RECLAMATION

Managing Water in the West

Evaluation of Field Repairable Materials and Techniques for Cavitation Damage

Research and Development Office
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Final Report ST-2019-8452-01
Technical Memorandum No. 8540-2019-39

U.S. Department of the Interior
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Mission Statements

Protecting America's Great Outdoors and Powering Our Future

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

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Finding material solutions that can reduce the progression of damage caused by cavitation on hydropower equipment, pipelines, draft tubes, outlet works, and other important Reclamation structures is of vital importance. It will generate cost savings by reducing the amount of downtime, labor, and frequency of repairs. In this project, researchers developed a test method using a submerged cavitating jet to test and compare various materials according to their cavitation resistance performance. It was found that the testing parameters may still need to be optimized to employ less aggressive material damage. Of the specimens tested it was found that the current proprietary cold spray and thermal spray specimens did not perform as well as the baseline stainless steel samples. Recommendations were made to re-adjust the testing parameters and re-test cold spray and thermal spray specimens, along with many other potential material candidates.

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Notices

Acronyms and Abbreviations

FIST	Facilities Instructions, Standards and Techniques
HP	Horsepower
mm	Millimeters
m/s	Meters per second
psi	Pound per square inch
Reclamation	Bureau of Reclamation
rpm	Revolutions per minute
TSC	Technical Service Center
USBR	Bureau of Reclamation

Definitions

Cavitation: The formation and subsequent collapse of vapor pockets in flowing liquid.

Partial Vacuums: Areas of low pressure in flowing water.

Saturated Vapor Pressure: Pressure exerted by the vapor over a liquid. The saturated vapor pressure is the point when the liquid phase and vapor/gas phase are in equilibrium. Vapor pressure is a function of temperature.

Impinging Jet: A high pressure jet of water that is created during the collapse of a cavitation bubble.

Submerged Cavitating Jet: A continuous, high-pressure liquid jet in which cavitation is induced by the nozzle design.

Stand Off Distance: The distance between the inlet edge of the nozzle and the target face of the specimen.

Executive Summary

The Bureau of Reclamation generates power, and collects, conveys, and stores water by using structures such as pipelines, hydro-turbines, pumps, draft tubes, and outlet linings. As a result of the flows and pressure changes that occur in these structures, they can be subject to cavitation damage. Currently, Reclamation's primary method for mitigating cavitation is the use of stainless steel weld overlays. These repair methods are time-consuming, with some instances requiring outages of up to six months. Typical weld overlays have a finite service life, typically requiring repair every three years. On hydropower units it costs $100-$250k every 1-3 years per unit per repair. As a result of these factors, cavitation damage has been identified as one of the most expensive maintenance items to Reclamation. Improving mitigation techniques for the effects of cavitation on Reclamation structures will greatly reduce cost, both in repairs and equipment downtime.

The objectives for this research were to develop a test method to comparatively test cavitation on a chosen substrate, compare baseline stainless steel specimens to cold spray and thermal spray specimens, and to make recommendations for further research using coatings and other potential cavitation-resistant materials.

This research successfully implemented a new testing methodology using a submerged cavitating jet to test specimens over a relatively reasonable duration of time. Other test methods were researched, and found to be inadequate for our testing needs: ASTM G134 and the 1960's Reclamation venturi cavitation test facility. They were either too small in specimen size, to be representative of the field, or they took far too much time to obtain sufficient data from multiple specimens. The submerged jet test method was chosen due to the reasonable sample size and test durations.

Cavitation damage results from cold spray, thermal spray, and stainless steel baseline samples were compared to each other. It was found under these testing conditions that the proprietary thermal spray samples sustained the most damage in the least amount of time. The cold spray also did not match up in performance to the baselines stainless steel samples.

The parameters used in the current submerged jet test method created hydrodynamic conditions on the material that were likely more intense than real life. It has been recommended that test parameters be re-evaluated to be more representative of actual field conditions. It was also recommended that dry times be observed more closely to more accurately reflect mass loss of the specimen. This can be done with oven-drying facilities. Utilizing this test method with improved testing parameters is recommended for many other sample types that were not tested in this research, including: coatings, additional cold spray samples with various application methods, additional thermal spray samples with various application methodologies, and other solid materials used in other industries.

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Introduction

The Bureau of Reclamation (Reclamation) utilizes hydraulic structures such as hydro-turbines, pumps, penstocks, draft tubes, and outlet pipes to generate power, and collect, convey, and store water. As a result of the hydraulic conditions in these structures, their associated equipment and fittings, including turbine blades, pumps, elbow pipes, and outlets, can be subject to damage from cavitation. In high-velocity liquid flows, a deterioration process called cavitation can occur when the pressure suddenly drops near the saturated vapor pressure and creates small vapor pockets, also known as cavitation bubbles. When these cavitation bubbles enter an area of higher pressure, they implode [1]. This releases a shockwave of energy, creating sound and exposing the surrounding surfaces to an impinging jet, which causes microscopic particles of the surface material to flake off [2]. Cavitation damage to turbine runners has been reported in the literature to be as high as 5 kilograms per cubic meter over 10,000 hours with about 200 kilograms loss after two years of operation [3]. Figure 1, shown below, represents a model of the cavitation process.

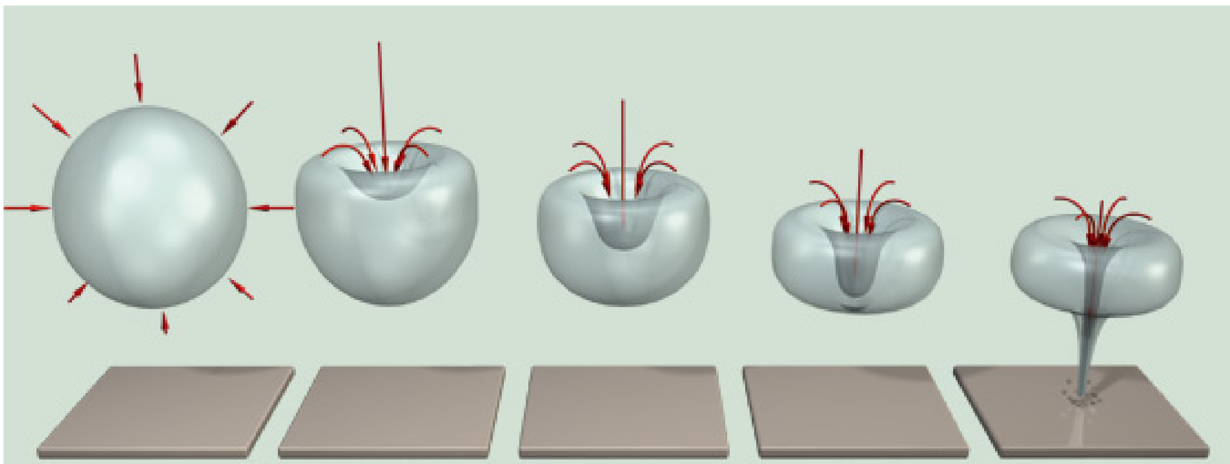

Figure 1. Series of graphics depicting a cavitation model. Reproduced from ref [4]**.**

Over time, the cavitation damage becomes visible in the form of pitting. Once cavitation has begun, the pitting rate becomes exponential due to the increasing surface area which creates new areas of low pressure, resulting in an increasing erosion rate. Over time, erosion of the material will decrease the performance of the equipment, and eventually wear through the material entirely. At that point, complete replacement is inevitable. Cavitation also creates an increase in vibrations of the hydropower equipment, generating significant noise and reducing the efficiency of the unit [2]. Examples of cavitation damage in turbines are shown in Figure 2. Costs of equipment repair, replacement, and downtime are high; therefore, mitigation of cavitation effects on water management structures is a high priority.

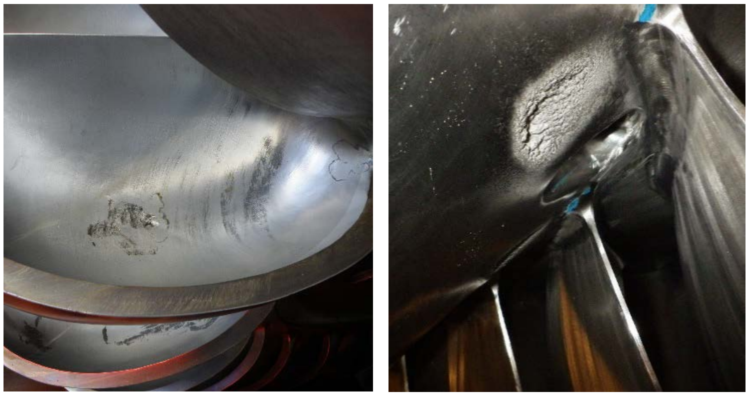

Figure 2. Examples of cavitation damage in turbine runners: (left) Upper Molina powerplant (right) Flaming Gorge powerplant.

Currently, Reclamation's primary method for mitigating cavitation is the use of 308 and 309 stainless steel weld overlays, in accordance with the Facilities Instructions, Standards and Techniques (FIST) Manual, Volume 2-5 [5]. However, this procedure is time-consuming and expensive, with some instances requiring outages of up to six months and using 2,000 pounds of welding rods. The welding process also induces stress to the structure and can create a galvanic corrosion cell if applied to mild steel. Another issue that can occur is stainless steel overlay disbondment, which allows cavitation to continue on the steel substrate. Typical weld overlays have a finite service life, typically requiring repair every three years.

As a result of these factors, cavitation damage has been identified as one of the most expensive maintenance items to Reclamation, costing $100k every 1-3 years per normal sized unit (approximately 15 foot diameter) repair. Larger units (approximately 32 foot diameter) can cost $250k per repair. This does not include the most significant cost which is lost revenue while the unit is down. Improving mitigation techniques for the effects of cavitation on Reclamation structures will greatly reduce cost, both in repairs and equipment downtime.

One commonly examined mitigation strategy is the use of cavitation-resistant coatings, such as stainless steel and nickel superalloys. These coatings can be applied to a substrate material using application techniques, such as cold spray or thermal spray. These rapid application methods are appealing because they would reduce maintenance outages compared with the traditional weld overlay repair method.

Thermal Spray

Thermal spray techniques were originally developed as early as 1909 [6]. However, the application process remained relatively slow until electric arc and plasma equipment were developed. Thermal spray techniques, of which there are many, typically use combustion or electric energy to generate a coating on a substrate [7, 8]. Materials (such as metallics) are deposited on substrates in a molten form to create a thermal based bond [9] at high temperatures and low velocities (Figure 3). Electric arc thermal spray is a high production rate method in which metal wire is melted, atomized, and propelled to a surface [8]. This technique minimizes internal stresses, which allows for application of material at any thickness without cracking [6].

The applied coating is of low porosity [8], which is desirable since denser materials should obtain a longer service life. So far, application of cavitation-resistant thermal-sprayed materials have been successful on mild steel and cast iron [10].

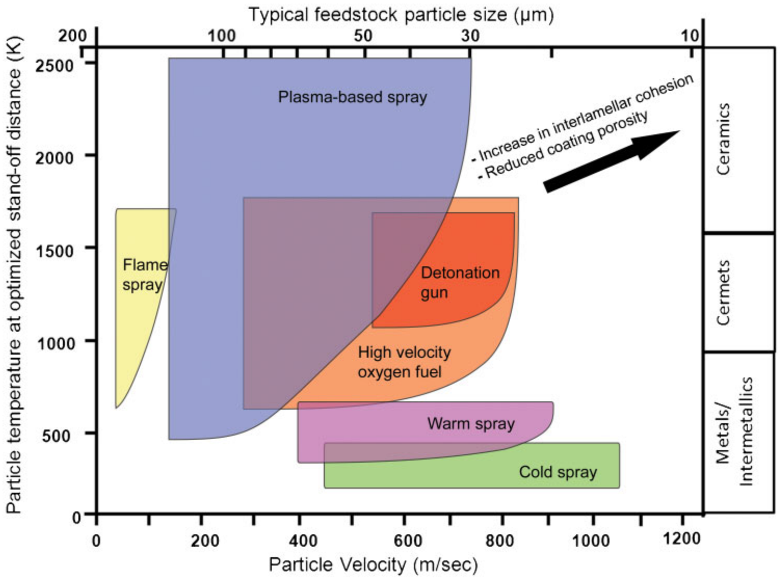

Figure 3. Thermal spray processes according to particle velocity, particle temperature, and feedstock material. Reproduced from ref [8]**.**

Cold Spray

Cold spray was originally developed in the 1990s [11], and has primarily been used as a repair method for air craft, automotive, and military component repairs. Cold spray is a very specialized form of thermal spray that utilizes a kinetic approach as opposed to a thermal one for deposition of particles: heated, micron-sized particles are accelerated to supersonic speeds in a carrier gas (either nitrogen or helium) onto the surface of a parent material [12]. The particles are deposited at a higher velocity and lower temperatures compared to traditional thermal spray techniques (Figure 3). The high-energy impact of the particles forms a metallurgic bond by plastic deformation of the metal. Metals, ceramics, polymers, or composite powders can be applied by the cold spray technique [12]. Aluminum alloys are primarily used because they are soft materials that more easily undergo plastic deformation [10]. A general schematic of the cold spray process in shown in Figure 4.

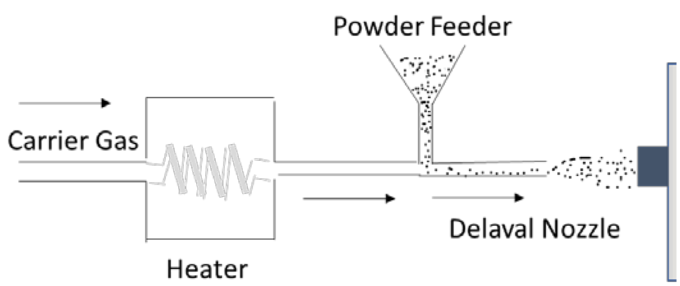

Figure 4. Schematic of the cold spray process.

One advantage of cold spray is that it does not induce thermal stresses in the parent or additive materials because it is applied at a cooler temperature with no heat affected zone as typically seen in thermal spray techniques [9]. Additionally, deposition efficiency is high, and can be increased with finer particle sizes and a lighter gas carrier which increases particle velocity [8]. Greater velocities result in higher film density and better coating quality, but also a more expensive application process. Particle velocity also depends on the pressure of the application system. Low-pressure systems are limited to around 300-600 meters per second (m/s) velocity, and are primarily used only to repair surface defects and blemishes [13, 14]. They are typically much smaller and more portable than high-pressure systems. High-pressure system velocities range from 800-1200 m/s [13, 14]. These systems produce a denser film with less porosity and higher adhesion values than traditional thermal spray techniques (Figure 3), allowing for enhanced material properties similar to the parent material [8].

Objectives

The objectives of this research include:

1. Develop a test method to comparatively test cavitation on a chosen substrate.
2. Compare baseline stainless steel specimens to cold spray and thermal spray specimens.
3. Make recommendations for further research using coatings and other potential cavitation-resistant materials.

Testing Methods

Throughout the investigation, three different testing procedures were used to determine the most feasible and optimal method. The original research scoping plan used a laboratory cavitating jet apparatus built by researchers in 2016. The apparatus was specified to ASTM-G134-95 (2010), Standard Test Method for Erosion of Solid Materials by Cavitating Liquid Jet [15]. However, ASTM G134 specifies that 12-square millimeter (mm^2) diameter specimens be tested with a perpendicular impingement jet, which would make comparison with field conditions difficult, so new testing approaches were pursued.

In 2017, researchers shifted to a 1960s venturi-style cavitation tester that used larger test specimens and more parallel cavitation flows. However, this procedure was abandoned after testing revealed lengthy test times. Finally in 2018, the Technical Service Center (TSC) Hydraulics Investigations and Laboratory Services group developed a submerged jet test using a 3,000 pound per square inch (psi) pressure washer and a water tank. This test produced significant cavitation damage to the specimens within a few days rather than weeks with a set-up that was believed to be more comparable to field conditions, resulting in the procedure being selected as most feasible and optimal to test the thermal spray and cold spray materials.

ASTM G134 Cavitating Jet Tester

Researchers constructed an apparatus utilizing a submerged cavitating jet chamber specified to ASTM G134 to perform tests for material resistance to cavitation damage. The submerged jet impinges on the test specimen so that cavitation bubbles collapse and cause erosion pits. Researchers selected metals and metal alloys as the test materials, but the apparatus also has the capability of testing other materials. The test apparatus is shown in Figure 5 with numbers labeling the components listed in

Table **1**.

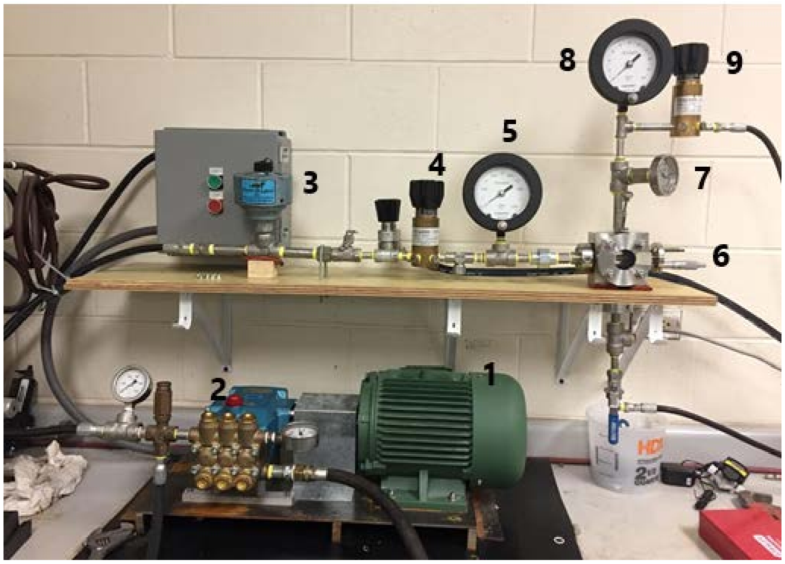

Figure 5. ASTM G134 test apparatus.

Table 1. Component list for ASTM G134 test apparatus.

1	Motor	6	Cavitation chamber
2	Pump	7	Water temperature thermometer
3	Dampener	8	Downstream pressure guage
4	Upstream control valve	9	Downstream control valve
5	Upstream pressure guage		

Cavitation in the apparatus is controlled by the upstream pressure, downstream pressure, stand off distance, and duration of the test. The stand off distance can be adjusted using a micrometer, and the orifice of the nozzle is 0.4 mm in diameter. The cavitation chamber, shown in Figure 6, was constructued with stainless steel following the guideline schematics provided in the ASTM G134 standard.

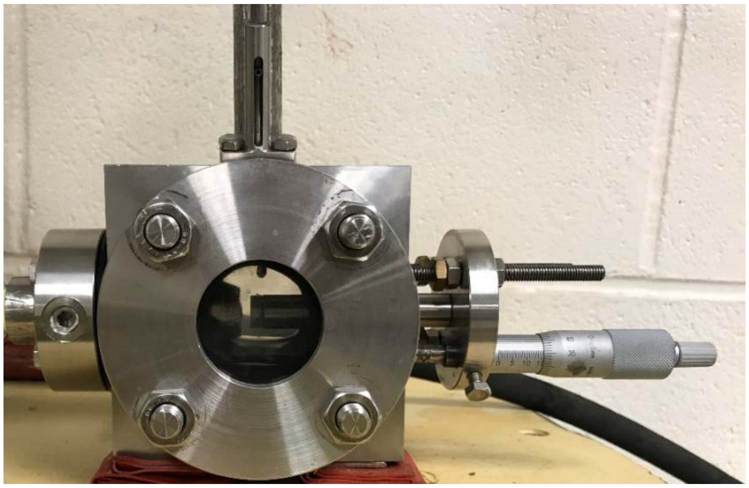

Figure 6. Cavitation testing chamber.

Test Specimen

The test specimens are solid 12-mm diameter discs. Coatings are not recommended for this testing procedure because the material could disbond and plug valves or drain lines. Figure 7 shows an aluminum specimen before and after cavitation damage has occurred. Notice that the area of cavitation damage is approximately 6 mm in diameter.

Figure 7. A 12-mm diameter aluminum specimen before (left) and after (right) cavitation damage.

Test Methodology

The cavitation potential of a flow can be quantified with a dimensionless parameter, the cavitation number. The definition of the cavitation number (σ), where p_d is the downstream pressure, p_v is the vapor pressure, ρ is the liquid density, and V is the jet velocity, are shown in the equations below [15]:

$$\sigma = \frac{(p_d - p_v)}{\frac{1}{2}\rho V^2}$$

For this system, the equation could be simplified further by substitution:

$$\frac{1}{2}\rho V^2 = p_u - p_d$$

$$\therefore\ \sigma = \frac{p_d}{p_u}$$

To provide proper comparison between materials, all tests must be run using the same cavitation number. Therefore, upstream and downstream pressures are determined and kept constant throughout experimentation. Downstream flow rate and water temperature are also monitored. Every 30 minutes, the test is stopped for cavitation evaluation. The specimen is dried and the weight is taken to determine mass loss and erosion rates. Curves of the mass loss and erosion rates can be generated and then examined and compared to determine relative cavitation resistance characteristics of each material. The test continues until the rate of increase of the cumulative mass loss plateaus on the generated curves.

Limitations Associated with Test Method

ASTM G134 only allows for evaluation of solid materials, and coated specimens are not recommended for testing. Additionally, the small size of the test specimen makes it difficult to compare cavitation results from the test with macro-sized cavitation observed on hydraulic structures. Because of these limitations, researchers decided to pursue a different testing approach to find a better fit for the needs of the investigation.

1960s Reclamation Venturi Cavitation Test Facility

As the next testing approach, researchers chose a venturi device that was developed by Reclamation in the 1960's which induces cavitation using flows that are almost parallel to the specimen [16]. This device was originally developed and used to test cavitation damage on concrete but has been used to test various coatings as well. The device uses a high-head pump with a variable frequency drive and a downstream control valve to adjust flows and pressures to optimum test conditions (Figure 8 and Figure 9).

Figure 8. 60 HP electric motor and 7 stage vertical lift pump used for testing in the venturi cavitation device.

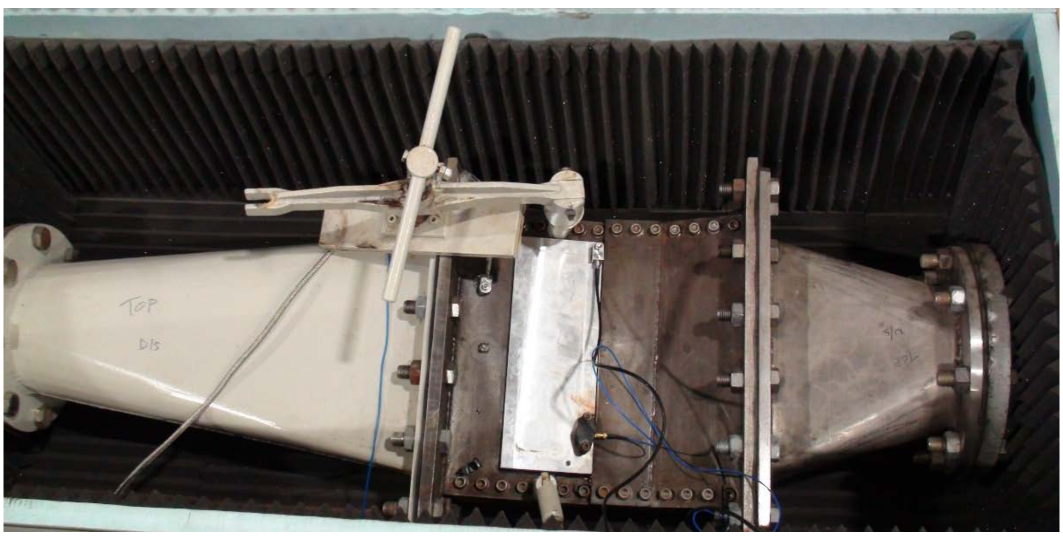

Figure 9. Venturi-style cavitation tester loaded with an aluminum test specimen.

The device is equipped with a 60 horsepower (HP) electric motor and 7 stage vertical lift pump to drive 2.1 cubic feet per second discharge of water through a 0.25-inch by 12-inch venturi opening to induce cavitation [16]. Figure 10 shows a drawing of the venturi device and Figure 11 shows the pressure gradient and location of the cavitation zone. Specimens were exposed to cavitation for up to 180 hours and were evaluated approximately every 8 hours.

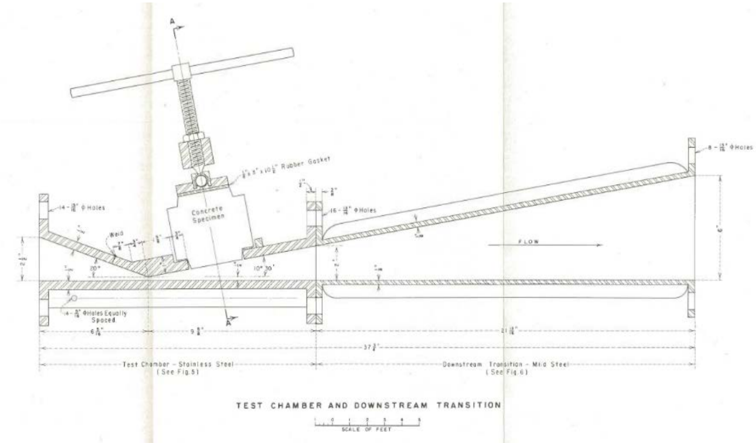

Figure 10. Drawing of the venturi-style cavitation tester [16]**.**

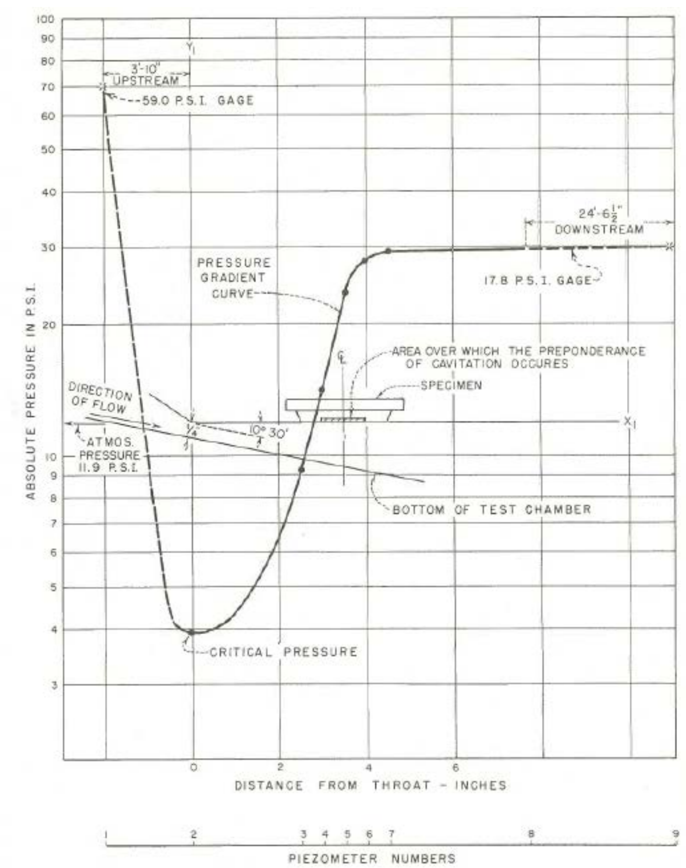

Figure 11. Pressure gradient showing the probable location of cavitation with known upstream and downstream pressures [16]**.**

Test Specimen

Figure 12 shows the test specimen size to be 3 inches by 10.5 inches, much larger than the ASTM G134 specimen size of a 12-mm diameter disc. The venturi-style cavitation tester allowed for the entire specimen to be subjected to cavitation (Figure 13), whereas the previous method ASTM G134 only focused cavitation on the central portion of the specimens (Figure 7).

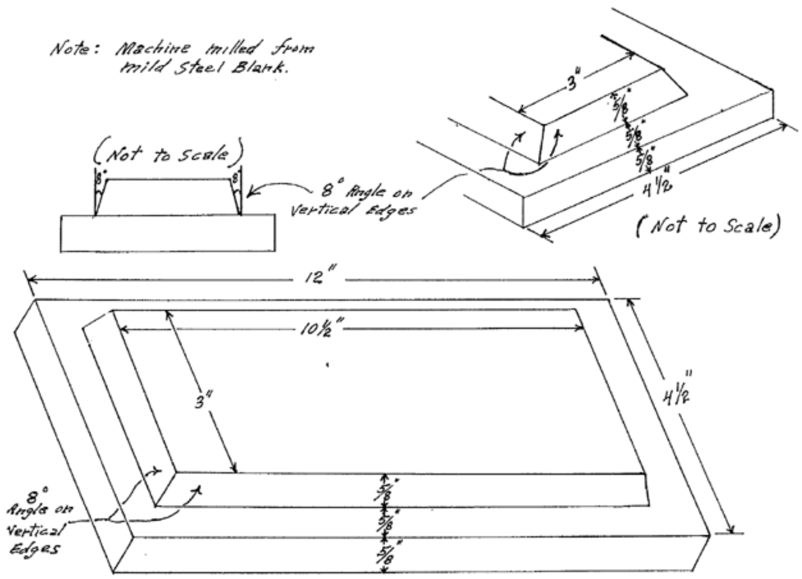

Figure 12. Test specimen size for the venturi-style cavitation tester [17]**.**

Figure 13 identifies the results of a calibration test on the venturi style cavitation tester. A mild steel sample was sprayed with a white spray paint on the top surface and used inside of the cavitation tester. The purpose was to confirm that cavitation damage would occur on the face of the test sample during subsequent testing. An aluminum sample was also tested and used in comparison to the submerged jet test method, discussed in the next chapter.

Figure 13. Mild steel test specimen with spray painted surface before (top) and after (bottom) cavitation by the venturi-style cavitation tester.

Limitations Associated with Test Method

The primary limitation was the duration of the test, which took close to 180 hours for a single aluminum test specimen. This proved too time-consuming to provide sufficient data from multiple samples of each material type. Therefore, after initial testing with the venturi-style cavitation tester, researchers again decided to pursue a less costly and less time-consuming approach.

Submerged Jet Testing Method

Researchers employed a new and final submerged jet test procedure to expose test specimens to intense cavitation, following suggestions in the Reclamation report HL-2017-10 [18]. This method tests material durability by exposing the material to an intense hydrodynamic environment that more rapidly produces cavitation and erosion damage compared to the venturi test method. This method induces cavitation using a submerged jet, similar to the ASTM G134 standard. However, the specimen is placed at a 30 degree angle to the jet, as shown in Figure 14, to account for other physical mechanisms that may cause damage and wear to the surface of the material (e.g. erosive hydrodynamic impact and shear forces).

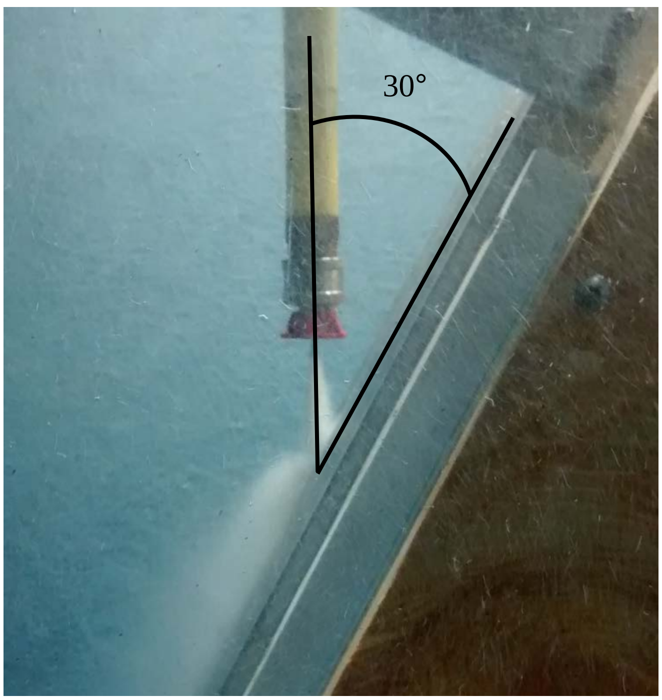

Figure 14. Test specimen exposed to cavitation from a submerged jet [18]**.**

The test set-up was arranged so that two specimens could be tested simultaneously as shown in Figure 15. During testing, flow was supplied to each of the two jets from 10 HP pressure pumps (one jet per pump).

Figure 15. Top view (left) and side view (right) of submerged jet test set-up.

Test Specimens

Baseline

Baseline test specimens were dimensioned the same as the venturi-style cavitation test specimen size, given in Figure 12. Specimens of T6061 Aluminum and 316 stainless steel were tested to calibrate the test and determine variability. These specimens represent solid parent material, machined from stock metals. Tested Aluminum baseline specimens were only used for time duration comparisons with the Venturi test method. Tested stainless steel specimens were used to compare with cold spray and thermal spray specimens.

Cold Spray

Cold spray specimens were prepared by Pacific Northwest National Laboratory using a proprietary method. Cold spray submerged jet testing specimens were dimensioned the same as the venturi-style cavitation test specimen size, shown in Figure 12. Steel substrates were machined to remove 0.125 inch of parent material from the testing area, allowing for the addition of a 0.125-inch thick, 316 stainless steel, cold-spray-applied coating. Each specimen was machined smooth prior to testing to alleviate surface roughness.

Thermal Spray

Thermal spray specimens were prepared by Extreme Industrial Coatings, LLC using proprietary application parameters. The metal alloys applied using thermal spray were Polymet PMET 596 Nickel Aluminum Bronze and Polymet PMET 888 Nickel Molybdenum Aluminum. The alloy coatings were applied to 4 x 6 x 0.625 inch steel parent material (different from the baseline and cold spray specimens). The thermal-sprayed coatings were applied to a thickness of 0.152 inches and machined smooth prior to exposure.

Test Methodology

Flow and pressure measurements were made to calculate the cavitation number of each jet using the same equation given in ASTM G134. The stand off distance between the jet orifice and the test specimen was 3 inches. For each test, the cavitation number and stand off distance remained constant. Cavitation damage to each test specimen was evaluated by shutting down the pumps and drying and weighing the specimen. Cavitation damage was evaluated approximately every 8 hours for stainless steel baseline specimens, and more frequently for cold spray and thermal spray specimens.

Limitations and Advantages of the Submerged Jet Test Method

While the submerged jet test method decreased the required testing time, the test parameters may have been too aggressive for the set-up and chosen materials. This is evidenced by the premature failure of both the cold spray and thermal spray repair materials compared to the stainless steel baseline, as will be discussed in the results section. An ongoing challenging in test method development is finding a reasonable balance between obtaining representative test results and the time and effort required to obtain those results.

One benefit of the submerged jet test method is flexibility in its operational parameters to control the aggressiveness of caviation at the surface of the test sample. A hydrodynamic environment is desired that exposes the test sample to pressure fluctuations and cavitation intensity that are representative of field conditions. To reduce the required test duration to obtain results these conditions are made more intense. If it is believed that the increased intensity causes damage or failure due to other physical mechanisms that are not representative of field conditions then test parameters can be changed and optimized until a reasonable balance between test conditions and test duration is found. The submerged jet method should be optimized to find a reasonable balance between required test time and aggressiveness of test flow conditions to allow for further testing of potential caviation resistant materials.

Results and Discussion

The ASTM G134 and the 1960s venturi-style cavitation test procedures only provided results of the initial material calibration, so no results are included from either method. However, Figure 16 and Figure 17 show a comparison of time required to obtain about 1.6 grams of mass loss of an aluminum test sample using the venturi (about 180 hours) and submerged jet test methods (about 7 hours). The venturi test method duration was approximately 25 times longer than the submerged jet method. This is why venturi testing was not further pursued.

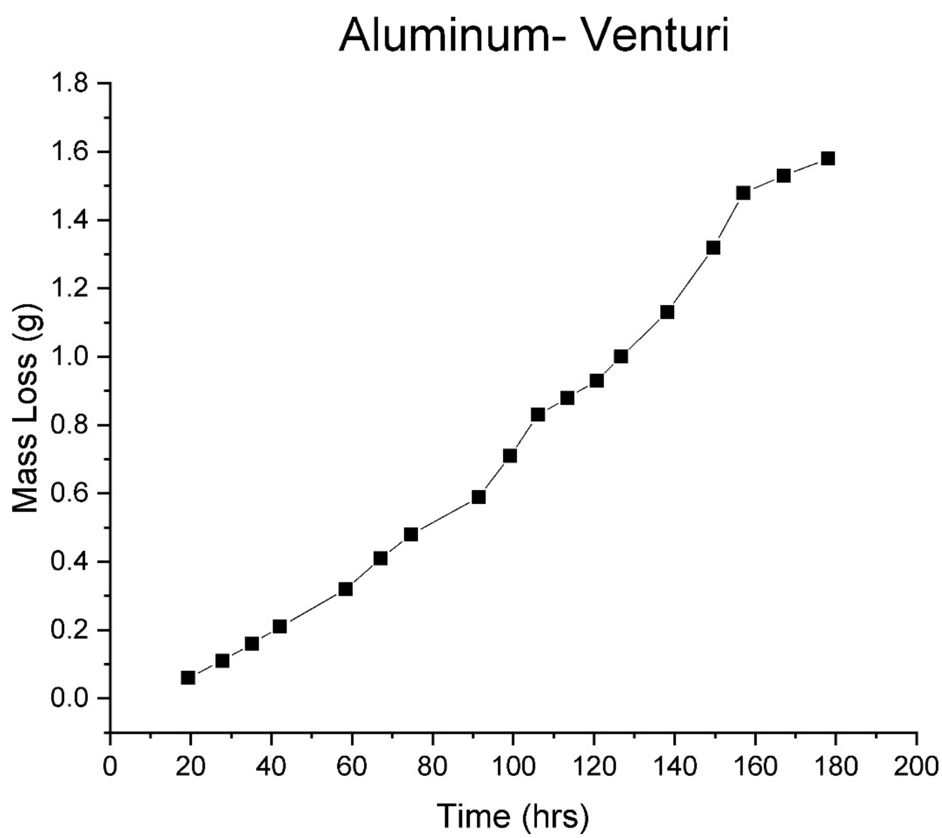

Figure 16. Mass loss of aluminum specimen in venturi cavitation test.

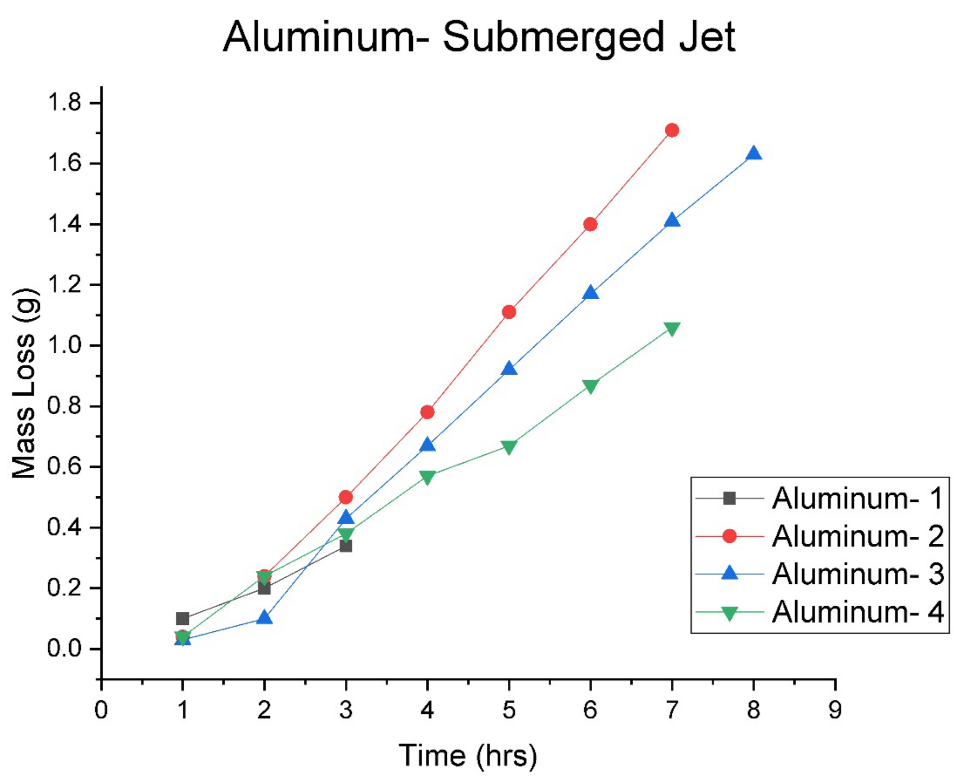

Figure 17. Mass loss of aluminum specimen in submerged jet cavitation test.

Baseline

Four test repititions on two stainless steel specimens were performed to establish a baseline. The test consisted of two test locations on two plates, as shown in Figure 18. Test results are shown in Figure 19. There was a large range in mass loss data for all four specimens, but in general the stainless steel specimens saw a mass loss of no more than 7 grams after 140 hours. This aggressive submerged jet method produces high impact pressures that typically erode a single hole that then becomes a source of caviation itself, resulting in pitting on the surface immediately downstream. This can be seen by the elongated damage pattern downstream of a the deepest hole which is similar to cavitation damage patterns observed in prototype penstocks and spillways. Figure 18 shows that Test 2 exhibited less drilling action of the initial hole, which could explain why it has the lowest mass loss.Test 1, Test 3, and Test 4 exhibit prominent cavitation damage within about an inch of the initial jet location of impact. These three tests track more closely to each other, with variability.

Figure 18. Stainless steel baseline test specimens with test locations.

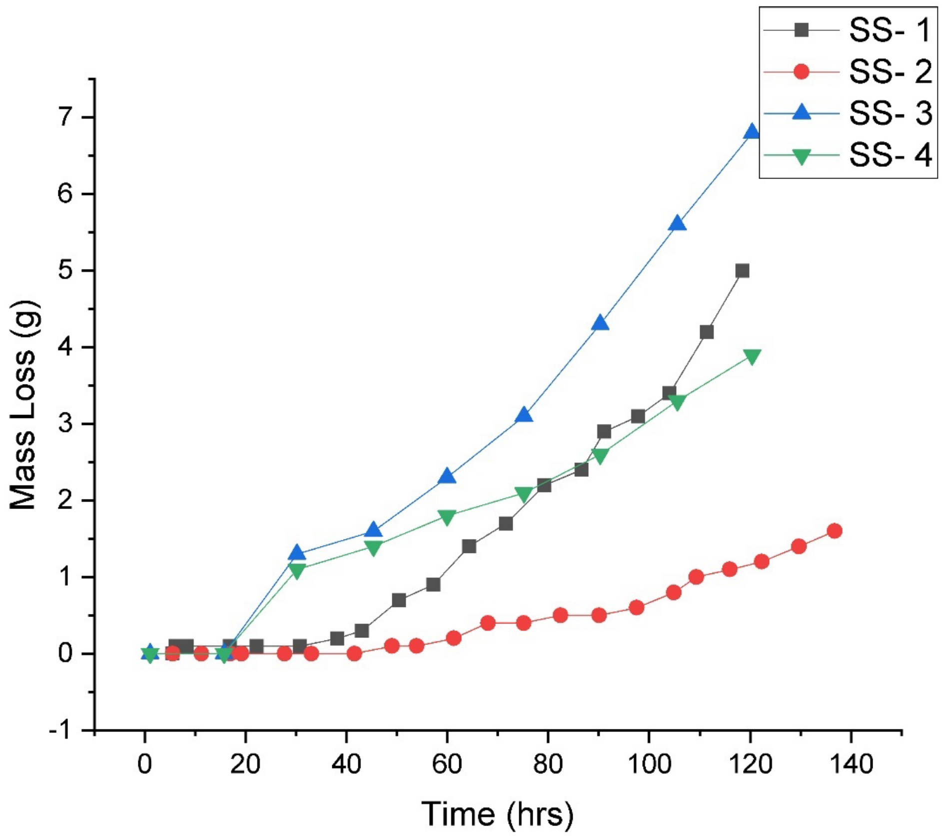

Figure 19. Stainless steel baseline test results.

Cold Spray

Cold spray specimens were tested using two test locations on the same specimen. Figure 20 shows a cold spray specimen that cracked due to the aggressive testing conditions. Test results are shown in Figure 21. Test 2 was inconclusive because of difficulty with the jet pump that required repair. Therefore, only Test 1 could be examined and compared to the baseline tests. Test 1 was only run for approximately 80 hours before a significant crack developed, as shown in Figure 22, which produced delimaination of the cold spray, seen in Figure 23. A mass loss of only about 2 grams occurred prior to the significant crack development, which is comparable to stainless steel baseline Tests 1, 3, and 4 at 80 hours. However, the cold spray was effectively unable to be compared to the baseline tests because of the crack and resulting delamination that occurred.

The cause of the crack in the cold spray sample is unknown. One possibility is fatigue cracking due to rapid stress oscillations of the material due to the impact pressures caused by the jet. Or perhaps a cavitation hole was first eroded through the cold spray lining which allowed for high stagnation pressures between the lining and the parent steel material. This uplift pressure could account for the crack formation as well as the delamination that is clearly shown in Figure 23.

Figure 20. Crack in tested cold spray specimen due to aggressive test conditions.

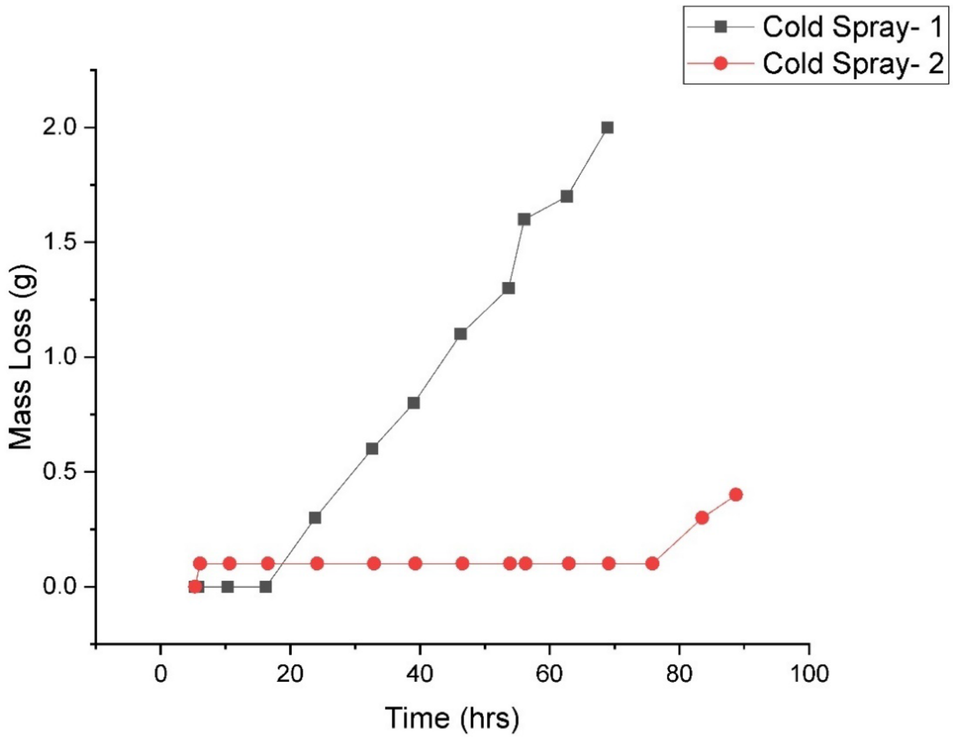

Figure 21. Cold spray test results.

Figure 22. Cold spray test specimens with test locations.

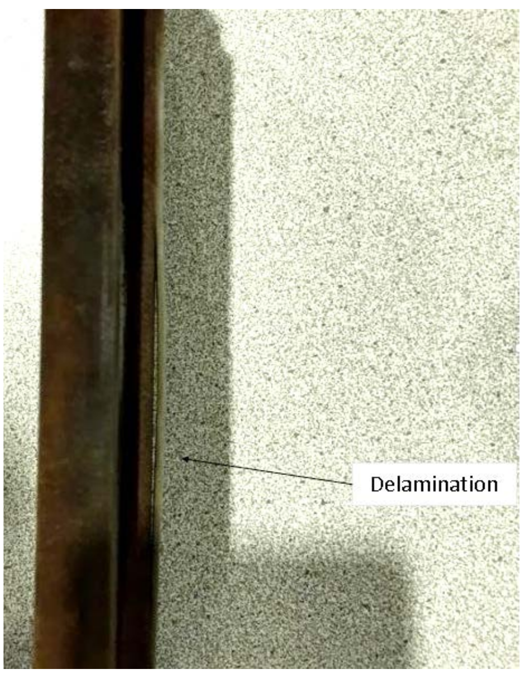

Figure 23. Side view of delamination in cold spray specimen.

Thermal Spray

Thermal spray specimens were tested using two test locations on two specimens, as shown in Figure 24. Test results are shown in Figure 25. During Test 1, it was discovered that the thermal spray specimens presented a unique problem of mass gain due to porosity. Test 2 for the thermal spray PMET 888 and PMET 596 specimens were allowed a longer dry time in between weight measurements, preventing the mass gain problem and allowing results to be compared to the other test results. For future testing the issue of mass gain can be addressed by oven drying specimens prior to each weight measurement.

The thermal spray specimens only lasted at most 7.5 hours before failure occurred under the aggressive testing conditions. After 6 hours of testing, mass loss was already around 1 gram, which is a faster rate than both the baseline and cold spray tests. Thermal spray test results, similar to cold spray results discussed in the previous section, were unable to be compared to the baseline because of specimen failure.

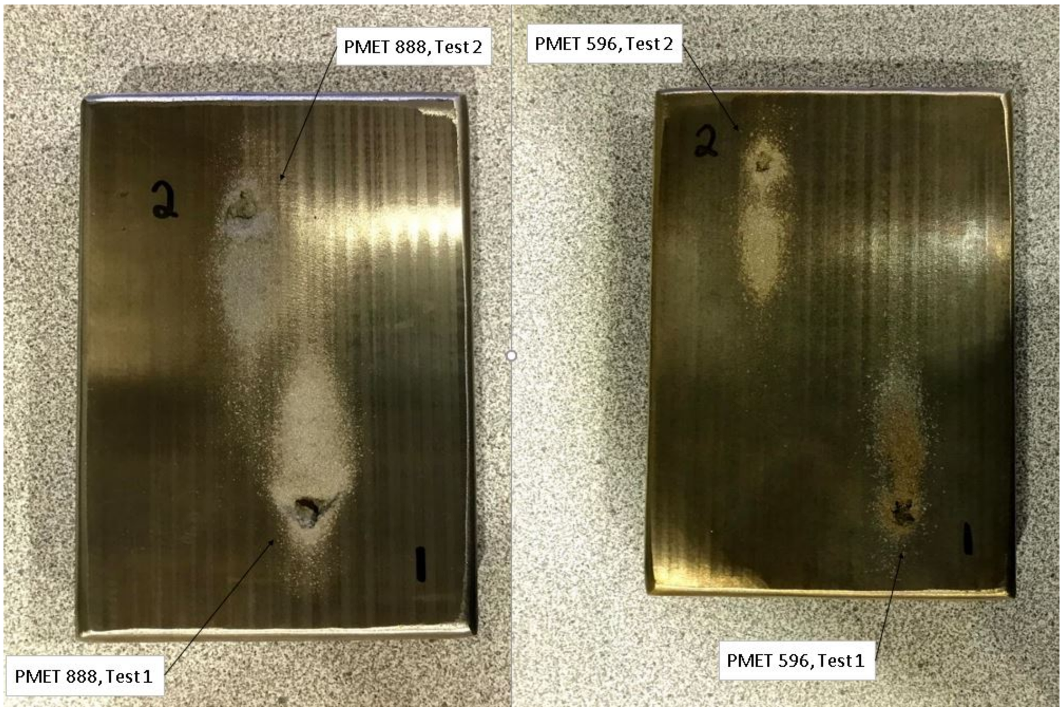

Figure 24. Thermal spray test specimens with test locations.

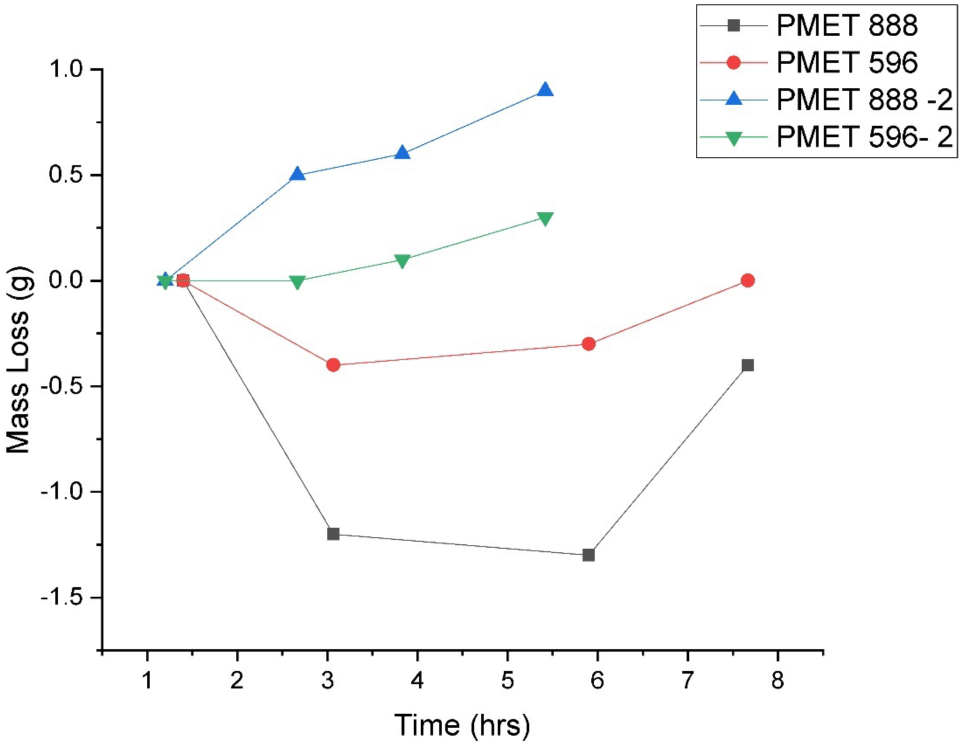

Figure 25. Thermal spray test results.

Conclusion

This research successfully implemented a new testing methodology using a submerged cavitating jet to test specimens over a relatively reasonable duration of time. The following conclusions can be drawn from this research:

1. The ASTM G134 method was abandoned for the following reasons:
    a. ASTM G134 only allows for evaluation of solid materials not coated specimens
    b. The small size of the test specimen is difficult to compare to macro-sized cavitation observed on hydraulic structures.
2. The Reclamation venturi cavitation test facility developed in the 1960's utilized sample sizes that better represented field conditions, but required testing durations that were too lengthy. Durations of 180 hours for one soft aluminum test specimen were not practical for laboratory testing. Therefore this test method was not pursued.
3. The submerged jet test method was chosen due to the reasonable sample size and test durations. At the parameters utilized in this research the cavitation conditions may have been too intense to be representative. Parameters need to be re-evaluated and samples need to be re-tested to obtain a more representative level of damage that represents field conditions.
4. Thermal spray samples sustained damage in less time compared to cold spray samples under the aggressive testing parameters, but still under-performed compared to stainless steel baseline samples. Improved testing parameters may change this observation in future testing.

5. Oven-drying test samples may be required to adequately dry samples between mass loss measurements. Thermal spray samples were noted to absorb water and affect the measurement results.

Recommendations

The submerged jet cavitation test method requires optimization to balance required test time and aggressiveness of test flow conditions. This could be accomplished by varying the cavitation number of the jet (varying flow through the nozzle) and by adjusting the stand off distance between the jet orifice and test specimen. The impact angle of the jet to the test sample could also be adjusted. Hydrodynamic impact pressures on the specimen surface should be measured within the test range to help determine optimal test parameters. After optimization, testing should be repeated to obtain new stainless steel baseline measurements, and cold spray and thermal spray repair material measurements under the new test conditions.

The submerged jet test set-up is already prepared for optimization of operating parameters. Preliminary testing of hydrodynamic impact pressures were completed in September of 2019. Only data analysis and re-testing the test samples are needed to continue work and further develop this unique test method.

Utilizing this test method with improved testing parameters is recommended for many other sample types: coatings, additional cold spray samples with various application methods, additional thermal spray samples with various application methodologies, and other solid materials used in other industries (naval bronze, for example).

Data Sets that Support the Final Report

- Drive folder name and path where data are stored: Z:\DO\TSC\Jobs\DO_NonFeature\Science and Technology\2015-PRG-Cavitation Coatings
- Point of Contact: Chrissy Henderson, Materials Engineer, USBR-TSC-MCL, chenderson@usbr.gov, 303-445-2348
- Folder includes all data, photographs, and reports associated with this project.
- Keywords: Cavitation, erosion, hydropower, turbine runners, cavitation jet, draft tubes.
- Approximate total size of all files: 550 MB

References

[1] P. Kumar and R. P. Saini, "Study of cavitation in hydro turbines- A review," *Renewable and Sustainable Energy Reviews,* vol. 14, pp. 374-383, 2010.

[2] R. Singh, S. K. Tiwari and S. K. Mishra, "Cavitation erosion in hydraulic turbine components and mitigation by coatings: Current status and future needs," *Journal of Materials Engineering and Performance,* vol. 21, no. 7, pp. 1539- 1551, 2012.

[3] D. Whale and D. Hart, "A review of cavitation-erosion-resistant weld surfacing for hydro turbines," in *Proceedings of the Asian-Pacific Welding Conference*, Auckland, New Zealand, 1996.

[4] "Cavitation," Focus-It, LLC, 2012. [Online]. Available: http://eswt.net/cavitation. [Accessed July 2019].

[5] "Facilities Instructions, Standards & Techniques Volume 2-5: Turbine Repair," US Bureau of Reclamation. Facilities Engineering Branch, Engineering Division, Denver, CO, September 2000.

[6] D. Tejero-Martin, M. R. Rad, A. McDonald and T. Hussain, "Beyond traditional coatings: A review on thermal-sprayed functional and smart coatings," *J Therm Spray Tech,* vol. 28, pp. 598-644, 2019.

[7] W. Li, C. Wang, F. Wang, Y. Xu and X. Yang, "'Cold spary +' as a new hybrid additive manufacturing technology: a literature review," *Science and Technology of Welding and Joining,* vol. 24, no. 5, pp. 420-445, 2019.

[8] A. Siao Ming Ang and C. C. Berndt, "A review of testing methods for thermal spray coatings," *International Materials Reviews,* vol. 59, no. 4, pp. 179-223, 2014.

[9] C. U. Hardwicke and L. Yuk-Chiu, "Advances in thermal spray coatings for gas turbines and energy generation: a review," *Journal of Thermal Spray technology,* vol. 22, no. 5, pp. 564-576, 2013.

[10] J. Mehta, V. Kumar Mittal and P. Gupta, "Role of thermal spray coatings on wear, erosion and corrosion behavior: a review," *Journal fo Applied Science and Engineering,* vol. 20, no. 4, pp. 445-452, 2017.

[11] S. Kuroda, J. Kawakita, M. Watanabe and H. Katanoda, "Warm spraying—a novel coating process based on high-velocity impact of solid particles," *Sci. Technol. Adv. Mater.,* vol. 9, no. 3, p. 033002, 2008.

[12] A. Moridi, S. M. Hassani-Gangaraj, M. Guagliano and M. Dao, "Cold spray coating: review of material systems and future perspectives," *Surface Engineering,* vol. 30, no. 6, pp. 369-395, 2014.

[13] J. A. Luhn, "Corrosion and thermal processing in cold gas dynamic spray deposited austenitic stainless steel coatings," [thesis]. Naval Postgraduate School. , Monterey, CA, June 2016.

[14] P. S. Patil, "Repairing casting defects by high pressure cold spraying method," [thesis]. Iowa State Univeristy., Ames, Iowa, 2017.

[15] ASTM International, "G134-95 Standard Test Method for Erosion of Solid Materials by Cavitating Liquid Jet.," ASTM International, West Conshohocken, PA, 2010.

[16] "Design and construction of new cavitation machine," Bureau of Reclamation. Concrete and Structural Laboratory. Report C-1070. , Denver, CO, November 1963.

[17] J. Baker, "Cavitation resistant properties of coatings systems tested on venturi type cavitation testing machiine," Bureau of Reclamation. Research and Laboratory Services Division., Denver, CO, 1994.

[18] J. Mortensen, "Cavitation detection- Method development to detect damaging cavitation," Bureau of Reclamation. Hydraulics Investigations and Laboratory Services Group. Report HL-2017-10. , Denver, CO, 2017.

[19] E. Ayli, "Cavitation in hydraulic turbines," *International Journal of Heat and Technology,* vol. 37, pp. 334-344, 2019.

[20] S. Li, Cavitation of Hydraulic Machinery, River Edge, NJ: Imperial College Press, 2000.