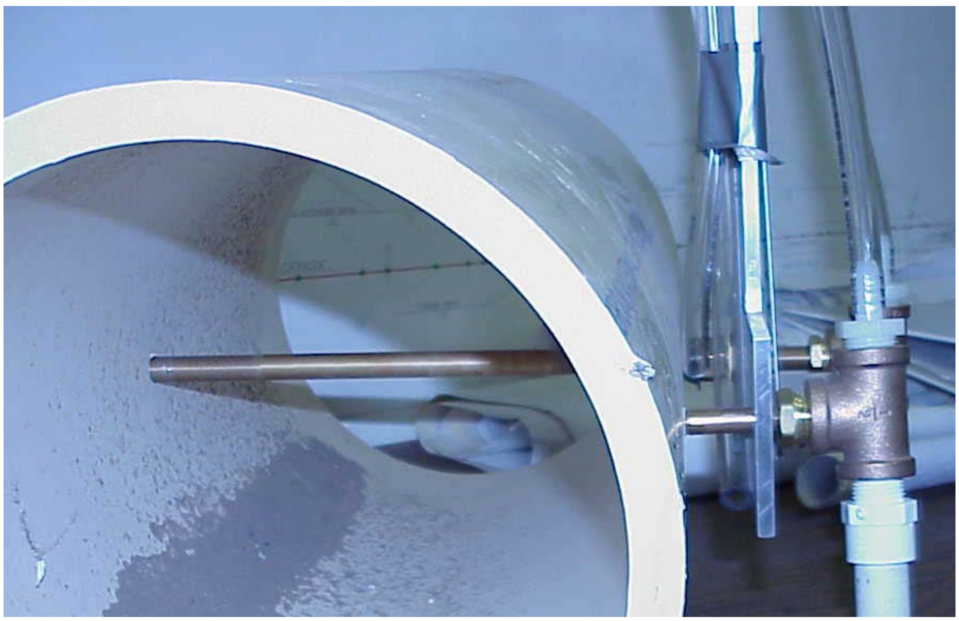
WATER OPERATION AND MAINTENANCE BULLETIN

No. 207 March 2004



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UNITED STATES DEPARTMENT OF THE INTERIOR **Bureau of Reclamation**

Available on the Internet at: **http://www.usbr.gov/pmts/infrastructure/inspection/waterbulletin**

This *Water Operation and Maintenance Bulletin* is published quarterly for the benefit of water supply system operators. Its principal purpose is to serve as a medium to exchange information for use by Bureau of Reclamation personnel and water user groups in operating and maintaining project facilities.

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***Cover photographs**: Mag-tube flow meter installed in a pipe. The upstream static pressure port through the pipe wall is in the right foreground.*

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INSPECTING INVERTED SIPHONS

by David E. Nelson[1] and Vic Feuerstein[2]

Inverted siphons are commonly used for transporting water under drainages, highways, and other structures. Siphons are very durable if well designed and constructed, but can experience problems such as pipe deterioration, cracking, leakage, or accumulation of rocks. Inspection can be difficult and dangerous. The Bureau of Reclamation (Reclamation) generally recommends that inspections be done at least every 6 years.

Siphons are designed to function with a specified normal water surface elevation at the intake, which should be indicated in the design drawing, or which may be estimated based on the freeboard required at the intake and in the canal upstream of the siphon. If this depth is exceeded, it may indicate that flow through the siphon is being restricted. Another indication of a problem is water flowing at an unexpected location or flow rate near the siphon, or which starts after the siphon is watered-up, which may indicate a leak.

The first step in planning an inspection is to review the construction drawings. Key characteristics to evaluate are the steepness of the pipe slopes and the diameter and length of the pipe. Slopes steeper than about 2h:1v may be difficult to walk safely and may require special non-slip boots and/or use of ropes.

Diameter is obviously important. Hopefully a stand-up inspection can be done. Diameters down to about 4½ feet can be inspected in a bent position if the siphon is not too long or possibly by using a sit-down cart or cycle. Crawling is possible down to about 3 feet diameter if length and claustrophobia are not problems. Smaller diameters down to about 8 inches can be inspected by lowering or pulling a video camera on a cart through the pipe or with special self-propelled cameras. Reclamation (D-8130) has self-propelled cameras for small-diameter siphon and drainpipe inspections (photo 1).

Preferably, the inspection should be done shortly after shutdown of deliveries so time is available to conduct any necessary cleaning or repair. When water is shut off, drain the siphon using the drain valve at the base of the siphon. If complete drainage is not possible with the drain valve, the remaining water should be pumped out to allow natural air flow through the siphon and to ensure a more thorough and safer inspection. If the siphon has air/vacuum valves, make sure they are operational before draining (see June 1986 issue of the *Water Operation and Maintenance Bulletin*). As soon as possible during the draining

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Photo 1.—Self-propelled inspection video camera entering a 24-inch-diameter siphon. Note the power cable and pull-out cable.

process, cover the inlet and exit with grates to prevent larger animals from taking up residence in the siphon. After completion of drainage, allow the siphon to dry and stabilize, if time allows. Control of any gates or valves which might create a hazard needs to be in accordance with Lock Out/Tag Out Facility Program and Standards (Reclamation Safety and Health Standards, 29 CFR 1910.147). All entrants must actively participate by physically locking out the controls and energy sources.

Safe entry into inverted siphons requires planning, training, and equipment. Inverted siphons are confined spaces that present safety and health hazards. Issues that need to be recognized and planned for can include protection from falls, removal of an injured entrant, and air quality. Air monitoring with a properly calibrated instrument throughout the space is necessary. Air quality problems can include oxygen deficiency, hydrogen sulfide, methane soil gases, and exhaust gases such as carbon monoxide from nearby vehicles. Oxygen deficiency can occur as a result of rust, decaying fish, or vegetation. In very small spaces with limited air flow, oxygen consumption and carbon dioxide exhaled by the entrants can render the space oxygen deficient. Inhaled air contains 21 percent oxygen; exhaled air contains 16 percent oxygen and 5 percent carbon dioxide. Hydrogen sulfide gases are common soil gases in some areas and are produced by some forms of bacteria and algae. Hydrogen sulfide is heavier than air and can build up in inverted siphons. Very low levels of hydrogen sulfide are toxic (10 parts per million). Carbon monoxide is produced by combustion engines, both gasoline and diesel. Carbon monoxide displaces oxygen in the space and on the entrant's red blood cells. It is toxic at 20 parts per million. Both carbon monoxide and hydrogen sulfide can collect in the lower portions of an inverted siphon.

Protection from falls is necessary when a fall of 6 feet or greater is possible. Depending on the configuration of the siphon, there may be locations where fall protection is necessary because of slope or slippery walking surfaces. Retrieval of an injured individual from an inverted siphon may require use of a rated man hoist and body harness. Where practical, having the entrants remain attached to the hoist would eliminate the need for an entry rescue. Rescue entry will be necessary when entrants do not remain attached and/or do not wear harnesses.

The following equipment is necessary or desirable for most siphon inspections:

1. Air monitor with an air pump and extendable probe for monitoring the space ahead of the entrants. Air monitors require a calibration kit. Spare batteries for both the monitor and pump should be carried along on the inspection.

2. Rope long enough to reach at least to the base of the siphon.

3. 2-way radios to allow communication between the person(s) in the pipe and the person(s) stationed at the entrance.

4. Flashlights (Class I, Division II rated, in case of explosive gases) and spare batteries.

5. Camera with sufficient film and spare batteries.

6. Non-slip boots (if slippery or steep slopes are a problem). Slopes steeper than 2h:1v may require a harness and lanyard, an examiner with special rope and climbing skills, or use of an approved personnel hoist system.

7. Life vests for the persons in the pipe (if there is a water hazard at the base).

8. Hard hats.

Depending on length, the pipe can be inspected from each end or by going all the way through. At least one person should be stationed at the entrance (and/or exit) who can communicate by radio or voice with the person(s) in the pipe. Before entering, detailed plans should be made on how problems or emergencies will be handled.

The ground surface above the siphon should be checked for undesirable woody vegetation, erosion of the cover above the siphon, and for sinkholes. Woody vegetation should be controlled for a distance of at least 15 feet on each side of the siphon barrel. Also check the condition of the warning signs; safety fencing; and the net, cable, or rack that helps prevent people from being drawn into the siphon when water is flowing. Downslope areas should be checked for signs of possible leakage from the siphon.

Inside the pipe, look for:

1. Cracks with excessive mineral deposits, which may be impeding water flow.

2. Open cracks or joints that may be allowing water loss or erosion of materials surrounding the pipe. Probes or hammer taps can be used to detect voids outside the pipe in the area of the crack.

3. Erosion of pipe material, particularly at the invert. Compare with the original pipe thickness.

4. Accumulations of rocks or other debris.

5. Spalling of concrete or displacement of grout.

6. Exposed reinforcing bar (if the pipe is made of concrete).

7. Coating failure and corrosion (if the siphon is metal).

8. Areas where distortion of the pipe has occurred.

9. Blocked weep holes (if weep holes were provided).

Be prepared for cleaning or repairs, especially if the siphon can be shut down only for a short time. Good lighting will almost certainly be needed, and possibly forced air ventilation. Shovels and carts may be needed to load and winch rocks out of the siphon. If one can be obtained (or built) and will fit in the pipe, a Fresno scraper works well for cleaning. A wheeled cart and a winch can be used to lower supplies and equipment for pipe repairs into the siphon.

An example siphon inspection program is that of the Northern Colorado Water Conservancy District, where siphons are inspected at 5-year intervals. Shutdown times are typically short because deliveries to cities occur nearly year round. Photos 2 and 3 show the district's personnel and material hoist unit and the associated steerable inspection cart, which are used on slopes too steep to walk.

One siphon maintained by the district had areas above the siphon barrel that were very wet. They speculated that water must have come from several locations on the siphon. The siphon was de-watered using the blowoff and then pumped as rapidly as possible. They then quickly examined the siphon barrel, and each joint where water was leaking back into the siphon was marked with spray paint. Hydrophobic urethane grout was injected into the marked joints, and in the following season the soil above the siphon was dry.

Photo 2.—Personnel and material hoist unit (exterior of unit, looking toward operator). The cable drum is visible through the open door. The hoist is placed in the canal near the entrance to the siphon.

Photo 3.—Cart, which has been modified to allow steering (to keep it from crawling up the sides of the conduit). The hoist cable attaches to the "steering" end of the cart, and the cart is lowered down the steep slope of the siphon.

On two siphons, the district used an all-wheel steer loader with a specially built curved bucket for removing material from the siphons. This must be done very carefully to avoid air quality problems. The district monitored the air constantly and used an exhaust scrubber on the diesel-powered loader. On one of the siphons, they also had to use a powerful ventilation fan.

For additional information on siphon repair, consult the following articles in the *Water Operation and Maintenance Bulletin* issues cited below:

"Operation and Maintenance" (June 1986)

"Excavating from Outside the Pipe to Access the Area Needing Repair" (September 2001)

"Sealing Joint Leaks from the Inside" (September 1994)

"Clearing Siphon Blowoff Drains from the Outside" (December 1983)

Re-filling the siphon after inspection and repair should be done slowly, typically using a flow rate of 10 percent to 20 percent of design capacity, or using the re-filling procedure specially developed for that specific siphon.

NONDESTRUCTIVE TESTING OF RECLAMATION STRUCTURES AND NONDESTRUCTIVE TESTING OF WIRE ROPES

by Connie M. Berte, P.E.

Reclamation's Science and Technology Program

A program to evaluate various nondestructive testing (NDT) techniques that can be used to perform condition assessments on hydraulic structures has been created through the Bureau of Reclamation's (Reclamation) Science and Technology Program. To implement state-of-the-art NDT on Reclamation structures and to disseminate these techniques throughout Reclamation, this program enables the performance of small-scale nondestructive evaluation and assessments on hydraulic structures. The cost of the assessments is carried by both the research program and the receiving area office.

It was concluded that Reclamation should begin using the NDT techniques to evaluate gate and valve structures because there are a number of industry-proven techniques that can easily be transferred to fulfill Reclamation needs.

Nondestructive Wire Rope Testing

Nondestructive wire rope testing provides a means to locate degradation in a rope that may be impossible to detect visually. It is shown that NDT, incorporated into a preventive maintenance program, reduces costs and improves safety. NDT does not impair the future usefulness and serviceability of a rope. The type and magnitude of degradation on a rope, broken wires, localized pitting-type corrosion, and wear can be detected.

Standards

The American Society for Testing and Materials (ASTM) E1571, Standard Practice for Electromagnetic Examination of Ferromagnetic Steel Wire Rope, offers guidance to professionals involved with wire rope. Those who test ropes should follow these guidelines to ensure reliable test results; the users of the ropes should be familiar with this standard and understand the NDT procedure followed and the test results provided by the testing company.

Principle of Operation

A test head encircles the wire rope. A constant flux magnetizes a length of rope as it passes through the test head (magnetizing circuit). Variations in a constant magnetic field are sensed and electronically processed to produce an output voltage proportional to the volume of steel or change in metallic cross-sectional area within the region of influence of the magnetizing circuit. Magnetic flux leakage created by a discontinuity in the rope, such as a broken wire or a pit in a wire from corrosion, is also sensed, processed, and displayed. Thus, two channels of information may be displayed: (1) changes in metallic cross-sectional area and (2) localized conditions, such as broken wires, pits in the wires, or inter-strand nicking. This information may be displayed on a two-channel strip chart recorder.

Recent developments make it possible to store and view data on a laptop or notebook computer.

Testing Procedure

The system consists of a test head, a console, and a two-channel strip chart recorder. The test head encircles the rope during the test. The rope moves through the test head at inspection speeds up to 400 fpm. The test head contains strong permanent magnets that magnetize the rope sufficiently to detect anomalies inside, as well as outside, the rope. One of the two channels on the strip chart recorder displays a signal, calibrated to show percent change in metallic cross-sectional areas. This signal makes it possible to determine percent loss of metallic cross-sectional area LMA (loss of metallic area) by studying the strip chart trace and comparing the degraded section(s) of the rope with the best section. The other channel displays local flaw LF (local fault) indications. If LMA is indicated, a corresponding indication also must be displayed on the LF trace; otherwise, the LMA indication may be erroneous. For example, relative movement between the test head and a nearby metallic object (other than the rope under test) may influence the LMA signal but will show no effect on the LF signal. If the test head is too close to the magnetic field produced by a motor, the LMA signal may be affected but not the LF signal. Consequently, it is important to evaluate the data carefully and compare two consecutive test runs to check for repeatability.

It is not possible to perform NDT at the termination of the wire rope (Babbitt or wedge socket) with this system. This part of the rope, and the socket, must be inspected visually or by another NDT method for broken wires and cracks in the sockets. It is wise to re-socket when there is more than one broken wire at the attachment.

Test Results

Figures 1 and 2 on the following pages show the test results from an actual test. They show that the metallic area LMA is reduced by 12.8 percent and the maximum estimated loss of breaking strength is 35.0 – 40.0 percent.

Replacement Factors

The estimated loss of breaking strength (LBS) is one of the factors that would be used to determine if a rope should be removed from service.

The removal criteria of a rope depend on a number of factors:

1. If the rope travels over a sheave wheel and is carrying its own weight plus the weight of the conveyance for materials, the following is the removal criteria:

    a. If the estimated LBS reaches 10 percent **or**

    b. If the number of broken wires in 1 lay length is equal to 5 percent of the total number of wires, excluding filler wires, used in the construction of the rope

2. If the rope is a static rope that does not travel over a sheave wheel and is essentially carrying its own weight (i.e., a guide rope), the following is the removal criteria:

    a. If the estimated LBS reaches 25 percent **or**

    b. If the number of broken wires in 1 lay length is equal to 5 percent of the total number of wires, excluding filler wires, used in the construction of the rope

The service life of a rope is determined by the rate of progression of deterioration in the rope. To make this determination, there must be two or more comparative tests completed over a period of time.

Baseline Test

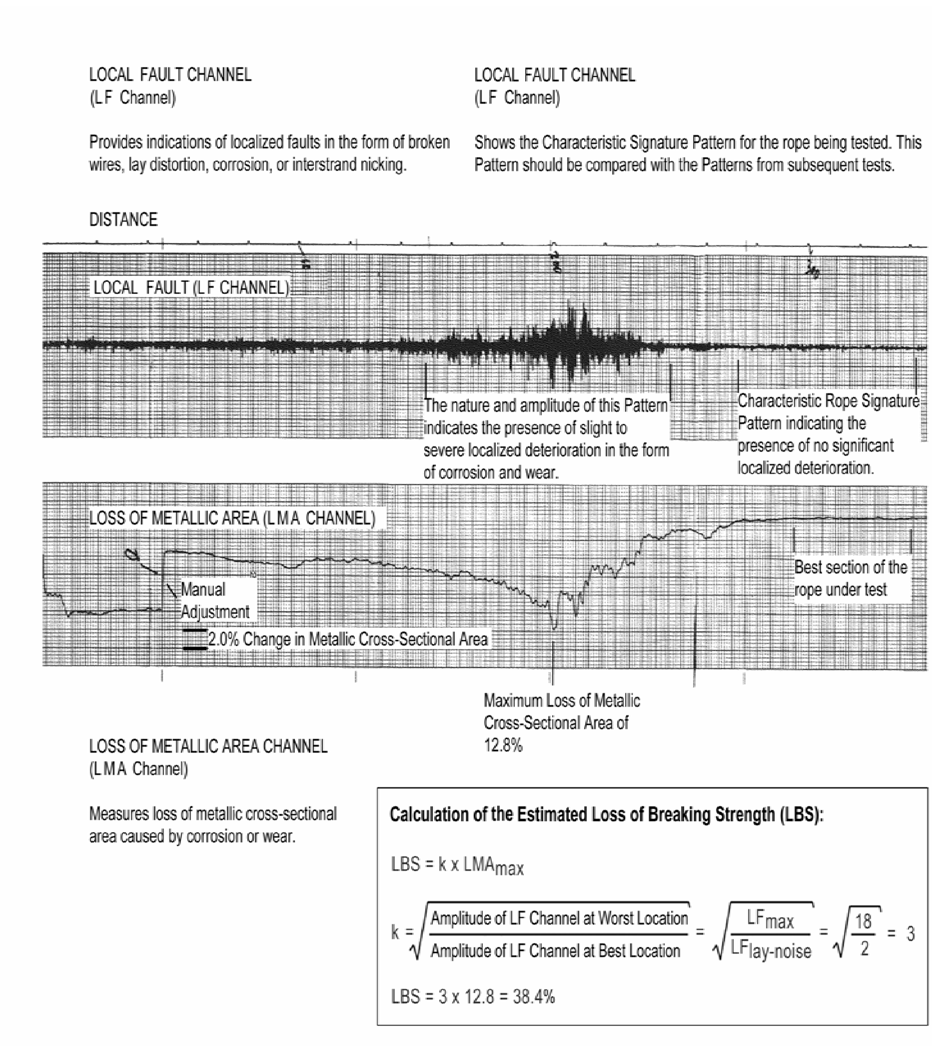
Newly installed ropes should be tested with NDT methods after initial construction stretch has occurred to obtain a baseline for the rope. If it is believed that light loading will cause minimal construction stretch, then the initial baseline test is important for comparison with

	TEST RESULTS					OCT. 8, 1995	
MINE:					SHAFT:		
COMPARTMENT:	C/WT	CONVEYANCE:	C/WT		ROPE NO./POS.:	RIGHT	
REEL NO.:	N/A	DIAMETER:	5/8"		LAY LENGTH:	4'	
CONSTRUCTION:	N/A	MFR.:	N/A		INSTALL. DATE:	1994	
TEST NO.:	MGFR-244			TEST DATE:	SEPT. 28, 1995		

MAXIMUM LOSS OF METALLIC AREA (LMA (LOSS OF METALIC AREA)) % :	12.8%
LOCATION OF MAXIMUM LMA (LOSS OF METALIC AREA):	200' – 205' ABOVE THE CWT.
NUMBER OF INDICATIONS OF BROKEN WIRES IN THE LOCAL FAULT LF (LOCAL FAULT) (LOCAL FLAW) CHANNEL :	NONE
MAXIMUM NUMBER OF INDICATIONS OF BROKEN WIRES IN 1 LAY LENGTH (xx INCHES):	N/A
LOCATION OF THE MAXIMUM NUMBER OF BROKEN WIRES IN 1 LAY LENGTH:	N/A
MAXIMUM ESTIMATED LOSS OF BREAKING STRENGTH (L.B.S.) % :	35.0 – 40.0%
LOCATION OF MAXIMUM L.B.S.:	200' – 205' ABOVE THE CWT.
VISUAL INSPECTION – DETERIORATION	
LOCATION:	200' – 205' ABOVE THE CWT.

Surface Wear		Peening/ Plastic Flow		Corrosion		Distortion		Lubrication		Rope Diameter (Inches)	Broken Wires
None		None	X	None		None	X	Good		N/A	NONE
Slight	X	Slight		Slight		Dog Leg		Fair			
Moderate	X	Moderate		Moderate		Crushing		Poor	X		
Severe		Severe		Severe	X	Birdcaging		Dry		Ave.	

Figure 1



LBS (LOSS OF BREAKING STRENGTH) = k x LMA_{max}

As shown, the LBS = 3 x 12.8 = 38.4%

Figure 2

future tests. This makes it possible to locate, and possibly remedy, potential problems that may have developed during rope installation or later. This baseline test will establish the norm from which to compare future test results.

Distinguishing Corrosion Pits from Broken Wires

If there are broken wires in the corroded part of the rope, they may not show above the hash on the LF channel. However, based on laboratory analyses of retired rope samples, safety is more adversely affected by deterioration from corrosion pits in the wires than actual broken wires. Eventually, wire ropes will break from corrosion. It is important to retire a set of ropes well before this happens, usually when a 10-percent loss in metallic cross-sectional area occurs. Visual examinations have determined that pits are well established. Quoting the *Wire Rope User Manual*, Third Edition, "Pitting of wires is cause for immediate rope removal."

Steel Wire Rope Testing Instruments

Ferromagnetic steel wire rope testing instruments are portable instruments that non-destructively test steel wire ropes for deterioration caused by corrosion, wear, broken wires, etc. These instruments can test for deterioration that is located both on the outside layer of a rope and on the inside layers of a rope. They can also test for this deterioration in all types of steel wire ropes, including locked coil ropes and plastic coated ropes. However, they can only test ropes that are ferromagnetic (i.e., steel, not aluminum).

The dual-function, electromagnetic instrument has been designed for the requirements of the underground mining industry. It simultaneously indicates local faults (localized deterioration) in the form of broken wires, lay distortion, inter-strand nicking, external wear, or corrosion pitting, and it measures LMA caused by corrosion, broken wires, external wear, and inter-strand nicking. The measured LMA, combined with the extent and nature of the pattern of the LF channel trace, can be used to assist with the determination of when a rope has reached the end of its safe working life and should be removed. The measured LMA, combined with the extent and nature of the pattern of the LF channel trace, can also be used to estimate the LBS of a rope.

Components of Instrument

- A computerized rope testing instrument that consists of a console and test head in which components are connected by a connecting cable.

Photo 1 (showing console and test head).

Console

- The console includes a built in/removable rugged notebook computer that is a signal processing/data logging unit. The console is PC-based with a user interface that controls the various functions of the instrument. The console is also able to store all information relating to the previous test results.

Test Head

- The test heads use sensor liners of different sizes for testing ropes of varying size. The sensor liners include the inductive pickup coils for detecting local faults. Because the inductive pickup coils are contained within the sensor liners, the inductive pickup coils are closer to the rope, which provides better detection of local faults.

- The test heads are fully enclosed; corrosion-protected test heads are designed to open up to facilitate ease in placing the test heads around the rope.

- Instruments are portable so that ropes are tested at location. The test heads for these instruments are similar to a donut ring that opens, allowing the test head to be placed around the rope that is to be tested. To test the rope, either the rope must be pulled through the test head or the test head must be pulled along the rope.

- Test heads are able to withstand environmental conditions underground (e.g., the test heads are water resistant).

- Test heads are designed to be easily cleaned, using industrial solvents, without damage. Cleaning the test heads and the console does not require any specialized tools (i.e., only rags, industrial solvents, glass cleaner, and water are required).

- The connecting plugs and cables are able to withstand harsh conditions.

System Capabilities

- The system is able to measure relative changes in average metallic cross-sectional areas of 0.1 percent of the total cross-sectional area of the rope.

- The system is able to detect local faults to 0.05 percent of total cross-sectional areas of rope.

- The system is able to operate within the temperature range of 0 °C to 50 °C.

- The system is capable of recording both the LMA signal and the LF signal, for each test in real time, with a resolution of 1 data point per 1 mm (0.06 inch) of rope or 1 data point per 2 mm (0.12 inch) of rope.

- The system is capable of exporting the test data to a format that could be included in reports (typically Microsoft Excel).

- The system is a dual-channel, high resolution, thermal digital chart recorder that has text printing capabilities.

- The system can compare on the computer screen two different test results simultaneously, with one test result below the other. This comparison can be made while a rope is being tested and/or after a rope has been tested.

Photo 2 (actual test).

Wire Rope Testing Services

As an alternative to purchasing steel wire rope testing instruments, you might want to have a company conduct on-site, nondestructive testing for you.

As part of service of nondestructive testing of steel wire ropes:

- Test the entire working length of the rope. Analyze test results and compare the current test results with the previous test results.

- Complete a visual inspection of those sections of the rope that are indicated to contain significant deterioration. Simultaneously, mark those locations on the rope.

- Provide a preliminary report before leaving the testing location. This report is written by the technician who conducts the testing and includes a preliminary estimate of the LBS and the results of any visual inspections that are completed.

- Review the test results twice: once by the technician who conducts the testing and writes the preliminary report and a second time by those who write the final report.

- Forward the final report within 2 weeks of the testing date (a sample copy is shown in figures 1 and 2). This report includes the final estimate of the LBS and the locations of any significant estimated losses of breaking strength of the rope during the future life of the rope. This trend line will assist an operator in determining when a rope should be removed from service because it has reached the end of its safe working life. (For some ropes, the end of the safe working life would be when the estimated LBS of the rope exceeds 10 percent).

- Steel wire rope testing quotes from:

  Rotesco, Inc.
  120 Melford Drive
  Unit 10, Scarorough
  Ontario, Canada
  Phone: (416-291-9821)

Number of ropes	Price per rope ($)	Total price ($)
1	289	289
2	215	430
3	195	585
4	188	752
5	180	900

LOW-COST PIPELINE FLOW METER

by Tony L. Wahl[1] and Henry Magallanez[2]

A new low-cost flow meter is being used to measure flows in the discharge pipelines from wells located on the Elephant Butte Irrigation District (EBID) near Las Cruces, New Mexico. The flow meter, called the Mag-tube, is a straightforward application of the Pitot tube concept. Two prototypes of the new flow meter were recently calibrated in the hydraulics laboratory of the Bureau of Reclamation. The meters are adaptable to a range of pipe sizes.

Meter Description

A prototype Mag-tube flow meter is shown in figure 1. The meter consists of a hollow 1/2-inch-diameter tube, threaded on both ends so that it may be passed through the walls of a circular pipe and sealed against the pipe wall at each end by a hex nut and rubber bushing. The tube is plugged at one end and open at the other. At the mid-point of the tube and at 2 inches off center to each side, three 1/16-inch-diameter holes are drilled through the wall of the tube to allow water to enter. The Mag-tube is installed so that these three pressure ports face directly upstream. Alignment marks on the plugged end of the tube ensure that the ports face upstream. A piece of clear vinyl tubing is connected to the open end of the Mag-tube and then to a manometer board or pressure transducer to allow measurement of the total pressure of the flow impacting the upstream pressure ports. The second part of the measurement system is a simple static pressure port drilled through the pipe wall, located about 6 inches upstream from the Mag-tube device. This port is also connected to the manometer board or transducer. The difference between the total pressure on the Mag-tube ports and the static pressure at the pipe wall is proportional to the square of the flow velocity in the pipe and can thus be used to compute the flow rate. The same tube design is used to make measurements in pipes ranging from 6 to 16 inches in diameter. Figure 2 shows a mock-up installation of the flow meter in a PVC pipe.

The Mag-tube flow meter is potentially a relatively low-cost device to produce and install. The highest cost is associated with the pressure transducer and data logging equipment, if such devices are chosen for measuring and recording the differential pressure. A simple pressurized U-tube manometer can be constructed for about $50 if automated measurement and data recording are not needed. Similar pressure measurement systems have been used on many flow meters in irrigation applications (e.g., Einhellig et al. 2002).

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Figure 1.—Prototype Mag-tube flow meter, with three pressure taps on the upstream side of the tube.

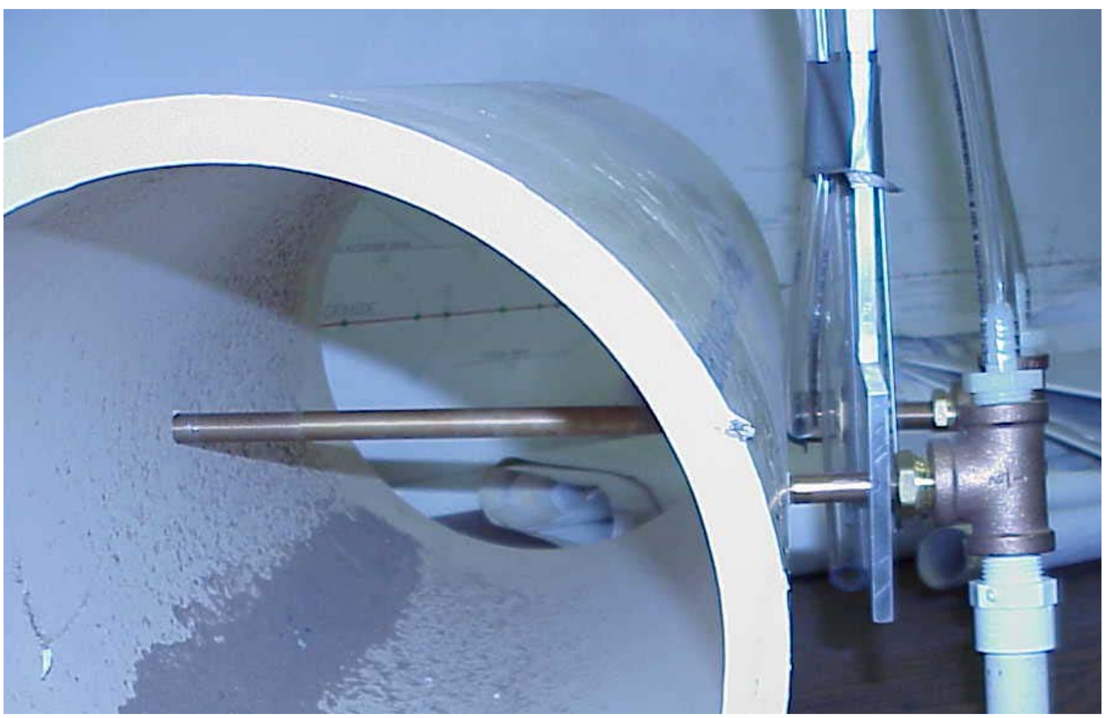

Figure 2.—Mag-tube flow meter installed in a pipe. The upstream static pressure port through the pipe wall is in the right foreground.

Calibration Testing

The calibration testing program for the Mag-tube flow meter used a test stand facility in the Water Resources Research Laboratory of the Bureau of Reclamation <www.usbr.gov/pmts/hydraulics_lab/> that provides 45-foot long straight sections of circular pipe with nominal diameters of 4, 6, 8, and 12 inches. All flows into the test stand are independently measured by venturi flow meters ranging in size from 3 to 14 inches inlet diameter. The venturi meters are periodically calibrated using a weight-tank and have a flow measurement uncertainty of ±0.5% or better. Pressure differentials between the Mag-tube ports and the pipe wall tap were measured with a 5 lb/in^2 differential pressure transducer and verified visually using a pressurized, air-and-water, inverted U-tube manometer. Inline dampening coils stabilized the pressures coming from the Mag-tube and pipe-wall ports, making it easy to accurately read and measure the pressures.

The test plan was designed to determine the calibration equations for the Mag-tube flow meters and the relative uncertainty of flow measurements made with the tubes. The testing could not evaluate every source of uncertainty that might affect a measurement in the field, but it did identify and evaluate factors such as the variability in construction of two different prototype tubes, the possibility for and effect of misalignment of the tube with the flow direction during installation, and the random noise inherent in repeated flow rate measurements performed with a single tube.

The testing led to the development of a discharge equation of the form

$$Q = C_v A\sqrt{2g\Delta H} \qquad (1)$$

where Q is the discharge, A is the cross-sectional area of the pipe, g is the acceleration of gravity, and ΔH is the differential pressure measured between the Mag-tube and the pipe-wall static pressure tap. The velocity coefficient was determined from calibration testing. The coefficient varied with the pipe diameter, and over the range of diameters tested (6 to 12 inches), the velocity coefficient could be estimated from the following equation:

$$C_v = 0.806 + 0.00274D \qquad (2)$$

where D is the pipe inside diameter expressed in inches.

Based on lab testing, the uncertainty of field flow measurements made with the Mag-tube was estimated to be ±2% or better, assuming the use of equipment similar to that used in the lab (i.e., dampening coils on the piezometer lines and the use of a suitable pressure transducer to measure the differential pressure). The tests showed that the probe alignment could be set with sufficient accuracy to avoid errors caused by misalignment. Figure 3 shows the discharge vs. differential head measurements for the calibration tests in 6-, 8-, and 12-inch diameter pipes (nominal pipe sizes, inside diameters were slightly smaller).

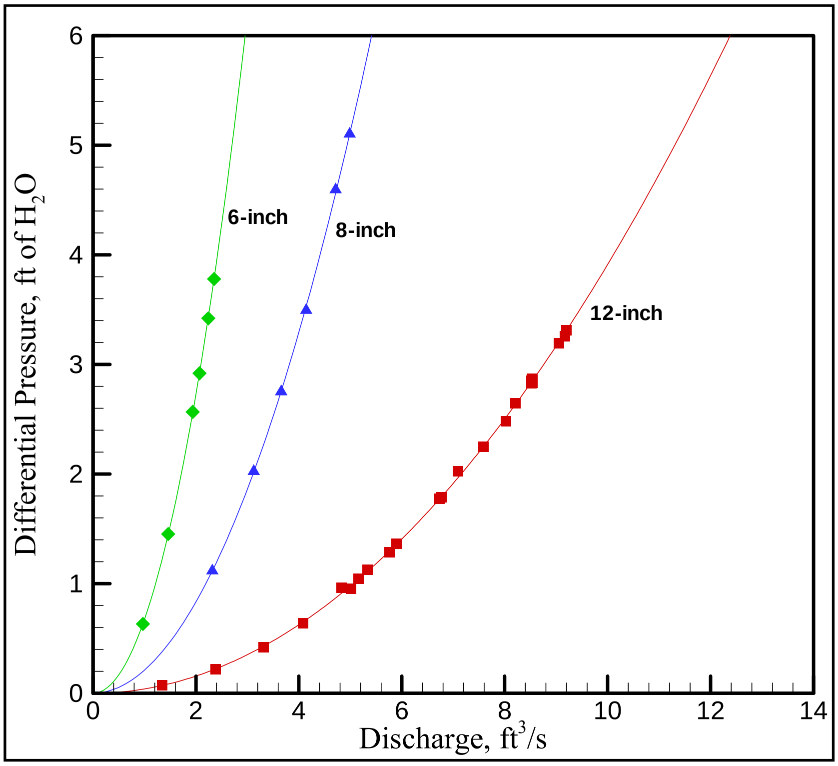

Figure 3.—Discharge vs. differential pressure for Mag-tube flow meters.

Field Installations

Following the completion of the calibration testing, the meter was accepted by the New Mexico Office of the State Engineer as a valid measurement device, and EBID began installing meters in the field. In order for the Mag-tube to function as a totalizing meter for management, reporting, and administration, the static and dynamic pressure taps were instrumented with pressure transducers that convert pressure to a voltage or current signal, which in turn can be read and stored by an electronic data logger. The electronic data are easily transmitted through a radio telemetry system for processing and storage as part of a Supervisory Control and Data Acquisition (SCADA) system. The sensors and electronics tend to be the most expensive component of the Mag-tube installation, typically costing about $700. To date, approximately 70 meters have been put into use in pipes ranging from 6 to 14 inches in diameter.

As a temporary measure or to keep the metering cost low, an inverted U-tube manometer can be used to determine the difference in the dynamic and static heads. Figure 4 shows a construction drawing for the manometer. Unlike a traditional U-tube manometer in which water fills the bottom of the U, in this manometer the U is inverted and air fills the top of the inverted U. The difference in water elevations between the two sides of the manometer indicates the difference between the dynamic head and the static head. Air is pumped into the top of the tube through a standard bicycle-type air valve. The height of the manometer is selected based on the pressure range that must be measured. Manometers must be read by an observer, and they do not have the ability without additional instrumentation to accumulate flow volumes by integrating instantaneous flow measurements, but they do allow for rapid, reliable, inexpensive flow measurement.

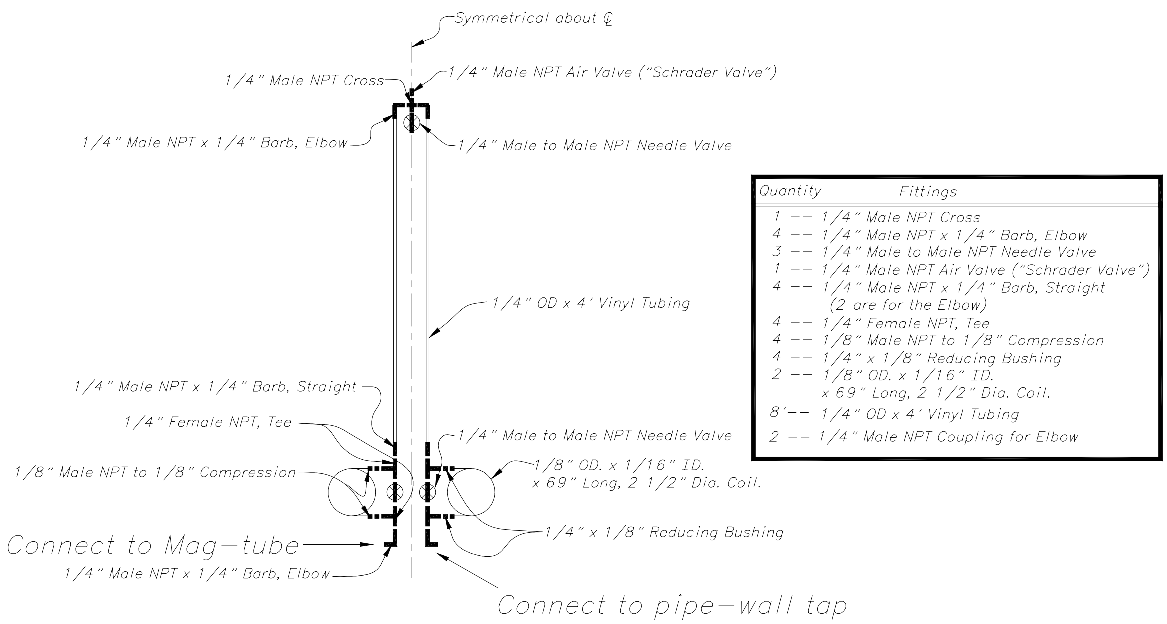

Figure 4.—Construction drawing for inverted U-tube manometer.

Most velocity-based flow meters require full-pipe flow, and the Mag-tube is no different. Some pipe flow meters, such as in-line impeller meters or orifice plates, can induce full pipe flow in a pipe that otherwise flows partially full due to the head loss caused by the meters themselves. In contrast, the Mag-tube causes an insignificant amount of head loss, so the flow of the well is not affected by metering, but one cannot depend on the meter to induce full pipe flow by itself. In cases where pipes are flowing partially full, full flow could be induced by a pipe constriction, an elevated section of pipe, or the installation of a flap gate at the outlet.

One common problem encountered was improper installation of the static pressure tap—it protruded into the pipe. It is important that the tap be flush with the inner wall of the pipe, or even recessed. A protruding tip generates lift in the flow field and inaccurate static pressure measurements. The hole for the tap should be drilled perpendicular to the inside surface of the pipe, and the edges of the hole should be deburred or slightly rounded, if possible. More information about good pressure tap installation practices can be found in Bean (1971).

The prototype Mag-tubes installed by EBID were fabricated from aluminum, which presented some problems. Scaling clogged the orifices in some cases, reducing the sensitivity of the meter. An example is shown in figure 5. Corrosion was also a problem, as the walls of the aluminum tube thinned at a rate that would compromise the integrity of the pipe in a fairly short service life. Switching to stainless steel Mag-tubes appears to have solved the problem. Installation of Mag-tubes in water with high total dissolved solids, very high or low pH, or other potentially active chemistry should be monitored carefully and Mag-tube material selected accordingly.

Figure 5.—Scale formation on aluminum Mag-tube.

In wells that discharge significant quantities of sand, particularly new wells, one may experience some problems with clogging of the orifices or the tube itself. Regular maintenance should include blowing out the orifice, tube, and fittings to ensure that clogging does not affect the accuracy of the meter.

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