Denver Water's Assessment of Interior Polyurethane Coating of 108-inch Water Pipeline

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ABSTRACT

Fast set, high solids polyurethane has been used as a coating for the interior and exterior of steel water transmission pipelines since the late 1980s, but it wasn't until 1999 that the American Water Works Association (AWWA) approved Standard C222 for polyurethane coating of steel pipe and fittings. Over the course of the following decade, the coating system gained wide acceptance for water transmission pipelines among many major water utilities. In 1997, Denver Water installed 8,090 lineal feet of 108-inch diameter steel water pipe with an interior coating of 20 mil thick polyurethane. As this was the utility's first use of polyurethane, Denver Water has undertaken testing of the pipe polyurethane lining during scheduled shut downs of the pipeline in 1999, 2002, 2006, 2009 and 2011. This paper presents what Denver Water learned from its field inspection and testing program of this early-generation polyurethane lining system. Physical and visual testing has thus far yielded favorable results, proving the integrity of the polyurethane lining after fourteen years of service.

INTRODUCTION

Though the first American Water Works Association (AWWA) standard for polyurethanes, AWWA C222, wasn't approved until 1999, fast-set, high-solids polyurethane has been used as a coating for the interior and exterior of steel water transmission pipelines since the late 1980s. The most recent update of AWWA C222 standard was approved in 2008 (AWWA 2008). The performance history of polyurethane on an anecdotal basis is arguably favorable, even for polyurethane coated pipe that pre-dates the introduction of the standard. However, there is little actual field data to verify how polyurethane coatings have performed over a longer term. The adhesion strength between the polyurethane coating and steel substrate is routinely measured as part of the application process. Comparing adhesion values between the original application and what can be obtained from field measurements provides a good overall assessment of polyurethane coating performance and integrity.

In 1997, Denver Water installed at its Marston Water Treatment Plant 8,090-feet of 108-inch internal diameter (ID) steel water pipe in accordance with AWWA C200-91 (AWWA 1991) with an interior coating of 20-mil thick polyurethane. In service today, the pipeline conveys raw water for a bypass around a storage reservoir. As this was Denver Water's first use of polyurethane, testing of the lining has been periodically undertaken during scheduled shut downs of the pipeline in 2002, 2006, 2009 and 2011 respectively.

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PURPOSE OF BYPASS PIPELINE

Denver Water is the largest treated water provider in the State of Colorado, serving 1.3 million people in the City and County of Denver and surrounding suburbs. Denver Water operates three major water treatment facilities, including the Marston Treatment Plant in southwest Denver. The plant draws from a 19,796 acre-foot raw water reservoir located on site. As is common with large, open reservoirs in a seasonally variable climate, the water in Marston reservoir thermally stratifies over the course of the year into distinct layers, or thermoclines. In autumn, as surface temperatures decline, the thermoclines invert, or "turn," bringing up anoxic, or oxygen depleted, water from the bottom of the reservoir. During inversion of the reservoir, significant taste and odor problems often resulted in the treated water produced by the plant.

To alleviate the problem, Denver Water designed an 8,090 lineal foot, 108-inch diameter steel pipeline to bypass the reservoir. The reservoir is supplied by a 12.2 mile-long, 90-inch diameter conduit that has its intake on the South Platte River. By connecting the reservoir inlet to the treatment plant intake, the Marston facility could produce treated water taken directly from the river, thus bypassing the reservoir during seasonal turnover.

POLYURETHANE LINING SELECTION

As originally designed, the 108-inch diameter pipe was to be cement-mortar lined in place, as the pipe was too large to be procured with factory-applied cement mortar. Based on past experience, there were concerns about the overall cost of cement-mortar lining in place, as the footage to be lined was relatively short given the mobilization that would be required to bring in a specialty subcontractor to perform the work. When analyzing the option of using flexible linings, it was determined that this would allow the pipe to be designed for greater earth load deflection, which in turn could reduce the required the pipe wall thickness.

Liquid epoxy in accordance with AWWA C210 Standard (AWWA 1992) was considered as a possible flexible lining as Denver Water did have large-diameter epoxy lined steel pipe in some of its treatment plant facilities. However, the Denver Water did not have any precedent for an entire epoxy-lined pipeline of the size and scope of the proposed Marston bypass. The durability of epoxy lining was also a concern as the pipeline would carry potentially heavy silt and debris loads. Subsequent investigation also revealed that epoxy would be cost prohibitive and more expensive than in place cement-mortar lining.

Against this background, Denver Water considered polyurethane as a possible lining alternate. At the time, Denver Water did not have any polyurethane lined or coated steel pipe in its system, nor was there an AWWA Standard for the product. Nevertheless, polyurethane had seen some limited use in the water and wastewater industry dating to the late 1980's, and there were positive reviews of the product. The abrasion resistance and hardness of the material made it particularly suitable for carrying silt-laden raw water. Furthermore, a local steel pipe manufacturer had recently furnished a 96-inch diameter polyurethane exterior coated pipeline for a major water district located out of state and now had the capability, though untested, to provide polyurethane interior coating as well. Budget estimates proved favorable as well.

There were no discernable operation and maintenance costs associated with either cement mortar or polyurethane linings. The bypass pipeline was not considered critical to the function of the treatment plant, as the plant had functioned without the pipeline for decades and could function even if the bypass lining developed problems. Thus the risk of using a new lining material was greatly mitigated. For these reasons, Denver Water deemed polyurethane a viable and equal performance option to in place cement-mortar lining and added it to the project specifications as a bid alternate. Contractor bids to furnish and install the bypass pipeline were taken in December 1996 and the awarded contractor[4] ultimately selected steel pipe[5] with factory-applied polyurethane[6] in lieu of in-place cement-mortar lining.

PIPE MANUFACTURE AND LINING APPLICATION

Steel Pipe: The steel pipe was 108-inch ID and factory coated with multi-layer polyethylene tape in accordance with AWWA C214-95 (AWWA 1995). The pipeline is low pressure with a static head of only 35 feet. The resulting steel cylinder thickness is 0.375 inch, based on a maximum diameter to thickness ratio (D/t) of 288, providing a working pressure rating of 120 psi. The pipe was furnished in 45 foot lay lengths with bell and spigot ends for interior field lap weld. Construction was completed in July 1997 under a tight series of milestones, just in time for the next inversion of the reservoir.

Application of Polyurethane Lining: The polyurethane material was plural component, 100 percent solids, consisting of polyisocyanate and polyol resins in accordance with ASTM D16, Type V (ASTM 2010). The two-component polyurethane was applied in a single coat using an airless spray unit at a 1:1 mix ratio. The steel surface was hand grit blasted to near white in accordance with Steel Structures Painting Council SSPC-SP 10 (SSPC 2007) to a profile depth of 2.5 mils. The minimum thickness of the coating was 20 mils dry film thickness (DFT). While the bypass was designed for raw water, the polyurethane was rated for potable water contact to minimize the introduction of any further taste and order issues into the treatment process.

Joint Completion for Lining: During factory application of the lining, the polyurethane was held back several inches from the ends to allow interior welding. After lap joint assembly, an uncoated area of approximately 4 inches wide extended around the circumference of the joint. A specialty subcontractor was utilized to grit blast the exposed steel areas and spray coat the joint areas with polyurethane. The field applied material at the joint overlapped the factory coating by 3 to 5 inches on each side.

INITIAL ASSESSMENT – December 1999

As the Marston bypass was Denver Water's first use of polyurethane, the utility recognized that regular, ongoing inspection of the coating was warranted. The bypass pipeline is only needed for a few months each year; thus it can be taken out of service without impacting the

[4] Contractor was Tierdael Construction Company, Denver, Colorado, now owned by Reynolds, Inc., Orleans, Indiana

[5] Pipe manufacturer and coating applicator was Thompson Pipe & Steel Company, Denver, Colorado, now owned by Northwest Pipe Company, Vancouver, Washington.

[6] Polyurethane material was CorroPipe II PW™, manufactured by Madison Chemical Industries, Milton, Ontario.

operation of the Marston plant, although dewatering a 108-inch diameter pipeline is certainly a significant undertaking. Ingress into the pipeline is provided by a series of 24-inch flanged manways. Two segments of the bypass can be readily drained by open discharge through outlets provided in the pipe. An intermediate segment of the bypass pipeline, extending 1,000 lineal feet, runs directly under the normal operating elevation of the reservoir. To date, this segment has not been dewatered or inspected. One of the earliest inspections of the bypass was performed in December 1999, two years and four months after the pipeline was placed into service. Denver Water personnel were joined by representatives of both the pipe manufacturer and coating supplier.

Visual Inspection: Mud film coated the walls of the pipe and several inches of sediment remained in the invert. A published observation at the time noted "*Visual inspection showed the polyurethane to be in extremely good condition. The lining still retained a gloss surface when wiped clean…Minor field touch-ups that were made to the polyurethane during installation are still intact*" (MCI, 2000). Close visual assessment was also made of the field coated joint areas. Delamination between the field and factory coating applications could potentially allow water to migrate to the steel joint surface. However, the same account noted: "*The field applied joint material did not show any delamination; in fact, it was difficult to detect the point of interface between the factory and field applied material*" (MCI, 2000).

INITIAL ADHESION TESTS – November 2002

While visual inspection showed the polyurethane to be well adhered to the pipe wall after several years of immersion, the actual tensile adhesion between the in-place polyurethane lining and steel substrate was unknown. An inspection in November 2002 established some basic adhesion values. The testing was performed by the pipe manufacturer under the supervision of Denver Water.

ASTM D4541 Adhesion Test: Adhesion testing in the pipeline industry is performed in accordance with ASTM D4541-09 (ASTM 2009), a test developed primarily to test coatings on a flat plate surface under laboratory conditions. As with any material tested to tensile failure, adhesion test results of polyurethane are variable, even under the best of testing conditions. Test result variability can be attributed to a number of parameters:

1) Type of glue utilized, resulting in variability of strength of adhesion of the dolly to the substrate
2) Test surface preparation
3) Thickness of polyurethane being tested
4) Diameter of the dolly utilized for the test
5) Environmental conditions such as humidity and ambient temperature
6) Proper calibration of the test equipment
7) Curvature of the surface on which testing is performed, the ASTM D4541-09 standard mentions the availability of 10mm and 14mm loading fixtures (dollies) for use on curved surfaces in Annex A4.1.5.
8) Manually operated equipment induce variable and inconsistent tensile forces, therefore automated test units are now preferred.

To account for the variations discussed above, ASTM D4541 allows for a 34 percent variation in test results. Results that are clearly statistical outliers are also addressed by the specification should any single test be below a required minimum value.

<u>Test Method</u>: The adhesion testing method consists of gluing a small aluminum plug, called a dolly, usually of 20 millimeter diameter, to the abraded polyurethane surface. The other end of the dolly is configured with a knob such that a hydraulic pulling device can be attached as shown in Figure 1. It shows the hydraulic tester being held over an affixed dolly that is partially visible. A second dolly, shown above the gloved hand, has been glued and ready for testing. The hand pump connected by hydraulic line to the tester is to the left and not shown in the picture.

Figure 1: Readings being taken with Hydraulic Tester, Nov. 2009

Tensile force, measured in psi, is induced on the dolly until the polyurethane coating breaks free from the steel substrate. In some cases the glue bond between the polyurethane and dolly will fail first, in which case the adhesion value of the polyurethane is considered at least equal to the strength of the glue. In other cases, the polyurethane is fully or partially disbonded from the surface of the steel, leaving portions of the material on the steel and dolly surfaces (referred to as *cohesive splitting*). Test results are thus broadly categorized by mode of failure: *adhesive*, *cohesive* or *glue*.

The first field adhesion test focused on three locations of lining used in the pipeline:

1) Lining applied to the exposed steel surface at the joint
2) Lining applied at the factory
3) Overlap between the field applied and factory applied lining.

A total of 9 tests were conducted in the vicinity of an access manway, with the results summarized in Table 1.

Table 1: Adhesion Testing Results, November 2002

Location	Field Coating	Factory Coating	Field Coating over Factory Coating
1	Glue Failure at 350 psi	Cohesive Failure, split at 950 psi	Glue Failure at 450 psi
2	Glue Failure at 800 psi	Glue Failure at 800 psi	Glue Failure at 450 psi
3	Glue Failure at 300 psi	Glue Failure at 925 psi	Glue Failure at 500 psi

Test Result Discussions: Clearly the glue holding the dollies did not adhere particularly well to a polyurethane coating that had been immersed in muddy water for 5 years. For reasons that are unclear, the glue performed worse on the field applied material. The polyurethane surface was thoroughly cleaned and allowed to dry for several days prior to gluing the dollies and conducting the test. Nevertheless, better glues would be needed if future adhesion testing was to be undertaken.

The question was also raised as to how the results for the factory coating compared to the original adhesion values obtained at the time of application in 1997. Unfortunately, the pipe manufacturer was unable to locate any records regarding the polyurethane application. While this is surprising given that the pipe manufacturer is now certified under ISO 9002, quality assurance documentation and record keeping systems of the manufacturer were much less stringent in the 1990s. Today, extensive application logs are kept, documenting everything from surface preparation to the time of day the applicator sprayed the pipe. In the 1990s, adhesion testing was recorded on a pass-fail basis. Nor was every pipe tested; as with current practice, only two tests per day's production were performed. It is known that the minimum adhesion value required for the Marston Bypass was 750 psi, which later became the first published adhesion value for polyurethane when AWWA C222 was approved in 1999. It is unknown what actual adhesion values were being achieved at the time of application in 1997.

FOLLOW-UP ADHESION TESTING - 2006, 2009, 2011

In April 2006, a new series of adhesion tests were undertaken using upgraded glue to affix the dollies to the polyurethane surface. As in 2002, tests were conducted on the factory and field applied coating as well as in the joint overlap areas. Testing in November 2009 included previously tested pipe, as well as reaches of the pipeline that had not been previously inspected. The testing was performed by the pipe manufacturer and witnessed by Denver Water personnel. By 2006, adhesion testing had become more sophisticated in that more emphasis was placed on documenting the mode of tensile failure. Where part of the coating may be left on the pipe or cohesively split as a result of the adhesion pull, the relative percentage of failure is now noted. The locations of the test were now also coordinated with the original pipe lay schedule, thereby denoting the test by MK number. Table 2 summarizes the test results.

Test Result Discussions: As mentioned previously, adhesion testing conducted in laboratory conditions provide variable results, by some accounts as much as 30 percent, and field conditions undoubtedly add an even greater element of variability. ASTM D4541 allows variability of up to 34 per cent in test results. Still, some general observations can be made about the 2006, 2009 and 2011 test results. Most notable is that glue failures greatly diminished compared to 2002. As a result, actual values for the adhesion between the polyurethane and steel substrate could be obtained in greater number. The adhesion values for the factory-applied lining can be characterized as falling within a relatively consistent range of 1,000 to 1,400 psi. The sample size for field-applied lining was relatively smaller, though the majority of values were below 1,000 psi.

Table 2: Adhesion Testing Result from 2006, 2009 and 2011

Pipe Mark Number (MK)	Failure Value (psi)	Failure Mode: A= Adhesive C= Cohesive G= Glue	Relative Percentage of Failure Modes (where <100%)	Test Date	Dry Film Thickness (Mils)	Coating Type, Factory/ Field
60	804	G		Nov. '09	41	Field
60	578	A		Nov. '09	18	Field
60	749	G		Feb. '11	21	Factory
71	881	G		Feb. '11	28	Factory
72	990	A		Nov. '09	24	Factory
147	1084	C, G	C-90, G-10*	Nov. '09	27	Factory
147	1066	C, G	C-30, G-70	Feb. '11	28	Factory
166	904	A, C, G	A-5, C-45, G-50	Nov. '09		Field
166	660	G		Feb. '11	28	Field
171	1118	A		Apr. '06	35	Factory
171	758	C, G	C-60, G-40	Nov. '09		Field
171	1348	A		Nov. '09	26	Factory
171	1021	G		Feb. '11	29	Factory
172	1497	A		Apr. '06	21	Factory
172	1064	A		Apr. '06	21	Factory
172	842	A		Nov. '09	22	Factory
172	1236	A		Feb. '11		Factory
175	1384	A		Apr. '06	60	Field
175	1639	G		Apr. '06	28	Factory
175	1496	A, G	A-10, G-90	Feb. '11	28	Factory
176	1600	G		Apr. '06	37	Field
176	151	G		Apr. '06	43	Factory
176	1951	A		Apr. '06	40	Factory
176	1089	A		Apr. '06	40	Factory
176	153	A		Apr. '06	32	Factory
176	1286	G		Apr. '06	57	Field
176	1978	A, G	A-50, G-50	Feb. '11	28	Factory
180	1540	A		Apr. '06	26	Factory
180	1179	A, G	A-40, G-60	Nov. '09	26	Factory
180	685	G		Nov. '09	42	Field
180	1553	A, G	A-30, G-70	Feb. '11	30	Factory

**C-90, G-10 indicates that 90% of the failure was Cohesive and 10% was Glue.*

A critical question is whether adhesion values decline as a function of time. On seven pipes, MK 147, 166, 171, 172, 175, 176 and 180, the factory coating was tested in 2011 and either or both of 2006 and 2009. The resulting values are highly consistent and range only by a few hundred psi across the various test dates. From the data presented herein, the adhesion values appear stable over the 5 year test period. Another important observation of these three rounds of testing is that the polyurethane coating still exceeded the original specified application adhesion value of 750 psi.

SUBSTRATE AND FORENSIC INVESTIGATIONS

An outcome of the adhesion test process is that a round area of the steel substrate, equal to the diameter of the dolly, is usually exposed. In general, the steel surfaces exposed by adhesion testing of the bypass pipeline were clean, bright, and exhibited a blast profile as shown in Figure 2a. However, closer visual examination under extremely bright light sometimes showed some slight discoloration and orange tint to the steel surface. In examination of the dollies which retained the coating, Figure 2b, the removed underside of the polyurethane that had been in contact with the steel substrate contained small black specks. The specks were not evident on the steel substrate and appeared to be embedded into the coating.

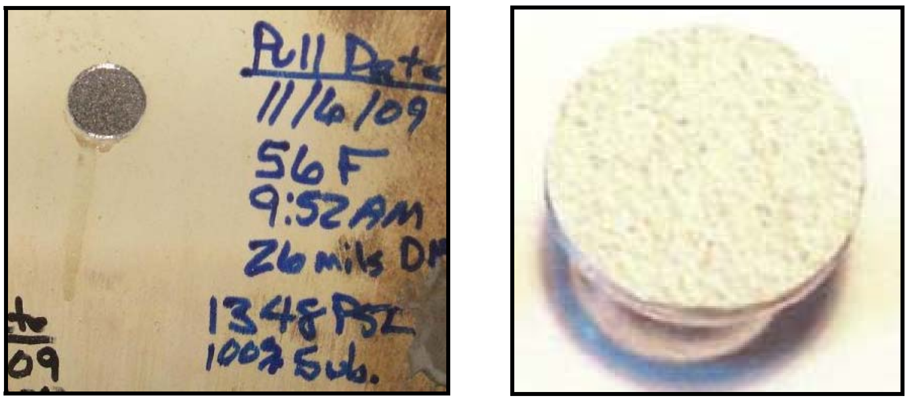

Figure 2a,b: Exposed steel substrate after adhesion pull, MK 171; Underside of dolly showing embedded material

One possible explanation is that the black specs are residual blast media or other contamination that was not fully cleaned from the pipe surface prior to application of the polyurethane. At the time, the manufacturer used hand blast equipment to prepare the pipe surface. Blasts of compressed air from a hand wand were used to clear the blast media from the pipe wall surface prior to spray application. As this was the manufacturer's first project with polyurethane interior coating for pipe, sufficient steps to adequately clean the pipe surface may not have been taken. Much more stringent protocols are followed today to ensure a clean pipe surface prior to coating application.

In order to learn more about the deposits embedded in the polyurethane, Denver Water sent the dollies to separate laboratories in 2006 and 2009[7]. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) was performed on debris dislodged from the polyurethane. Both laboratories confirmed that the material was composed largely of iron oxide and hydroxide products, with much smaller quantities of other trace elements present. As polyurethane is not completely impervious to moisture, some transmission of water to the underlying steel surface possibly occurs in a fully immersed coating environment. The oxygen in the water could react with iron elements, producing a corrosion byproduct such as the deposits found embedded in the polyurethane underside. To the extent the oxygen is depleted and not replenished, active corrosion under the polyurethane surface is likely very

[7] Testing laboratories were Corrosion Technologies, Inc., Palo Alto, California and Exponent, Inc., Natick, Massachusetts

minor and short lived. The amount of debris varied by dolly, but no correlation could be established between adhesion value and what was found embedded in the polyurethane.

Manufacturing Defects: Polyurethane is factory applied using an airless sprayer, with the reactive resin components mixed as they are expelled from the nozzle. The required mix ratio varies by coating manufacturer but is commonly 1:1. Should there be any off ratio application, due perhaps to a pump issue, the exothermic chemical reaction required to create the finished material is incomplete. Blisters or bubbles will then appear under the surface, usually in a matter of hours or sometimes days.

Within the pipeline coating, very sporadic blisters have been noted, but almost all appear in clusters. In one case, the blisters followed a helical pattern, very similar to the path the spray head would have taken when the coating was applied. Thus, the blisters appear to be the result of an off ratio mix problem that was slow to develop and not observed prior to the pipeline being placed into service. Again, much of the problem can be attributed to the state of technology used to apply the lining fourteen years ago. Some of the blisters have been marked for continued observation. Some have been cut out and repaired, and close observation showed no evidence of corrosion on the underlying steel surface. In essence, despite the suspected material mix issues in these isolated areas, the material proved to be an excellent barrier to the development of corrosion. In the case of the helical pattern, the coating has been removed and reapplied.

ASSESSMENT OF OVERALL COATING PERFROMANCE

The Marston Bypass Pipeline was Denver Water's first use of polyurethane coating. It was applied in accordance with the industry practices of its time as there were no AWWA standards. From the pipe manufacturer's standpoint, the application and inspection process was extremely rudimentary in comparison to the equipment and practices used today.

Adhesion testing has been one focus of Denver Water's continuing inspection program. There are numerous other performance criteria such as hardness, abrasion resistance, flexibility and resistance to cathodic disbondment that make polyurethane a good coating. Performance values are generally established in laboratory settings following testing methods recognized by the American Society of Testing Materials (ASTM) or other sanctioning organizations. For products used in the water industry, AWWA establishes a body of standards, relying in part on ASTM specifications and general industry consensus as to acceptable performance requirements.

Adhesion is an important measure of any coating performance, but it is only one measure; furthermore, it is one of the few measures that can be accurately taken under field conditions. Nevertheless, the adhesion values obtained to date are very good relative to what was required at the time, i.e. 750 psi. Comparing the results to the current AWWA C222 Standard which requires a factory adhesion value of 1,500 psi is not particularly useful, in that no correlation has been established between adhesion value and long term lining performance.

The small debris found embedded under the polyurethane is obviously not desirable from the standpoint of good coating application practice. It is not definitively known what the debris is or the extent to which the coating may have been compromised because of it. Future observations and testing will monitor the issue.

Overall, the lining is in excellent condition given it was an early generation of the product for Denver Water and the pipe manufacturer. After fourteen years of service, there is little doubt the polyurethane lining inside the Marston bypass pipeline will continue to perform satisfactorily for years to come.

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