RECLAMATION
Managing Water in the West

Using Robotics Technology to Reline Large Diameter Piping on Steep Slope

Research and Development Office
Science and Technology Program
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14. ABSTRACT *(Maximum 200 words)* This report documents a demonstration at the Central Arizona Project's Mark Wilmer Pumping Plant where the contractor used robotic equipment to reline the 12-foot diameter discharge tube with slopes up to a 77 percent grade. The work consisted of approximately 105,000 square feet of surface area and was completed in less than three months. This is the first known relining project to use robotics on a steep slope.

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Acronyms and Abbreviations

Bureau of Reclamation, Reclamation

CTE	Coal tar enamel
DFT	Dry film thickness
Ft	Feet
Hrs	Hours
ID	Inner diameter
LF	Linear feet
LC	Lower Colorado
N/A	Not applicable
R&D	Research and Development
S&T	Science and Technology
SF	Square feet

Executive Summary

Penstocks, discharge tubes, and outlet works relining projects are dangerous due to the nature of the work, i.e., confined spaces, non-level footing, and steep slopes. In 2007, fire broke out inside of the penstock at the Cabin Creek powerplant during relining application. Five people on the painting crew died. There were a number of contributing factors that caused the accident:

- Poor safety plan for working in permit required confined space
- Lack of Emergency Response plan
- Use of highly flammable solvent for cleaning equipment that produced flammable atmosphere

Advancements in robotics relining jobs are changing the way contractors conduct business by increasing production rates, lowering costs, and reducing worker exposure to harmful chemicals. The potential safety improvements are further magnified by this new opportunity to minimize the number of employees in the permit required confined space. The benefits are safer work environments, reduced liability, shorter downtimes, and reduced cost.

This case study documents a 2016 relining project at the Central Arizona Project Mark Wilmer Pumping Plant. This work demonstrated the state of the art for the use of robotics on steep inclined structures, with the 105,000 total square feet (SF) of the 12-foot diameter pipe being relined in less than 90 days. Contractor personnel guided and monitored the robotic equipment from inside the pipe while the robots prepared the surface and relined the structure. The physical labor required by employees was reduced significantly because the robots did the majority of the work. The approximate production rates during this project for each robot are as follows:

- Ultra-high pressure water jet robot: 100 linear feet (LF) (3,600 SF) per shift
- Abrasive blast robot: 50 LF (1,800 SF) per shift
- Coating robot: 150 LF (6,000 SF) per shift at 60 mils dry film thickness

The next step is to develop an autonomous (person free) robot that is controlled or monitored from outside the confined space work environment. A new research proposal has been submitted to help the technology advance. These advancements could allow for the application of a wider variety of coating systems where safety and health concerns currently preclude their use.

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Background

The majority of the world's penstocks, discharge tubes, and outlet works were originally lined with coal tar enamel (CTE). In most cases, CTE provided an extremely long service life exceeding 50 years [1]. CTE eventually requires replacement requiring these water agencies to reline their infrastructure [2]. Traditional rehabilitation procedures include manually abrasive blast cleaning and applying the new coating, i.e., relining, using mobile scaffolding, which is extremely dangerous on steep inclined surfaces. Work is extremely challenging and slow due to laborers doing the manual labor, resulting in long outages for the facility, and often high opportunity costs as a result of forgoing power generation. Furthermore, the success and quality of the relining work is highly dependent upon the skills of the applicators.

Health and safety considerations for coating in confined spaces improved as a result of the 2007 Cabin Creek accident where a fire broke out inside of a penstock and five workers died [3]. A number of contributing factors that caused the accident:

- Poor safety and rescue plans for working in permit required confined space
- Flammable atmosphere due to use of solvents for cleaning equipment, which was exacerbated by including a large volume of these flammables within the pipe

Since the Cabin Creek fire, Reclamation and other agencies gained interest in using robotics technology for relining projects in penstocks and similar features. BC Hydro and Reclamation wrote reviews highlighting the benefits of robotics technology for use in their agencies [4] [5]. In addition to an estimated 37 percent savings by using robotics technology, Reclamation can benefit from:

- Safer application methods, exposure conditions, and reduced liability
- Higher quality end products resulting in fewer holidays
- Shorter outage times to complete work
- Reduced labor costs, resulting in overall lower project costs
- Utilizing robotic equipment on pipes up to 32-foot inner diameter (ID)

Contractors began using robotics for relining pipelines around 2009 [6]. Almost all of those relining jobs were on minimally inclined surfaces. Some examples of the production rates, shown as square feet (SF) and outage durations are shown in table 1. The primary benefit for these jobs were the reduced outage time and reduced number of outages. In 2016, a contractor relined a discharge tube with areas as high as 77% slope using robotics. This advancement has allowed for almost any relining pipe project to be completed using robotics at an increase production rate.

Table 1. Examples of projects completed using robotics on minor slopes [6]

Project	Project Year(s)	Scope	Duration	Area (SF)
Western Electric Power Coop.	2013, 2014, 2015	Remove existing scale, abrasive blast, reline	50 days per unit	110,000 SF 130,000 SF 130,000 SF
Midwestern Electric Utility	2014-2015	Abrasive blast, reline	110 days	160,000 SF
Southwestern Electric Utility	2009, 2010, 2012, 2014	Remove cement mortar lining, abrasive blast, reline	40 days per unit	60,000 SF 53,000 SF 60,000 SF 50,000 SF

Central Arizona Project Demonstration

The Mark Wilmer Pumping Plant, built in 1981, is located on the south side of Lake Havasu, Arizona. The discharge tubes were originally coated with coal tar enamel. The service life was 35 years, which is on the short end for coal tar enamel. The existing coal tar enamel was in very poor condition shown in Figure 1. It was uncertain why the coal tar enamel failed prematurely when two miles away the coal tar enamel in the Parker Dam penstocks is 80 years old and still in excellent condition.

In 2016 and 2017, the two 12-foot diameter, 2600-foot long discharge pipes were relined. The total surface area per discharge tube was 105,000 SF. The CAP was limited to a 90 day outage from June 1 to August 30. There was an 824-foot change in elevation with slopes ranging from 16% to 77%. Figure 2 shows the terrain of the buried twin barrel discharge tubes, with three staging and access areas to the pipes. The fourth access point is inside the pumping plant. There were approximately 900 linear feet (LF) between access points and all blast media and coating materials were delivered to the robotic equipment via hoses. The contractor used a winch system anchored inside the discharge tube to control the robot at a given rate on the steep inclines as seen in Figure 3.

Figure 1. Existing condition of coal tar enamel, large areas of damaged coating.

Figure 2. Site and terrain conditions at the Mark Wilmer Pumping Plant discharge tubes; access points and staging areas are circled in red.

Figure 3. Electronically controlled winch system to allow the robot to work on steep inclines.

Water Jetting Robot

Severely degraded coal tar enamel is easily removed by water jetting methods, and a water jetting robot was used to remove coal tar enamel. Dust levels were significantly reduced, and the coating was removed without having the workers wear respirators. The workers use rope access equipment for safety, and eliminating the need for supplied air respiratory protection prevented the risk of entanglement with the rope access lines. Figure 4 show the water jetting robot at work removing the coal tar enamel. An average production rate of 3600 SF per 8-hour work shift was achieved for this job. The humidity levels were high while the water jetting procedure were conducted and caused instantaneous flash rusting of the steel surface. Once the water jetting robot was far enough into the penstock, the contractor ran the abrasive blast robot behind it. Bulkheads were used to isolate sections of the discharge tube to control the environmental conditions to prevent flash rusting of freshly blast cleaned steel.

Figure 4. Water jetting robot removing existing coal tar enamel.

Abrasive Blast Cleaning Robot

The abrasive blast cleaning robot was used to obtain a white metal blast with a 3 mil profile as seen in Figure 5. Coal slag blast media was used for cleaning. The media travelled through a 3-inch blast hose to the robot, where it splits off into three smaller 1.5-inch diameter hoses. The average production rate for this job was 1800 SF per 8-hour shift. These production rates were lower than prior work on minimally inclined surfaces. Generally, abrasive blast cleaning is always the slowest process in recoating or relining, so it is the rate limiting step. The faster the abrasive blasting, the faster the entire job is completed. The robotic process is continuous and only stops when the abrasive blast pot needs to be refilled. This is significantly more efficient than manually cleaning on a steep slope. In addition, less abrasive is wasted due to a continuous process than a manual process. Figure 6 shows a close-up of the surface of the blasted steel. The metal loss areas look like alligator skin due to the degradation pattern of the coal tar enamel. The flash rusting of the white metal blast was prevented by using dehumidification equipment and blowing in dry air into the pipe. This was a requirement because many LF can be coated in a single day. Once the abrasive blast cleaning robot was far enough along in the pipe, the coating robot was used to apply the lining to the blasted areas.

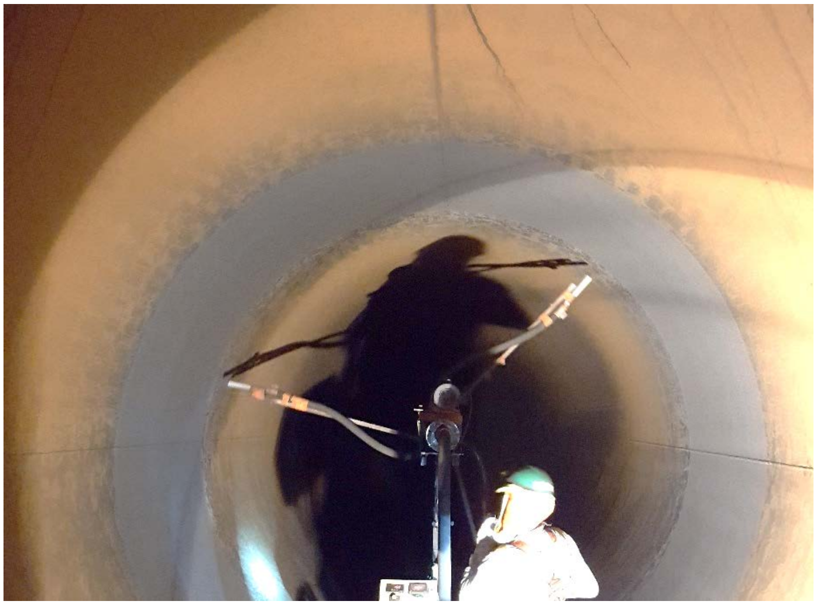

Figure 5. Abrasive blast cleaning robot achieving a white metal blast.

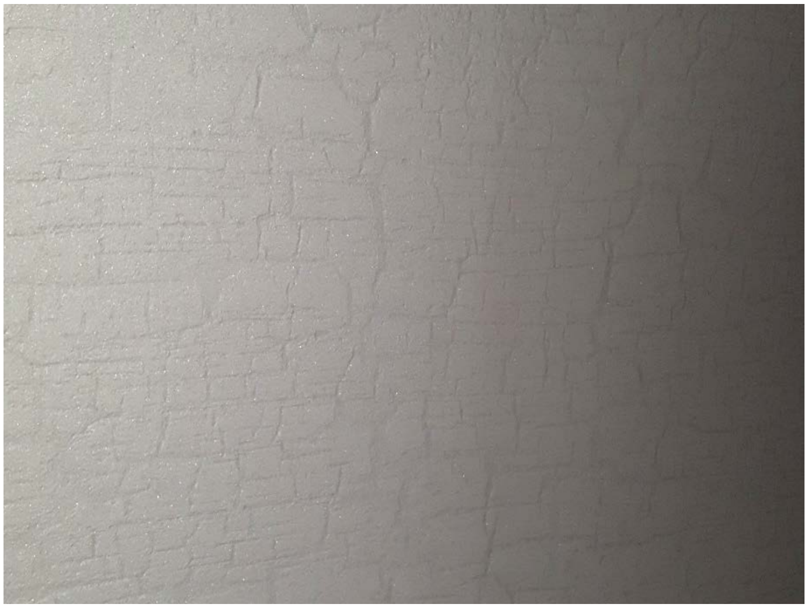

Figure 6. Steel surface after abrasive blast cleaned, notice the metal loss has an alligator pattern.

Coating Robot

The coating robot was the most critical piece of equipment for this work. The contractor has developed their own robotic sprayer that meets their requirements, as seen in Figure 7. Coating material is pumped from a trailer using a plural component pump, as seen in Figure 8. The coating is pumped through heated dual plural component lines until about 20 feet from the robot, where it goes through a mixing blocks to a single whip hose that feeds the robot, as seen in Figure 9. The contractor used solvent-free coatings and replaces the mixing blocks and whip hose after each work stoppage exceeding the material pot life. This eliminated the use of any solvents in the confined space, thus greatly reducing the flammability hazard.

The average production rate was 6,000 SF per 8-hour shift applied at 60 mils dry film thickness (DFT). This equates to 150 LF of 12-foot diameter pipe, and four 55-gallon drums of coating material applied. Compared to conventional application methods, the robot provided high production rates with better quality control. Figures 10 and 11 show the final product and coating appearance. Notice no sags, runs, drips, or similar undesirable features and a uniform coating thickness. The one year inspection showed no signs of wear or defects.

Figure 7. Coating application robot set up.

Figure 8. Plural component pump trailer that pumps the materials through the heated hoses to the coating robot.

Figure 9. Dual heated plural component hose bundles for feeding the coating robot with material to apply.

Figure 10. Final coating inspection after curing.

Figure 11. Close-up of final coating appearance.

Robotics Compared to Traditional Methods

Table 2 compares the Mark Wilmer project to the Flatiron Penstocks that Reclamation relined in 2010. The projects provide for a good comparison with some change to the outage duration, the steepness of the incline, and the diameter. On other relining jobs, such as Grand Coulee, Hoover, and Glen Canyon, the scaffolding costs were as much as 45 percent of the contract costs due to accessibility issues and steep inclines [7]. Fortunately, scaffolding was not required at Flatiron so the costs are more appropriate for comparison to the CAP project completed with robotic equipment.

Table 2. Comparison of the robotics vs. manual application

Facility	Diameter (ft)	Length (ft)	Area (SF)	Outage	Hours (hrs) per day	Incline
Mark Wilmer Discharge Tube (robot applied)	12	2,600	105,000	90 days (June 1, 2016- Aug. 30, 2016)	16 (2 shifts)	16-77%
Flatiron Penstock (manual application)	6	5,800	110,000	180 days (Oct. 1, 2010- Mar. 1, 2011)	12 (1 shift)	8-33%

An accurate cost comparison is not readily available due to construction during a recession, special equipment requirements, inflation, and other project differences. A detailed cost benefit analysis will be completed in the next couple of years comparing Flatiron and Mark Wilmer. Additional similar robotics projects will be added to the economics study as information becomes available.

The contractor at Flatiron utilized manual, traditional methods and took the approach of abrasive blast cleaning and coating in the same day to prevent flash rusting. The contractor had two workers abrasive blasting for 8 hrs per day, followed by 2-3 hrs for clean-up, then coating application for a total of about 12 hrs of work per day. The average production rate was 1,300 SF per 12 hrs. This contractor abrasive blast cleaned the coal tar enamel from the surface rather than use water jetting. The LF production rate was approximately 60-80 feet, resulting in a coating termination between each day’s work at these intervals. Some application defects witnessed were, runs, sags, overspray, disbondment due to recoat window issues, and stalactites. There were also weather delays due to the time of year.

Table 3 directly compares typical daily production rates for various tasks. The robotic application took about a third of the operation time compared to manual methods. Note the total work days is based on actual production, and doesn't account for days when there is mobilization or other delays in production. It should also be noted that multiple robots can be working simultaneously in multiple locations within the pipe, whereas the manual operation is normally done in localized sections of pipe. The crew size remained the same for both the robotics and manual approaches. However, the tasks and physical labor for workers was significantly reduced because the robot performs the majority of the work.

Table 3. Typical production rates for robotic equipment vs. manual

Facility	Water Jetting (SF/hr)	Abrasive blast cleaning (SF/hr)	Coating Application (SF/hr)
Mark Wilmer Discharge Tube (robot applied)	450	225	750
Flatiron Penstocks (manual application)	N/A	108	108

The contractor also has additional benefits from using robotic equipment:

- Reduced exposure to hazardous conditions or materials in confined spaces
- Reduced cost of personal protective equipment due to reduced usage
- Reduced number of employees in confined space using ropes access equipment
- Improved surface cleanliness consistency and coating thickness control
- Fewer coating holidays occur, resulting in less touch-up work
- Reduced blast media and coating material wastage
- Reduced fuel consumption due to faster production rates
- Faster return to service, moving onto next job
- Reduced fatigue of employees

Conclusions

Advancements in relining jobs completed with robotic equipment are changing the way contractors conduct business by increasing production rates, lowering costs, and reducing worker exposure to harmful chemicals. The potential safety improvements are further magnified by this new opportunity to minimize the number of employees in the permit required confined space. The benefits are safer work environments, reduced liability, shorter downtimes, and reduced cost.

As contractors fine tune their robotic operations, the production rates may get even faster. Multiple robots can work simultaneously, and larger jobs may be completed with compressed schedules. The cost to recoat may be lowered as time progresses and contractors become even more efficient in operating the robotic equipment.

The next step in this technology is to develop an autonomous (person free) robot that is controlled or monitored from outside the confined space work environment. A new research proposal has been submitted to help the technology advance by building collaborations, sharing ideas, and investigating autonomous applications. These advancements could allow the application of a wider variety of coating systems where safety and health concerns currently preclude their use.

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