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WEAR RATE TO STAINLESS STEEL PIPE FROM LIQUID-SOLID SLURRY

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ABSTRACT

The United States Department of Energy is building a Waste Treatment Plant (WTP) at the DOE Hanford Site in the state of Washington to process stored radioactive wastes for long-term storage and disposal. The Savannah River National Laboratory (SRNL) is helping resolve technical concerns with the WTP, which are related to piping erosion/corrosion (wear). SRNL is assisting in the design of a flow loop to obtain long term wear that will use prototypic simulant chemistry, operating conditions, and materials for total wear rate. The challenge is to accurately measure slurry wear to a pipe wall thickness tolerance of ~47 microns/year anywhere in the test flow loop in a timely manner. To help in the design of the flow loop a test was performed with a smaller loop, which contained many of the pipe fittings expected in WTP to determine where high wear locations exist. One aspect of this test was to understand the rate of wear to straight pipe and to protrusions from the surface of the pipe. Initially, wear to straight pipe was studied because wear in other flow loop situations, e.g., around bends, through tees, etc. will be higher. To measure such low wear rates requires sensitive measurement techniques. To that end, twelve wear coupons were placed in one section of the pipe system and at different protrusion heights into the flow stream. They were made of 316L stainless steel, which is the expected material of pipe to be utilized. From the wear coupons, an estimate of wear rate was obtained, as well as illustrating when a protrusion above a pipe surface no longer disturbs the flow streams with respect to slurry wear. It appears when a surface is just above the laminar sublayer it produces a wear rate equivalent to a surface with no protrusions. The slurry was a mixture of water and 30 wt% of sand, d_{50} ~ 200 microns. The test flow conditions were a velocity of 4 m/s in a 0.07793-m inside diameter (3-inch, Schedule 40) pipe system, resulting in Reynolds number just above 3×10^5, i.e., turbulent flow at a temperature of 25°C. The wear was to a vertically oriented straight section of pipe that was 1.86 meter long. The twelve wear coupons were located on the inside surface starting from 10 diameters from the pipe entrance to 21 diameters, with a separation of 1-pipe diameter between each successive coupon. Furthermore, each set of two adjacent coupons were rotated 180 degrees apart which were then rotated 30 degrees from the next set to minimize disturbance to the flow for the downstream coupon. This paper describes the wear rates obtained, the effect of increasing a wear coupon's protrusion into the flow stream, and the overall operation of the test apparatus.

INTRODUCTION

The soundness of the piping system in any radioactive operation is very important to maintain a safe environment. A leak may release contamination that will increase costs due to clean up and down time and present health risks to personnel. It is important to understand the effects of a slurry flow on the piping system so that proper maintenance intervals can be developed. One problem from slurry flow is the wear it causes from the solids in the slurry that causes erosion on wetted surfaces. Furthermore, aggressive chemical species may increase wear and wear rate by corroding surfaces exposed by erosion. The synergistic effects of erosion with corrosion can accelerate wear[1] on pipe walls and other equipment.

[1] In this paper the word erosion is used to indicate the loss of material from a surface due to the flow of slurry. In reality mass loss from slurry is generally referred to as wear because it can be caused by any of the mechanisms of erosion, corrosion, and the synergistic effect of both together. From a fundamental point of view to understand wear, knowledge of all three slurry mechanisms is important and there are many studies that attempt to quantify them individually. However, the goal of this work is to locate areas of high erosion by employing the flow of sand and water, which eliminates, or minimizes, slurry wear due to corrosion, and thereby any synergistic effects. For this paper the term wear is used interchangeably with erosion, unless specified differently.

The Waste Treatment and Immobilization Plant (WTP) being built as part of the River Protection Project at the Department of Energy's (DOE) Hanford Site will contain pipe systems that will carry radioactive slurries. To ensure safe operation the wall thickness corrosion/erosion allowance for black cell[2] pipe was set at 0.00189 m over the life of plant, which is currently set at 40 years (This allowance rate is 47.2 micron / year.) The pipe systems are designed to last the entire life of the WTP; however, equipment that has high rates of wear, e.g., pumps, is designed for repair or replacement.

To evaluate the planned pipe systems for slurry wear an experiment was performed, which included 316L stainless steel seamless 0.07793 inside diameter (3-inch Schedule 40) pipe, pipe fittings: Straight pipe, 90° Long Radius elbow, 45° elbow, 3D bend, tee, and cap. Before designing a full slurry flow loop to measure wear it was important to know where the highest wear could be expected, so that sensitive wear measurement instrumentation could be properly placed. Therefore, a simple flow loop with prototypic pipe fittings was constructed and internally painted in order to demonstrate high erosion locations. A requirement was to have fully developed flow between fittings; however, that was not possible, and is not expected in the actual plant design. Fully developed flow occurs only after approximately 50D for straight pipe [1, 2], which, for 0.0762-m pipe, is over 3.8 meters. Very few plant designs include straight runs of that length; therefore, the length of pipe before and after each fitting must be considered.

Literature [e.g., 3-6] shows that there are many parameters to consider on how solids particulates in slurry erode the pipe wall. A detailed discussion of these parameters can be found in a previous paper [7] as well as the results of finding high-wear locations. Along with wear locations, an attempt was made to estimate wear rate, employing installed wear coupons, which is the focus of this paper.

To accurately measure mass loss rate by measuring the loss of paint with time has been done before [8-9]. However, to estimate mass loss rates by measuring the loss of paint is difficult and limited to pipe sections that can be easily accessed. To obtain an accurate measurement using paint the layers need to be applied so they are of a uniform thickness that is accurately known before testing begins and then accurately measured after testing. For the current test, time and funding did not allow for a paint coating to be accurately applied. An easier method to measure wear is to simply install wear coupons, which have their own set of problems, e.g., flow disturbance. To estimate wear rate and flow disturbance, a straight pipe section of the flow loop was chosen to install wear coupons. Those coupons protruded into the flow stream at different heights in an attempt to understand the minimum height that would not disturb the flow so that such a coupon could be used to accurately estimate slurry wear to the pipe wall. This paper discusses the results from the installed coupons.

NOMENCLATURE

d	Diameter of solid particle
d_{50}	50 Percentile of solids particle
D	Pipe Diameter
#D	Number of pipe diameters, e.g., 10D
DOE	U.S. Department of Energy
L	Length
R	Pipe Radius
oc	o'clock
PSD	Particle Size Distribution
Re	Reynolds Number
SRNL	Savannah River National Laboratory
U	Fluid Velocity
v*	Friction Velocity
WTP	Waste Treatment and Immobilization Facility

Greek

δ_l	Laminar Sublayer
μ	Dynamic Viscosity
ν	Kinematic viscosity
ρ	Density

EXPERIMENTAL FLOW LOOP

The overall flow loop utilized is shown in Figure 1. The loop is broken in five sections so that attention could be focused on each. A previous paper [7] described pipe sections 1 through 4 and discussed the slurry wear locations observed it those sections. This paper is focused only Section 5 and will discuss the slurry wear rate measured from wear coupons located in that section. This pipe section contained twelve (12) 316L stainless steel coupons to demonstrate the effect of protrusion in the pipe flow and possibly be a rough measure of the erosion rate of this material. That is, the coupons were placed in the tube wall at different protrusion heights from flush with the pipe wall to approximately 0.229 cm. One such trial protrusion is shown in Figure 2, before the tube wall was painted and with a conceptual sketch of the flow disturbance, Figure 3. Figure 4 show a close up of Section 5, which was a straight section of plastic PVC pipe, with an inside diameter, D, of 0.07793 m (3-inch Schedule 40).

The coupons were located along the length of the vertically straight pipe and began approximately 10D from the start of the upstream part of the pipe as seen in Figure 4 and Figure 5, with the last coupon located 3.3D from the pipe end. The angles between the 12 coupons are shown in Figure 6 and they are equally spaced along the pipe. The first coupon placement at 10D from the entrance of the straight pipe was based on a project assumption that fully developed flow occurs at this point. It was also convenient to allow all 12 coupons to be placed with 1D separation between each, and then ending a few diameters before the end of the pipe. However, fully developed flow probably did not exist anywhere in this test rig.

At 4 m/s in the 0.0779-m inside diameter pipe the Reynolds number (for water at 25°C) was approximate 309,000, which is turbulent flow. Fully developed flow occurs at L/D= 2.44/(Fanning Friction Factor)^{½} [1]. The friction factor is f~0.0019 for standard commercial pipe, with a standard roughness, which is obtained from a standard Moody diagram. Note that the Moody (or Darcy) friction factor is 4 X Fanning Friction Factor, then this indicates an L/D=2.44/(0.019/4)^{½} ~ 35 is necessary to attain fully developed flow, meaning

[2] Black cell refers to the part of the WTP where radioactive operation occurs and has limited, or no, access by design, to minimize personnel exposure.

approximately 2.7 m of straight 0.0779-m diameter pipe is required. This means that nowhere in this vertical test pipe that is 1.86-m tall is the flow fully developed because it was only ~ 24D in length, and much less in the first 10D of the entrance length, before the first wear coupon.

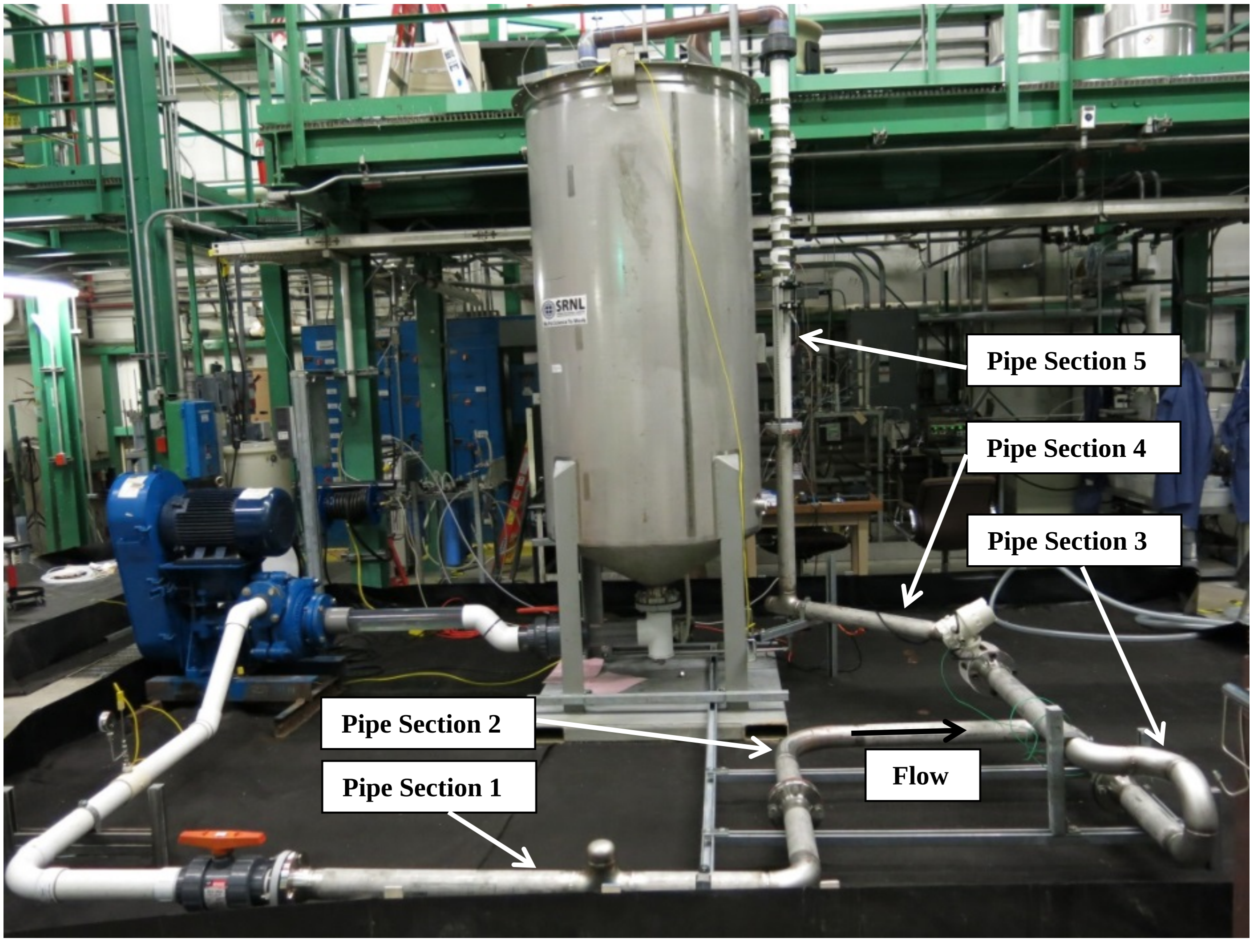

Figure 1. Internally painted slurry flow loop

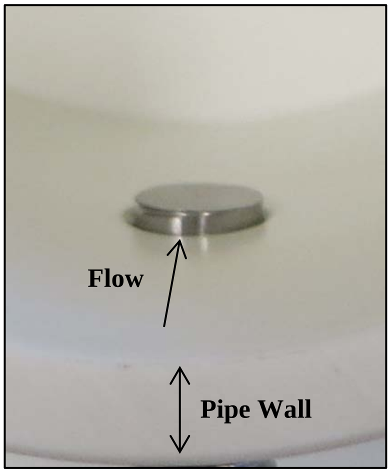

Figure 2. Coupon to demonstrate placement

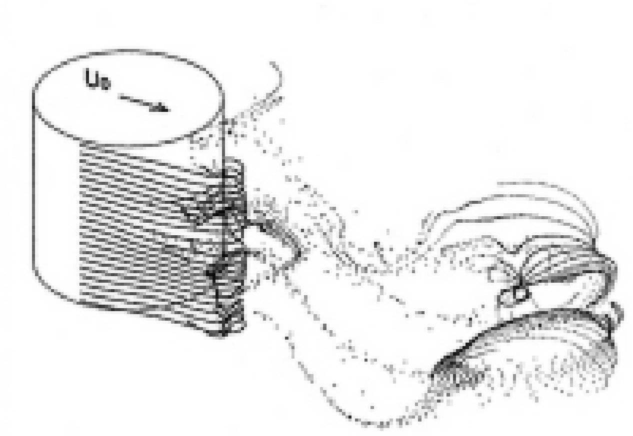

Figure 3. Flow disturbance behind a cylinder

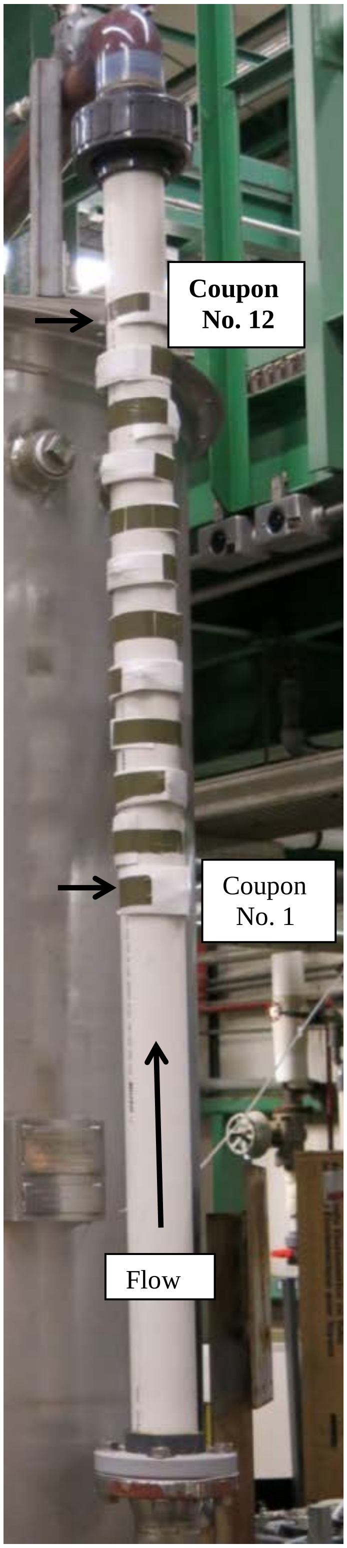

Figure 4. Pipe Section 5 was a 1.86-m tall vertically oriented PVC plastic pipe. Tape covered the twelve wear coupons for protection.

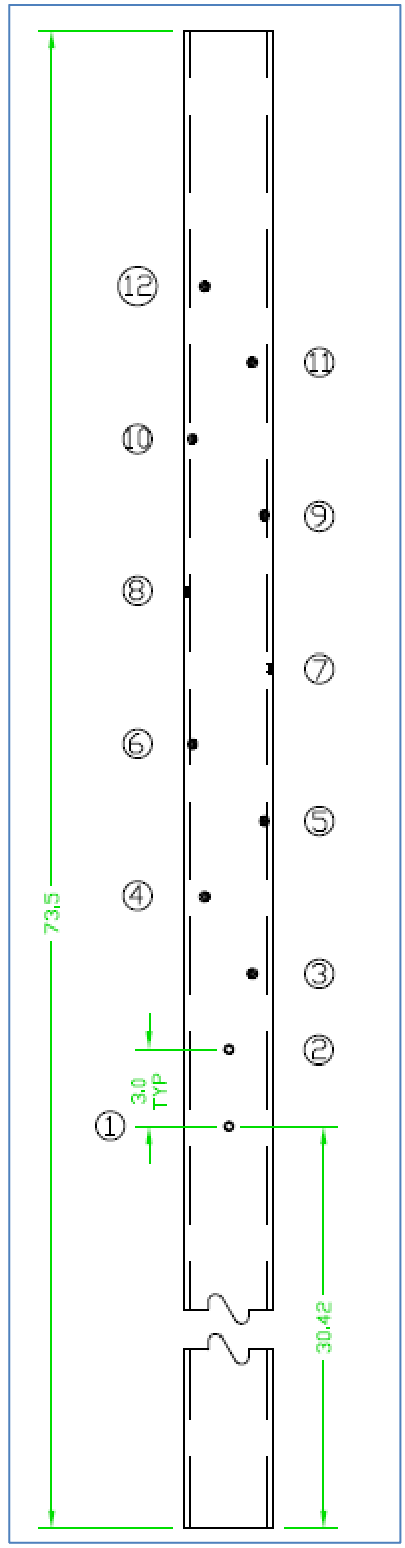

Figure 5. The placement and locations of the coupons in pipe section 5 are shown on the drawing. Dimensions are inches.

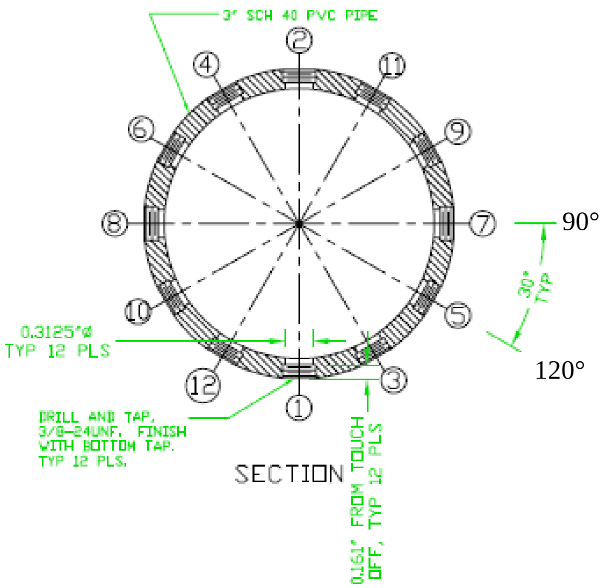

Figure 6. Plan view of the pipe shown in preceding figure to illustrate placement angles between the twelve coupons. Dimensions shown are in inches

To quote Ward-Smith [1], "The influence of the bend on the pressure distribution exists a few diameters upstream from the bend and a large distance downstream (fifty or more diameters in turbulent flow, and almost certainly even more in laminar flow)." The use of 10D for straight sections of pipe is more concerned with recommended pipe lengths for measurement equipment to operate as designed. That is, flow meters commonly require 10D of upstream pipe to read accurately. This does not mean fully developed flow is achieved.

After Section 5 was painted and the coupons installed, photographs were taken inside the pipe. Figure 7 shows the coupons looking upstream with the last coupon, i.e., number 12, in the forefront.

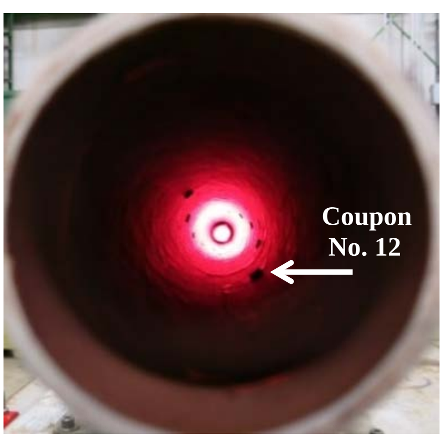

Figure 7. Coupons in place and looking from the downstream side of the tube with Coupon 12 in foreground.

Figure 8 shows a close up of coupon No. 11, as looking from the downstream side of the tube. All 12 coupons were exactly the same as the one shown in Figure 9, which is a photograph of one coupon after it was modified from a 316L stainless steel set screw. Note that while both the slurry pipe and the screw material were of 316L they are different. That is, off-the-shelf pipe metal is generally annealed, so the wear coupons should have been, too. However, the method used to fabricate the screw is partially through cold working, i.e., the threads are cold rolled, which causes work hardening.

Figure 8. Coupons in place with Coupon No 11 in the forefront.

Figure 9. Coupon was made from a 316L stainless steel set screw and was machined to 7.94-mm diameter.

Furthermore, the metal stock to make the screw is probably first extruded, which elongates the grain structure. That diameter was chosen based on the set screws that were available. The exposed head of the screw was machined to a 0.794-cm diameter with a 32 micro-inch surface finish[3]. By machining the top threads off the top of the screw and cutting

[3] The surface roughness of new standard commercial steel pipe is on the order of 4000 micro-inch (Avallone and Baumeister, 1986; Table 3.3.9). For the low erosion wear expected from the current test, no special surface preparation was done to match the surface finish, but left the surface finish that resulted from careful machining, which is 32 micro-inch. This finish gives a relative surface roughness of 0.000032 in / 3.068 in = 0.000001, which is close to smooth pipe.)

the top flat, then most of the work hardened surface is removed; however, the cutting does cause some level of work hardening. Therefore, the 316L metal of the screws has a surface hardness and a grain structure that differ from the 316L pipe wall. It is not known if these differences would tend for the coupons to wear faster or slower than the prototypic pipe wall, but these differences must be considered when comparing wear rates due to erosion. For example, based on the literature discussed in Duignan [7], erosion is categorized as being brittle or ductile. Brittle erosion occurs for substances that eroded faster at 90° angles (direct impacts shatters pieces of material from a surface, e.g., glass, cast iron, etc.), while ductile materials erode faster at approximately 30° angles (shear forces push, scrape, and gouge material from a surface, e.g. steels).

Table 1 shows the dimensions used to place each coupon to set its protrusion in the flow path. The protrusion heights were selected to be multiples of 0.02 cm. As will be explained in the next paragraph, the flat head of 0.794-cm diameter coupon would not be exactly flush with the round 0.07793-m diameter pipe, but it will either be recessed or protrude the surface by 0.02 cm. That dimension was used to set the heights for all 12 coupons, i.e., 0 to 0.224 cm. Setting the protrusion height accurately was made difficult by the length of the long straight pipe, which made coupons hard to access. Therefore, the known dimensions of the screw threads were used to assist in the placement, i.e., 9.45 threads per cm (24 threads per inch). After each coupon was cleaned and weighed, the method of setting each coupon height was as follows.

The coupon was set into its location until the top surface was flush with the pipe wall, as judged visually with a borescope camera. The coupon, which was an outside-threaded setscrew with 9.45 threads per cm, was turned the number of fractional turns shown in the table. This was initially verified after Coupon No. 12 because it was the nearest to the pipe end. Several trials were done and each trial protrusion was within 0.0025 cm of the target. In the actual PVC pipe, after all twelve coupons were set, Coupon 12 was again checked by comparing the protrusion height to a drill bit. It was within 0.005 cm of the target. Finally, because each protrusion height was attained by a very specific fractional turns of the screws, which would be very difficult to produce, the fractions were rounded to the nearest 1/5 turn of the screw, which was much easier to set. Both the target and actual number of screw turns are indicated in the table. Note that for the 0.794-cm diameter coupons the surface was flat and the pipe was round. This means that even a “flush” coupon will be 0.02 cm above the pipe surface, if the center of coupon were flush with the pipe wall, or below the pipe surface by 0.02 cm if the coupon’s surface outer periphery were flush with the pipe surface, as shown in Figure 10.

Table 1. Coupon protrusion into Section 5 pipe – See Figure 5 & Figure 6 for locations.

Coupon No.	Angle - Deg (see Fig. 6)	Vertical Location (1)	Target cm (4)	Target Screw Turns (2)	Actual Screw Turns (3)	Actual cm (4)
1	180	0.00	0	0.00	0	0.00
2	0	0.08	0.020	0.19	0.2	0.02
3	150	0.15	0.041	0.39	0.4	0.04
4	330	0.23	0.061	0.58	0.6	0.06
5	120	0.30	0.081	0.77	0.8	0.08
6	300	0.38	0.102	0.96	1	0.11
7	90	0.46	0.122	1.15	1.2	0.13
8	270	0.53	0.142	1.34	1.4	0.15
9	60	0.61	0.163	1.54	1.6	0.17
10	240	0.69	0.183	1.73	1.8	0.19
11	30	0.76	0.203	1.92	2	0.21
12	210	0.84	0.224	2.12	2.2	0.23

(1) This is the distance in meters vertically above Coupon No. 1.
(2) Based on 9.45 threads per cm.
(3) Rounded to nearest 1/5 turn for ease of placement.
(4) Protrusions of coupons. What the target was and what was actual used.

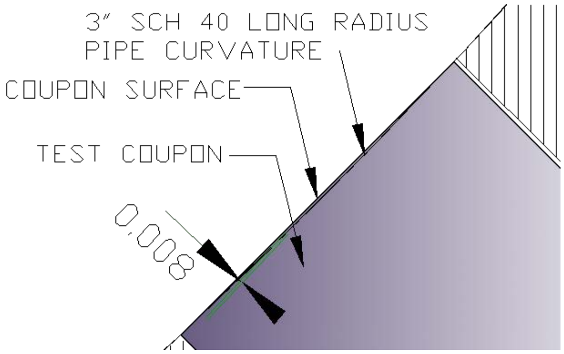

Figure 10. Flat-faced wear coupon when placed "flush" with round pipe wall surface. Shown is 0.008 inch = 0.02 cm.

Besides providing a possible means to demonstrate flow disturbance, the coupons were subject to the same erosive environment as the rest of the flow loop. The flow loop test was stopped when there was enough paint removed to determine high wear locations, based on paint removed from a transparent section of pipe. Because the duration of the paint loop test only lasted 81 minutes, rather than weeks or months, the amount of erosion expected was very small. The following example quantifies an expected erosion rate, based on the design wear tolerance.

- Target acceptable wear rate of < 0.004724 cm/year or 5.3927×10^{-7} cm/h
- Exposed Top Surface Area = 0.495 cm^2
- Coupon material = 316L stainless steel
- Measured coupon density = 7.7671 g/cm^3

Volume loss per hour =
$(5.3927 \times 10^{-7}$ cm/h)(0.495 cm^2)
= 2.669×10^{-7} cm^3/h

Mass loss per hour =
$(2.669 \times 10^{-7}$ cm^3/h)(7.7671 g/cm^3)
= 2.073×10^{-6} grams/h

For a flow test that lasts 81 minutes, or 1.35 hours, the maximum acceptable mass loss from a coupon would be 2.8×10^{-6} g, corresponding to a thickness loss is 7.2×10^{-7} cm.

SLURRY & TEST OPERATION

For this flow loop only a simple mixture of water and sand was used. The particle diameter was d_{50} = 199 microns, with a standard deviation of ±55 microns. The particle sizes range from 81 to 498 microns. Once the slurry was loaded into the flow loop at a concentration of 30 wt% the flow was started and brought to a steady state velocity of 4 m/s. At 81 minutes the test was terminated when flow loop was estimated to have enough slurry wear to the paint to make meaningful measurements.

DISCUSSION

In analyzing the wear data with a pipe system it is important to have a convention on orientation. An intuitive approach is to rely on the fixed orientation of gravity when referring to the top or bottom of pipe flow; therefore, the top of a horizontal pipe will always be located at a clock orientation of 12 o'clock, indicated by 12 in the accompanying photographs. For the vertical pipe under discussion the 12 o'clock position is on the side the corresponded to the top of the last upstream horizontal pipe, which was pipe Section 4, see Figure 1. In the descriptions that follow for internally painted pipe oc = o'clock.

Looking downstream through the 1.86-m tall pipe, which was vertically oriented, Figure 11 shows the 1st half of the coupon section of the Section 5 pipe. Coupon No. 3 is visible at approximately the 4 oc position. The pipe was generally well coated with paint, but some streaks are visible exposing the underlying plastic surface. Figure 12 shows the pipe after 81 minutes of flow. The wear was very evident and the predominant wear was from 6 oc to 12 oc, clockwise. Coupon No 2 is in the foreground at approximately the 9 oc position.

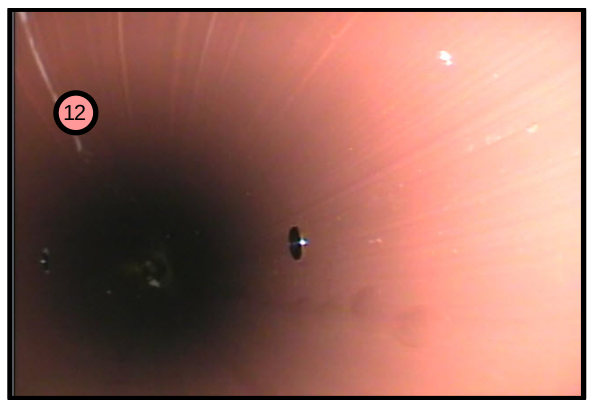

Figure 11. 1st half of pipe at start.

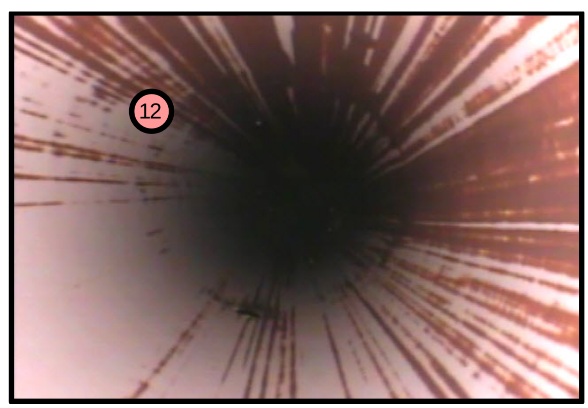

Figure 12. 1st half of pipe after 81 min.

When looking from about the midpoint of the pipe Figure 13 shows a well coated pipe, at the start of the test, with Coupon 6 in the foreground at the 3 oc position. Figure 14 shows that after 81 minutes the wear was extensive, but still on one side, from 6 oc to 12 oc, clockwise. Coupon No. 7 is in the foreground at the 9 oc position.

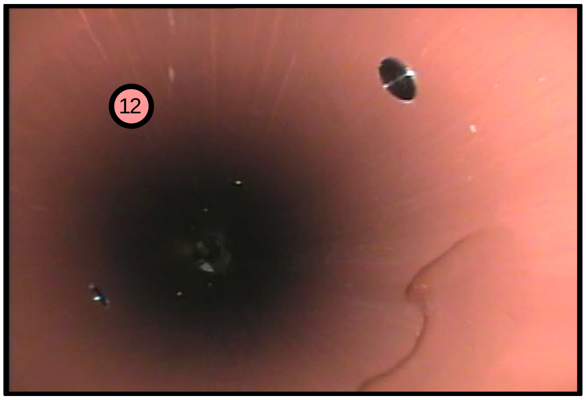

Figure 13. 2nd half of pipe at start.

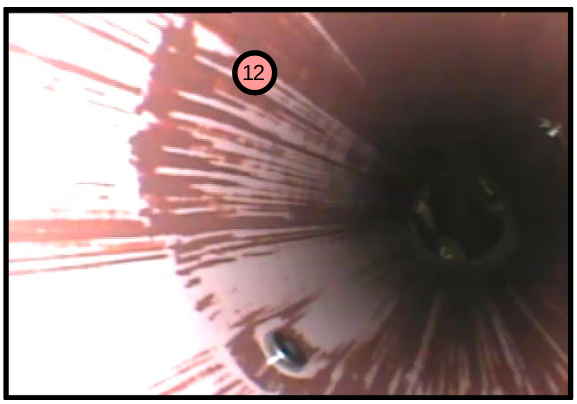

Figure 14. 2nd half of pipe after 81 min

At the start of the test the end of Section 5 pipe was well covered with paint, too, as seen in Figure 15 with a fairly even coat. Figure 16 show the results of the wear that occurred at the pipe end. Once again, the wear was principally at the 6 oc to 12 oc location[4] in the clockwise direction. Coupon number 12 is in the foreground at the 3 oc position.

[4] This one-sided wear was assumed to occur because at the end of Section 4 the upstream flow began straightening out to encompass the entire pipe. This pattern continues in the vertical plastic pipe, Section 5. However, about midway up this pipe the flow rotates because the wear pattern tends appears to be stronger on the 6 oc to 12 oc side, clockwise, of the pipe. This flow rotation is probably due to influence of the upstream 90° elbow which forces the flow to turn towards this side of the pipe.

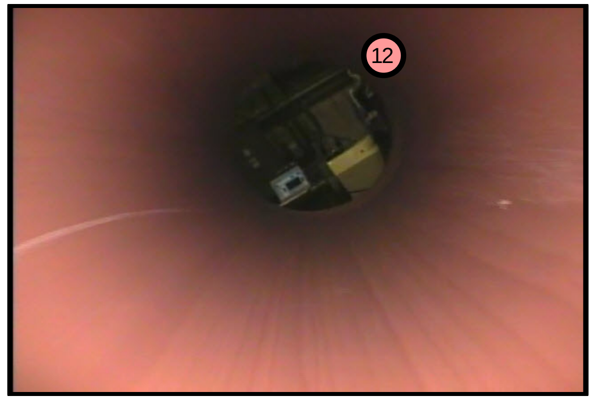

Figure 15. View of end of pipe at start.

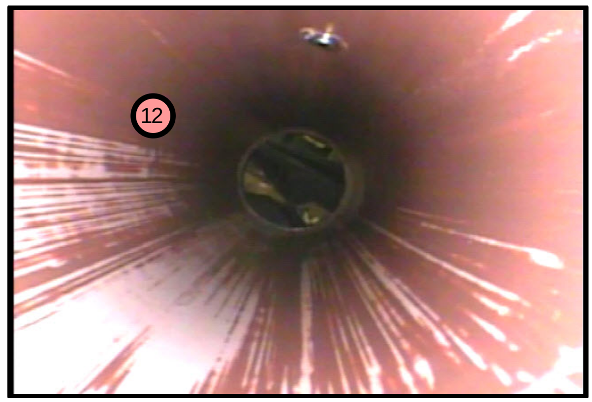

Figure 16. View of end of pipe after 81 min

Figure 17 and Figure 18 show close-ups of Coupon No. 11 seen in Figure 14, before and after the test.

Figure 17. Coupon No. 11 before test.

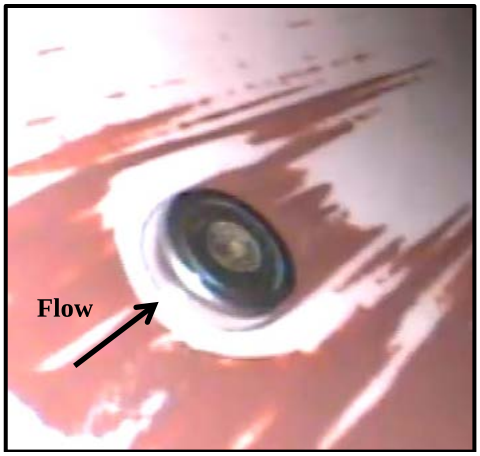

Figure 18. Coupon No. 11 after 81 minutes of slurry flow.

Wear Coupon Flow Disturbance

Initially, the test was stopped after only 22 minutes of flowing slurry because a section of the internally painted transparent plastic pipe indicated significant paint removal. If too much paint were removed the concern was that the high wear locations could not be found. However, once the test was stopped and the flow loop was disassembled it became obvious that more time was needed to clearly indicate the high wear locations. That is, the paint eroded faster from the plastic than from the steel surfaces, so more flow time was needed. It was fortunate, that the test was stopped at 22 minutes because the protruding wear coupons showed turbulent wakes through a discoloring of the paint, immediately downstream of the coupons, see Figure 19.

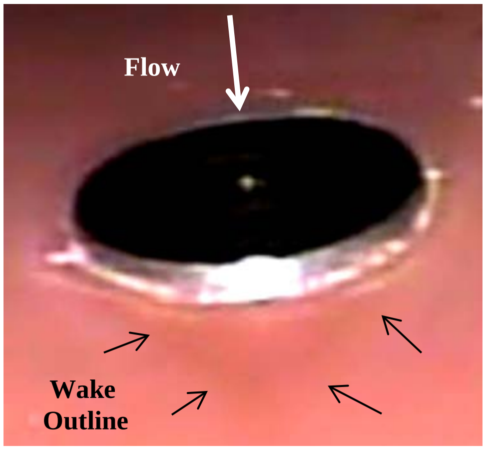

Figure 19. Turbulent wake shadow downstream of Coupon No. 3, after 22 minutes of flow.

If the test had not been stopped at that point these shadows would have been worn away. Figure 20 shows a measurement being made on the wake of Coupon No. 11, which was estimated visually at 0.95-cm long, or 0.16-cm longer that the diameter of the coupon, i.e., 0.79 cm. Unfortunately, the wake shadow is not really visible in the figure because it is a photograph of video still image. Viewing the actual video provided a better and more accurate measure of a wake's length. The wake of each of the coupons was measured, where it existed, using the videos taken in both the downstream and upstream directions. Even still, it was very difficult to estimate a wake's length using a borescope and accurate ruler because of the small working area and the limitations to manipulate the borescope camera.

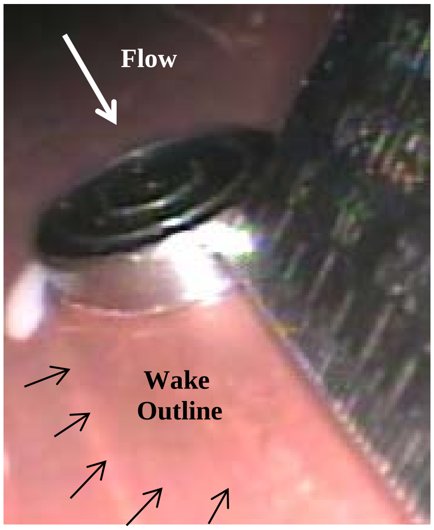

Figure 20. Turbulent wake shadow downstream of Coupon No. 11, after 22 minutes of flow.

Figure 21 shows the result of the measurement, which indicates that at or below 0.02 cm^5 there is no impact on the flow, i.e., no turbulent wake was noticeable.

Note, there are two points missing, Coupon Nos. 1 and 4, from Figure 21 because the installation of those two coupons created problems to obtain an accurate measurement of the respective wakes. That is, the long plastic tube made it challenging to internally deburr each of the coupon holes. For Coupon No. 1 it had a considerable amount of plastic surrounding the coupon and the plastic created a flow barrier, which obstructed the flow path. For Coupon No. 4, too much plastic was removed from around the coupon; therefore, there was a groove, a moat, around the coupon. That is, there was very little pipe wall material in the vicinity of the Coupon No. 4 on which to leave a shadow. Despite the difficulty in measuring the turbulent wakes the results are fairly good and indicate that while a perfectly flush coupon would always be preferred, a slight protrusion on the order of less than 0.02 cm should not significantly affect wear results. That is, if a coupon protrudes into the flow path by approximately 3% or less of the largest

[5] Figure 21 actually shows the coupon height normalized to the coupon diameter of 0.794 cm. The zero wake location was at a height of 0.02 cm, which is normalized to 0.02/0.794 ~ 0.025.

surface dimension of a coupon, then the disturbance of the flow around the coupon should be insignificant.

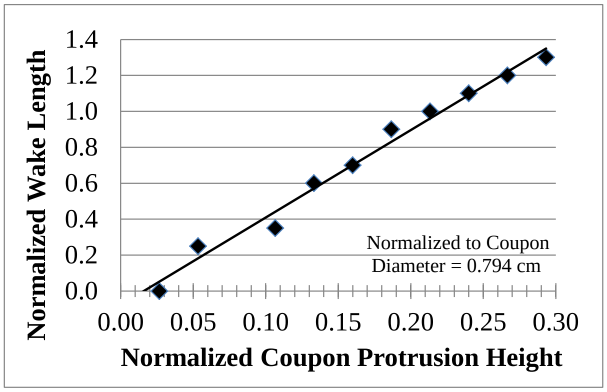

Figure 21. Effect of wear 0.794-inch diameter coupon protruding into flow stream.

The protrusion height is above the laminar sublayer in the pipe, Figure 22, by a factor of 6, which can be estimated from Schlichting [see the equation that precedes Eq. 20.9 and Eq. 20.15a, respectively, in that Ref. 10].

$$\frac{U}{v^*} = 6.99\left(\frac{v^*R}{\nu}\right)^{1/7} \qquad (1)$$

$$\delta_l \sim 5\left(\frac{\nu}{v^*}\right) \qquad (2)$$

Where:

U = average pipe velocity, m/s

ν = kinematic viscosity = 1.007 x 10-6 m^2/s [water at 25°C]

R = pipe inside radius = 0.039 m

Re = Reynolds Number = DU/ν = [(0.0779 m)(4 m/s) /1.007 x 10-6 m^2/s = 309,434 (turbulent)]

v* = friction velocity = 0.1638 m/s [from Eq. (1): a function of density, viscosity, and wall shear stress]

δ_l = the laminar sublayer = 0.0031 cm

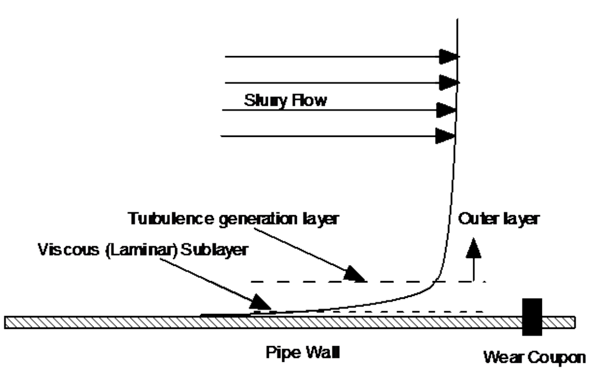

Figure 22. Fully developed turbulent fluid flow structure in a pipe.

The fact that no turbulent shadow was seen for the 0.02-cm coupon indicates that it is in a layer that does not generate turbulence. However, any protrusion that goes beyond that height will create increased erosion at that location.

Coupon Wear Rate

The twelve wear coupons were ultrasonically cleaned and then weighed before the test. After 81 minutes of the test, the coupons were removed, cleaned exactly as they were before the test, and weighed. These measurements had to be performed under very controlled conditions, e.g., dust- and vibration-free. Even oil from a hand could affect the small differences in mass loss expected. What was not known before the test was how much mass would be lost from the coupons because it could be insignificant. Fortunately, the amount of mass lost was well within the measurement range of the 6-place balance (with an uncertainty of ±6 μg) used. For example, the smallest mass loss weight measured was 332 μg from Coupon No. 2. The steel removed from the coupons ranged from 0.3 to 3.7 mg.

The data are shown in Figure 23 and there are two principal items of focus, the lowest wear rate and the trend with increasing exposure of coupon surface area to wear. As previously explained, due to either added and subtracted plastic around Coupons No. 1 and No. 4, their results are more questionable than the other coupons, but the measurements are included for completeness.

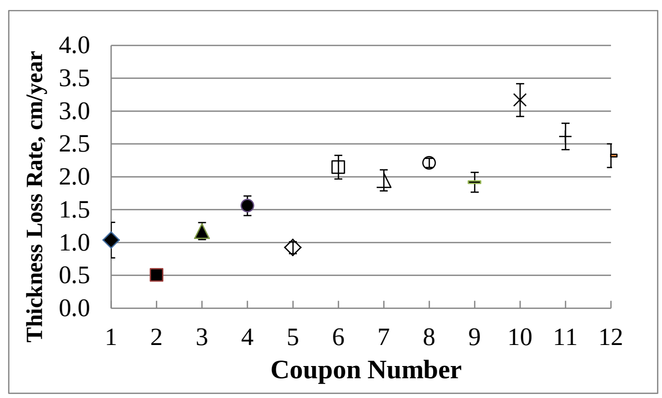

Figure 23. Wear rate of 316L coupons[6].

Furthermore, as was also previously discussed and shown in Figure 21, at a protrusion of 0.02 cm above the pipe wall surface Coupon No 2 is considered equivalent to it being a coupon flush with the wall. With that assumption then the Coupon No. 2 wear rate of 0.5 cm/year, ±0.08 cm/year, should be similar to the wear rate of the straight pipe wall under the

[6] The measurement uncertainty is the result of a Propagation of Errors Analysis [11] and only indicates the uncertainty of quantities used to obtain the thickness loss rate (which are coupon mass loss (±0.000023 grams), coupon diameter (±0.00127 cm), coupon height (±0.005 cm), test time (±10 minutes), and 316L density (±0.0056 g/mL). This uncertainty does not include effects of flow regime, turbulence level, location from pipe fitting, etc.

slurry conditions used for this test, which is two orders of magnitude faster that the required tolerance of 0.0047 cm/year.

The second item of focus is the exposed coupon surface area. Recall from Table 1 that each successive coupon protrudes further into the flow stream. From the data it is clear that as the exposed surface area of a coupon increases, so does the wear rate. Furthermore, as a surface protrudes further into the flow stream more turbulence is created, as illustrated from Figure 3. In fact, as the surface area exposed to slurry flow increased by a factor of 2 the amount of mass lost increased by an order of magnitude. This occurs because two effects occur simultaneously, i.e., there is more surface area to be attacked by the slurry solids and the increased surface is creating more turbulence, thus enhancing the secondary flows that in turn increase wear.

Finally, it is important to realize that the wear rates shown in Figure 23 are only a snapshot of the rates at 81 minutes of slurry flow at 4 m/s through a 0.0779-m pipe. What is not known is if the rate will change, specifically become lower, with time. It is conceivable that the continual impingement of solids against the steel pipe wall with change the metal structure, e.g., work hardening, of the wall, which, in turn, will affect the rate wear occurs. To accurately measure the long-term wear rate then it is very important to establish the steady-state wear rate. The period when that will occur is not known; however, Wood and Jones [12] used 22 wt% of d_{50} = 1-mm sand in water at 3m/s through 304L stainless steel pipes showed a steady state rate of wear after 210 hours, which was approximately one half of the rate that occurred during the first 20 hours of testing. Unfortunately, that reference does not show the rate for the first hour of operation, which could be considerably higher.

CONCLUSIONS

Based on Coupon No. 2, the erosion wear rate after 81 minutes of slurry flow at 4 m/s on straight pipe wall was calculated to be 0.5 cm/year ±0.08 cm/year. This result was for measurements with a slurry of water and sand at a solids loading of 30 wt% and particle sizes ranging from 96 to 498 microns with a d_{50} = 211 microns. Furthermore, surfaces raised in the pipe flow above approximate 0.02 cm will be affected by the flow disturbance caused by the presence of that surface, which increases the wear rate. Finally, it is important to note that the wear rate in the first few hours has been shown to be much higher than a long-term rate [210-hours in Ref. 12]; therefore, a longer-term test is recommended to measure average wear rate.

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