

Terminal Sinking Velocity for Waste Packages Falling in a Deep Borehole

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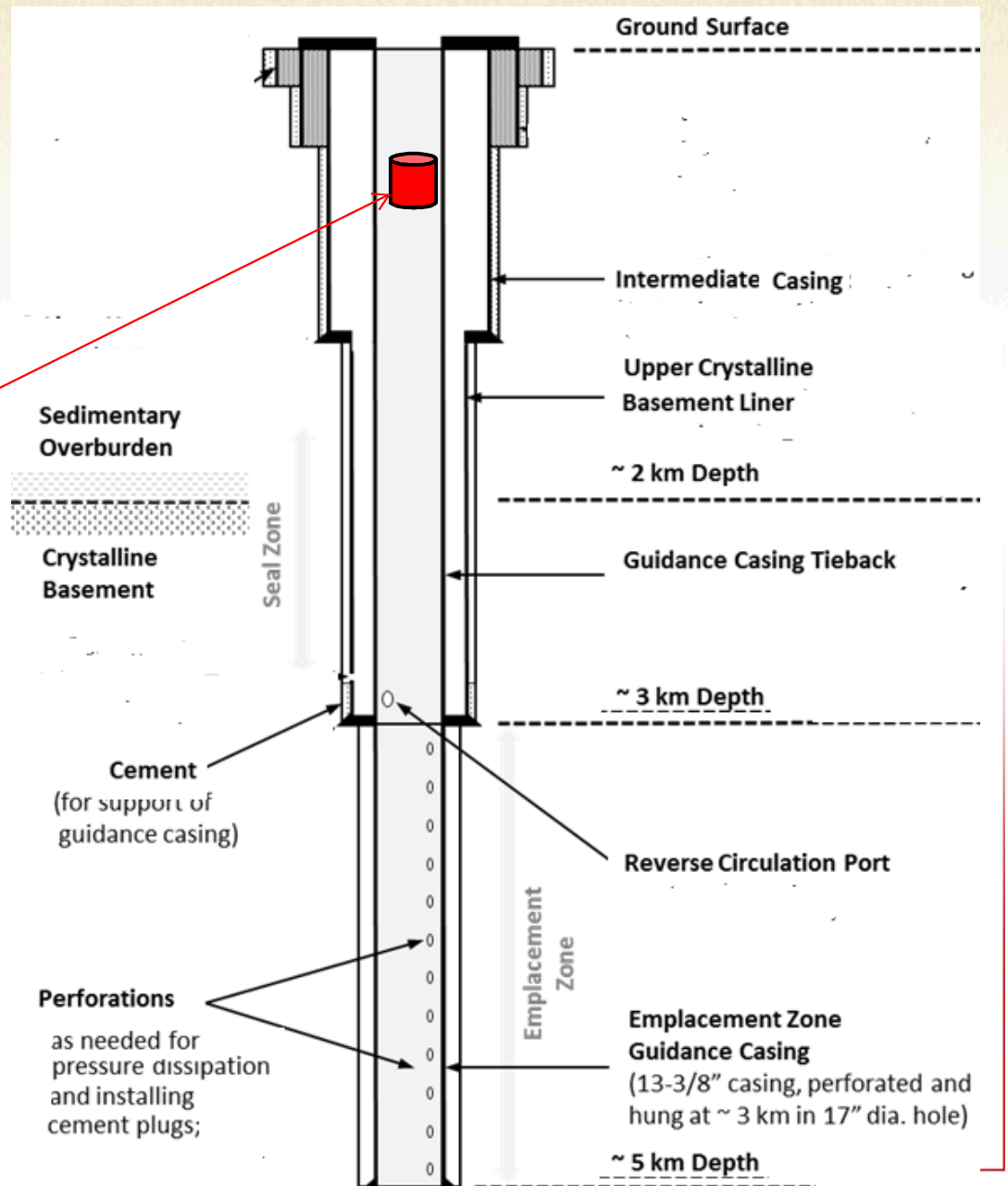
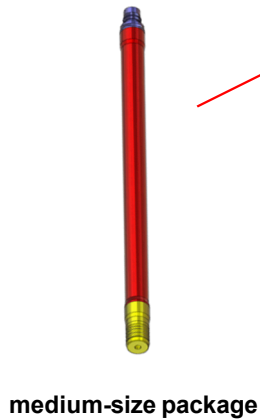
Phoenix, Arizona, March 5-9, 2017.

Introduction

- ❑ This analysis was a part of **Deep Borehole Field Test (DBFT)** program.
- ❑ **DBFT** objective is to evaluate the safety and feasibility of deep borehole disposal for certain radioactive wastes.
- ❑ The proposed method of waste package (WP) emplacement is lowering on electric wireline.
- ❑ Accidental drop of a WP could be an important risk, particularly if a waste package is breached.
- ❑ **Terminal sinking velocity** is needed for designing WPs and impact limiters to ensure that breach does not occur if a package is dropped.
- ❑ The numerical model was developed to overcome the limitations of the existing analytical solution and to extend predictions to different package dimensions and fluid properties.

Disposal Borehole Schematic

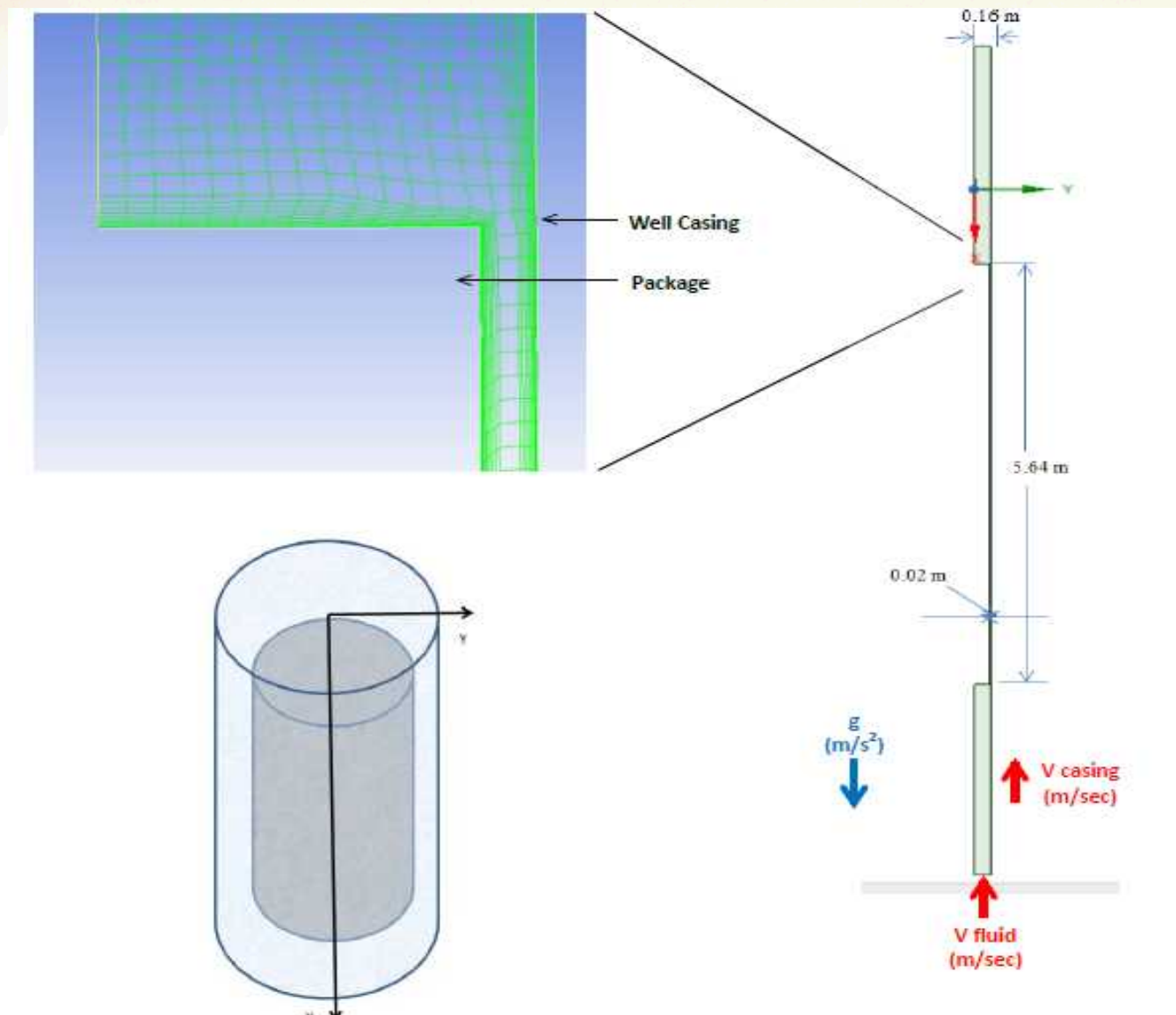
(not to scale)



Modeling Approach

- ❑ 2-D axisymmetric numerical model (ANSYS Fluent CFD code).
- ❑ Shear-stress transport (SST) $k-\omega$ for highly turbulent flow with significant wall/boundary effects.
- ❑ The WP was held stationary and the borehole casing moved with specified constant velocity with fluid flow between them.
- ❑ The casing perforation was not modeled.
- ❑ Terminal velocity was estimated by changing relative velocity until the drag force equaled the package weight.
- ❑ Constant fluid velocity was specified at the lower boundary and a pressure outlet condition was specified at the upper boundary.

Modeling Setup



Modeling Parameters

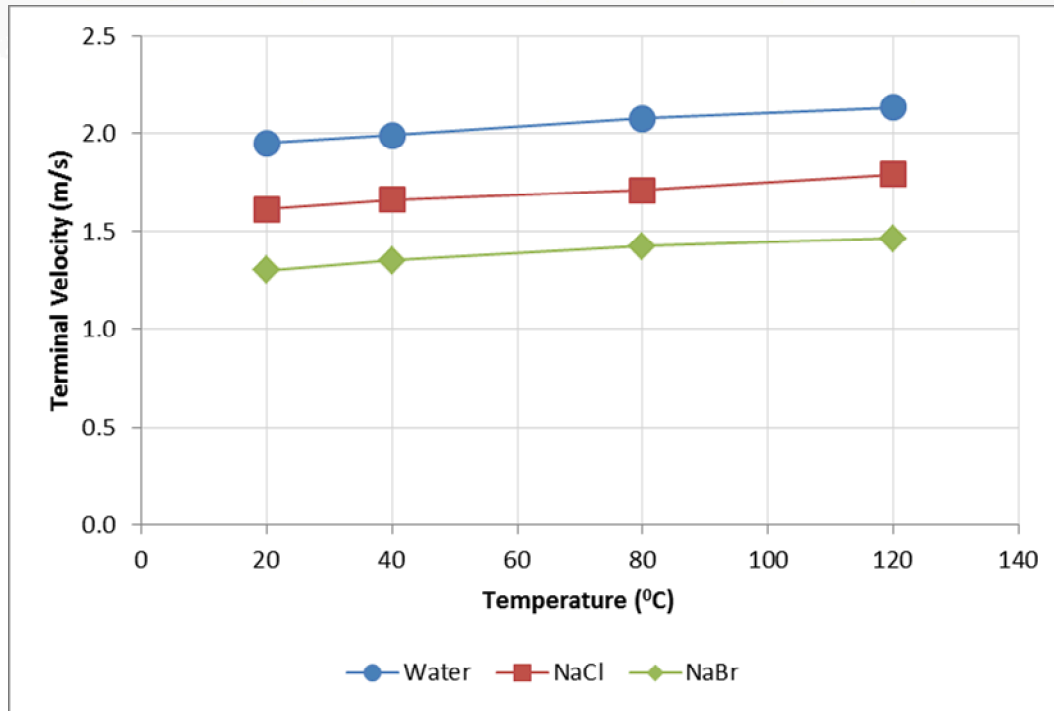
- ❑ The WP dimensions: **0.14 m** (radius) **5.64 m** (length).
- ❑ The WP weight: **4,620 lb** (not a direct input).
- ❑ The nominal gap between the package and the casing is **2 cm** (considered range – 2 cm to 9 cm).
- ❑ The gap between the casing and the borehole wall is **7.6 cm**.
- ❑ Temperature and pressure range applicable to the borehole condition: **20°C** to **120°C** and **0 MPa** to **65 MPa** hydrostatic pressure.
- ❑ Emplacement fluids: **water**; 300 g/L **NaCl** brine and **40% NaBr** brine.
- ❑ Fluid properties: density and dynamic viscosity (function of temperature and pressure).
- ❑ Temperature effects on water and brine density are much greater than pressure effects.

Terminal Velocity 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

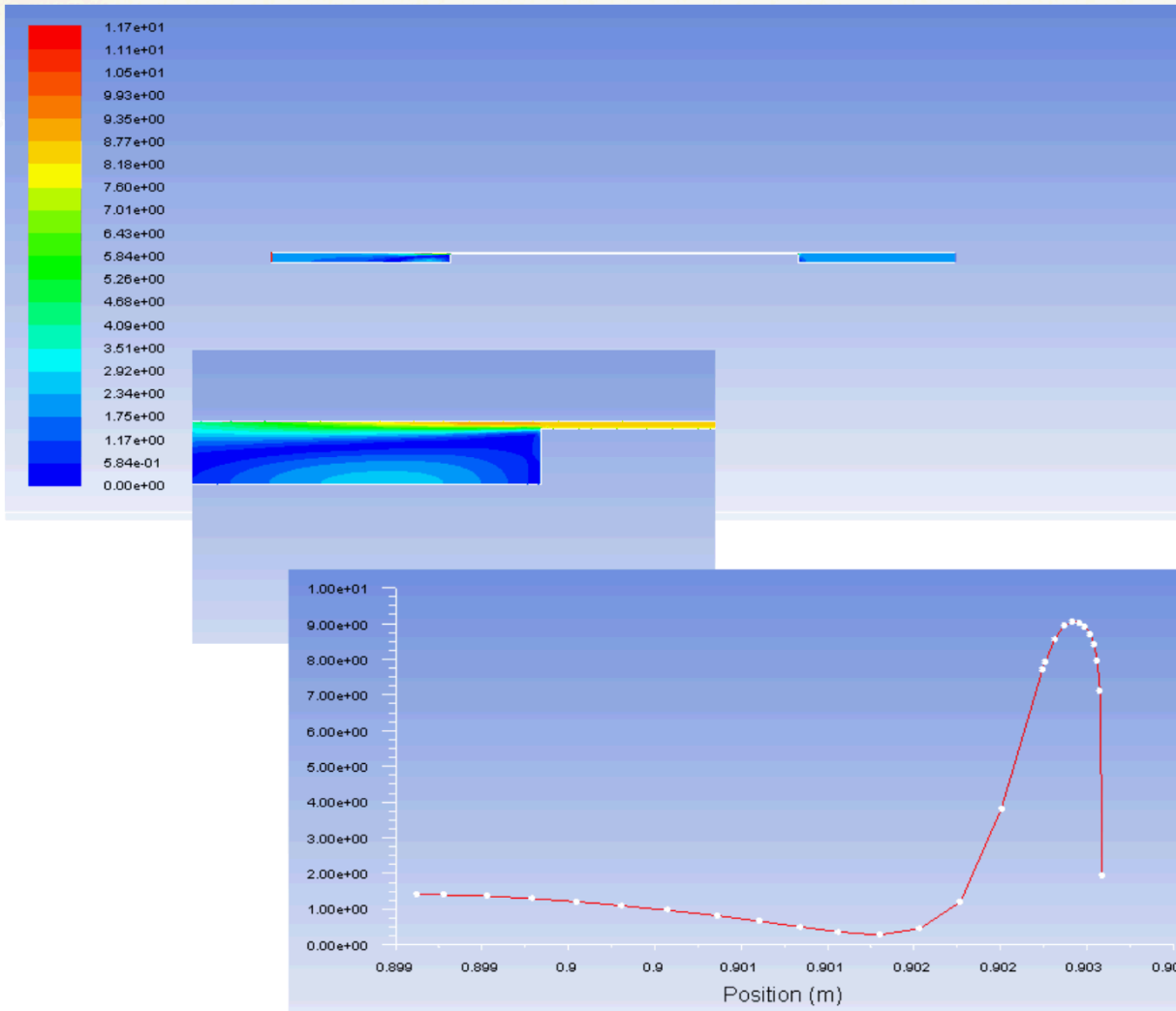
- ❑ The main force acting on the WP is pressure drag (~95% of total force).
- ❑ Viscosity has minor effect on sinking velocity, and the effect of viscosity is inversely related to fluid density.

Terminal Velocity in Different Emplacement Fluids



- ❑ Fluid density has major impact on the terminal velocity.
- ❑ Temperature impact is relatively small (~10% over the considered range).

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

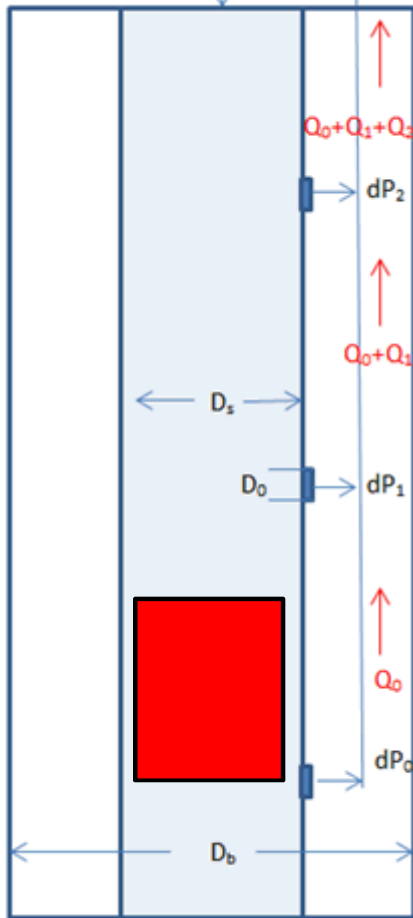


Bounding Estimate of Terminal Velocity in Perforated Casing

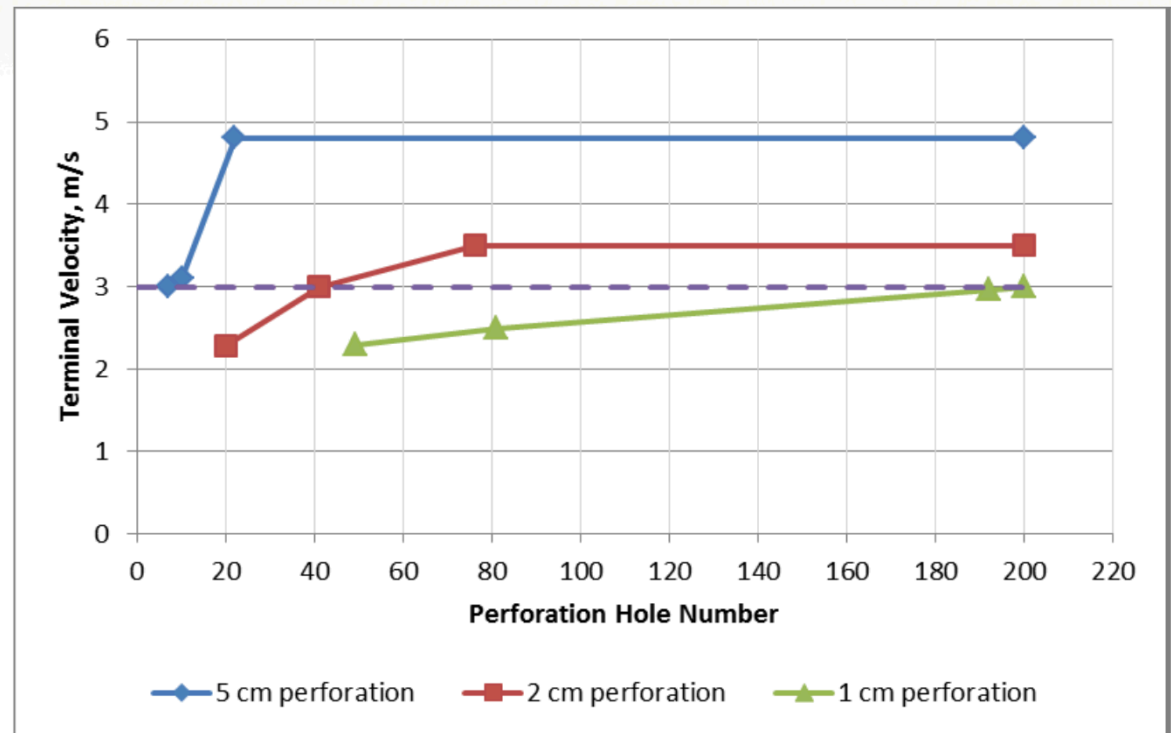
- ❑ The lower limit (**1.95 m/s**, water, 20°C) corresponds to non-perforated casing.
- ❑ The upper limit (**7.0 m/s**) corresponds to the case with no casing (**7.6 cm** gap between WP and the borehole wall).
- ❑ The actual terminal velocity in perforated casing will be between the lower and upper limit.
- ❑ WP falling through perforated casing will cause bypass flow along the well annulus.
- ❑ The bypass flow will depend on perforation and will increase the terminal velocity compared to non-perforated casing.
- ❑ It was assumed that **3 m/s** is “safe” terminal velocity (no WP breaching with impact limiters).
- ❑ Bounding estimate was needed to understand the conditions under which the 3 m/s limit can be achieved.

Terminal Velocity for Different Perforation Schemes

Conceptual Model of Bypass Flow



Terminal Velocity for Three Perforation Sizes

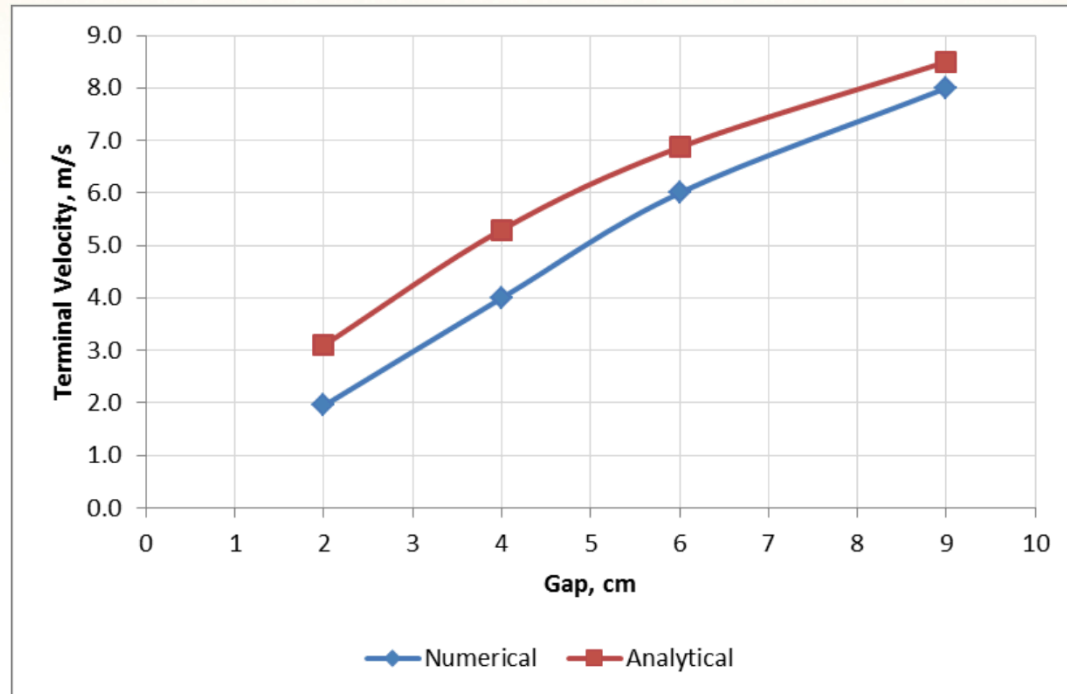


Acceptable Perforation Scheme ($v < 3$ m/s)

- Seven 5-cm perforations
- < 41 2-cm perforations
- Any number of 1-cm perforations

Comparison with Analytical Solution

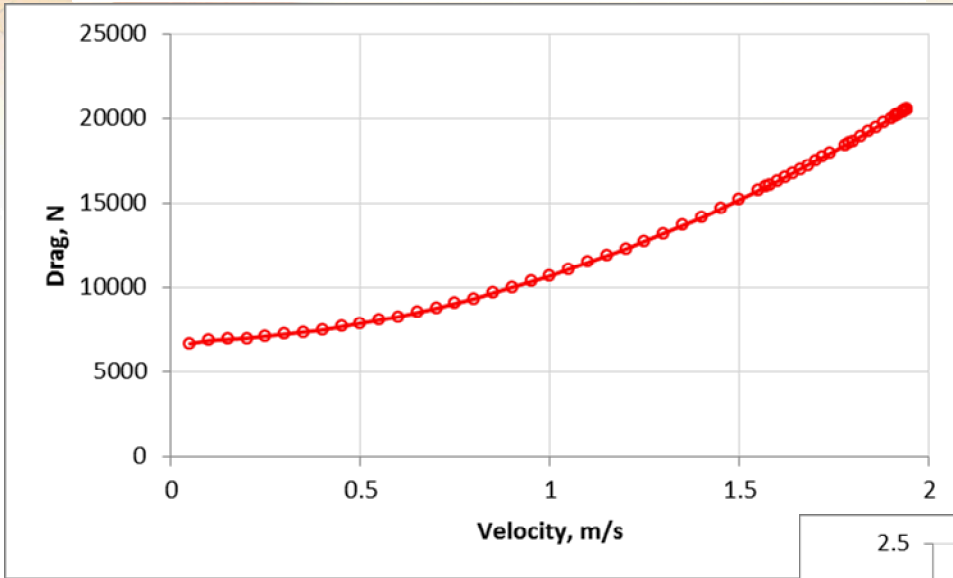
Terminal Velocity as a Function of Gap



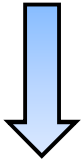
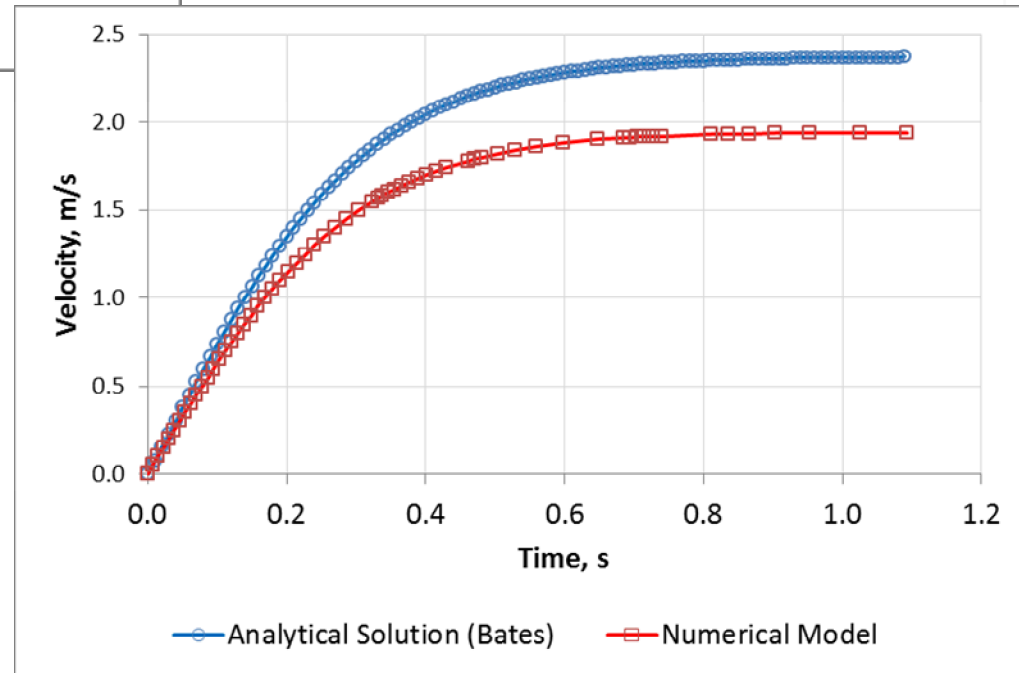
- ❑ The analytical solution assumes that the velocity in the gap is a function of the package diameter and the gap size.
- ❑ The numerical solution calculates the velocities using the turbulent model and predicts larger velocity in the gap for the small gaps.
- ❑ The larger the gap, the closer the analytical solution is to the numerical solution.

Time to Steady-State

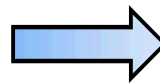
Total Drag Force (F) as a Function of Velocity



Velocity as a Function of Time



$$v^{i+1} = v^i + \frac{mg - F(v^i)}{m} \Delta t$$



Conclusions

- ❑ The terminal velocity in non-perforated casing is:
 - 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 WP is pressure drag (~ **95%**).
- ❑ The terminal velocity increases by ~ **10%** at bottom-hole conditions mainly due to lower density.
- ❑ The decrease in viscosity with increased temperature has negligible effect on the terminal velocity.
- ❑ Use of viscosifying additives would have a negligible effect.
- ❑ The analytical solution underestimates the velocity of fluid in the small gaps and overestimate the terminal velocity.
- ❑ Terminal velocities in perforated casing are higher and are affected by the perforation size and number of perforations.
- ❑ The time to reach the terminal velocity is ~0.8 s.