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subject: Increasing the WIPP Shaft Seal Diameter: A Scoping Calculation to Estimate of the Impact on Hydrologic Performance

Background and Motivation

This memo addresses the question of whether enlarging the new utility shaft at the WIPP by approximately 30% in diameter will have an appreciable effect on the sealing function of the WIPP Shaft Seal design. The current WIPP Shaft Seal System contains four shafts seals (exhaust, intake, salt handling, and waste) that were designed for a maximum diameter of 22 feet (WIPP CCA Appendix Seal). A critical question is if there is an effect on hydrologic seal performance associated with increasing the seal diameter beyond 22ft. While a detailed, comprehensive analysis is the *de facto* method to make a detailed response to such a question, a simplified engineering analysis is employed in this document to provide an order of magnitude estimate to address the question.

The change proposed for the WIPP Shaft Seal System diameter is related to the addition of an additional exhaust, needed to meet the ventilation needs of WIPP in the period after the radiologic release event of 2014. It is proposed that this shaft be constructed with a shaft diameter of 28 feet in the upper and lower sections and 30 feet in diameter in the middle section– see Zeitler 2019 for more details. Because the analysis method employed in this document is to within an order of magnitude, the dimensional difference is approximated as 30% or a factor of 1.3. Within this document, caveats are provided, where appropriate, that indicate the upper bound associated with the diameter increase to 30 feet, which translates into 36% or a factor of 1.36.

Objective and Assumptions

The objective of this memo is to provide an order of magnitude estimate to assess Resource Conservation and Recovery Act (RCRA) concerns and RCRA timescales associated with a 30% larger shaft seal diameter. In the context of WIPP, the RCRA timeframe covers a 300 year time period. The analysis herein assumes that the stratigraphy remains the same between the two different sizes of shaft seal diameter. It is also assumes that the radial extent of the DRZ is proportional to the radius of the borehole excavation (Hou 2003, Perras and Diederichs 2016), such that the annular flow region width (see Figure 1 below) in the flow region of R_{new} is slightly larger than R_0. As a consequence of this assumption, the aperture width remains constant relative to the diameter of the seal (for details, see Appendix).

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The Multi-Barrier WIPP Shaft Seal Design

The shaft seal design at WIPP (WIPP CCA Appendix SEAL, Hansen and Knowles 1999) is a multi-barrier system that contains alternating layers of seal elements, which function together with the express purpose of providing engineered redundancy if one (or more) of the layers suffer some sort of catastrophic failure outside of the predicted service conditions. In this way, the shaft seal system can sustain failure in certain layers, such that the overall transport and flux of radionuclides from the repository and upwards through the shaft remains low and does not represent a significant contribution to overall releases.

Generally speaking, the weakest aspect of any subsurface seal, especially a multi-barrier design such as the WIPP Shaft Seal System, will not be in the matrices of the seal materials themselves, but at the interfaces between the Disturbed Rock Zone (DRZ) of the host and/or stratigraphic lithofacies and the seal matrices. In other words, the greatest risk for fluid transport (i.e. leakage) through the seal system will be at the interface between seal layer matrices and the rock. The reason for this is two-fold: 1) there may be incomplete bonding between seal materials and the surrounding rock such that there is a zone of higher permeability at the interface, and 2) there is also a zone of increased permeability – relative to the intact rock – in the DRZ, such that it could, in theory, compromise the seal integrity of the seal system and/or serve as a preferential flow pathway that instigates catastrophic failure of the seal system. This is an **extremely unlikely event** given the unsaturated/minimally saturated geologic environment of the WIPP. However, the WIPP CCA Appendix SEAL describes this scenario as the major hydrologic seal system failure, and also presents calculations using Darcy's Law, and design mitigations to address this scenario.

Analysis Approach and Results

For the purposes of performing a simple engineering analysis on the effect of increasing a circular shaft seal diameter, we take this failure mechanism as an example scenario of seal failure that can be used as a basis of comparison. That is, the flow rates for this scenario can be calculated for preferential flow along an annular region at the seal-DRZ interface. A schematic of this domain for the flow calculations is provided in Figure 1.

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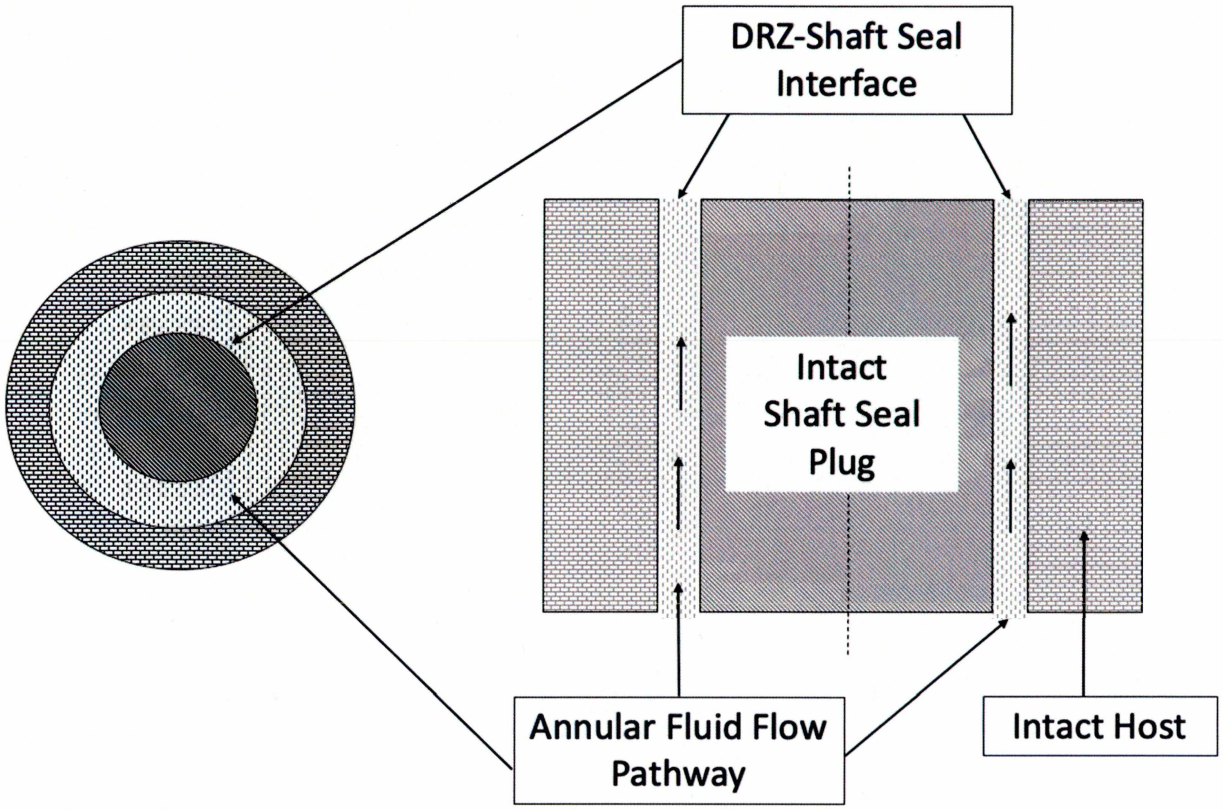


Figure 1. Schematic conceptualization of the annular flow pathway used for the scoping calculations of flow rate (not to scale). On the left-hand side of the figure, an axial cross-sectional view is illustrated, showing the annular flow pathway at the seal-DRZ interface. The right-hand side of the figure shows a lateral cross-section.

For a given shaft seal diameter, R, a corresponding volumetric flow rate, Q, can be calculated. The impact of a change in R, from R_0 to R_{new}, can be quantified by looking at a normalized volumetric flow rate, Q_{new}/Q_0.

A simplified three-dimensional case of the Navier-Stokes Equation, the so-called Hagen-Poiseuille Equation, can be used to simplistically analyze the case where there is preferential flow at the seal-rock interface in an annular geometry (for more details, see Appendix). Remarkably, the ratio of calculated flow rates in an annular leakage pathway in a cylinder, reduces to a simple equation:

$$\frac{Q_{new}}{Q_0} = \left(\frac{R_{new}}{R_0}\right)^4 \quad (1)$$

This result can be used to show that the effect of increasing the shaft seal diameter, as shown in Figure 2.

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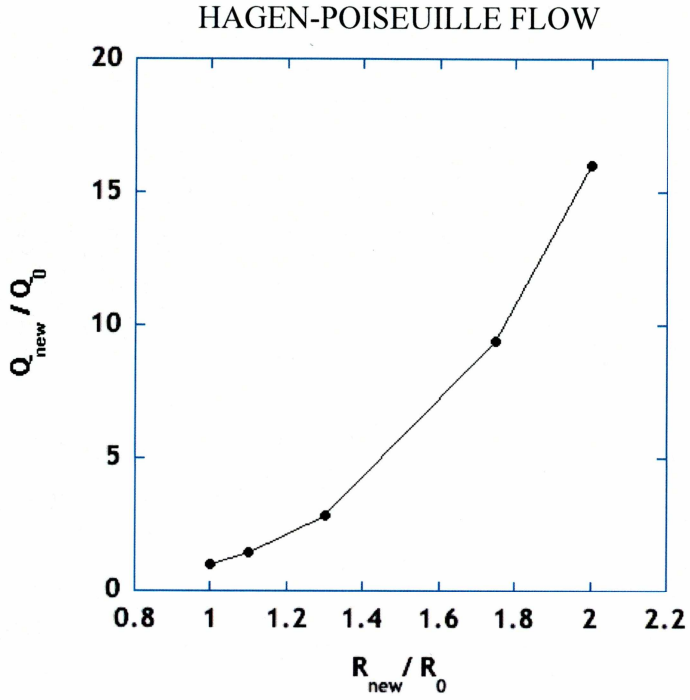


Figure 2 – A plot of normalized volumetric flow rate vs. radii ratio, using the Hagen-Poiseuille Equation.

Figure 2 shows that for an R_{new}/R_0 value of 1.3 – equivalent to a 30% increase in shaft radius – the volumetric flow rate increases by a factor of 2.856, which reflects the 4th power of the 1.3.[1] One could estimate that in order to have a meaningful effect on the estimated repository performance, a shift of at least 1-2 orders of magnitude in transport rates (e.g. Darcy velocity) would be required (Dverstorp et al. 1996). For EQ-1, an order of magnitude change to Q would be achieved at R_{new}/R_0 of ~1.778 (the 4th root of 10), a ~78% increase of the shaft seal dimension. Two orders of magnitude effects would require a 3-fold increase of shaft radius. The flow predictions using Hagen-Poiseuille introduce a fair degree of conservatism, since it is a purely advective flow in an annular flow path at the interface between the seal and the DRZ. This approach is conservative, since the WIPP shaft seal design contains multiple barriers for the distinct purpose of eliminating this scenario (Appendix SEAL).

A less conservative analysis can be performed using Darcy's Law. The plot of normalized, volumetric flow rate, Q^{D}_{new}/Q^{D}_{0}, can be derived from Darcy's Law in a similar manner to the derivation of EQ-1 (see Appendix for derivation), resulting in

$$\frac{Q^{D}_{new}}{Q^{D}_{0}} = \left(\frac{R_{new}}{R_0}\right)^2. \qquad (2)$$

Notice that this expression has a similar form to EQ-1, such that a plot for $\frac{Q^{D}_{new}}{Q^{D}_{0}}$ vs. $\frac{R_{new}}{R_0}$ can be constructed, as is done in Figure 3.

[1] For the upper bound of this factor relevant to the problem at hand, increasing the shaft seal diameter from 22 feet to 30 feet, this factor is 1.36^4 ~ 3.4

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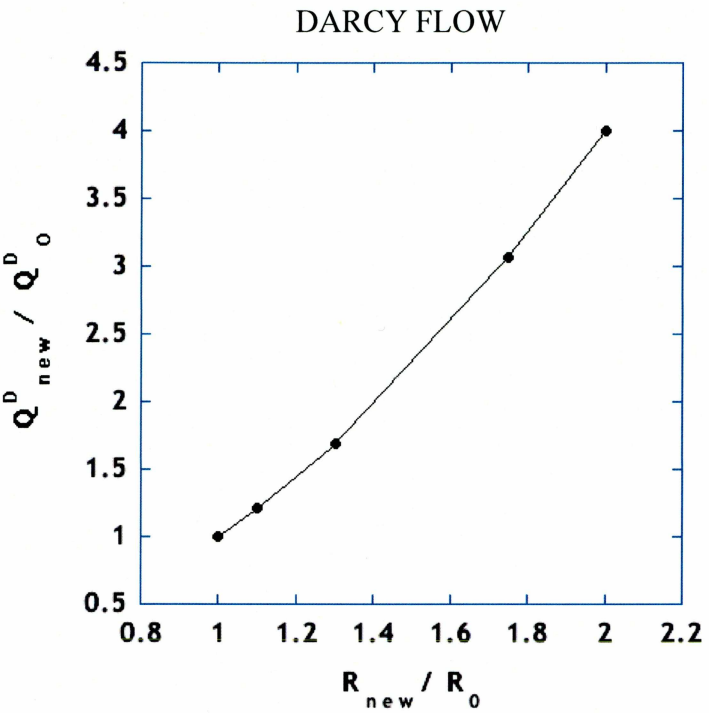


Figure 3 – A plot of normalized volumetric flow rate vs. radii ratio, using the Darcy's Law.

As was done with EQ-1, conclusions can be drawn from EQ-2 and Figure 3, i.e., the increase in flow rate will be a parabolic function of the form $y = x^2$. A 30% increase in shaft dimension will result in a 1.69^2 times increase in Q.

While the Hagen-Poiseuille Equation provides an estimate that is very conservative, the Darcy's Law derived change in flow rate arguably may underestimate the flow rate changes as a function of $\frac{R_{new}}{R_0}$. The Hagen-Poiseuille Equation overestimates the effect because it represents a completely unhindered, advective flow pathway, while Darcy's Law represents a hindered flow pathway through a porous media. A more detailed examination of the reasons for the differences between EQ-1 and EQ-2, as well as a brief discussion, can be found in the Appendix. It can be assumed that the "actual" change in flow rate is bounded by the results of each equation – bounded on the low end by Darcy's Law and on the high end by Hagen-Poiseuille. Since both equations can be derived from the Navier-Stokes Equation (Bear 1976, Greenkorn 1984, Whitaker 1986), it seems reasonable to compare the results of these two equations to the problem at hand.

As mentioned, it is expected that changes to flow rate that are less than an order of magnitude are likely to be negligible relative to overall seal performance. This assertion can be bolstered by examining some expected flow rates considered by the WIPP safety case. According to an analysis by Day et al. (2019) projected brine and gas flow rates are on the order of 10^0-10^3 m^3 per 10,000 years for the six performance scenario at WIPP. It reasonable to assume that the Day et al. (2019) report provides bounding conditions on the range of flow rates through the shaft seal, and that these values will range over a few orders of magnitude. This range of values for flowrate and the variability for flow values from Day 2019 are also on the same order of magnitude for hydrologic seal performance values given in the WIPP CCA (Appendix SEAL C).

[2] For the 36% increase, representing an increase of shaft diameter to 30 feet, this factor is 1.36^2 ~1.85

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Conclusions

The above scoping calculations show that a 30% increase in shaft diameter could result in a roughly 2X to 3X increase in flow rate. Given the several orders of magnitude variance in the projected WIPP flow rates in the shaft seal, it is reasonable to assume that the increased shaft diameter will not significantly impact mass transport calculations for the performance scenarios at WIPP.

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Appendix

Some basic assumptions contained in the analysis are:

- The DRZ has the same permeability and vertical critical length scales for dimensionless numbers, i.e., Reynolds number and Darcy's Law parameters. The critical length scale length is assumed to be parallel to the axial length of the shaft seal.
- The aperture width is assumed to scale with diameter.
- Thermal effects are negligible.

As derived in Bird, Stewart, and Lightfoot (2002), the mass flow rate for the Hagen-Poiseuille Equation for Flow through an Annulus (p.55, 2.4-17) can be divided by ρ, fluid density, to yield, Q, the volumetric flow rate, such that:

$$Q = \left(-\frac{\Delta P \cdot R^4}{8\mu L}\right)\left[(1-\kappa^4) - \frac{(1-\kappa^2)^2}{1-\ln(1/\kappa)}\right] \quad \text{(A.1)}$$

where ΔP is the axial pressure difference, R is the outer radius of the annulus, μ is the dynamic fluid viscosity, L is the axial length of the annulus, and κ is the ratio of the inner : outer radii of the annulus. Sine we have assumed that aperture width scale with diameter, κ remains constant for the initial and new diameter.

Knowing that $R_{new} = 1.3 \times R_0$, and to normalize the new velocity of the larger shaft seal, using A.1, we can divide Q_{new}/Q_0, cancel terms, and arrive at:

$$\frac{Q_{new}}{Q_0} = \left(\frac{R_{new}}{R_0}\right)^4 \quad \text{(A.2)}$$

For $R_{new}/R_0 = 1.3$, a 30% increase in shaft radius, we see that $\frac{Q_{new}}{Q_0} = 2.856$.

For Darcy's Law, the derivation starts with:

$$Q^D = -\frac{k \cdot A \cdot \Delta P}{\mu L}, \quad \text{(A.3)}$$

where Q^D is the volumetric flow rate associated with Darcy's law, k is the permeability, and A is the annular cross-sectional area. Substituting $A = \pi R^2(1-\kappa^2)$, dividing Q^D_{new}/Q^D_0, and cancelling terms, becomes:

$$\frac{Q^D_{new}}{Q^D_0} = \left(\frac{R_{new}}{R_0}\right)^2. \quad \text{(A.4)}$$

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In Darcy's Law the inertial (frictional) fluid losses from the conduit walls are incorporated into the permeability, which captures the interaction of the fluid with the pore walls of the porous media in a manner that is independent of the radius and depends solely on A. These losses are distributed across the entire cross-sectional area via the distribution of pore walls. Because of this distribution of inertial forces, the Darcy's Law solution doesn't reflect the geometry beyond the cross-sectional area, such that if you had two differently shaped domains with equal cross-sectional, the same solutions would be obtained. In contrast, the Hagen-Poiseuille Equation incorporates the geometry into the calculation of inertial (frictional losses), such that the calculation of these forces, as well as the ensuing calculation of fluid velocity and flow rates, may differ for different shaped domains, even if the cross-sectional areas are equivalent.

It is also worth mentioning that while a range of flow conditions could necessitate more specialized analyses, e.g. Forscheimer or Brinkman terms added to Darcy's Law or a more generalized version of the Navier-Stokes Equation, most of those corrections would reduce the overall transport rates (for a given pressure drop, say) and in many or most cases, impact R_0 and R_{new} almost equally.

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