Evaluation of Seven Flexible Linings to Determine Suitability as an Alternative to Mortar Lining

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ABSTRACT

Southern Nevada gets nearly 90 percent of its water supply from the Colorado River which is currently facing the worst drought on record. To ensure a more reliable long term water supply for the Las Vegas Valley, the Southern Nevada Water Authority (SNWA, Authority) is planning to develop water resources in east-central Nevada. The Groundwater Development (GWD) Project is proposed to ultimately consist of a pipeline and power conveyance system and well fields. The main pipeline system, made up of welded steel pipe ranging in size from 66-inches to 96-inches in diameter, will transmit groundwater from well fields to be developed in Lincoln and White Pines Counties, Nevada over 200 miles into Clark County, Nevada. SNWA enlisted the preliminary design services of HDR Engineering to perform system hydraulic analysis and facility definition of the main pipeline.

The preliminary design effort included evaluation of various options for pipe procurement. Any option considered would likely result in the pipe being stored for extended periods of time. The duration and harsh climate where the pipe would be stored caused concern that that the integrity of a mortar lining could be compromised. In addition, SNWA experience caused concern that, because of the water chemistry, leaching of alkalinity from the mortar lining could necessitate extensive flushing of the line. Lastly, due to the magnitude of the project, the use of flexible linings had the potential to reduce the tonnage of steel and thus reduce the overall project cost. These factors contributed to convincing the project team that alternate lining materials should be considered.

Investigations showed that flexible linings, specifically polyurethane linings, were gaining more acceptance as an alternative to cement mortar linings. However, experience with flexible linings in water pipelines is limited. Epoxy systems were added to the evaluation after considering that recent developments in the formulation of epoxy systems have resulted in quicker set times. Epoxies, as a family of products, have been available longer than polyurethane systems.

To better understand the properties of polyurethane lining systems, SNWA decided to undertake an extensive testing program. The goal of the program was to:

Estimate a reasonable life expectancy for polyurethane lining systems, including potential life cycle costs for periodic maintenance activities;

Identify properties critical to obtaining good installation/application,

Develop a guide specification for use on future projects, and

Define critical quality control parameters for polyurethane lining systems that would allow plant and field inspectors to effectively assess the application and installation.

After the initial testing program was developed, epoxy systems were added to the evaluation. Recent developments in the formulation of epoxy has resulted in quicker set times and epoxies, as a family of products, has been available longer than polyurethane systems. The program tested 5 polyurethane systems and 2 epoxy systems, side by side. Products were tested in a "blind" environment; that is to say that the name of the product manufacturer for each lining system was kept confidential and an arbitrary letter was assigned to identify each system.

Each of the 7 products was applied to test plates (carbon steel coupons) by a single applicator that was qualified to apply each of the products. The samples were labeled and shipped to KTA Tator's (KTA) laboratories in Pittsburgh, Pennsylvania, where the testing was conducted over the course of approximately nine (9) months.

This paper describes the details of the application and testing and discusses the testing data.

PROJECT BACKGROUND

During the preliminary design for the Southern Nevada Water Authority's (SNWA) Groundwater Development (GWD) Project, several design decisions had the potential to impact implementation of the project.

Historically, SNWA has specified and installed mortar lined and dielectric coated steel pipe for the majority of its projects located in southern Nevada. This particular pipe material configuration met SNWA's design criteria, installation, construction, and maintenance requirements and appeared to also be acceptable for the GWD Project.

Pipe has typically been procured and installed by the selected construction contractor. However, several new and unique conditions for construction were identified in preliminary planning for the GWD Project.

Timing: It was anticipated that design, construction and installation would be on a "fast track" approach, and that the large quantities of pipe required would necessitate pre-purchase and long term storage of the pipe. Long term storage could occur in regions of Nevada where temperatures could range from well below freezing to over 100 ˚F (38˚ C), and humidity is measured in the single digits.

Cost: At a time when fabricated steel pipe prices were exceeding $1000 per ton, and expected to go higher, the use of steel with a higher stress value and thinner wall pipe designs could produce a significant cost savings to the project. The downside was that a more flexible pipe wall would result in deflections higher than allowed by either current design guidelines or SNWA.

Operation: Operational scenarios of the GWD Project pipeline could leave raw groundwater in the pipe for extended periods of time. SNWA had noted on past projects that long term storage of treated water in its pipelines lead to leaching of alkalinity from the mortar lining. This leaching would produce milky and cloudy water within the pipe. When this leaching occurs, large quantities are required to flush the pipeline.

Given these potential conditions for the GWD Project pipeline, the recommendation was made to SNWA to consider the use of polyurethane linings. Following this recommendation, SNWA requested an evaluation of the suitability of flexible lining systems for the GWD Project.

TESTING PROGRAM DEVELOPMENT - BACKGROUND

To assist in the development of a testing program, it was decided that there needed to be an independent technical review panel (TRP). This panel would be tasked with reviewing the proposed testing for appropriateness, based on the goals; reviewing the data as the testing proceeded and utilize their personal and real-world experience to assist in interpreting the results.

Initial steps were to develop a testing protocol, or series of tests to utilize in the program. Current industry standards are AWWA C210, Liquid-Epoxy Coating Systems for the Interior and Exterior of Steel Water Pipelines and AWWA C222, Polyurethane Coatings for the Interior and Exterior of Steel Water Pipe and Fittings.

Ultimately, the team settled on fourteen property and characteristic tests to evaluate the suitability of polyurethanes and epoxies as potential lining material for steel pipe.

PRODUCT APPLICATION

Following development of the testing protocol, and selection of members of the technical review panel (TRP), a qualified applicator had to be identified, selected, and contracted with to receive materials, prepare samples, and apply various materials in accordance with the manufacture’s recommendations and requirements.

The applicator would also be required to provide and follow a QA/QC program, identify the various test plates after application and ship the completed samples to the testing facility. Following application and shipment of the coated samples, all documentation, including inspection and environmental reports would be transmitted to the project team.

A request for proposal (RFP) was prepared and issued.

The RFP included the following:

1. Surface preparation of the steel substrate to a White Metal Blast (SSPC-SP 5/NACE No. 1) with a profile depth of 3.25 (±0.25) mils and a minimum of 90 relative peak count (Rpc) as measured with a portable stylus instrument, per ASTM D 7127).
2. All samples should be tested for the correct surface preparation (visual, replicae tape and portable stylus instrument) by the applicator prior to coating. All records would be provided to the owner.
3. The coated sample should be inspected and show no sags, dimpling, curtaining, off-ratio areas, blisters, bubbles, holidays, or other defects.
4. Applicator should maintain environmental conditions as required by the manufacturer's requirements.
5. Applicator should be knowledgeable and certified in both shop and field applications of product onto a variety of shapes, including welds, angles and curved surfaces.
6. Applicator should be actively adopting, implementing and monitoring quality control of the process.
7. Application should consist of one designated thickness of product to each sample, all sides or as required by the testing requirements.
8. Applications would be a single coat spray application and be air cured.
9. Applicator should provide QA/QC monitoring of the surface preparation, product application, curing and handling of the samples.
10. All samples will be "blind" identified in order to remove the perception of bias during subsequent laboratory testing.
11. All samples would be tested for the appropriate dry film thickness after curing and prior to shipment. Deficient samples would be destroyed and new samples prepared.
12. The project team and product manufacturer personnel may observe the surface preparation and production application activities.
13. Application services are to be completed to allow delivery to the testing laboratory according to the required schedule.
14. The applicator should prepare and ship the completed samples directly to the testing laboratory as designated;
15. Conduct holiday testing on the samples.

The RFP was sent to six applicators and four responses were received. Following review of the RFPs with the project team and members of the TRP, an applicator was selected and a contract was issued. In the final contract it was estimated that a total of 1400 sample plates, "free films" and "Q-plates" would be required.

MANFACTURERS/SUPPLIERS

Concurrently with applicator selection, a list of possible material manufacturers / suppliers were contacted to determine if there was interest in participating and supplying lining materials and technical data for their product.

The "ground rules" were explained to the suppliers:

Testing was not performed for the purpose of "pre-qualifying" a product for inclusion in any current or future specifications. Testing was to evaluate and determine properties of potential flexible lining materials;

The testing was to be conducted "blind" to avoid any bias during application, inspection and shipping, with only the project team being aware of which data set was applicable to which supplier;

Individual results may be shared with the supplier, based on direction from the owner;

Participation was voluntary and products were to be donated for testing;

Suppliers could participate in and observe the application process, however all applications and requirements had to meet current, published directions and guidelines. Suggestions could be provided on-site, however no direction would be accepted from the manufacturer's representative. The manufacturer signed a letter that stated, based on their observations, that their products had been prepared and applied correctly.

CERTIFIED INDEPENDENT TESTING FACILITIES

A qualified, third-party testing facility had to be contracted and the required tests instigated. Identification, evaluation, tracking and reporting of the test samples and results had to be in accordance with the accepted QA/QC program. During testing, monthly reports were required to be compiled and transmitted to the project team.

As contact was being made with the applicator and suppliers, a 2nd RFP was issued to select a testing facility for the project. .

During this time, an additional requirement was added to the testing facility RFP: to supply the required carbon steel coupons to be coated and, subsequently, tested.

The proposed scope of work for the testing facility included:

- Perform laboratory testing services in accordance with the testing protocol and provide monthly data reports of the results.

- The product testing samples would be provided as follows:

    1) Only one thickness of product will be evaluated for all the samples.
    2) There would be seven suppliers, with two products ("Parent" and "Repair") per supplier.

- The laboratory schedule included :

    1) A proposed start date and;

2) An estimated duration of 180 calendar days with the option of extending, in 3-month increments, up to one year.

PRODUCT APPLICATION

In August 2009, an application schedule was provided to American Pipeline Services LLC/COBLACO, Henderson, CO ("applicator") and suppliers with the expected delivery times of for their product. Suppliers were provided a copy of the testing criteria and asked to provide adequate materials to coat the samples to a nominal thickness of 50 mils (0.050 inch) and prepare "free films" (lining material applied to a release agent), taking into account over-spray, equipment cleaning and unforeseen conditions.

Carbon steel coupons were sent by the testing lab and received by the applicator. The first application began in September 2009 and was scheduled to occur over a three day window. In reality, some applications took longer, due to product requirements, including re-coat windows, handling of materials and maintaining the QA/QC requirements.

If the manufacturer opted to have onsite representation, an orientation meeting was held with the applicator and their staff, the manufacturer's representative and a member of the project team prior to the start of each new material application. The objective of the meeting was to establish the schedule and discuss the requirements and expectations for the application process. If there was a concern or misunderstanding, the orientation meeting provided a forum to discuss the issues prior to beginning product application.

Figure 1 – Replica Tape Testing

At the beginning of each application, the required number of plates were transported to the surface preparation site and abrasive blast cleaned to a White Metal Blast (SSPC-SP 5/NACE No. 1) with a minimum relative peak count (Rpc) of 90 and a 3.25 (±0.25) mil surface profile depth. Each plate was examined using SSPC VIS 1 and replica tape. (Figure 1) Sample plates from each batch were assessed for relative peak count characteristics (Figure 2). Each plate then received a unique identifier number: an alphabetic identifier to indicate the manufacturer and a "P" or "R," indicating "Parent" or "Repair" material, respectively.

Following verification of the peak count and surface profile, samples were labeled for identification and prepared for coating.

Figure 2 – Relative Peak Count Assessment

The applicator had control of all spray equipment, as well as preparing the lining materials for application, including product ratios, mixing times and required durations for curing prior to handling, based on the manufacture's published data. If the manufacturer's representative was present, they were asked to verify information and settings, but had no direct input other than verifying conformance to the "manufacturer's information" provided with the specific materials.

Figure 3 Application

Application of the material was applied by hand spraying, within a temperature-controlled, environmental setting (Figure 3). The coating was allowed to dry prior to measuring the dry film thickness Depending on the environmental conditions (temperature) and the manufacturer's recommendations, this drying period ranged from 30 minutes to two hours before the test samples could be handled. As application progressed, the applicator learned to anticipate the drying period and factor it into the overall application schedule, both for the individual product, "parent" or "repair" material, as well as the potential impacts for other materials that would be coming on-site for application.

Following application of material, each sample was examined to verify that the required dry film thickness had been achieved. Measurements were taken at each corner of the plate, front and back (Figure 4). If the applied thickness deviated by more than 10% of the required thickness, the plate was rejected and a new test plate was prepared and coated. During the application process, two liquid samples of each material being applied was taken from the shipping container or drum. These liquid samples were sealed, labeled and set aside. The liquid samples were included in the shipment to the testing facility. The purpose of the liquid samples was to provide material to be analyzed, utilizing infrared spectrometry analysis, thus identifying the chemical "fingerprint" of the materials. The intent of this testing was to identify, chemically, each material against possible future "formulations" of similar products.

Figure 4 Dry Film Thickness Measurement

Also, a large surface (3'x4') was prepared with a release agent, as identified by each supplier. A "free film" of the material was applied to the surfaces prepared with the release agent. These "free films" were then removed from the board and packaged in large sheets for shipping to the testing laboratory. These free-films would be processed into shapes required for the testing procedure such as a "dog bone" shape for tensile and elongation testing.

Other samples were prepared and coated, utilizing "Q-sheets," or thin metal sheets, which would later be used in the bending (flexibility) testing.

Large (2.5 gallon) steel buckets equipped with lids and spouts were used to for samples for taste and odor testing.. The buckets were cleaned and a film of polyurethane or epoxy was applied to the interior surface, including the underside of the lid. Since this test was designed for taste and odor detection only, no measurement of the applied thickness was performed.

After each sample plate had fully cured, a final visual examination and holiday test (Figure 5) was conducted. The samples were then boxed and shipped to the testing facility. Each material's test samples, "free films" and Q-plates were shipped "whole" and complete, with no other manufacturer's material included in the same shipment. This was done to minimize confusion and mixing of samples at the testing facility.

Figure 5 Holiday Testing of Coated Sample Plates

Following the application of linings (both parent and repair materials), and the quality assurance inspections, a post-application meeting was held with the applicator, the manufacturer's representative (if available), the onsite owner's representative and the lining crew foreman. The purpose of the meeting was to review the lining process and obtain the team's perspective on the overall process and verify that all application conformed to the scope of work

Overall, the applicator provided a quality service, showing innovation and adaptation during the application process. At the beginning of the applications, the applicator has to make adjustments in schedule and work force to account for time restrictions on handling and coating. On another occasion, a wide spread power outage interrupted the application. The applicator was able to wire a generator into the building circuit and complete the application without exceeding the required recoat window time limits.

TESTING

The selected testing facility (KTA-Tator, Inc. Pittsburgh PA.) was required to be a certified third party independent testing facility, having a minimum of five (5) years experience with the proposed ASTM testing procedures. The testing facility provided a letter and credentials stating that they understood the requirements of the testing and had the proper staff, equipment and expertise to complete the testing within the time frame of the contract. The letter also stated that the testing facility had no conflict of interest, including connections with any proposed applicator or supplier of materials related to the project. During the early portion of the testing program, a representative from the owner and the technical review panel visited the laboratory and observed the testing in progress.

The final contract with the testing facility included five (5) tasks: 1. Receipt of Test Panels, including coding and assessment of each panel; 2. Measurement of Coating thicknesses and evaluation of the condition of received panels; 3. Preparation of Free Film Matrix samples; 4. Testing of Panels in accordance with the project requirements; 5. Reporting of Generated Data on a monthly basis, including a final report.

As samples were received from the applicator, the testing facility chose to conduct their examination of each piece and assign their identifier to each plate as a group. The lab facility documented, inventoried and evaluated each sample panel to verify that the sample was adequate for the required testing. The testing laboratory obtained digital images of each sample group, by manufacturer. Non-destructive thickness measurements were obtained. These measurements were taken at three locations in each quadrant of the sample and then averaged. The thickness of the "free films" was also measured and documented.

Also, during receipt, each sample or plate was identified by a unique identifier, maintaining the "blind" testing process. At no time was the lab provided the "key" to identify samples by named manufacturer.

The timing of moving samples from the inventory process to testing was left to the discretion of the testing facility, to better combine procedures, recording and reporting of data as the testing progressed.

PROTOCOL

The testing protocol, or matrix, was comprised of sixteen (16) tests, including:

Test 1, Resistance to Water Immersion (ASTM D 870). Testing involved immersing coated panels in de-ionized water baths at 100˚F±2˚ (38˚C±2˚) and 140˚F±2˚ (60˚C±2˚), with evaluations at 30, 60, 90, 120, and 180 days. (Figure 6).

Figure 6 Test 1 Resistance to Water

Test 2, Electrical Impedance Spectroscopy (EIS) or Coating Impedance, (ISO 16773) utilizes 5% salt solution prepared with de-ionized water and cells attached to the sample. Tests were conducted at two temperatures : at 100˚F±2˚ (38˚C±2˚), evaluated every seven days, with data at 60, 90, 120, 150, and 180 days, and at 140˚F±2˚ (60˚C±2˚), evaluated every seven days, with data points at 60, 90, and 120 days. Figure 7 illustrates an EIS test cell.

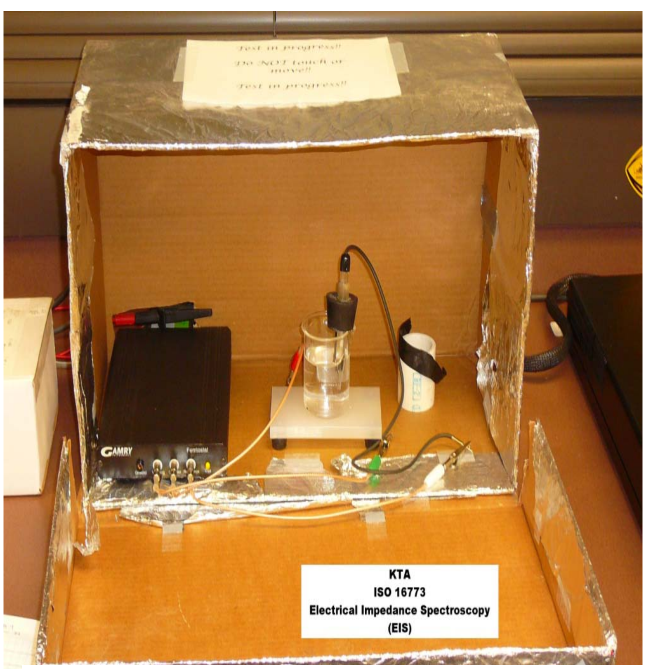

Figure 7 Test 2 EIS

Test 3, Test Methods for Cathodic Disbondment of Pipeline Coatings (ASTM G8) was conducted over 120 days at ambient temperature using an impressed current of -1.5V. Test readings were taken at 30 and 120 days, or until coating failure.

Test 4, Cathodic Disbondment, (ASTM G 95) was conducted at ambient temperature using an impressed current of -3.0V. Readings were taken 30, 60, 90, 120 and 180 days, or until coating failure. (Figure 8).

Test 5, Water Absorption (ASTM D 570) was conducted in de-ionized water at ambient temperature at 30, 60, 90, 120, 150 and 180 days.

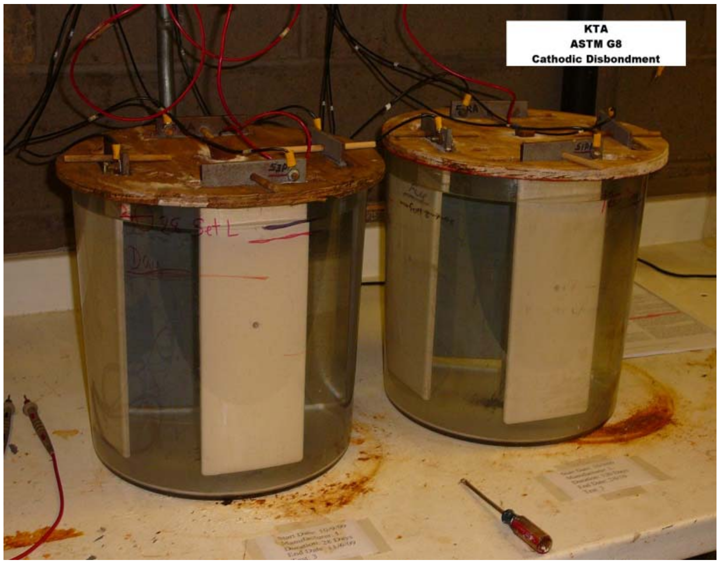

Figure 8 Test 4 Disbondment

Test 6, Adhesion to Steel (ASTM D 4541) was performed to determine the pull-off strength, or adhesion of the lining to the substrate material. A self-aligning hydraulic adhesion tester (Type V) was employed. Specimen linings were scored through the material to steel surface prior to conducting the test.

Test 7, Cyclic Salt Fog/UV Exposure (ASTM D 5894) was conducted in a cycling salt fog/dry cabinet (Figure 10) and a fluorescent UV/Heat condensation cabinet. The temperatures range between 95˚F-140˚F (35˚C- 60˚ C). The fog consisted of 0.05% sodium chloride and 0.35% ammonium sulfate. (Figure 9)

Figure 9 Test 7 Salt Fog Testing

Test 8, Resistance to Water Immersion and Vapor ("Atlas Cell;" ASTM C 868). Coating performance assessments were made in three zones: liquid (immersion), transition (inter-phase) and gas/vapor phase. The test duration was 30 days.

Test 9, High Velocity Cavitation (ASTM G 32). The test apparatus utilizes a 500 watt ultrasonic probe, oscillating at 20 kHz. (Figure 10) The erosion rate is determined by calculating the net weight loss after testing.

Test 10, Chemical Resistance (ASTM D 543), utilizing 10% sulfuric acid, 20% sodium chloride, 30% sodium hydroxide and No. 2 diesel fuel solutions.

Test 11, Water Vapor Transmittance (Permeability) (ASTM E 96) was conducted to determine the materials' resistance to the movement of water vapor thru the material. Results can be reported in a number of formats. This project selected "inch-pounds". A lower water vapor transmittance number is preferable.

Figure 10 Test 9 Cavitation

Tests 12, Impact Resistance (ASTM G 14); Test 13, Flexibility (ASTM D 522 as modified by CSA Z245.20); and Test 14, Tensile Strength and Elongation (ASTM D 412) were conducted to assess the physical properties of the materials.

SNWA decided that Test 15, Leachability (for Taste and Odor) would be conducted "in-house". The testing was performed by the owner (SNWA) and conducted in SNWA's laboratory, located at the River Mountains WTF in Henderson, NV. The test protocol was developed internally, utilizing lined buckets and a local groundwater source. Testing was conducted to determine the potential for leaching of polyurethane and epoxy materials that could result in the release of micro-contaminants, for taste and odor indices and the potential for the formulation of disinfection byproducts.

Test 16, Infrared Spectroscopic Analysis of liquid components was conducted using Fourier transform infrared spectroscopy. Spectra for each tested component were obtained using two methods, providing a "fingerprint" for future batch verification.

RESULTS

Two current standards addressing epoxy and polyurethane materials are AWWA C210, Liquid-Epoxy Coating Systems for the Interior and Exterior of Steel Water Pipelines and AWWA C222, Polyurethane Coatings for the Interior and Exterior of Steel Water Pipe and Fittings.

Materials listed in AWWA C210 (liquid epoxy-based coating systems) have a minimum thickness requirement of at least 16 mils (AWWA C210 4.3.2.1). AWWA C210 Table 1 (Coated inspection tests) addresses electrical inspection, and adhesion (based on ASTM D 3359 or ASTM D 4541, minimum requirement, 800 psi). AWWA C210 Table 2 (Qualification requirements of laboratory-applied epoxy coating system) lists testing for immersion in de-ionized water, sulfuric acid and sodium hydroxide. A cathodic disbondment test, based on ASTM G8 with a maximum disdondment radius of 9.53 mm is specified.

Test thicknesses for materials in AWWA C222 (polyurethane-based systems) have a minimum thickness of 20 mils for an interior lining. AWWA C222 Table 1 provides required results for materials tested in accordance with AWWA C222. These requirements are provided below.

Property	Requirement	Method
Cathodic Disbondment (28 days)	12-mm disbondment radius, max.	ASTM G95
Flexibility, 180 degrees, 3-inch mandrel	No cracking or delamination	ASTM D522
Impact Resistance	75 in-lb, min.	ASTM G14
Abrasion Resistance	100-mg loss per 1,000 revolutions, max.	ASTM D4060
Chemical Resistance (30 days)	5% change in mass, length or width, max.	ASTM D543
Dielectric Strength	250 V/mil, min.	ASTM D149
Water Absorption	2.0%, max.	ASTM D570
Hardness	65 Shore D, min.	ASTM D2240

In AWWA C222, Section 5 Verifications, additional testing for production coatings include a cure test, appearance, dry film thickness verification, electrical continuity (per NACE RP-0188, at 100V/mil minimum or the manufacturer's recommendation) and pull-off adhesion, per ASTM D4541, with a minimum value of 1,500 psi, minimum).

Below are the minimum/maximum/average results for some of the SNWA polyurethane and epoxy testing results.

Test 1A-Resistance to Water Immersion @ 100°F (38°C)	ASTM D87	Base	30 days	60 days	90 days	120 days	150 days	180 days
Parent		PSI						
Poly	min	2361	1115	960	566	694	1347	904
Poly	max	3000	2143	1933	2293	2903	2547	1838
Epoxy	min	2342	2042	1645	1545	1604	2093	1757
Epoxy	max	2951	2275	2209	1917	1924	2102	2141
	avg	**2744**	**1779**	**1650**	**1590**	**1667**	**1856**	**1550**
Repair								
Epoxy	min	2173	1277	1080	1249	1261	1427	1308
Epoxy	max	2988	2095	2070	1777	1929	2145	1768
Poly	min	2048	1415	1048	1029	865	1246	1391
Poly	max	2386	1661	1419	1347	1109	1593	1442
	avg	**2477**	**1633**	**1535**	**1429**	**1481**	**1750**	**1530**

As a group, the shop applied materials maintained an average adhesion greater than 1500 psi. Field applied materials also reported around 1500 psi.

Test 2- EIS Log Z, 100°F (38°C)		base		60 days	90 days	120 days	150 days	180 days
Parent				Log Z				
poly	min	11.39		11.34	11.41	11.40	11.39	11.41
poly	max	11.73		11.66	11.76	11.68	11.66	11.74
epoxy	min	11.32		11.33	11.35	11.42	11.38	11.35
epoxy	max	11.40		11.54	11.55	11.50	11.48	11.54
	avg	**11.52**		**11.51**	**11.52**	**11.51**	**11.52**	**11.52**
Repair								
epoxy	min	11.24		10.70	10.87	10.93	10.99	10.83
epoxy	max	11.61		11.44	11.49	11.52	11.61	11.54
poly	min	11.53		11.37	11.42	11.37	11.37	11.45
poly	max	11.65		11.62	11.61	11.69	11.71	11.63
	avg	**11.47**		**11.17**	**11.28**	**11.30**	**11.34**	**11.25**

For the EIS data, the impedance values did not vary greatly.

Test 3- Cathodic Disbondment	ASTM G8, -1.5 V	30 days	120 days
Parent		mm	mm
poly	min	2	8.4
poly	max	15.9	50
epoxy	min	2.8	5.6
epoxy	max	3.9	9
	avg	**5.46**	**16.97**
Repair			
epoxy	min	2.5	3.1
epoxy	max	4.5	11.5
poly	min	8.3	40.1
poly	max	11.50	50.00
	avg	**5.34**	**18.36**

The average disbondment area after 30 days for "parent" materials lining systems is 17 mm, and 18 mm for "repair" materials after 120 days.

Test 4- Cathodic Disbondment	ASTM G95, -3.0 V (12 mm, 28 day)	30 days	180 days
Parent		mm	mm
poly	min	3.00	12.50
poly	max	28.90	45.00
epoxy	min	3.40	7.10
epoxy	max	5.00	11.10
	avg	**8.93**	**21.16**
Repair			
epoxy	min	3.30	6.90
epoxy	max	6.40	10.60
poly	min	8.40	50.00
poly	max	18.60	52.90
	avg	**7.40**	**20.89**

The average disbondment area after 30 days for "parent" materials is 9 mm, and 7 mm for repair materials. Note, that for AWWA, this test has a 28-day duration.

Test 5-Water Absorption	ASTM D 570	30 days	60 days	90 days	120 days	150 days	180 days
Parent							
poly	min	0.71%	0.79%	0.81%	0.92%	0.97%	0.93%
poly	max	1.30%	1.63%	1.60%	2.18%	2.40%	2.73%
epoxy	min	0.72%	0.77%	0.87%	0.94%	0.96%	1.11%
epoxy	max	2.04%	2.24%	2.20%	2.37%	2.43%	2.46%
	avg	**1.08%**	**1.23%**	**1.30%**	**1.45%**	**1.57%**	**1.68%**
Repair							
epoxy	min	0.31%	0.27%	0.56%	0.64%	0.64%	0.88%
epoxy	max	1.40%	1.85%	2.20%	2.39%	2.71%	2.93%
poly	min	1.00%	1.00%	1.30%	1.40%	1.47%	1.47%
poly	max	1.04%	1.23%	1.39%	1.47%	1.62%	1.74%
	avg	**1.07%**	**1.25%**	**1.45%**	**1.55%**	**1.73%**	**1.86%**

Water absorption for the 30-day test produced an average value of 1.08% for all materials tested, and approximately 1.7 % after 180 days.

Test 6-Adhesion to Steel	ASTM D 4541	Base Value
Parent		PSI
poly	min	2361
poly	max	3000
epoxy	min	2342
epoxy	max	2951
	avg	2744
Repair		
epoxy	min	2173
epoxy	max	2988
poly	min	2048
poly	max	2386
	avg	2477

For Test 7, Cyclic Salt Fog and QUV, there was no effect on the samples after 30 days. After 120 days, one sample showed slight failure, registering 9.9/10.

Test 8-Atlas Cell	Base Adhesion, psi	Phase, Adhesion, PSI		
Parent		Vapor	Interphase	Immersion
BP	3000	N/A	N/A	N/A
KP	2825	1581	1866	1425
QP	3000	N/A	N/A	1983
LP	2728	1422	1312	1468
TP	2361	2033	1212	2159
JP(E)	2951	1349	1338	1332
SP(E)	2342	1372	1453	1485
Repair				
BR(E)	2650	996	1245	1634
KR(E)	2593	996	1190	1130
QR(E)	2504	1279	1268	1252
JR(E)	2988	1632	1483	1648
SR(E)	2173	1313	1267	1309
LR	2048	1639	1794	1281
TR	2386	1585	1728	1860

The average adhesion value for all tested systems in the "Atlas Cell" testing decreased to 57% of the baseline value, with a range of 43-77%.

Test 9 - Cavitation	1 hr	11 hr	24 hr
Parent	Rate of Loss, mg/hr		
BP	2.3	1.1	1.2
KP	2.3	4.6	2.8
QP	1.7	1.2	1.5
LP	0.7	3.2	3.7
TP	5.5	3.6	n/a
JP(E)	11	13.9	n/a
SP(E)	5.5	6.8	n/a
Repair			
BR(E)	5.1	1.6	3.9
KR(E)	8.6	4.7	4.3
QR(E)	4.7	n/a	n/a
JR(E)	18	n/a	n/a
SR(E)	2.4	11.2	10.8
LR	4.2	4.9	6.5
TR	4.8	3.8	n/a

The average rate of loss for all samples, at the 11 hr mark, is 5.2 mg/hr/ At 24 hours, eight (8) samples remained intact, with a loss rate of 4.3 mg/hr.

Results for Test 10 (Chemical Resistance) are not included. After thirty (30) days, the average weight change for all samples is 0.87% and the average dimensional change is 0.12%. Both values are below the maximum value listed in AWWA C222.

Results for Test 11 (Water Vapor Permeability) show that the average water vapor permeability for all samples is 4.1 inch-pounds, ranging from 0.07 to 12.29 inch-pounds.

For Test 12 (Impact Resistance), all samples withstood the test impact without significant damage.

For Test 13 (Flexibility), the test conditions and protocol are more severe than the requirements of AWWA C222; consequently, most lining systems exhibited delamination and cracking. However, given the severe nature of the test, it is expected that each system would remain intact under normal conditions.

For Test 14 (Tensile Strength), the average tensile strength for 12 of 14 systems was 2977 psi. Two systems were too brittle to test.

CONCLUSIONS

The testing results indicate that flexible lining materials such as polyurethane and epoxies, as a group of materials, provide a viable alternative for pipe linings. The team recognizes that there are many variables in using these materials, including surface preparation, environmental factors, formulations of product, application techniques, implementation of QA/QC processes and life cycle cost analysis.

Development and implementation of a testing program of this magnitude for polyurethane and epoxy materials requires the efforts and expertise of many individuals. While each member of the team brought a component of the knowledge required, it took all members to select, implement, and conduct the testing. A level of flexibility and almost daily communication between all members of the team was necessary to keep the project moving forward and to address the many details that arose during the implementation of the testing protocol.

Utilizing flexible linings will help address the project issues identified, including timing and long term storage, flexibility in using higher strength steels and operational scenarios.

From the data acquired, we anticipate being able to develop a basis for a guide (performance based) specifications for possible use on the GWD Project. The current timeline for the GWD Project will allow for future evaluation and development of criteria for possible use flexible lining materials on the project.