Preliminary Design and Assessment
Of Injection Well Array
For Fortune Minerals Limited
Saskatchewan Metals Processing Plant

Prepared for:

Submitted by:

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TABLE OF CONTENTS

1.0 INTRODUCTION .................................................................................................................... 1
  1.1 Scope ................................................................................................................................. 1

2.0 BACKGROUND.................................................................................................................. 1

3.0 STRATIGRAPHY............................................................................................................... 2
  3.1 General ............................................................................................................................ 2
  3.2 Mannville Group ............................................................................................................. 4
  3.3 Alternative Horizons ...................................................................................................... 6
    3.3.1 Judith River Formation ............................................................................................... 7
    3.3.2 Duperow Formation ................................................................................................ 7
    3.3.3 Souris River Formation ............................................................................................ 7
    3.3.4 Dawson Bay Formation ............................................................................................ 7
    3.3.5 Winnipegosis Formation .......................................................................................... 8
    3.3.6 Interlake Formation .................................................................................................. 8
    3.3.7 Deadwood Formation .............................................................................................. 8

4.0 DESIGN CALCULATIONS .............................................................................................. 8
  4.1 Review of Existing Information ..................................................................................... 8
  4.2 Injection Well Design Considerations ......................................................................... 10
  4.3 Preliminary Design ....................................................................................................... 10
  4.4 Analytical Modelling Methodology ............................................................................. 14
    4.4.1 Aquifer Loss ............................................................................................................. 15
    4.4.2 Well Skin Loss ........................................................................................................ 16
    4.4.3 Tubing Friction Loss ............................................................................................... 17
  4.5 Model Calculations ..................................................................................................... 18

5.0 CLOSURE ..................................................................................................................... 20

6.0 REFERENCES ............................................................................................................... 21

LIST OF FIGURES

Figure 3.1 – Stratigraphic column in the Saskatoon area (not to scale). .................................................. 3
Figure 3.2 – Borehole locations with Mannville Group water chemistry ........................................... 5
Figure 4.1 – Summary of well hydrostratigraphy ......................................................................... 9
Figure 4.2 – Groundwater and injection well locations ............................................................... 11
Figure 4.3 – Components of typical injection well design. .......................................................... 12
Figure 4.4 – Preliminary injection well design. ........................................................................... 13
Figure 4.5 – Head losses for injection ....................................................................................... 14
Figure 4.6 – Single region model for radial flow to a well bore ..................................................... 16
Figure 4.7 – Two-region model for radial flow to a well bore ....................................................... 16
Figure 4.8 – Positive and negative skin for pumping and injection wells .................................... 17

LIST OF TABLES

Table 3.1 – Available Mannville Group water chemistry in the vicinity of the site vs. predicted chemistry of injection fluid ........................................................................................................... 6
Table 4.1 – Fixed design parameters. .......................................................................................... 18
Table 4.2 – Variable design parameters. .................................................................................... 19
1.0 INTRODUCTION
This report provides Fortune Minerals Limited (FML) with the design of a deep injection well array and preliminary feasibility assessment of the Mannville Group's capacity for the injected fluids. Details of the project scope, methodology, and results of the preliminary injection well design and assessment at the proposed Saskatchewan Metals Processing Plant (SMPP) are presented herein.

1.1 Scope
The scope of the work is to provide a report of preliminary injection well design and assessment of the Mannville Group’s capacity for injected fluids using design calculations at the FML’s SMPP site.

2.0 BACKGROUND
The proposed SMPP is a hydrometallurgical processing facility designed to process mine concentrates into high-value metal products. The proposed facility will purify metal concentrates produced from FML’s NICO Gold-Cobalt-Bismuth-Copper (NICO) project in the Northwest Territories (NWT). The proposed SMPP site is located in the Rural Municipality of Corman Park (RM 344), 2.5 km east of Langham, Saskatchewan. The legal land description of the proposed SMPP is the southeast quarter of Section 23 in Township 39, Range 07, West of the 3rd Meridian (SE¼ 23-39-07-W3) and north half of Section 14 in Township 39, Range 07, West of the 3rd Meridian (N½ 14-39-07-W3).

The wastewaters, generated from the SMPP, do not have significant heavy metal contents but are high in the common ions found in natural groundwater: sodium, magnesium, sulphate and chloride. The approximate total dissolved solids (TDS) content is 47,500 mg/L, consisting primarily of sodium (Na⁺) and sulphate (SO₄²⁻) ions with subsidiary magnesium (Mg²⁺) and chloride (Cl⁻) ions. This wastewater is to be injected into the Mannville Group, which has a natural anticipated TDS content of 30,000 to 70,000 mg/L in the vicinity of the SMPP.

The Minister of Environment (MOE) determined that an Environmental Impact Statement (EIS) was required for the project. Project Specific Guidelines (PSGs) were issued on 22 January 2011 pursuant to the Province’s Environmental Protection Act. The PSG’s specified that the EIS should include a deep well injection model to assess capacity for disposal.

This report provides an analytical model to establish that the Mannville Group, which has been previously used for wastewater disposal in the Saskatoon area, is a disposal formation capable of receiving the proposed injection volumes (110 ipgm, 30 m³/hr or 720 m³/d) for the operational period of the SMPP (18 years). The report also provides a preliminary design and location for the associated injection well(s) at the SMPP site.
3.0 STRATIGRAPHY

3.1 General

The stratigraphic nomenclature, geological succession, and generalized lithology in the vicinity of Saskatoon, SK are provided in Figure 3.1. In general, the stratigraphic column can be divided into three primary lithological units. There is a basal clastic (sandstone, siltstone, mudstone, etc.) group ranging in age from Cambrian to Ordovician overlain by a carbonate (limestone, dolomite) group ranging in age from Ordovician to Mississippian. The third group consists of clastic sediments ranging from Jurassic to Quaternary in age.

The hydrostratigraphy in the vicinity of Saskatoon can be divided into a series of aquifers and aquitards. An aquifer is defined as a saturated permeable geological unit that can transmit significant quantities of water under ordinary hydraulic gradients. An aquitard is defined as a less-permeable unit capable of limited transmission within a stratigraphic sequence. These beds are permeable enough to transmit water in quantities that are significant in the study of regional groundwater flow, but their permeability is generally not sufficient to allow the completion of wells within them. In general, silts, clays, and evaporites are aquitards and units comprised of sand are effective aquifers. Limestone and dolomite can act as either aquifers or aquitards depending on their physical makeup (porosity and the extent of fracturing). Figure 3.1 provides a summary of the eight primary regional scale bedrock aquifers in the Saskatoon area. The primary regional bedrock aquifers in the vicinity of Saskatoon in descending order are:

1. The Judith River Formation;
2. The Mannville Group;
3. The Duperow Formation;
4. The Souris River Formation;
5. The Dawson Bay Formation;
6. The Winnipegosis Formation;
7. The Interlake Formation; and
8. The Deadwood Formation.

The Mannville Group would be the primary target for completion of the injection well(s), as it is the first available aquifer horizon that is saline, is not used as a potable water source, and has already been used as a waste water injection horizon in the Saskatoon area. The majority of the stratigraphic and hydrogeologic data presented in this report focuses on the Mannville Group sediments. A brief summary of the other available stratigraphic horizons has been provided as a reference and as a contingency in the unlikely event that the Mannville Group be deemed inappropriate for the well installation.
3.2 Mannville Group

The Mannville Group forms the oldest Cretaceous strata over much of the Western Canadian Sedimentary Basin. The strata range in thickness between 700 m along the Rocky Mountain Foothills to less than 40 m in regions of Saskatchewan. In the vicinity of Saskatoon, the thickness of the Mannville Group varies between approximately 80 m to over 100 m (Christopher, 1989) and is at a depth of approximately 550 m below ground. Borehole 7-22-39-7W3, located northwest of the site, identified the Mannville Group at a depth of 475 m and a thickness (including the Success Formation) of 140 m. Figure 3.2 shows the location of this deep exploration borehole east of Langham.

The thickness and depth of the Mannville Group can be affected by collapse of underlying strata into dissolution structures of the Middle Devonian Evaporite beds. One such dissolution structure exists in the vicinity of Saskatoon. This structure is called the Saskatoon Low and could affect the thickness, depth, and continuity of the unit in the immediate vicinity of Saskatoon. Limited deep drill data exists in the vicinity of the Fortune Minerals site. As a result, the effect of the Saskatoon Low on the continuity and depth of the Mannville Group cannot be quantified at the proposed location. The proposed SMPP site is approximately 40 km north of the Saskatoon Low, and as a result is not anticipated to significantly affect the Mannville Group’s ability to be used as a waste injection horizon.

The Mannville Group is comprised of an extremely complex arrangement of stratified sediments, including channel sands, blanket sands, coal, and shale. These sediments sit unconformably on the underlying Paleozoic sediment and are overlain by the shales of the Joli Fou Formation. Relatively little information exists on the geology of the Mannville Group in the Saskatoon area. Most of the drilling associated with the Group comes from hydrocarbon investigations in the Lloydminster area. However, several boreholes associated with the Saskatchewan Potash industry provide stratigraphic data in the area. In general, the Mannville Group can be divided into an Upper, Middle, and Lower unit with different depositional environments associated with each unit (Vigrass, 1977).

The lower unit was deposited in a fluvial environment within a series of ridges and valleys formed on the Paleozoic carbonate rocks. The middle unit was formed by a series of transgressive and regressive events that deposited delta sands, distributary channel sands, and near shore beach deposits. Regression events resulted in the deposition of prevalent coal horizons within this unit. As a result of the complex depositional environment, the location and extent of the blanket and channel sands is variable. In the Saskatoon area, the middle part of the Mannville Group is dominated by laterally extensive blanket sands. The upper part of the Mannville Group consists of thick, narrow stacked, “shoestring,” channel sandstone surrounded by siltstone, shale, and coal deposited in an anastomising channel network. The complex network of anastomising channel sands and off channel blanket sands form the aquifer horizons of the Mannville Group, which are surrounded by lower permeability silt, shale, mudstone, and coal.
The recharge area of the Mannville Group can be traced to outcrops in the Rocky Mountains of central Montana. Groundwater flow is primarily in a northeast direction to discharge points in central Saskatchewan and Manitoba along the northern and eastern edge of the sedimentary basin. The potentiometric elevation of the Mannville Group in the vicinity of the PotashCorp Cory and Agrium Vanscoy mine sites range between 530 masl to 500 masl.

Due to the presence of aquifer and aquitard units in the Mannville Group, it is possible to intersect this Group at locations that will not accept (or produce) large quantities of water (i.e. aquitards). Hydraulic testing completed in the vicinity of the PotashCorp Cory and Agrium Vanscoy potash mines by Christopher (1989) indicated a hydraulic conductivity of the Mannville Group sands at 2.3x10^-6 m/s. This value is typical of a silty sand and may provide sufficient injection capacity for the volumes needed (average and instantaneous rate of 28 tph and 35 tph, respectively). It is anticipated that sufficient accumulations of aquifer horizons of the Mannville Group will be present at the proposed drill location. It is noted that the actual geology cannot be determined prior to drilling.

The TDS concentration within the Mannville Group is variable across Saskatchewan and ranges between approximately 5,000 mg/L to over 80,000 mg/L. It is typically sodium-chloride type water. The highest TDS within the Mannville Group occurs along a NW-SE trend that correlates well to the presence of underlying salt of the Prairie Evaporite Formation. Four wells nearest to the proposed facility show that the water chemistry ranges from 7,500 mg/L to 80,000 mg/L. The water chemistry in Table 3.1 was taken from drill stem tests and purchased from the Saskatchewan Ministry of Energy and Resources (SER); the predicted chemistry of the brine solution process water that is to be injected is provided in this table for comparison. The approximate location of the sample locations is provided in Figure 3.2, which also shows the location of the nearest deep stratigraphic borehole. The water chemistry in the Manville Group is similar to the concentrations predicted for the brine solution process water.

### Table 3.1 – Available Mannville Group water chemistry in the vicinity of the site vs. predicted chemistry of injection fluid.

| LSD | SEC | TWP | RNG | MER | Distance (km) | Na+ (mg/L) | K+ (mg/L) | Ca2+ (mg/L) | Mg2+ (mg/L) | Cl- (mg/L) | HCO3- (mg/L) | SO42- (mg/L) | CO32- (mg/L) | TDS (mg/L) |
|-----|-----|-----|-----|-----|---------------|------------|----------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-----------|
| 7   | 20  | 30  | 7   | 3   | 87            | 2,057      | 0        | 199         | 99          | 1,472       | 250         | 3,388       | 0           | 7,465      |
| 1   | 20  | 30  | 11  | 3   | 97            | 3,535      | 0        | 464         | 57          | 1,955       | 605         | 5,600       | 0           | 12,216     |
| 4   | 20  | 39  | 3   | 3   | 63            | 26,926     | 0        | 1,794       | 689         | 43,300      | 320         | 4,382       | 0           | 77,411     |
| 15  | 36  | 32  | 29  | 2   | 91            | 28,400     | 0        | 1,560       | 58          | 44,000      | 329         | 5,210       | 0           | 79,557     |
|     |     |     |     |     | Approximate distance from the SMPP site | 12,930 | 0 | 180 | 1,610 | 1,620 | 0 | 31,260 | 0 | 47,600 |

3.3 Alternative Horizons

The following sections provide a brief overview of the other bedrock aquifer horizons in the Saskatoon area in the unlikely event that the Mannville Group be determined to be inappropriate for completion of the waste water injection well(s). Estimated depths and
position with respect to the Mannville Group is provided in Figure 3.1. Additional information on each of the horizons in the Saskatoon area may be obtained from SER; however, this compilation was beyond the scope of the project. With the exception of the Judith River Formation, all of the major bedrock aquifers are likely suitable alternatives to the Mannville Group.

3.3.1 Judith River Formation
The Judith River Formation consists of unconsolidated to partially consolidated sands, silts, and clays up to 60 m thick, at a depth of approximately 160 m. The continuity of the aquifer in the vicinity of Saskatoon has been affected by collapse structures and post-depositional erosion; however, it is generally laterally continuous. The Judith River Formation is not interpreted to exist below the site. As a result, a significant pipeline would be required if it was used as the injection horizon.

The Judith River Formation is used as a source for water supply in the Saskatoon area, with expected safe yields generally varying between 325 m$^3$/d to less than 25 m$^3$/d. Commonly, the waters are of the sodium-sulphate or sodium-bicarbonate type and have TDS concentrations of less than 2,500 mg/L. Because of the low TDS values, the waters are suitable for private and municipal water supplies and are thus not an acceptable target horizon for waste water disposal.

3.3.2 Duperow Formation
The Duperow Formation consists of thick accumulations of dolomite and limestone. In the Saskatoon area it is over 200 m thick and located at a depth of approximately 640 m below ground. Waters of the Duperow Formation are generally sodium-chloride type with TDS values ranging from 5,000 mg/L (in south-central Saskatchewan) to over 300,000 mg/L (in the southeast corner of the province). In the Saskatoon area, the TDS is estimated to be between 35,000 mg/L and 70,000 mg/L.

3.3.3 Souris River Formation
The Souris River Formation consists of accumulations of limestone, dolomite, anhydrite, and dolomitic shale. In the Saskatoon area, it is approximately 170 m thick, and located at a depth of approximately 860 m. Waters of the Souris River Formation are typically the sodium-chloride type with TDS values ranging from 5,000 mg/L to over 300,000 mg/L. In the Saskatoon area, the TDS is estimated to be between 200,000 mg/L and 300,000 mg/L.

3.3.4 Dawson Bay Formation
The Dawson Bay Formation consists of dolomite, limestone, and red dolomitic shale. In the Saskatoon area, it is approximately 30 m thick and located at a depth of approximately 1,040 m. Waters of the Dawson Bay Formation are typically a sodium-chloride type, with TDS values ranging from 5,000 mg/L to over 300,000 mg/L. In the Saskatoon area, the TDS is estimated to be greater than 300,000 mg/L.
3.3.5 Winnipegosis Formation

The Winnipegosis Formation primarily consists of dolomite. In the Saskatoon area, it is approximately 90 m thick and located at a depth of approximately 1,180 m. Waters of the Winnipegosis Formation are generally a sodium-chloride type, with TDS values typically ranging from 70,000 mg/L to over 350,000 mg/L. In the Saskatoon area, the TDS is estimated to be greater than 200,000 mg/L.

3.3.6 Interlake Formation

The Interlake Formation primarily consists of accumulations of dolomite. In the Saskatoon area, it is approximately 70 m thick and located at a depth of approximately 1,280 m. The waters of the Interlake formation are generally a sodium-chloride type, with TDS values typically ranging from 150,000 mg/L to over 300,000 mg/L. In the Saskatoon area, the TDS is estimated to be between 150,000 mg/L and 200,000 mg/L.

3.3.7 Deadwood Formation

The Deadwood Formation primarily consists of accumulations of siltstone and sandstone. In the Saskatoon area it is over 200 m thick and located at a depth of approximately 1,460 m. Waters of the Deadwood Formation are generally a sodium-chloride type, with TDS values typically ranging from 100,000 mg/L to over 300,000 mg/L. In the Saskatoon area, the TDS is estimated to be greater than 200,000 mg/L. Several brine disposal wells inject into this formation in the vicinity of Saskatoon.

4.0 DESIGN CALCULATIONS

4.1 Review of Existing Information

The Lower Cretaceous Mannville Group of Saskatchewan has been extensively studied by Christopher (1974, 1980, 1989, 2003), Christopher et al. (2003), Mossop and Shetson (1994), Vigrass (1977) and regional information has been recently collated and summarized by Marsh and Heinemann (2005) in the form of Saskatchewan regional maps. The regional maps include structure contours of tops (elevations of the top of a formation relative to sea level) and isopachs (thicknesses). These maps (which include data from the well 07-22-39-07-W3M closest to the FML site) were used to determine the approximate elevation of the top of the Mannville Group disposal formation to be 45 masl (above sea level) or approximately 475 mbgl (below ground level). The thickness of the Mannville Group disposal formation (Mannville Group and Success Formation) at the southern edge of the SMPP was determine to be approximately 125 + 15 = 140 m placing the lower surface at approximately 615 mbgl or -95 masl.

The expected water level in the Mannville Group disposal formation at the site was estimated from public drill stem test results and Saskatchewan Geological Survey (SGS) reports on the Mannville Group (Christopher, 1980). Based on these sources, the anticipated fluid head in the disposal formation is expected to be 480 masl (or approximately 40 mbgl).
The Mannville Group Aquifer is overlain by the Colorado Group shales, the Lea Park shale. These upper Cretaceous units are in turn overlain by a sequence glacial tills and aquifers as described in the groundwater sourcing study for the site MDH (2010) and the environmental impact study, MDH (2011).

The information pertinent to the design of the disposal wells is summarized in Figure 4.1. The Dalmeny Aquifer, identified as a water source for the SMPP, is shown at an approximate depth of 15-20 m. The disposal formation is approximately 450 m below this aquifer and the intervening units are primarily low-permeability tills and shales. The water level in the Dalmeny Aquifer is approximately 10 mbgl, relative to the anticipated water-level in the disposal formation at approximately 40 mbgl.

![Figure 4.1 – Summary of well hydrostratigraphy.](image-url)
4.2 Injection Well Design Considerations

Injection wells for waste disposal are designed to protect shallow aquifers, such as the Dalmeny Aquifer, and provide access to a deep disposal formation. Protection of the shallow formations is achieved using a cemented outer casing with internal concentric tubing which carries the injected fluid. For corrosive injection fluids, the annulus between the casing and the tubing can be filled with a slightly pressurized inhibitor fluid which both acts as a leak-detection mechanism and protects the outer casing from corrosion.

Depending on the depth, multiple sections of telescoping casing may be utilized. At the top of the disposal horizon, the tubing passes through a packer of some kind which isolates the annular inhibitor fluid from the disposal formation. For more benign injection fluids, the tubing can be replaced by a perforated hanger starting at the top of the disposal horizon.

The disposal horizon completion can range from a gravel pack and well screen, to an open-hole, to perforated casing depending on the lithology, degree of cementation and the expected hydraulic conductivity of the disposal formation. Figure 4.3 shows the components of a typical injection well design with a hanger, gravel pack and well screen.

4.3 Preliminary Design

The regulatory requirements for the drilling, completion and installation of a waste water disposal well are controlled by SER. The Oil and Gas Conservation Act and The Oil and Gas Conservation Regulations, 1985 form the primary body of Saskatchewan Legislation. The location of the injection wells (Figure 4.2) was based on the required 75 m buffer from above ground utilities, 40 m buffer from below ground utilities, 200 m offset from the property line, and 100 m offset from any building, as outlined in these Regulations.

At this time, there is limited information on the Mannville Group near the proposed Fortune Minerals hydrometallurgical facility. The nearest borehole to the proposed injection well location is located in 07-22-39-07-W3M (Figure 3.2). The depths and thickness of the proposed injection well(s) are based on information from the nearby well. Geology can be unpredictable and it is possible that the total depths and thicknesses indicated in this report will not be the same at the actual site. However, this report provides a best estimate of the geology at this site based on available information.

MDH recommends the use of Directive 51 from the Alberta Energy and Conservation Board (ERCB) as a guideline for the injection well construction; this Directive provides more specific guidelines for injection and disposal wells, as it includes well classifications, completion, logging and testing requirements in greater detail than the SER Oil and Gas Conservation Regulations.
Note
1. PROPOSED SITE LAYOUT PLAN PROVIDED BY FORTUNE MINERALS LIMITED. (July 21 2010 2000g001.dwg)
2. 2008 AIR PHOTO OBTAINED FROM INFORMATION SERVICES CORPORATION OF SASKATCHEWAN (ISC).
3. UTM COORDINATES ARE IN NAD 83 ZONE 13.

GROUNDWATER AND INJECTION WELL LOCATIONS

Legend
- PROPOSED INJECTION WELL
- PROPOSED PRODUCTION WELL
- EXISTING PRODUCTION WELL
- LEACHATE COLLECTION
- LEAK DETECTION MONITORING WELL
- PROPOSED SITE LAYOUT
- FLOOR GRADING (0.5 %)
- RAILWAY
- PROJECT BOUNDARY
- 75 METER BUFFER
- CONTAINMENT CELLS

Note
1. PROPOSED SITE LAYOUT PLAN PROVIDED BY FORTUNE MINERALS LIMITED. (July 21 2010 2000g001.dwg)
2. 2008 AIR PHOTO OBTAINED FROM INFORMATION SERVICES CORPORATION OF SASKATCHEWAN (ISC).
3. UTM COORDINATES ARE IN NAD 83 ZONE 13.
Based on available data, it is anticipated that one active injection well will be sufficient. According to ERCB, the maximum allowable well head injection pressure (WHIP) should be approximately 3,300 kPa (480 psi) at this location; the pump should be able to inject at pressures slightly higher than this if necessary. However, due to the lack of data, it is difficult to predict that performance of the Mannville Group at this time. While it is possible that Fortune Minerals required disposal capacity could be met by the use of only one injection well, a second well may be required in order to inject the proposed amount of waste water produced from the Fortune Minerals hydrometallurgical facility. Even if one well is capable of injecting all of the waste water, a back-up injection well is required to prevent the plant from shutting down during annual testing, well maintenance, or an unforeseen situation where the primary injection well is no longer able to operate.

Figure 4.3 – Components of typical injection well design.

Figure 4.4 shows a preliminary injection well design for the Fortune Minerals site based on available data. Figure 4.2 provides the proposed locations of the injection wells (IW 1 and IW 2) at the site; the facility layout and groundwater production wells (M2212-38, PW2 and PW3) are also shown on this figure.
PRELIMINARY INJECTION WELL
FORTUNE MINERALS

- 14,000 kPa RATING BOWLS, HANGERS, SLIPS, SEALS, RINGS, SIDE VALVES, COVER PLATES, BULL PLUGS, VENT KIT

SURFACE CASING BIT SIZE Ø349.3 mm

CEMENT - 10 tonnes CLASS A OR CLASS G WITH 2% CaCl

SURFACE CASING - Ø244.5 mm, 48.11 kg/m, H-40, S.T. & C.

MAINHOLE BIT SIZE Ø222.3 mm

CEMENT - 18 tonnes CLASS G NEAT

MAINHOLE CASING - Ø177.8 mm, 34.26 OR 29.77 kg/m, J-55 or K-55, S.T. & C.

INJECTION LINER - Ø114.3 mm, 14.14 kg/m J-55, S.T. & C.

INHIBITOR FILLED ANNULUS

LH PACKER 2
LH PACKER 1

MANNVILLE COMPLETION BIT SIZE Ø159 mm

MILL SLOTTED LINER - Ø114.3 mm, 17.26 kg/m J-55, S.T. & C.

NOTE: DEPTHS ARE APPROXIMATE FROM GROUND LEVEL AND ARE IN METRES (m).

SCALE: NOT TO SCALE
DATE: 18-MAY-10

DESIGN BY: J. HUNTER, B.E., E.I.T.
DRAWN BY: A. COLE / C. CLARKE

CLIENT
TITLE
PRELIMINARY INJECTION WELL DESIGN

PRODUCED BY
PROJECT No. M2289–2840010 FIG. No.4.4
DRAWING No. M2289–68–2
4.4 Analytical Modelling Methodology

The analytical model used to design the injection well is based on the Theis (1935) solution which simulates the bottom-hole injection pressure (BHIP) in the disposal formation. In order to compare observed data at the well head (i.e. WHIP) with simulated results, a series of assumptions are necessary. These assumptions involve the pressure/head losses in the tubing/casing from surface, and the local pressure/head losses in the immediate vicinity of the wells. These pressure/head losses are critically dependent upon well completion details.

A simple injection well model was used to adjust the simulated BHIP data for comparison with measured WHIP data. This is necessary because licenses to inject in Saskatchewan normally specify a maximum wellhead injection pressure rather than a bottom-hole pressure. Figure 4.5 defines components and terminology used in the discussion of pressure/head loss for injection wells.

All wellhead pressures in this report are referred to the base of the disposal formation as a datum. This elevation is approximately 615 m below ground level or 95 m subsea (-95 masl). All bottom-hole injection pressures are referenced to sea level and reported as masl.
Closer examination of Figure 4.5 demonstrates the importance of ground level and the depth to the fluid-level in the disposal formation from the surface in determining WHIP. BHIP is determined almost exclusively by the hydraulic characteristics of the disposal formation (with a small contribution from well skin).

Skin loss is determined by the completion of the well: well development and the installation of gravel packs tend to reduce the total head loss (negative skin); chemical or physical clogging of the formation tends to increase the total head loss (positive skin). Well development and periodic well work-overs can improve and/or maintain well performance. The ratio of the well skin hydraulic conductivity ($K_s$ local annulus) and the disposal formation hydraulic conductivity ($K$) determines the skin loss. If the ratio exceeds unity ($K/K_s < 1$) skin loss is negative; and if ($K/K_s < 1$) skin loss is positive. The Hawkins (1956) formula was used to calculate skin loss.

Friction losses in tubing/casing are increased as the tubing/casing diameter reduces and depend on the velocity of the fluid entering the well, that is, friction losses increase as the injection rate increases. Choice of casing, liner and tubing materials can be made to minimise friction losses which are mostly determined by well depth and diameter. The Hazen-Williams (1920) formula and tables were used to calculate friction losses.

Reduction of skin losses and friction losses reduces WHIP but has no effect on BHIP. BHIP is the pressure which is applied to the disposal formation and which must be controlled to prevent formation damage and preserve cap rock integrity.

### 4.4.1 Aquifer Loss

The head change at an injection or pumping well as a result of head loss in the surrounding aquifer or reservoir can be predicted for the steady state condition using the well known Thiem solution for radial flow to a cylindrical well (Thiem, 1906). The situation is illustrated in Figure 4.6.

$$h_e - h_w = \frac{Q}{2\pi K b} \ln\left(\frac{r_e}{r_w}\right)$$  \hspace{1cm} (1)

where: 
- $h_w$ is the hydraulic head [L] at radius $r_w$, the outer boundary of the well [L];
- $h_e$ is the hydraulic head [L] at radius $r_e$, the radius of influence of the well [L];
- $Q$ is the injection or pumping rate [$L^3T^{-1}$];
- $K$ is the hydraulic conductivity of the aquifer or reservoir [$LT^{-1}$]; and
- $b$ is the thickness of the aquifer or reservoir [L].

If transient estimates of head are required, the Theis equation (1935) can replace the Thiem equation. Although these equations are widely used, they do not provide realistic estimates of the head change at a well because they neglect head losses due to all factors other than flow through the aquifer.
4.4.2 Well Skin Loss

Hawkins (1956) developed a two-region reservoir model to allow for local changes in reservoir/aquifer properties in the immediate vicinity of a well (called skin). This model is widely used in the petroleum industry to model production and injection wells. The situation is illustrated in Figure 4.7.

For the two region case, the relevant equations are:

\[ h_s - h_w = \frac{Q}{2\pi K_s b} \ln\left(\frac{r_s}{r_w}\right) \quad (2) \]
\[ h_s - h_a = \frac{Q}{2\pi K_b} \ln\left(\frac{r_s}{r_a}\right) \quad (3) \]

Equations (2) and (3) can be combined to give:

\[ h_a - h_w = \frac{Q}{2\pi K_b} \left( \frac{K_s}{K_a} \ln\left(\frac{r_s}{r_w}\right) + \ln\left(\frac{r_a}{r_s}\right) \right) \quad (4) \]
Defining $S_f$ as a dimensionless skin factor:

$$h_e - h_w = \left(\frac{Q}{2K\pi b}\right) \left( \ln\left(\frac{r_e}{r_w}\right) + S_f \right)$$  \hspace{1cm} (5)

Solving for $S_f$ gives Hawkins' formula:

$$S_f = (K/K_s - 1) \ln\left(\frac{r_s}{r_w}\right)$$  \hspace{1cm} (6)

where:  $K_s$ is the skin permeability; and  
$r_s$ is the skin radius.

Positive skin effects ($S_f>0$; $K>K_s$) are created by mechanical effects such as partial penetration, limited perforation, and any phenomenon which can decrease the permeability around the well bore. Negative skin effects ($S_f<0$; $K<K_s$) are created by processes that increase local permeability such as well development, acidizing, and hydraulic fracturing. The pressure cones for positive and negative skin factors are illustrated in Figure 4.8.

![Figure 4.8 – Positive and negative skin for pumping and injection wells.](image)

The skin factor can assume a large positive value for a damaged or clogged well or a well where the perforations do not coincide with the intended injection or production interval. Negative skin factors, even for stimulated wells, are rarely less than $-7$ since this would require $r_s/r_w$ to be more than 1,000.

### 4.4.3 Tubing Friction Loss

Head losses are also commonly associated with friction losses in the pumping or injection tubing string. Such losses can be significant when high volumetric flow rates are applied through narrow or rough (corroded or degraded) tubing strings. Friction losses can be computed using the empirical Hazen-Williams (1920) formula:

$$\Delta h_t = 10.643 \frac{L(Q/C)}{d^{-4.87}}$$  \hspace{1cm} (7)

where:  $\Delta h_t$ is the head loss (m);  
$L$ is the length of tubing (m);  
$Q$ is the volumetric flow rate (m$^3$/s);
C is a dimensionless Hazen-Williams pipe roughness coefficient; and d is the internal diameter of the tubing (m).

The value assumed for C depends on the material and state of the tubing walls. Typically, this will range from approximately 140 (representing perfectly smooth tubing), through 100 (for tubing in good condition) to 80 (for degraded tubing). A value of C=140 is used for newer wells employing modern coated tubing.

For injection at constant head (or constant pressure), the injection head (Δh) determines the transient flow rate Q(t) which in turn depends on the aquifer properties (K and S_s) and the skin factor (S_f). The effective injection head (Δh) is the total applied head less the friction loss (Δh_f) which depends on the flow rate. This results in a system of non-linear equations which can be solved for Q(t) using linear superposition and iteration.

The transient flow rate is calculated using the Theis equation:

\[ Q(t) = \frac{4\pi Kb \Delta h}{W(u)} \]  

where:  
- W(u) is the dimensionless well function [unit];  
- u is a dimensionless well parameter \( u = \frac{r_w^2 S_s}{4Kt} \) [unit];  
- \( \Delta h \) is the head loss [L];  
- K is the hydraulic conductivity [L²/T];  
- S_s is the specific storage [L⁻¹];  
- \( r_w \) is the well radius; and  
- t is the elapsed time corresponding to the head change \( \Delta h \) [T].

The analysis provides a breakdown of total injection head \( \Delta h_{tot} \) into three components: friction loss, aquifer loss, and well skin loss:

\[ \Delta h_{tot} = \Delta h_{fr} + \Delta h_{aq} + \Delta h_{skin} \]  

### 4.5 Model Calculations

The analytical model assumes the following parameters and parameter ranges:

<table>
<thead>
<tr>
<th>Table 4.1 – Fixed design parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fixed design parameters:</strong></td>
</tr>
<tr>
<td>Injection Rate (specified)</td>
</tr>
<tr>
<td>Open-hole Diameter (specified)</td>
</tr>
<tr>
<td>Injection Liner (tubing) Diameter (specified)</td>
</tr>
<tr>
<td>Total Vertical Depth (estimated from regional map data)</td>
</tr>
<tr>
<td>Disposal Formation Thickness (estimated from regional map data)</td>
</tr>
<tr>
<td>Fluid Unit Weight (expected value for Mannville waters)</td>
</tr>
<tr>
<td>Hazen-Williams Friction Coefficient (smooth lined tubing)</td>
</tr>
</tbody>
</table>
Based on the total vertical depth and fluid specific weight the ERCB specifies a maximum allowable wellhead pressure (WHIP) of approximately 3,300 kPa (480 psi). For injection pressures in excess of this value the ERCB requires an injectivity test to establish that the disposal formation can accept the injected fluid without hydrofracturing.

Table 4.2 – Variable design parameters.

<table>
<thead>
<tr>
<th>Variable design parameters</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin Factor $r_s/r_w = 5$ (assumed range from developed well $K/K_s = 0.2$ to clogged/smeared well $K/K_s = 5$)</td>
<td>-1.3</td>
<td>6.4</td>
<td>unit</td>
</tr>
<tr>
<td>Depth to well fluid-level (estimated range from regional maps)</td>
<td>25</td>
<td>40</td>
<td>mbgl</td>
</tr>
<tr>
<td>Disposal Formation Hydraulic Conductivity (centre of range corresponds to closest field measurement*)</td>
<td>$7 \times 10^{-6}$</td>
<td>$7 \times 10^{-7}$</td>
<td>m/s</td>
</tr>
<tr>
<td>Disposal Formation Specific Storage (centre of range corresponds to closest field measurement*)</td>
<td>$7 \times 10^{-6}$</td>
<td>$7 \times 10^{-7}$</td>
<td>1/m</td>
</tr>
<tr>
<td>Disposal Formation Transmissivity (centre of range corresponds to closest field measurement*)</td>
<td>$1 \times 10^{-3}$</td>
<td>$1 \times 10^{-4}$</td>
<td>m²/s</td>
</tr>
<tr>
<td>Disposal Formation Storativity (centre of range corresponds to closest field measurement*)</td>
<td>$1 \times 10^{-3}$</td>
<td>$1 \times 10^{-4}$</td>
<td>unit</td>
</tr>
</tbody>
</table>

* Values reported by Christopher (1989) for a well at the Agrium Vanscoy mine site.

The model was used to calculate the well head injection pressures (WHIP) for every combination and permutation of variable design parameters. The most critical parameter (by far) is transmissivity. For the highest transmissivity ($1 \times 10^{-3}$ m²/s) the predicted WHIP ranges from -283 kPa to 303 kPa. A negative WHIP means that the fluid can be gravity fed with no pumping at the high end of the transmissivity range with a well-developed well completion. For the lowest transmissivity ($1 \times 10^{-4}$ m²/s) the predicted WHIP ranges from 1,090 kPa to 1,820 kPa. These pressures are substantially less than the allowable pressures, based on the ERCB regulations (3,300 kPa), even when a clogged well is modelled.

It is concluded that within the range assumptions made for the analytical modelling, the Mannville Group is capable of readily accepting fluid injection at rates of 720 m³/d, with a WHIP no greater than 1,820 kPa (260 psi).
5.0 CLOSURE

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Regards,

MDH Engineered Solutions Corp.

Association of Professional Engineers
And Geoscientists of Saskatchewan
Certificate of Authorization Number 662
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