to changes in concentration of certain gases.
4. Addition of foreign materials through the top of the well (Lindorff, et al., 1987).

Approximately four well volumes of water were removed for those wells screened in high permeability sediments (e.g., lignite and sand). Wells screened in low permeability sediments were bailed dry and allowed just enough time to recover to collect an adequate volume of sample. The well purging technique involved lowering the PVC bailer to the top of the column of water. The bailer was then allowed to fill and brought slowly to the surface. The water was removed from the top of the water column so that: (1) the entire column of stagnant water would be replaced by fresh water, (2) contamination from the rope would be minimized, and (3) agitation of sediment that may be present at the bottom of the well would be prevented.
Figure 8. Background Water Quality Monitoring Wells
**EXPLANATION**

- ▲ Monitoring Well
- Ephemeral Tributary
- Glacially-Filled Valley

**INTERVAL**

- Antelope Creek Lignite
- Soar Lignite
- Soar Sand
- Lower Beulah-Zap Lignite
- Upper Beulah-Zap Lignite
- Coleharbor Pebble Loam

**MONITORING WELLS**

- 1701
- 1714
- 1721
- 1709
- 1463
- BP2-A
- BP4-U
- 1709
- 1710
Groundwater sampling was conducted using a PVC bailer with a check valve at the base. Prior to sampling, the bailer was rinsed with distilled water to remove any contaminants that may have collected on the bailer between sampling locations and to prevent aquifer cross-contamination. A plastic garbage bag was then placed around the well to prevent the rope from touching the ground. The bailer was lowered slowly into the well until the water column was reached. The sample was again taken from the top of the water column to prevent rope contamination and sediment incorporation. The sample was then slowly retrieved and evacuated from the bottom of the bailer into a container using the check valve to minimize aeration. Field water quality parameters were then measured, including temperature, pH, and specific conductivity. Temperature and conductivity were measured contemporaneously due to the temperature dependence of electrical conductivity. Conductivity values were then standardized to 25°C. Color, odor, and turbidity were also noted. The temperature, conductivity, and pH probes were then rinsed with distilled water.

The sample was filtered using a peristaltic pump, connected to an in-line, positive pressure, filtering apparatus containing a 0.45 micron filter. The filtering apparatus drained into a plastic sample bottle placed beneath the filter. Approximately 500 mL of distilled water were then flushed through the filtering system to remove
contaminants. If the sample was turbid, an 8.0 micron prefilter was placed upon the 0.45 micron filter to remove sediment which could clog the 0.45 micron filter. Two water samples were collected at each well, 1000 mL for major ion analysis, and 500 mL for trace element analysis. Samples collected for trace element analysis were preserved by adding 5 mL of nitric acid to stabilize the appropriate chemical constituents.

Temperature, pH, conductivity, date, and well number were recorded on the sample bottle. All samples were then placed in an ice chest to cool to prevent heating above ambient ground temperature. Major and trace element analyses were conducted at the Energy and Mineral Research Center Fuels Analysis Laboratory using various standardized inorganic analytical techniques (Hassett, 1988).
RESULTS

Results from previous investigations are contained in the Permit Application (Montana-Dakota Utilities Co., 1987). Results of the present investigation are included in their entirety in the Appendices of this report. Water level data, including well number, depth, elevation screened, water level, and interval screened, are included for newly installed instrumentation (Appendix A). Updated water level information for preexisting instrumentation is also contained in Appendix A. Composite water level information for newly installed monitoring wells, including well number, date, and static water level, are presented in Appendix B, including water level information for preexisting monitoring wells. Descriptive logs, including well number, interval, and lithologic description, are contained in Appendix C.

Several in situ hydraulic conductivity tests were conducted on sediments which directly underlie the proposed pit. The values obtained are included in Appendix D. The results of the background water quality analysis are presented in Appendix E. Background water quality concentrations of several major and trace element constituents, as well as several field and laboratory chemical parameters, are included. Well completion reports which contain data on the drilling operation details of piezometer and water-table-observation-well construction and installation information (coordinates and elevations) plus other data, are presented
in Appendix F.

A base map of the study site and several hydrostratigraphic cross-sections are included in a series of three plates and are discussed in detail in the next section.

Geology

Groundwater occupies the pores of the material at the study site. Consequently, an understanding of the geology at the site is necessary to fully understand the interactions of groundwater within the geologic framework. A geologic map and several hydrostratigraphic cross-sections were constructed using data collected from newly-installed, as well as existing groundwater monitoring instrumentation (Plates 1, 2, and 3). The locations of the test holes, piezometers, and water table observation wells used to characterize the geology and the hydrogeology of the site are also shown on Plate 1.

The study site lies within the Coleharbor and Sentinel Butte Formations which are shown in relation to the general stratigraphy of the area in Figure 9. The Sentinel Butte Formation is the surficial bedrock unit of the area and is exposed in the highwalls of the Black Pit. The Coleharbor Formation is represented by surficial lag deposits of boulders and a large glacially-filled valley in the northern and eastern portions of the proposed disposal site (Plate 1).
Figure 9. Generalized Stratigraphic Column
Coleharbor sediments are also exposed in the highwalls of the Black Pit.

**Coleharbor Formation**

The Coleharbor Formation, as it exists in the Knife River Basin, consists of glacially derived gravel, sand, silt, clay, and pebble loam. All unconsolidated Pleistocene age sediments deposited during glacial and interglacial periods are included in the Coleharbor Formation. Valley fill, consisting of outwash gravels, sand, silt, clay, and pebble loam, occurs in diversion trenches and preglacial and glacial stream channels and valleys. These valley fills range up to 91 metres or more in thickness (Groenewold, et al., 1979). The Coleharbor Formation unconformably overlies the Sentinel Butte Formation. The dominant lithology of the Coleharbor Formation in the study area is pebble loam with lesser amounts of interbedded gravel, sand, silt, and clay. The pebble loam consists of clay with silt, sand, pebbles, cobbles, boulders, and interspersed lignite fragments. Where the pebble loam is oxidized, it is olive-colored and iron stained. Where it is unoxidized, or reduced, it is grey. Beds of gravel, sand, silt, and clay occur throughout the valley fill as laterally discontinuous lenses. Glacio-lacustrine and glacio-fluvial sedimentation is the probable origin of the gravel, sand, silt, and clay lenses in the till. Glacio-fluvial sediments are exposed in the eastern highwall of the present pit. The sediments consist of
lenses of brown, well-sorted, fine sand in a pebble loam matrix.

The formation occupies a large glacial fill in the northern and eastern portions of the study area and is also found in terrace deposits which lie along the intermittent tributary to the Knife River in the southern and eastern portions of the area. These sediments are depicted in Plates 2 and 3, cross-sections B-B' and C-C', respectively.

Coleharbor sediments were penetrated during the drilling of monitoring wells 1708, 1709, 1710, 1714, 1719, 1720, 1715 and 1721, and bore holes 1705, 1706, and 1707. Coleharbor sediments were also encountered in preexisting monitoring wells BP3-U, BP3-L, 1462, 1463, 1564, and test holes 1562 and 1563 of the Black Pit proper, and preexisting monitoring wells GMW-4, 1-1, 1-2, 1-3, 1-4, 2-1, and 2-2 in the vicinity of the Green Pit. Penetrated thickness exceeded 30 metres in bore holes 1707 and 1563, and at monitoring wells 1721 and 820 (Plate 2, cross-section B-B').

The preglacial topography was probably similar to the Little Missouri Badlands topography of western North Dakota (Beaver, 1988). The glacial fill feature at the Black Pit site originated as a canyon which filled as glacial lobes advanced upon the area; this is suggested by the steep unconformable contact at the base of the fill area and the great thickness of till (Plate 2, cross-section B-B').

Glacio-fluvial and glacio-lacustrine sedimentation probably
occurred between glacial advances. Preglacial erosion was deep, as indicated by the depth of the fill. The local erosional base level was probably somewhat below the present Knife River base level, allowing for the depth of alluvium that has accumulated in the Knife River valley during recent times.

**Sentinel Butte Formation**

The Sentinel Butte Formation is a lignite-bearing, terrestrial, Paleocene unit which is generally somber grey and brown in outcrop. Individual beds vary from less than 0.3 metres to several metres in thickness. Where the total thickness of the formation is preserved in the Knife River Basin, it varies in thickness from 160 to 175 metres (Groenewold, et al., 1979). Nine major lignite units are also recognized in this formation. Three of these units are economically recoverable with today's mining technology: the Schoolhouse and Beulah-Zap beds are mined in the vicinity of Beulah, and the Hagel bed is mined in the vicinity of Center, Stanton, and Underwood.

In the proposed disposal site, the Sentinel Butte Formation consists of pale yellow-brown to red-brown (oxidized) to grey (reduced) silty clay and clay-rich silt with interbedded zones of white, weathered, finely laminated, very fine-grained sandstone, thinly laminated dark-brown to black coal of lignite rank, and limestone. Beds of fine, well-sorted, yellow-brown to red-brown to grey sand were
also encountered.

Groenewold, et al., (1979) described sedimentation intervals in the coal-bearing strata of the upper Fort Union Group as sequences of clastic sediments capped by a lignite unit. Due to the regional extent of the study, they were able to demonstrate the lateral continuity of the many lignites in the Bullion Creek and Sentinel Butte Formations of the Knife River Basin. The practice of naming sedimentation intervals and the system of nomenclature established by these workers will be used in this investigation. Three separated lignite units, or splits, were penetrated during the drilling operation. The lowermost unit encountered was the Antelope Creek lignite split overlain by the Spaer and Beulah-Zap lignites and associated sediments, respectively (Figures 2 and 3).

The Schoolhouse interval directly overlies the upper split of the Beulah-Zap lignite. The Schoolhouse interval was penetrated by wells 1701, 1702, 1703, 1704, 1711, 1712, 1713, 1716, 1717, 1718, and 1720. In the study area, the interval is represented by beds of reddish-brown to buff silty clay and clay-rich silt. The upper portion of the Schoolhouse interval, including the Schoolhouse lignite, has been removed by erosion in the Black Pit area.

The Beulah-Zap interval was penetrated in observation wells 1701, 1703, 1711, 1714, 1716, 1719, and 1720, piezometers 1702, 1704, 1712, 1713, 1715, 1717, and 1718, and
test hole 1705. In the proposed disposal area, the Beulah-Zap interval consists of beds of reddish-brown silty clay, reddish-brown clay-rich silt, grey carbonaceous clay, or reddish-brown silty sand, overlain by a split lignite seam. The upper split, the main focus of mining activity in the Beulah area, ranges from 2.4 to 4.0 metres in thickness, averaging approximately 3.7 metres. The lower split is thinner, averaging approximately 1.2 metres in thickness. The lignite seams are separated by a unit of reddish-brown silty clay, 1.0 to 2.0 metres in thickness, averaging approximately 1.5 metres. Figures 10 and 11 illustrate the structure contour of the upper and lower Beulah-Zap lignite split, respectively.

The Spaer interval was penetrated by monitoring wells 1701, 1703, 1711, 1714, 1716, 1720, 1702, 1704, 1715, and 1717. In the study area, the Spaer interval includes beds of grey silty clay, black carbonaceous clay, grey clay-rich silt, or grey silty sand. These beds are capped by two lignite seams averaging 0.6 metres in thickness, and are separated by a layer of grey silty clay or clay-rich silt 0.6 to 2.4 metres in thickness. The structure contour map of the base of the lower lignite is included in Figure 12.

The Antelope Creek interval was encountered in monitoring wells 1701, 1703, 1714, and 1721. It was also penetrated by test holes 1706 and 1707. In the study area, the Antelope Creek interval occurs as a pair of lignite seams
Figure 10. Structure Contour Map Of The Base Of The Upper Beulah-Zap Lignite
Figure 11. Structure Contour Map Of The Base Of The Lower Beulah-Zap Lignite
Figure 12. Structure Contour Map Of The Base Of The Lower Spaer Lignite
EXPLANATION

- Ephemeral Tributary
- Glacially-Filled Valley
- 570 - Elevation of the base of the Spaer Lignite lower split in metres (Dashed where inferred)

Scale:

300 m
1000 ft
separated by brown or grey silty clay, underlain by light grey silty clay. The lignites range from 0.6 to 1.5 metres in thickness, separated by 1.7 to 2.7 metres of grey silty clay. Figure 13 depicts the structure contour of the base of the Antelope Creek lignite.

Of the preexisting wells and boreholes, tests holes 1462, 1467, 1469, 1474, and 1562, and monitoring wells 1467 and 1564 penetrate the sediments of the Antelope Creek interval. Several additional previously existing wells, which penetrate the Spaer, Beulah-Zap, and Schoolhouse intervals, are displayed on Plates 1, 2, and 3.

Mine Spoils

Mine spoils consisting of the various lithologies of the Sentinel Butte and Coleharbor Formations lie in piles at the surface of the mined-out Black Pit (Plates 2 and 3, cross-sections A-A', C-C', and D-D'). The sediments are placed in piles by dragline during the strip-mining process. Dragline displacement results in a generally non-homogeneous pile of spoil with some sorting occurring as fine materials tend to concentrate near the top of the pile while coarse materials tend to end up near the base (Winczewski, 1977, p. 79-88).

Hydrogeology

Hydrogeology constitutes the interactions of water within porous material. The hydrogeology of the proposed ash-disposal site was defined using water level information
Figure 13. Structure Contour Map Of The Base Of The Antelope Creek Lignite
EXPLANATION

- - - Ephemeral Tributary
--- Glacially-Filled Valley
--- 568 Elevation of the base of Antelope Creek
     Lignite lower split in metres
     (Dashed where inferred)
from newly installed and existing groundwater monitoring instrumentation. Groundwater hydraulic head distributions were mapped and the groundwater gradient was determined. A water table contour map of the uppermost bedrock aquifer is depicted on Figure 14, and a water table contour map of the glacial fill is shown on Figure 15. The water level information was then superimposed upon the geology of the site to define the hydrostratigraphy (Plates 2 and 3). These hydrostratigraphic cross sections depict the occurrence and flow of groundwater in the various geologic units of the proposed disposal area.

The local water table ranges from approximately 600 to 565 metres msl across the study site (Figures 14 and 15). The main areas of recharge appear to be northeast, east, and southeast of the proposed disposal site, where surface elevations exceed 610 metres, msl (Figure 4). Groundwater discharge occurs directly north and west of the study area where the Antelope Creek lignite subcrop intersects the valley of the unnamed tributary to the Knife River. This general trend is exhibited on the cross sections by a drop in water table elevation from east to west and south to north beneath the proposed disposal site (Plates 2 and 3). This general water table gradient across the study site is also depicted on Figures 14 and 15. Two major hydrogeologic components therefore exist at the study site, the local
Figure 14. Water Table Contour Map Of Coyote I FGC Waste Disposal Area (Bedrock)
Figure 15. Water Table Contour Map of Coyote I FGC Waste Disposal Area (Glacial Fill)
bedrock water table flow system (Figure 14), and the superimposed local flow system in the glacially-filled valley (Figure 15).

**Bedrock Local Flow System**

Bedrock water table elevations range from approximately 590 metres msl in the southeastern portion of the Black Pit to approximately 565 metres in the northwestern portion (Figure 14). Flow is predominantly through the Antelope Creek lignite the uppermost aquifer of the site, and generally east to west. Lignite units and sandy intervals of the Sentinel Butte Formation form the aquifers. Monitoring wells 1721, 1467, 1564, 1701, 1703, and 1714, screened in the Antelope Creek lignite, and monitoring well 1463, screened in the Spaer sand, define the local bedrock water table in several locations at the study site (Plates 2 and 3). Much of the material that lies between the lignite units is low-permeability silt and clay. These form aquitards.

Several permeability tests were run on the low-permeability sediments of the Sentinel Butte Formation from the proposed disposal site (Montana-Dakota Utilities Co., 1987). The laboratory permeability measurements were conducted on the Spaer silty clay and both a clay-rich silt and sandy silt of the Beulah-Zap interval (monitoring well 1463). Values of $8.0 \times 10^{-9}$ m/sec, $1.9 \times 10^{-11}$ m/sec, and $1.7 \times 10^{-11}$ m/sec were obtained, respectively. Several hydraulic conductivity determinations were also performed (Appendix D).
An hydraulic conductivity test was conducted on the Antelope Creek lignite, the uppermost aquifer beneath the site, using monitoring well TA5. A conductivity of $6.6 \times 10^4$ m/sec was measured for the unit. Several additional in situ hydraulic conductivity measurements were made on the sediments of the Beulah-Zap interval. Monitoring wells 1466 and 1472, screened in sandy silt units, yielded hydraulic conductivity values of $1.1 \times 10^9$ m/sec and $2.0 \times 10^4$ m/sec, respectively, whereas monitoring wells 1470 and 1473, screened in silty clay sediments, yielded values of $1.5 \times 10^4$ m/sec and $7.6 \times 10^9$ m/sec, respectively (Appendix D). These monitoring wells are included on cross section A-A' of Plate 2. An acceptable pit permeability for fly ash disposal is roughly $10^9$ m/sec as defined by the NDSDH (Ronnei, 1987, p. 122).

Perched conditions exist at several points in the bedrock part of the study site. In the Beulah-Zap lignite, perched water levels were encountered in monitoring wells BP4-U, BP2-A, and 1718, at elevations of 588.2, 585.4, and 585.9 metres above sea level, respectively (Appendix A). These wells lie in the vicinity of the planned ash-disposal pits with proposed bottom elevations of 588 and 582 metres. In the Spaer interval, monitoring wells 1702 and 806 indicate perched water at elevations 580.3 and 580.2 metres, respectively. Topographic low points in the lignite units, surficial topographic depressions in highly permeable disturbed bedrock (spoils) which concentrate recharge and
promote infiltration, and lateral recharge from the relatively higher water table of the glacial valley fill, all may contribute to the perched conditions in these lignite units.

**Glacially-Filled Valley Local Flow System**

Water levels in the glacially-filled valley are significantly higher than water levels in the bedrock area of the study site, as shown on Plates 2 and 3 (cross-sections B-B' and D-D'). Water table elevations in the valley fill range from approximately 600 metres, southeast of the Green Pit (cross-section B-B', well 2-1), to approximately 570 metres near well 1565 (Figure 15 and Plate 1).

A large proportion of the fill is composed of pebble loam sediments (Plate 2, cross-section B-B'). These low-permeability sediments result in slow flow of water through that part of the area. An hydraulic conductivity value of $5.2 \times 10^{-10} \text{ m/sec}$ was obtained for the Coleharbor pebble loam of monitoring well 1566 (Appendix D). In contrast to these low-permeability materials, beds of sand and gravel interspersed within the fill constitute localized zones of higher permeability (cross-section B-B').

The observation wells, piezometers, and test holes that penetrate the glacial fill sediments are shown on Plates 2 and 3. Observation wells 1708, 1709, and 1710, and piezometers 1565, 1566, 820, 1-4, and 2-2 are all screened in the Coleharbor strata and record saturated conditions at eleva-
tions of 596.8, 594.2, 593.8, 579.0, 583.8, 581.4, 598.6, and 600.4 metres, respectively (Appendix A). An elevated water table condition occurs near observation well 1708 at 596.8 metres, msl. This is beneath a topographically flat area of the valley fill surface which may impede runoff and promote recharge. Water levels of 568.3 and 567.9 metres are recorded for monitoring wells 1564 and 1721, respectively (Appendix A), which are screened in the Antelope Creek lignite, directly beneath the glacial fill. Bedrock and Coleharbor sand underlie the pebble loam in several places. Monitoring well 1468 is screened in the Spaer sand and is dry, whereas monitoring well 820, screened in the Coleharbor sand, reveals saturated conditions.

Groundwater levels in monitoring wells at the site were recorded on November 29, 1987 (Appendix A). The presence of perched water table conditions in the glacially-filled valley were indicated: (1) in the vicinity of monitoring well 1468, where a zone of unsaturation lies below a zone of saturation; (2) in the vicinity of the Green Pit, where partially saturated conditions existed in the upper Beulah-Zap and lower Beulah-Zap lignites, beneath a zone of saturation; and (3) in the vicinity of monitoring well 1721, where partially saturated conditions existed in the Antelope Creek lignite, below a zone of saturation (Plate 2, cross-section B-B'). Monitoring well 1468 is screened in bluish-grey silty fine sand of the Sentinel Butte Formation and dry
conditions existed at an elevation of 571.0 metres (Appendix A). Monitoring wells 1565, 1566, and 1710 lie adjacent to monitoring well 1468 and saturated conditions occur at elevations of 579.0, 583.8, and 593.8 metres, respectively, all well above the unsaturated zone of monitoring well 1468. Monitoring wells 1-3 and 1-2, emplaced near the Green Pit, are screened in the upper Beulah-Zap and lower Beulah-Zap lignites, respectively. Water levels existed at elevations of 590.5 metres, for monitoring well 1-3, and 589.3 metres, for monitoring well 2-1, just above the base of the screen in each monitoring well (Cross-section B-B'). Monitoring wells 1-4 and 2-2 lie adjacent to monitoring wells 1-3 and 2-1 and are screened in Coleharbor sediment. Water levels of 598.7 and 598.0 metres, msl, recorded for these monitoring wells, occur above the water levels in monitoring wells 1-3 and 2-1. In addition, monitoring well 1721 is screened in the Antelope Creek lignite and a water level of 568.4 metres, msl, existed beneath an unsaturated zone in the vicinity of monitoring well 1468.

Hydrogeochemistry

Site Specific Groundwater Quality

Several wells were monitored for water quality to define the hydrogeochemical characteristics of the study site (Figure 8). The sampling procedure was designed to define the chemical characteristics of groundwater at several stratigraphic horizons and positions beneath the study
site to determine a relationship between lithology and depth, and groundwater chemistry. Monitoring wells BP4-U, BP2-A, and 1715, screened in the upper Beulah-Zap lignite, lower Beulah-Zap lignite, and the upper Spaer lignite, respectively, were chosen to define the chemical characteristics of water that is perched in near-surface lignite units (Plate 2, cross-section A-A'). These units are in direct or nearly direct hydraulic contact with spoil-originated infiltration at the study site. Monitoring well 1463, screened in a sand of the Spaer interval, was sampled to determine the quality of water typical of a sand aquifer beneath the study site. Monitoring wells 1701, 1714, and 1721 were sampled to define the chemical quality of water that occupies the Antelope Creek lignite, and monitoring wells 1709 and 1710 were sampled for water quality of the Coleharbor pebble-loam that occupies the glacially-filled valley in the northern and eastern portions of the study site.

The groundwater chemical analysis results are presented in Appendix E. Major cation analysis included: calcium (Ca²⁺), magnesium (Mg²⁺), sodium (Na⁺), potassium (K⁺), and iron (Fe). Major anion analyses included: fluoride (F⁻), chloride (Cl⁻), sulfate (SO₄²⁻), nitrate (NO₃⁻) and alkalinity (as calcium carbonate (CaCO₃)). Trace metal analyses were conducted on water sampled from monitoring wells 1701, 1714, and 1721, screened in the Antelope Creek Lignite (Appendix
E). Trace elemental concentration analyses included: arsenic (As), barium (Ba), boron (B), cadmium (Cd), chromium (Cr), lead (Pb), manganese (Mn), mercury (Hg), molybdenum (Mo), selenium (Se), and silver (Ag). Several other laboratory and field measurements were made, including: field temperature and pH, specific conductivity determinations in the field and laboratory setting, and pH and TDS determinations in the laboratory. The sodium adsorption ratio (SAR), in milliequivalents per liter, which defines the relative activity of Na⁺ ions in exchange reactions in the soil, and total hardness, which defines the total concentrations of Ca²⁺ and Mg²⁺ ions in milligrams per liter equivalent CaCO₃, were also calculated (Appendix E).

**Water Quality Types**

The groundwater chemical analysis resulted in identification of two major water quality types (Tables 1-3): (1) A calcium-bicarbonate, sulfate (Ca²⁺-HCO₃⁻, SO₄²⁻) type, identified in monitoring wells BP4-U, BP2-A, and 1715 and monitoring wells 1709 and 1710; and (2) A sodium-bicarbonate, sulfate (Na⁺-HCO₃⁻, SO₄²⁻) type water, identified in monitoring wells 1701, 1714, and 1721.

The water of monitoring wells BP4-U, BP2-A, and 1715, screened in the upper Beulah-Zap, lower Beulah-Zap, and upper Spaer lignites, respectively, is perched above the local water table. The resulting data are summarized in Table 1. The water of these wells is characterized by a
TABLE 1

STATISTICAL ANALYSIS SUMMARY
GROUND WATER QUALITY

Calcium-Bicarbonate, Sulfate Water Quality Type (Ca\(^{2+}\)-HCO\(_3\)^{2-}, SO\(_4\)^{2-}\))

<table>
<thead>
<tr>
<th>Well Number</th>
<th>TDS mg/L</th>
<th>Temperature (Celsius)</th>
<th>Field pH</th>
<th>Field Cond. umohs/cm</th>
<th>Ca(^{2+}) mg/L</th>
<th>Mg(^{2+}) mg/L</th>
<th>Na(^+) mg/L</th>
<th>SO(_4)^{2-} mg/L</th>
<th>HCO(_3)^{-} mg/L</th>
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</thead>
<tbody>
<tr>
<td>BP4-U</td>
<td>398</td>
<td>5.9</td>
<td>6.70</td>
<td>1100</td>
<td>109</td>
<td>28</td>
<td>21</td>
<td>221</td>
<td>---</td>
</tr>
<tr>
<td>BP2-A</td>
<td>3880</td>
<td>8.2</td>
<td>5.38</td>
<td>4100</td>
<td>595</td>
<td>271</td>
<td>123</td>
<td>2220</td>
<td>547</td>
</tr>
<tr>
<td>1715</td>
<td>2200</td>
<td>7.8</td>
<td>7.26</td>
<td>2100</td>
<td>233</td>
<td>138</td>
<td>71</td>
<td>1080</td>
<td>315</td>
</tr>
</tbody>
</table>

| Mean:       | 2159     | 7.3                   | 6.45     | 2433                | 312.0           | 145.7           | 71.7         | 1174.0          | 431.0           |
| High:       | 3880     | 8.2                   | 7.26     | 4100                | 595.0           | 271.0           | 123.0        | 2220.0          | 547.0           |
| Low:        | 398      | 7.8                   | 5.38     | 1100                | 109.0           | 28.0            | 21.0         | 221.0           | 315.0           |

\(^1\)insufficient sample to perform analysis
### TABLE 2

**STATISTICAL ANALYSIS SUMMARY**

**GROUNDWATER QUALITY**

Calcium-Bicarbonate, Sulfate Water Quality Type \((\text{Ca}^{2+}-\text{HCO}_3^-, \text{SO}_4^{2-})\)

<table>
<thead>
<tr>
<th>Well Number</th>
<th>TDS (\text{mg/L})</th>
<th>Field Temperature (\text{Celcius})</th>
<th>Field pH</th>
<th>Field Cond. (\text{umohs/cm})</th>
<th>(\text{Ca}^{2+}) (\text{mg/L})</th>
<th>(\text{Mg}^{2+}) (\text{mg/L})</th>
<th>(\text{Na}^+) (\text{mg/L})</th>
<th>(\text{SO}_4^{2-}) (\text{mg/L})</th>
<th>(\text{HCO}_3^-) (\text{mg/L})</th>
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<tr>
<td>1709</td>
<td>4580.0</td>
<td>6.1</td>
<td>7.2</td>
<td>1900.0</td>
<td>462.0</td>
<td>326.0</td>
<td>147.0</td>
<td>721.0</td>
<td>646.0</td>
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<td>1710</td>
<td>2980.0</td>
<td>7.6</td>
<td>7.5</td>
<td>3200.0</td>
<td>428.0</td>
<td>242.0</td>
<td>166.0</td>
<td>1640.0</td>
<td>617.0</td>
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<td>Mean:</td>
<td>3780</td>
<td>6.9</td>
<td>7.3</td>
<td>2550.0</td>
<td>445.0</td>
<td>284.0</td>
<td>156.5</td>
<td>1180.5</td>
<td>631.5</td>
</tr>
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</table>
TABLE 3
STATISTICAL ANALYSIS SUMMARY
GROUNDWATER QUALITY

Sodium-Bicarbonate, Sulfate Water Quality Type (Na⁺-HCO₃⁻, SO₄²⁻)

<table>
<thead>
<tr>
<th>Well Number</th>
<th>TDS (mg/L)</th>
<th>Field Temperature (Celsius)</th>
<th>Field pH</th>
<th>Field Cond. (umohs/cm)</th>
<th>Ca²⁺ (mg/L)</th>
<th>Mg²⁺ (mg/L)</th>
<th>Na⁺ (mg/L)</th>
<th>SO₄²⁻ (mg/L)</th>
<th>HCO₃⁻ (mg/L)</th>
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</thead>
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<tr>
<td>1463</td>
<td>1180.0</td>
<td>9.0</td>
<td>7.2</td>
<td>1700.0</td>
<td>29.0</td>
<td>9.5</td>
<td>239.0</td>
<td>60.0</td>
<td>750.0</td>
</tr>
<tr>
<td>1701</td>
<td>1390.0</td>
<td>7.6</td>
<td>6.4</td>
<td>2000.0</td>
<td>106.0</td>
<td>66.0</td>
<td>208.0</td>
<td>510.0</td>
<td>589.0</td>
</tr>
<tr>
<td>1714</td>
<td>1730.0</td>
<td>8.2</td>
<td>7.3</td>
<td>2700.0</td>
<td>20.0</td>
<td>12.0</td>
<td>488.0</td>
<td>612.0</td>
<td>648.0</td>
</tr>
<tr>
<td>1721</td>
<td>2180.0</td>
<td>7.8</td>
<td>7.2</td>
<td>3300.0</td>
<td>192.0</td>
<td>76.0</td>
<td>248.0</td>
<td>884.0</td>
<td>----</td>
</tr>
</tbody>
</table>

Mean: 1620.0  8.2  7.0  2425.0  86.8  40.9  296.0  516.5  662.3
High: 2180.0  9.0  7.3  3300.0  192.0  76.0  488.0  884.0  750.0
Low: 1180.0  7.6  6.4  1700.0  20.0  9.5  208.0  60.0  589.0

1 insufficient sample to perform analysis
significant sulfate concentration, averaging 1174 mg/L, and up to 2220 mg/L. The bicarbonate concentration is also fairly high, ranging between 315 mg/L and 547 mg/L, and averaging 431 mg/L. Calcium and magnesium concentrations average 312 mg/L and 146 mg/L, respectively, much higher than the average sodium concentration of 72 mg/L. The pH is near neutrality for monitoring wells BP4-U and 1715, and slightly acidic for monitoring well BP2-A. TDS concentrations range from 398 mg/L to 3880 mg/L, with an average of 2159 mg/L. The average TDS concentration is probably too low, as the 398 mg/L value recorded for monitoring well BP4-U was calculated by summing the concentrations of the major ions in parts per million (ppm); bicarbonate was not included, as insufficient sample was collected. A TDS concentration near 900 mg/L was inferred by assuming a bicarbonate concentration of about 500 mg/L, typical of the other two samples.

A calcium-bicarbonate, sulfate (Ca\(^{2+}\)-HCO\(_3\)^- , SO\(_4^{2-}\)) water quality type was also identified in monitoring wells 1709 and 1710, screened in the Coleharbor pebble-loam, as noted above (Table 2). High concentrations of sulfate were again detected with values ranging from 721 mg/L to 1640 mg/L, and averaging 1181 mg/L. Calcium and magnesium concentrations were also high, averaging 445 mg/L and 284 mg/L, respectively. The small range of calcium concentrations show little variation. Sodium concentrations averaged 157 mg/L and are
2 to 3 times lower in concentration with respect to calcium and magnesium. This water is nearly neutral and moderately mineralized, possessing an average pH of 7.3 and an average TDS concentration of 3780 mg/L.

The second water quality type, a sodium-bicarbonate, sulfate (Na\textsuperscript+·\(\text{HCO}_3\)-, \(\text{SO}_4\)) water, was identified in monitoring wells 1701, 1714, and 1721 (Table 3). Bicarbonate and sulfate concentrations are similar. The bicarbonate concentrations range from 589 mg/L to 750 mg/L, with an average value of 662 mg/L, whereas sulfate concentrations range from 60 mg/L to 884 mg/L, with a mean of 517 mg/L. Sodium concentrations range from 208 mg/L to 488 mg/L, and average 296 mg/L. This average is three times higher than the average calcium concentration of 87 mg/L and greater than 7 times the average magnesium concentration of 41 mg/L. This water is close to neutrality, with a pH ranging from 6.4 to 7.3, and is moderately mineralized, the TDS ranging between 1180 mg/L and 2180 mg/L.

Ash Characterization

Extraction Procedure Toxicity Testing

The FGC dry waste generated by Coyote Station is a mixture of fly ash, sodium sulfate (Na\textsubscript{2}SO\textsubscript{4}), and unreacted sodium carbonate (Na\textsubscript{2}CO\textsubscript{3}) that has accumulated in the plant's pollution control devices (Montana Dakota Utilities Co., 1988). A water leachate extraction procedure (EP Toxicity Method 1310), on a grab sample of FGC dry waste from Coyote
Station's antipollution devices, was performed in October 1987 by the Minnesota Valley Testing Laboratories of Bismarck, North Dakota. The analysis was conducted using the ASTM "Shake Extraction of Solid Waste with Water" method D 3987-81 (Montana-Dakota Utilities Co., 1988). A leachate analysis was conducted on a Coyote ash sample collected during an earlier permit application to authorize disposal of FGC waste in the Green Pit. The analysis consisted of extraction procedure (EP) testing of eight heavy metals. The North Dakota State Department of Health (NDSDH) suggested that a new analysis be carried out for this particular permit application as high levels of sodium, sulfate, and other dissolvable solids and trace amounts of heavy metals are characteristic of FGC waste generated by Coyote Station (Tillotson, 1987).

The Coyote Station ash EP toxicity test results for Black Pit ash disposal authorization are presented in Table 4 (Montana-Dakota Utilities Co., 1988). High concentrations of dissolved solids were detected and a highly alkaline solution (pH>12) was generated. Fly ash, flue gas desulfurization (FGD) waste and bottom ash leachate are commonly highly alkaline and high in TDS. The highly mineralized and highly alkaline solution generated by leachate analysis can be attributed directly to the fly ash constituent of the ash, as fly ash leachate typically approaches a pH near 13 and typically exhibits greater mineralization
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Conductivity</td>
<td>umhos/cm</td>
<td>33265</td>
</tr>
<tr>
<td>pH</td>
<td>standard units</td>
<td>12.1</td>
</tr>
<tr>
<td>Solids (Total Dissolved)</td>
<td>mg/L</td>
<td>32706</td>
</tr>
<tr>
<td>Alkalinity (Total) as CaCO₃</td>
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</tr>
<tr>
<td>Bicarbonate as CaCO₃</td>
<td>mg/L</td>
<td>2830</td>
</tr>
<tr>
<td>Calcium</td>
<td>mg/L</td>
<td>137.5</td>
</tr>
<tr>
<td>Carbonate as CaCO₃</td>
<td>mg/L</td>
<td>1551</td>
</tr>
<tr>
<td>Chloride</td>
<td>mg/L</td>
<td>1191.3</td>
</tr>
<tr>
<td>Magnesium</td>
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<td>&lt;1.0</td>
</tr>
<tr>
<td>Sodium</td>
<td>mg/L</td>
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</tr>
<tr>
<td>Sulfate</td>
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</tr>
<tr>
<td>Potassium</td>
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</tr>
<tr>
<td>Total Hardness</td>
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</tr>
<tr>
<td>Arsenic</td>
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</tr>
<tr>
<td>Barium</td>
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</tr>
<tr>
<td>Boron</td>
<td>mg/L</td>
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</tr>
<tr>
<td>Cadmium</td>
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<td>0.042</td>
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<td>Chromium</td>
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</tr>
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<td>Iron</td>
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</tr>
<tr>
<td>Lead</td>
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</tr>
<tr>
<td>Manganese</td>
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</tr>
<tr>
<td>Mercury</td>
<td>mg/L</td>
<td>0.0004</td>
</tr>
<tr>
<td>Molybdenium</td>
<td>mg/L</td>
<td>0.3</td>
</tr>
<tr>
<td>Selenium</td>
<td>mg/L</td>
<td>&lt;0.003</td>
</tr>
<tr>
<td>Silver</td>
<td>mg/L</td>
<td>0.07</td>
</tr>
<tr>
<td>Nitrate-Nitrogen</td>
<td>mg/L</td>
<td>2.0</td>
</tr>
<tr>
<td>Fluoride</td>
<td>mg/L</td>
<td>1.7</td>
</tr>
</tbody>
</table>
than other ash types (Beaver, 1986; Ronnei, 1987). Dissolved solids concentrations as high as 52,650 mg/L have been reported for ash-affected groundwater (Groenewold, et al., 1985).

Water Quality Comparisons

U.S. Environmental Protection Agency (EPA) water quality standards are presented in Table 5 (Freeze and Cherry, 1979, p. 386). The summary of the water quality analysis results is shown in Appendix E. Past analysis of contaminated water from the Green Pit disposal site indicated TDS concentrations of 30,000 to 40,000 parts per million (Tillotson, 1987). High concentrations of several cation and anion components also exist in the ash-generated leachate in comparison to both background water quality (Appendix E) and drinking water standards (Table 5). Specifically, high concentrations of sodium and sulfate are recorded (Table 4). The SO$_4^{2-}$ concentration is more than 15,000 mg/L higher than recommended drinking water standards. Bicarbonate and carbonate concentrations are also high. HCO$_3^-$ and CO$_3^{2-}$ concentrations are 2000 mg/L and 1500 mg/L higher than the average background water quality levels. This is reflected by the highly alkaline pH value. Ash leachate-derived chloride concentrations are also high, nearly 1000 mg/L higher than drinking water quality standards and about 1200 mg/L greater than background water quality levels. Concentrations of calcium, potassium, and magnesium are
### TABLE 5

DRINKING WATER QUALITY STANDARDS
(Modified From Freeze And Cherry, 1979, p. 386)

<table>
<thead>
<tr>
<th>Chemical Constituent</th>
<th>Recommended Concentration Limit¹</th>
<th>MaximumPermissible Concentration²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Dissolved Solids (TDS)</td>
<td>(mg/L) 500</td>
<td></td>
</tr>
<tr>
<td>Sulfate (SO₄²⁻)</td>
<td>(mg/L) 250</td>
<td></td>
</tr>
<tr>
<td>Chloride (Cl)</td>
<td>(mg/L) 250</td>
<td></td>
</tr>
<tr>
<td>Nitrate (NO₃⁻)</td>
<td>(mg/L) 45</td>
<td></td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>(mg/L) 0.3</td>
<td></td>
</tr>
<tr>
<td>Manganese (Mn)</td>
<td>(mg/L) 0.05</td>
<td></td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>(mg/L) 1.0</td>
<td></td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>(mg/L) 5.0</td>
<td></td>
</tr>
<tr>
<td>Boron (B)</td>
<td>(mg/L) 1.0</td>
<td></td>
</tr>
<tr>
<td>Hydrogen Sulfide (H₂S)</td>
<td>(mg/L) 0.05</td>
<td></td>
</tr>
<tr>
<td>Arsenic (As)</td>
<td>(mg/L) 0.05</td>
<td></td>
</tr>
<tr>
<td>Antimony (Sb)</td>
<td>(mg/L) 0.01</td>
<td></td>
</tr>
<tr>
<td>Barium (Ba)</td>
<td>(mg/L) 1.0</td>
<td></td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
<td>(mg/L) 0.01</td>
<td></td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>(mg/L) 0.05</td>
<td></td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>(mg/L) 0.05</td>
<td></td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>(mg/L) 0.002</td>
<td></td>
</tr>
<tr>
<td>Selenium (Se)</td>
<td>(mg/L) 0.01</td>
<td></td>
</tr>
<tr>
<td>Silver (Ag)</td>
<td>(mg/L) 0.05</td>
<td></td>
</tr>
<tr>
<td>Fluoride (F)</td>
<td>(mg/L) 1.4-2.4</td>
<td></td>
</tr>
</tbody>
</table>

¹ Recommended concentration limits for these constituents are mainly to provide esthetic and taste characteristics.

² Maximum permissible limits are set according to health criteria.

³ Limit depends on average air temperature of the region; fluoride is toxic at about 5-10 mg/L if water is consumed over a long period of time.
moderately low; cadmium and magnesium are present at levels below average concentrations detected by background water quality analysis (Appendix E). Leachate potassium concentration is slightly higher than the average background water quality value.

EP toxicity analysis revealed trace element concentrations above drinking water quality standards for arsenic, barium, boron, cadmium, chromium, lead, and silver, whereas iron, manganese, mercury, and selenium are all below established limits (Tables 4 and 5). As, Ba, Bo, and Pb are at concentrations of at least one order of magnitude higher than drinking water quality standards, whereas Cd, Cr, and Ag are only slightly above. Of these, As, Bo, and Pb, are two orders of magnitude higher than average background water quality levels, whereas Ba is present at concentrations three orders of magnitude higher than average background levels. Cd, Cr, Mn, Hg, and Mo were detected at concentrations near background levels. Leachate silver (Ag) concentration is one order of magnitude higher than background levels but is only slightly above the maximum permissible drinking water standard (0.02 mg/L above), and molybdenum, at a concentration of 0.3 mg/L, is unregulated. Leachate selenium (Se) concentration, less than $3.0 \times 10^3$ mg/L, is one order of magnitude lower than the water quality standard (Table 5). The average Se background water quality concentration at the study site is less than 2.0 mg/L
Nutrient leachate analysis revealed a nitrate concentration of 2.0 mg/L, well below recommended quality standards for drinking water, while miscellaneous testing detected a fluoride concentration of 1.7 mg/L, within maximum permissible limits for that particular element (Table 5).
DISCUSSION

The proposed ash disposal will take place within a complicated hydrogeological flow network. The main objective of the investigation was to define the hydrogeological suitability of the site for FGC dry waste disposal. A secondary objective was to determine the potential impact that ash disposal may have on background water quality. These goals were met first, by characterizing the geological framework and secondly, by defining the occurrence, flow, and quality of water moving through that geologic framework. EP leachate toxicity testing of Coyote-generated ash made it possible to predict the potential impacts of ash disposal on the water quality at the study site.

Hydrogeology

The proposed site is geologically and hydrogeologically complex, as illustrated in Plates 2 and 3. The overall hydrogeology is best considered in terms of hydrogeologic interactions between its two major components, the local bedrock water table flow system and the superimposed local flow system in the glacially-filled valley. The discussion of the mine-spoils flow system is included within the bedrock flow discussion.

Bedrock Local Flow System

The local bedrock water table flow system carries groundwater from the highland recharge areas southeast of the site, beneath the proposed site, and ultimately to the
Knife River aquifer system northwest of the site (Figure 4). The bedrock flow regime contains two basic flow components, lignite and sand aquifers and clay and silt aquitards. This local flow system, summarized in Figure 16, subcrops beneath the glacial fill to the northeast.

Flow occurs predominantly through the lignite and sand aquifers of the Sentinel Butte Formation. Hydraulic conductivities of lignite aquifers average $3 \times 10^{-4} \text{ m/sec}$, while sand and sandstone aquifers average $1 \times 10^{-6} \text{ m/sec}$ (Rehm, et al., 1980). A value of $6.6 \times 10^{-3} \text{ m/sec}$ was measured for the Antelope Creek lignite at the study site (Appendix D) which corresponds to about 2 metres (7 feet) of flow per year.

The hydraulic conductivity of lignite is controlled by fractures (Rehm, et al., 1980). Fracture spacing of 0.5 to 2.0 metres was noted for two major steeply dipping fracture sets of an exposed coal seam at the Falkirk mine in west-central North Dakota. This suggests a high probability that a well emplaced in a lignite unit will intersect a fracture (Rehm, et al., 1980). However, the low hydraulic conductivity value derived for the Antelope Creek lignite of monitoring well TA5 (Appendix D) may reflect interstitial permeability rather than secondary fracture permeability. Water table observation well 1701, screened in the Antelope Creek lignite at the study site, apparently intersected a fracture, as a gurgling sound could be heard in the pipe.
Figure 16. Generalized Bedrock Groundwater Flow System
Examination of lignite units suggests that horizontal permeability is greater than vertical permeability; horizontal fractures are more numerous than vertical fractures (Gilman, 1975, p. 86). Sand or sandstone aquifers are also fractured but this secondary permeability is less important to the bulk hydraulic behavior of sand than for fine grained sediments (Rehm, et al., 1980).

Flow is predominantly downward and downgradient through the low-permeability silt and clay sediments that compose the Sentinel Butte aquitards. The average hydraulic conductivity of these Paleocene aquitards is $3 \times 10^{-6}$ m/sec (Rehm, et al., 1980). An average hydraulic conductivity of $1.0 \times 10^{-8}$ m/sec was calculated for sandy silt and silty clay sediments of the Black Pit site (Appendix D). This corresponds to approximately 0.34 metres (1.1 feet) of flow per year.

Most recharge in central and western North Dakota occurs as depression-focused recharge with runoff and evapotranspiration occurring in interfluve areas (Gilman, 1975; Rehm, et al., 1982). A monitoring well finished in an interfluvial area showed a rise in water level as a result of a stock dam which induced depression-focused recharge near Center, North Dakota (Beaver, 1986). Perched groundwater conditions may exist in topographic lows in the lignite aquifers and temporarily below spoil piles at the study site as a direct result of depression-focused mine spoil
recharge and infiltration of meteoric water through the exposed seam of the upper Beulah-Zap lignite at the base of the Black Pit (Figure 16). A depression-focused recharge event was witnessed in early March of 1988 when several centimetres of heavy snow fell upon the site and depressions in the base of the Black Pit were filled with water, directly adjacent to the exposed seam of the upper Beulah-Zap lignite.

Glacially-Filled Valley Local Flow System

The integrated bedrock and glacially-filled valley hydrogeologic configuration of the northern portion of the study site is more complex (Plate 2, cross-section B-B'). This may be a result of textural and mineralogical heterogeneities that are characteristic of glacial valley fill materials in western North Dakota (Morin, 1979, p. 38). Hydraulic conductivities reflect these textural heterogeneities and vary over several orders of magnitude, dependent on sediment type. In addition to these complexities, water levels are higher than in wells emplaced in the bedrock part of the study site and zones of unsaturation separate saturated zones from the main body of groundwater (Plate 2, cross-section B-B').

Complex geological environments result in complex saturated-unsaturated conditions. The perched water table configuration of the valley fill is a reversal of the general definition of a perched water table in that a relatively
high-permeability unsaturated sand or lignite lies beneath or within a zone of relatively low-permeability saturated silty clay or pebble loam (cross-section B-B'). But, the existence of a zone of saturation separated from the main groundwater body by an unsaturated zone warrants the use of the term "perched water table" to describe the water table configuration of the glacial valley fill. Although the perched water table configuration of the glacial valley fill may not fit the general definition of a perched water table, such water table situations are not uncommon to western and central North Dakota. Zones of unsaturated, high-permeability materials were identified beneath zones of saturated, low-permeability materials in several monitoring wells at the Falkirk mine near Underwood (Rehm, et al., 1982). At one site, saturated low-permeability materials overlie unsaturated sandy materials which, in turn, overlie lignite. Similar configurations were identified at several other sites at the Falkirk mine where pebble-loam overlies sand which is the exact hydrogeologic configuration that exists at the Black Pit study site.

Several possible interpretations have been considered for the perched water table conditions identified in the vicinities of monitoring wells 1468, 1721, and 1-3 in the glacially-filled valley. A perched water table by definition must lie above a zone of unsaturation. Such an unsaturated zone possesses a negative pressure head, whereas
the overlying zone of saturation possesses a positive pressure head value. Groundwater flow is from higher pressure head to lower pressure head. This suggests flow from the overlying saturated zone to the underlying unsaturated zone, as shown on cross-section B-B' (Plate 2). The areal extent of water affected by the localized flow configuration above the unsaturated zone defines the perched water table.

If perched hydrologic conditions are correctly interpreted to exist throughout the glacially-filled valley then the bedrock water table must range from 585 to 565 metres (Figure 14). The perched water table of the valley fill, then, lies superimposed upon the bedrock water table, ranging in elevation from 600 metres to 570 metres (Figures 15 and 17). This interpretation is indicated by the partially saturated condition of the Antelope Creek lignite in the vicinity of monitoring well 1721, beneath the saturated valley fill (Cross-section B-B'). Coal beds commonly form unconfined aquifers, containing very little water, or are completely unsaturated (Gilman, 1975; Groenewold, et al., 1979; Rehm, et al., 1982; Winbourn, 1986). This semi-saturated to unsaturated condition common to lignite units may explain the anomalous water level reading of monitoring well 1721. This may be a reflection of the permeability contrast between the low hydraulic conductivity clays that transmit
Figure 17. Generalized Glacially-Filled Valley Flow System
(Perched Conditions Assumed Throughout Glacially-Filled Valley)
water sluggishly and the underlying high conductivity lignite units which transmit water rapidly, leaving an unsaturated gap in the hydrogeologic flow system (Figure 17).

An additional, alternative interpretation is also suggested. The glacially-filled valley local flow system is an elevated extension of the bedrock local flow system, interrupted by localized unsaturated zones. Figures 18 and 19 depict this interpretation. This integration is indicated by: (1) monitoring well 820, which contains a water table elevation intermediate between water table observation well 1720, screened in bedrock, and monitoring well 1708, screened in the glacial fill (Plate 3, cross section D-D'), and (2), a former water table, identified by a red-brown to grey color change in the sediments of the glacial fill at about 7 metres below the present water table. Below this relict water table, the sediments remained grey to the bottom of the hole. This observation suggests the continuity of saturated conditions of the bedrock with saturated conditions of the fill. The screened interval of the 1700 series monitoring wells, emplaced within the fill, were centered on the relict water table, the color change (cross section B-B').

The relict water table, encountered in test holes 1462, 1562, 1706, 1707, and 1721 during the drilling procedure (Montana-Dakota Utilities Co., 1987 and Appendix C), records
Figure 18. Generalized Glacially-Filled Valley Flow System
Figure 19. Integrated Water Table Contour Map Of Coyote I FGC Waste Disposal Area
a transition from predominantly oxidizing conditions to predominantly reducing conditions. Oxidizing conditions impart yellow-brown, brown, and red colors to the soil due to the presence of iron in the oxidized state, and reducing conditions impart grey and bluish colors to the soil due to the presence of ferrous iron and manganese in the reduced state, to form gleyed horizons. Such horizons are associated with high regional or local water tables or horizons within the soil that impede the downward movement of water (Birkeland, 1974, p.118).

The water table in the valley fill is high (approximately 20 metres higher than bedrock levels) and material permeabilities are sufficiently low to impede downward migration of water. An hydraulic conductivity of $5.2 \times 10^{-6}$ m/sec was recorded for the Coleharbor pebble loam of monitoring well 1566 (Appendix D), which corresponds to about 1.6 centimetres (0.6 inches) of flow per year.

The localized, high-permeability bedrock sand and lignite units beneath the valley fill, may act as groundwater drains for downward moving recharge which originates in the overlying low-permeability pebble loam sediment. This may explain the presence of the unsaturated zones which interrupt the flow regime of the glacial fill. But, several other possibilities may also explain the saturated/unsaturated flow conditions observed in the vicinity of monitoring well 1468. These include; (1) faulty well construction, a
plugged well screen restricting water from entering the well, or (2), alteration of the ground-water flow regime due to well installation; the drill hole may have penetrated the highly permeable lignite unit which underlies the sand interval of that monitoring well, forming a groundwater drain that quickly evacuated any water that may have flowed through the sand. This second possibility is more likely, as monitoring well 1468 is screened in bluish-grey fine sand, indicating that reducing (or saturated) conditions formerly existed and is separated from the underlying lignite by 0.3 metres of low-permeability dark gray silty clay. This clay interval may have been penetrated during drilling, forming an hydraulic continuum between the sand and the highly permeable underlying lignite (Cross-section B-B'). Faulty well construction may also explain the partly saturated condition in monitoring well 1-3 (Cross-section B-B'), although coal beds commonly form unconfined aquifers.

The hydraulic conductivity within the valley fill varies over several orders of magnitude, depending upon whether the material is silt and clay-rich glaciolacustrine sediments, or glaciofluvial sand and gravel, or till. At specific sites where higher hydraulic conductivity material underlies lower conductivity material, an unsaturated zone may exist beneath the water table, resulting in perched conditions in the till. However, at other locations continuous saturated conditions may exist from the valley fill
water table to the bedrock aquifer. Direct vertical recharge to the valley fill, in addition to water which may move laterally into the valley fill from the intersection with the bedrock aquifer subcrop, results in an elevated, irregular water table in the valley fill (Plate 2, cross-section B-B').

The bedrock local flow system is generalized in Figure 16. The complex hydrogeological situation of the glacially-filled valley is generalized in Figures 17 and 18. The valley fill local groundwater flow system lies superimposed upon the bedrock groundwater flow system (Figure 19).

In general, the bedrock groundwater flow system near the proposed disposal site consists of direct groundwater recharge by precipitation and snowmelt at the site as well as at the bedrock highs, northeast, east, and southeast of the site (Figure 4). Flow radiates laterally and downward into bedrock sediments and the glacially-filled valley, ultimately discharging into the intermittent tributary of the Knife River. The water flows downgradient from one bedrock aquifer (generally lignite or sand intervals) to the next underlying aquifer, in response to a general downward vertical flow gradient in the aquitards (silts and clays), and a predominantly horizontal gradient in the aquifers (Figure 16). The water in the valley fill moves more slowly in the low-permeability sediments of the fill (Figure 17 and 18). The water then flows northwest into the Antelope Creek
Hydrogeochemistry

Groundwater Chemical Evolutionary Sequence

Groundwater obtains its chemical composition through interaction with the atmosphere, soil, and the three-dimensional mineralogical earth matrix. The hydrogeochemical processes occurring in western North Dakota are described in detail by several previous workers (Moran, et al., 1978a, 1978b; Groenewold, et al., 1979, 1983; Houghton, et al., 1984). Five major processes operating almost exclusively in the zone above the water table are: (1) carbon dioxide production due to biochemical decomposition; (2) oxidation of pyrite; (3) dissolution of calcite and dolomite; (4) precipitation and dissolution of gypsum; and (5) cation exchange on smectite clays. Sulfate reduction, an additional process, occurs only at relatively great depths in the saturated zone and leads to high concentrations of sodium and bicarbonate ions (Groenewold, et al., 1980, 1981). These five hydrogeochemical processes are believed to be occurring in the near surface unsaturated and shallow saturated zone at the proposed FGC dry waste disposal site.

Carbon dioxide ($CO_2$) is generated in the soil zone of the study site through decay of organic material. This is represented by the following reaction:
This reaction has considerable acidic effects on the soil zone regime. As partial pressures of carbon dioxide \( (P_{CO_2}) \) increase from \( 10^{-35} \) bar, typical of meteoric water, to \( 10^{-3}-10^{-1} \) bar, typical of soil zone pore water, pH values decrease from 5.0-6.0 to 4.3-4.5 (Freeze and Cherry, 1979, p.241). The decrease in pH results from increased concentration of carbon dioxide. Carbonic acid is then produced through combination of carbon dioxide and water in the soil zone:

\[
CO_2 \text{ (gas)} + H_2O = H_2CO_3
\]

The result is a carbon dioxide-charged water that is low in pH.

Another important process that effects the chemistry of groundwater at the study site is oxidation of pyrite or marcasite which occurs just below the root zone. Finely disseminated pyrite is believed to exist throughout the overburden sediments of western North Dakota, including the study site. The generation of sulfate and hydrogen ions result:

\[
4FeS_2\text{(pyrite)} + 15O_2 + 14H_2O = 4Fe(OH)_3 + 16H^+ + 8SO_4^{2-}
\]

The generation of hydrogen \((H^+)\) ions through pyrite...
oxidation results in an highly acidic water that readily
dissolves carbonate-bearing minerals present in the near
surface sediments. Calcite and dolomite dissolution imposes
a buffering mechanism upon the shallow pore-water regime due
to dissociation of carbonic acid ($H_2CO_3$) to two bicarbonate
ions ($2HCO_3^-$). This reduces the $H^+$ ion concentration and
consequently increases the pH of the shallow groundwater at
the study site to near neutrality (Appendix E). If it were
not for the buffering capacity of the overburden sediments
of western North Dakota, the generation of a highly acidic
water would result. Such water is common to the coal-mining
settings of the eastern United States and is known as acid
mine-drainage. A pH minimum value near 2 can result from
pyrite oxidation in a system closed with respect to air
replenishment, depending upon percent saturation and porosi-
ty of the porous medium (Groenewold, et al., 1983, p.9).

Calcite and dolomite dissolution occurs through the
following reactions:

\[
\begin{align*}
\text{CaCO}_3 (\text{calcite}) + H_2CO_3 &= Ca^{2+} + 2HCO_3^- \\
\text{CaMg}(&\text{CO}_3)_2 (\text{dolomite}) + 2H_2CO_3 &= Ca^{2+} + Mg^{2+} + 4HCO_3^-
\end{align*}
\]

Calcite and dolomite minerals are abundant in the sediments
of the Sentinel Butte Formation. This is indicated by the
presence of abundant calcium ($Ca^{2+}$) and magnesium ($Mg^{2+}$) ions
in the shallow groundwater at the site (Appendix E). The
amount of calcite dissolution that can occur is dependent on the initial $P_{CO_2}$ of the percolating water and the extent to which the $CO_2$ in the water can be replenished by exchanging with a gas phase (Drever, 1982, p.55). If the $CO_2$ that is used up during calcite dissolution is not replaced, the system is closed. If $CO_2$ is replenished, the system is open and calcite mineral dissolution can continue. Open system dissolution generates a water that is generally near equilibrium with respect to calcite. Therefore, open systems generally have higher concentrations of calcite ($Ca^{2+}$) and bicarbonate ($HCO_3^-$) than do closed systems.

An additional process that may effect the chemistry of shallow groundwater at the study site is gypsum precipitation and dissolution:

$$Ca^{2+} + SO_4^{2-} + 2H_2O = CaSO_4 \cdot 2H_2O(gypsum)$$  \hspace{1cm} (6)

This process may decrease the concentration of calcite and sulfate ions (through gypsum precipitation that typically occurs during normal precipitation events) or may supply calcite and sulfate ions (during high precipitation events which lead to gypsum dissolution and groundwater recharge).

In addition to gypsum dissolution, pyrite oxidation also contributes sulfate ions to shallow groundwater at the proposed FGC dry waste disposal site (Appendix E). The highest concentration of $SO_4^{2-}$ ions (2220.0 mg/L) was found
in monitoring well BP2-A (Appendix E).

Cation exchange is also important to the evolution of shallow groundwater at the study site. As recharge waters percolate downward, calcium (Ca\(^{2+}\)) and magnesium (Mg\(^{2+}\)) ions, generated during calcite and dolomite dissolution, exchange for sodium (Na\(^+\)) ions bound on the surfaces of smectite (montmorillonite) clays. Smectite clays are abundant in the sediments of western North Dakota (Groenewold, et al., 1983). Chemical modification of groundwater by cation exchange results in a net increase in Na\(^+\) concentration and a net decrease in Ca\(^{2+}\) concentration of the pore solution. This is indicated by high Na\(^+\) content relative to Ca\(^{2+}\) and Mg\(^{2+}\) concentrations (Table 3). This Ca\(^{2+}\) adsorption is selected strongly over both Na\(^+\) and Mg\(^{2+}\) adsorption. Selectivity of Mg\(^{2+}\) over Ca\(^{2+}\) occurs only when the concentration of Mg\(^{2+}\) is two times that of Ca\(^{2+}\) (Houghton, et al., 1984).

The large amounts of smectite clays coincide with abundant volcanic-rich fragments common to the sediments of the Sentinel Butte Formation, as montmorillonite is an alternation product of volcanic rock (Jacob, 1976). Na-montmorillonite is the most abundant smectite clay in the overburden sediments of western North Dakota (Groenewold, et al., 1983).

**Generation of Water Quality Types**

Two main types of infiltration events are noted in western North Dakota: (1) normal infiltration events in
which precipitation percolates below ground surface but not below the root zone; and (2) high precipitation events in which precipitation infiltrates below the root zone to produce groundwater recharge (Moran, et al., 1978b; Groenewold, et al., 1979, 1983). During a normal precipitation event infiltration percolates below ground surface but not below the rooting zone. A combination of processes occurs during such an event. CO₂ is generated as a result of biochemical decay of organic matter. H⁺ ion production occurs and a pore water low in pH is generated. Pyrite and marcasite dissolution also occurs. This produces high concentrations of SO₄²⁻ and H⁺ ions. The highly acidic water readily dissolves any calcite and dolomite that it encounters along its flow path. This, in turn, generates high Ca²⁺, Mg²⁺, and HCO₃⁻ levels and imposes a buffering mechanism upon the shallow pore-water regime. This may lead to precipitation of gypsum through a combination of SO₄²⁻ ions, supplied by pyrite oxidation, and Ca²⁺ ions, supplied by calcite and dolomite dissolution. The result is a Ca²⁺-HCO₃⁻, SO₄²⁻ type groundwater (monitoring wells BP4-U, BP2-A, 1715, 1709, and 1710) high in Ca²⁺, Mg²⁺, HCO₃⁻, and SO₄²⁻ ions (Tables 1 and 2). The low Na⁺ concentration of these waters relative to Ca²⁺ and Mg²⁺ implies little cation exchange has occurred. This is anticipated owing to the near-surface stratigraphic position in which these waters obtain their chemical characteristics. Direct exposure of the upper
Beulah-Zap lignite unit at the base of the Black Pit to meteoric waters may have resulted in the lower TDS concentration in monitoring well BP4-U (Table 1).

The chemical evolutionary sequence that has generated the \( \text{Ca}^{2+}-\text{HCO}_3^-\), \( \text{SO}_4^{2-}\) type water in monitoring wells 1709 and 1710 (Table 2), screened in Coleharbor pebble loam, was probably similar to the evolutionary sequence that generated the water in monitoring wells BP4-U, BP2-A, and 1715, screened in near-surface lignite units of the Sentinel Butte Formation. Slightly higher values of TDS, \( \text{Ca}^{2+}\), \( \text{Mg}^{2+}\), and \( \text{HCO}_3^-\) were detected; however, \( \text{SO}_4^{2-}\) concentrations are nearly identical. A water that has evolved in the base of mine-spoil piles is generally more highly mineralized than water that occupies an undisturbed setting (Van Voast and Hedges, 1975; Groenewold, et al., 1981, 1983, 1985; Groenewold and Manz, 1982; Groenewold and Koob, 1984). Consequently, water in lignite aquifers which lie in direct contact or in close proximity to the base of the spoils and receive mine-spoil recharge would also tend to be more highly mineralized. The water in the undisturbed glacially-filled valley, however, exhibits greater mineralization than the perched water of the near-surface lignite units at the study site (Table 2). Water which has evolved in glacial materials, particularly pebble-loam, is typically more highly mineralized than water in other undisturbed settings (Morin, 1979, p.36).

During an high precipitation event, infiltration ex-
tends below the root zone to produce groundwater recharge. In addition to CO$_2$ production, sulfide mineral dissolution, calcite and dolomite dissolution, and gypsum precipitation, cation exchange occurs on Na-montmorillonite which leads to an increase in concentration of Na$^+$ ions and a decrease in concentration of Ca$^{2+}$ and, to a lesser degree, Mg$^{2+}$ ions. The removal of Ca$^{2+}$ and Mg$^{2+}$ ions from solution through cation exchange, in turn, increases the solubility of gypsum and other carbonate minerals. Dissolution of gypsum, calcite, and dolomite, along with removal of Ca$^{2+}$ and Mg$^{2+}$ ions through cation exchange, results in high concentrations of Na$^+$, HCO$_3^-$, and SO$_4^{2-}$ ions in solution.

High concentrations of Na$^+$, HCO$_3^-$, and SO$_4^{2-}$ ions in groundwater of monitoring wells 1463, 1701, 1714, and 1721 (Table 3) suggest that cation exchange is an active hydrogeochemical process at the proposed FGC dry waste disposal site. Na$^+$-HCO$_3^-$, SO$_4^{2-}$ type water is the most common shallow subsurface water in western North Dakota (Winbourn, 1986, p.61).

Several observations were made based upon chemical analysis of groundwater from monitoring wells 1463, 1701, 1714, and 1721. Chemical analysis for monitoring well 1463 indicates a low SO$_4^{2-}$ and TDS concentration relative to 1701, 1714, and 1721. This may be a result of the sediment that the well screen penetrates. Coarser textured materials generally produce a less-highly mineralized water (Groene-

Chemical analyses of monitoring wells 1701 and 1721 indicate an increase of Ca$^{2+}$ relative to monitoring wells 1714 and 1463 (Table 3). This may reflect the close proximity of these wells to the glacially-filled valley. The samples obtained from the valley fill contain high Ca$^{2+}$ concentrations (Table 2). This suggests mixing of groundwater in the till with the water in the Antelope Creek lignite. Sulfate concentrations of water beneath the study site are generally high, independent of stratigraphic position. This suggests pyrite oxidation and reprecipitation of gypsum during normal infiltration events, and gypsum dissolution during abnormally high precipitation events. However, a general decrease in $\text{SO}_4^{2-}$ ion concentration is noted from the groundwater in the near surface lignite units (monitoring wells BP4-U, BP2-A, and 1715) and in the glacially-filled valley (1709 and 1710) to groundwater in the Antelope Creek lignites and sand units, the uppermost aquifer at the site (monitoring wells 1463, 1701, 1714, and 1721). This suggests the removal of sulfate from solution is occurring through gypsum precipitation as groundwater percolates from near surface stratigraphic units downward to the uppermost bedrock aquifer.

Several other factors may affect the groundwater chemistry at the proposed FGC dry waste disposal site. These include: (1) the presence or absence of several key in-
ingredients in the overburden sediments (e.g., pyrite, Na-montmorillonite clays, calcite, dolomite); (2) the amount of hydrogen ion production in the overburden sediments; (3) the sulfate concentration, which is dependent on pyrite oxidation and the solubility of gypsum (and thus ultimately dependent upon the Ca\(^{2+}\)/Na\(^+\) ratio which is controlled by cation exchange on Na-montmorillonite clays); (4) the direction and rate of water movement through the sediment, which affects the concentration of dissolved salts (the greater the rate of flow the lower the soluble salt concentration); and (5) the type of sediment groundwater encounters along its flow path.

The background water quality data collected during this investigation will provide meaningful information when compared to water quality data collected after FGC dry waste disposal has occurred. This will enable the quantification of the effects of waste disposal on the hydrogeologic regime of the study site. The collected data reflect the quality of the shallow (less than 37 metres in depth) groundwater flow regime. This is of significance as ash disposal will take place within this near-surface setting.

**Water Quality Comparisons**

The water quality of the lignite aquifers of the Upper Fort Union Group is generally poor. Concentrations of TDS, sulfate (SO\(^4\)), iron (Fe), fluoride (F) and various trace elements generally exceed drinking water standards (Croft,
Mineralization of groundwater at the site is fairly high. TDS concentrations here range from approximately 1200 mg/L to about 5000 mg/L (Appendix E). This is significantly above recommended concentration limits and, in some cases, is unfit for livestock and irrigation purposes (Table 5).

Electrical conductance is a good general predictor of total dissolved solids (Freeze and Cherry, 1979, p. 84). The field conductances measured at the study site do reflect TDS concentrations (Appendix E). Values range from 1100 umohs/cm to 4100 umohs/cm. Field pH values ranged between 5.4 to 7.5 and field temperatures ranged between 5.9 to 9.0 degrees Celsius.

A fairly wide range of fluoride concentrations were detected, from less than 1.0 mg/L to 7.3 mg/L. Values of 4.0 mg/L and 7.3 mg/L measured for the upper Beulah-Zap and Antelope Creek lignites (monitoring wells BP4-U and 1721, respectively) were 2 to 3 times higher than maximum permissible concentrations. Values within and exceeding the drinking water standards for fluoride are generally restricted to lignite aquifers (Appendix E). Sulfate concentrations are also high, ranging between 60 mg/L and 2220 mg/L. Many wells exhibited sulfate concentrations well above the drinking water quality standard of 250 mg/L. Monitoring well BP2-A, screened in the lower Beulah-Zap lignite, had
the highest value. This near surface lignite unit receives water that has infiltrated through the spoils of the present mined-out Black Pit. The mining process results in material redistribution in which significant amounts of unoxidized sediments are placed in the oxidizing zone and significant amounts of oxidized sediments are placed in the reducing zone (Groenewold et al., 1979, 1981; Groenewold and Koob, 1984). This overturning process places unoxidized finely-disseminated pyrite in the oxidizing zone and has the potential to generate high concentrations of sulfate in water at the base or in close proximity to the base of the mine-spoil piles. A sulfate concentration of 9,408 mg/L was recorded for groundwater from spoils at the Indian Head Mine near Zap, North Dakota (Groenewold, et al., 1981). The overburden at this mine is characterized by high sodium content. Fairly high sulfate concentrations, 1080 mg/L and 1640 mg/L, were detected in monitoring wells 1715 and 1710, screened in the upper Spaer lignite and the Coleharbor pebble-loam, respectively (Appendix E). This suggests pyrite oxidation and gypsum dissolution are primary processes occurring in the shallow unsaturated zone at the study site.

Total alkalinity is approximately equal to bicarbonate and carbonate concentration in most natural waters (Drever, 1982 p. 40), but for natural waters between pH of about 6 and 9, total alkalinity is approximately equal to the bicarbonate concentration (Hassett, 1988). Bicarbonate concen-
tration was assumed equal to total alkalinity in this study as nearly all field and laboratory pH values fall within this range. Bicarbonate concentrations ranged between 315 mg/L and 750 mg/L with an average of 587 mg/L (Appendix E). The highest value was noted in monitoring well 1463, screened in the Spaer sand and the low value was in monitoring well 1715, screened in the upper Spaer lignite. There is little variation in bicarbonate concentration, probably a result of uniform calcite and dolomite distribution throughout the overburden sediments at the study site. There are no water quality standards for bicarbonate.

The remaining anion analyses included NO₃⁻ and CO₃²⁻. Because it was assumed that total alkalinity equals bicarbonate concentration, all CO₃²⁻ values are, by definition, zero. NO₃⁻ concentration in the groundwater at the site is low, less than 2.0 mg/L in all cases, except for monitoring wells BP4-U and 1721 where there was insufficient sample to conduct the analysis.

Ca²⁺ concentrations of 20 mg/L to 595 mg/L are characteristic of monitoring wells at the study site (Appendix E). Mg²⁺ content ranged from 9.5 mg/L to 326 mg/L. Na⁺ concentrations ranged from 21 mg/L (monitoring well BP4-U) to 488 mg/L (water table observation well 1714). In general, high concentrations of Ca²⁺ and Mg²⁺ are accompanied by a low Na⁺ concentration and a high Na⁺ concentration is typically accompanied by low concentrations of Ca²⁺ and Mg²⁺ (Appendix
The generally higher abundance of Ca\(^{2+}\) versus Mg\(^{2+}\) may be the result of the fact that both Ca\(^{2+}\) and Mg\(^{2+}\) ions are generated during calcite and dolomite dissolution whereas dolomite dissolution is the only chemical process that generates Mg\(^{2+}\) ions. Water quality standards for Ca\(^{2+}\), Mg\(^{2+}\), and Na\(^+\) do not exist. Potassium (K\(^+\)) concentrations range from 4.4 mg/L to 49 mg/L. The low concentrations suggest that potassium is not chemically important to the groundwater of the study site. No water quality standards exist for this particular ion, either.

Iron (Fe) concentrations ranged from less than 0.5 mg/L to 1.4 mg/L. The recommended water quality standard is 0.3 mg/L. The analytical detection limit for iron is above the water quality standard for the analysis used in this study. Consequently, all samples possibly exceed the water quality standard. High Fe concentrations are typical of the coal-bearing strata of the upper Fort Union Group sediments (Croft, 1973; Woodward-Clyde Consultants, 1975; Gilman, 1975; Morin, 1979). It should be noted that the water quality standard for Fe is the recommended concentration limit and is cited mainly to provide acceptable aesthetic and taste characteristics (Table 5).

Trace element analyses were conducted on samples from monitoring wells 1701, 1714, and 1721 that penetrate the Antelope Creek lignite, the uppermost aquifer beneath the study site (Appendix E).
Three chemical trace element parameters are of interest: cadmium (Cd), manganese (Mn), and molybdenum (Mb). Cadmium concentrations were less than 0.02 mg/L in all samples, although the drinking water quality standard of 0.01 mg/L is below the detection capabilities of this analysis. Manganese concentrations exceed the water quality standard of 0.05 mg/L, in every case. This limit is set for aesthetic and taste considerations. Molybdenum elemental trace concentrations ranged from less than 0.05 mg/L to 0.15 mg/L. No water quality standard exists for this particular trace element. All other trace element concentrations are below the drinking water standards.

Ash Characterization

The results of EP leachate toxicity testing directly reflect the bulk mineralogical composition of the ash that generated the leachate (Ronnei, 1987, p. 107). Characterization of fly ash and bottom ash samples from Heskett Station, a coal-fired power plant near Mandan, North Dakota, was performed through scanning electron microscopy (SEM), electron microprobe analysis (EMPA), and leachate extraction procedure (EP) (Ronnei, 1987). The coal that supplies the power plant is mined from the Sentinel Butte Formation near Beulah, North Dakota. X-ray diffraction analysis revealed several major solid mineralogical phases present in the ash samples, including quartz (SiO₂) and melilite \([(Ca₅(Mg, Al) (Al, Si)₉O₃₆ (SO₄)₂₈)], in bottom ash
samples, and alkali sulfates [(Na, K)₂SO₄], anhydrite [CaSO₄], and periclase [MgO], in fly ash samples. Most soluble mineral phases present are lime (CaO), anhydrite, calcite (CaCO₃), and alkali sulfates with the more soluble phases apparently concentrated in the fly ash (Ronnei, 1987, p. 103).

The high sodium (Na⁺) and sulfate (SO₄²⁻) concentrations of FGC dry waste-generated leachate directly reflect abundant solid phases of sodium sulfate (Na₂SO₄) and sodium carbonate (Na₂CO₃) which partially compose the waste. Abundant alkali sulfates (sodium and potassium sulfates) are common in fly ash and may also contribute to the high Na⁺ and SO₄²⁻ concentrations. If the alkali sulfate phase is present in the fly ash component of the FGC dry waste, one would also expect to find elevated concentrations of potassium (K⁺). This is indeed the case, as a concentration of 99.0 mg/L was detected, 82 mg/L higher than the average background water quality level (Table 4 and Appendix E).

FGC Dry Waste Disposal Impacts

Analyses Comparison

Background water quality at the study site is moderately poor (TDS concentration averaging 2515 mg/L, approximately 2000 mg/L higher than recommended water quality standards), placing the study site groundwater within the brackish water quality category (Freeze and Cherry, 1979, p. 84). Major chemical constituents include sulfate, bicarbonate,
calcium, sodium, and magnesium. Of these components, sulfate is the only regulated ion, ranging from 60 to 2220 mg/L, with an average background water quality concentration of 883 mg/L, higher than the recommended drinking water concentration of 250 mg/L.

Leachate generated by Coyote FGC dry waste will be more highly mineralized than the groundwater at the study site. Results of EP toxicity testing reveal a TDS concentration equaling 32,706 mg/L (Table 4).

This comparison of EP toxicity and background water quality analyses illustrates the potential degradational effects of FGC dry waste disposal on the background water quality at the study site. However, attenuation and neutralization capabilities of western North Dakota overburden sediment significantly reduce the potential degradational effects of FGC dry waste disposal on groundwater in western North Dakota. These mechanisms have been documented by laboratory and field studies (Koob and Groenewold, 1984; Groenewold, et al., 1985; Hassett and Groenewold, 1986; Beaver, 1986).

Attenuation and Neutralization Mechanisms

EP toxicity testing indicates that arsenic, barium, boron, cadmium, chromium, lead, and possibly silver are present at elevated concentrations in FGC dry waste leachate (Table 4). These trace elements are the main chemical parameters of concern and are mobile at the high pH condi-
tions characteristic of ash-disposal settings. The two most important variables in trace element attenuation are the pH of the leachate and the alkaline buffering capacity of the geologic media in which ash disposal has taken place. The pH of the FGC dry waste leachate is very alkaline (pH > 12). Fly ash is a component of FGC dry waste. Fly ash leachate oxide phases react readily with water to form high concentrations of hydroxide ions which makes the ash solution strongly alkaline. Several buffering mechanisms may occur through addition of protons (H⁺) or removal of hydroxyls (OH⁻) to the leachate-affected groundwater to significantly reduce ash-leachate pH. One possible mechanism is the addition of H⁺ ions to the ash solution from colloidal oxide surface groups, characteristically abundant in ash-leachate. Oxides are known to lose protons in highly alkaline solutions (Beaver, 1986). The hydrogen ions are then available to combine with hydroxyl ions to form water, effectively neutralizing the fly ash solution. Acid producing reactions such as pyrite oxidation and organic matter decomposition also provide hydrogen ions to ash-effected groundwater, thus lowering pH.

Several other buffering mechanisms may occur in western North Dakota overburden sediment. The ability of these sediments to reduce ash-leachate pH significantly is confirmed by laboratory and field investigations (Koob and Groenewold, 1984; Groenewold, et al., 1985; Beaver, 1986).
Attenuation of several potentially toxic trace elements is directly related to pH. Arsenic attenuation may exceed 90% (greater for clay-rich sediments than for sandy sediments) and is most strongly attenuated in the pH range of 7-9 (Hassett and Groenewold, 1986). Attenuation of cadmium and lead is also pH dependent. Removal of cadmium can be expected to be near 100% at solution pH values greater than 6.5-7.0 (Groenewold, et al., 1985). This is due to the strong tendency of heavy metals, such as cadmium and lead, to precipitate as hydroxide carbonates at alkaline pH's. Molybdenum, in the +6 valence state, is virtually unattenuated at pH levels greater than 7.5 (Hassett and Groenewold, 1986). This particular trace element is unregulated and occurs in relatively minor amounts in the FGC dry waste leachate (Table 4).

Several other trace element constituents of FGC dry waste are not attenuated in the pH range characteristic of ash disposal settings in western North Dakota. Barium, for example, generally remains unattenuated. But, the solubility product for barium sulfate indicates that barium in a sulfate-rich system (characteristic of an FGC dry waste disposal setting) simply precipitates and is maintained at levels that do not present a regulatory problem or cause health concerns (Beaver, 1986). Silver detected at a concentration of 0.07 mg/L in EP toxicity testing leachate (Table 4), is slightly higher than the drinking water stan-
standard of 0.05 mg/L (Table 5) and may also remain unattenuated. Boron, at a concentration of 31.8 mg/L, is well above the drinking water standard of 1.0 mg/L and may present a water quality hazard to the ash-affected groundwater.

In general, arsenic, cadmium, lead, and chromium are immobilized in the western North Dakota field setting. Attenuation of arsenic, cadmium, and lead is pH dependent and it appears that sorption and precipitation processes significantly reduce the concentration of these trace constituents in the pH range of 6.0-9.0. Of the other trace elements, it appears that boron may produce regulatory concern.

**Ash Disposal Setting**

FGC dry waste disposal at the Black Pit site may have several impacts on the immediate groundwater regime. The disposal of FGC dry waste within the saturated zone at the study site would place the ash waste mass in direct contact with groundwater. This type of setting would lead to the downgradient migration of several potentially harmful chemical constituents. A decrease in major ion and trace element concentration would result as dilution and leaching continued. FGC dry waste disposal within the unsaturated zone would allow the intrinsic buffering and attenuation processes of the overburden sediments at the site to reduce the concentrations of several potentially toxic trace elements in the ash-derived leachate. As the leachate comes in
contact with the overburden sediment at the site, the harmful trace element constituents of the leachate are removed through precipitation and sorption processes. Dry pit-bottom ash disposal settings (similar to the Black Pit), typically result in slow, continuous dissolution of the ash deposit, with a small amount of downward migration occurring initially due to ponded rainwater and water entrained in the waste deposit (Beaver, 1986).

A gently-sloped cover constructed of low-permeability materials over the ash-waste mass would further reduce the potential degradational effects of FGC dry waste disposal on local groundwater. Recharge in central and western North Dakota occurs primarily as depression-focused recharge. A gently-sloped cap would eliminate depression-focused recharge by promoting runoff and evapotranspiration and low-permeability materials would minimize the amount of infiltration that would reach the ash-waste mass. Infiltration of water through a waste deposit promotes water table mounding within or beneath the deposit (Freeze and Cherry, 1979, p.436). Groundwater mounding, common to humid regions, would bring the ash-waste mass in direct contact with groundwater and produce a zone of leachate contaminated groundwater. A gently-sloped, low-permeability cap, would minimize leachate formation and ultimately prevent the formation of a groundwater mound beneath the FGC dry waste deposit.

The long-term effects of FGC dry waste disposal are
speculative. Comparison of background water quality and EP toxicity analysis allows quantitative insight to short-term effects. The average TDS concentration of the groundwater at the proposed FGC dry waste disposal site is 2515 mg/L with a maximum value of 4580 mg/L (Appendix E) whereas results of EP toxicity testing reveal that leachate generated from Coyote FGC dry waste will be more highly mineralized (>30,000 mg/L, Table 4). From this comparison, it is evident that the interaction of groundwater and FGC dry waste must be eliminated to assure long-term ash disposal success. If the FGC dry waste disposal setting is maintained above the water table, intrinsic attenuation and buffering capabilities of the overburden sediment at the site will significantly reduce the long-term degradation effects of ash disposal. If a low-permeability, gently-sloped cap is constructed over the ash-waste mass, dissolution and leaching will be reduced or eliminated, further minimizing long-term degradation effects of FGC dry waste disposal. Decrease in the leaching and dissolution potential of an unsaturated fly ash setting allow pozzolanic reactions to occur within the ash deposit to further reduce leaching and dissolution by forming a relatively nonreactive solid. Significant decrease in major ion and trace metal concentrations can be expected after 1 to 2 years in this type of setting (Groenewold and Manz, 1982).

The climatic conditions will also govern the long-term
disposal success at the study site. If climatic conditions remain semi-arid, recharge will remain primarily depression-focused, and the opportunity for groundwater mounding beneath the waste deposit will be eliminated. If the climate becomes humid, recharge in interfluve areas may occur, allowing infiltration of water through the ash mass and the formation of a groundwater mound.

It is evident, from the above discussion, that FGC dry waste disposal should take place above the water table, in an unsaturated setting beneath a gently-sloped compacted surface. If infiltration cannot reach the waste deposit, no leachate can form. If climatic conditions change and leachate does form, the local sediment will buffer the highly alkaline leachate solution (pH>12) to an equilibrium pH in the range of 6.0 to 9.0. Because the attenuation of several potentially toxic trace elements is pH dependent, these constituents will be immobilized.
CONCLUSIONS

The occurrence and flow of groundwater beneath the proposed Coyote Station FGC dry waste disposal site, located near Beulah, North Dakota, has been investigated. This investigation was necessary to determine the hydrogeologic suitability of the Black Pit site for ash disposal. The site is hydrogeologically complex and, in general, contains two hydrogeologic units, the bedrock lignite and sand aquifers, and the associated silt and clay aquitards. The glacial valley fill is predominantly pebble-loam with lesser amounts of glaciolacustrine and glacio-fluvial sediments.

Perched conditions within the Spaer and Beulah-Zap intervals of the bedrock have been further characterized. These conditions are localized. The only significant occurrence of water in the upper Beulah-Zap lignite is identified in well BP4-U which is screened in a shallow topographic low in the lignite (Plate 2, cross-section A-A'). Wells TA2, 1713, 1718, all screened in the upper Beulah-Zap lignite, show dry or nearly dry conditions. The only water encountered in the lower Beulah-Zap lignite was in well BP2-A. Wells TA1, BP1, BP3-U, BP4-L, BP5, and 1712 are all screened in the lower Beulah-Zap lignite and are all dry. The perched conditions are also variable. BP5 revealed dry conditions during the present investigation whereas 1.2 metres of water was reported for the monitoring well in the original permit application (Montana Dakota Utilities Company, 1987
and Appendix B). Fluctuations in perched water table conditions may reflect fluctuations in precipitation. Bedrock perched conditions will probably diminish as mine-spoil piles are leveled, during modification of the present strip-mined pit, eliminating depression-focused recharge to the near-surface lignite units.

Further characterization of the glacially-filled valley has led to a better understanding of the three-dimensional hydrogeological regime in that part of the study site. In areas where higher hydraulic conductivity sand and lignite units underlie lower conductivity pebble loam sediment, an unsaturated zone may exist beneath the water table, resulting in perched conditions in the till. The existence of an unsaturated gap in the hydrogeologic flow system, beneath the glacially-filled valley, suggests the water table of the glacial valley fill lies perched upon the bedrock water table (Figure 17). However, at other locations continuous saturated conditions may exist from the valley fill water table to the bedrock aquifer. This suggests the water table of the glacially-filled valley is an elevated extension of the bedrock water table (Figure 18). Therefore, the hydrogeologic conditions in the vicinity of the glacially-filled valley are represented best by a combination of interpretations. More information may be needed to further delineate the hydrogeology of the valley fill.

The proposed Phase I pit boundaries lie well above and
away from the saturated zone. The proposed pit bottom will range between 12 and 18 metres above the water table. In a study of coal-conversion waste disposal in western North Dakota it was determined that 18 metres is a more than adequate distance between a waste deposit and the base of mine spoils to prevent leachate movement to the water table (Beaver, 1986). The proposed Phase I pit also lies, in part, within the sediments of the glacial valley fill. The closest this pit boundary comes to the elevated water table in the valley fill is at the northeast corner in an area where the fill is shallow and dry conditions prevail, approximately 180 metres from the glacial fill water table (Plate 3, cross-section D-D'). The hydrogeological conditions of the valley fill indicate that an ash disposal pit should not be located in this vicinity as the glacial fill retains moisture, holding groundwater levels well above the local bedrock water table, forming a groundwater mound superimposed on the bedrock water table. A relict water table, below the present water table, is indicated in the fill sediments by a red-brown to grey color change. The red-brown to grey color change records a transition from predominantly oxidizing to predominantly reducing conditions. This suggests water levels in the glacially-filled valley have been rising.

Groundwater quality analysis resulted in identification of two water quality types, (1) a Ca²⁺-HCO₃⁻, SO₄²⁻ water quali-
ty type and (2), a Na\(^+\)-HCO\(_3\), SO\(_4\)^{2-}\) water quality type (Tables 1, 2, and 3). The low sodium (Na\(^+\)) content of the Ca\(^{2+}\)-HCO\(_3\), SO\(_4\)^{2-}\) water implies that little cation exchange on sodium montmorillonite has occurred. This is a reflection of the near-surface stratigraphic position that this water is found. The Na\(^+\)-HCO\(_3\), SO\(_4\)^{2-}\) water quality type was found in stratigraphically deeper units and represents a water that has advanced farther along the chemical evolutionary sequence. The relatively high sodium content is a result of the exchange of Ca\(^{2+}\) and Mg\(^{2+}\) ions for Na\(^+\) ions on smectite clays. This process generally occurs during high precipitation events that lead to groundwater recharge.

The comparison of background water quality and leachate generated by EP toxicity testing indicates the potential for groundwater degradation exists at the Black Pit site (Tables 1, 2, 3, and 4). Attenuation and neutralization processes should significantly reduce the deleterious effects of FGC dry waste disposal at the Black Pit site by immobilizing several toxic trace elements such as arsenic, cadmium, and lead. Maintenance of the waste disposal pit above the water table beneath a gently-sloped, low-permeability cap will further reduce the potential for groundwater quality degradation by maximizing runoff, minimizing infiltration, and preventing leachate formation. This setting should provide long-term ash disposal success.
RECOMMENDATIONS

Proposed Pit Location

The proposed Phase I pit is hydrogeologically suitable for ash disposal (Plate 1). The pit bottom should be maintained at an elevation near the base of the present strip-mined pit. Leveling of spoil piles should be accomplished to eliminate depression-focused recharge to the near-surface lignite units by eliminating surface depressions in the post-reclamation landscape. The proposed phase II pit, on the other hand, is not recommended for ash disposal, as placement of ash in a zone of saturation may lead to groundwater contamination.

Water Level Monitoring

A groundwater monitoring plan should be implemented using newly installed and preexisting instrumentation. The initial groundwater level monitoring network should consist of monitoring wells 1701 and 1714 for the Antelope Creek lignite; BP3-U, 1702, and 1715 for the Spaer lignite; 1463 for the Spaer sand; BP2-A, and BP4-L for the lower Beulah-Zap split; TA2, BP4-U, and 1718 for the upper Beulah-Zap lignite; and monitoring well 820 for the Coleharbor Formation (Figure 20). These wells are strategically located around the proposed disposal pit and would effectively document any effects of waste disposal on the hydrogeology of the site. The water level monitoring wells are
Figure 20. Water Level Monitoring Plan For Coyote I FGC Waste Disposal Area
positioned for monitoring different stratigraphic levels, with the high-permeability lignite units of particular interest. These locations are based on study of the hydrologic and stratigraphic information displayed on the cross-sections. Water level measurements should be made on a monthly basis for the initial year of operation and may be reduced to quarterly thereafter.

**Water Quality Monitoring**

The water quality monitoring plan focuses upon the uppermost aquifer of the study site and is based upon Resource Conservation and Recovery Act (RCRA) requirements (U.S. Environmental Protection Agency, 1986). Initial monitoring will aid in defining the hydrogeochemical nature of the site. Continued monitoring of the uppermost bedrock aquifer, the Antelope Creek lignite, will provide adequate detection of contaminated recharge, in the unlikely event that any would occur.

As outlined in the permit application (Montana-Dakota Utilities Co., 1987), groundwater quality monitoring will focus upon the Antelope Creek lignite, which is the water table aquifer beneath the study site. Monitoring wells TA5, 1467, and an additional well emplaced 91 metres west of monitoring well 1466 should be monitored for downgradient groundwater quality (Figure 21). Monitoring well 820, screened in the Coleharbor Formation and a monitoring well emplaced adjacent to 812, screened in the Antelope Creek
Figure 21. Water Quality Monitoring Plan For Coyote I FGC Waste Disposal Area
EXPLANATION

- Ephemeral Tributary
- Glacially-Filled Valley
- Monitoring Well

INTERVAL

- Antelope Creek
- Lignite

PIEZOMETER

- TA5
- 1467
- 300'W. 1466
- Coleharbor Sand
- 820
lignite, will provide background groundwater quality data upgradient of the recommended disposal site (Figure 21). The background water quality monitoring network placement is based on the groundwater gradient displayed on Figure 19. This demonstrates flow from the east-southeast to the west, across the bedrock portion of the study site and north-northeast, out of the glacial fill, to the south-southwest, beneath the recommended disposal site, ultimately turning west and discharging into the unnamed tributary to the Knife River via the Antelope Creek lignite aquifer.

Quarterly groundwater monitoring for the first year, with semiannual monitoring for the second year, is recommended by the NDSDH.

**Cap and Liner**

It is recommended that a 0.3-metre scarified and uncompacted layer, of *in situ* materials, form a base for the proposed Phase I pit. The removal of remaining lignite, which forms the pit bottom in the southern portion of the pit, may be required. Infilling of low-permeability sediments up to the proposed bottom elevation in the area of lignite removal would then form a continuum between the base of the pit and the unsaturated silty-clay sediments which directly underlie the proposed Phase I disposal pit (Plates 2 and 3). Laboratory permeabilities of $1.9 \times 10^{-11}$ m/sec and $1.7 \times 10^{-11}$ m/sec (Montana Dakota Utilities Co., 1987) and *in situ* hydraulic conductivities of $1.1 \times 10^{-9}$ m/sec, $2.0 \times 10^{-4}$
m/sec, $1.5 \times 10^4$ m/sec, and $7.6 \times 10^9$ m/sec (Appendix D), were derived for these sediments. These values lie within the accepted pit bottom permeability range (about $10^9$ m/sec) (Ronnei, 1987).

Beaver (1986) recommended that a disposal site above the groundwater table, protected from recharge, is the best setting for disposal of fly ash and flue gas desulfurization (FGD) wastes because little leachate will form. Naturally occurring attenuation mechanisms within the native sediments immobilize As, Se, Pb, Cd, and Ba to acceptable levels and quickly buffer the pH of any leachate that may leave the waste deposit. It is suggested that reactions involving native clays, carbonates, sulfate, and iron oxy-hydroxides provide the observed attenuation capacity. The Black Pit ash disposal site should provide adequate long-term disposal success as long as the site is maintained above the post-closure water table and a gently-sloped compacted clay cap is constructed to prevent infiltration from reaching the deposit. Figure 22 is a generalized illustration of the proposed Black Pit ash disposal setting. The underlying sediments are of sufficiently low permeability to retard leachate movement. The chemical buffering and attenuation studies suggest that liners are unnecessary to retard major ion or trace element transport in an unsaturated setting. If clay exists in the native sediments, the placement of a liner is redundant; such material is better placed over the
Figure 22. Diagrammatic Illustration Of The Post-Ash Disposal Setting (Modified from Ronnei, 1987)
deposit to prevent infiltration from above (Beaver, 1986, p. 265). Because clay does in fact exist in the native sediments as at this site, the placement of a clay liner is unnecessary.

Cap construction should begin as final ash storage elevations are reached. A final cover consisting of a 0.6 metre-thick compacted clay cap overlain by 0.6 metres of less compacted clay and approximately 0.3 metres of topsoil and subsoil should provide sufficient protection from infiltration. A gently-sloped final surface will prevent depression-focused recharge.
APPENDICES
APPENDIX A

WATER LEVEL INFORMATION

(Water Levels Taken 11/29/87; See Plate 1 for Locations)
### COYOTE I FGC ASH DISPOSAL NEWLY INSTALLED WELLS

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APPENDIX B

COMPOSITE WATER LEVEL INFORMATION

(See Plate 1 For Locations)
COYOTE I FGC WASTE DISPOSAL AREA (NEWLY INSTALLED WELLS)

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### COYOTE I FGC ASH DISPOSAL AREA (PREEXISTING WELLS)

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COYOTE I FGC ASH DISPOSAL AREA (PREEXISTING WELLS)

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<th>DATE</th>
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APPENDIX C

DESCRIPTIVE WELL LOG DATA

(See Plate 1 or Figure 15 for Locations)
### DESCRIPITIVE LOGS - COYOTE I FGC ASH DISPOSAL AREA

#### WELL #1701

<table>
<thead>
<tr>
<th>DEPTH (m)</th>
<th>DESCRIPTION</th>
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<tbody>
<tr>
<td>0.0-0.3</td>
<td>Topsoil</td>
</tr>
<tr>
<td>0.3-1.6</td>
<td>Sand, silty, yellowish brown</td>
</tr>
<tr>
<td>1.6-3.6</td>
<td>Clay, silty, yellowish brown</td>
</tr>
<tr>
<td>3.6-6.2</td>
<td>Lignite, brownish black</td>
</tr>
<tr>
<td>6.2-8.3</td>
<td>Clay, yellowish brown</td>
</tr>
<tr>
<td>8.3-9.3</td>
<td>Lignite, brownish black</td>
</tr>
<tr>
<td>9.30-12.9</td>
<td>Clay, silty, reddish brown</td>
</tr>
<tr>
<td>12.9-14.7</td>
<td>Silt, clayey, reddish brown</td>
</tr>
<tr>
<td>14.7-15.6</td>
<td>Clay, silty, reddish brown</td>
</tr>
<tr>
<td>15.6-16.3</td>
<td>Lignite, brownish black</td>
</tr>
<tr>
<td>16.3-16.9</td>
<td>Clay, silty, reddish brown</td>
</tr>
<tr>
<td>16.9-17.5</td>
<td>Lignite, brownish black</td>
</tr>
<tr>
<td>17.5-22.1</td>
<td>Clay, medium gray</td>
</tr>
<tr>
<td>22.1-26.0</td>
<td>Clay, silty, medium gray</td>
</tr>
<tr>
<td>26.0-27.5</td>
<td>Lignite, brownish black</td>
</tr>
<tr>
<td>27.5-29.7</td>
<td>Clay, silty, medium gray</td>
</tr>
<tr>
<td>29.7-30.3</td>
<td>Lignite, brownish black</td>
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#### WELL #1702

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<th>DESCRIPTION</th>
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<tbody>
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<td>0.0-17.0</td>
<td>Same location and description as well #1701</td>
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#### WELL #1703

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<th>DESCRIPTION</th>
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<tbody>
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<td>0.0-5.4</td>
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<tr>
<td>5.4-6.3</td>
<td>Clay, silty, medium gray</td>
</tr>
<tr>
<td>6.3-7.8</td>
<td>Silt, clayey, blackish gray</td>
</tr>
<tr>
<td>7.8-8.1</td>
<td>Clay, blackish gray</td>
</tr>
<tr>
<td>8.10-12.5</td>
<td>Lignite, black</td>
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<tr>
<td>12.5-13.6</td>
<td>Clay, blackish gray</td>
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<tr>
<td>13.6-14.9</td>
<td>Lignite, black</td>
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<tr>
<td>14.9-17.7</td>
<td>Clay, blackish gray</td>
</tr>
<tr>
<td>17.7-21.2</td>
<td>Silt, clayey, medium gray</td>
</tr>
<tr>
<td>21.2-21.6</td>
<td>Lignite, black</td>
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<tr>
<td>21.6-22.6</td>
<td>Silt, medium gray</td>
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<tr>
<td>22.6-23.4</td>
<td>Lignite, black</td>
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<td>23.4-25.3</td>
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<td>25.3-32.8</td>
<td>Clay, medium gray</td>
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<tr>
<td>32.8-33.4</td>
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</table>
## DESCRIPTIVE LOGS - COYOTE I FGC ASH DISPOSAL AREA

### WELL #1704

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<tbody>
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### WELL #1705

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<th>DESCRIPTION</th>
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</thead>
<tbody>
<tr>
<td>0.0-8.8</td>
<td>Pebble-loam, olive brown, iron stained, w/lignite clasts</td>
</tr>
<tr>
<td>8.80-11.0</td>
<td>Sand, fine, Bedrock</td>
</tr>
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<td>11.0-12.2</td>
<td>Clay, blackish gray</td>
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### WELL #1706

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<th>DESCRIPTION</th>
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<tr>
<td>17.7-23.0</td>
<td>Pebble-loam, medium gray, w/lignite clasts</td>
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<tr>
<td>23.0-24.1</td>
<td>Sand, medium, gray, Bedrock</td>
</tr>
<tr>
<td>24.1-26.2</td>
<td>Clay, medium gray</td>
</tr>
<tr>
<td>26.2-26.8</td>
<td>Silt, clayey, blackish gray</td>
</tr>
<tr>
<td>26.8-29.3</td>
<td>Clay, medium gray</td>
</tr>
<tr>
<td>29.3-30.5</td>
<td>Lignite, brownish black</td>
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<tr>
<td>30.5-33.2</td>
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<td>33.2-34.4</td>
<td>Lignite, black</td>
</tr>
<tr>
<td>34.4-37.2</td>
<td>Clay, medium gray</td>
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### WELL #1707

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<td>0.0-0.6</td>
<td>Topsoil</td>
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<td>0.60-3.10</td>
<td>Pebble-loam, whitish brown</td>
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<td>3.10-15.2</td>
<td>Pebble-loam, olive brown, iron stained, w/lignite clasts</td>
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<tr>
<td>15.2-27.4</td>
<td>Pebble-loam, gray</td>
</tr>
<tr>
<td>27.4-33.5</td>
<td>Sand, fine, gray</td>
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<tr>
<td>33.5-38.1</td>
<td>Clay, blackish gray, Bedrock</td>
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<tr>
<td>38.1-38.7</td>
<td>Lignite, black</td>
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<tr>
<td>38.7-39.6</td>
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</table>
### DESCRIPTIVE LOGS - COYOTE I FGC ASH DISPOSAL AREA

#### WELL #1708
**DEPTH (m)**  
0.0-19.8

**DESCRIPTION**  
Same location and description as well #1707

#### WELL #1709
**DEPTH (m)**  
0.0-1.5  
1.5-3.1  
3.1-6.1  
6.10-19.8  
16.8-19.8

**DESCRIPTION**  
Pebble-loam, whitish brown  
Pebble-loam, olive brown, iron stained  
Pebble-loam, reddish brown, iron stained, w/lignite pebbles  
Pebble-loam, olive brown, iron stained, w/lignite pebbles  
Pebble-loam, gray, w/lignite pebbles

#### WELL #1710
**DEPTH (m)**  
0.0-19.4

**DESCRIPTION**  
Same location and description as well #1706

#### WELL #1711
**DEPTH (m)**  
0.0-0.3  
0.3-1.3  
1.3-5.6  
5.6-8.9  
8.90-10.8  
10.8-12.0  
12.0-14.7  
14.7-16.3  
16.3-19.3  
19.3-19.9  
19.9-22.4  
22.4-22.7  
22.7-23.7

**DESCRIPTION**  
Topsoil  
Silt, clayey, yellow brown, Spoils  
Silt, clayey, yellow-reddish brown, interbedded orange clay laminations  
Lignite, black  
Clay, blackish gray  
Lignite, black  
Clay, blackish gray  
Lignite, black, carbonaceous  
Lignite, black, trace  
Sand, silty, gray
DESCRIPTIVE LOGS - COYOTE I FGC ASH DISPOSAL AREA

WELL #1712
DEPTH (m) DESCRIPTION
0.0-12.4 Same location and description as well #1711

WELL #1713
DEPTH (m) DESCRIPTION
0.0-9.5 Same location and description as well #1711

WELL #1714
DEPTH (m) DESCRIPTION
0.0-4.1 Sand, brown, fine to medium
4.1-6.0 Gravel, brown, interbedded fine to medium sand
6.0-7.1 Clay, silty, gray, Bedrock
7.1-7.5 Siltstone, white
7.50-10.9 Clay, silty, gray
10.9-11.5 Lignite, black
11.5-12.7 Clay, gray
12.7-13.3 Lignite, black
13.3-20.0 Clay, silty, gray
20.0-21.5 Lignite, black
21.5-22.9 Clay, silty, gray
22.9-23.4 Lignite, black

WELL #1715
DEPTH (m) DESCRIPTION
0.0-11.5 Same location and description as well #1714

WELL #1716
DEPTH (m) DESCRIPTION
0.0-2.8 Clay, silty, yellow-reddish brown
2.8-4.4 Clay, blackish gray, interbedded reddish brown clay
4.4-8.2 Lignite, black
8.2-9.8 Clay, gray
### DESCRIPTIVE LOGS - COYOTE I FGC ASH DISPOSAL AREA

**WELL #1716**

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<td>9.80-11.2</td>
<td>Lignite, black</td>
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<tr>
<td>11.2-15.9</td>
<td>Clay, blackish gray</td>
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<tr>
<td>15.9-16.4</td>
<td>Lignite, black</td>
</tr>
<tr>
<td>16.4-17.3</td>
<td>Clay, blackish gray</td>
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<tr>
<td>17.3-17.8</td>
<td>Lignite, black</td>
</tr>
<tr>
<td>17.8-21.7</td>
<td>Clay, blackish gray</td>
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**WELL #1717**

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**WELL #1720**

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<th>Description</th>
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</thead>
<tbody>
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<td>Pebble-loam, olive brown, iron stained, w/lignite clasts</td>
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<tr>
<td>14.8-15.7</td>
<td>Pebble-loam, gray, w/lignite clasts</td>
</tr>
<tr>
<td>15.7-17.8</td>
<td>Clay, blackish gray, Bedrock</td>
</tr>
<tr>
<td>17.8-20.9</td>
<td>Lignite, black</td>
</tr>
<tr>
<td>20.9-21.6</td>
<td>Clay, blackish gray</td>
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<tr>
<td>21.6-22.4</td>
<td>Lignite, black</td>
</tr>
<tr>
<td>22.4-27.6</td>
<td>Clay, gray, w/iron stained nodules</td>
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<td>27.6-28.1</td>
<td>Lignite, black</td>
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<tr>
<td>28.1-29.1</td>
<td>Clay, blackish gray, w/iron stained nodules</td>
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### WELL #1720

<table>
<thead>
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<th>DEPTH (m)</th>
<th>DESCRIPTION</th>
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</thead>
<tbody>
<tr>
<td>29.1-29.9</td>
<td>Lignite, black</td>
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<tr>
<td>29.9-34.3</td>
<td>Clay, gray, w/iron stained nodules</td>
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### WELL #1721

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<td>Pebble-loam, olive brown, iron stained, w/lignite clasts</td>
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<tr>
<td>16.8-25.2</td>
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<td>25.2-28.1</td>
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<td>28.1-31.4</td>
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<td>31.4-32.3</td>
<td>Lignite</td>
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<td>Clay, medium gray</td>
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<tr>
<td>34.5-35.7</td>
<td>Lignite</td>
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APPENDIX D

IN SITU HYDRAULIC CONDUCTIVITY DATA

(See Plate 1 For Locations)
## Coyote I FGC Ash Disposal Area
### In Situ Hydraulic Conductivity Data

<table>
<thead>
<tr>
<th>Well Number</th>
<th>Interval Screened</th>
<th>Hydraulic Conductivity</th>
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</thead>
<tbody>
<tr>
<td>1466</td>
<td>Beulah-Zap sandy silt</td>
<td>$1.08 \times 10^{-7}$ cm/sec</td>
</tr>
<tr>
<td>1470</td>
<td>Beulah-Zap silty clay</td>
<td>$1.45 \times 10^{-6}$ cm/sec</td>
</tr>
<tr>
<td>1472</td>
<td>Beulah-Zap sandy silt</td>
<td>$2.40 \times 10^{-6}$ cm/sec</td>
</tr>
<tr>
<td>1473</td>
<td>Beulah-Zap silty clay</td>
<td>$7.58 \times 10^{-7}$ cm/sec</td>
</tr>
<tr>
<td>1566</td>
<td>Coleharbor pebble loam</td>
<td>$5.23 \times 10^{-8}$ cm/sec</td>
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APPENDIX E

BACKGROUND WATER QUALITY DATA

(See Plate 1 and Figure 8 for Locations)
<table>
<thead>
<tr>
<th>Well Number</th>
<th>Date Sampled</th>
<th>Stratigraphic Position</th>
<th>TDS mg/L</th>
<th>Field Temperature (Celsius)</th>
<th>Lab pH</th>
<th>Field pH</th>
<th>Lab Cond. umohs/cm</th>
<th>Field Cond. umohs/cm</th>
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</thead>
<tbody>
<tr>
<td>BP4-U</td>
<td>03/08/88</td>
<td>Upper Beulah-Zap lignite</td>
<td>---- 1</td>
<td>5.9</td>
<td>--- 1</td>
<td>6.7</td>
<td>48200.0</td>
<td>1100.0</td>
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<td>BP2-A</td>
<td>03/08/88</td>
<td>Lower Beulah-Zap lignite</td>
<td>3880.0</td>
<td>8.2</td>
<td>6.9</td>
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<td>57000.0</td>
<td>4100.0</td>
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<tr>
<td>1715</td>
<td>03/08/88</td>
<td>Upper Spaer lignite</td>
<td>2200.0</td>
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<td>7.9</td>
<td>7.3</td>
<td>1840.0</td>
<td>2100.0</td>
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<tr>
<td>1463</td>
<td>03/08/88</td>
<td>Spaer sand</td>
<td>1180.0</td>
<td>9.0</td>
<td>8.8</td>
<td>7.2</td>
<td>1790.0</td>
<td>1700.0</td>
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<td>7.4</td>
<td>7.5</td>
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Mean: 2515.0 7.6 7.6 6.9 14820.5 2455.6
High: 4580.0 9.0 8.8 7.5 57000.0 4100.0
Low: 1180.0 5.9 7.0 5.4 1695.0 1100.0

1 insufficient sample to perform analysis
2 sample acidified and value calculated from TDS
3 measurement conducted on an acidified sample
### CHEMICAL ANALYSES: ANIONIC CONCENTRATIONS AND % DIFF.

#### BLACK PIT SITE

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<tr>
<th>Well Number</th>
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<th>F</th>
<th>Cl</th>
<th>SO$_4^{2-}$</th>
<th>NO$_3^-$</th>
<th>CO$_3^{2-}$</th>
<th>HCO$_3^-$</th>
<th>Anions</th>
<th>Cations</th>
<th>% Diff.</th>
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Mean: 2.0 9.0 883.0 <2.0 0.0 587.4 28.8 32.0 7.0
High: 7.3 15.5 2220.0 <2.0 0.0 750.0 55.7 57.9 35.2
Low: <1.0 1.2 60.0 <2.0 0.0 315.0 13.8 8.8 0.2

1 insufficient sample to conduct analysis
CHEMICAL ANALYSES: CATIONIC CONCENTRATIONS, SAR, AND TOTAL HARDNESS
BLACK PIT SITE

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<tr>
<th>Well Number</th>
<th>Date Sampled</th>
<th>Stratigraphic Position</th>
<th>Ca²⁺ (mg/L)</th>
<th>Mg²⁺ (mg/L)</th>
<th>Na⁺ (mg/L)</th>
<th>K⁺ (mg/L)</th>
<th>Fe (mg/L)</th>
<th>SAR (mg/L)</th>
<th>Total Hardness (mg/L)</th>
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<td>BP4-U</td>
<td>03/08/88</td>
<td>Upper Beulah-Zap lignite</td>
<td>109.0</td>
<td>28.0</td>
<td>21.0</td>
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<td>Lower Beulah-Zap lignite</td>
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<td>123.0</td>
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<td>Upper Spaer lignite</td>
<td>233.0</td>
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<td>Spaer sand</td>
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<td>12.0</td>
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<td>49.0</td>
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Mean: 242.0 130.0 190.0 17.0 0.6 13.4 1077.3
High: 595.0 326.0 488.0 49.0 1.4 54.5 2599.0
Low: 20.0 9.5 21.0 4.4 <0.5 2.2 99.0

\[
SAR = \frac{Na^+}{(mg^{2+} + Ca^{2+})^{1/2}}
\]

\[
Total\ Hardness = 2.5(Ca^{2+}) + 4.1(Mg^{2+})
\]
<table>
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<tr>
<th>Well Number</th>
<th>Date Sampled</th>
<th>Stratigraphic Position</th>
<th>As mg/L</th>
<th>Ba mg/L</th>
<th>B mg/L</th>
<th>Cd mg/L</th>
<th>Cr mg/L</th>
<th>Pb mg/L</th>
<th>Mn mg/L</th>
<th>Hg mg/L</th>
<th>Mo mg/L</th>
<th>Se mg/L</th>
<th>Ag mg/L</th>
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<td>&lt;0.5</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
<td>6.0</td>
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<td>&lt;0.001</td>
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<td>03/08/88</td>
<td>Antelope Creek lignite</td>
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<td>0.04</td>
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<td>&lt;0.02</td>
<td>&lt;0.02</td>
<td>&lt;5.0</td>
<td>0.18</td>
<td>&lt;0.003</td>
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<td>0.15</td>
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Mean: <0.002 0.06 0.2 <0.02 <0.02 0.002 0.70 <0.003 0.09 <2.0 <0.001

High: <0.002 0.08 0.7 <0.02 <0.02 0.006 1.57 <0.003 0.15 <2.0 <0.001

Low: <0.002 0.04 <0.5 <0.02 <0.02 0.005 0.18 <0.003 <0.05 <2.0 <0.001
APPENDIX F

WELL COMPLETION REPORTS

(See Plate 1 and Figure 6 for Locations, Information in Centimetres (cm), Metres (m), and Litres (L)).
WELL COMPLETION REPORT

Well Number: 1702
Owner: MDU-Coyote
Well Location: N-4236.39 W-3807.85
County: Mercer
State: North Dakota
Drilling Company: Mohl Drilling Company
Method Drilled: Air Mist Rotary
Bit Size: 13.3 cm
Depth Drilled: 16.97 m
Condition Of Hole: Good

Date Drilled: 10 November 1987
Date Set: 10 November 1987
Date Sealed: 17 November 1987
Date Filled:

Well Head Elevation: 597.4 m
Ground Elevation: 596.8 m
Bottom Of Screen Elevation: 579.8 m

CASING
Type: PVC
Diameter: 5.1 cm
length From: +0.6 m
Length To: 15.4 m

SCREEN
Type: PVC
Slot Size: 0.025 cm
Set From: 15.4 m
To: 17.0 m

PERFORATIONS
Type Of Perforator Used:
Size Of Perforations: in/cm by: in/cm
Perforations From: ft./m to: ft/m

WASHDOWN VALVE: Yes X No
FORMATION PACKERS USED: Yes No X

GRAVEL
Type: Silica Sand
Volume: 2 Sacks
Bottom At: 16.97 m
Top At: 15.14 m
Tremied: Yes X No
From What Depths: 16.97 m to 15.14 m

GROUT SEAL
Type: Grout Cement
Mixture (water/sacks): 124.3 L/m #5 Grout
Volume: 254 L
Tremied: Yes No X
From What Depths:

BACKFILL
Type: From:
To:

OTHER WELLS IN HOLE
Types: Diam.: Depths:

OTHER DATA
Sample Desc.: Nate Hunke, EMRC, Grand Forks, ND
Geophys. Logs:

Drilling Time Log: Water Chem.:
DST: Other:
COMMENTS: Spaer lignite. W.L. 16.4 m BLS (580.0 m), 11/29/87.

BLS=Below Land Surface
W.L.=Water Level
WELL COMPLETION REPORT

Well Number: 1703
Owner: MDU-Coyote
Well Location: N-4037.27 W-3268.27
County: Mercer
State: North Dakota
Drilling Company: Mohl Drilling Company
Method Drilled: Air Mist Rotary
Bit Size: 13.3 cm
Depth Drilled: 33.8 m Condition Of Hole: Good

Date Drilled: 10 November 1987 Date Set: 10 November 1987
Date Sealed: 17 November 1987 Date Filled:
Well Head Elevation: 603.6 m Ground Elevation: 602.9 m
Bottom Of Screen Elevation: 569.1 m

CASING
Type: PVC Diameter: 5.1 cm
length From: +0.7m Length To: 27.6 m

SCREEN
Type: PVC Diameter: 5.1 cm
Slot Size: 0.025 cm To: 33.8 m
Set From: 27.7 m

PERFORATIONS
Type Of Perforator Used: 
Size Of Perforations: in/cm by: in/cm
Perforations From: ft./m to: ft/m

WASHDOWN VALVE: Yes X No

FORMATION PACKERS USED: Yes No X
Type: Base: ft/m

GRAVEL
Type: Silica Sand Volume: 6.5 Sacks
Bottom At: 33.8 m Top At: 27.4 m
Tremied: Yes X No
From What Depths: 33.8 m to 27.4 m

GROUT SEAL
Type: Grout Cement
Mixture (water/sacks): 124.3 L/m #5 Grout
Volume: 394 L Tremied: Yes No X
From What Depths:

BACKFILL
Type: From: To:
Type: From: To:

OTHER WELLS IN HOLE Types: Diam.: Depths:

OTHER DATA
Sample Desc.: Nate Hunke, EMRC, Grand Forks,ND
Geophys. Logs: Mark Spitzer, Dakota Geophysics Dickinson,ND

Drilling Time Log: Water Chem.: 
DST: Other:
COMMENTS: A-C lignite. W.L. 31.1 m BLS (571.8m), 11/29/87.

BLS=Below Land Surface
W.L.=Water Level
WELL COMPLETION REPORT

Well Number: 1704
Owner: MDU-Coyote
Well Location: N-4041.95 W-3278.30
County: Mercer
State: North Dakota
Drilling Company: Mohl Drilling Company
Method Drilled: Air Mist Rotary
Bit Size: 13.3 cm
Depth Drilled: 21.8 m
Condition Of Hole: Good

Date Drilled: 10 November 1987
Date Set: 10 November 1987
Date Sealed: 17 November 1987
Date Filled:
Well Head Elevation: 603.6 m
Ground Elevation: 602.9 m
Bottom Of Screen Elevation: 581.1 m

Casing
Type: PVC
Diameter: 5.1 cm
Length From: +0.7 m
Length To: 20.3 m

Screen
Type: PVC
Diameter: 5.1 cm
Slot Size: 0.025 cm
Set From: 20.3 m
To: 21.8 m

Perforations
Type Of Perforator Used:
Size Of Perforations: in/cm by: in/cm
Perforations From: ft./m to: ft./m

Washdown Valve: Yes X No
Formation Packers Used: Yes X No X

Gravel
Type: Silica Sand
Volume: 2 Sacks
Bottom At: 21.8 m
Top At: 20.0 m
Tremied: Yes X No
From What Depths: 21.8 m to 20.0 m

Grout Seal
Type: Grout Cement
Mixture (water/sacks): 30 gal/yrd #5 Grout
Volume: 315 L
Tremied: Yes X No X
From What Depths:

Backfill
Type:
From: To:

Other Wells In Hole
Types: Diam.: Depths:

Other Data
Sample Desc.: Nate Hunke, EMRC Grand Forks, ND
Geophys. Logs:

Drilling Time Log:
Water Chem.:
DST:
Other:


BLS=Below Land Surface
W.L.=Water Level
WELL COMPLETION REPORT

Well Number: 1705
Owner: MDU-Coyote
Well Location: N-4540.09 W-3804.04
County: Mercer State: North Dakota
Drilling Company: Mohl Drilling Company
Method Drilled: Air Mist Rotary
Bit Size: 13.3 cm
Depth Drilled: 12.2 m Condition Of Hole: Good

Date Drilled: 11 November 1987 Date Set:
Date Sealed: Date Filled:
Well Head Elevation: 594.6 m
Bottom Of Screen Elevation:

CASING
Type: Diameter:  
length From: Length To: 

SCREEN
Type: Diameter:  
Set From: To: 

PERFORATIONS
Type Of Perforator Used:  
Size Of Perforations: in/cm by: in/cm  
Perforations From: ft./m to: ft/m

WASHDOWN VALVE: Yes No
FORMATION PACKERS USED: Yes No
Type: Base: ft/m

GRAVEL
Type: Volume:  
Bottom At: Top At:  
Tremied: Yes No  

From What Depths:

GROUT SEAL
Type: Mixture (water/sacks):  
Volume: Tremied: Yes No  

From What Depths:

BACKFILL
Type: From: To:  
Type: From: To:  

OTHER WELLS IN HOLE Types: Diam.: Depths:

OTHER DATA
Sample Desc.: Nate Hunke, EMRC, Grand Forks, ND
Geophys. Logs: Mark Spitzer, Dakota Geophysics, Dickinson, ND

Drilling Time Log: Water Chem.:  
DST: Other:  
COMMENTS: Test hole. No piezometer installed.

BLS=Below Land Surface
W.L.=Water Level
WELL COMPLETION REPORT

Well Number: 1706
Owner: MDU-Coyote
Well Location: N-4701.30 W-2961.34
County: Mercer
State: North Dakota
Drilling Company: Mohl Drilling Company
Method Drilled: Air Mist Rotary
Bit Size: 13.3 cm
Depth Drilled: 39.6 m
Condition Of Hole: Unstable

Date Drilled: 11 November 1987
Date Set:
Date Sealed: Date Filled:
Well Head Elevation: Ground Elevation: 601.4 m
Bottom Of Screen Elevation:

CASING
Type: Diameter:
length From: Length To:

SCREEN
Type: Diameter:
Slot Size: To:
Set From:

PERFORATIONS
Type Of Perforator Used:
Size Of Perforations: in/cm by: in/cm
Perforations From: ft./m to: ft/m

WASHDOWN VALVE: Yes No
FORMATION PACKERS USED: Yes No

GRAVEL
Type: Volume:
Bottom At: Top At:
Tremied: Yes No
From What Depths:

GROUT SEAL
Type:
Mixture (water/sacks):
Volume:
Tremied: Yes No
From What Depths:

BACKFILL
Type: From: To:
Type: From: To:

OTHER WELLS IN HOLE Types: Diam.: Depths:

OTHER DATA
Sample Desc.: Nate Hunke, EMRC, Grand Forks, ND
Geophys. Logs: Mark Spitzer, Dakota Geophysics, Dickinson, ND
Drilling Time Log: Water Chem.:
DST: Other:
COMMENTS: Test hole. No piezometer installed.

BLS=Below Land Surface
W.L.=Water Level
WELL COMPLETION REPORT

Well Number: 1707
Owner: MDU-Coyote
Well Location: N-4674.53 W-2227.51
County: Mercer  State: North Dakota
Drilling Company: Mohl Drilling Company
Method Drilled: Air Mist Rotary
Bit Size: 13.3 cm
Depth Drilled: 32.6 m  Condition Of Hole: Unstable

Date Drilled: 11 November 1987  Date Set:
Date Sealed:  Date Filled:  
Well Head Elevation:  Ground Elevation: 605.9 m
Bottom Of Screen Elevation:

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<td>To:</td>
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PERFORATIONS
Type Of Perforator Used:
Size Of Perforations: in/cm by: in/cm
Perforations From: ft./m to: ft/m

WASHDOWN VALVE: Yes  No
FORMATION PACKERS USED: Yes  No
Type:  Volume:  Base: ft/m

GRAVEL
Type:  Volume:
Bottom At:  Top At:
Tremied: Yes  No
From What Depths:

GROUT SEAL
Type:  Mixture (water/sacks):
Volume:  From What Depths:
Tremied: Yes  No

BACKFILL
Type:  From:  To:
Type:  From:  To:

OTHER WELLS IN HOLE Types: Diam.: Depths:

OTHER DATA
Sample Desc.: Nate Hunke, EMRC, Grand Forks, ND
Geophys. Logs: Mark Spitzer, Dakota Geophysics, Dickinson, ND

Drilling Time Log: Water Chem.:
DST: Other:
COMMENTS: Test hole. No piezometer installed.

BLS=Below Land Surface
W.L.=Water Level
WELL COMPLETION REPORT

Well Number: 1708
Owner: MDU-Coyote
Well Location: N-4674.87
County: Mercer  State: North Dakota
Drilling Company: Mohl Drilling Company
Method Drilled: Air Mist Rotary
Bit Size: 13.3 cm
Depth Drilled: 19.8 m  Condition Of Hole: Unstable

Date Drilled: 10 November 1987  Date Set: 10 November 1987
Date Sealed: 17 November 1987  Date Filled:
Well Head Elevation: 606.6 m  Ground Elevation: 605.9 m
Bottom Of Screen Elevation: 586.1 m

CASING  Type: PVC  Diameter: 5.1 cm
Length From: +0.7 m  Length To: 13.7 m

SCREEN  Type: PVC  Diameter: 5.1 cm
Slot Size: 0.025 cm
Set From: 13.7 m  To: 19.8 m

PERFORATIONS  Type Of Perforator Used:
Size Of Perforations:  in/cm by:  in/cm
Perforations From: ft./m to:  ft./m

WASHDOWN VALVE: Yes X  No

FORMATION PACKERS USED: Yes No X

GRAVEL  Type: Silica Sand  Volume: 10.5 Sacks
Bottom At: 19.8 m  Top At: 13.4 m
Tremied: Yes X  No
From What Depths: 19.8 m to 13.4 m

GROUT SEAL  Type: Grout Cement
Mixture (water/sacks): 124.3 L/m  5# Grout
Volume: 243 L  Tremied: Yes No X
From What Depths:

BACKFILL  Type:  From:  To:
Type:  From:  To:

OTHER WELLS IN HOLE  Types:  Diam.:  Depths:

OTHER DATA
Sample Desc.: Nate Hunke, EMRC, Grand Forks, ND
Geophys. Logs:

Drilling Time Log:  Water Chem.:
DST:  Other:
COMMENTS: Coleharbor pebble-loam. W.L. 18.3 m BLS (587.7), 11/29/87.
BLS=Below Land Surface
W.L.=Water Level
WELL COMPLETION REPORT

Well Number: 1709
Owner: MDU-Coyote
Well Location: N-44.92 W-1530.86
County: Mercer  State: North Dakota
Drilling Company: Mohl Drilling Company
Method Drilled: Air Mist Rotary
Bit Size: 13.3 cm
Depth Drilled: 19.8 m  Condition Of Hole: Unstable

Date Drilled: 10 November 1987  Date Set: 10 November 1987
Date Sealed: 17 November 1987  Date Filled:
Well Head Elevation: 607.1 m  Ground Elevation: 606.5 m
Bottom Of Screen Elevation: 586.8 m

CASING
Type: PVC  Diameter: 5.1 cm
length From: +0.6m  Length To: 13.7 m

SCREEN
Type: PVC  Diameter: 5.1 cm
Slot Size: 0.025 cm
Set From: 13.7 m  To: 19.8 m

PERFORATIONS
Type Of Perforator Used:
Size Of Perforations: in/cm by: in/cm
Perforations From: ft./m to: ft/m

WASHDOWN VALVE: Yes X No

FORMATION PACKERS USED: Yes No X
Type: Base: ft/m

GRAVEL
Type: Silica Sand  Volume: 10.5 Sacks
Bottom At: 19.8 m  Top At: 13.4 m
Tremied: Yes X No
From What Depths: 19.5 m to 13.4 m

GROUT SEAL
Type: Grout Cement
Mixture (water/sacks): 124.3 L/m 5# Grout
Volume: 243 L  Tremied: Yes No X
From What Depths:

BACKFILL
Type: From: To:
Type: From: To:

OTHER WELLS IN HOLE Types: Diam.: Depths:

OTHER DATA
Sample Desc.: Nate Hunke, EMRC, Grand Forks, ND
Geophys. Logs:

Drilling Time Log: Water Chem.:
DST: Other:
COMMENTS: Coleharbor pebble-loam. W.L. 13.0 m BLS (593.5), 11/29/87.
BLS=Below Land Surface
W.L.=Water Level
WELL COMPLETION REPORT

Well Number: 1710
Owner: MDU-Coyote
Well Location: N-4696.39 W-2951.55
County: Mercer State: North Dakota
Drilling Company: Mohl Drilling Company
Method Drilled: Air Mist Rotary
Bit Size: 13.3 cm
Depth Drilled: 19.4 m Condition Of Hole: Unstable

Date Drilled: 10 November 1987 Date Set: 10 November 1987
Date Sealed: 17 November 1987 Date Filled:
Well Head Elevation: 602.3 m Ground Elevation: 601.6 m
Bottom Of Screen Elevation: 582.1 m

Casing
Type: PVC Diameter: 5.1 cm
length From: +0.7 m Length To: 13.3 m

Screen
Type: PVC Diameter: 5.1 cm
Slot Size: 0.025 cm
Set From: 13.3 m To: 19.4 m

Perforations
Type Of Perforator Used: Size Of Perforations: in/cm by: in/cm
Perforations From: ft./m to: ft./m

Washdown Valve: Yes X No
Formation Packers Used: Yes No X

Type: Base: ft./m

Gravel
Type: Silica Sand Volume: 11 Sacks
Bottom At: 19.4 m Top At: 13.0 m
Tremied: Yes X No
From What Depths: 19.4 m to 13.0 m

Grout Seal
Type: Grout Cement Mixture (water/sacks): 124.3 L/m 5# Grout Volume: 239 L Tremied: Yes No X
From What Depths:

Backfill
Type: From: To:
Type: From: To:

Other Wells In Hole Types: Diam.: Depths:

Other Data
Sample Desc.: Nate Hunke, EMRC, Grand Forks, ND
Geophys. Logs:

Drilling Time Log: Water Chem.:
DST: Other:
Comments: Coleharbor pebble-loam. W.L. 8.5 m BLS (593.1), 11/29/87.
BLS=Below Land Surface
W.L.=Water Level
WELL COMPLETION REPORT

Well Number: 1711
Owner: MDU-Coyote
Well Location: N-3759.60 W-3232.67
County: Mercer
State: North Dakota
Drilling Company: Mohl Drilling Company
Method Drilled: Air Mist Rotary
Bit Size: 13.3 cm
Depth Drilled: 23.9 m
Condition Of Hole: Good

Date Drilled: 10 November 1987
Date Set: 10 November 1987
Date Sealed: 17 November 1987
Date Filled:
Well Head Elevation: 600.0 m
Ground Elevation: 599.6 m
Bottom Of Screen Elevation: 575.6 m

CASING
Type: PVC
Diameter: 5.1 cm
length From: +0.5 m
length To: 20.9 m

SCREEN
Type: PVC
Diameter: 5.1 cm
Slot Size: 0.025 cm
Set From: 20.9 m
To: 23.9 m

PERFORATIONS
Type Of Perforator Used:
Size Of Perforations: in/cm by: in/cm
Perforations From: ft./m to: ft/m

WASHDOWN VALVE: Yes X No
FORMATION PACKERS USED: Yes No X

GRAVEL
Type: Silica Sand
Volume: 5 Sacks
Bottom At: 23.9 m
Top At: 20.6 m
Tremied: Yes X No
From What Depths: 23.9 m to 20.6 m

GROUT SEAL
Type: Grout Cement
Mixture (water/sacks): 124.3 L/m #5 Grout
Volume: 318 L
Tremied: Yes No X
From What Depths:

BACKFILL
Type: From: To:
Type: From: To:

OTHER WELLS IN HOLE
Types: Diam.: Depths:

OTHER DATA
Sample Desc.: Nate Hunke, EMRC Grand Forks,ND
Geophys. Logs: Mark Spitzer, Dakota Geophysics Dickinson,ND

Drilling Time Log: Water Chem.:
DST: Other:

BLS=Below Land Surface
W.L.=Water Level
WELL COMPLETION REPORT

Well Number: 1712
Owner: MDU-Coyote
Well Location: N-3762.30 W-3239.89
County: Mercer  State: North Dakota
Drilling Company: Mohl Drilling Company
Method Drilled: Air Mist
Bit Size: 13.3 cm
Depth Drilled: 12.4 m  Condition Of Hole: Good

Date Drilled: 10 November 1987  Date Set: 10 November 1987
Date Sealed: 17 November 1987  Date Filled:
Well Head Elevation: 600.1 m  Ground Elevation: 599.5 m
Bottom Of Screen Elevation: 587.0 m

CASING
Type: PVC  Diameter: 5.1 cm
length From: +0.6m  Length To: 10.9 m
SCREEN
Type: PVC  Diameter: 5.1 cm
Slot Size: 0.025 cm
Set From: 10.9 m  To: 12.4 m

PERFORATIONS
Type Of Perforator Used:
Size Of Perforations:  in/cm by:  in/cm
Perforations From:  ft./m to:  ft/m

WASHDOWN VALVE:  Yes X  No
FORMATION PACKERS USED:  Yes No X
GRAVEL
Type: Silica Sand  Volume: 3 Sacks
Bottom At: 12.4 m  Top At: 10.6 m
Tremied:  Yes X  No
From What Depths: 12.4 m to 10.6 m

GROUT SEAL
Type: Grout Cement
Mixture (water/sacks): 124.3 L/m  5# Grout
Volume: 212 L  Tremied:  Yes No X
From What Depths:

BACKFILL
Type:  From:  To:
Type:  From:  To:

OTHER WELLS IN HOLE
Types:  Diam.:  Depths:

OTHER DATA
Sample Desc.: Nate Hunke, EMRC, Grand Forks, ND
Geophys. Logs:

Drilling Time Log:  Water Chem.:
DST:

BLS=Below Land Surface
W.L.=Water Level
WELL COMPLETION REPORT

Well Number: 1713
Owner: MDU-Coyote
Well Location: N-3765.44 W-3521.26
County: Mercer State: North Dakota
Drilling Company: Mohl Drilling Company
Method Drilled: Air Mist
Bit Size: 13.3 cm
Depth Drilled: 9.6 m Condition Of Hole: Good

Date Drilled: 10 November 1987 Date Set: 10 November 1987
Date Sealed: 17 November 1987 Date Filled:
Well Head Elevation: 600.0 m Ground Elevation: 599.4 m
Bottom Of Screen Elevation: 589.9 m

CASING
Type: PVC Diameter: 5.1 cm
length From: +0.6 m Length To: 8.0 m
SCREEN
Type: PVC Diameter: 5.1 cm
Slot Size: 0.025 cm
Set From: 8.0 m To: 9.6 m

PERFORATIONS
Type Of Perforator Used: Size Of Perforations: in/cm by: in/cm
Perforations From: ft./m to: ft./m

WASHDOWN VALVE: Yes X No
FORMATION PACKERS USED: Yes No X
Type: Base: ft./m

GRAVEL
Type: Silica Sand Volume: 3 Sacks
Bottom At: 9.6 m Top At: 7.7 m
Tremied: Yes X No
From What Depths: 9.6 m to 7.7 m

GROUT SEAL
Type: Grout Cement Mixture (water/sacks): 124.3 L/m 5# Grout
Volume: 190 L Tremied: Yes No X
From What Depths:

BACKFILL
Type: From: To:
Type: From: To:

OTHER WELLS IN HOLE Types: Diam.: Depths:

OTHER DATA
Sample Desc.: Nate Hunke, EMRC, Grand Forks, ND
Geophys. Logs:

Drilling Time Log: Water Chem.:
DST: Other:

BLS=Below Land Surface
W.L.=Water Level
WELL COMPLETION REPORT

Well Number: 1714
Owner: MDU-Coyote
Well Location: N-2472.67 W-3521.26
County: Mercer
Drilling Company: Mohl Drilling Company
Method Drilled: Air Mist Rotary
Bit Size: 13.3 cm
Depth Drilled: 23.8 m Condition Of Hole: Good

Date Drilled: 10 November 1987 Date Set: 10 November 1987
Date Sealed: 17 November 1987 Date Filled:
Well Head Elevation: 586.9 m Ground Elevation: 586.5 m
Bottom Of Screen Elevation: 562.8 m

CASING
Type: PVC Diameter: 5.1 cm
length From: +0.4 m Length To: 17.6 m

SCREEN
Type: PVC Diameter: 5.1 cm
Slot Size: 0.025 cm
Set From: 17.7 m To: 23.8 m

PERFORATIONS
Type Of Perforator Used: Size Of Perforations: in/cm by: in/cm
Perforations From: ft./m to: ft/m

WASHDOWN VALVE: Yes X No

FORMATION PACKERS USED: Yes No X
Type: Base: ft/m

GRAVEL
Type: Silica Sand Volume: 8 Sacks
Bottom At: 23.8 m Top At: 17.4 m
Tremied: Yes X No
From What Depths: 23.8 m to 17.4 m

GROUT SEAL
Type: Grout Cement
Mixture (water/sacks): 124.3 L/m #5 Grout
Volume: 284 L Tremied: Yes No X
From What Depths:

BACKFILL
Type: From: To:
Type: From: To:

OTHER WELLS IN HOLE Types: Diam.: Depths:

OTHER DATA
Sample Desc.: Nate Hunke, EMRC Grand Forks, ND
Geophys. Logs: Mark Spitzer, Dakota Geophysics Dickinson, ND

Drilling Time Log: Water Chem.:
DST: Other:
COMMENTS: A-C lignite. W.L. 15.7 m BLS (570.8 m), 11/29/87.

BLS=Below Land Surface
W.L.=Water Level
WELL COMPLETION REPORT

Well Number: 1715
Owner: MDU-Coyote
Well Location: N-2477.10 W-2951.55
County: Mercer
Drilling Company: Mohl Drilling Company
Method Drilled: Air Mist
Bit Size: 13.3 cm
Depth Drilled: 11.1 m Condition Of Hole: Good

Date Drilled: 10 November 1987 Date Set: 10 November 1987
Date Sealed: 17 November 1987 Date Filled:
Well Head Elevation: 586.8 m Ground Elevation: 586.5 m
Bottom Of Screen Elevation: 575.4 m

CASING
Type PVC Diameter: 5.1 cm

SCREEN
Type PVC Diameter: 5.1 cm
Slot Size: 0.025 cm
Set From: 9.6 m To: 11.1 m

PERFORATIONS
Type Of Perforator Used:
Size Of Perforations: in/cm by: in/cm
Perforations From: ft./m to: ft/m

WASHDOWN VALVE: Yes X No

FORMATION PACKERS USED: Yes No X

GRAVEL
Type Silica Sand Volume: 2 Sacks
Bottom At: 11.1 m Top At: 9.2 m
Tremied: Yes X No
From What Depths: 11.1 m to 9.2 m

GROUT SEAL
Type: Grout Cement
Mixture (water/sacks): 124.3 L/m 5# Grout
Volume: 197 L Tremied: Yes No X
From What Depths:

BACKFILL
Type: From: To:
Type: From: To:

OTHER WELLS IN HOLE Types: Diam.: Depths:

OTHER DATA
Sample Desc.: Nate Hunke, EMRC, Grand Forks, ND
Geophys. Logs:

Drilling Time Log: Water Chem.:
DST: Other:

BLS=Below Land Surface
W.L.=Water Level
**WELL COMPLETION REPORT**

- **Well Number:** 1716  
- **Owner:** MDU-Coyote  
- **Well Location:** N-2623.18 W-2953.64  
- **County:** Mercer  
- **State:** North Dakota  
- **Drilling Company:** Mohl Drilling Company  
- **Method Drilled:** Air Mist Rotary  
- **Bit Size:** 13.3 cm  
- **Depth Drilled:** 21.9 m  
- **Condition Of Hole:** Good

- **Date Drilled:** 10 November 1987  
- **Date Set:** 10 November 1987  
- **Well Head Elevation:** 595.1 m  
- **Ground Elevation:** 594.6 m  
- **Bottom Of Screen Elevation:** 572.7 m

<table>
<thead>
<tr>
<th>CASING</th>
<th>SCREEN</th>
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<tbody>
<tr>
<td>Type: PVC</td>
<td>Diameter: 5.1 m</td>
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<td>length From: +0.5m</td>
<td>Length To: 15.8 m</td>
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<th>PERFORATIONS</th>
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<tbody>
<tr>
<td>Type Of Perforator Used:</td>
</tr>
<tr>
<td>Size Of Perforations: in/cm by: in/cm</td>
</tr>
<tr>
<td>Perforations From: ft./m to: ft/m</td>
</tr>
</tbody>
</table>

- **WASHDOWN VALVE:** Yes  
- **FORMATION PACKERS USED:** Yes  
- **GRAVEL**  
  - Type: Silica Sand  
  - Volume: 8 Sacks  
  - Bottom At: 21.9 m  
  - Top At: 15.5 m  
  - Tremied: Yes  
  - From What Depths: 21.9 m to 15.5 m

<table>
<thead>
<tr>
<th>GROUT SEAL</th>
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<tbody>
<tr>
<td>Type: Grout Cement</td>
</tr>
<tr>
<td>Mixture (water/sacks): 124.3 L/m #5 Grout</td>
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<tr>
<td>Volume: 265 L</td>
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| Tremied: Yes  
  - From What Depths: |

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<th>BACKFILL</th>
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<tr>
<td>Type:</td>
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<td>From:</td>
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<th>OTHER WELLS IN HOLE</th>
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<tbody>
<tr>
<td>Types:</td>
</tr>
<tr>
<td>Diam.:</td>
</tr>
<tr>
<td>Depths:</td>
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</tbody>
</table>

**OTHER DATA**

- Sample Desc.: Nate Hunke, EMRC Grand Forks, ND  
- Geophys. Logs: Mark Spitzer, Dakota Geophysics Dickinson, ND  
- Drilling Time Log:  
- Water Chem.:  
- DST:  
- Other:  

**BLS=Below Land Surface**  
**W.L.=Water Level**
WELL COMPLETION REPORT

Well Number: 1717  
Owner: MDU-Coyote  
Well Location: N-2625.59 W-2958.78  
County: Mercer  
State: North Dakota  
Drilling Company: Mohl Drilling Company  
Method Drilled: Air Mist Rotary  
Bit Size: 13.3 cm  
Depth Drilled: 16.9 m  
Condition Of Hole: Good

Date Drilled: 10 November 1987  
Date Set: 10 November 1987  
Date Sealed: 17 November 1987  
Date Filled:  
Well Head Elevation: 595.2 m  
Ground Elevation: 594.5 m  
Bottom Of Screen Elevation: 577.5 m

CASING  
Type: PVC  
Diameter: 5.1 cm  
Length From: +0.8 m  
Length To: 15.4 m

SCREEN  
Type: PVC  
Diameter: 5.1 cm  
Slot Size: 0.025 cm  
Set From: 15.4 m  
To: 16.9 m

PERFORATIONS  
Type Of Perforator Used:  
Size Of Perforations:  in/cm by:  in/cm  
Perforations From: ft./m to:  ft/m

WASHDOWN VALVE: Yes X  
No

FORMATION PACKERS USED: Yes No X  
Type:  Base:  ft/m

GRAVEL  
Type: Silica Sand  
Volume: 2 Sacks  
Bottom At: 16.9 m  
Top At: 15.1 m  
Tremied: Yes X  
No  
From What Depths: 16.9 m to 15.1 m

GROUT SEAL  
Type: Grout Cement  
Mixture (water/sacks): 124.3 L/m 5# Grout  
Volume: 265 L  
Tremied: Yes No X  
From What Depths:

BACKFILL  
Type:  From:  To:  
Type:  From:  To:

OTHER WELLS IN HOLE  Types: Diam.: Depths:

OTHER DATA  
Sample Desc.: Nate Hunke, EMRC, Grand Forks, ND  
Geophys. Logs:  
Drilling Time Log:  
Water Chem.:  
DST:  
Other:  
COMMENTS: Lower B-Z lignite. W.L. 13.9 m BLS (580.5),  
11/29/87.  
BLS=Below Land Surface  
W.L.=Water Level
WELL COMPLETION REPORT

Well Number: 1718
Owner: MDU-Coyote
Well Location: N-2628.31 W-2964.42
County: Mercer
Drilling Company: Mohl Drilling Company
Method Drilled: Air Mist
Bit Size: 13.3 cm
Depth Drilled: 8.9 m
Condition Of Hole: Good

Date Drilled: 10 November 1987
Date Set: 10 November 1987
Date Sealed: 17 November 1987
Well Head Elevation: 595.3 m
Ground Elevation: 594.6 m
Bottom Of Screen Elevation: 585.7 m

CASING
Type: PVC
Diameter: 5.1 cm
length From: +0.7 m
Length To: 7.4 m

SCREEN
Type: PVC
Diameter: 5.1 cm
Slot Size: 0.025 cm
Set From: 7.4 m
To: 8.9 m

PERFORATIONS
Type Of Perforator Used:
Size Of Perforations: in/cm by: in/cm
Perforations From: ft./m to: ft/m

WASHDOWN VALVE:
Yes X
No

FORMATION PACKERS USED:
Yes No X

GRAVEL
Type: Silica Sand
Volume: 2 Sacks
Bottom At: 8.9 m
Top At: 6.8 m
Tremied:
Yes X
No
From What Depths: 8.9 m to 6.8 m

GROUT SEAL
Type: Grout Cement
Mixture (water/sacks): 124.3 L/m
5# Grout
Volume: 174 L
Tremied:
Yes No X
From What Depths:

BACKFILL
Type: From:
To:

OTHER WELLS IN HOLE
Types: Diam.: Depths:

OTHER DATA
Sample Desc.: Nate Hunke, EMRC, Grand Forks, ND
Geophys. Logs:

Drilling Time Log:
Water Chem.:
DST:
Other:
COMMENTS:
Upper B-Z lignite. W.L. 8.7 m BLS (585.9),
11/29/87.
BLS=Below Land Surface
W.L.=Water Level
WELL COMPLETION REPORT

Well Number: 1719
Owner: MDU-Coyote
Well Location: N-4008.75 W-2276.36
County: Mercer  State: North Dakota
Drilling Company: Mohl Drilling Company
Method Drilled: Air Mist Rotary
Bit Size: 13.3 cm
Depth Drilled: 18.2 m  Condition Of Hole: Unstable

Date Drilled: 10 November 1987  Date Set: 10 November 1987
Date Sealed: 17 November 1987  Date Filled:
Well Head Elevation: 609.5 m  Ground Elevation: 608.8 m
Bottom Of Screen Elevation: 590.8 m

CASING  Type: 7VC  Diameter: 5.1 cm
length From: +0.6m  Length To: 12.1 m
SCREEN  Type: PVC  Diameter: 5.1 cm
Slot Size: 0.025 cm
Set From: 12.1 m  To: 18.2 m

PERFORATIONS  Type Of Perforator Used:
Size Of Perforations: in/cm by: in/cm
Perforations From: ft./m to: ft/m

WASHDOWN VALVE: Yes X No
FORMATION PACKERS USED: Yes No X
Type:  Base: ft/m
GRAVEL  Type: Silica Sand  Volume: 8 sacks
Bottom At: 18.2 m  Top At: 11.8 m
Tremied: Yes X No
From What Depths: 18.2 m to 11.8 m

GROUT SEAL  Type: Grout Cement
Mixture (water/sacks): 124.3 L/m 5# Grout
Volume: 227 L  Tremied: Yes No X
From What Depths:

BACKFILL  Type:  From:  To:
Type:  From:  To:

OTHER WELLS IN HOLE  Types:  Diam.:  Depths:

OTHER DATA
Sample Desc.: Nate Hunke, EMRC, Grand Forks,ND
Geophys. Logs:

Drilling Time Log:  Water Chem.:
DST:  Other:
COMMENTS: Coleharbor pebble-loam upper B-Z lignite contact
Dry 11/29/87.
BLS=Below Land Surface
W.L.=Water Level
WELL COMPLETION REPORT

Well Number: 1720
Owner: MDU-Coyote
Well Location: N-4014.76 W-2279.68
County: Mercer State: North Dakota
Drilling Company: Mohl Drilling Company
Method Drilled: Air Mist Rotary
Bit Size: 13.3 cm
Depth Drilled: 34.3 m Condition Of Hole: Good

Date Drilled: 10 November 1987 Date Set: 10 November 1987
Date Sealed: 17 November 1987 Date Filled:
Well Head Elevation: 609.4 m Ground Elevation: 609.0 m
Bottom Of Screen Elevation: 574.7 m

CASING
Type: PVC Diameter: 5.1 cm
length From: +0.4 m Length To: 28.2 m

SCREEN
Type: PVC Diameter: 5.1 cm
Slot Size: 0.025 cm
Set From: 28.2 m To: 34.3 m

PERFORATIONS
Type Of Perforator Used:
Perforations From: in/cm by: in/cm
Perforations From: ft./m to: ft./m

WASHDOWN VALVE: Yes X No
FORMATION PACKERS USED: Yes No X

GRAVEL
Type: Silica Sand Volume: 7.5 Sacks
Bottom At: 34.3 m Top At: 27.9 m
Tremied: Yes X No
From What Depths: 34.3 m to 27.9 m

GROUT SEAL
Type: Grout Cement
Mixture (water/sacks): 124.3 L/m #5 Grout Volume: 398 L Tremied: Yes No X
From What Depths:

BACKFILL
Type: From: To:
Type: From: To:

OTHER WELLS IN HOLE
Types: Diam.: Depths:

OTHER DATA
Sample Desc.: Nate Hunke, EMRC Grand Forks, ND
Geophys. Logs: Mark Spitzer, Dakota Geophysics Dickinson, ND

Drilling Time Log:
Water Chem.:
DST:
COMMENTS: Spaer silty clay and Spaer lignites. W.L. 33.4 m
BLS (575.6)
BLS=Below Land Surface
W.L.=Water Level
WELL COMPLETION REPORT

Well Number: 1721
Owner: MDU-Coyote
Well Location: N-4717.11 W-2747.54
County: Mercer  State: North Dakota
Drilling Company: Mohl Drilling Company
Method Drilled: Air Mist Rotary
Bit Size: 13.3 cm
Depth Drilled: 33.8 m  Condition Of Hole: Good

Date Drilled: 10 November 1987  Date Set: 10 November 1987
Date Sealed: 17 November 1987  Date Filled:
Well Head Elevation: 604.3 m  Ground Elevation: 604.9 m
Bottom Of Screen Elevation: 572.6 m

CASING  Type: PVC  Diameter: 5.1 cm
length From: +0.6 m  Length To: 32.3 m
SCREEN  Type: PVC  Diameter: 5.1 cm
Slot Size: 0.025 cm
Set From: 32.3 m  To: 33.8 m

PERFORATIONS  Type Of Perforator Used:
  Size Of Perforations: in/cm by: in/cm
  Perforations From: ft./m to: ft/m

WASHDOWN VALVE: Yes  No
FORMATION PACKERS USED: Yes  No  X

GRAVEL  Type: Silica Sand  Volume: 3 Sacks
  Base: ft/m
Bottom At: 33.8 m  Top At: 32.0 m
Tremied: Yes  No  X
From What Depths: 33.8 m to 32.0 m

GROUT SEAL  Type: Grout Cement
  Mixture (water/sacks): 124.3 L/m #5 Grout
  Volume: 265 L  Tremied: Yes  No  X
  From What Depths:

BACKFILL  Type: From:  To:
  From:  To:

OTHER WELLS IN HOLE  Types:  Diam.:  Depths:

OTHER DATA
Sample Desc.: Nate Hunke, EMRC Grand Forks, ND
Geophys. Logs: Mark Spitzer, Dakota Geophysics Dickinson, ND

Drilling Time Log:  Water Chem.:
DST:  Other:

BLS=Below Land Surface
W.L.=Water Level
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Coyote I FGC Dry Waste Disposal Site
(T.143 N., R.88 W.)
Geologic Interpretations, Glacial Valley Fill Boundary, Proposed Pit Boundary, Location and Test Holes, Piezometers, and Cross Section Locations
Nathan Halvorson
1999

LEGEND

A PIEZOMETER LOCATION
• TEST HOLE LOCATION
--- GLACIAL FILL BOUNDARY
------------------ CROSS-SECTION LOCATIONS
---------------------- PROPOSED PIT BOUNDARY

PLATE # 1