Plugging Nuclear Waste Pipelines: Impact of High Level Waste Slurry Characteristics and Pipe Diameter

M. Daas, R. Srivastava, P. Skudarnov

Applied Research Center

Florida International University

10555 West Flagler Street #2100, Miami, FL 33172

USA

ABSTRACT

The work presented here focuses on experiments carried out in 22-mm ID and 45-mm ID pipelines utilizing slurries composed of spherical glass beads having particle size distribution following the Rosin-Rammler distribution and mean size of 50 μm. The spreads of the distribution were 1.7 and 7, corresponding to wide and narrow distributions, respectively. The slurries utilized in this study had concentrations ranging from 5% to 25% by volume.

Results obtained in the same pipeline diameter indicated that the slurry of the narrower distribution experienced higher pressure drops and lower critical deposition velocities than those for the slurry of wider distribution. Pressure drop increased markedly with increasing slurry concentration regardless of the pipe diameter and slurry PSD. However, the pipe diameter was found to have more significant influence on the pressure drop than the slurry concentration does.

INTRODUCTION

An enormous amount of radioactive waste has been in storage for a long time. Most of this waste is stored in tanks and is transferred in a slurry form to treatment facilities. During transfer operations, however, the potential for solid particles to deposit along the pipeline is frequently present, due to physical and flow conditions, resulting in partial or sometimes full blockage. Partial blockage is commonly accompanied by heightened pressure buildup and eventually leads to full blockage. Blocked nuclear waste pipelines are considered hazardous and hard to repair. Consequently, most plugged nuclear transfer pipelines are abandoned.

The transport of solid-liquid slurries is frequently encountered and of great importance in many applications, such as the coal, oil and gas, and food industries. There is a large body of scientific literature devoted to transportation of solid-liquid slurries in pipes. Many references can be found in Govier & Aziz [1], Wasp et al. [2], and Brown & Heywood [3], to name a few. In the past, many correlations for friction losses and critical deposition velocity were developed to facilitate pipeline design or predict pipeline-operating conditions. It is generally agreed that solid particle size is an important parameter for solid-liquid multiphase flows, and most models and correlations take this parameter into account in terms of mean particle size, d_{50} (particles of such a diameter that 50% by weight of them are finer than d_{50}), or similar. However, the entire particle size distribution (PSD) is rarely taken into account with the exception of the Wasp model for pressure losses. In addition, most experimental studies report either median particle size or particle size range, without giving a detailed particle size distribution for the studied slurry. Recently, several researchers (Roco [4], Sundqvist et al. [5], and Allen [6]) have indicated the importance of inclusion of whole particle size distribution in models or experimental work. Nevertheless, to the best of the authors' knowledge, there is no systematic study on this subject.

A computational analysis along with experimental work, utilizing solid-liquid slurry of specific average mean diameter and particle size distribution, has been carried out to understand quantitatively the effects of pipe diameter on pressure drop and critical deposition velocity at which solid particles start to precipitate. The Wasp et al. [2] model and the Oroskar-Turian [7] correlation were applied to calculate pressure loss and critical deposition velocity, respectively. Other independent correlations were applied to incorporate slurry viscosity into the Wasp model. Calculated and measured values were compared for model validation purposes.

The slurry utilized in this study was a glass bead-water mixture. The solid particles had a median diameter of 50 μm, and their particle size distribution followed Rosin-Rammler distribution with two distinct spreads of distribution, wide and narrow. The slurry concentration varied in the range of 5% to 25% by volume, and the mean slurry velocity varied in the range of 0.7 m/s to 2.5 m/s.

EXPERIMENTAL SETUP

The system setup is shown in Fig. 1. Two flow loops of different pipe diameters were utilized in this study. The 22-mm ID flow loop consisted of a 30-gallon slurry tank, a 30-gallon water tank, a Moyno 1000 progressive cavity positive displacement pump, and 30 meters of stainless steel pipes. The pipelines had an outer diameter of 25.4 mm and an inner diameter of 22 mm. The schematic diagram of the loop is shown in Fig. 1. In the slurry tank, a mixer powered by an electric motor was installed to agitate the slurry mixture to obtain homogeneous solids distribution in the tank. The rotation rate of the mixer was monitored by an ACT-2A electronic tachometer from Monarch Instruments. The loop was equipped with a MAG 1100 MAGFLO® electromagnetic flow meter from EMCO, BL-15 and BL-25 gage pressure transmitters at the loop inlet and outlet, and Model 1151DP differential pressure transmitters in the horizontal sections of the loop. The gage pressure transmitters had a measuring accuracy of 0.1 psi. The differential pressure transmitters had a measuring accuracy of 0.3 in H_2O. The electromagnetic flow meter had a measuring accuracy of 0.16 l/min. Slurry concentration was measured through a monitoring system. This system consisted of a Coriolis mass-flow meter (F 050-Series by MicroMotion).

The 45-mm ID flow loop consisted of approximately 30 meters of stainless steel pipeline. The inside diameter of the larger pipe was twice the inside diameter of the smaller one. Tubing of the 45-mm ID flow loop was assembled parallel to the 22-mm ID flow loop on the same frame. This loop had a 30-gallon supply tank equipped with an electric mixer. Slurry was pumped through the loop with an HM50 centrifugal slurry pump from Svedala. The pump was equipped with variable speed drive in order to adjust the flow rate in the loop. The flow rate in the loop was measured by a MAG 3000 magnetic flow meter. The loop had two 6.1-m measuring sections over which the pressure drops were measured with differential pressure transmitters from Rosemount (Model 3051DP). The loop was equipped with two Model 1151 GP gage pressure transmitters also from Rosemount, one gage transmitter near the inlet and the other near the discharge of the loop. The loop had a 1-ft transparent section for critical deposition velocity measurements. All flow loop instrumentation was connected to a data acquisition system from National Instruments, which facilitated data collection via the LabView program. This system was equipped with a Coriolis mass-flow meter (F 200-Series by MicroMotion).

A CCD video camera was used to tape the flow in the transparent section for critical velocity measurements.

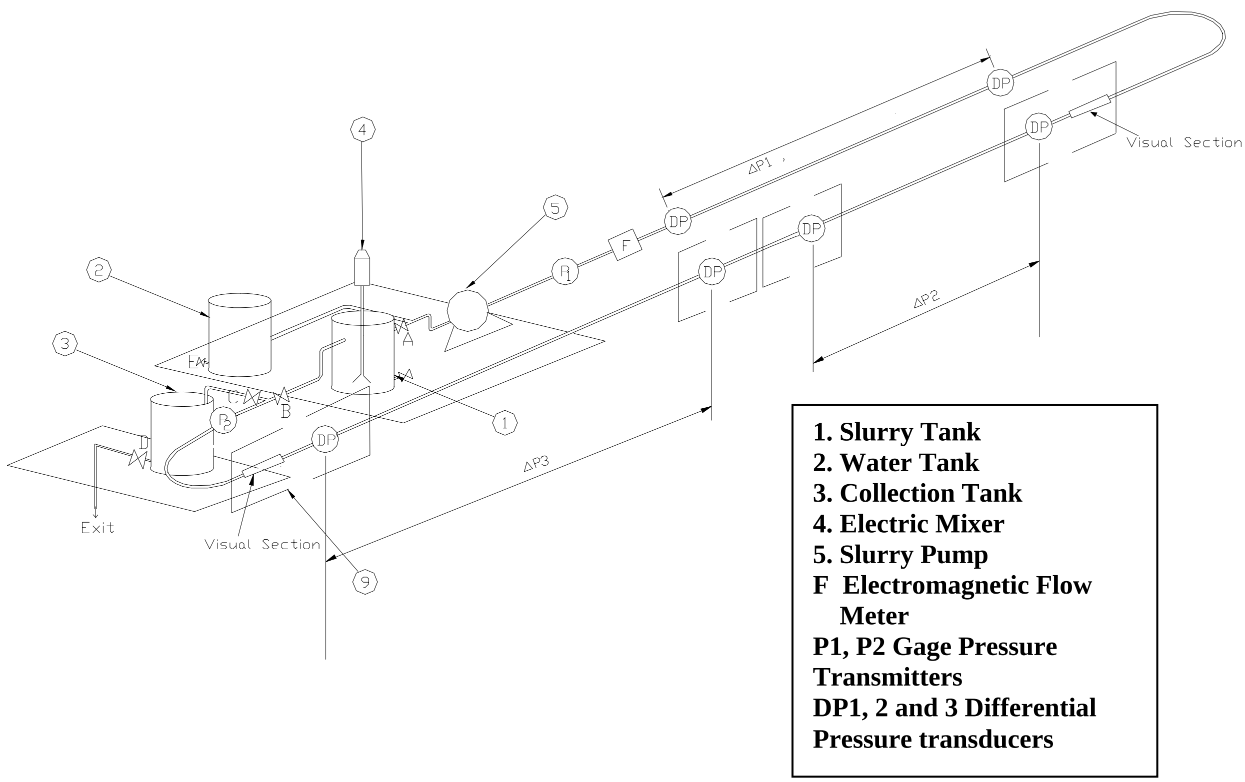

Fig. 1. Schematic diagram of the flow loop

WASP'S MODEL FOR PRESSURE GRADIENT IN A HORIZONTAL PIPELINE

Wasp et al. [2] developed an empirical method for calculating the pressure gradient in a horizontal pipeline as the sum of the gradients due to the symmetrically suspended material and to the asymmetrically suspended and sliding material. Wasp et al. pointed out that with a reasonable range of particle sizes present in a slurry, the smallest particles will normally be in the symmetric concentration flow pattern, the intermediate and large particles will be in the asymmetric pattern, and the largest may slide on the bottom of a pipe. Wasp's method provides a systematic means of interpolating between the two flow pattern extremes of homogeneous flow and asymmetric suspension and sliding bed flow, thus obtaining the results for usual mixed-size slurries. The central feature of the Wasp's model is determination of split between the homogeneous and heterogeneous portions of the slurry. This is done using the method proposed by Ismail [8]:

$$\log \frac{C}{C_A} = -1.8 \frac{W_t}{0.4 \cdot U^*} \qquad \text{(Eq. 1)}$$

where C/C_A is the ratio of solids volume concentrations at 0.08 D from pipe top and at the pipe center, W_t is the terminal settling velocity of solids, and U^* is the friction velocity. Then the pressure gradient due to homogeneously suspended solids is determined by single-phase methods. The pressure gradient due to asymmetrically suspended solids is determined by the empirical correlation of Durand [9]:

$$\Delta p_{asym} = 150 \cdot \Delta p_w \cdot C_v \cdot \left[\frac{g \cdot D \cdot (\rho_s/\rho_l - 1)}{V^2 \cdot \sqrt{C_D}} \right] \qquad \text{(Eq. 2)}$$

where C_v is the solids volume concentration in the slurry; D is a pipe internal diameter; ρ_s and ρ_l are density of solids and of carrier fluid, respectively; V is the average flow velocity, and C_D is the drag coefficient of the particles. Finally, total pressure gradient is taken as the sum of pressure gradients due to the symmetrically suspended material and that due to the asymmetrically suspended one.

Wasp's model calculations presented here were performed with Thomas [10] correlation for slurry viscosity:

$$\mu_{sl} = \mu_w \cdot \left(1 + 2.5 \cdot C_v + 10.05 \cdot C_v^2 + 0.00273 \cdot \exp(16.6 \cdot C_v)\right) \qquad \text{(Eq. 3)}$$

where μ_w is the viscosity of carrier liquid (water in our case).

OROSKAR-TURIAN CORRELATION FOR CRITICAL VELOCITY

Oroskar and Turian defined critical velocity as "the minimum velocity demarcating flows in which the solids form a bed at the bottom of the pipe (bed load flows) from fully suspended flows" [7]. It is not completely clear from this definition if thus-defined critical velocity refers to moving bed or stationary bed velocity. We believe it should refer to moving bed velocity, because when the particles start to settle out of the carrier liquid, they first form a moving bed at the bottom of the pipe, and this bed becomes stationary only at lower flow velocity (defined in this paper as critical deposition velocity).

A correlation for critical velocity developed by Oroskar and Turian [7] incorporated the earlier work of several authors and was based on balancing the energy required to suspend the particles with that derived from dissipation of an appropriate fraction of the turbulent eddies. The general form of Oroskar and Turian correlation is:

$$\frac{V_c}{\sqrt{gd(S-1)}} = \left\{ 5C_v(1-C_v)^{2n-1}\left(\frac{D}{d}\right)\left[\frac{D\rho_l\sqrt{gd(S-1)}}{\mu}\right]^{\frac{1}{8}}\frac{1}{x}\right\}^{\frac{8}{15}} \quad \text{(Eq. 4)}$$

where V_c is the critical velocity of slurry, D is a pipe internal diameter, d is the diameter of slurry particles, C_v is the solids volume concentration in the slurry, n is an adjustable constant, ρ_l and μ are the carrier liquid density and viscosity, S is the ratio of solid to liquid densities, and x is the correction factor for dissipation of turbulent energy, which can be written as follows:

$$x = \frac{4}{\pi}\gamma\exp\left[\frac{-4\gamma^2}{\pi}\right] + \frac{\sqrt{\pi}}{2}erfc\left[\frac{2\gamma}{\sqrt{\pi}}\right] \quad \text{(Eq. 5)}$$

In this expression, γ is the ratio of particle settling velocity to critical velocity. For a range of critical velocities of 0.02 to 1.62 m/s, the value of x is roughly 0.96.

After regression analysis on 357 data points, Oroskar and Turian present their correlation as

$$\frac{V_c}{\sqrt{gd(S-1)}} = 1.85 \cdot C_v^{0.1536}(1-C_v)^{0.3564}\left(\frac{D}{d}\right)^{-0.378} Re_p^{0.09} x^{0.3} \quad \text{(Eq. 6)}$$

where Re_p is the particle Reynolds number defined as

$$Re_p = \frac{wd\rho_l}{\mu} \quad \text{(Eq. 7)}$$

Overall root mean square deviation of critical velocity obtained by this form of correlation from experimental values was 21.8%. Nevertheless, this correlation was better than seven other correlations cited by Oroskar and Turian.

SLURRY CHARACTERIZATION

The two tested slurries were composed of glass beads (ρ_s = 2500 kg/m^3) and water. The slurries had particle size distribution following the Rosin-Rammler distribution [6] with median size of 50 µm in order to simulate the nuclear waste at Hanford site (USA). The spreads of the distribution were n = 1.7 and n = 7. The general form of the Rosin-Rammler distribution is

$$R = 100 \exp\left[-(x / x_R)^n\right] \quad \text{(Eq. 8)}$$

where R is the weight percentage retained on a sieve of aperture x, n is a measure of the spread of the distribution, and x_R is the degree of comminution of the solid material.

In order to obtain such particle size distribution, the following procedure was used to prepare the solids for the slurry. First, the solids were sieved into several narrow size fractions. Next, these fractions were combined according to weight percentage obtained from Rosin-Rammler distribution to obtain the desired PSD. Measured and theoretical PSD were in good agreement for all slurries tested in this study. The glass beads composing the slurries are highly spherical with a specific gravity of 2.5, similar to that of transported waste.

INFLUENCE OF PSD AND PIPE DIAMETER ON PRESSURE GRADIENT

Experimentally measured pressure gradients for slurries with median particle size 50 µm and n = 1.7 (wide PSD) and n = 7 (narrow PSD) with concentrations of 10% and 25% are illustrated in Fig. 2. Predictions of Wasp model for the same slurries are also plotted in these figures. It can be seen from these figures that measured and calculated values of pressure gradients are close at low slurry concentrations and velocities, whereas the difference between measured and calculated values increases with increasing either slurry concentration or velocity for both tested slurries in both flow loops. The model also correctly predicts the effect of PSD on the pressure gradient by predicting higher-pressure gradients for the slurry with narrow PSD. In general, calculated values of pressure gradient in the 22-mm ID flow loop were in good agreement with measured ones. Wasp model under predicted pressure gradient, at all slurry concentrations, in the 45-mm ID flow loop. In contrast to expectations, Wasp model predictions for pressure gradient were better in the 22-mm ID flow loop than in the 45-mm ID flow loop despite the fact that the model was developed for large diameter pipelines.

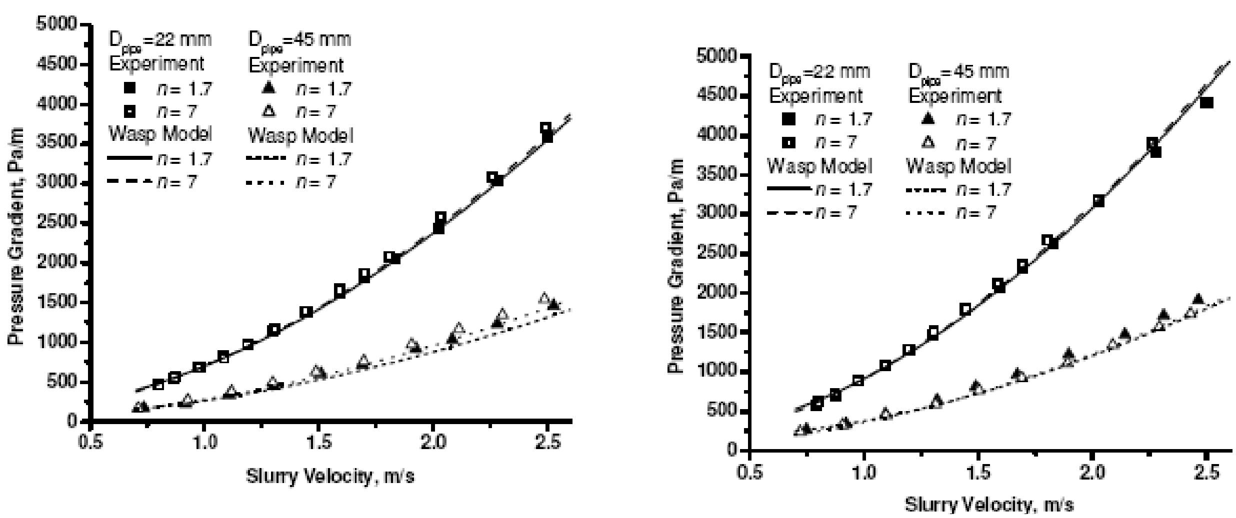

Fig. 2. Comparison of experimental results with Wasp model predictions for slurries with Cv = 10% (left) and Cv = 25% (right)

In order to illustrate the influences of pipe diameter and slurry concentration on pressure loss, measured pressure gradients for the slurry of narrow spread of distribution (n = 7) at both the highest and the lowest concentrations in both pipes were plotted in Fig. 3. It is clear from this figure that pipe diameter has greater influence on the pressure loss than slurry concentration and particle size distribution do.

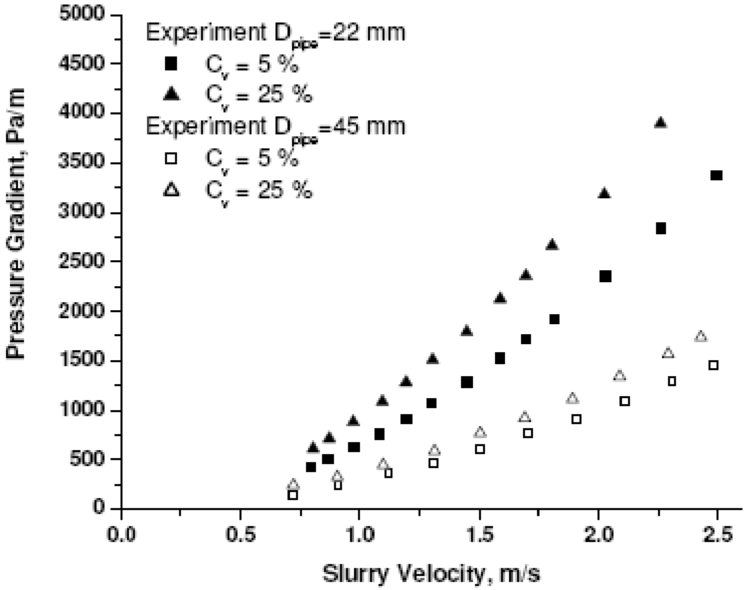

Fig. 3. Effect of pipe diameter on the pressure gradient for the slurry with Rosin-Rammler PSD, n = 7

CRITICAL DEPOSITION VELOCITY MEASUREMENTS

Figure 4 shows the experimental results for two characteristic velocity values associated with settled bed motion identified during the experiments: V_{mb} - mean slurry velocity at which a sliding bed of solid particles begins to form on the bottom of the pipeline; however, the formed bed continued to move; and V_{sb} - mean slurry velocity associated with the moving bed becoming stationary.

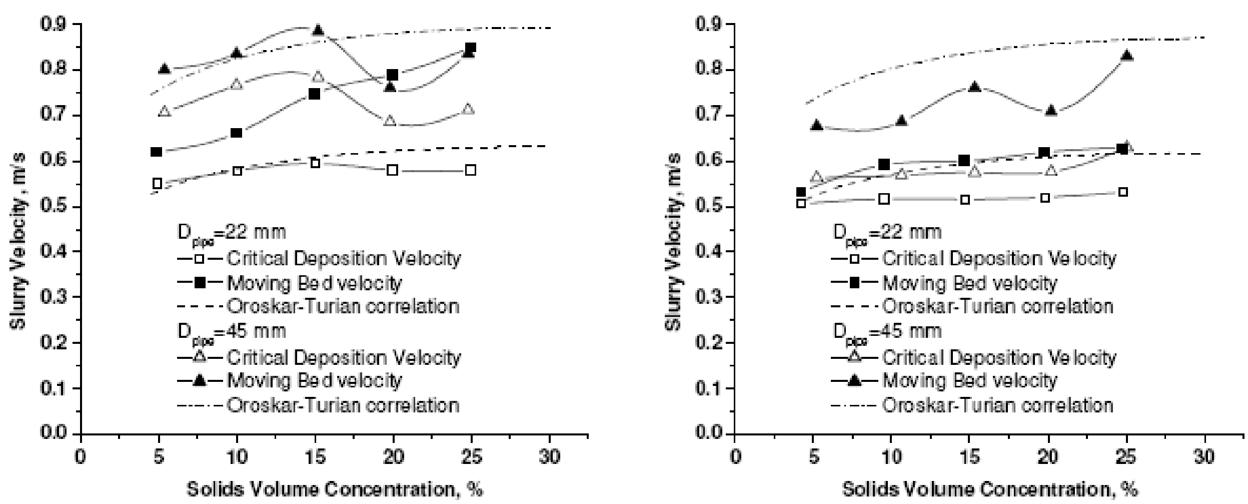

Fig. 4. Critical deposition and moving bed velocities for glass bead-water slurry with median d = 50 µm, n = 1.7 (left) and n = 7 (right)

Critical deposition velocity increased slightly with increasing slurry concentration, in the 22-mm ID flow loop, for the slurry of broad spread of distribution n = 1.7, while it was fairly constant for the slurry of narrow distribution; n = 7.

Moving bed velocity was found to increase steeply and significantly with increasing slurry concentration, in the 22-mm ID flow loop, for the wide distribution; n = 1.7, while it increased moderately in the case of the slurry of narrow distribution; n = 7.

Critical deposition velocity and moving bed velocity, in the 45-mm ID flow loop, were noticed to have a maximum and a minimum except for the critical deposition velocity for the slurry of narrow distribution. At n = 7 the critical deposition velocity was fairly constant up to slurry concentration of 20% beyond which it increased steeply as the concentration increased to 25%

Measurements from visual observations demonstrate that solid particles start to deposit at higher slurry velocity in the 45-mm ID flow loop than in the 22-mm ID flow loop.

Oroskar-Turian correlation predicted values for the critical deposition velocity were close to their corresponding measured values, especially at low slurry concentrations, for the flow of the slurry of broad distribution, n = 1.7, in the 22-mm ID flow loop. This correlation over predicted critical deposition velocity for the slurries with n = 7 by 20% at maximum in the same flow loop. Oroskar-Turian correlation over predicted the critical deposition velocity for all the slurries tested in the 45-mm ID flow loop. The over-prediction became greater as the PSD, of tested slurry, became narrower. Oroskar-Turian correlation gave better predictions of critical velocity in the 22-mm ID flow loop than in the 45-mm ID flow loop.

CONCLUSIONS

Experimentally measured pressure gradients for slurries with narrow and wide PSDs are close at low slurry velocities, whereas pressure gradient is greater for the slurry of narrow distribution especially at relatively high concentrations and velocities. Wasp's model predictions of pressure gradient were close to their corresponding measured ones at low slurry concentrations and velocities. Although Wasp model was designed for pipes of relatively large diameters, Wasp model predictions for pressure gradient were better in the 22-mm ID flow loop than in the 45-mm ID flow loop.

The influence of pipe diameter on pressure gradient seems to be more significant than slurry concentration and particle size distribution.

Critical deposition velocity and moving bed velocity have different behavior for both slurries and in the different pipe diameters. Critical velocity and moving bed velocity of the slurry with n = 1.7 increased with increasing slurry concentration in the 22-mm pipe while it was fairly constant for the slurry with n = 7. Whereas these velocities had maximums and minimums in the larger pipe except for the slurry with n = 7 and at concentrations equal to and exceeding 20%, at which the critical deposition velocity decreased steeply.

The best predictions of the critical velocity using Oroskar-Turian correlation were for the slurry of n = 1.7 in the 22-mm ID pipe and at low velocities. This correlation over predicted critical velocity for the narrow distributed slurry in both flow loops.

ACKNOWLEDGMENTS

The results presented in this article were developed from a work supported by the U.S. Department of Energy (DOE), Environmental Management (EM), Office of Science and Technology (OST), under Grant No. DE-FG21-95EW55094.

NOMENCLATURE

C	concentration, %
C_D	drag coefficient, dimensionless
D	internal diameter of a pipeline, m
d	diameter of spherical solid particle
f	friction factor, dimensionless
g	gravitational acceleration, m/s
Δp	pressure drop, Pa
U^*	$= V\sqrt{\frac{f}{2}}$ friction velocity, m/s
V	mean velocity, m/s
W_t	terminal settling velocity of solid particle, m/s

Greek Symbols

ρ	density, kg/m^3
μ	dynamic viscosity, Pa s
γ	shear rate, 1/s

Subscripts

asym	asymmetric
c	critical
l	liquid
s	solid
sl	slurry
v	volume
w	water
wt	weight

REFERENCES

1. Govier, G.W. and Aziz, K. (1977). The Flow of Complex Mixtures in Pipes. Robert E. Krieger Publishing Company, Inc.
2. Wasp, E.J. Kenny, J.P. and Gandhi, R.L. (1979), Solid-liquid Flow Slurry Pipeline Transportation, Gulf Publishing Company, Houston, Texas.
3. Brown, N.P. and Heywood, N.I. (1991), Slurry Handling. Design of Solid-Liquid Systems. Elsevier Science Publishers, Ltd., New York.
4. Roco, M.C. (1996). Multiphase flow: summary paper. *Powder Technology* 88: 275-284.
5. Sundqvist, A. Sellgren, A. and Addie, G. (1996). Pipeline friction losses of coarse sand slurries. Comparison with a design model. *Powder Technology* 89: 9-18
6. Allen, T. (1997). Particle Size Measurement. Chapman & Hall, Fifth Edition.

7. Oroskar, A.R. and Turian, R.M. (1980). The critical velocity in pipeline flow of slurries. *AIChE*, 26(4): 550-558.

8. Ismail, H. (1952). Turbulent transfer mechanism and suspended sediment in closed channels. *Tran. ASCE,* 117: 409-447.

9. Durand, R. (1952). The hydraulic transportation of coal and other materials in pipes. *Colloq. of National Coal Board*, London. Cited in [2].

10. Thomas, D.G. (1965). Transport characteristics of suspensions: Part VII. A note on the viscosity of Newtonian suspensions of uniform spherical particles. *Colloid Sci*ence, 20: 267