Characterization of the Gas and Liquid Conductivity of an Aboveground, Commercial-Scale Sulfur Block

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Elemental sulfur (S0) is commonly stored in aboveground blocks formed by pouring molten S0 in thin lifts. The long-term storage of S0 blocks is a potential source of high acidity effluent as a result of the oxidation of S0 to H2SO4, resulting in effluent waters with low pH and elevated SO42− concentrations. These blocks are currently managed during operations within a secure, engineered, containment facility. Characterization of the accessibility of the S0 block to O2 and water ingress is required to fully understand the generation of H2SO4 within the block. The O2 and water ingress are defined by the gas (Kg) and liquid (Kl) conductivity of the S0 block. We present the results of in situ gas pumping tests in vertical and angled boreholes conducted on an aboveground S0 block to determine Kg within the block and to indirectly determine Kl. The Kg test results showed that the block is highly conductive in both the horizontal (geometric mean = 2.3 × 10−4 m s−1) and vertical (geometric mean = 1.7 × 10−5 m s−1) directions and heterogeneous with respect to Kg. Results of the cross-hole tests were considered to yield more representative estimates of bulk Kg than single-well tests because cross-hole tests are relatively insensitive to high head loss associated with turbulent flow conditions that develop near the borehole. In addition, numerical modeling of cross-hole test data provided insight into the anisotropic nature of Kg of the S0 block. Corresponding values of anisotropic Kl computed from Kg were 2.6 × 10−3 m s−1 (horizontal) and 1.9 × 10−4 m s−1 (vertical). Given that S0 blocks are constructed in a similar manner throughout the world, the results of this study should be generally applicable to other S0 blocks.

Increasingly stringent environmental regulations have required the removal of SO2 and H2S from waste streams containing S compounds. The removal of these forms of S0 has resulted in periodic global surpluses of S0 (Heffer and Prud’homme, 2011). These surpluses drive down the market price of S0 and make this valuable element uneconomical for many companies to sell. As a result, on-site stockpiling of S0 in large, aboveground blocks is common.

The production of H2SO4 in the S0 blocks via the microbial oxidation of the S0 and reduction of O2 (Janzen and Bettany, 1987; Birkham et al., 2010b) in the presence of water (Birkham et al., 2011) and its flushing from the block by periodic infiltration of precipitation (Birkham et al., 2010a) is a key environmental challenge. For example, Birkham et al. (2010a) measured pH values of 0.4 to 1.0 and SO42− concentrations of 12 to 34 g L−1 in drainage water seeping from the base of S0 blocks, while Ledding (2013) measured a mean pH value of −1.7 in the S0 block.

Quantifying the controls on the production of H2SO4 and its migration in aboveground S0 blocks is challenging because the blocks are unsaturated and hydrophobic (Birkham et al., 2011). In addition, the S0 blocks are extensively fractured both vertically and horizontally.
Characterization of the generation and release of $H_2SO_4$ from $S^0$ blocks requires an understanding of the magnitude and distribution of the gas ($K_g$) and liquid ($K_l$) conductivities, which are currently poorly understood. Bonstrom (2007) characterized the bulk saturated liquid conductivity of an $S^0$ block using laboratory-based methods on core samples and field-based packer testing. The field-based results, however, were found to be unrepresentative of in situ conditions due to clogging of the fractures with the $S^0$ powder produced during drilling.

A variety of field-scale tests have been used to determine the liquid conductivity characteristics of unsaturated media. These include Guelph permeameter tests (Reynolds and Elrick, 1985; Elrick et al., 1989), falling-head tests (Bagarello et al., 2004; Rodgers and Mulqueen, 2006), water pumping tests (Hsieh, 2000), water injection tests (Rasmussen et al., 1990), pneumatic injection tests (Guzman et al., 1996; LeCain, 1998; Cook, 2000; Illman and Neuman, 2000, 2001; Illman, 2005), and pneumatic pumping tests (Edwards and Jones, 1994; Massmann and Madden, 1994). Despite the array of available tests, liquid testing in unsaturated fractured rock (analogous to the $S^0$ blocks) can be difficult to undertake (Illman, 2006; Illman and Neuman, 2003).

The utility of field-based gas tests to determine the conductivity of an unsaturated medium has been illustrated by Guzman et al. (1996), Bassett et al. (1997), and Illman and Neuman (2000, 2001, 2003). These tests offer advantages over liquid tests including the fact that the effect of gravity can be neglected, steady-state conditions can be reached more quickly, and the complexities associated with variable saturation when interpreting field data are also minimized (Rasmussen et al., 1993; Leven et al., 2004). In addition, gas tests eliminate the injection of a liquid, which may alter the physical and chemical conditions of the site (Cook, 2000; Rasmussen et al., 1993). In light of these advantages, in situ gas testing was utilized in this study to characterize $K_g$ and $K_l$ of an aboveground $S^0$ block. The current study ignores diffusion because transport in $S^0$ blocks is thought to be dominated by advection when total pressure gradients exist (Mendoza and Frind, 1990).

Materials and Methods

Study Site

This study was conducted on a commercial-scale $S^0$ block, referred to as the Phase 1 block. This block is located at the Syncrude Canada Ltd. Mildred Lake synthetic crude-oil production facility in northern Alberta, Canada (57°23′44.89″ N, 111°38′36.14″ W). The Phase 1 block (Fig. 1) was constructed between 1994 and 2004 by pouring molten $S^0$ in thin lifts (typically <0.10 m) from three towers and allowing the $S^0$ to flow laterally via gravity (Fig. 1). The Phase 1 block was approximately 359 m long, 168 m wide, and 175 m high at the time of this study.

Borehole Construction

A solid-stem auger was used to drill four vertical boreholes and three angled boreholes (drilled at an angle of 45° below horizontal) in the Phase 1 block. The total vertical depth of each borehole was approximately 13 m, and the diameter of all boreholes was 15 cm. The locations of these boreholes are shown in Fig. 2. Three vertical boreholes ($A_V$, $B_V$, and $C_V$) and three angled boreholes ($A_A$, $B_A$, and $C_A$) were used for the gas pumping tests. Because the solid-stem auger technique produced a fine dust that can clog fractures in the borehole (Bonstrom, 2007), dust was removed following drilling by repeatedly brushing the borehole annulus with a plastic bristled chimney brush and removing the dust using a truck-mounted industrial vacuum.

Existing gas sampling ports, installed in 11 vertical boreholes (Fig. 2 and 3), were used as monitoring locations to observe the pressure response within the block during the gas pumping tests. The gas sampling ports were constructed of a single piece of continuous multichannel tubing (CMT; Solinst) with an outside diameter of 0.043 m. Each CMT contained seven individual sample channels. In each individual sample channel, a small opening was cut (area of ~0.0001 m²) at regular intervals (typically 2 m) along the length of the CMT. Alternating layers of bentonite and sand/pea gravel were used to isolate the specific CMT sampling depths. The open intervals occurred at depths of approximately 0.5 to 15 m below the surface of the $S^0$ block. Detailed construction information for the CMT sampling ports can be found in Birkham et al. (2010a).
**Fracture Observation**

A Geovision Jr. (Marks Products) analog video camera was used to capture video in four of the newly drilled boreholes (B_V, B_A, C_V, and C_A). The camera was equipped with a tilt-and-pan function to allow rotation of the camera head horizontally and vertically. Observations made during the borehole imaging were recorded on a digital recorder and headset and merged with the video files using Final Cut Pro (Apple Inc. Canada) video editing software to provide a continuous visual and audio record of the borehole. Although direct measurements of the fracture aperture could not be determined from the borehole imaging, observations regarding the depth, orientation, relative openness, fracture spacing, and fracture length were determined from the borehole camera study.

**Gas Pumping Tests**

Gas pumping tests in each borehole were undertaken using a straddle packer system (Vanderlans and Sons). Packer systems are commonly used for field-based liquid and gas pumping and injection tests (Bassett et al., 1997; Cook, 2000; Illman and Neuman, 2000, 2001, 2003). A straddle packer system was utilized so that specific intervals could be isolated within the open boreholes and to allow various test configurations (i.e., length of intake and depth) to be utilized in the vertical and angled holes (Fig. 3). The straddle packer system consisted of two 114.3-mm-diameter rubber diaphragms (uninflated length of 0.86 m) that could be inflated to isolate a specific interval in a borehole. A hollow steel line (inner diameter of 6.35 mm), installed through the upper packer, was used to inflate both the upper and lower packers. A hollow steel pipe (inner diameter of 25.4 mm), installed through the center of the upper packer, allowed gas to be extracted from the isolated interval. The packers were manufactured with threaded ends such that various lengths of pipe could be inserted between the packers to modify the length of the test interval. A secondary hollow steel line (inner diameter of 6.35 mm) was installed through the upper packer such that a pressure transducer installed at the surface could be used to monitor the pressure response within the test interval.

The packers were inflated in the field using a tank of compressed N₂ gas. A Dwyer dial-type pressure gauge (range 0–1500 kPa; accuracy ±0.5% at full scale) was used to monitor the rate of inflation and to monitor the packer pressure during each test to ensure that a leak had not developed. The gas pumping rate (flow rate) was monitored using an Omega OEM-Style Acrylic Rotameter (Model FL7411; accuracy 4%) capable of measuring flow rates in the range of 1.9 × 10⁻³ to 1.9 × 10⁻² m³ s⁻¹ with a pressure drop of 2.4 kPa at full capacity. The pressure response in the pumped interval was measured using an Omega pressure transducer (Model PX209–30VACI; accuracy 0.25%) with an operating range of zero to full vacuum (Fig. 3). The transducer output signal was recorded using a Campbell Scientific CR10X datalogger. The output signal was converted to pressure using a laptop computer and the manufacturer-supplied calibration curves so that the pressure response in the test interval could be monitored in real time.
This resulted in 197 individual cross-hole data sets after data culling. In four of the six boreholes, the pressure response for each applied flow rate was recorded at designated monitoring locations, resulting in a total of 40 cross-hole test configurations. This resulted in 197 individual cross-hole data sets after data culling. The procedure for the gas pump testing was similar to that conducted by Cook (2000) and Illman and Neuman (2003).

**Determination of Gas Conductivity**

**Analytical Solution**

The single-hole and cross-hole $K_g$ values were evaluated using steady-state analytical solutions through the determination of the intrinsic permeability ($k_g$). The applicability of steady-state solutions was based on field observations and a review of the test data, which illustrated that steady-state flow conditions were obtained virtually instantaneously. For the single-hole pumping tests, $k_g$ was calculated using the analytical solution of LeCain (1998):

$$k_g = \frac{P_{sc} Q_{sc} \mu}{\pi L \left( P_{sc}^2 - P_0^2 \right) T_{sc}} \ln \left( \frac{L_T/2r_w}{1 + \left( L_T/2r_w \right)^2} \right) T$$  \[1\]

where $k_g$ is the intrinsic permeability ($m^2$) determined from the single-hole gas pumping test data; $P_{sc}$ (kPa) and $Q_{sc}$ ($m^3 s^{-1}$) are the pressure and flow rates, respectively, under standard operating conditions; $\mu$ is the dynamic viscosity (kPa s); $r_w$ is the borehole radius (m); $L_T$ is the length of the test interval (m); $T$ is the absolute air temperature (K); $P_{sc}$ is the pressure at steady state (kPa); $P_0$ is the initial pressure (kPa); and $T_{sc}$ is the absolute temperature under standard conditions (K).

For the cross-hole pumping tests, $k_{gs}$ was determined using the following equation simplified from the theoretical expression of Hsieh and Neuman (1985a) for steady-state gas flow:

$$\Delta p = \frac{Q \mu}{4\pi \sqrt{\sum x^2 k_y + y^2 k_z + z^2 k_y k_z}}$$  \[2\]

where $\Delta p$ is the change in pressure during the monitoring interval (kPa); $Q$ is the flow rate ($m^3 s^{-1}$); $x$, $y$, and $z$ are the Cartesian coordinates of the centroid of the monitoring interval, with the origin at the centroid of the pumped interval; and $k_x$, $k_y$, and $k_z$ are the permeabilities in the $x$, $y$, and $z$ directions. The $z$ axis is defined as the vertical plane, while the $x$ and $y$ axes represent the horizontal plane. If it is assumed that the permeability is isotropic within the horizontal plane ($k_x = k_y$), Eq. [2] simplifies to

$$\Delta p = \frac{Q \mu}{4\pi \sqrt{k_z r^2 + z^2 k_z}}$$  \[3\]

where $r$ is the radial distance between the centroid of the pumped interval and the monitoring interval ($r^2 = x^2 + y^2$), and $k_z$ is the horizontal permeability ($k_x = k_y = k_z$).

Equation [3] is nonlinear, and the horizontal and vertical permeabilities ($k_x$ and $k_y$) were optimized using the NLIN program (SAS Institute, 2008) using the minimum least-square difference between the monitored and predicted pressure response at the monitoring locations as an objective function (Fig. 4).

The following assumptions were made when using Eq. [3]: (i) the flow is at steady state; (ii) the pumping and monitoring intervals can be treated mathematically as finite points; and (iii) the medium is isotropic within the horizontal plane. Field observations and a review of the pressure response data from both the pumping and

![Fig. 4. The optimized intrinsic gas permeability $k_{gs}$ and $k_{sc}$ values in Eq. [3] with the minimum least-square error between the measured and estimated pressure responses, where $r$ is the radial distance between the centroid of the pumped interval and the monitoring interval. The series test 140909-A-Vert-1 was used as an example (the center of rest interval was 1.73 m below the surface and the flow rate was 0.0146 $m^3 s^{-1}$).](image-url)
monitoring intervals illustrated that steady-state conditions were obtained virtually instantaneously. This suggests that the pressure pulse induced at the pumped location traveled very rapidly through the fractured S0 system, highlighting the relatively high permeability and/or low air-filled porosity (i.e., gas diffusivity is high) of the S0 blocks. The procedure and associated discussion proposed by Hsieh and Neuman (1985a, 1985b) to determine the applicability of treating the pumping and monitoring intervals as finite points was evaluated and was determined to be applicable for the given test setup and geometry.

It is important to note that neither Eq. [1] nor [3] consider the atmospheric boundary at the surface and consequently are not as valid for shallow borehole tests in which the observed drawdown may be influenced by the presence of the atmospheric boundary.

Once $k_g$ is determined from Eq. [1] or [3], $K_g$ can be calculated using the relationship of intrinsic permeability (Bloomfield and Williams, 1995):

$$K_g = k_g \left( \frac{\rho_g g}{\mu_g} \right)$$  \hspace{1cm} [4]

where $\mu_g$ and $\rho_g$ are the dynamic viscosity (kPa s) and density of the gas (kg m$^{-3}$), respectively, and $g$ is the gravitational constant (m s$^{-2}$).

**Numerical Approach**

Numerical modeling was also used to compute $K_g$ values from the single- and cross-hole pumping test data. Two commercial finite element simulation packages, SEEP/W and SEEP3D (Geo-Slope International) were used to analyze the single- and cross-hole gas pumping test data. SEEP/W and SEEP3D are typically used to simulate water flow; however, water flow models may be used to simulate gas flow if certain assumptions can be satisfied (Massmann, 1989). Massmann (1989) noted that a water flow model will produce reasonable estimates of $K_g$ if the change in pressure is limited to approximately 20.3 kPa. In this study, the flow rate was maintained as low as possible such that the corresponding pressure response at the pumped monitoring intervals did not result in a pressure difference greater than 20.3 kPa. The maximum pressure difference observed between the pumped monitoring intervals during the cross-hole tests was approximately 16.5 kPa, suggesting that the use of a water flow or linearized flow model could be used to accurately estimate air flow from the pumping tests conducted on the S0 block.

Because SEEP/W simplifies the three-dimensional domain as a two-dimensional axisymmetric flow system, it could only be used to analyze the gas pumping test results for test configurations where: (i) the pumping and monitoring intervals were sufficiently far from the lateral block boundaries; and (ii) the boreholes were vertical. SEEP/W was used to analyze the pumping test results for the A_V and B_V test series because they satisfied these conditions (Fig. 5). The remaining test results were analyzed using the SEEP3D package (Fig. 6) either due to their proximity to the block boundary (C_V) or because the boreholes were constructed at an angle (A_A, B_A, and C_A).

Normalized material properties (e.g., $K = 1$) and boundary conditions (e.g., $Q = 1$ and total head = 1 or 0) were used in the numerical...
The open borehole was not discretized and was instead assigned different boundary conditions to account for the differences between the open portions of the borehole and the packers. The following boundary conditions were applied within the numerical model: (i) the top and sides of the block were treated as constant-head boundary conditions (i.e., total head = 0 m); (ii) the pumped interval was treated as a constant-flux boundary condition; (iii) the area where the packers were located were treated as no-flow boundary conditions; (iv) the open borehole above the upper packer was assigned a constant head equal to the sides and top of the block (i.e., total head = 0 m) so as to not limit the potential for short-circuiting through the open borehole; and (v) the open borehole below the packer was treated as a no-flow boundary because it was assumed that short-circuiting of gas through the lower portion of the borehole (below the packer assembly) would not have an appreciable effect on the results given the highly conductive nature of the block. The boundary conditions used in SEEP/W and SEEP3D are shown in Fig. 5 and 6, respectively.

Anisotropy in the permeability of the block was considered probable given the genesis of the fractures within the blocks (Birkham et al., 2010a). Consequently, a range of horizontal gas conductivity \( K_{gx} \) values and anisotropy ratios \( A_{gr} \), the ratio of the vertical to horizontal gas conductivity, were used. However, only a single conductivity value and anisotropy ratio was used in each simulation in spite of the fact that the block was probably heterogeneous with depth (Bonstrom et al., 2009). It was felt that this simplification was justified given the limited lateral extent of the observed drawdown and the number of combinations of conductivity and anisotropy that would be required to assess all potential variations in these parameters across the entire block.

The best-fit values of \( K_{gx} \) and \( A_{gr} \) were determined by manually adjusting the conductivity and anisotropy values within the simulation results until a best fit was observed between a plot of the measured and simulated pressure response for all monitoring locations for a single test configuration. The goodness of the fit was also evaluated quantitatively by computing the sum of squared differences between the measured and simulated pressure response for each monitoring interval (for each of the seven individual sampling ports at each monitoring location). This procedure is similar to the procedures used for the interpretation of single-hole gas pumping tests; however, for the single-hole tests, the conductivity value was adjusted until the simulated pressure in the pumped interval matched the measured pressure.

**Calculation of Liquid Conductivity**

The liquid conductivity, \( K_l \), was calculated from the relationship of the intrinsic permeability:

\[
K_l = k_l \left( \frac{\mu_g}{\mu_l} \right)
\]

where \( \mu_g \) and \( \rho_g \) are the dynamic viscosity (kPa s) and density (kg m\(^{-3}\)) of the liquid, respectively. Equations [4] and [5] are identical and vary only in the subscripts \( g \) and \( l \), which have been incorporated to indicate that the variables relate to the use of a gas or liquid, respectively.

In this study, it was assumed that \( k_g \) and \( k_l \) were equal such that Eq. [4] and [5] could be combined into a single relationship to calculate \( K_l \) from the field-measured \( K_g \) values:

\[
K_l = \left( \frac{\mu_g}{\rho_l} \right) \mu_l \left( \frac{\mu_g}{\mu_l} \right) K_g
\]

Theoretically, the intrinsic permeability measured using either a gas or a liquid should be identical because differences in the permeating fluid are accounted for in the physical properties of the fluids in Eq. [4] or [5]. However, it is understood that the assumption of equivalence between \( k_g \) and \( k_l \) may result in error in the estimation of \( K_l \) from \( K_g \) as a result of: (i) capillary forces drawing water into the block matrix inhibiting air flow (Illman and Neuman, 2000); (ii) variable saturation (Rasmussen et al., 1993); and (iii) gas slippage (Klinkenberg, 1941).

Although inhibition of gas flow due to capillarity and variable saturation would be problematic in many types of porous fractured media, it was hypothesized that in the case of the \( S^0 \) blocks, these differences would be minimal and that the dominant flow path for either of these fluids would be within the fractures. The primary reason for this is based on previous research on the Phase 1 \( S^0 \) block, which has shown that the matrix pores are hydrophobic (Bonstrom, 2007; Bonstrom et al., 2009) and that drainage of the blocks following wetting
events is very rapid, with very low residual water contents (Birkham et al., 2011). Much of this water is associated with thin layers of adsorbed water (located on the fracture faces) associated with fractures containing dirt or organic matter or within dead-end fractures. The residual water located on the fracture face would inhibit gas flow into the block matrix. As a consequence, the airflow pathways through the block would be dominated by the same fracture system as that controlling water flow at water saturation.

Gas slippage has been shown to be negligible in larger flow passages (Massmann, 1989) where the flow passage is much larger than the mean free gas path. Based on these assumptions, airflow during the gas pumping tests conducted on the block under standard conditions (low water saturation) should reflect liquid flow under high water saturation levels, providing justification for the assumption of nearly equivalent $K_g$ and $K_l$.

It can be seen from Eq. [6] that the physical properties of gas and liquid in the block have an influence on the $K_g$ and $K_l$ values. Because gas pumping tests were used in this study, control of the gas properties (density and viscosity) was not possible and an approximation of the ambient gas characteristics of the block was required. In addition, because the block contains solutions of high-strength acids, the physical properties of the various concentrations of aqueous H$_2$SO$_4$ needed to be considered. To simplify the analyses, the average gas concentrations (AGCs) in the vicinity of the gas tests were used for each test. The AGCs were assigned based on previous measurements collected by Birkham et al. (2010a) in the vicinity of the test locations. The major constituents of the AGCs consisted of N$_2$, O$_2$, CO$_2$, and Ar. Dry and humid air were also considered for comparison in the computation of $K_g$. Pure water and varying strengths of H$_2$SO$_4$ solutions to a maximum pH of $\approx$2 were considered for calculating $K_l$. The AGC dynamic viscosity was determined using a semi-empirical relationship proposed by Wilke (1950), while gas densities were calculated using the ideal gas law relationships of mass and volume based on the various concentrations of each constituent.

### Results and Discussion

#### Fracture Characterization

The digital images from the borehole videos were interpreted to determine a number of qualitative (e.g., orientation, “open” vs. “closed” fractures) and quantitative (e.g., depth, length, fracture spacing) characteristics of the S0 block fractures. An “open” fracture was defined as a fracture in which the there was no visible blockage of the fracture that would restrict flow, whereas a “closed” fracture was visibly blocked by infilling. The fracture spacing was determined per 1.38-m test interval and across the entire length of each borehole.

The horizontal fracture spacing (calculated per test interval), including open and closed fractures, ranged from 0.03 to 0.07 m with a mean spacing of 0.05 m. The spacing of open fractures (per test interval) ranged from 0.09 to 0.33 m with a mean of 0.16 m. The mean fracture spacing across the entire length of the borehole was 0.05 m for all fractures (open and closed) and 0.15 m for open fractures. A similar horizontal fracture spacing of the Phase 1 block was observed by McKenna (2004a) and Bonstrom (2007; horizontal fracture spacing was inferred from the data). Many of the horizontal fractures appeared to be coincident with lift interfaces, as also observed by Bonstrom et al. (2009).

Vertical fractures were categorized based on the number of fractures and the length of each fracture rather than spacing and were determined from the borehole camera logs. In the angled boreholes, vertical fractures were also characterized based on their orientation relative to the borehole. The number of vertical fractures per test interval (including open and closed fractures) ranged from 5 to 24 with a mean of 12 and lengths ranging from 0.07 to 0.20 m with a mean length of 0.15 m. For the angled boreholes, the number of open fractures running parallel to the borehole ranged from one to three with a mean of two and lengths ranging from 0.04 to 0.25 m with a mean length of 0.14 m. The number of perpendicular vertical fractures ranged from one to six with a mean of three and lengths ranging from 0.06 to 0.31 m with a mean of 0.19 m. Although vertical fractures were identified in both vertical and angled boreholes, the apparent (visible observation) interconnectedness of vertical fractures was more prominent in the angled boreholes.

The fracture spacing per test interval was compiled to determine if a relationship between the fracture density (inverse of spacing) and $K_g$ could be defined. No relationship between the fracture density per test interval and the corresponding $K_g$ was observed. Rasmussen et al. (1993), Illman and Neuman (2001), Leven et al. (2004), and Illman (2005) noted similar findings and indicated that it may be invalid to estimate the flow and transport properties of a medium based on fracture data alone.

#### Analytical Solution of Gas Conductivity Tests

It has been illustrated by numerous researchers that the logarithmic values of hydraulic (Freeze and Cherry, 1979; Sudicky, 1986; Woodbury and Sudicky, 1991) and gas conductivity (Vesselinov et al., 2001; Illman, 2005) for various media types are normally distributed. A probability plot of the log-transformed data was used to determine if the distribution could be considered to be log-normally distributed (Filliben, 1975). As can be seen in Fig. 7, the probability plot of log-transformed data for each $K_{ge}$ and $K_{gg}$ data set is linear, indicating a lognormal distribution. Consequently, the geometric mean was used to represent the mean values of the gas conductivity data.

The $K_{ge}$ values determined using Eq. [1] ranged from $3.4 \times 10^{-6}$ to $2.3 \times 10^{-4}$ m s$^{-1}$ with a geometric mean of $1.9 \times 10^{-5}$ m s$^{-1}$ ($n = 261$).
The $K_{gx}$ values determined using Eq. [3] ranged from $8.9 \times 10^{-6}$ to $9.9 \times 10^{-4}$ m s$^{-1}$ with a geometric mean of $3.4 \times 10^{-4}$ m s$^{-1}$ ($n = 176$), while the $K_{gz}$ values ranged from $7.4 \times 10^{-7}$ to $5.9 \times 10^{-4}$ m s$^{-1}$ with a geometric mean of $2.1 \times 10^{-5}$ m s$^{-1}$. The $A_{gr}$ values ranged from 0.01 to 0.5 with a geometric mean of 0.06.

Numerical Modeling of Gas Conductivity Tests

Numerical modeling was used to estimate $K_g$ values from the pressure response of the single- and cross-hole conductivity test data. Because the single- and cross-hole test data were collected simultaneously during the same test setup, only a single numerical model was required to analyze both. The only difference was that for the single-hole tests, the $K_{gs}$ values were determined based on the match of the simulated and measured pressure response in the test interval. Due to the similarity of the numerical modeling approach for the single- and cross-hole tests, only the cross-hole test technique is described in detail.

For the single-hole tests, the $K_{gs}$ values were estimated from the numerical simulations for only the $A_V$ and $B_V$ test series for comparison with the $K_{gs}$ values determined from Eq. [1]. The $K_{gs}$ values from these test series ranged from $5.1 \times 10^{-6}$ to $9.4 \times 10^{-5}$ m s$^{-1}$ with a geometric mean of $2.1 \times 10^{-5}$ m s$^{-1}$ ($n = 75$; Table 1). Because no information regarding anisotropy can be obtained directly from a single-hole test, it was not included in the single-hole numerical modeling analyses. However, because the results of the cross-hole numerical analyses indicated that the block is highly anisotropic, the validity of neglecting anisotropy in the single-hole models was assessed by reanalyzing the 140909-$A_V$–4 test series using select anisotropy ratios determined from the cross-hole tests. Inclusion of anisotropy (range of $A_{gr}$ values used: 0.04–0.1) in the single-hole model resulted in an increase in $K_{gs}$ of 1.4 to 1.6, with the greatest increase in $K_{gs}$.

### Table 1. Summary of the geometric means of the gas conductivity from the single-hole tests ($K_{gs}$), the horizontal ($K_{gx}$) and vertical ($K_{gz}$) gas conductivities from the cross-hole tests, and the anisotropy ratio ($A_{gr}$) data for the combination of the average gas concentration (AGC) and liquid at a pH of 0.

<table>
<thead>
<tr>
<th>Test series</th>
<th>Single-hole tests</th>
<th>Cross-hole tests</th>
<th>Numerical model</th>
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<tbody>
<tr>
<td></td>
<td>$K_{gs}$†</td>
<td>$K_{gs}$†</td>
<td>$K_{gr}$†</td>
</tr>
<tr>
<td>A vertical ($A_V$)</td>
<td>$2.2 \times 10^{-5}$</td>
<td>1.9 $\times 10^{-5}$</td>
<td>1.9 $\times 10^{-5}$</td>
</tr>
<tr>
<td>A angled ($A_\lambda$)</td>
<td>$2.3 \times 10^{-5}$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>B vertical ($B_V$)</td>
<td>$2.4 \times 10^{-5}$</td>
<td>2.2 $\times 10^{-5}$</td>
<td>2.8 $\times 10^{-4}$</td>
</tr>
<tr>
<td>B angled ($B_\lambda$)</td>
<td>$2.9 \times 10^{-5}$</td>
<td>–</td>
<td>3.5 $\times 10^{-4}$</td>
</tr>
<tr>
<td>C vertical ($C_V$)</td>
<td>$1.7 \times 10^{-5}$</td>
<td>35</td>
<td>3.4 $\times 10^{-4}$</td>
</tr>
<tr>
<td>C angled ($C_\lambda$)</td>
<td>$9.9 \times 10^{-6}$</td>
<td>–</td>
<td>3.7 $\times 10^{-4}$</td>
</tr>
<tr>
<td>All data</td>
<td>$1.9 \times 10^{-5}$</td>
<td>2.1 $\times 10^{-5}$</td>
<td>3.4 $\times 10^{-4}$</td>
</tr>
</tbody>
</table>

† Geometric means.
‡ Total number of results for each series.
corresponding with the smallest value of $A_{gr}$. It was concluded, therefore, that exclusion of anisotropy in the single-hole test analysis had a negligible effect on the results.

The pressure response for the cross-hole A series tests 140909-AV–4 and 140909-AV–1 are shown in Fig. 8a and 8b, respectively. The 140909-AV–4 and 140909-AV–1 series tests were conducted at depths (to the center of the pumping test interval) of 5.97 and 1.73 m below the surface, respectively. Five flow rates were applied for each test, and the relative position of the monitoring locations with respect to the test borehole can be observed in Fig. 2. Figure 8a shows the measured and simulated drawdown for the greatest applied flow rate of 0.0125 m$^3$s$^{-1}$ for the A series test 140909-AV–4. Although the simulated drawdown was in good agreement with the measured drawdown at radial distances of 3.70, 4.20, and 4.73 m, the measured drawdown at $r = 4.02$ m did not fit a consistent pattern relative to the measured pressure response at the other monitoring locations, probably due to heterogeneity. In most cases, when such a response was observed, it was consistently observed for all five flow rates and was amplified at the greatest applied flow rate. In such a case, the sum of least squares method underestimated the fit between the measured and simulated drawdown, as this one set of apparently anomalous measurements skewed the sum of least squares value. Figure 8b (A series test 140909-AV–1) shows a much more consistent response at the $r = 4.02$ m monitoring location, with the exception of the location 10.5 m below the surface, where the measured pressure response was positive.

Inconsistent or null responses were noted in other test locations and were usually associated with greater distances between the test and monitoring intervals. For the B and C series tests, a recognizable trend was identified in only the single closest monitoring location (B: 6.2 m; B: 7.2 m; C: 6.5 m; C: 7.1 m). The second closest monitoring location for each of the B and C series tests was a minimum of 2.5 times the distance of the closest monitoring location (B: 29.0 m; B: 31.0 m; C: 17.3 m; C: 21.9 m). At larger distances between the pumping and monitoring interval, a similar null response was reproduced in the numerical model. To simulate even a small measurable pressure response in the numerical model at these larger distances, uncharacteristically small $A_{gr}$ and larger $K_{gz}$ values were required. A null response at greater distances between the pumped and monitoring intervals was assumed reasonable because the induced air flow would be divided among an exponentially increasing number of fractures as the distance between the pumped and monitoring interval increased. Under these circumstances (i.e., null response associated with great distance to the monitoring location), such measurements were omitted from the sum of least squares calculations because the observed response was so small that it could have been caused by barometric pressure fluctuations rather than a change affected by the pumping test.

Another factor that caused inconsistent responses at the monitoring locations was meteorological conditions. The U-tube manometer used to measure the pressure response at the monitoring locations was open to the atmosphere. Therefore, during periods of moderate gusting winds, only those depths that showed a distinct and steady drawdown were unaffected by wind fluctuations. During periods of strong gusting winds, virtually no measurements could be obtained due to fluctuations in the manometer readings.

In general, the $K_{gz}$ of the S$^0$ block was estimated to be much smaller than the horizontal (i.e., small values of $A_{gr}$). The reason for small $A_{gr}$ values may be due to the genesis of the block fractures.
Horizontal fractures associated with lift interfaces, as noted by others (Bonstrom, 2007; McKenna, 2004b), would be more likely to be interconnected. This would result in greater conductivity, connectivity, and reduced tortuosity of the horizontal flow paths than the vertical flow paths. There were several cross-hole tests in which the best-fit $A_{gr}$ values were larger (0.2–0.5). In the example shown in Fig. 9 (Test 230909-BV–5), the pressure response shows a best fit to the measured data with an $A_{gr}$ value of 0.5. These $A_{gr}$ values could be the result of greater interconnectedness of the vertical fractures.

The cross-hole gas conductivity, $K_{gx}$, determined from all of the numerical modeling simulations ranged from $5.5 \times 10^{-5}$ to $9.0 \times 10^{-4}$ m s$^{-1}$ with a geometric mean of $2.3 \times 10^{-4}$ m s$^{-1}$ ($n = 197$). The $A_{gr}$ values ranged from 0.01 to 0.5 with a geometric mean of approximately 0.07 ($n = 197$). The corresponding $K_{gz}$ values ranged from to $9.0 \times 10^{-7}$ to $1.0 \times 10^{-4}$ m s$^{-1}$ with a geometric mean of $1.7 \times 10^{-5}$ m s$^{-1}$ ($n = 197$).

**Comparison of Analytical and Numerical Modeling Results**

The results of the single-hole analytical solution and numerical model for the A0 and B0 test series are plotted in Fig. 10a. The geometric means of the $K_{g0}$ values (A and B series tests only) computed using the analytical solution and numerical model were $2.3 \times 10^{-5}$ and $2.1 \times 10^{-5}$ m s$^{-1}$ ($n = 75$), respectively. Although both interpretive techniques produced similar $K_{g0}$ values for the single-hole data, the $K_{g0}$ values computed using Eq. [1] were always slightly greater (the error increasing with $K_{g0}$) than those determined using the numerical simulation, with an overall maximum error of 18%.

The $K_{g0}$ values computed using Eq. [3] and the $K_{g0}$ values approximated through numerical modeling are shown in Fig. 10b. In contrast to the single-hole results, the analytical solution consistently produced $K_{g0}$ (geometric mean of $3.4 \times 10^{-4}$ m s$^{-1}$) and $K_{g0}$ (geometric mean of $2.1 \times 10^{-5}$ m s$^{-1}$) values for the cross-hole results that were larger than the $K_{g0}$ (geometric mean of $2.3 \times 10^{-4}$ m s$^{-1}$) and $K_{g0}$ (geometric mean of $1.7 \times 10^{-5}$ m s$^{-1}$) values computed using the numerical model. In addition, there is a greater amount of scatter in the data presented in Fig. 10b than Fig. 10a. The analytical solution (Eq. [3]) assumes an infinite medium (Hsieh and Neuman, 1985a), while the numerical model...
incorporates the test-specific boundary conditions and geometry and also incorporates anisotropy.

**Comparison of Single- and Cross-Hole Conductivity Results**

An order of magnitude difference was observed between conductivity values determined from the single- (geometric mean of $K_g^x$ data calculated from Eq. [1] for all test series $= 1.9 \times 10^{-5}$ m s$^{-1}$) and cross-hole results (geometric mean of $K_g^x$ data calculated from Eq. [3] for all test series $= 3.4 \times 10^{-4}$ m s$^{-1}$). It was hypothesized that this difference could be the result of skin effects, the onset of turbulent flow, or both. It was concluded that although skin effects could be partially responsible for the observed differences between the single- and cross-hole conductivity values, skin effects could not explain the nonlinear increase in the difference between the measured and simulated pressure in the test interval when the simulated pressure in the test interval was back-calculated from the best-fit pressure response at the monitoring locations for the cross-hole test data.

The onset of turbulent flow conditions was evaluated through the Reynolds number (Re) for fracture flow (Iwai, 1942; Lee and Farmer, 1993, Louis, 1969). The Re values within the pumping interval approached but did not exceed the critical Re value (1200; Louis, 1969), and therefore flow in the vicinity of the pumping interval should have remained laminar. However, to determine a number of the parameters required to assess Re (e.g., fracture velocity, effective aperture), it was assumed that the fractures could be represented as orthogonal sets of uniform, parallel, smooth-walled fractures. In reality, the fractures are not necessarily orthogonal, probably vary in aperture along their length, and the fracture faces are rough, resulting in flow irregularities and the onset of turbulent or inertial flow losses in the vicinity of the pumping test interval before the critical Re. The nonlinear increase in the difference between the measured and simulated pressure response in the test interval could be explained by the onset of turbulent flow and may have been the cause for the observed differences between the single- and cross-hole conductivity results. Development of turbulent flow conditions within the pumped interval was also assessed using the graphical procedure proposed by LeCain (1998). These plots indicated that turbulent flow conditions had developed within the vicinity of the pumped interval. The procedure proposed by LeCain (1998) to estimate the permeability from the portion of the data where the flow rate approaches 0 (i.e., the portion of data where laminar flow conditions should exist) was used to assess the single-hole permeability data. This procedure resulted in a closer correlation of the single- and cross-hole permeability data but did not completely reconcile the observed differences.

The observed differences between the single- and cross-hole conductivity values could also be partially attributed to scale effects because there appeared to be a scale effect observed when the length of the test interval was increased. The presence of scale effects may also be indicated by the lower mean conductivity values determined from the cross-hole tests in this study compared with those determined by Birkham et al. (2011) ($1 \times 10^{-2}$ m s$^{-1}$) based on observations of the transient water outflow following precipitation events. However, an in-depth study of scale effects was determined to be outside the scope of this study.

**Changes in Gas Conductivity with Depth**

The conductivity of a fractured medium typically decreases with depth and is usually associated with a decrease in the aperture size due to increasing overburden pressure (Louis, 1969; Zhao, 1998). In this study, only weak correlations were observed between $K_g^x$, $K_g^z$, (data not shown because $A_{gr} = K_g^z/K_g^x$), and $A_{gr}$ and the depth of the S0 block (Fig. 11). In general, slight decreasing trends with depth were observed for $K_g^x$ and $K_g^z$. Although a slight increasing trend with depth was observed for the $A_{gr}$ values for the B vertical, B angled, and C angled series tests, the remaining data were fairly consistent with depth because 78% of the total ($n = 197$)
values were \( \leq 0.2 \). There was also no noticeable difference in the \( A_g \) values between the angled and vertical boreholes. Although the purpose of the angled boreholes was to intercept a greater number of vertical fractures, in theory there should be no change in the anisotropy ratio.

**Resulting Liquid Conductivity Values**

The relationship between the ratio of \( \frac{K}{\gamma} \) (\( \gamma = 2.7 \times 10^{-3} \) m s\(^{-1} \) calculated by Bonstrom (2007). Resulting Liquid Conductivity Values

Birkham et al. (2011) simulated the outflow response of the Phase 1 block to discrete rainfall events. Their simulations produced a best fit to the measured outflow with an estimated \( K_l \) of \( 1 \times 10^{-2} \) m s\(^{-1} \). Although the estimated conductivity of Birkham et al. (2011) was nearly an order of magnitude greater than that determined in this study, the discrepancy may be due in part to uncertainties in the value of the specific yield and/or the scale of measurement. To determine a best fit between the simulated and measured outflow response, Birkham et al. (2011) adjusted both the specific yield and conductivity and noted that alteration of both the specific yield and \( K_l \) could produce a similar outflow response time. If the specific yield was increased, a proportional decrease would have to be made to \( K_l \) and vice versa. Considering both the pore-water head and outflow modeling, Birkham et al. (2011) estimated that the specific yield at the base of the blocks ranged from 4 to 7% of rainfall, with a \( K_l \) of \( 1 \times 10^{-2} \) m s\(^{-1} \). When the \( K_l \) value was \( 1 \times 10^{-3} \) m s\(^{-1} \), closer to the measured value of \( 1.1 \times 10^{-3} \) m s\(^{-1} \) in this study (geometric mean for the combination of dry block gas and aqueous \( H_2SO_4 \) with pH −2), the modeled outflow rates were much delayed relative to the measured response. In addition, modeling the flow response through the block during a rainfall event would assume that it would occur throughout the entire length of the block and therefore would invoke flow through the most conductive fractures.

**Comparison of Conductivity Values from Studies of the Phase 1 Block**

Bonstrom (2007) computed a theoretical \( K_l \) for the Phase 1 block using the cubic law of Snow (1969) based on fracture mapping data and a minimum fracture aperture that would be fluid filled for a specific matric potential. It was assumed that all fractures with apertures greater than this minimum would be capable of transporting fluid for the corresponding matric potential. The unsaturated hydraulic conductivity, \( K_{unsat} \), was estimated at each measured aperture interval between 0.1 and 13.8 mm (minimum and maximum measured apertures). The maximum \( K_{unsat} \) for the fractured pore space was nearly equivalent to the \( K_{unsat} \) estimated for the largest aperture increment (13.7 mm) and was determined to be \( K_{unsat} \) of \( 2.7 \times 10^{-3} \) m s\(^{-1} \). For comparison, the theoretical value computed by Bonstrom (2007) was referenced to the \( K_{unsat} \) value determined in this study for the combination of dry air and water because water was the permeating fluid used by Bonstrom (2007). The resulting \( K_{unsat} \) value in this study (geometric mean of \( 2.7 \times 10^{-3} \) m s\(^{-1} \)) was close to the theoretical value of \( 2.7 \times 10^{-3} \) m s\(^{-1} \) calculated by Bonstrom (2007).

**Conclusion**

Analysis of the gas pumping data using both analytical solutions and numerical modeling produced similar \( K_g \) values. However, \( K_g \) would invoke flow through the most conductive fractures.

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**Table 2. Summary of Liquid Conductivity \( K_l \)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dry air and water</th>
<th>Avg. gas conc. and pH −2 ( H_2SO_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min.</td>
<td>Geometric mean</td>
</tr>
<tr>
<td>( K_{lx} )</td>
<td>( 1.1 \times 10^{-5} )</td>
<td>( 1.9 \times 10^{-4} )</td>
</tr>
<tr>
<td>( K_{lz} )</td>
<td>( 6.8 \times 10^{-4} )</td>
<td>( 2.6 \times 10^{-3} )</td>
</tr>
</tbody>
</table>
values determined from numerical modeling were slightly different from the corresponding analytical solution result for the single-hole and cross-hole tests due to the boundary condition limitations. The relative error was 11.8% for the single-hole tests and 8.6% for the cross-hole tests.

An approximation of the anisotropy of $K_g$ in the S0 block was simulated using numerical models. Anisotropy ratios of $K_g$ ranged from 1:100 to 1:2 with a geometric mean of approximately 1:14. The corresponding geometric mean of the $K_{g\text{ge}}$ values was $1.7 \times 10^{-5}$ m s$^{-1}$. Although the $K_{g\text{ge}}$ values of the block were an order of magnitude smaller than $K_{g\text{ge}}$, it should be noted that the Phase 1 block at the Syncrude Canada Ltd. site was highly conductive in both the horizontal and vertical directions.

Poor correlation was observed between the measured fracture characteristics of the block and the corresponding $K_f$ data, indicating that the use of fracture geometry data alone may not be an accurate technique to estimate flow and transport parameters of the S0 block. Rasmussen et al. (1993), Illman and Neuman (2001), Leven et al. (2004), and Illman (2005) studied flow and transport through fractured media at other sites in different geological environments and reported similar conclusions.

Two combinations of gases and liquids were assessed in the determination of $K_f$ from the results of the gas pumping test data: pure water to pH $\sim 2$ H$_2$SO$_4$ and dry air to AGC. The larger $K_{f\text{ge}}$ value was obtained when the liquid within the block was assumed to be pure water and decreased with increasing acid strength due to changes in the viscosity and density of the liquid. The geometric mean of the resulting $K_{f\text{ge}}$ values using pure water and H$_2$SO$_4$ with a pH $\sim 2$ was $2.6 \times 10^{-3}$ m s$^{-1}$ and $1.4 \times 10^{-3}$ m s$^{-1}$, respectively.

The resulting $K_{f\text{ge}}$ (assuming pure water) determined in this study was comparable to the theoretical $K_f$ ($2.7 \times 10^{-3}$ m s$^{-1}$) computed by Bonstrom (2007) using the cubic law equation. Discrepancies in $K_f$ between this study and that of Birkham et al. (2011) may be attributable to the combined use of the specific yield and $K_f$ to simulate the flow response and/or the test scale.

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References


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McKenna, G.T. 2004a. Geo-environmental observations of 17 sulphur blocks in Alberta, Canada. Syncrude Canada Ltd., Fort McMurray, AB.

McKenna, G.T. 2004b. Geo-environmental characterization of a large sulphur block at Syncrude: Results from the 2003 field investigation. Syncrude Canada Ltd., Fort McMurray, AB.


