Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

Disclaimer:

Proceedings of the ASME 2015 International Mechanical Engineering Congress & Exposition
IMECE2015
November 13-19, 2015, Houston, Texas, USA
SRNL-STI-2014-00515

IMECE2015-53460

WEAR LOCATIONS IN STAINLESS STEEL PIPE FITTINGS FROM THE TURBULENT FLOW OF A LIQUID-SOLID SLURRY

Mark R. Duignan, Marissa M. Reigel, Kenneth J. Imrich,
Michael L. Restivo and Mark D. Fowley
Savannah River Nuclear Solutions
Savannah River National Laboratory
Aiken, South Carolina, USA

ABSTRACT
The United States Department of Energy (DOE) 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 rates that will use prototypic simulant chemistry, operating conditions, and materials. 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. A first step in such a test is to secure knowledge of high wear locations so that highly sensitive measurement techniques can be incorporated and properly located. Literature exists to help locate such wear locations in pipe and pipe fittings but most of the information deals with slurry flows that have significantly different velocities, different flows steams, e.g., steam, gas-liquid-solids, or made from different materials. To better estimate these high wear rate locations under the WTP conditions a separate pre-test flow loop was constructed and operated. This loop is referred to as the paint loop because it was internally coated with paint, which wears faster than the steel pipe, when a solids-laden slurry is circulated. The test flow conditions were a slurry velocity of 4 m/s in a 0.0762 -m (3-inch) Schedule 40 pipe system, resulting in Reynolds number just above 3 x 10^5, i.e., turbulent flow at a temperature of 25°C. The slurry was a mixture of water and sand, d_{50} ~ 199 microns. This paper describes the test paint loop, its operation, and indicates the high slurry wear locations, as well as a comparison of those locations to existing literature sources.

INTRODUCTION
A key concern with radioactive operation of a piping system is the integrity of the pipe, fittings, and accompanying equipment. A breach anywhere in such a system may release contamination, which, at a minimum, will increase operational costs due to clean up and down time, but more importantly would increase the health risks to personnel. It is very important to thoroughly understand the effects of a slurry flow on the piping system so that proper maintenance intervals can be developed, or the flow system adequately designed, to minimize equipment failure and guarantee safe operation. One problem from slurry flow is the wear[1] it exhibits on the pipe wall, which results, partially,

[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 report the term wear will be used interchangeably with erosion unless specified differently.

from the solids in the slurry that causes erosion. The aggressive chemical species in the slurry may accelerate wear by corroding surfaces exposed by erosion. That is, the synergistic effect of the combination of both erosion and corrosion, results in an accelerated wear on pipe walls and other equipment.

The Waste Treatment and Immobilization Plant (WTP), which is being built as part of the River Protection Project (RPP) at the Department of Energy's (DOE) Hanford Site, will contain pipe systems that will carry 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.) Most of the pipe systems are expected to safely last the entire life of the WTP. Equipment that will wear at higher rates, e.g., pumps, is designed for repair or replacement. However, a confidence must be established as to how fast inaccessible pipe will wear due to waste slurries.

This study included the following 316L stainless steel seamless 0.0762-m (3-inch) Schedule 40 pipe fittings: Straight pipe, 90° Long Radius elbow, 45° LR elbow, 3D bend, tee, and cap. For this paint test the base material of pipe was not important because only changes in the paint surface were investigated, which means that pipe fittings of different metals were not necessary and, therefore, not used. The other requirement was to have fully developed flow between fittings; however, that was not possible, as it is more than likely not to exist in the actual plant design. Literature shows [1, 2] that for slurries of sand fully developed flow occurs only after approximately 50D for straight pipe, which, for 0.0762-m (3-inch) pipe, is over 3.8 meters. Very few plant designs include straight runs of that length. With this in mind the length of pipe before and after each fitting must also be considered.

Literature [e.g., 3-6] shows that there are many parameters to consider on how solids particulates in slurry erode pipe wall. Such knowledge would help to better analyze and understand wear results include:

[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.

1.1 Impingement angle of slurry particles

The stress on pipe walls due to the shearing action of flowing slurry was thought to be an important feature of erosion because of the ductile nature of annealed stainless steel. Erosion of a surface can also depend on the angle at which particles approach the surface. Literature that deals with the direction of a particle towards an eroding surface fall into two categories: particle trajectory angles that cause ductile wear or brittle wear. Ductile wear is defined [7-9] when a surface has the highest wear rate at an impingement angle of about 30° and brittle wear at an angle of about 90°. Finnie [7] states that ductile wear occurs between 20-30°, but he adds that it is always the predominate type of wear when particles are less the 10 microns in diameter and move at "slow" velocities. Using 304L stainless steel Burstein and Sasaki [10] stated that sand particles attacking surfaces at oblique impingement angles (40-50°) remove the passive oxide layer more effectively than at 90°. In fact, Foley and Levy [11] showed that 304 stainless steel does indeed wear fastest with a particle angle of 30°. Singh et al. [12] showed that both 304 and 316 stainless steels have the same rate of wear when impinged with an air jet containing SiC particles that were 160 microns in diameter, and had angular shapes. Both metals wore the fastest when the impingement angle was at 30° and it was the slowest at 90°. This information is very useful when designing a test because it indicates where attention must be directed to evaluate the maximum wear locations. That is, wear measurement must not be concentrated only at a section of a flow loop where the flow makes an abrupt 90° change. This was well demonstrated by Smith and Elmore [13] who studied the wear on a steel specimen from a perpendicularly (90°) oriented slurry jet, only to find that another steel specimen, which only received oblique-angle particle attacks, unexpectedly showed more wear. The conclusion is that, for ductile materials like stainless steel, measurements should be made where particles hit a surface at lower angles. Since small angles of attack are important for stainless steel, the shear being transmitted to a surface is thought to be important for erosion. It is thus important to set up a similar wear environment and, fortunately, coating the inner pipe surface with paint is expected to result in similar erosion to that of stainless steel because paint has been found to respond to slurry erosion as a ductile material [8-

9]. That is, tests with painted surface demonstrated that erosion rate occurs closer to angle of attack of 30° than 90°.

1.2 Slurry particle size

While knowledge of the particle impingement angle is useful in developing insights on high stress locations, it may not be directly applicable to locations of high wear rates. The difference between high stress and high wear rate locations will increase as slurry solids become heavier and larger; that is, as the flow path of particulates become increasing different from fluid streamlines. Erosion primarily occurs from the mechanical interaction of the solid particles impinging on the surfaces of wall boundary. Subsequently, wear is accelerated by corrosion as the protective oxide layer is removed from the impacted surfaces and exposed to the slurry chemistry. To estimate where high erosion locations exist, it is important to know the movement of those particles, which is affected by size.

Particle size has been studied by several investigators but there is no consistent conclusion. At one extreme, Zhong and Minemura [14] determined that erosion rate increases with size but the effect is "small" until a particle reaches 1000 microns. Iwai and Nambu [15] determined that erosion rate becomes independent of particle size above 300 microns. Mishra and Finnie [16] found that the erosion rate does not change particles larger than 100 microns. Mills and Mason [17] say that the cut off occurs at 50 microns. Gandhi et al. [18] found that the erosion rate is always affected by particle size, although "weakly." However, Finnie [7] quantified the relative effect of particle size on erosion rate and states that a 10-micron particle is only 25% effective as a 100 micron size. This wide range of results seem to be confusing, but in the context of the present need, where the particle size used was d_{50} = 199 microns, with a standard deviation of ±55 microns, many studies imply that this size is considered small, or fine, with respect to particulate flow [19-21]. Furthermore, when dealing with particle size it is also important to consider the carrier fluid. The big distinction is between gas-solid flow and liquid-solid flow because in the latter the solids are more controlled by the higher viscosity. The way to judge this is through the Stokes number, which is a ratio of a particle's response time to turbulent eddy time of the fluid [22]. It is defined as Eq. (1):

$$\mathrm{Stk} = \frac{\rho_p d_p^2 U_f}{18 \mu_f D} \tag{1}$$

Where ρ_p and d_p are the density and size of the particles, respectively, U_f, and μ_f, are the velocity and dynamic viscosity of the fluid, respectively, and D is the pipe diameter. For Stk < 0.25 particle, e.g., liquid-solid flow, the particles are tightly connected to the carrier flow. For Stk > 2, e.g., gas-solid flow, particulate flow is highly inertial and would be dominated by particle-wall interactions in a confined geometry. For the parameters of the test discussed herein with sand (at d_{50} ~ 199 microns), U_f = 4 m/s, D = 0.0762 m (3 inches), and water, resulting in a Stk ~ 0.3; therefore, the solids are expected to follow the streamlines of the water much more than if the carrier fluid were a gas. Knowing this information helps to determine were high-erosion locations will occur when flow is redirected from straight travel.

Note that an implicit assumption in particle size is that all the particles are uniform in size. At times this is an unavoidable simplification, but it is important to remember that in real systems the transported particles in most cases have a non-uniform size distribution. Most literature studies state the mean particle size, without giving information on the actual distribution of particle sizes within a group and few studies discuss the attrition that occurs during the flow of slurry. However, a group of particles having all the same size and another, which has a wide range of sizes - with a mean size equal to the uniform-size group, may give different wear results. In fact, wear results from the two different groups of particles would not be expected to match because the interaction energy and the rate of material removal are nonlinear with particle size. Some experiments performed for particles with a broad quasi-logarithmic size distribution suggest that the "equivalent wear diameter" for slurry pipes or pumps is larger than the mean particle size [23-24]. The "equivalent wear diameter" refers to a particle diameter that is assigned to a group of particles, which has a range of sizes that would cause the same wear rate as a group of particles that all have that same (assigned) size. The difference between actual diameters and equivalent wear diameter should be taken into account when discussing erosion rates based on a mean particle diameter. As will be discussed later, for this test the range of particle size is relatively small, but if waste streams have a larger range results may vary from what will be shown in the current test.

1.3 Slurry flow through pipe bends and tees

The principle fittings of concerned with this test are 45° and 90° elbows and tees. Furthermore, the bend radius of the elbows of concern fall into two categories Long Radius (LR) and 3D Radius. Standard LR elbow is defined as having a Bend Radius = 1.5D, while the 3D elbow has a Bend Radius = 3D, where D indicates the nominal pipe diameter. Note, the LR elbow has a shorter radius than a 3D elbow. The LR elbow name convention is in comparison to the Short Radius elbow, i.e., 1D, which is not used in this study.

Unfortunately, most of the literature sources that deal with erosion in pipe fittings are concerned with the flow of gas and solids, or gas, solids, and liquids due to the Oil and Gas Industry, e.g., Parshow et al. [8], Wu et al. [9], Ting and Ma [25], Salama [26], Chen et al. [27], Zhang et al. [28], Mazumder et al. [29], Njobuenwu and Fairweather [30]; or the Nuclear Industry, e.g., Ferng et al. [31], just to name a very few. While some useful information can be obtain from gas-solid flow, the fact that Stk > 2 implies solid particles have fewer tendencies to follow the flow streams when a flow direction is changed. However, some work with liquid-solid flows are available and include: Wu et al. [9], Blanchard [19], Azimian and Bart [22], Zhang et al. (28], Njobuenwu and Fairweather [30], Blanchard et al. [32], Toda et al. [33], Mishra et al. [34], Brown [35], Lee et al. [36], Wood and Jones [37], Wood et al. [38], El-Sayed and Lipsett [39], Gnanabelu [40], and Zhang et al. [41]. These references give some indications of what to expect with the flow of slurries in pipe systems:

1. The need to have at least 50D of pipe length to obtain fully developed flow.
2. For slurry flow through elbows:
   a. Maximum wear is generally on the outside radius of the bend.
   b. Maximum wear is generally near the exit, at angle locations between 75° and 110° (e.g., 0D (mitre-elbow) ~105°, 1.5D (Long Radius) ~85°, 5D ~75°, but as velocity increases the point of maximum wear moves further downstream). This fact was also shown using a CFD model in a previously planned erosion test [42], see Fig. 1, indicating an angle of 90° in a 0.0762-m (3-inch) LR 90° elbow with a slurry velocity of 3.5 m/s.

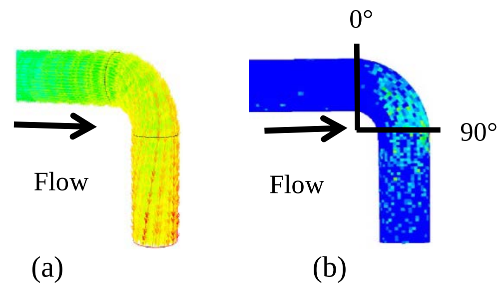


Figure 1. CFD model of a water-sand flow through LR 90° elbow. (from [43]): (a) particle trajectories, (b) relative erosion rates.

   c. More viscous carrier fluid creates secondary flows that affect solids movements.
   d. Erosion location may be independent of particle size; however, particle size seems to affect erosion rate with fastest wear for particles > 250 microns.
   e. Wear in elbows is several factors greater than in straight pipe.
   f. Bend orientation affects wear location.
3. The importance of the spacing and orientation of pipe fittings. (Especially, for fitting separated by less than 50D of straight pipe – Item 1.)
4. The angle of attack between 20 and 30° creates the most erosion for ductile materials, which includes steels.
5. Pipe tees sustain most erosion when the branch is blanked off, but the least erosion occurs when straight through is blanked off; however, tees are sometimes recommended as they sustain less erosion than elbows under certain orientations [44].
6. Erosion rate with solids loading is not well understood, but it appears to significantly increase above 30 wt%.
7. Erosion is not linear with time. As erosion occurs the damaged site accelerates wear in those locations.

1.4 Considerations for the Paint Loop Test

As clearly shown by tests performed with painted pipe [8-9] to accurately measure mass loss rates the techniques to paint pipe are quite extensive and limited to pipe sections that can be easily accessed. That is, layers of paint need to be applied so they are of a uniform thickness that is accurately known before testing begins. For the current test, time and funding did not allow for an accurately applied paint coating, but the hope was, even with unevenly painted surfaces, that as long as the entire internal pipe surface was coated with a layer of paint then qualitative indications of high wear locations would be visible to compare to wear locations found in literature. This information would be helpful to guide the design of a more accurate flow loop test containing more sensitive instruments. Therefore, goals of this scoping test were to determine:

1. Locations of high slurry wear in required pipe fittings by observing paint removed.
2. The shifting of wear locations resulting from straight pipe entrance lengths of 0D, 5D, and 10D.
3. General erosion patterns from the loop arrangement chosen.

NOMENCLATURE

d	Diameter of solid particle, micron
d_{50}	50 Percentile of solids particle, microns
D	Pipe Diameter, in
#D	Number of pipe diameters, e.g., 10D
DOE	U.S. Department of Energy
L	Length
LR	Long Radius (elbow)
PSD	Particle Size Distribution
SRNL	Savannah River National Laboratory
Stk	Stokes Number, Eq. (1)
U	Fluid Velocity
WTP	Waste Treatment and Immobilization Facility

Greek

ρ	Density, g/mL
μ	Dynamic Viscosity, Pa•s
ν	Kinematic viscosity, m^2/s

Subcripts

p	Particle
f	Fluid

EXPERIMENTAL FLOW LOOP

The parts of the loop shown in Fig. 2 are described below.

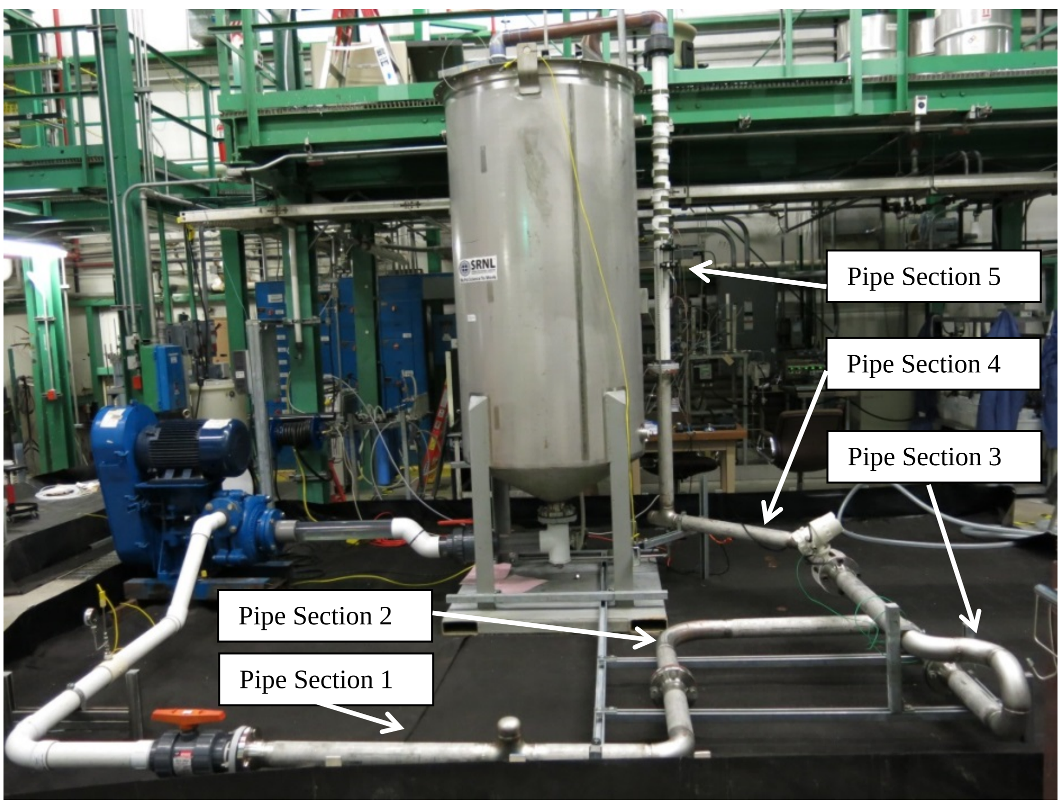


Figure 2. Overall sketch of paint loop

Section 1, seen in Fig. 3, begins immediately after the plastic pump discharge pipe. It starts with a 10D straight section that leads into a tee fitting with the branch blocked off with a cap. The D is the inside diameter of the pipe, which for a 0.0762-m (3-inch) Schedule 40 pipe is 0.07793 m. The tee is followed by a 5D straight section that leads into a Long Radius (LR) 90° elbow. Finally the elbow is followed by one half of a 10D straight section, which is split in the middle with an access flange.

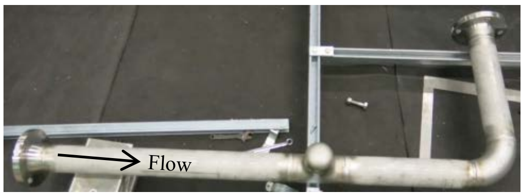


Figure 3. Pipe Section 1: Contained tee, LR 90° elbow, and 10D & 5D straight pipe

Section 2, seen in Fig. 4, begins with the second half of the 10D straight section at the end of the Section 1 pipe. The straight pipe is followed by a 3D 90° elbow leading to another 10D straight pipe, which leads into a Long Radius (LR) 90° elbow. Section 2 ends as Section 1, with one half of a 10D straight section, which is split in the middle with an access flange.

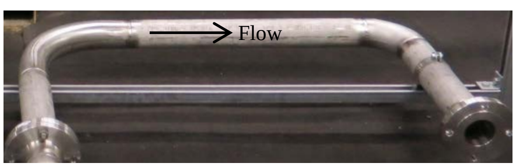


Figure 4. Pipe Section 2: Contained 3D 90° elbow, LR 90° elbow, and 10D & 5D straight pipe

Section 3, seen in Fig. 5, begins with the second half of the 10D straight section at the end of the Section 2 pipe. The straight pipe is followed by a LR 90°elbow leading to three more LR 90° elbows that have 0D or straight pipe between each section. While such a combination of pipe bends is not expected to be purposely installed in a black cell, its existence is possible per the allowable technical specification to construct pipe; therefore, these close-joined bends were included to evaluate the effect of erosion in such situations. This section ends with a 10D straight pipe leading into Section 4.

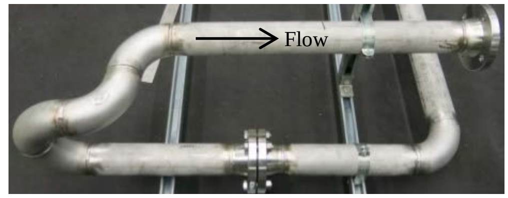


Figure 5. Pipe Section 3: Contained four 0D LR 90° elbows, and 10 & 5D straight pipe

Section 4, seen in Fig. 6, begins with a 5D straight section, which when combined with the last pipe section results in a total of 15D of straight pipe. That straight section ends at a LR 45°elbow and is followed by a straight section of 10D. Here the pipe ends in a tee fitting with the straight section of the tee terminating with a pipe cap. However, the flow continues through the branch section of the tee into another 10D straight section, which directs the flow vertically upwards.

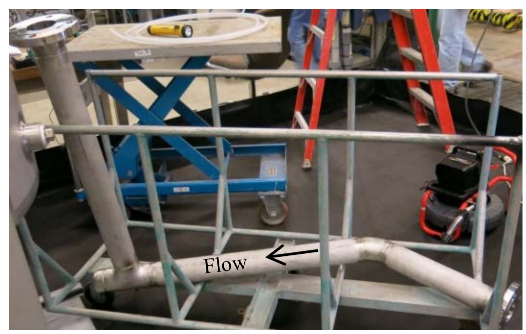


Figure 6. Pipe Section 4: Contained LR 45° elbow, LR 90° elbow, tee with branch flow, and 10D & 5D straight pipe

Finally, Section 5, is a straight section of plastic PVC pipe, seen near the top of the feed tank in Fig. 2.

PIPE PAINTING

The five pipe sections and their included pipe fittings were painted internally with the intention of finding the locations where erosion of the pipe walls is most likely to occur. While this technique is not new and could be used to quantitatively determine pipe wear [8-9], for this test it is being used to indicate where measurement equipment can be placed to obtain very accurate measurements of erosion and corrosion. There are probably many ways to internally paint a pipe and if a quantitative result is desired a lot of time and effort would be needed to have the surfaces uniformly painted with an accurately known thickness. However, this test was only concerned with location of highest wear; therefore, there was less concern with uniformity and thickness. Many paint trials were performed to determine an adequate applicator and method to accomplish the painting. A sponge was chosen that was relatively soft, porous, but was strong enough to hold paint and be drawn by a cord and bolt. The process began directing a cord through a pipe section, soaking the sponge with the paint, connecting the cord to the sponge, and then drawing it through the pipe. To make sure that the entire surface was painted, including tee and capped sections the sponge was considerably larger than the inside diameter, which would allow it to expand into the various cavities. The sponge had to be squeezed into place at the start of the pipe run. The sponge was then drawn through each section and just before being its travel more paint was injected above the sponge surface to make sure the sponge didn't dry out before reaching the end when it exited the section, Fig. 7. In general the inside surface of all pipe sections were well covered; however, the simple method used did not produce an even paint coat and there were drips, as seen in the borescope video still photograph of Fig. 8, but it was sufficient to locate high wear locations. Note that the paint used was appropriate to cover stainless steel and the pipe surfaces were cleaned prior to application to ensure good adherence.

Figure 7. Pipe paint trial: Sponge at exit

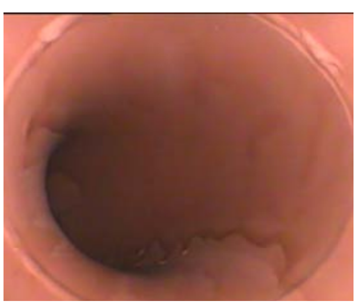


Figure 8. Painted elbow – uneven coat

SIMULANT

For this flow loop only a simple slurry of water and 30 wt% of sand was used with the PSD shown in Fig. 9. The particle diameter was d_{50} = 199 microns, a standard deviation of ±55 microns, and the particle sizes range from 81 to 498 microns.

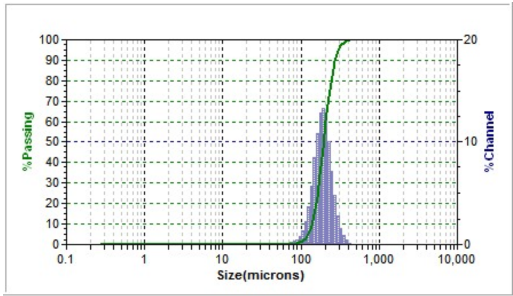


Figure 9. Particle size distribution of sand with, d_{50}~199 microns

TEST OPERATION

A summary of the test operation is:

1. Load feed tank with 30 wt% slurry.
2. Start slurry mixing.
3. Start flow loop pump.
4. Bring slurry to 4 m/s then sample slurry.
5. Monitor flow and observe transparent straight and elbow pipe sections, located downstream of Section 5 pipe on the top of the feed tank, until the paint removal is observable and demonstrated local wear areas. See Fig. 10. (Darker areas indicate paint.)
6. Stop test.
7. Isolate slurry flow loop and drain slurry.
8. Dismantle pipe to clean, dry, and document.
9. Repeat the entire process if further slurry wear is warranted.

Figure 10. Elbow and straight transparent section used to monitor paint removal during test. The dark colored areas indicted paint on the inside surface and the light areas show where the slurry eroded the paint from the pipe wall.

With respect to Step 9 a repeat test was necessary because the first test was stopped when significant wear to the paint was evident in the transparent pipe, Fig. 10, which was surprising because one reference [9] indicated that for liquid-solid flows demonstrable wear would occur "within a few hours". With significant paint eroded from the plastic pipe, after about 30 minutes, the slurry flow was stopped, the five pipe sections were drained, cleaned, and dried, after which the wear in those sections was documented with borescope equipped with a video camera. It was apparent that the metal pipe sections were still mostly covered with paint. While some sections showed erosive wear it was clear that the flow loop should have operated for a longer time to clearly show wear patterns. It was decided to reassemble the flow loop and run the test longer. During this interval most of the sand in the test was recovered and returned to the flow system. Once the flow loop was circulated for approximately another 60 minutes it was terminated to repeat the documentation so a comparison could be made. The time periods of stable slurry flow were estimated to be:

Test 1 = 22 minutes ± 4 minutes
Test 1 + Test 2 = 81 minutes ± 10 minutes

DISCUSSION

In analyzing the wear data with a pipe system it is important to have a convention on orientation. There are probably many ways to define flow orientation through a pipe, but it is very important that when it is being viewed and described the locations and orientations are understood correctly. 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. A clock orientation is defined at the positions of the hands on an analytical clock facing the flow direction. Note, oc = o'clock was used for the pipe wear descriptions and the steel ball seen is some of the photographs was used for scale. It has a 12.7-mm diameter and held in place with a magnet outside of the pipe.

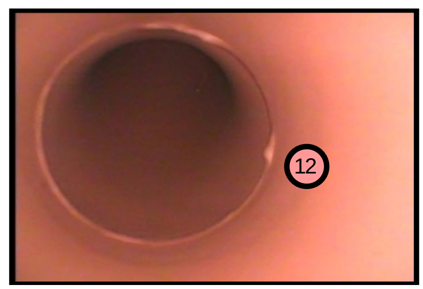
Due to the many pipe sections and fitting this presentation is only limited to the first Long Radius elbow and after one of the major flow diversions, e.g., tee fitting, as examples on how the entire pipe loop was analyzed. However, the conclusions relate to the entire set of observations made. Note, for Figs. 11 to 13 the views are in the direction of flow.

Pipe Section 1: LR 90° elbow entrance (Fig. 11)

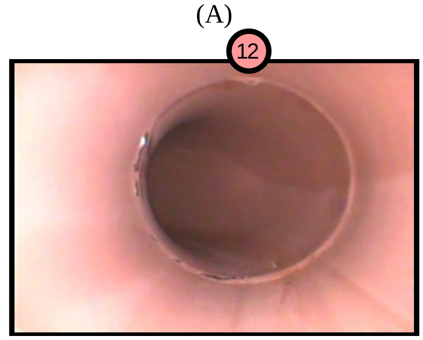
0 min - Weld is well covered with paint. [Photo (A)]

22 min – Some erosion to the weldment is evident as well as a start of wear on the intrados (inner wall) of the elbow, just behind the tack weld at 9 oc. The higher slurry velocity on the extrados (outer wall) of the elbow is evident by the streak of lighter colored paint at approximately 3 oc, which widens near the exit of the elbow. [Photo (B)]

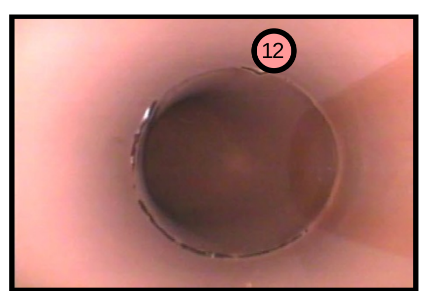
81 min – Erosion is evident around the weldment especially in the intrados portion of the elbow as the slurry changes direction. This can be seen in the close-up below of the intrados tack weld. The darker stain at 3 oc may have been where water dried after cleaning. [Photos (C and D)]



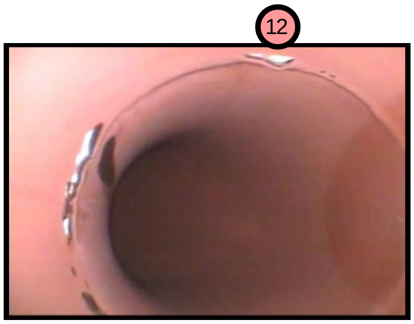
(A)



(B)



(C)



(D)

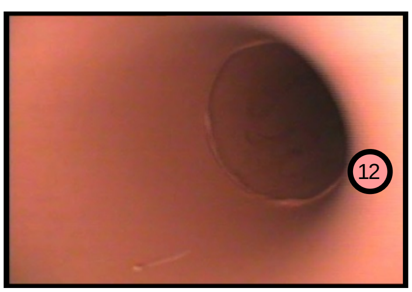
Figure 11. LR 90° elbow entrance: (A) 0, (B) 22, and (C) 81 minutes of slurry flow

Pipe Section 1: LR 90° elbow exit (Fig. 12)

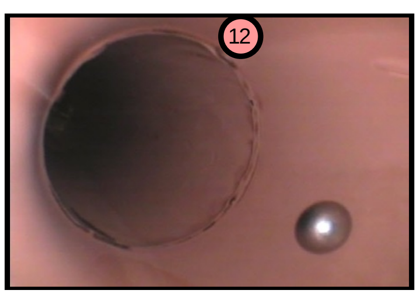
0 minute – Weld is well covered with paint. The drip seen on the bottom of the photograph was approximately a the 3 oc position. [Photo (A)]

22 minutes – All the paint is discolored (lighter) and some wear is evident along the weld and the intrados. [Photo (B)]

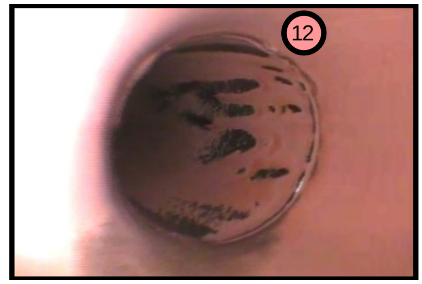
81 minutes – Wear is evident at approximately 90 to 100° (just downstream of the elbow) on the extrados, which is what was expected. There is also wear on the intrados, but closer to the bottom at around 7 oc and around the weld. [Photos (C and D)]



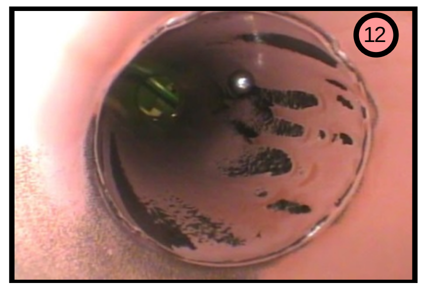
(A)



(B)



(C)



(D)

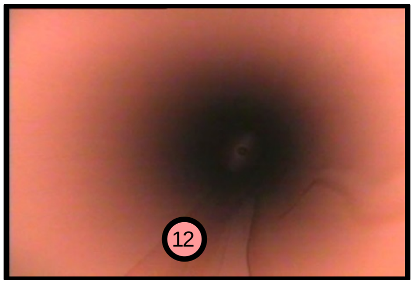
Figure 12. LR 90° elbow exit: (A) 0, (B) 22, and (C)&(D) 81 minutes of slurry flow

Pipe Section 4: Vertical straight pipe after tee fitting (Fig. 13)

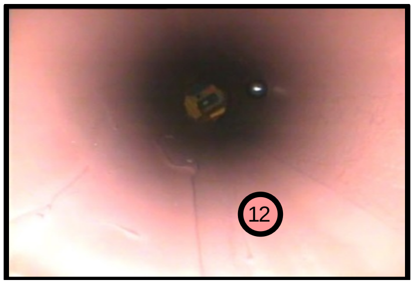
0 minute – There are a few uneven streaks of paint, but in general this pipe is well coated. Note, this view is against the flow direction because the pipe section was not filmed in the flow direction because of the inability to push the borescope through the pipe from around the tee fitting. This difficulty was overcome in subsequent evaluations by pulling the borescope up the tube. [Photo (A)]

22 minutes – The pipe is still basically covered with paint, but the paint is lighter in color, which indicates some level of wear. From the video still it not easy to see, but some exposed metal can be seen very close to the wall. [Photo (B)]

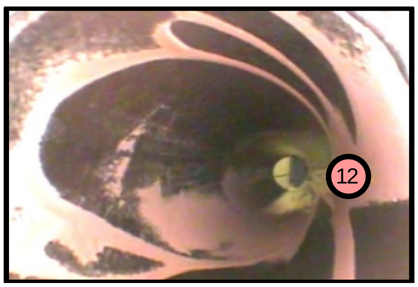
81 minutes – Photo (D) shows the vertical pipe from the bottom and Photo (C) is a location approximately half way up the pipe, i.e., the 5D location. Most of the paint is removed from the bottom as the flow comes out of the tee fitting indicating a lot of secondary flow scouring. However, as the flow moves up the pipe the largest wear appears to be on one side, from approximately 6 oc to 12 oc, clockwise.



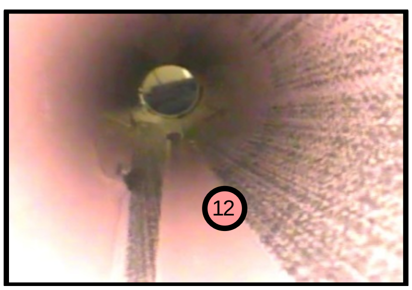
(A) [note - view against flow]



(B)



(C)



(D)

Figure 13. Vertical 10D straight pipe: (A) 0, (B) 22, and (C)&(D) 81 minutes of slurry flow

CONCLUSIONS

- All similar pipe fittings, i.e., elbows, tees, had slightly different wear patterns, estimated to be the result of different upstream and downstream flow conditions, e.g., 0D, 5D, or 10D lengths of straight pipe.
- All LR 90° elbow indicated wear on the intrados surfaces, especially at the entrances, and on the extrados surfaces, principally at the exit from 80° to 110°.
- The tee fitting with straight through flow, and not flow into the branch, showed wear on the upstream and downstream knees of the branch pipe.
- The 3D 90° elbow had wear primarily on the intrados, throughout its travel. Some extensive wear was observable on the extrados near the exit but it appeared to be considerably less than LR 90° elbows.
- When the flow was subject to a major change in flow pattern, the downstream pipe experienced considerable wear due to the setup of turbulent secondary flow. Major flow disruptions were present in Pipe Section 3 (that contained four LR 90° bends) and in Pipe Section 4 (that contained a tee fitting, which directed flow to the branch and a dead end to straight through flow).
- All raised surface were a source of higher wear due to turbulent secondary flows, including: weldments, tack welds, misaligned straight pipe to pipe fittings, seals, etc.
- Fully developed flow was not obtained even after 30D of vertically oriented straight pipe, which was evident from Section 4 to Section 5 pipes, Fig. 2. The higher wear seemed to be principally on one side of the pipe, but it slowly rotated as it straightened from a very traumatic flow change caused by the upstream tee fitting to the downstream LR 90° elbow at 34D.

These observations will help to design a more accurate flow loop to measure wear rates. It is important to note that slurry wear locations on a pipe fitting in isolation cannot be determined accurately, except under very special and rare circumstances. In general, it will be necessary to place a fitting in a prototypic environment, mechanically, chemically, etc. to elicit accurate wear data.

ACKNOWLEGMENT
The U.S. Department of Energy supported this work.

REFERENCES

[1] Ward-Smith, A.J., 1980, *Internal Fluid Flow:The fluid dynamics of flow in pipe and ducts*, Clarendon Press, Oxford [pp. 164-167, 233, and 279]

[2] Colwell, J.M. and Shook, C.A., 1988, "The Entry Length for Slurries in Horizontal

Pipeline Flow," Can. J. Chem. Eng., 66, pp. 714-720.

[3] Hutchings, I.M., 1987, "Wear by Particulates," Chem. Eng. Sci., 42, pp. 869-878.

[4] Clark, H.McI., 1990, "Slurry Erosion," Proc. Corrosion-Erosion-Wear of Materials at Elevated Temperature, held at Berkeley, CA, Jan. 31 to Feb. 2, pp. 10-1 to 10-14.

[5] Duignan, M.R. and Lee, S.Y., 2001, "RPP-WTP Slurry Wear Evaluation: Literature Review," SRNL Report No. WSRC-TR-2001-00156.

[6] Clark, H.McI., 2002, "Particle Velocity and Size Effects in Laboratory Slurry Erosion Measurements OR… Do You Know What Your Particles are Doing?" Tribol. Int., 35, pp. 617-624.

[7] Finnie, I., 1995, "Some Reflections on the Past and Future of Erosion," Wear, 186-187, pp. 1-10.

[8] Parslow, G.I., Stephenson, D.J., Strutt, J.E., and Tetlow, S., 1997, "Paint Layer Erosion Resistance Behaviour for Use in a Multilayer Paint Erosion Indication Technique," Wear, 212, pp. 103-109.

[9] Wu, J. Graham, L.J.W., Lester, D., Wong, C.Y., Kikpatrick, T., Smith, S., and Nguyen, B., 2011, "An Effective Modeling Tool for Studying Erosion," Wear, 270, pp. 598-605.

[10] Burstein, G.T. and Sasaki, K., 2000,"Effect of impact angle on the slurry erosion-corrosion of 304L stainless steel," Wear 240, 80-94.

[11] Foley, T. and Levy, A., 1983, "The erosion of heat-treated steels," Wear 91, 45-64.

[12] Singh, T., Tiwari, N., and Sundararajan, G., 1991, "Room temperature erosion behaviour of 304, 316, and 410 stainless steels," Wear 145, 77-100.

[13] Smith H.D. and Elmore, M.R., 1992, "Corrosion studies of carbon steel under impinging jets of simulated slurries of neutralized current acid waste (NCAW) and neutralized cladding removal waste (NCRW)," PNNL Report No. PNL-7816 (also UC-721), (January).

[14] Zhong, Y. and Minemura, K., 1996, "Measurement of erosion due to particle impingement and numerical prediction of wear in pump casing," Wear **199**, 36-44.

[15] Iwai, Y. and Nambu, K., 1997, "Slurry wear properties of pump lining materials," Wear 210, 211-219.

[16] Mishra, A. and Finnie, I., 1981, "On the Size Effect in Abrasive and Erosive Wear," Wear 65, 359-373.

[17] Mills, D. and Mason, J.S., 1981, "Conveying Velocity Effects in Bend Erosion," J. Pipelines 1, 69-81.

[18] Gandhi, B.K., Singh, S.N., and Seshadri, V., 1999, "Study of the parametric dependence of erosion wear for the parallel flow of solid-liquid mixtures," Tribology International 32, 275-282.

[19] Blanchard, D.J., 1981, "Erosion of Metal Pipe by Solid Particles Entrained in Water," M.S. Thesis, MIT, pp. 1-97.

[20] Nasr-El-Din, H., Shook, C.A., and Colwell, J.M., 1987, "The Lateral Variation of Solids Concentration in Horizontal Slurry Pipeline Flow," Int. J. Multiphase Flow, 13(5), pp. 661-670.

[21] Jacobs, B.E.A., 1991, *Design of Slurry Transport*, BHR Group, Elsevier Applied Science, London.

[22] Azimian, M. and Bart, H. , 2014, "Investigation of Hydroabrasion in Slurry Pipeline Elbows and T-Junctions," J. Energy and Power Eng., 8, pp.65-78.

[23] Roco, M.C. and Cader, T., 1990, "Energy approach for wear distribution in slurry pipelines", Jap. Journal of Multiphase Flow 4, 2-20.

[24] Roco, M.C and Minani, L.K., 1989. "Effect of particle size distribution and gravitation on wear in centrifugal pump castings", American Society of Mechanical Engineers, Paper No. 89-FE8.

[25] Ting, K., Ma, Y.P., 1999, "The Evaluation of Erosion/Corrosion Problems of Carbon Steel Piping in Taiwan PWR Nuclear Power Plant," Nucl. Eng. Design, 191, pp. 231-243.

[26] Salama, M.M.,2002, "An Alternative to API 14E Erosion Velocity Limits for Sand-Laden Fluids," ASME J. Energy Res. Tech., 122, pp. 71-77.

[27] Chen, X., McLaury, B.S., and Shirazi, S.A., 2004, "Application and Experimental Validation of a Computational Fluids Dynamics (CFD)-based Erosion Prediction Model in Elbows and Plugged Tees," Computers & Fluids, 33, pp. 1251-1272.

[28] Zhang, Y, Reuterfors, E.P., McLaury, B.S., Shirazi, S.A., and Rybicki, E.F., 2007, "Comparison of Computed and Measured Particle Velocities and Erosion in Water and Air Flows," Wear, 263, pp. 330-338.

[29] Mazumder, Q.H., Shirazi, S.A., and McLaury, 2008, "Experimental Investigation of the Location of Maximum Erosive Wear Damage in Elbows," J. Pres. Vessel Tech., 130, pp. 011303-1 to 7.

[30] Njobuenwu, D.O. and Fairweather, M., 2012, "Modelling of Pipe Bend Erosion by Dilute Particle Suspensions," Comp. Chem. Eng. 42, pp. 235-247.

[31] Ferng, Ma, and Chung, 2000, "Application of Local Flow Models in Predicting Distributions of Erosion-Corrosion Locations," Corrosion, pp. 116-126.

[32] Blanchard, D.J., Griffith, P., and Rabinowitz, E., 1984, "Erosion of a Pipe Bend by Solid Particles Entrained in Water," J. Eng. Ind., 106, pp. 213-217.

[33] Toda, M, Komori, N., Saito, S., and Maeda, S., 1972, "Hydraulic Conveying of Solids through Pipe Bends," J. Chem. Eng. Japan, 5 (1) 4-13.

[34] Mishra, R., Singh, S.N., Seshadri, V., 1998, "Study of Wear Characteristics and Solid Distribution in Constant Area and Erosion-Resistant Long-Radius Pipe Bends for the Flow of Multisized Particulate Slurries," Wear, 217, pp.297-306.

[35] Brown, G.J., 2002, "Erosion Predictions in Slurry Pipeline Tee-Junctions," Applied Math. Mod., 26, pp. 155-170.

[36] Lee, S. Y., Dimenna, R.A., and Duignan, M.R., 2002, "Designing a scaled Erosion Test with Computational Fluid Dynamics Methods," Paper FEDSM2002-31285, *Proc. FEDSM2002*, July. 14-18.

[37] Wood, R.J.K. and Jones, T.F., 2003, "Investigations of Sand-Water Induced Erosion Wear on AISI 304L Stainless Steel Pipes by Pilot-Scale and Laboratory-Scale Testing," Wear, 255, pp. 206-218.

[38] Wood, R.J.K., Jones, T.F., Ganeshalingam, J., and Miles, N.J., 2004, "Comparison of Predicted and Experimental Erosion Estimates in Slurry Ducts," Wear, 256, pp. 937-947.

[39] El-Sayed, S. and Lipsett, M.G., 2009, "Simple Predictive Model of Slurry Wear in a Pipeline with Bed Flow," Proc. Global Petroleum Congress, Calgary, pp. 1-28.

[40] Gnanabelu, A.B., 2010, "A Geometry Independent Integrated Method to Predict Erosion Wear Rates in a Slurry Environment," Ph.D. Thesis, The Univ. Leeds, School of Mech. Eng. (December), pp.1-241. [Section 7.5, "Preliminary application of the method to plant equipment," pp. 172-178]

[41] Zhang, H., Tan, Y., Yang, D., Trias, F.X., Jiang, S., Sheng, Y., and Oliva, A., 2012 , "Numerical Investigation of the Location of Maximum Erosive Wear Damage in Elbow: Effect of Slurry Velocity, Bend Orientation and Angle of Elbow," Powder Tech. 217, pp. 467-476.

[42] Duignan, M.R., 2001, "Slurry Wear Evaluation of the Pretreatment Cross-flow Filtration and Evaporator Systems," Westinghouse Savannah River Company Report No. WSRC-TR-2000-00145 (also SRT-RPP-2000-00038), (October).

[43] Lee, S. Y. and Dimenna, R.A., 2002, "Design Analysis for a Scaled Erosion Test," Westinghouse Savannah River Company Report No. WSRC-TR-2001-00591(also SRT-Rpp-2001-00227), (April).

[44] Det Norske Veritas, 2007, *Recommended Practice RP O501 Erosive Wear in Piping Systems*, Technical report, DNV RP O501 – Revision 4.2., pp. i-iii, 1-39.