Terminal Sinking Velocity for Waste Packages Falling in a Deep Borehole - 17063

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ABSTRACT

This evaluation of terminal velocity for a waste package sinking in a deep borehole filled with emplacement fluid was done to support concept development for the Deep Borehole Field Test (DBFT). The DBFT objective is to evaluate the safety and feasibility of the deep borehole disposal (DBD) concept for certain radioactive wastes. The DBD concept calls for emplacing waste packages in the lower 2 km of a borehole drilled into crystalline basement rock to a depth of 5 km. Previous studies identified that accidentally dropping one or more waste packages during emplacement could be an important risk, particularly if a waste package is breached. This study evaluated the range of terminal sinking velocity, which can be used to design waste packages and impact limiters to ensure that breach does not occur.

Based on an analytical model of a sinking container, a highly turbulent flow is expected to develop in the emplacement fluid. Turbulence is a complex three-dimensional phenomenon and the applicability of analytical models is limited. To backstop the analytical model and to extend predictions to other package dimensions and fluid properties, numerical simulation was performed using the ANSYS Fluent computational fluid dynamics code.

Terminal velocity was calculated for downhole temperatures up to 120^{0}C, and three emplacement fluids (water, NaCl brine, and NaBr brine). Simulation results confirmed that flow around the sinking container is highly turbulent (Reynolds number 5.6×10^4 to 7.3×10^5). Turbulence increases with temperature and decreases with density.

Calculated terminal velocity ranges from 1.95 (20^{0}C) to 2.13 m/s (120^{0}C) in water; 1.61 (20^{0}C) to 1.79 m/s (120^{0}C) in NaCl; and 1.30 (20^{0}C) to 1.46 m/s (120^{0}C) in NaBr. Terminal velocity is inversely related to fluid density, and the temperature effect on density appears to have a stronger effect on terminal velocity than the temperature effect on viscosity.

The foregoing results are for non-perforated casing, but in practice the casing may be perforated to prepare for cementing, and to allow relief of fluid pressure from thermal expansion after emplacement of heat generating waste, and after final borehole closure. To represent the effect from perforations, the analytical solution was modified to include bypass flow through perforations and in the annulus. A workable perforation scheme is identified, consistent with borehole construction and closure requirements, using 2-cm and 5-cm diameter perforations. This scheme is estimated to limit the terminal velocity to 3 m/s, for reference waste packages falling in water at 40^{0}C.

INTRODUCTION

Evaluation of terminal velocity for a waste package sinking in a deep borehole filled with emplacement fluid was done as part of the Deep Borehole Field Test (DBFT) [Ref. 1]. The test objective is to evaluate the safety and feasibility of deep borehole disposal (DBD) for certain radioactive wastes. Previous studies selected a method of emplacing waste packages by lowering on electric wireline, and identified that accidentally dropping one or more waste packages during emplacement could be an important risk, particularly if a waste package is breached. Terminal sinking velocity is needed for design of waste packages and impact limiters to ensure that breach does not occur if a package is dropped.

An analytical model for a sinking container, validated by laboratory experiments, was used to estimate terminal velocity of 2.37 m/s (at surface temperature) and 2.6 m/s (at 120°C, representing bottom-hole temperature) for a cylindrical waste package. Reference size and weight for this calculation are 28-cm diameter, 5-m length, and weight corresponding to 2,100 kg mass [Ref. 2]. The analytical model was also used to estimate terminal velocity in an open body of fluid assuming stable vertical orientation while sinking, at 11.51 m/s. The Reynolds number for this velocity range, and geometry and fluid properties, is 1.1×10^5 to 5.4×10^5. Thus, the flow regime for waste packages sinking in casing is highly turbulent.

Turbulence is a complex three-dimensional phenomenon and the applicability of analytical models is limited. To backstop the analytical model and to extend predictions to other package dimensions and fluid properties, a numerical computational fluid dynamic (CFD) model was developed using the ANSYS Fluent computational fluid dynamics code [Ref. 3]. The numerical model assumes non-perforated casing. In practice, the casing may be perforated to prepare for cementing, and to allow relief of fluid pressure from thermal expansion after borehole closure. The estimate in Ref. 2 was for non-perforated casing, whereby fluid displaced by downward package movement flows upward through the gap between the package and the casing. To represent the effect from perforations, the analytical solution was modified to include bypass flow as a function of pressure drops associated with flow through perforations and flow in the annulus behind the casing.

MODELING APPROACH AND SETUP

The 2-D axisymmetric numerical model was developed using the ANSYS Fluent 16.2 CFD code. The shear-stress transport (SST) k-ω model in Fluent was selected because of its suitability for highly turbulent flow with significant wall or boundary effects [Ref. 4-6]. The presence of walls at the waste package and casing surfaces gives rise to turbulent momentum with the steepest variation in the near-wall regions, and the variation is represented by the k-ω models. Adequate modeling of near-wall regions is important because frictional drag and the distribution of fluid pressure depend on the local shear at solid boundaries.

In the modeling framework the waste package was held stationary and the borehole casing moved with specified constant velocity, with fluid flow between them. Terminal velocity was estimated by changing relative velocity until the drag force equaled the package weight. The two-dimensional, axisymmetric model incorporated a steady-state turbulence approximation. Constant fluid velocity was specified at the lower boundary and a pressure outlet condition was specified at the upper boundary.

Figure 1 represents how the conceptual model of package sinking was translated into the numerical model. The numerical model domain radius is equal to 0.16 m corresponding to the casing ID. The package with radius of 0.14 m and length of 5.64 m is centered.

Fluid flow next to the package is restricted to the gap between the package and the casing. Fluid flow below and above the package is restricted by the casing. Note that the weight of the package (4,620 lb) is not a direct input into the model. The total forces acting on the package are calculated for the different velocity values and compared to the package weight to determine if the terminal velocity is reached. Also shown in Figure 1 is a close-up of the model mesh. All the regions close to the package and casing walls have fine discretization to represent boundary layers.

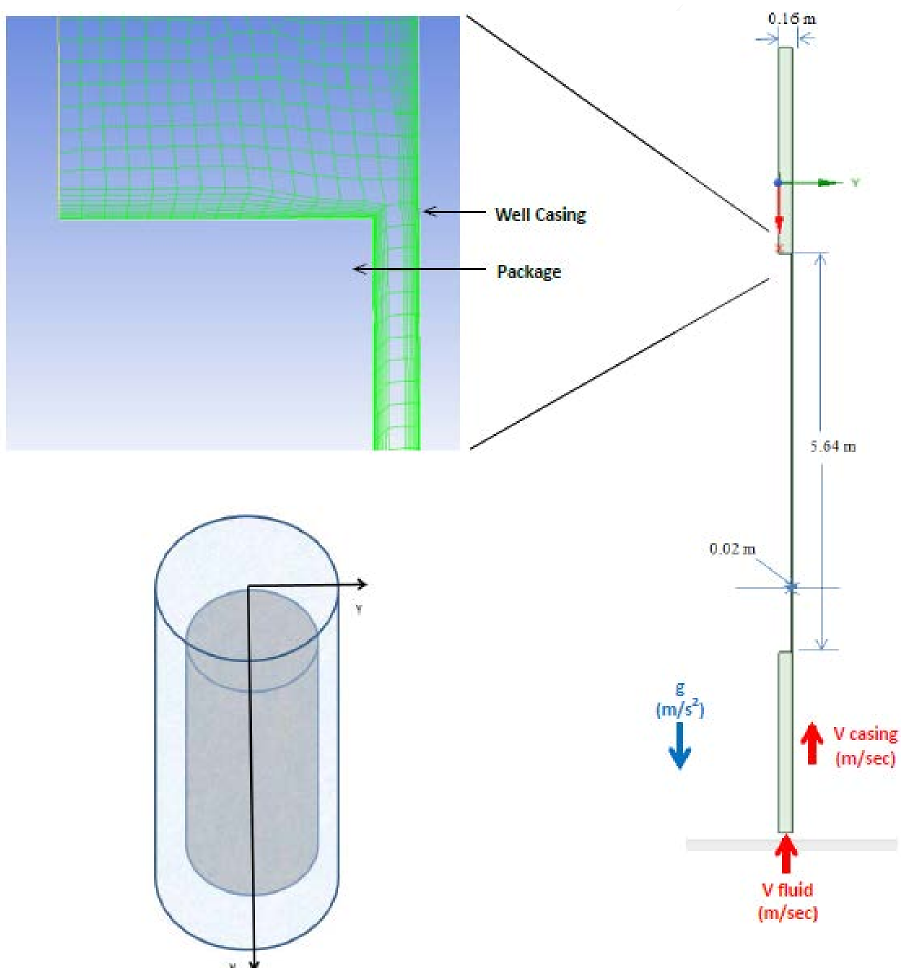


Fig. 1. CFD Modeling Setup.

The model shown in Figure 1 was modified to simulate different gap widths. A gap of 7.6 cm was used to represent the condition in which the effects of casing are negligible and fluid flow is controlled by the gap between the package and the borehole wall. Gaps of 4, 6, and 9 cm were considered in comparing numerical and analytical solutions.

The fluid properties needed for the model are density and dynamic viscosity. Because these properties change with temperature and pressure, a few calculations were done to represent the temperature and pressure range applicable to the borehole condition (ranging from 20°C to at least 120°C, and 0 to 65 MPa hydrostatic pressure). Water was chosen for a lower bound on the density and viscosity, and two brines were selected to represent upper bound behavior. Brines were recommended as emplacement fluids for compatibility with formation fluid [Ref. 1].

The brines considered were: 300 g/L sodium chloride (NaCl) representing a highly concentrated natural brine, and 40% sodium bromide (NaBr) as an upper bound. Sodium bromide is used in oilfield applications by itself or in combination with sodium chloride to make up workover and completion fluids with density up to 1,527 kg/m^3 [Ref. 7]. Note that temperature effects on brine density are much greater than pressure effects.

MODELING RESULTS

Two options were evaluated for the casing: non-perforated and perforated with circular holes distributed vertically.

Terminal Velocity in Non-Perforated Casing

The CFD model was used for the simulations in the non-perforated casing. The results of the terminal velocity calculations in three emplacement fluids are summarized in Table I. Table I also provides the calculated pressure drag and viscous drag forces expressed as percent of the total force acting on the package, and the maximum Reynolds number in the model domain.

TABLE I. Results of Terminal Velocity Calculations in Non-Perforated Casing.

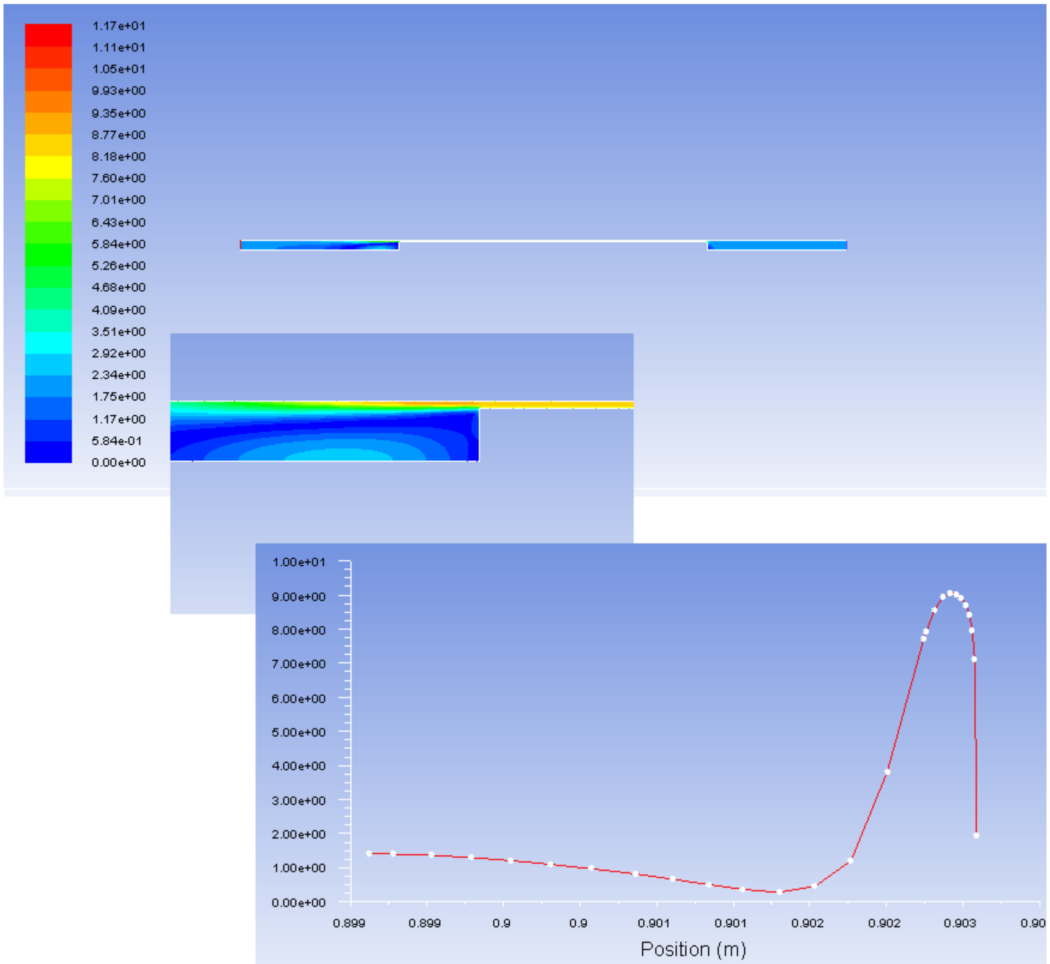
Fluid	Terminal Velocity (m/s)	Temperature (°C)	Pressure Drag	Viscous Drag	Maximum Reynolds Number
Water	1.95	20	95.1%	4.9%	1.67E+05
	1.99	40	95.3%	4.7%	2.57E+05
	2.073	80	95.5%	4.5%	4.74E+05
	2.13	120	95.6%	4.4%	7.22E+05
NaCl	1.61	20	95.5%	4.5%	1.11E+05
	1.66	40	95.7%	4.3%	1.66E+05
	1.71	80	95.8%	4.2%	2.56E+05
	1.79	120	95.9%	4.1%	4.51E+05
NaBr	1.3	20	96.0%	4.0%	5.58E+04
	1.35	40	96.1%	3.9%	8.61E+04
	1.42	80	96.2%	3.8%	1.77E+05
	1.46	120	96.2%	3.8%	1.99E+05

The terminal velocity in water ranges from 1.95 m/s (20°C) to 2.13 m/s (120°C) with slight temperature dependence (about 10%) over the range. Terminal velocity in brines is less than in water, with similar temperature dependence: for NaCl the range is from 1.61 (20°C) to 1.79 m/s (120°C), and for NaBr the range is from 1.30 (20°C) to 1.46 m/s (120°C).

The main force acting on the package is the pressure drag (also known as form drag, about 95% of total force on the waste package). The sinking package generates upstream-downstream total pressure difference of 65 kPa (NaBr) to 90 kPa (water) at steady state. The total pressure above the package is hydrostatic, while that below the package is hydrostatic plus the pressure difference.

Viscosity has only a minor effect on sinking velocity, and the effect of viscosity (viscous drag force) is inversely related to fluid density. Lower viscosity with increasing temperature causes greater turbulence, while turbulence in brines is less than in the water.

Figure 2 shows contours of velocity in the r-z plane, and a radial profile of axial velocity, in the wake of the package (above) sinking in water at 20°C. The fluid velocity ranges from 0 to 9 m/s. The highest velocities are in the middle of the gap between the package and the casing. The complex distribution of the velocities above the package is due to turbulence in the wake.



NOTE: Upper - velocity contours in the r-z plane. Lower - radial profile of axial velocity.

Fig2. Distribution of Fluid Velocity (m/s) in Water at 20°C.

Bounding Estimate of Terminal Velocity in Perforated Casing

Lower and upper limits for the terminal velocity in perforated casing can be estimated from the numerical CFD models. The lower limit (1.95 m/s in water at 20^{0}C) corresponds to non-perforated casing. The upper limit (7.0 m/s) corresponds to casing that is perforated to the extent at which its presence can be ignored. In this case, the gap is the distance between the package and the borehole wall (7.6 cm).

The actual range of terminal velocity will be between the lower and upper limit. This is because a waste package falling through perforated casing will cause bypass flow along the annulus between the casing and borehole wall, so that the terminal velocity must be greater to provide the same pressure drag.

It was assumed that a terminal velocity of 3 m/s can be managed safely using impact limiters to arrest dropped packages without breaching. A more accurate estimate of the upper bound of the terminal velocity was needed to understand the conditions under which the 3 m/s limit can be achieved.

To represent the effect from perforations, the analytical solution in Ref. 2 was modified to include bypass flow as a function of pressure drops associated with flow through perforations and flow in the annulus. The total bypass flow was iteratively calculated for perforation diameters from 1 cm to 5 cm, and used to calculate the corresponding terminal velocities. This approach is based on bounding assumptions and may overestimate the increase in terminal velocity due to perforations.

There is a direct relationship between the number, size, and distribution of guidance casing perforations and the package terminal velocity. Figure 3 shows the calculated terminal velocity as a function of the number of perforations.

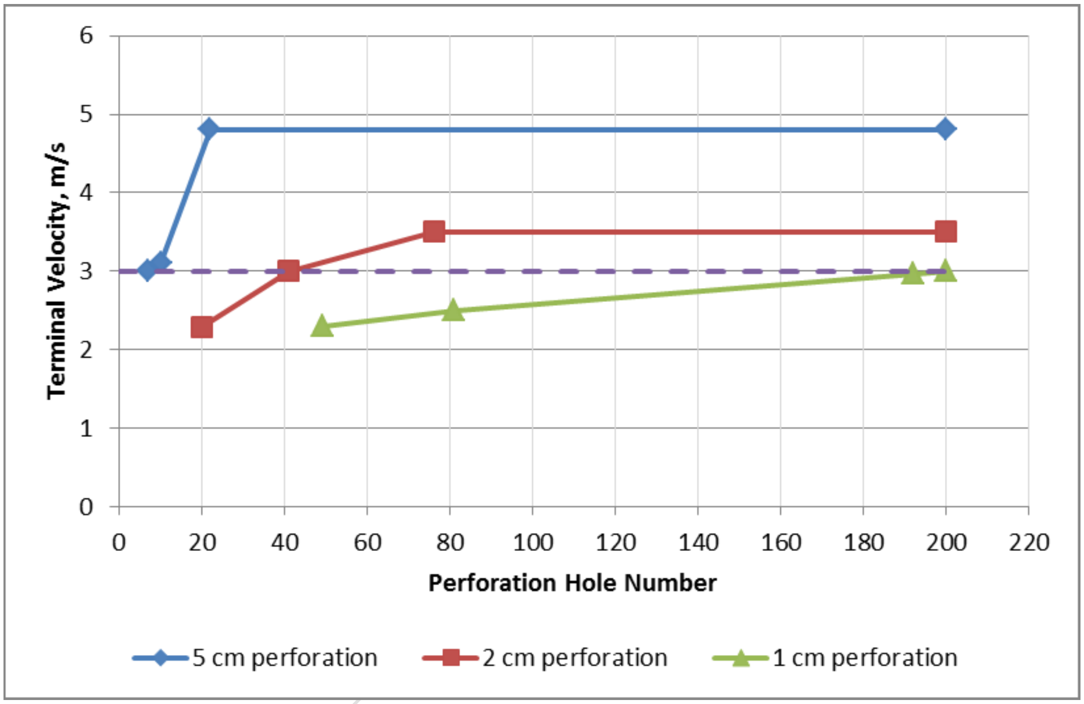


Fig. 3. Terminal Velocity as a Function of the Number of Perforations.

To limit terminal velocity to 3 m/s, no more than seven 5-cm perforations should be constructed in the 2 km long guidance casing. The terminal velocity rapidly increases with the number of holes until it reaches 4.8 m/s at 22 perforations. Additional perforations are predicted to have no impact on the terminal velocity.

For 2-cm perforations, the number should be fewer than 41 (in the 2-km guidance casing) to limit terminal velocity to 3.0 m/s. The terminal velocity increases with the number of holes until it reaches 3.5 m/s corresponding to 76 perforations. Additional perforations (more than 76) are predicted to have no impact on the terminal velocity.

The analysis also shows that 1-cm diameter perforations in any analyzed configuration will not increase the terminal velocity above 3 m/s

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Comparison with Analytical Solution

Figure 4 compares the terminal velocities calculated for the different gaps using the CFD model and the analytical model (Ref. 2). The larger the gap, the closer the analytical solution is to the numerical solution.

The difference between the analytical and numerical solutions can be explained by the difference in the velocity ratio, which is the ratio of the fluid velocity in the gap between the package and casing, to the terminal package velocity. The analytical solution assumes that the velocity ratio is a simple function of the package diameter and the gap size. The numerical solution calculates the velocities in the model domain using the turbulent model with a fine mesh, and predicts larger velocity ratios for the small gaps.

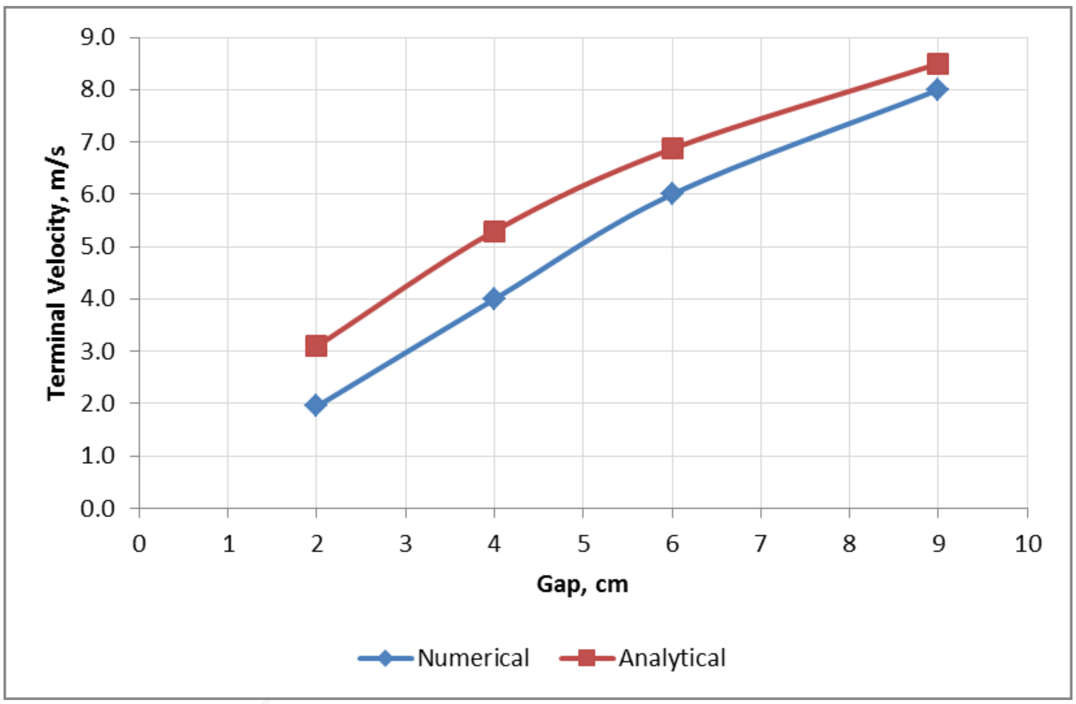

Figure 4. Terminal Velocity as a Function of Gap between the Package and Casing.

CONCLUSIONS

This study evaluated the range of terminal sinking velocity, which can be used to design waste packages and impact limiters to ensure that breach does not occur if the package is accidentally dropped during emplacement. Two conceptual casing designs, non-perforated and perforated with circular holes distributed vertically, were considered.

The calculated terminal sinking velocity assuming non-perforated casing varies with the fluid and temperature:

- Water: 1.95 (20°C) to 2.13 m/s (120°C)

• Sodium chloride brine: 1.61 (20°C) to 1.79 m/s (120°C)

• Sodium bromide brine: 1.30 (20°C) to 1.46 m/s (120°C)

The main force acting on the package is the pressure drag (about 95%). The terminal velocity increases slightly (by about 10%) at bottom-hole conditions mainly due to lower density.

Because the viscous drag is small, the decrease in viscosity with increased temperature has negligible effect on the terminal velocity. By analogy, use of viscosifying additives to the emplacement fluid would also have a negligible effect.

The reference design has a small gap (less than 2 cm) between the package and the casing. In this condition, the terminal velocity calculated with the numerical model is lower than the analytical solution. This is because the analytical solution underestimates the velocity of fluid in the small gaps.

An increase in terminal velocity due to casing perforations was estimated from a modified analytical solution, which includes the total flow that discharges from the casing into the borehole annulus.

Terminal velocities in perforated casing were calculated in water at 40°C, but calculated velocities in brines would be smaller. Importantly, the predicted terminal velocities for non-perforated casing are low (generally less than 2 m/s) allowing margin for increases in velocity with perforations.

For 1-cm perforations, the terminal velocity would be less than the target maximum velocity of 3 m/s regardless of the number.

For 2-cm perforations, the terminal velocity would be less than 3 m/s with approximately 40 or fewer perforations, which translates to perforation spacing of 50 m in the EZ (2 km). The maximum terminal velocity would be approximately 3.5 m/s.

For 5-cm perforations, the terminal velocity would be less than 3 m/s with seven or fewer perforations, which translates into perforation spacing of approximately 280 m in the EZ. The maximum terminal velocity would be approximately 4.8 m/s.

The estimated upper limit for terminal velocity in perforated casing is 7 m/s. This is based on using a gap of 7.6 cm between the package and borehole wall, and produces the result that the casing has little effect on the terminal velocity.

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