Evaluation and Development of Innovative High-Level Waste Pipeline Unplugging Technologies - 10136

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ABSTRACT

In this paper, the experimental results and data analysis of AIMM Technologies' Hydrokinetics™ method are presented. A heavily instrumented 3-inch diameter pipeline was used with three types of plugs that replicated the material properties typical of Department of Energy (DOE) high-level waste (HLW). One of these plug types was a Bentonite-water mixture typically used in emulating slurry mixes. Two additional salt crystallized plugs were selected for their ability to withstand greater hydraulic pressures. One was based on potassium-magnesium-sulfate and the second was based on sodium-aluminum-silicate (recommended by the Hanford Waste Treatment and Immobilization Plant (WTP) engineers). Three different test bed lengths (310, 646, and 1822 ft) were utilized to determine the effectiveness of the Hydrokinetics™ method with respect to distance from the pipeline inlet to the blockage. Testing trials demonstrated that pressure pulses and vibrations were significantly attenuated from the inlet to the plug. The Hydrokinetics™ method was generally successful in removing the Bentonite plugs but had difficulty removing the crystallized salt plugs. Additionally, FIU is currently evaluating two proposed alternative pipeline unplugging methods that may remove blockages in pipelines. These are an asynchronous pulsing system, and an *in situ* peristaltic crawler technology. The asynchronous pulsing method is based on the idea of creating pressure pulses in the pipeline filled with water from both ends of the blocked section. The pulses are created asynchronously in order to shake the blockage as a result of the unsteady forces exerted by the pulses. The peristaltic crawler is a pneumatic-operated crawler that propels itself by a sequence of pressurization/depressurization of cavities (inner tubes). These pressurization sequences translate to forward/reverse propagation of the crawler by the peristaltic movements. The inner tubes are mounted on a flexible skeleton emulating a spine. This allows it to turn around elbows. Once the crawler reaches the plug it can employ different unplugging technologies (water drilling, chemical dispensing, pressure waves, etc.).

INTRODUCTION

As Hanford moves into a more active retrieval and disposal program, the site engineers will be encountering increasing cross-site pipeline transfers with a corresponding increase in the probability of a pipeline getting plugged. In the past, some of the pipelines have plugged during waste transfers, resulting in schedule delays and increased costs. Furthermore, pipeline plugging has been cited as one of the major issues that can result in unplanned outages at the Waste Treatment and Immobilization Plant (WTP), causing inefficient operations and extra costs. As such, the availability of a pipeline unplugging tool/technology is crucial to ensure effective operation of the waste transfers and to ensure Hanford tank farm cleanup milestones are met. Previous studies at Florida International University (FIU) included the testing and evaluation of unplugging technologies through an industry call. Based upon these tests, two commercial technologies were identified that could withstand the rigors of operation in 2 or 3 inch diameter pipelines and had the ability to work through multiple sharp 90° elbows [1,2]. The testing and evaluation of these two technologies extends the technology validation performed earlier and attempts to provide a fundamental understanding of how the technology functions and what limitations they may have when operating within strict site operation requirements. Last year we published results of the NuVision Eng. Inc. technology [8] and this paper focuses on results from testing of AIMM Technology's Hydrokinetics™ method as well as presents new concepts for pipeline unplugging that are being developed at FIU to attempt to improve unplugging capabilities and performance of these technologies.

The outline of the paper is as follows. First, unplugging principles of the Hydrokinetic process are summarized. The experimental set-up is described and blockage materials are explained next, followed by the experimental results. Finally, two approaches that FIU is beginning to develop will be described and then conclusions will be presented.

HYDROKINETICS' UNPLUGGING PRINCIPLES

The Hydrokinetics™ method is a patented technology that has been used to unplug pipelines partially or fully plugged with a variety of materials. It has been reported by others that the technology works by breaking the mechanical bonds between the plug and the pipe wall by first filling the pipeline with liquid up to the plug and then creating cavitations in the fluid filled pipe by applying pressure pulsations at the inlet [1]. The cavitations formed in the water column collapse due to the applied pressure cycles that vibrate the blockage and the pipe wall. The difference in vibration frequencies of the blockage and the pipe wall breaks the mechanical bond between them and the blockage is pushed out by the fluid pressure.

The Hydrokinetics™ system consists of a water/solvent tank, a plunger type pump, a portable air compressor and a control unit. First, the connections between the air compressor, water pump and pipeline with the control unit are established using high pressure hoses. The water pump is turned on and switched to the desired RPM value. The pressure level in the control unit is adjusted using the pressure regulating valve at the control unit. There are two switches on the control unit that allow the water collected in the control unit to be directed into the pipeline. Using these switches, the pipeline is filled at the flow rate of the pump until the pressure in the pipeline has reached the pressure set at the control unit.

The Hydrokinetics™ process does not require that a vacuum be created in the pipeline prior to the pipeline being filled. Since the air is not evacuated from the pipe, a two-component fluid system is formed inside the pipeline. Using the switches on the control unit, pressure fluctuations are created in the pipeline in a randomized manner. This process is repeated until the blockage is successfully removed or the operator terminates the attempt of unplugging the pipeline. The frequency and duration of pulsations are set by the AIMM operator, while the pressure of pulsations is set to the maximum pressure permitted.

Benefits of AIMM's Hydrokinetics™ technology include:

- Short mobilization and demobilization time
- Can be used to deliver chemical solvent to the blockage where a solvent may be of assistance in loosening a blockage
- System does not cause significant pressure amplifications
- Technology can negotiate many 90 degree elbow turns
- Technology can be operated remotely
- Unplugging times are short compared to other technologies

Limitations of AIMM's Hydrokinetics™ technology include:

- Time to fill the pipeline is long
- Pulsations are manually controlled and are not automated

EXPERIMENTAL TESTING

Process variables important to this study include unplugging rates, pipeline pressure distributions (maximum pipe pressure), and the variability of the distributions with respect to the equipment control parameters. The equipment control parameters, which are provided later in this report, are the parameters AIMMs must select to operate their equipment. The effects of these parameters on the pipeline pressure and unplugging rates need to be well understood. In addition, to qualify AIMM's technology, maximum pressures need to be determined and compared with site safety requirements. Due to the lack of information on exactly how the AIMM's technology scales to longer pipes, we have 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
- Temperature of the water in the test bed pipeline
- Operation time
- Plug weight – before and after technology operation
- Unplugging efficiency
- Control unit pressure and pump RPM

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

TEST BED DETAILS

Experiments were conducted using three test bed lengths at 310 ft, 646 ft and 1822 ft. Using a non-linear regression analysis, the measurements taken at these three lengths can be used to forecast the performance of the technology for longer pipeline lengths.

The instrumented test bed was designed and constructed with the capability to evaluate the impact of a number of parameters on the technology effectiveness, including: the distance to the plug and pipe layout (e.g., bends, expansions, reducers, etc.). Elbows found in pipelines and expansion joints can provide significant obstacles to unplugging technologies. For technologies that utilize the pulsation of fluid that propagates toward the blockage area in a liquid/gas environment, the elbows can adversely affect the propagation of the pulse and hamper the effectiveness of the unplugging technology. This is also true for abrupt reductions in pipeline area which is emulated in our testing with a pipe reducer.

A schematic diagram of the 1822 ft test bed is shown in Fig. 1. The three pipelines are connected to each other using two-way ball valves. This allows switching from one pipeline to another with minimum down time. In Fig. 1, the lines in grey demonstrate the pipes that are not used for that length and the black lines show the pipes that are in use. The test beds were constructed from 3-inch diameter, 21-foot long, Schedule 10, carbon steel pipe sections joined by Victaulic couplings. The pipes were clamped to 4x4's that were fixed to the ground with rebars.

The test bed was designed such that the inlet and exit sections remained in the same location for each of the three test beds. To simulate the connection to the transfer lines in a pit, a 3 ft long inlet section was connected vertically to the long horizontal section via a sharp 90^{o} elbow. A 300 psi pressure relief valve was placed at the bottom of the inlet section. The relief valve was sized according to the maximum pressure limit in the DOE waste transfer lines. The test bed entry point was equipped with a 1" tee section. A 3-way ball valve was used at the inlet which enabled the connection of the water tank to the pipeline during flooding of the pipes and to AIMM's pump during the unplugging operation.

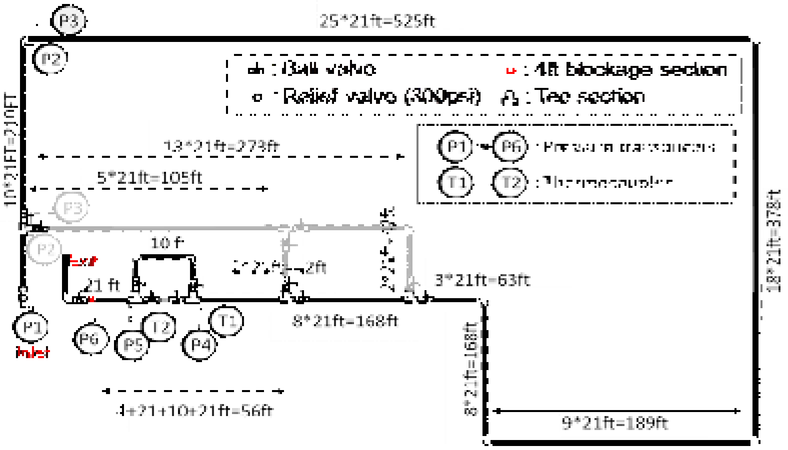

Fig. 1. Schematic of the 1822 ft test bed (Dimensions not to scale).

In Fig. 1, it is shown that pressure transducers were located throughout the test bed. P2 and P3 were placed around a 90° turn to evaluate the effect of turns on pressure propagation. Similarly P4 and P5 were placed to determine the effect of an expansion joint on the unplugging process. One dynamic and one static pressure transducer were used at each pressure point on the pipeline. The static pressure sensors were Omega PX319-1KGI type with 0-1000 psig range and had less than 1 ms of response time. Dynamic pressure sensors were of Omega DPX101-1K type with 0-1000 psig range and 0.0083 response time. The dynamic sensors provided any fluctuation in the nominal pressure that static pressure sensors could not detect. In Fig. 1, T1 and T2 represent the locations where water temperature was recorded. Two K-type thermocouples with 1 second of response time were used for temperature measurements. Two 34201A type accelerometers with ±2g range were used during the tests in order to capture acceleration in three degrees of freedom of the pipes at the inlet and blockage sections. The sensors were connected to a data acquisition (DAQ) system from National Instruments with Field-Programmable Gate Array capability that allowed recording high speed data and LabView software was used to observe real-time variation of collected data.

For the unplugging experiments, the blockage section was also made out of 3-inch diameter, 4-foot long, Schedule 10, grooved-end carbon steel pipes. The blockage sections were connected to the rest of the pipeline using the same Victaulic 77 type elastic couplings. In cases where 8 ft or 12 ft blockages were required, multiple 4 ft blockage sections were coupled together to make a longer blockage section.

Also shown in the test bed drawing (Fig. 1), is a removable expansion joint located just upstream of blockage section. This joint, containing three 10-ft sections, emulates the expansion joints typical of the cross-site lines at Hanford. The expansion joint can be removed in order to evaluate the effectiveness of the technology with and without the joint by using the two-way ball valves.

For one test at 310 ft a constricted section in the pipeline was created by placing a pair of 3 to 2-inch reducers to evaluate its effects on the performance of the technology. The constriction was installed on the 310-ft test bed during parametric testing with no blockage, upstream of the expansion joint.

The various lengths of the test beds were used to evaluate how the effectiveness of the unplugging technology was impacted by the distance to the blockages as well as pipe layout (e.g., bends, expansions, reducers, and elevation changes before and after the plug).

BLOCKAGE MATERIALS

Although one of the primary functions of this research is to provide a fundamental understanding of how the unplugging technology operates, blockage materials were also generated to assist in the evaluation of the technology. The types of blockage material (clay, salt, etc.) utilized for testing was selected based on recommendations from site engineers in conjunction with FIU engineers. For the AIMM Technologies unplugging evaluation, three different blockage materials were utilized to simulate various plugging scenarios at DOE sites. The criterion in choosing the specific blockage materials for AIMM Technologies was related to their mechanical strength characteristics. Since the test bed operating pressure was limited to 300 psi, plugs with extrusion pressures greater than 300 psi were required. Otherwise, AIMMs could easily remove plugs by simply raising the pressure in the system to a value greater than the plug extrusion pressure. In order to prepare for this criterion, various plugs were manufactured and tested on a small extrusion test bed. The extrusion test bed consisted of a hand pump that was rated to 700 psi, two pressure gauges, a pressure relief valve and an air release valve. In order to achieve the desired extrusion pressure, a number of variables were considered including plug length and plug material.

The procedure of the extrusion test is straightforward. The air release valve was opened and the water was turned on. Once the air was removed from the pipe, the release valve was closed and pressure built up in the system. The pressure was further increased by using the hand pump until the plug started moving. The maximum pressure attained was noted. In case the plug did not come out, the pressure was applied for 15-20 minutes and then the procedure was halted. The summary of blockage materials tested for extrusion pressures are listed in Table I.

In Powell, et al. it was reported that shear strength, cohesiveness and water-absorption rate were among key sludge properties that determined the performance of unplugging methods [5]. In previous unplugging tests, Kaolin clay water mixture was used because it was recommended as a sludge simulant by Golcar, et al. [4] and Powell [6] since it's shear strength, cohesiveness, particle size distribution, and density (at 66-67 wt% kaolin in water) were similar to those of tank sludge. The shear strength of 66% Kaolin water mixture is 3.5 kPa, which can be multiplied with the surface area to estimate the dynamic friction force applied by the pipe walls on the plug.

When a 4 ft plug of 66% Kaolin was used, the minimum hydrostatic pressure required to remove the plug was 12.8 psi, which was significantly lower than AIMM's minimum operating pressure limit. Bentonite clay, however, was a better choice for testing with AIMM Technologies since it had a higher shear strength value (~19.2 kPa at 66%) at the same composition [5]. For a 4 ft 68% Bentonite plug, the hydrostatic pressure required to remove the plug was found to be between 100 and 170 psi (Table I).

Plug extrusion tests were also conducted for 8 ft Bentonite plugs. The extrusion pressure for the 4 ft plug, although higher than the Kaolin plug, was still low for the testing purposes. The 8 ft Bentonite plugs had extrusion pressures of approximately 300 psi.

The Bentonite-water mixture was prepared in a large bucket and mixed using a drill attachment until uniformity was achieved. Four-foot steel pipes that were closed on one side were then completely filled with the mixture by dropping small pieces in and compressing with a long plunger rod. In order to remove air gaps that can get entrapped inside the blockage during filling, the blockages were compressed using a torque wrench.

Phosphate and aluminum based plugs, which were used in previous unplugging experiments, were also not qualified for testing with AIMM Technologies because of low extrusion pressures (30 and 5 psi respectively). A potassium-magnesium sulfate (Kmag) plug was selected to represent a crystallized salt plug, and a Na-Al-Si plug was selected to emulate a crystallized chemical plug. The recipe for the Na-Al-Si plug was provided from engineers at Pacific Northwest National Laboratory (PNNL). The chemicals and procedure required to prepare a Na-Al-Si plug can be found in Roelant, et al. [7].

Table I. Summary of Extrusion Tests with Various Types of Blockages.

Plug Type	Plug Length (ft)	Max Pressure (psi)
Aluminum Gel	4	5
Aluminum Gel	4	15
Phosphate	4	30
30% Bentonite, 30% Kaolin	4	45
60% Bentonite	4	150
65% Bentonite	4	190
60% Bentonite	4	100
60% Bentonite	4	150
65% Bentonite	4	185
60% Bentonite	8	230
68% Bentonite	8	300
68% Bentonite	4	100
68% Bentonite	8	300
68% Bentonite	4	130
68% Bentonite	4	170
90% Kmag non-pulverized	4	200
80% Kmag non-pulverized	1	55
90% Kmag pulverized	1	300
90% Kmag pulverized	4	650*
90% Kmag pulverized	4	600*
90% Kmag pulverized	2	300
Na-Al-Si	4	500

* Plug did not fail

The Na-Al-Si and Kmag plugs had significantly higher extrusion pressures. The 4 ft Na-Al-Si plug had an extrusion pressure of 500 psi and the 2 ft Kmag plug had water leakage at 300 psi. It should be noted that Kmag is water soluble and its extrusion pressure may be time dependent.

The Kmag plug was selected due to its high mechanical strength. The product was in a granular form and had to be pulverized using a grinding machine before mixing with water. For a 4 ft plug containing 90% of Kmag and 10% water mixture, 1.5 liters of water was mixed with 13.5 kg of Kmag in a bucket using a drill mixer for about 30 minutes. The mixture was then poured into a 4 ft steel pipe that was closed on one side using a Victaulic cap and a Victaulic 77 coupling. The material was packed using a plunger during filling. When the pipe was full the open end was sealed using parafilm and the pipe was left to cure overnight.

All of the plugs were created in 4-ft pipe lengths except Kmag plug which was manufactured in 2-ft and 4-ft pipes. They were weighed before and after each unplugging test to determine the weight of removed plug material and effective unplugging rates. After each plug was completed, parafilm was placed on both ends of the pipe to preserve the plug material in its original configuration.

AIMM TECHNOLOGY'S EQUIPMENT

The Hydrokinetics™ system comprised of a water tank, plunger pump, air compressor and a control unit. Water was stored in a 2500-gallon storage system and was fed to the plunger pump during the unplugging operation. An air compressor provided compressed air at 75 psi. The compressed air was connected to a control unit in order to operate the pneumatic valves that control the flow in and out of the control unit. A pressure gauge on control unit was used to track the water pressure in the unit and a regulating valve was used to adjust the pressure in the pipeline. Switches were used to let water in and out the control unit and create pulses. The frequencies of pulsations were determined manually by the operator. Further details regarding the system configuration are provided in Roleant, et al [7].

TEST PLAN

A number of test trials were run during the commissioning stages of the equipment. The commissioning test cases and results can be found in Roelant, et al. [7]. Table II provides the details of the final test plan.

Three different blockages were used on each of the three pipelines. The blockages were placed into 4-ft carbon steel sections which were combined together using couplings for the 68% Bentonite 8 ft and 12 ft cases. A 21 ft discharge section was placed after the blockage section which was connected using a 90º Victaulic elbow. The blockage had to make its way around the elbow before getting unplugged.

Table II. Final Test Plan.

Trial #	Reducer	Expansion Joint	Blockage Type	Blockage Length	Distance to Blockage
1	0	1	Bentonite	8 ft	310 ft
2	0	1	Bentonite	12 ft	310 ft
3	0	1	Kmag	4 ft	310 ft
4	0	1	Na-Al-Si	4 ft	310 ft
5	0	0	Na-Al-Si	4 ft	310 ft
6	0	1	Capped	N/A	310 ft
7	1	1	Capped	N/A	310 ft
8	0	1	Bentonite	8 ft	646 ft
9	0	1	Bentonite	12 ft	646 ft
10	0	1	Kmag	4 ft	646 ft
11	0	1	Na-Al-Si	4 ft	646 ft
12	0	1	Capped	N/A	646 ft
13	0	1	Bentonite	8 ft	1822 ft
14	0	1	Bentonite	12 ft	1822 ft
15	0	1	Kmag	4 ft	1822 ft
16	0	1	Na-Al-Si	4 ft	1822 ft
17	0	1	Capped	N/A	1822 ft
18	0	0	Capped	N/A	1822 ft

The final test plan also shows that an expansion joint was used in the baseline test bed for all plug types and all pipe lengths. (The number 1 in the test plan indicates that it was used in the trial and the number 0 indicates that it was not used in the trial.) For the 310 ft test bed, one trial was conducted without the expansion joint using a Na-Al-Si blockage to determine the effects of the expansion joint. For the 310-ft test bed, a constriction was inserted using two 3” to 2” reducers just upstream of the expansion joint to see what effects it would have on the pipeline pressures during testing with the capped pipeline. Capped pipeline testing (no plug) was conducted in which the control unit pressures and pulsation frequencies were varied to analyze their effects on the pulsation mechanics and resulting pressures.

Additionally, parametric testing was conducted on various parameters of AIMM’s system (RPM, and pressure) to determine the effect of these control parameters on the system operating conditions. These tests were conducted on various pipeline configurations with the pipeline capped, having no blockage. Details of the specific parametric testing is included in Roelant, et al [7].

RESULTS AND OBSERVATIONS

The test performed using AIMM’s Hydrokinetics™ method is shown in Table III. The table includes pipeline length, configuration (expansion loop on or off) and plug type. It also includes some results such as maximum pressure attained, whether the plug was removed, and the length of time the trial lasted.

AIMMs was able to unplug 6 out of 13 cases tested at three different pipeline lengths. The shortest unplugging time was 16 min, while the longest unplugging time was 73 min. In all of the cases, the technology was kept from pressurizing the pipeline above 300 psi. It is clear from the results that AIMMs had much more difficult time removing the Kmag and Na-Al-Si plugs than the 68 % Bentonite plugs. Only one of the salt based stimulant plugs was removed during the final test plan whereas all but one of the clay stimulant plugs were removed.

Table III. Summary of Unplugging Cases in the Final Test Plan.

Trial #	Expansion Joint	Distance to Blockage	Blockage Type	Blockage length	Maximum Pressure	Success	Time
1	1	310 ft	Bentonite	8 ft	272.2 psi	Yes	16 min
2	1	310 ft	Bentonite	12 ft	286.3 psi	Yes	30 min
3	1	310 ft	Kmag	4 ft	265.1 psi	Partial	40 min
4	1	310 ft	Na-Al-Si	4 ft	292.8 psi	No	52 min
5	0	310 ft	Na-Al-Si	4 ft	285 psi	No	21 min
6	1	646 ft	Bentonite	8 ft	225.3 psi	Yes	17 min
7	1	646 ft	Bentonite	12 ft	264.2 psi	Yes	18 min
8	1	646 ft	Kmag	4 ft	287.1 psi	No	54 min
9	1	646 ft	Na-Al-Si	4 ft	278.3 psi	No	41 min
10	1	1822 ft	Bentonite	8 ft	291.7 psi	No	115 min
11	1	1822 ft	Bentonite	12 ft	214.2 psi	Yes	73 min
12	1	1822 ft	Kmag	4 ft	318.7 psi	No	40 min
13	1	1822 ft	Na-Al-Si	4 ft	286.8 psi	No	52 min

Based on the collected data, the pressure for the successful unplugging cases demonstrated a common profile in pressure cycling during the unplugging process. Specifically, two distinct operating regions were observed for the Hydrokinetics™ process: a *flooding zone* where the pipeline pressure was increased up to a specified static limit, and a *target pressure zone* where the pulsations were created once the pressure was built up to the required limit. Unplugging typically occurred during the target pressure zone but occasionally occurred in the flooding zone. The need to analyze both zones required the use of different analytical techniques, depending on the zone. The zones were numerically determined by an algorithm that uses the moving averages of the data and computes the slope of the resulting curve. The drop of the slope of that curve below a pre-set value marks the boundary between the *flooding* and *target pressure zone.* An extensive description of the data analysis can be found in Roelant, et al [7]. Fig. 2 presents the pressure profile for a successful unplugging trial at specific transducers, with the flooding zone and the target pressure zones delineated. The red line shows the pressure at the test bed inlet, while the green line is the pressure adjacent to the second elbow 45 ft apart. To determine the pressure amplification or attenuation effects of the pressure pulses along the pipeline, maximum pressure values at each transducer were compared.

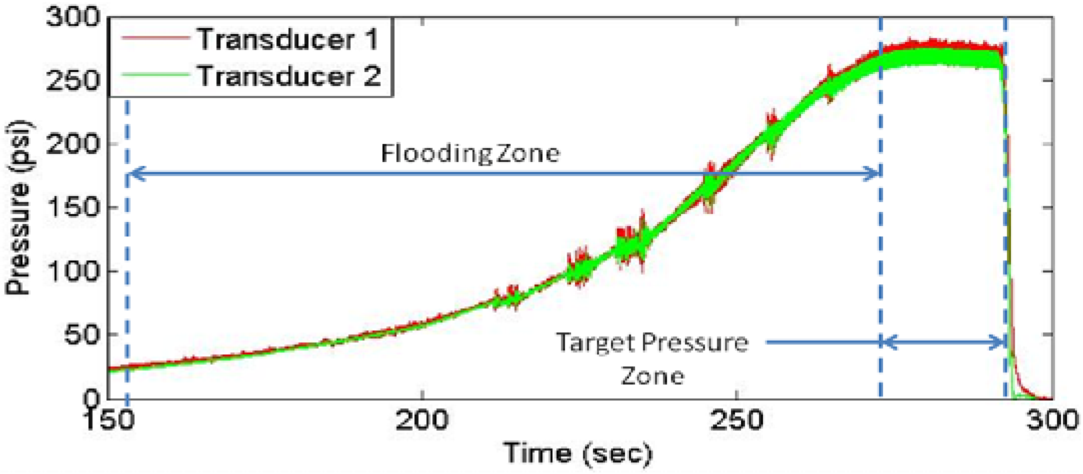

Fig. 2. Typical pressure curve of a successful unplugging trial.

The results showed that during the target zone, as the distance between the pressure transducers increased, the fluctuation created by the Hydrokinetics™ process around the nominal pressure in the target zone decreased except for the 1822 ft case. The case at the 310 ft test bed is given in Fig. 3(a) where the ratios of positive deviations from the nominal pressures at various pressure points in the pipeline are plotted with respect to the separation of distance between each transducer. It was observed that as the distance between sensors increased, the final pressure observed close to the plug approached the mean average value, meaning that the fluctuations diminished as the distance to the plug location was approached. It should be mentioned that, the first data point in Fig. 3(a), which is $\Delta P_2/\Delta P_1$ includes only the effect of the straight 42 ft of pipe whereas $\Delta P_4/\Delta P_3$ includes the effects of two 90° elbows and $\Delta P_6/\Delta P_1$ includes the effects of three 90° elbows and the expansion joint.

It was also observed that the pressure pulsations created by the Hydrokinetics™ process during the flooding zone had a similar profile compared to the target pressure zone. The fluctuations in the pressures reduced significantly compared to the inlet pressure as shown in Fig. 3(b) for the case at 310 ft test bed. For the majority of the pulsations created at the inlet, the resulting disturbance in the pipeline pressures was reduced by 42% over the first straight pipe section of 42 ft in length. This value went up to 80% from the third transducer to the fourth, which was 189 ft apart and included a 90° elbow. Plots for 4 ft Kmag and 4 ft Na-Al-Si plugs are missing in Fig. 3(b) because no data was collected for these cases in the flooding zone.

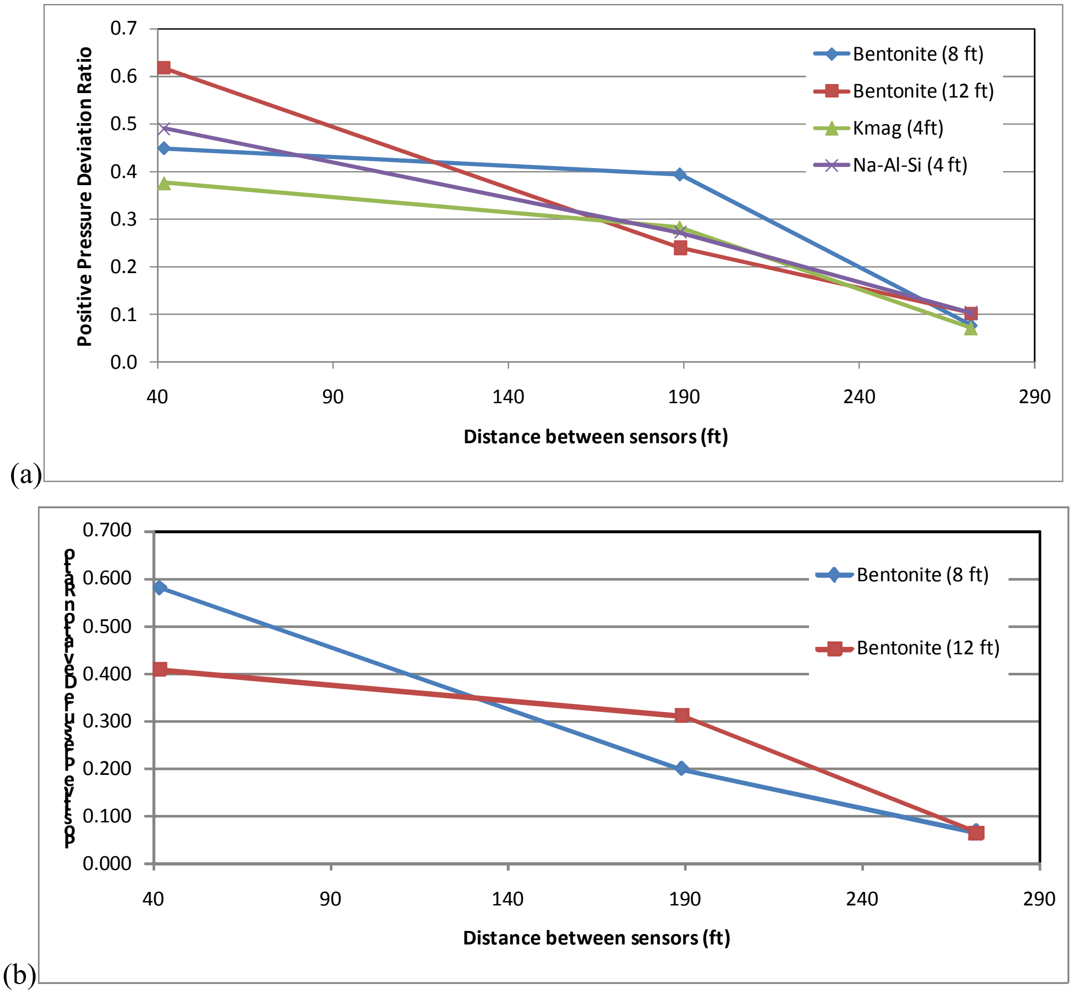

Fig. 3. Pressure ratios ΔP2/ΔP1, ΔP4/ΔP3 and ΔP6/ΔP1 at corresponding distances of 42 ft, 189 ft and 272 ft.

In addition to the effect of distance on pressure in the pipeline, pressure ratios across elbows were analyzed for different pipeline lengths. The general trend of the pressure values yielded that the ratio of mean pressures before and after the elbow is close to unity (0.995-1.003) whereas the pressure fluctuations around the mean across the elbows were generally amplified (Table IV). The amplification in the fluctuation in pressure after the elbow was expected to result from the compression of pressure waves reflected into the exit of the elbow. It should be mentioned that the elbows used in the current work for the 310 ft and 646 ft pipelines were not perfect 90° sweeping elbows, rather three way ball valves with one end closed creating a T-shape with two ends open. Generally, the amplification increased with increasing pipeline length during the target pressure zone. However, this did not hold for the flooding zone.

The effect of an expansion joint on pipe pressures were evaluated during parameter testing trials at the 1822 ft test bed with the pipeline end blocked with a cap in place of a real plug. The expansion joint consisted of 4 elbows and three 10 ft pipe sections, and three different engine RPMs (1350, 1413, 1450) and three different pulsing pressures (150, 200 and 250 psi) were used during testing. While the mean pressure before and after the expansion joint remained almost constant ($1.002<P_6/P_5<0.995$), the ratio of pressure deviations from the mean pressures across the expansion joint were found to be smaller with the expansion joint connected (Table V). Especially for lower pump RPMs, the expansion joint reduced the fluctuations around the mean pressure more, which was observed for all three different inlet pressure tested. However, an increase in the RPM value did not result in a particular trend in the effect of expansion joint. It should be noted that as the inlet pressure was increased, the mean pressures after the expansion joint increased slightly. In general, the ratios showed to be very similar for all trials, indicating there was no trend with respect to the engine RPM or operating pressure. It should be noted that the vibration ratios were small, which means that very little vibration was transmitted to the blockage area. As expected, the trials with the expansion joint off have better attenuation rates than the trials with the expansion joint on. There did not appear to be a significant trend varying the pump RPM or the operating pressure. For the 150 psi trials, the cases with the expansion joint off had slightly higher vibration ratios than the trials with the expansion joint on. This was not the case, however, for the other operating pressures. This change was possibly due to the nature of the imposed boundary conditions of the pipe clamps.

Table IV. Effect of Elbows on Pressure Deviations from the Mean.

	Target Zone							
	Bentonite (8 ft)		Bentonite (12 ft)		Kmag (4ft)		Na-Al-Si (4 ft)	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
310 ft	1.082	1.151	1.109	1.079	0.983	0.917	0.985	1.038
646 ft	1.151	0.988	1.110	1.158	1.117	1.090	1.188	1.157
1822 ft	1.350	1.231	1.431	1.270	1.290	1.208	1.183	1.464
	Flooding Zone							
310 ft	1.326	1.307	1.434	1.300	N/A	N/A	N/A	N/A
646 ft	1.138	1.113	1.324	1.388	1.226	1.318	1.277	1.150
1822 ft	1.314	1.386	1.110	1.206	1.373	1.355	1.212	1.229

Table V. Effect of Expansion Joint on Pressure Deviations from the Mean on the 1822 ft Test Bed.

	150 PSI				200 PSI				250 PSI			
	EJ ON		EJ OFF		EJ ON		EJ OFF		EJ ON		EJ OFF	
RPM	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
1350	0.469	0.457	0.548	0.540	0.459	0.461	0.487	0.488	0.456	0.455	0.515	0.480
~ 1413	0.510	0.490	0.530	0.519	0.450	0.477	0.501	0.487	0.437	0.450	0.489	0.476
1450	0.501	0.488	0.547	0.535	0.484	0.466	0.488	0.487	0.424	0.421	0.491	0.496

Evaluation of the effect of a reduction of pipe cross-sectional area was conducted during parameter testing at 310 ft test bed and at 200 psi pipe pressure. It was observed that when the reducer was placed on the pipeline, the mean pressure slightly increased, while the fluctuations around those mean pressures were found to be generally amplified as well as seen in Table VI. The increase in pump frequency adversely affected the amplification of the pressure fluctuations and the mean pressures around the reducer. The trials with the reducer removed had a slightly lower vibration ratio than the ones with the reducer installed. This suggests that the restriction induced by the reducer caused additional vibrations near the blockage. For this set of data, as the pump RPM was increased, the vibration ratios also increased.

Table VI. Effect of the Reducer on Pressure for the 310 ft Test Bed at 200 psi.

	Ratio of Mean Pressures				Ratio of Deviations from the Mean			
	Reducer ON		Reducer OFF		Reducer ON		Reducer OFF	
RPM	Range		Range		Upper	Lower	Upper	Lower
1350	1.000	1.001	0.996	0.997	0.353	0.338	0.365	0.344
~ 1413	0.997	0.999	0.996	0.998	0.312	0.292	0.278	0.285
1450	0.996	0.999	0.996	0.998	0.252	0.237	0.230	0.229

Significant attenuation in pipeline vibration between the inlet and plug location was observed for all of the unplugging cases, particularly at the longer pipe lengths. For the target pressure zone, the reduction in vibration amplitude was observed to be between 61% and 97.9%. At this zone, as the distance to the plug location was increased for the same plug type, the vibration observed at the plug was reduced. In the flooding zone, the reduction in vibration at the plug section was found to be between 62.4% and 97.7%.

The data for vibration of the pipe walls and internal pipe pressure variations were utilized in a Fast Fourier Transform (FFT) analysis to determine the frequencies of the fluctuations observed in the pipeline. Figure 3 shows the data for one of the trials during the flooding zone captured by a pressure transducer at the inlet in time domain (top) and frequency domain (center and bottom). The frequency domain is divided in two ranges from 0 to 250 Hz (center) and from 250 to 500 Hz (bottom). This allows for better resolution resulting in more accurate visualization of the peak frequencies on the plots.

From Fig. 4, it can be seen that the dominating frequencies for this parametric trial (no blockage) during the flooding zone is at or below 35 Hz. A difference on the pipeline length showed differences in the frequencies captured. As the distance from the pipeline inlet was increased, frequencies above 10 Hz decreased in number (

Table **VII**).

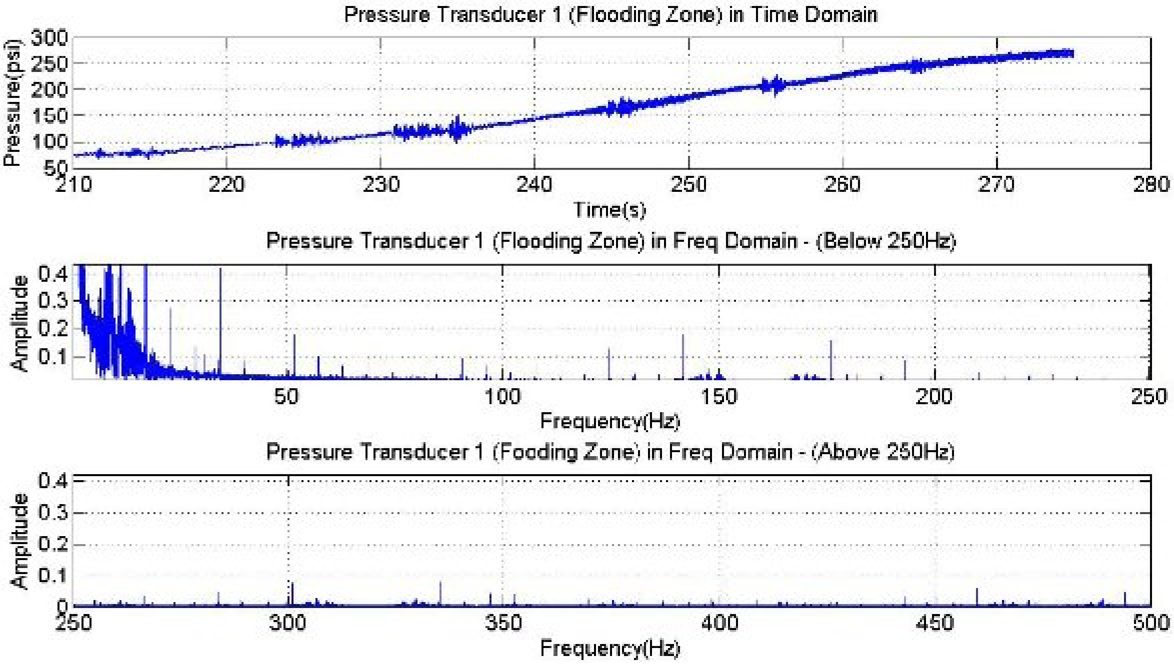

Fig. 4. Signal from inlet pressure sensor in time and frequency domain after FFT analysis.

Table VII. List of Frequencies Obtained from FFT Analysis.

P1	P2	P3	P4	P5	P6	Common Frequencies
1 Hz	1 Hz	1 Hz	1 Hz	1 Hz	1 Hz	1 Hz
2 Hz	2 Hz	2 Hz	2 Hz	2 Hz	2 Hz	2 Hz
3 Hz	3 Hz	3 Hz	3 Hz	3 Hz	3 Hz	3 Hz
4 Hz	4 Hz	4 Hz	4 Hz	4 Hz	4 Hz	4 Hz
5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz
6 Hz	6 Hz	6 Hz	6 Hz	6 Hz	6 Hz	6 Hz
7 Hz	7 Hz	7 Hz	7 Hz	7 Hz	7 Hz	7 Hz
8 Hz	8 Hz	8 Hz	8 Hz	8 Hz	8 Hz	8 Hz
9 Hz	9 Hz	9 Hz	9 Hz	9 Hz	9 Hz	9 Hz
10 Hz	10 Hz	10 Hz	17 Hz	17 Hz	31 Hz	
11 Hz	11 Hz	11 Hz	31 Hz	31 Hz		
12 Hz	12 Hz	12 Hz	60 Hz	60 Hz		
13 Hz	13 Hz	13 Hz				
14 Hz	14 Hz	14 Hz				
15 Hz	15 Hz	15 Hz				
16 Hz	16 Hz	16 Hz				
17 Hz	17 Hz	17 Hz				
19 Hz	23 Hz	23 Hz				
23 Hz	34 Hz	29 Hz				
29 Hz		31 Hz				
31 Hz		34 Hz				
34 Hz						
51 Hz						
125 Hz						
142 Hz						
176 Hz						

As a result of the data analysis on the Hydrokinetics™ process, it was observed that the pressure pulses and pipe vibration attenuated significantly from the inlet to the blockage section during the unplugging process. Since a vacuum was not applied to the pipeline prior to each trial, the environment inside the pipeline can be described as a multiphase system comprised of water and air. The compressibility of water with respect to air is negligible and thus, the remaining air contained inside the pipeline acts as a dampening mechanism to the fluctuations imposed at the inlet. This suggests that the remaining air within the pipeline combined with the low operating pressure, inhibited the ability of the process to operate at its optimum capability. For the complete data analysis of AIMM Technologies, see Roelant, et al [17].

Potential Alternative Pipeline Unplugging Methods

Using the lessons learned from previous unplugging testing, FIU has proposed two alternative unplugging concepts. Recently, proof-of-concept studies for the alternative unplugging techniques have been conducted and presented to site engineers. The following sections provide a description of each of the new approaches and a synopsis of the proof-of-concepts studies.

Asynchronous Pulsing

The Asynchronous Pulsing method is based on the idea of creating pressure waves in the pipeline filled with water from both ends of the blocked section in order to dislodge the blocking material by the forces created by the pressure waves. The waves are created asynchronously in order to break the mechanical bonds between the blockage and the pipe walls as a result of the vibration caused by the unsteady forces created by the waves. The feasibility of using this system is based on a previous study that has shown to effectively create pulses using hydraulic operated machinery coupled with a high speed servo valve [9]. Also, a similar study using vibrations from both sides as opposed to pressure waves indicates that asynchronous pulsing has the potential of being a highly effective technology [10].

In order to design the asynchronous pulsing technology that will be used to remove blockages in pipelines using a sequence of pressure pulses, the propagation of a single pulse in water filled pipes with entrapped air was investigated using the computational fluid dynamics software package, Fluent. In the test cases that were conducted, straight rigid pipes of 3 in inner diameter were used in which the initial water pressure was assigned to 250 psi and a layer of air existed on the top of the water.

For the simulations, a time dependent pressure profile was assigned to create the effect of a pulse at the inlet. The pressure was raised to 300 psi at the inlet for 5 milliseconds and then reduced instantaneously to 250 psi. Three pipes at different lengths, 21 ft, 42 ft and 63 ft, were used in order to investigate the effect of the pressure pulse at the plug which was represented by the rigid wall at the end of the pipe. All lengths, pressures and applied times have been chosen to demonstrate the proof-of-concept and do not represent applied scenarios.

It was found that the pressure at the plug was observed to be amplified when compared to the pulse pressure assigned at the inlet as shown in the simulations in Fig. 5. The amplification depends on the pressure magnitude of the pulse that is able to travel down to the end of the pipe which was found to decay exponentially. However, as the distance to the plug increased the decay in the pressure pulse became more and the amplification of the pressure was reduced. The reduction in plug pressure with distance to the plug was found to be exponential, which showed that in 200 ft the amplification would not be seen.

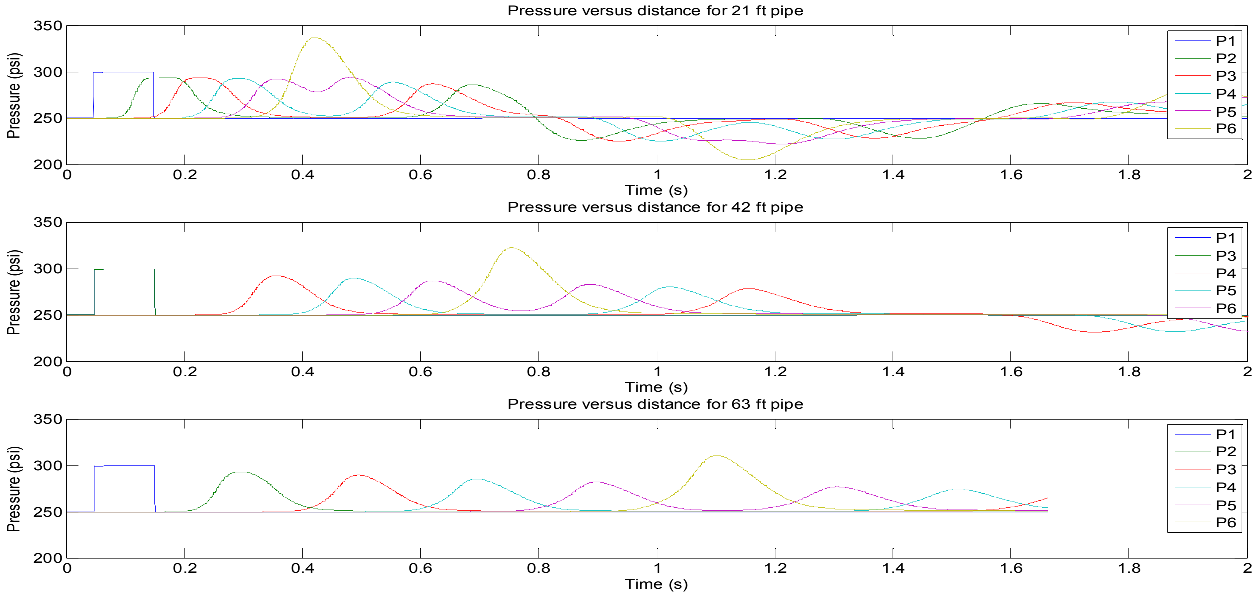

Fig. 5. Pressure variations along the pipes in time.

It was also concluded that the duration of the pulse determined the amount of energy input to the system. The higher energy input the longer distance the pulse could travel. It was concluded that by selecting a long enough pulse according to the distance of the plug, the technology could be used to create unsteady loading on the plug at any distance. The results also suggested that vacuuming the initial air in the pipeline could improve the performance of the technology proposed.

Peristaltic Crawler

The Peristaltic Crawler is a pneumatic/hydraulic operated crawler that propels itself by a sequence of pressurization/depressurization of cavities (inner tubes). The changes in pressure result in the translation of the vessel by peristaltic movements. The inner tubes are mounted on a flexible skeleton emulating a spine. The use of a peristaltic movement mechanism to propel a device inside a pipeline has been previously used in inspection devices [11]. Another device with a similar propelling system was invented by Zollinger [12] which was designed to pull tethers behind underground boring devices. No system using peristaltic movement on a pipe unplugging device was found during this literature review.

The crawler was modeled to have the ability to navigate inside a 3 in diameter pipe and to turn over a 90° elbow having a centerline radius of 3.125 inches. Based on these parameters, the overall dimensions of the unit were calculated. Further design considerations included manufacturability, ease of decontamination, durability to withstand field handling operations and simplicity of maintenance. The crawler consists of two stainless steel rims, four 2.25 diameter inner tubes and a 6 in hollow bellow. Fig. 6 shows the overall dimension of the Peristaltic Crawler.

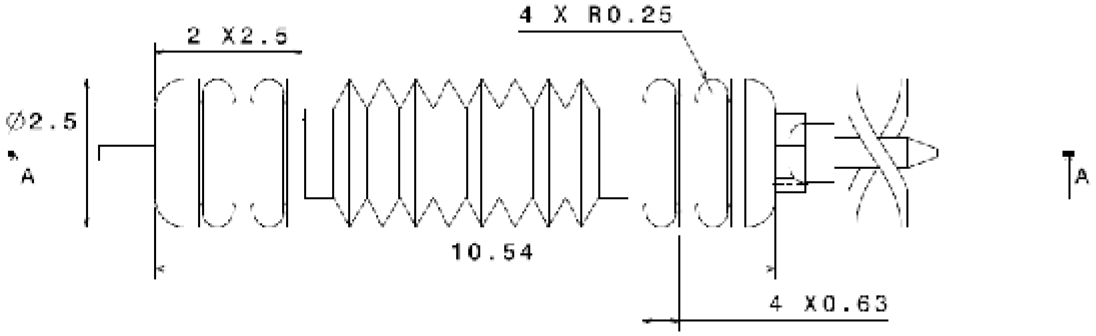

Fig. 6. Overall dimensions of the Peristaltic Crawler (units are in inches).

A finite element analysis (FEA) of the motion of the crawler across an elbow was performed using ABAQUS version 6.8. A simplified 2-D version of the crawler is shown in Fig. 7(a). The stainless steel rims were modeled as rigid bodies and the inner tubes and bellow were defined with hyperelastic materials. Fig. 7(b) shows the computational modeling unit across a 90° elbow.

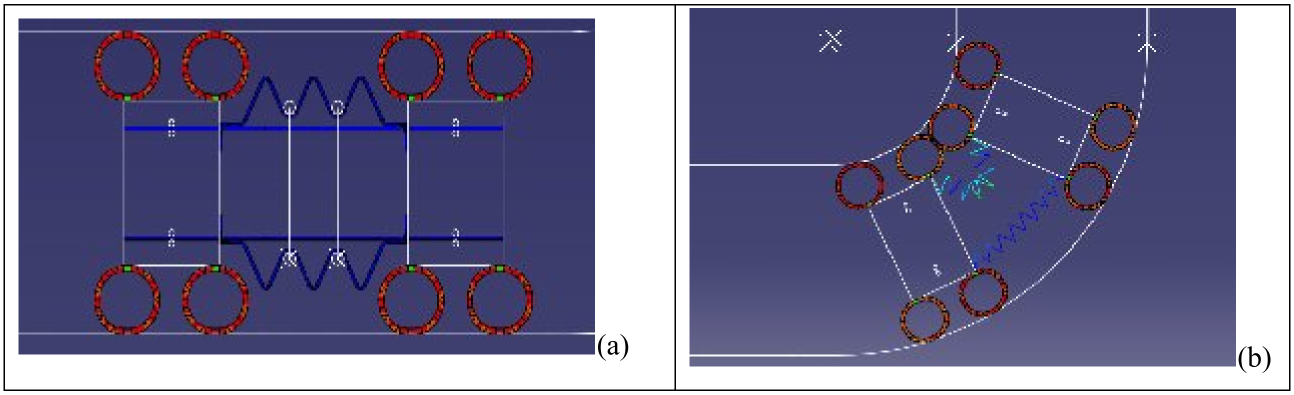

Fig. 7. (a) 2-D representation of crawler (b) turn on a 90° elbow.

Additional analysis regarding the capabilities of the crawler included the maximum pulling force that it could achieve. This force is directly proportional to the ability of the crawler to drag a tether line inside the pipeline. It was found that for the maximum pulling force (about 600 Lb), the unit would slip about 1.6 inches before initiating its forward motion.

In addition to the study of the motion of the crawler, two unplugging attachments were considered on the conceptual design. Both unplugging tools could be securely attached to the front of the crawler depending on the unplugging scenario. The first consisted of a high pressure nozzle and the other of a hydraulic powered auger.

CONCLUSIONS AND DISCUSSIONS

AIMM Technologies Hydrokinetics process was evaluated using an instrumented test bed at three pipeline lengths with three types of blockages. Experiments were conducted to provide an understanding of the underlying principles of how the unblocking technology functioned. Pressure pulses were created at the inlet of the pipeline by opening and closing valves on a pressurized manifold in AIMM's control box. The air in the pipeline was not vacated prior to filling with water, so the pipeline consisted of both air and water. The amount of air in the pipeline line was not monitored. In addition, the testing trials were conducted with a restricted pressure limit in the pipeline of 300 psi. This limit was a safety requirement for HLW cross-site lines at the DOE.

During the testing trials, AIMM Technologies was more successful removing the Bentonite plugs than the salt-based plugs in which they were able to remove 5 of the 6 Bentonite plugs. AIMM did successfully unplug one Na-Al-Si plug during the commission trials but could not unplug three others during the final trials. They were able to partially get flow through a 4 ft Kmag plug at the 310 ft test bed, but could not remove the Kmag at the other pipeline lengths. It should be noted that the Bentonite plugs required lower extrusion pressures than the salt-based plugs.

In general, the data from the unplugging and parametric trials showed that the pressure pulses attenuated significantly from the inlet to the blockage section during the unplugging process. The vibrations were also attenuated significantly from the inlet to the blockage during the unplugging process. The attenuation of the pressure pulses is related to the distance of the pulsing from the inlet. Although the amount of entrained air in the pipe system was not measured, the air would certainly act as an energy sink and work to reduce the effectiveness of the pulsing. The variability of the remaining air in the pipeline at different lengths also likely affected the data analysis adversely, in that trends for pressure and vibration propagation were difficult to identify in some trials. This suggests that the remaining air within the pipeline and the low required operating pressure were key elements which inhibited the ability of AIMM's Hydrokinetics process to operate at its optimum capability.

The significant attenuation of the pressure pulses and vibration suggests that the mechanism for removing the blockages on the successful trials was a combination of the static pressure and the small residual pressure pulses propagated to the blockage. Imposing a vacuum on the pipeline prior to filling would likely decrease the attenuation rate and improve performance.

Each of the unplugging technologies that were investigated at FIU using computational modeling have their own advantages and disadvantages. Asynchronous Pulsing method is a remote, non-invasive approach that would not require intensive maintenance and radioactive cleaning between operations, however when the blockage occurs at a far distance in the pipeline, the performance of the technology can degrade due to the large volume of entrapped air. Peristaltic Crawler technology can be very effective to remove the blockages by incorporating various plug breaking and scouring mechanisms such as an auger or water jet, however, the range of the crawler may be limited due loadings caused by the required tether. Such concerns will be further evaluated by initially using bench-scale experiments at FIU.

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