Full-Scale Testing of Pipeline Unplugging Technologies - NuVision's Fluidic Wave-Action Technology - 9236

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ABSTRACT

In this paper, we present a technical evaluation of a pipeline unplugging method that can be used as a feasible tool to clean fouled pipes at Department of Energy (DOE) sites. The unplugging method depends on running water against the plugged section in the pipeline for multiple times and breaking the mechanical bonds of the material that hold the plug together. The working principles of the method are similar to beach erosion since a water wave is generated using the suction and drive mechanisms caused by the system in the pipeline that erodes the plug from one end. The technology tested also is capable of creating an external force on the plug that helps the unplugging process however this characteristic of the technology was not tested during the testing reported in this work. More focus was given to the erosion capability of the technology and how wave characteristics affected that. Results obtained demonstrated that there is a correlation between the suction and drive characteristics of the wave generated in the pipeline with the maximum pressures attained in the plug region, the velocity of the wave prior to colliding with the plug and the erosion. It was found that the technology was most effective in unplugging Phosphate based chemical plugs and Kaolin clay based plugs while it took more time to erode Aluminum based plugs for the same pipeline test layouts.

INTRODUCTION

Plugging can occur at some of the pipelines at DOE sites during high level waste (HLW) transfers, which may result in schedule delays and increased costs. Availability of a pipeline unplugging tool/technology is crucial to ensure smooth operation of the waste transfers and to ensure tank farm cleanup milestones are met. Florida International University (FIU) had previously tested and evaluated various unplugging technologies through an industry call. Based on mockup testing, one technology that was identified to be able to withstand the rigors of operation in a radioactive environment and have the ability to handle sharp 90° elbows was NuVision Engineering's Fluidic Wave-action Technology. A second set of experiments were conducted using the Fluidic Wave-action technology with the objective to further understand the underlying physics of the method by utilizing a pipeline test-bed instrumented with sensors that can simultaneously track the changes in the flow in the pipeline during the unplugging process Detailed information on the test set-up and NuVision's Hydraulic Wave-Action Method were reported previously by the current authors [1]. In this paper, the experimental results and data analysis of NuVision's technology are presented. Based on the analysis presented here, it is still not clear whether NuVision's technology can be safely used for unplugging DOE lines as discussed in the conclusions section.

The second phase of testing comprised of a heavily instrumented 3-inch diameter full-scale pipeline, facilitating extensive data acquisition for design optimization and performance evaluation, as it applies to three types of plugs typical of DOE HLW. One of these plug types is a kaolin-water mixture typically used in emulating slurry mixes. The other two plugs are crystallized salt plug simulants recommended by Hanford Waste Treatment and Immobilization Plant (WTP) engineers. Three different test bed lengths

(285, 621, and 1797 ft) were utilized to determine the effectiveness of NuVision's technology with respect to blockage distance. Erosion rates were determined for each plug type and at each test bed length. An amplification of pressure was observed at the blockage area which demonstrated the need for a complete analysis of the pressure pulse propagation through the pipeline [1].

The outline of the paper is as follows. First, unplugging principles of NuVision Engineering are summarized. The experimental set-up is described and blockage materials are explained next. Finally the results are presented and conclusions and discussions follow.

NUVISION'S UNPLUGGING PRINCIPLES

NuVision's technology is based on a fluid wave-action principle, which operates much like ocean wave-action on beach erosion, possibly aided by use of a solvent, coupled with positive and negative pressure pulses that tend to loosen the blockage. It can operate on a long pipeline that has drained down below a blockage. The blockage section must be elevated relative to the inlet of pipeline in order for an air cavity to be created adjacent to the blockage. The system consists of a water/solvent tank, a pressurize/vacuum vessel (charge vessel), a portable air compressor, jet pump pair and valve manifold, a fluidic control unit, a vacuum finishing pump, a system controller, and a system module. First, a vacuum pump is used to evacuate a majority of the air in the pipeline below the blockage in elevation. Once a partial vacuum has been established, a ball valve is opened, and the fluid is allowed to back fill the pipeline. Since a portion of the air remains, a cavity forms near the elevated blockage which is inserted at the end of the pipeline. The fluidic control system is then used to create waves in the pipeline by providing positive and negative pressures at the inlet of the pipeline in a cyclic manner. A cycle consists of three phases; a suction phase, a drive phase and a vent phase. During the suction phase the fluid is pulled back into the charge vessel. The fluid is quickly expelled during the drive phase, creating a wave in the cavity near the blockage. In the vent phase, the system is vented to atmosphere, allowing the fluid to settle. This process is repeated numerous times until the blockage is removed.

The duration and pressure level of each cycle can be controlled via the fluidic control unit. This coupled with the dissolving action of a selected solvent and the physical action of the vacuum and pressure cycles works to both erode and loosen the blockage.

Benefits of NuVision's technology include:

- Short mobilization and demobilization time possible with an adaptive jumper.
- Can be used to deliver chemical solvent to the blockage where a solvent may be of assistance in loosening a blockage.
- Can be applied to the section of the pipeline that has drained down below the elevation of the blockage.
- System works under relatively low drive pressures (689.5 kPa (100 psi) tested.)
- Technology can negotiate many elbows.
- Technology can be operated remotely.
- No water discharged until the blockage is cleared - minimizing the amount of liquid added.
- Relative location of the blockage can be determined by the amount of water required to back-fill the pipeline.

Limitations of NuVision's technology include:

- Length of reach in an empty pipeline is limited by the strength of the vacuum pump.
- Unplugging times are relatively long.

EXPERIMENTAL TESTING

Process variables important to this study include unplugging rates and pipeline pressure variation along the pipeline (maximum pipe pressure) and their variability with respect to the equipment control parameters. The equipment control parameters, which are discussed later in this text, are the parameters NuVision must select to operate their equipment. The effect of these parameters on the pipeline pressure and wave mechanics/unplugging rates needed to be well understood. In addition, to qualify NuVision's technology, maximum pressures needed to be determined and compared with site safety requirements. Due to the lack of information on exactly how the NuVision's technology scales to longer pipes, FIU adopted a parametric approach to evaluate the technology functionality and how it is expected to affect the process variables.

The following data was collected to provide understanding of the technology, its capability, limitations and safety:

- Pressure profile along the test bed, time dependent pressure measurements at several pressure taps along the test bed.
- Maximum pressure in the test bed pipeline during technology operation.
- Temperature of the process fluid (water) in the test bed pipeline.
- Atmospheric temperature and pressure.
- Cycles of operation (time).
- Plug weight – before and after technology operation.
- Unplugging rate.
- Equipment control parameters.

Other data from the test bed that was used in the analysis include:

- Distance to the plug, distance from the test bed entry point to the plug.
- Plug length.
- Nature of the plug, composition of the material used to create the plug.
- Number of elbows in the test bed from entry point to the plug.
- Distances between pressure transducers.

BLOCKAGE MATERIALS

In order to evaluate how the effectiveness of the unplugging technology is impacted by the chemical and rheological characteristics of the plug, three blockage materials were used. A kaolin clay water mixture was used to emulate settled sludge and phosphate and aluminum gel was used to emulate a crystallized salt plug.

Literature suggests that the most relevant blockage material property with respect to conveyance system potential of plugging, choking, and slugging is cohesiveness [2, 3]. Cohesiveness characterizes the tendency of the material to adhere to itself and to conveyance system equipment. For many sludge-like materials, the expected cohesiveness is a function of the shear strength [3]. Kaolin clay water mixture was recommended as a sludge simulant [2, 4] because its shear strength, cohesiveness, particle size distribution, and density (at 66-67 wt% kaolin in water) are similar to those of tank sludge. Comparison of material properties of kaolin water mixture to those of Hanford tank sludge is given in Table I. The data in this table is extracted from graphs contained in literature [3]. Detailed comparisons are also reported by Powell *et al*. [3, 4]. FIU also conducted shear strength, tensile strength, and stickiness measurements of kaolin clay water mixtures to verify that the kaolin obtained by FIU. The result of this characterization demonstrates that shear and tensile strength of kaolin-water mixtures studied by Powell et al.[3] and FIU are similar. The results of this test were published previously [5].

Table I. Comparison of Material Properties of Kaolin Water Mixture with Those of Hanford Tank Sludge

	Mean Particle Diam, µm	Shear Strength, kPa	Density, g/cm^3
Kaolin water mixture (66 wt% kaolin in water)	1.02	3.5	1.65
Tank Sludge	1.2	0 to 5	1 to 2

Table II. Compositions of Phosphate and Al-Gel Blockage Simulant

Component	Molality	
	Al-OH gel	Phosphate plug
Al(NO3)3 9H2O	1.0	0
$NaAlO_2$	0	1
NaOH	3.0	2
Na_2CO_3	0.5	0.1
$NaNO_3$	0	7
$Na_3PO_4\ 12H_2O$	0	0.3

The kaolin-water mixture was prepared in a large bucket and mixed using a drill attachment until uniformity was achieved. Four-foot PVC pipes were then completely filled with the mixture. In order to remove air gaps that can get entrapped inside the blockage during filling, the blockages were compressed to 40.7 Nm (30 ft-lbs) using a torque wrench.

Hanford and WTP engineers recommended that phosphate and aluminum gel be used as the crystallized salt blockage simulants. This type of plug may form in a pipeline due to precipitation of waste salts caused by temperature changes or supersaturation due to mixing of different waste types. Composition of the phosphate simulant is given in **Error! Reference source not found.** and was obtained from a master thesis at Mississippi State University [6].

This composition was first prepared in small samples in the laboratory and it was observed to form a gel when cooled to room temperature. In order to get 1.22 m (4 ft) of the phosphate blockage, two batches of 3 liters of gel were prepared. The ends of the clear pipe were closed and the gel was poured into the pipe until full. It was left to drain in an upright position and new gel was added from the top as the water drained from the pipe. This process was repeated until water no longer drained from the pipe, which took approximately 5-7 days.

The recipe for the aluminum gel was provided by WTP and PNNL. Beaker testing was performed at FIU and gelling was observed. The aluminum nitrate was dissolved in water separately to prepare the matrix solution. Sodium hydroxide and sodium carbonate were dissolved in a separate cup to prepare the gelling solution. Finally, the gelling solution was added to the matrix solution to get the final Al-OH gel. The compositions of the ingredients are given in **Error! Reference source not found.**. A draining procedure similar to phosphate gel was carried out for the Al-gel blockage. A hand plunger was used to increase the mechanical integrity of the blockage.

All of the plugs were created in 1.22 m (4 ft) pipe lengths. They were weighed before and after each unplugging test to determine the weight of removed plug material and effective unplugging rates. Multiple compositions of the same plug were manufactured following the same procedure for each plug. The weights of the plugs were used as a reference for consistency. Kaolin plugs were compressed from both ends in order to eliminate forming of air gaps in the plug and impose uniformity.

RESULTS AND OBSERVATIONS

Table III. NuVision Control Parameters, Suction time (Ts), drive time (Td) and vent time (Tv).

		Ts (sec)	Td (sec)	Tv	Drive Pressure	Vacuum Level
86.9 m (285 ft)	Kaolin (EJ)	11	6	20 kPa (.2 bar)	200 kPa (2 bar)	-88.6 kPa (-0.886 bar)
	Al Gel (EJ)	11	6	20 kPa (.2 bar)	200 kPa (2 bar)	-88.8 kPa (-0.888 bar)
***	Phosphate (EJ)	15	5	1 sec	200 kPa (2 bar)	-88.5 kPa (-0.885 bar)
	Kaolin (NEJ)	8	4	20 kPa (.2 bar)	200 kPa (2 bar)	-88.9 kPa (-0.889 bar)
189.3 m (621 ft)	Kaolin (EJ)	14	6	20 kPa (.2 bar)	300 kPa (3 bar)	-88.6 kPa (-0.886 bar)
	Al Gel (EJ)	18	7	20 kPa (.2 bar)	300 kPa (3 bar)	-88 kPa (-0.880 bar)
***	Phosphate (EJ)	15	7	20 kPa (.2 bar)	300 kPa (3 bar)	-88 kPa (-0.880 bar)
	Kaolin (NEJ)	8	4	20 kPa (.2 bar)	300 kPa (3 bar)	-88 kPa (-0.880 bar)
547.7 m (1797 ft)	Kaolin (EJ)	17	8-10	20 kPa (.2 bar)	300 kPa (3 bar)	-88 kPa (-0.880 bar)
	Al Gel (EJ)	14-16	7-9	20 kPa (.2 bar)	150-200 kPa (1.5-2 bar)	-91.6 kPa (-0.916 bar)
	Phosphate (EJ)	15-16	7-10	20 kPa (.2 bar)/ 8 sec	150-200 kPa (1.5-2.5 bar)	-92.8 kPa (-0.928 bar)
	Kaolin (NEJ)	17	11	6-8 sec	200 kPa (2 bar)	-92.8 kPa (-0.928 bar)

The pipeline diagrams and test bed details were published in McDaniel et al. [5] and are not repeated in this article. The control parameters utilized for each of the tests is shown in **Error! Reference source not found.**. "EJ" indicates that the test was conducted with an expansion joint in place and "NEJ" indicates that an expansion joint was not utilized. It should also be noted that some of the early tests were run with the charge vessel empty. This potentially resulted in adding air into the pipeline during the drive phase and ultimately required changes in the control parameters during testing. These tests were rerun with a partially filled charge vessel with the exception of the phosphate tests since the phosphate plugs was observed to dissolve relatively easily in the presence of water. The (***) in **Error! Reference source not found.** indicates that these tests were conducted without a partially filled charge vessel.

In general, NuVision varied three of the five equipment control parameters: suction time, drive time and drive pressure. Vent time was initially set to a specific time but after a few tests it was set to a specific level of pressure (20 kPa (0.2 bar)). The vacuum level was generally fixed until the 547.7 m (1797 ft) test bed where higher levels of vacuum were pulled to try and reduce the cavity size. Separate blind flange testing was also conducted at FIU's request at each pipe length, varying drive pressure, drive time and suction time. These tests were conducted to determine the effects of each of the equipment control parameters on the wave and pressure dynamics without the influence of the blockages.

A key observation from **Error! Reference source not found.** relates to the variation in the equipment control parameters. As the pipe length test bed increases, the variability in the control parameters utilized also increase. This is believed to be due to the environmental variations such as environmental temperature, pressure and humidity and observed during testing which affected the cavity size and ultimately the performance of the technology.

PRESSURE DATA

Thirteen pressure transducers create a pressure profile for the entire test bed during the testing of NuVision's wave erosion technology. LabView software was used to recreate virtual simulations of the pressure dynamics as shown in **Error! Reference source not found.** which shows the pressure readings at each transducer location along the pipeline as a function of time.

During the erosion process, the drive pressure adds momentum to the column of fluid in the pipe which has two effects; 1) it compresses the air remaining in the cavity causing an increase in pressure at the plug and 2) the fluid near the cavity will interact with the air and create a wave which in turn attempts to erode the plug. The increase in pressure can sometimes result in the plug pressure being significantly greater than the drive pressure. In this text, the ratio of plug pressure to drive pressure is referred to as the amplification factor. Understanding this amplification of the pressure is the key concept in qualifying NuVision's technology. The maximum pressure values (P13) closest to the blockage are stored in memory for each cycle with a specified drive pressure and the ratio $P13/P_{drive}$ is calculated to find the amplification factor for that cycle.

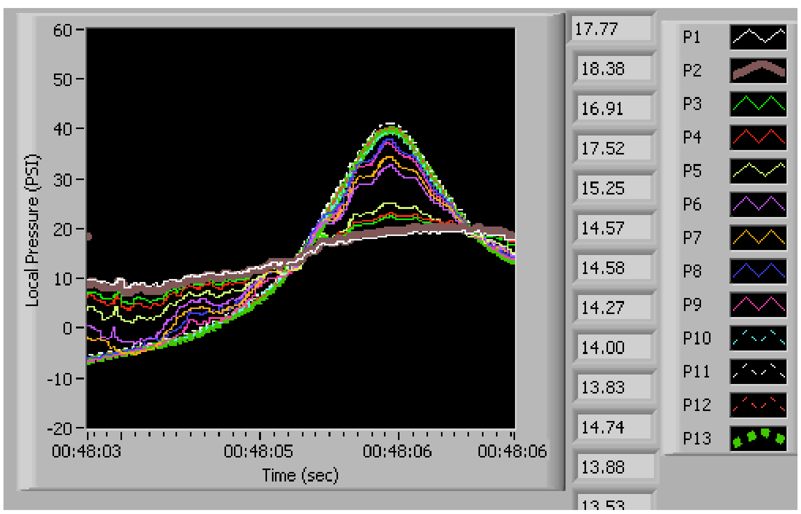


Fig. 1. Virtual simulation of pipeline at 86.9 m (285 ft) using a blind flange during a suction phase.

Effects of NuVision's process control parameters on the amplification factor

In this section, three of NuVision's process control parameters are varied to determine their effects on the amplification factor. Amplification factor is vital for qualification of this technology since the maximum pressure that can be attained in the Hanford transfer lines is limited to 300 psi. Safety concerns will arise if the amplification factor is large enough to cause the maximum pressures to exceed the threshold limit. The factors studied are the drive time, suction time and the drive pressure. This analysis is conducted without a plug, using a blind flange placed at the end of the pipeline to eliminate any effect of the blockages on the amplification factor.

The air in the charge vessel works as a piston pushing the water into the pipeline almost at a constant pressure value specified by the NuVision engineers. The water level in the charge vessel is reduced by dV=dL*Area during the total drive time which is also a NuVision process control parameter.

In Fig. 2, the left hand side shows the amplification factor versus drive time as the drive pressure and suction time are varied. The right hand side shows the amplification factor versus suction time as the drive pressure and drive time are varied. In general, it can be seen that for increasing drive times and maintaining the same suction time and drive pressure, an increase in the amplification factor is observed.

This can be explained by the fact that the drive and suction times determine the amount of water injected into the pipeline. If the amount of water introduced during the drive phase is increased, i.e. a longer drive period, the air bubble is compressed more which increases the pressure of the air cavity and the amplification factor. For this scenario, it would be expected that a point would be reached where the increase in drive time would cease to compress the air cavity and would only result in a loss in energy.

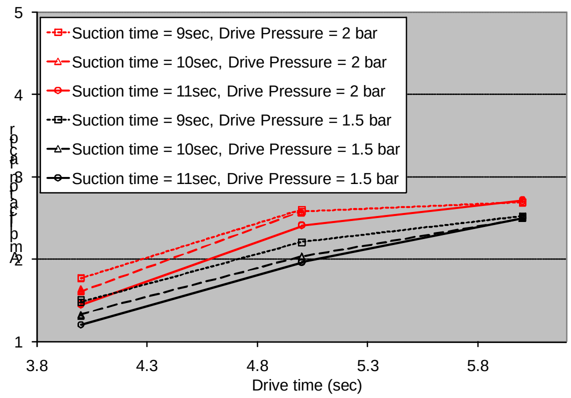
The opposite is observed for the suction time. For increasing suction times the amplification factor was seen to decrease almost linearly as shown in the right hand side of Fig. 2. As the suction duration increases and the drive time is kept constant, the volume of the fluid in the pipeline being cycled becomes less which increases the volume of the air cavity at the pipe end. This reduces the amplification factor since water left in the pipeline is not able to compress the same air volume as it does at a smaller suction time.

Fig. 2 shows that in general, the drive pressure works in favor of the amplification factor. For all lengths, the general trend shows that for the same drive and suction times, an increase in the drive pressure assigned by the NuVision engineers yield in an increase in the amplification factor. A higher drive pressure corresponds to a higher piston force in the charge vessel. If the drive and suction times remain constant, a higher force would increase the energy input into the system and would result in higher wave velocities hitting the blockage. As a result, the net momentum compressing the air cavity is increased with an increase in drive pressure which would result in a higher amplification factor.

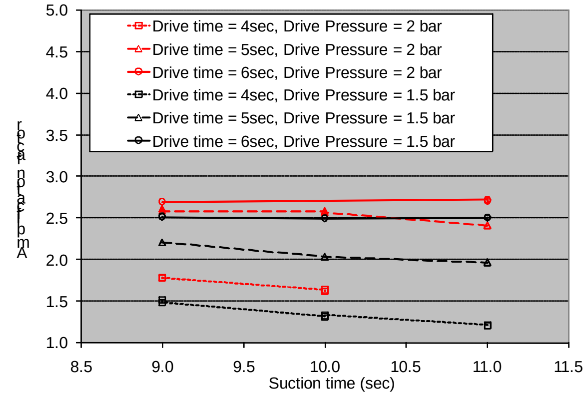
Pressure Amplification for Cases with Blockages

In Fig. 3 the average blockage amplification factors are superimposed over the blind flange data for each of the three test bed lengths. These plots provide the effects the blockage may have on the amplification factors that are obtained. In Fig. 3 (a) the kaolin and aluminum gel trials appear to be in line with the blind flange results, for the 86.9 m (285 ft) test bed. Note that the variance for each run has also been provided in the figure. The phosphate trial has a large variance which is due to the testing without a pre-charged vessel. Although the average drive time appears to be similar to the amplification factor for the 5 second drive time, the 15 second suction time does not have a corresponding trend line on the figure. The kaolin trial without the expansion joint is also shown at a drive time of 4 seconds with a significantly larger amplification factor, as expected.

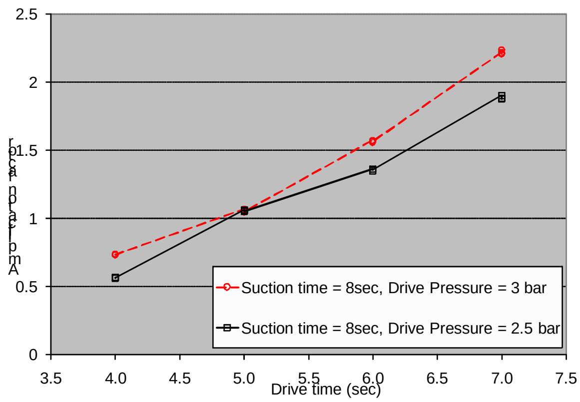
Although the suction times for the blockage cases for the 189.3 m (621 ft) test bed, Fig. 3 (b), does not correspond to the trend line, the variance of the phosphate and the kaolin encompass the amplification factor trend line. In addition, the kaolin trial without the expansion joint again is significantly higher for the same suction time (8 seconds) at a 4 second drive time. For the 547.7 m (1797 ft) case, the variance of the process control parameters from plug-to-plug make it difficult to determine any correspondence between the plug data and the blind flange data. The variance of the process control parameters was due



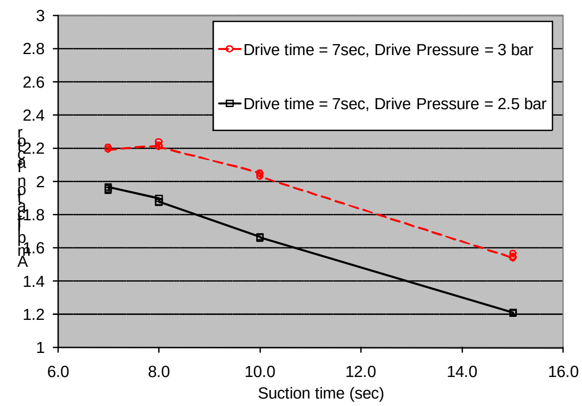
(a) 86.9 m (285 ft)



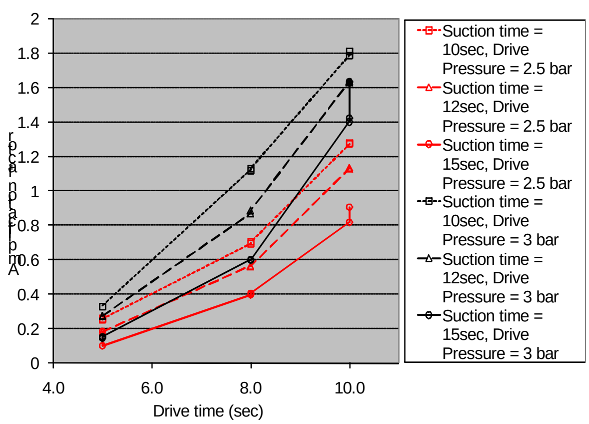
(d) 86.9 m (285 ft)



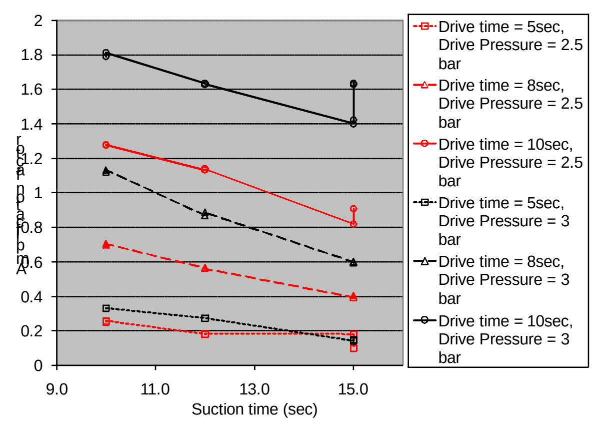
(b) 189.3 m (621 ft)



(e) 189.3 m (621 ft)



(c) 547.7 m (1797 ft)



(f) 547.7 m (1797 ft)

Fig. 2. Effect of the NuVision's drive time (on the left) and suction time (on the right) on the amplification factor at various blockage lengths (blind flange data).

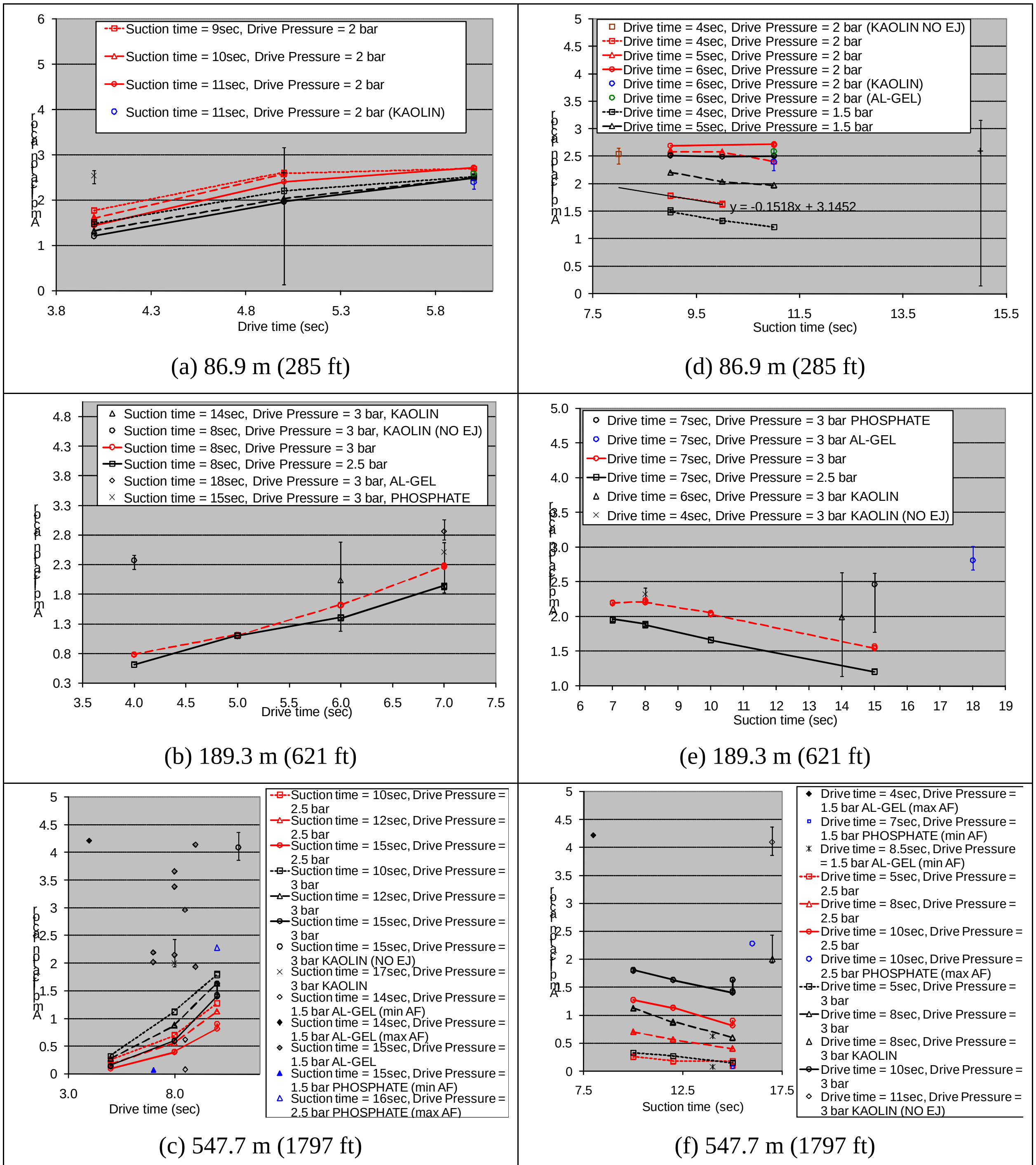


Fig. 3. Effect of the NuVision's drive time (on the left) and suction time (on the right) on the amplification factor at various blockage lengths (blind flange data).

to the chance in the environmental conditions which, in turn, varied the cavity size and pressures and wave speeds. The right hand side of Fig. 3 shows similar plots with suction time replacing the drive time on the x-axis. It is easily seen that the kaolin and aluminum gel trials match well with the corresponding trend lines in the 86.9 m (285 ft) test bed. The kaolin trial without the expansion joint again appears to be significantly higher than the extrapolated trend line. For the 189.3 m (621 ft) test bed, there appears to be more scatter in the data with the exception of the kaolin trial without the expansion joint which corresponds well with the 7 second drive time trend line even though the drive time for that trial was 4 seconds. For the 547.7 m (1797 ft) test bed, variations in the process control parameters make it difficult to access any correlation between the two sets of data.

Table IV. Unplugging Rates

Pipeline Length	Blockage Type	Unplugging Rate (kg/hour)
86.9 m (285 ft)	Kaolin	0.452
86.9 m (285 ft)	Phosphate	9.500
86.9 m (285 ft)	Aluminum Gel	0.704
86.9 m (285 ft)	Kaolin w/o exp. joint	0.900
189.3 m (621 ft)	Kaolin	0.650
189.3 m (621 ft)	Phosphate	10.31
189.3 m (621 ft)	Aluminum Gel	0.477
189.3 m (621 ft)	Kaolin w/o exp. joint	0.282
547.7 m (1797 ft)	Kaolin	0.214
547.7 m (1797 ft)	Phosphate	6.332
547.7 m (1797 ft)	Aluminum Gel	0.146
547.7 m (1797 ft)	Kaolin w/o exp. joint	0.088*

UNPLUGGING RATES

Unplugging rates are obtained using the initial and final weights of the section containing the blockage material and the total time of unplugging spent on the blockage as given by

$$Rate = \frac{M_{final} - M_{initial}}{Time} \quad \text{(Eq. 1)}$$

where M_{final} and $M_{initial}$ are the final and initial weights of the blockage section and Time is the total unplugging time.

Unplugging rates for various blockages and test bed configurations are shown in Table IV. Blockages were typically eroded between 25 to 50% of the original mass with the exception of the phosphate blockage which was completely dissolved/eroded at each test bed length. In general, the aluminum gel blockages produced unplugging rates similar to those produced by the kaolin blockages. The trials without the expansion joints were unpredictable. For the 86.9 m (285 ft) test bed, the unplugging rate of the kaolin was significantly higher when the joint was removed.

This was not the case for the longer runs. In the 547.7 m (1797 ft) trial without the expansion joint, an extremely low rate was observed (*). This was due, in part, to the fact that the kaolin near the wave did not erode easily, but water did manage to penetrate into the plug. When weighing the blockage to determine the percentage of erosion, the additional water retained by the plug may have skewed the final calculated rate, indicating a less effective unplugging rate than what actually occurred. Unplugging rates for the longest pipeline length were lower than the rates for the other two lengths, as expected. However, there was not a pattern for the unplugging rates between the 86.9 m (285 ft) and 189.3 m (621 ft) test beds. It should also be noted that during the 547.7 m (1797 ft) trials, the process control parameters were varied over the erosion process. Although altering the parameters would affect the unplugging rate, the average unplugging rates are still presented. Note that the phosphate plug data is included in Table IV but these trials were conducted without a pre-filled charge vessel.

WAVE SPEED ANALYSIS IN THE CLEAR SECTION

In this section, analysis was conducted to calculate the wave speeds seen during the NuVision testing based on the video collected, and determine mean speeds for the three different test lengths. It was also aimed to qualitatively analyze the associated wave profiles, if more than one, seen during video analysis.

In order to quantify the wave speed, a method was needed to track the wave along certain points in the video. During the tests, an adhesive ruler attached to a backplane was used to measure distance within the video through a 50 inch length. Using this marker to measure distance, time estimates were now needed. The video cameras used maintain a mean frame rate of 30 fps throughout the capture. This equaled a 0.033 time lapse between frames, or a 33 ms period.

Accurate determination of the wave speed was achieved by sampling several waves throughout the video, and visually measuring the wave location and time stamp on varying frames. Four frame locations (based on measurement markers) and their associated timestamps were collected, **Error! Reference source not found.**.

These frame locations and time stamps were inserted into a spreadsheet that calculated the wave speeds from the moment the wave enters the video area, until making contact with the plug/blind flange. For each video collected, frame information was collected for one to four cycles, in order to obtain a mean wave speed for the run. The wave speed calculated for each cycle was between the first frame collected and the second, third and fourth frame. The wave speeds were based on the following equations:

$$v_{1-2} = \frac{x_2 - x_1}{t_2 - t_1},\ v_{2-3} = \frac{x_3 - x_2}{t_3 - t_2},\ v_{4-3} = \frac{x_4 - x_3}{t_4 - t_3}\quad v_{4-1} = \frac{x_4 - x_1}{t_4 - t_1} \qquad \text{(Eq. 2)}$$

and $v_{wave} = 0.25(v_{1-2} + v_{3-2} + v_{4-3} + v_{4-1})$.

This allowed speed tracking based on the first reference frame (usually located within the 0.76 m (30”) to 1.27 m (50”) portion of the measurement ruler), which is the clearest to spot in the video and thereby minimizes additional human error to the process. Also, a wave speed for the last two frames was calculated to see if the wave was slowing down as it got closer to the blind flange/plug. Initial

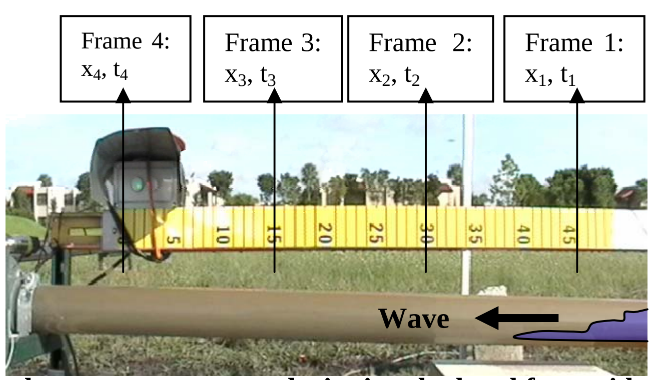
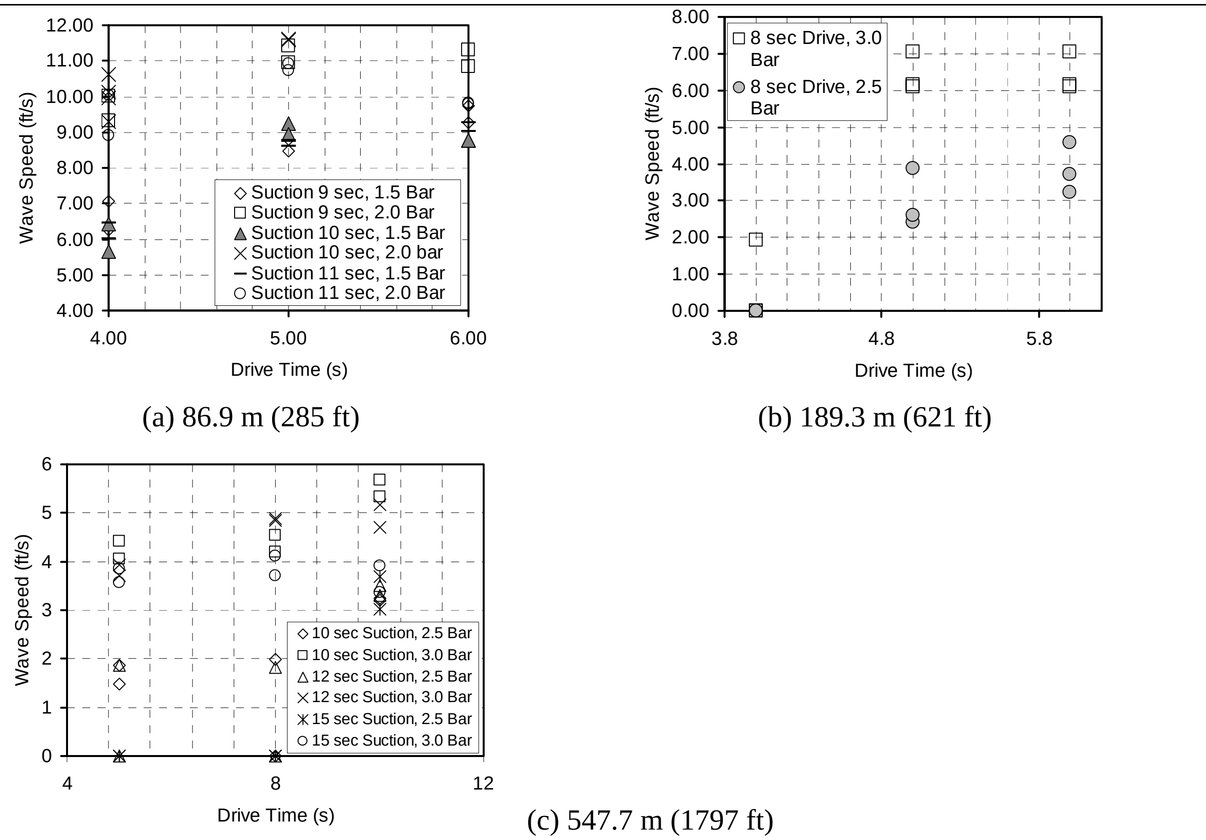


Fig. 4. Schematic showing how average wave velocity is calculated from videos.



(a) 86.9 m (285 ft) (b) 189.3 m (621 ft)

(c) 547.7 m (1797 ft)

Fig. 5. Effect of the drive time on the wave speed at various blockage lengths (blind flange data).

measurements indicated that the wave would be moving too fast to capture any information for distances less than (0.127 m) 5”, so measurements were taken for distances greater than or equal to five.

The wave speed estimation yielded variations between the blind flange testing and the plug testing performed on the three test beds. Blind flange testing provided a method to examine more consistent wave speed estimates than analyzing the plug tests, and was expected to set a baseline range for plug test velocities.

Wave Speeds versus NuVision Parameters

For the three pipe lengths tested, varying wave speeds were observed as the NuVision operating parameters were adjusted. **Error! Reference source not found.** depicts the wave speed versus drive time for varying suction time and drive pressure data sets. The graphs depict a general increasing trend as the drive time is increased. The variability in the graphs cannot explicitly predict if the wave speeds continue to increase, or become stable as the drive time is increased. Field observations showed that longer drive time did not seem to increase wave speed significantly, so it may be that a peak value is reached with longer drive times only adding air into the system. Significant variability is observed in the 189.3 m (621 ft) case; this could be due to the limited blind flange data collected for this case.

Wave speeds were also obtained for most unplugging trials conducted. **Error! Reference source not found.** summarizes the wave speeds calculated at different test bed lengths for the various blockages. Note that video was not taken for the aluminum gel plug for the 86.9 m (285 ft) test bed due to inclement weather. Phosphate data is not reported for the 86.9 m (285 ft) and the 189.3 m (621 ft) test bed because the trials were conducted without a pre-charged vessel. The average velocities were obtained by taking measurements during each set of cycles. A weighted average velocity is obtained based on the number of cycles.

Table V. Average Wave Velocities at Different Test Bed Lengths

Material	Test Bed	Expansion Joint	Velocity (ft/s)
Kaolin	86.9 m (285 ft)	Yes	8.95
Kaolin	86.9 m (285 ft)	No	9.52
Kaolin	189.3 m (621 ft)	Yes	9.64
Kaolin	189.3 m (621 ft)	No	9.58
Al. Gel.	189.3 m (621 ft)	Yes	8.02
Kaolin	547.7 m (1797 ft)	No	6.20 – 7.81
Kaolin	547.7 m (1797 ft)	Yes	6.33 – 8.37
Al. Gel.	547.7 m (1797 ft)	Yes	5.23 - 8.13
Phosphate	547.7 m (1797 ft)	Yes	4.96

For the 547.7 m (1797 ft) trials, a range of velocities is presented. Since the process control parameters were varied during the unplugging process, and in some cases the variations were extreme, reporting an average velocity has no meaning.

Average velocities for the 86.9 m (285 ft) and 189.3 m (621 ft) test beds appear to have shown little difference. This is due in part to NuVision engineers selecting the optimal parameters prior to testing. The velocities at the 547.7 m (1797 ft) test bed were generally lower. This could be due to a number of factors including the fact that the process control parameter selection was limited by the relief valve setting of 1.034 MPa (150 psi). This test bed also will see higher pressure losses and will have larger air cavities due to the limitations of the vacuum pump. In addition, the variability in the cavity size at 547.7 m (1797 ft) test bed required numerous attempts to adjust the parameters during the unplugging process. The variability was likely caused by the environmental conditions.

Correlation of Wave Speeds with Pressures

It is anticipated that the maximum pressure and amplification factor have a relationship to the wave speed generated near the plug. In this section, the wave speeds from the blind flange testing are compared against the amplification factors and maximum pressures. Although individually results do not show a direct correlation, when all of the test bed data is considered a linear trend seems to be more discernable. It should also be noted that for the test parameters selected, as the test bed is increased in length, the amplification factor and wave speed decreases.

Similar consideration can be obtained for the maximum pressure. For the 86.9 m (285 ft) and 189.3 m (621 ft) test beds, it was found to be a relationship for the maximum pressure with the wave speed. Unlike with the amplification factor, discernable group correlation was found to exist with the wave speed. The results associated with the 86.9 m (285 ft) test bed appear to produce higher wave speeds with similar maximum pressures. The plug speed data from **Error! Reference source not found.** can also be compared to average amplification factors and maximum pressures. These values are shown in Table VI. Note that the wave speed reported for the phosphate only encompasses one set of cycles. A number of 5-cycle sets with different parameters were run and wave speeds were not obtained (*).

Correlations between wave speeds and the pressure data are difficult to establish. The variability for 547.7 m (1797 ft) trials is clear with maximum pressure ranging from 793 kPa (115 psi) to 344.7 kPa (50 psi). Similar variability is shown for the amplification factors.

Table VI. Average Wave Speeds at Different Test Bed Lengths

Material	Test Bed	Expansion Joint	Wave Speed	Max Pressure	Amp Factor
Kaolin	86.9 m (285 ft)	Yes	2.73 m/s (8.95 ft/s)	484 kPa (70.20 psi)	2.42
Kaolin	86.9 m (285 ft)	No	2.9 m/s (9.52 ft/s)	508.2 kPa (73.71 psi)	2.54
Kaolin	189.3 m (621 ft)	Yes	2.94 m/s (9.64 ft/s)	613.5 kPa (88.98 psi)	2.05
Kaolin	189.3 m (621 ft)	No	2.92 m/s (9.58 ft/s)	775.7 kPa (112.51 psi)	2.60
Al. Gel.	189.3 m (621 ft)	Yes	2.44 m/s (8.02 ft/s)	778.8 kPa (122.96 psi)	2.83
Kaolin	547.7 m (1797 ft)	No	1.89-2.38 m/s (6.20-7.81 ft/s)	788 kPa (114.29 psi)	3.94
Kaolin	547.7 m (1797 ft)	Yes	1.93-2.55 m/s (6.33-8.37 ft/s)	603.36 kPa (87.51 psi)	2.01
Al. Gel.	547.7 m (1797 ft)	Yes	1.6-2.47 m/s (5.23-8.13 ft/s)	343 kPa (49.75 psi)	2.13
Phosphate	547.7 m (1797 ft)	Yes	1.51 m/s *(4.96 ft/s)	533 kPa (77.319 psi)	2.13

Correlation of Wave Speeds with Erosion Rates

Error! Reference source not found. combines the wave speeds and unplugging rates for the various plugs and test beds. During testing, it was observed that on some 86.9 m (285 ft) trials the wave had a different form than for the 189.3 m (621 ft) and 547.7 m (1797 ft) test beds. In the 86.9 m (285 ft) trials, the wave form often approaching the plug could be described as a slug wave, which could actually compress the plug instead of erode it. Even though the wave speed may be high, the erosion rate may be adversely affected. For the longer test beds, the wave had more of a slicing form. This wave form did not appear to have any adverse affects. Note that phosphate results are not presented for the shorter test beds because the charge vessel was not pre-charged during testing.

Table VII. Average Wave Speeds and Unplugging Rates at Different Test Bed Lengths

Material	Test Bed	Expansion Joint	Wave Speed	Unplugging Rate (kg/hr)
Kaolin	86.9 m (285 ft)	Yes	2.73 m/s (8.95 ft/s)	.452
Kaolin	86.9 m (285 ft)	No	2.9 m/s (9.52 ft/s)	.900
Kaolin	189.3 m (621 ft)	Yes	2.94 m/s (9.64 ft/s)	.650

Kaolin	189.3 m (621 ft)	No	2.92 m/s (9.58 ft/s)	.282
Al. Gel.	189.3 m (621 ft)	Yes	2.44 m/s (8.02 ft/s)	.477
Kaolin	547.7 m (1797 ft)	No	1.89 – 2.38 m/s (6.20 – 7.81 ft/s)	.088**
Kaolin	547.7 m (1797 ft)	Yes	1.93 – 2.55 m/s (6.33 – 8.37 ft/s)	.214
Al. Gel.	547.7 m (1797 ft)	Yes	1.6 – 2.48 m/s (5.23 - 8.13 ft/s)	.146
Phosphate	547.7 m (1797 ft)	Yes	1.51 m/s (4.96* ft/s)	6.332

For the 86.9 m (285 ft) and 189.3 m (621 ft) kaolin trials with the expansion joint, the wave speed is slightly higher for 189.3 m (621 ft), however, the unplugging rate is .65 kg/hr compared to .452 kg/hr. This likely has to do with the different wave forms previously mentioned. This trend is opposite for the trial without the expansion joint, where similar wave speeds for the two test bed lengths produce extremely different unplugging rates (189.3 m (621 ft) case is lower). In general there is a decrease in wave speeds and erosion rates from the 189.3 m (621 ft) test bed to the 547.7 m (1797 ft) test bed. Interestingly, the phosphate plug at the 547.7 m (1797 ft) test bed had the lowest wave speed and the highest unplugging rate. This was because the phosphate plug dissolved very easily in the presence of water.

CONCLUSIONS AND DISCUSSIONS

The objective of this study was to further understand underlying physics of NuVision's unplugging technology. Experimental testing was conducted using three pipeline lengths and three types of blockages. Erosion rates have been obtained and pressure data has being analyzed. An amplification of the inlet pressure was observed along the pipeline and is considered the key to determining the maximum pipe lengths the technology can be used without surpassing the site pressure limit. The technology was capable of eroding the three plugs at the three test bed lengths.

Field observations indicate that the pressure cycling during suction and drive phases aid in the unplugging process. Wave speeds have also been analyzed to determine correlations between the amplification factors, unplugging rates and equipment control parameters utilized by NuVision. Although some correlation is observed between erosion rates and other test parameters, the parameters that directly influence the correlation are not easily discernable. The amplification factors were correlated to the process control parameters (i.e. an increase in drive time for the same drive pressure will increase the amplification factor – an increase in suction time will decrease the amplification factor). The process control parameter, in turn, directly affects wave speeds. It was also noted that the cavity size affected the amplification factor and resulting wave speeds. Variability in the environmental conditions at the 1797 ft pipe length makes it difficult to draw conclusions related to the unplugging performances.

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