

## City of Phoenix Superior Pipeline PCCP Investigation and Assessment

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The City of Phoenix is currently in a multi-year program to investigate 150 miles of prestressed concrete cylinder pipelines (PCCP). The failure of a 60-inch pipeline focused the efforts of the investigation to a pipeline known as the “Superior” pipeline.

The Superior pipeline is a 2.2-mile long, 29-year old pipeline that ruptured on October 3, 2006, resulting in extensive damage to the surrounding community. The pipeline was immediately shutdown and the failed section of pipeline was repaired. However, the condition of the remaining pipe and the potential for additional failures was a concern.

To identify wire breaks, Pressure Pipe Inspection Company (PPIC) conducted Remote Field Transformer Coupling investigations. In addition, visual and sounding investigations were conducted by Openaka of Branchburg, New Jersey to identify internal defects. These investigations identified pipe segments that were in need of immediate repair prior to putting the pipeline back in service. This information provided baseline wire break information for the subsequent investigations.

Prior to putting the pipeline back into service, 11,700 linear feet of fiber optic was installed by Pure Technologies allowing the City to acoustically monitor wire breaks in real time. This information was critical as the pipeline needed to be back in service to meet the high demand for water during the hot Phoenix summer. Real time wire break monitoring allowed the City and Brown and Caldwell to slowly resume the operation of the pipeline to prevent another failure. Monitoring of the pipeline was conducted from February 2007 through January 2008 and the pipeline was found to be extremely active with an initial average of three wire breaks occurring each day.

This paper focuses on the investigations conducted and conclusive results relative to:

- Benefits of multiple technologies for PCCP investigations
- Calibrated vs. non-calibrated curves for electromagnetic analysis
- Real time data collection through fiber optics to monitor pipeline conditions
- Verification of fiber optic results using electromagnetic analysis
- Pressure and surge monitoring

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## Project Background

The Superior Pipeline is a 60-inch diameter pipeline that conveys surface water from the Val Vista Water Treatment Plant to customers in southern Phoenix. The location of the pipeline is illustrated in Figure 1. The pipeline was manufactured in 1978 by Ameron Pipe Products Group. The 60-inch diameter pipeline has a 5-inch thick concrete core, embedded 16-gage cylinder, Class III, 8-gage diameter prestressing wire, and a 1-inch mortar coating over the prestressing wire. The pipe was designed for 125 psi working pressure with a 40 percent surge allowance (175 psi allowable surge pressures).

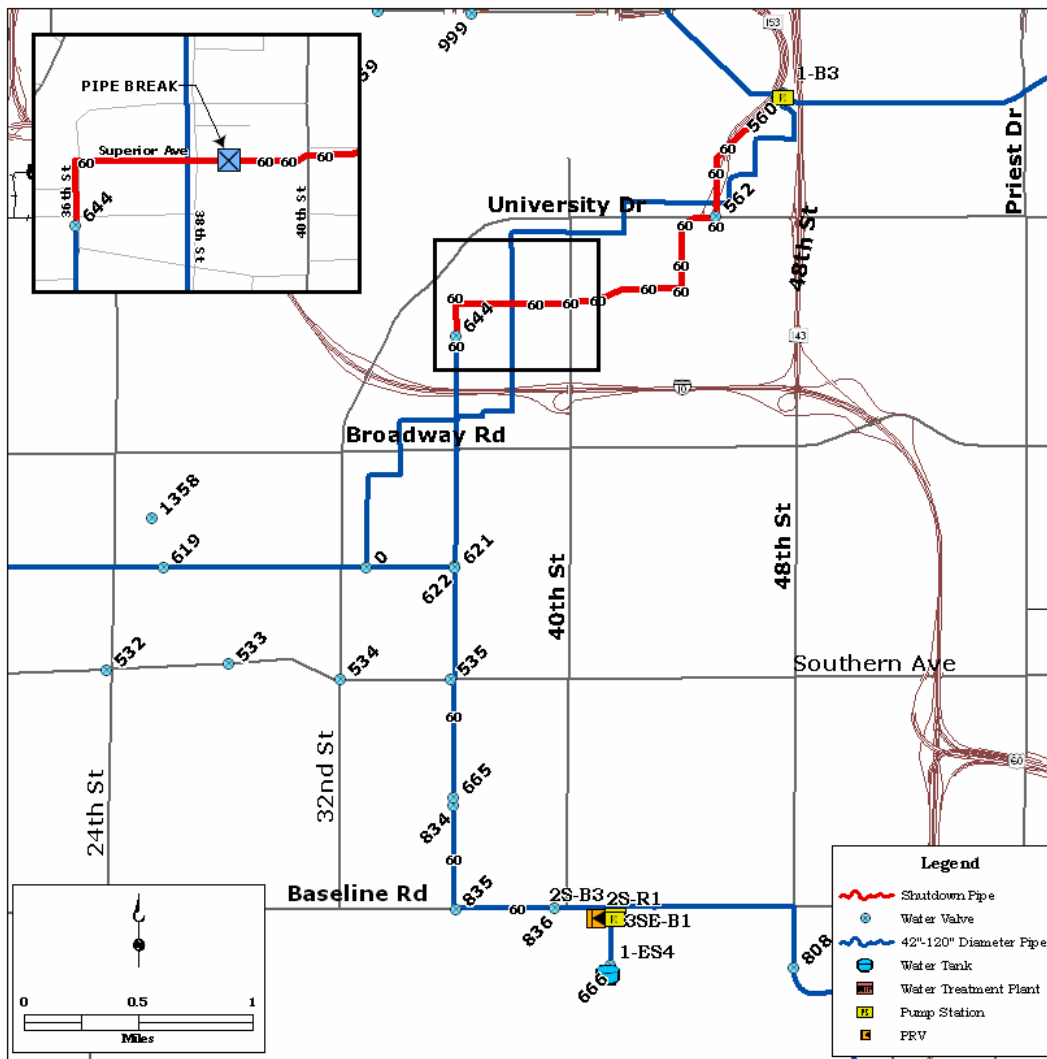


Figure 1 – Project Location

The pipe failure occurred on October 3, 2006, at approximately 3:15 a.m. The location of the failure was at approximately 38<sup>th</sup> Street and Superior Street, as shown on Figure 1.

### **Initial Failure Investigation**

After the failure, investigations were conducted to identify the primary reasons for the failure. The investigation of the pipeline failure was focused on the following issues:

***Record and Shop Drawing Review.*** The first step in the investigation was to collect and review the original design drawings as well as the pipe manufacturer's shop drawings. This review indicated that the pipe was manufactured in 1978 using Class III, 8-gage prestressing wire. It should be noted that 8-gage wire was eliminated as an allowable PCCP prestressing wire size in the 1988 ASTM A648 specification revisions due to the many documented failures of PCCP pipe across the country that were manufactured with this wire. The 1988 Standards were also revised to require additional testing procedures to reduce the potential for dynamic strain aging and sensitivity to hydrogen embrittlement of the high strength Class III wire.

***Initial Internal Inspection.*** Immediately after the pipeline was isolated, an investigation was conducted to look for obvious damage to other adjacent sections of pipe. The internal surface was found to be covered with a thick layer of alum that tended to hide any cracks in the concrete pipe wall. In addition, the slope of the pipeline was found to be substantially different than shown on the design drawing. The pipeline was designed with a constant slope to allow for draining, but the actual construction had included several significant low points that prevented draining. Several individual pieces of pipe were in different locations than shown in the shop drawings and many lengths of pipeline were found with significant horizontal or vertical deflection points that were also not shown on the shop drawings.

***Petrographic Mortar Evaluation.*** Durability of PCCP is dependent upon the ability of the mortar coating to protect the wire from mechanical damage and corrosion. Steel embedded in concrete or mortar is passivated by encasement in a highly alkaline cement paste. Passivation is attributed to the formation of a thin film of gamma ferric oxide on the metal surface by the hydroxyl ions produced in the hydrating Portland cement. Mortar samples from the pipe that failed and the pipe immediately upstream were collected and evaluated. The mortar for both samples was found to be marginal. The mortar sample from the upstream pipe was of higher quality than the sample from the pipe that failed. Mortar samples from both locations had high chloride contents. The high chloride content in the area of the prestressed wires explains the corrosion products found on the wire cast surfaces in the samples. The measured level of chloride content indicates a high potential for continued corrosion of the prestressing wires. Both mortar samples also had significant depths of carbonation. Carbonation of the mortar reduces its pH of the coating from 13 to as low as 6 or 7, compromising the ability of the coating to protect the prestressing wires from corrosion.

***Prestressing Wire Evaluation.*** The primary strength of PCCP relies upon compression in the pipe core imparted by the prestressing wire. Prestressing wire samples from the pipe that failed and the pipe immediately upstream of the failure were collected and evaluated. The wire from the failed section of pipe was found to be unsuitable for conducting wire tests due to significant surface corrosion. The wire from the upstream pipe was clean and suitable for testing. The tensile test confirmed the wire to be Class III wire, 8-gage wire. The torsion test confirmed the presence of a moderate to severe degree of dynamic strain aging (DSA) of the wire. DSA effects occur in wire that has been drawn at excessive temperatures during manufacturing process. The DSA phenomenon artificially imparts a higher tensile strength to high carbon prestressing wire, but at the expense of torsional ductility. The hydrogen embrittlement sensitivity test indicates that the wire has a severe sensitivity to hydrogen embrittlement. Although the wire samples conform to the specifications in place at the time of manufacture, the hydrogen embrittlement sensitivity and torsion testing indicate the wire has a high potential for embrittlement failure at the onset of corrosion.

***Visual Inspection of Failure Area.*** A detailed visual inspection was made of the failure area after the pipe was removed from the pipe trench. It appeared that a portion of the 16-gage embedded steel cylinder was missing and may have been lost at the time of failure or during removal of the pipe from the trench. No evidence was found to indicate that the steel cylinder had a hole that may have let water penetrate through the pipe core from the inside. The outside surface of the steel cylinder exhibited signs of surface corrosion in a large area that appeared to have been there for quite some time. This indicates that the concrete core may have been cracked. The prestressing wire in the immediate area of the failure exhibited signs of severe corrosion and embrittlement type wire breaks. In addition, several broken prestressing wires were observed beyond the failure area after the mortar coating was removed and the wires exposed.

***Surge Analysis.*** Because there are no pressure recorders in the failure area, a surge analysis was performed to estimate the magnitude of the pressure increases that may have occurred near the failure location. The rate of change of the valve closing cycle was estimated from the SCADA log and a theoretical estimate of the maximum surge pressure was prepared.

At about 22 minutes prior to the failure, the 665 Valve RTU lost communications with the City's SCADA control system. The SCADA data log indicates that the valve was at approximately 17 percent open when the signal was lost. When a loss of signal occurs, the 665 valve is designed to go to a 60 percent open and wait for communications to be re-established. However, because of the measured pressure increase at the booster pump station, it appears that the valve closed rather than opened when communications were lost. Because of the lost signal, data is not available concerning how fast or how far the valve may have closed. The surge program was modeled with the assumption that the valve closed from 17 percent open

to fully closed over a 20-second period which is the time shown on the SCADA log for the maximum pressure to occur. The surge program estimates that at this closing speed, a pressure increase of approximately 49 psi would have been experienced on the upstream side of the 665 valve and would have resulted in calculated maximum pressures of 129 psi at the 665 valve, 127 psi near the failure location, and 108 psi at the discharge side of pumping station. The SCADA log indicates that the pressure at the booster station increased from about 92 psi to about 109 psi during the time when communications were lost with the RTU and triggered a high pressure alarm. This pressure increase at the booster station is approximately the same as modeled with the surge program for a full valve closure. It appears that the lost communications event may have resulted in a maximum surge pressure at the failure location of about 127 psi. This estimated maximum surge pressure is considered to be within normal water system pressure variations and would not be expected to cause a failure to a good quality, undamaged pipeline rated for a working pressure of 125 psi.

***Failure cause.*** The team's conclusion concerning the probable cause of the pipeline failure is that the pipe had been experiencing corrosion to the prestressing wires for a number of years and there were a high number of broken wires in the pipe prior to October 3<sup>rd</sup>, 2006. On the morning of October 3<sup>rd</sup>, the number of wire breaks reached the point where the internal pressure and core compression from the prestressing wires became unbalanced and the failure occurred. This imbalance was likely triggered by a minor surge event that occurred about 20 minutes prior to the failure.

### **Additional Field Investigations**

Prior to putting the pipeline back into service, investigations were conducted to identify the condition of the remaining pipe sections. The pipeline needed to be back in service for the summer months and the City wanted to make sure that the pipeline would not have another failure. Electromagnetic and visual inspections were completed on the pipeline to determine if additional rehabilitation would be required. Field investigations identified 22 sections of pipeline that needed immediate repair prior to putting the pipeline back in service. Twenty one of the sections were carbon fiber rehabbed and one was removed for calibration testing and replaced with a top outlet manhole. The pipeline was placed back into service on February 9, 2007.

After the pipeline was placed back into service, monitoring of the pipeline was completed using fiber optics to monitor wire breaks and pressure monitors to identify surge and operating conditions. A description of the multiple technologies utilized during the investigations is summarized in the following sections.

***Visual and Sounding.*** Visual and sounding investigations were conducted by Openaka for approximately 11,700 linear feet of pipeline. The investigation identified 8 pipe segments that had longitudinal cracking around the 3 and 9 o'clock positions. These are typically indicative of delaminating of the concrete core due to extensive wire breaks in a concentrated area.

***Electromagnetic Investigations.*** PPIC performed RFTC inspections of the Superior Pipeline in October and November 2006. A total distance of approximately 2.2 miles (567 pipe sections) was inspected.

Initially, PPIC used a 14-gauge cylinder calibration curve to quantify all wire break estimations based on the following available information and observations:

- Limited Ameron lay sheet data – preliminary lay sheets were incomplete, but generally showed a greater number of wraps per foot than lay sheets obtained later in the project and analysis. Application of a 14-gauge calibration curve provided increased conservatism considering the incomplete information.
- Field observations – observational data indicated longitudinal cracks, hollow areas and mortar delamination. With the use of a 14 gauge cylinder calibration curve, the field observations were consistent with some of PPIC’s past experience of fully distressed pipes with broken wires across the entire span.

Draft preliminary data analyses based on the 14 gauge cylinder calibration curve, and yielding higher-than-anticipated wire break numbers were reported in November 2006. After the investigation, additional data became available including:

- Lay drawings – lay drawings were received showing 16-gauge was the predominant cylinder thickness.
- Field observations – actual lengths of the longitudinal cracks observed in the pipeline by PPIC were shorter than originally thought.

This additional information supported the application of a 16-gauge cylinder calibration curve to the data. The re-analyzed data showed significantly fewer wire breaks in every pipe section with distress. To obtain further information supporting the application of the 16-gauge cylinder calibration curve, the City supplied a pipe section to PPIC to complete validation testing. The results of the validation strongly supported the use of the 16 gauge cylinder calibration curve. The longitudinal locations and numbers of wire breaks strongly matched those predicted by the 16 gauge calibration curve.

The calibration curve does not impact which areas are identified to have distress. Rather, the calibration curve is used to quantify the amount of distress in each region identified to have distress. The calibration curve generated using the City’s pipe section very strongly correlated with the non-Phoenix 16 gauge calibration curve used to analyze the data.

The calibration exercise performed on the Superior Pipeline underscores the importance of obtaining as much data as possible about the pipeline to be inspected. This pipeline was originally thought to be constructed of pipe sections with 14 gauge cylinders. Application of this calibration curve resulted in over-reported distress across the entire pipeline. When the additional information was received, in the form

of complete design information and calibration data specific to the Superior Pipeline, the number of broken wires reported in all pipe sections was significantly reduced.

**Fiber Optic.** Acoustic Fiber Optic (AFO) monitoring from Pure Technologies was installed to collect wire break data on actively deteriorating pipe sections. The data collection cable is a ¼-inch diameter, 2-pair fiber optic line, installed in the pipe while dewatered. The cable was held in place using stainless steel tension hoops at 300 to 400-foot intervals. The technology utilized two of the fibers in the cable to collect data on wire breaks and the locations of those breaks. The information was gathered and stored by an on-site computer at one of the termination points of the fiber optic cable. Using a high-speed internet connection the computer sent the information to Pure Technologies in Calgary, where an analyst confirmed that the event was a wire break and confirmed its location in the pipeline.

In the Superior Pipeline, there was approximately 8,300 linear feet of AFO installed in January 2007. The data acquisition computer was placed on-site at a booster station where the cable was terminated. When the pipeline was placed back into service, the AFO showed a large amount of wire break activity in the pipeline. This was anticipated due to the “relaxing” that the prestressed wires experience when pressure is taken out of the line for a prolonged amount of time. The wire breaks started to taper from 79 wire breaks in February, 76 in March, and 57 in April. During that time the average pressure of the pipeline was around 75 psi. When the higher summer demands started in May, the average pipeline pressure increased by around 10 psi, which resulted in another increase in wire, breaks due to added stress. In May 2007 there were 82 wire breaks, followed by 65 in June, and 49 in July. A total of 561 wire breaks were reported on the Superior pipeline from February 2007 to January 2008.

**Pressure Monitoring.** A TP1 pressure sensor was installed to monitor and collect data. The sensor reads the pressure of the pipeline every 30 seconds and collects the data on an on-site hard drive. There were two sensors installed, one at the upstream booster station and one at the pipeline break location. The sensors were set to collect snapshot pressure data when there was a change of 5 psi or greater. The pressure sensors identified pressure changes of concern given the structural condition of the pipeline. These pressure spikes and drops were identified to be caused by turning pumps on or off too quickly at the booster station as well as opening and closing a motor operated valve upstream of the booster station.

Due to low demands in the first couple months of operating this pipeline, there were not many correlations to pressure and wire breaks. When the pressure was increased to meet higher demands in May 2007, there was an increase of wire breaks when compared to the prior month’s wire break data. Over the year, there were not enough pressure transients during wire breaks to confirm that the pressure resulted in wire breaks. However, the pressure data collected did result in operational changes to prevent pressure transients on this pipeline.

## **Verification of Fiber Optic Data**

In February 2008, the Superior Pipeline was removed from service to allow the trenchless installation of a new steel pipeline within the existing pipeline. During this time period additional investigations were performed using electromagnetic and visual investigations. The purpose of these investigations was to verify the accuracy of the fiber optic data and investigate areas that were not accessible during the 2006 investigation. At the time of this paper the results of that investigation were not available. The results of this verification will be provided at the conference.

## **Conclusions**

Assessment of embedded prestressing wire is difficult. By identifying existing conditions and providing real time monitoring the City of Phoenix was able to maintain operation of a severely deteriorated pipeline. By combining multiple technologies, the City was able to gain a complete and accurate understanding of the pipeline conditions and the needs for future rehabilitation.