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Inspection of Steel Penstocks and Pressure Conduits

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The Bureau of Reclamation operates and maintains 53 hydroelectric powerplants and many switchyards, pumping plants, dams, canals, and associated facilities that are important to electric power and water delivery systems. This document establishes consistent procedures for inspection of penstocks and pressure conduits at Reclamation's facilities.

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Prepared by

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Bureau of Reclamation
Power Resources Office
Denver, Colorado

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Table of Contents

Figures

Page

Codes and Standards

American Society for Testing Material, C803--Standard Test Method for Penetration Resistance of Hardened Concrete, 2018.
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FAC 01-07 *Review/Examination Program for High and Significant Hazard Dams*
FAC 04-01 *Power Review of Operation and Maintenance (PRO&M) Program*
FAC 04-14 *Power Facilities Technical Documents*
FIST 1-1 *Hazardous Energy Control Program*
FIST 2-3 *Mechanical Maintenance of Mechanical and Digital Governors for Hydroelectric Units*
FIST 2-7 *Mechanical Overhaul Procedures for Hydroelectric Units*
FIST 4-1A *Maintenance Schedules for Mechanical Equipment*
FIST 4-1B *Maintenance Schedules for Electrical Equipment*
FIST 4-5 *Corrosion Protection*
RCD 03-03 *Request for Deviation from a Reclamation Manual Requirement and Approval or Disapproval of the Request*
RSHS *Reclamation Safety and Health Standards*
Section 13, Walking and Working Surfaces
Section 16, Fall Protection
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Reclamation Forms

POM: https://teamssp.bor.doi.net/printanddup/forms/POM%20Forms/Forms/AllItems.aspx
POM-184, Load Rejection Test Data Sheet
POM-186, Penstock Inspection Checklist
POM-190, Hydroelectric Unit, Mechanical Inspection Report
POM-226, FIST Revision Request
POM-300, FIST Variance Form

Acronyms and Abbreviations

ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing Material
D&S	Directives and Standards
DOC	Designers' Operating Criteria
EIS	Electrochemical Impedance Spectroscopy
FAC	Project Planning and Facility Operations, Maintenance, and Rehabilitation (of the Reclamation Manual)
FIST	Facilities Instructions, Standards, and Techniques
MT	Magnetic Particle Examination
NDE	non-destructive examination
O&M	operations and maintenance
PRO	Power Resources Office
PRO&M	Power Review of Operation and Maintenance
PT	Liquid Penetrant Examination
RCD	Records Management (of the Reclamation Manual)
Reclamation	Bureau of Reclamation
RIV	remote inspection vehicle
RM D&S	Reclamation Manual Directive and Standard
ROUV	remotely operated underwater vehicle
RSHS	Reclamation Safety and Health Standards
RT	Radiographic Examination
TSC	Technical Services Center
UAV	unmanned aerial vehicle
UT	Ultrasonic Examination
UV	ultra-violet light

Symbols

%	percent
°F	degrees Fahrenheit

1.0 Introduction

The Bureau of Reclamation operates and maintains hydroelectric powerplants, switchyards, pumping plants, water delivery equipment and associated facilities in the 17 western United States. These facilities house complex electrical and mechanical equipment that must be kept operational because they are critical to the electric power and water delivery systems relied on by many. FISTs are technical documents that provide criteria and procedures that should be utilized by the offices involved in managing Reclamation facilities and assets.

This document establishes standard technical practices to ensure the safe, reliable, economic, and efficient O&M of federal facilities by keeping related assets in good condition and ultimately protecting federal investments. These technical practices provide a sufficient level of detail to ensure consistent application, while providing flexibility for the use of innovative techniques and approaches. This document was developed with input from staff in Reclamation's Denver, regional, and area offices.

1.1 Purpose and Scope

This document is intended to promote uniformity in the manner that assets are managed, documented, and coordinated, and may be utilized by transferred facilities and other entities as appropriate. It establishes consistent procedures, minimum standards and O&M criteria for equipment and systems owned and operated by Reclamation. Other technical documents may provide additional electrical and mechanical maintenance information for the equipment or systems discussed in this document.

O&M requirements are based on industry standards and experience. Maintenance requirements vary based on equipment condition and past performance, and sound engineering practices and maintenance management should be employed for special circumstances. Manufacturer recommendations and instructions should be consulted for additional maintenance that may be required beyond what is stated in this manual.

This volume includes standards, practices, procedures, and advice on day-to-day operation, maintenance, and testing of mechanical equipment in Reclamation facilities.

1.2 Reclamation Standard Practices

FIST manuals are designed to provide guidance for maintenance and testing on equipment in Reclamation's facilities. There may be multiple ways to accomplish tasks outlined in this document. Facilities may exercise discretion as to how to accomplish certain tasks based on equipment configurations and available resources.

Reclamation's regions, PRO, and TSC agree that certain practices are required to be consistent across all Reclamation facilities. Mandatory FIST procedures, practices, and schedules that appear in

{Red, bold, and bracketed} or **[Black, bold, and bracketed]** text are considered Reclamation requirements for the O&M of equipment in power facilities. RM D&S FAC 04-14, *Power Facilities Technical Documents*, describes the responsibilities required by text designations: **{Red, bold, and bracketed}**, **[Black, bold, and bracketed]**, and plain text, within this technical document. Refer to RM D&S FAC 04-14 for more details concerning technical documents.

1.3 Maintenance Tables

Maintenance tables for tasks described in this document are included in FIST 4-1A, *Maintenance Scheduling for Mechanical Equipment*, and FIST 4-1B, *Maintenance Scheduling for Electrical Equipment*.

1.4 Manufacturer Recommendations

The information in this document is based on manufacturers' documentation and historic Reclamation practices. Due to the differences in equipment designs, owner's manuals and manufacturer's recommended maintenance should be consulted when developing job plans. Not following the manufacturer's guidance may void the warranty of new equipment. If there is a discrepancy between the FIST and the manufacturer's recommendations, the job plan must use the more stringent practice unless there is a reason that a less restrictive maintenance practice is warranted. Use of a less restrictive maintenance practice must be approved as outlined in RM D&S FAC 04-14 by either a deviation or a variance. A deviation maybe granted in accordance with RCD 03-03 and variances are approved in accordance with FAC 04-14 using POM Form 300.

1.5 FIST Revision Requests

The FIST Revision Request Form (POM-226) is used to request changes to a FIST document. The request should include a summary of the recommended changes and a basis for the revision or new FIST. These forms will be submitted to the Manager, PRO. The PRO Manager will keep a list of Revision Requests for each FIST and include these in the next scheduled revision unless the change is prioritized sooner.

1.6 Mechanical Database

The TSC Mechanical Equipment Group created and maintains a Mechanical Equipment Database. All Reclamation employees have access to the database, which contains test data, operating data, and general information about the following:

1) Turbines
2) Governors
3) Gates and valves
4) Pressure vessels
5) Penstocks
6) Elevators

7) Hoists
8) Cranes

The database:

1) Provides visibility of other Reclamation facilities with similar equipment; i.e., find all Reclamation facilities with Obermeyer Gates.
2) Is a critical tool for facility reviewers, i.e., reviewers can obtain printable forms from the database website for each asset being reviewed. The form can be taken to the site and used to compare and update information.
3) Tracks equipment testing frequencies and critical data comparison. For example, governor alignment results can be compared to the previous governor alignment results. An increase in operating pressures or opening/closing times can indicate gate repairs are required.
4) Provides updated testing and inspection dates for gates, valves, pressure vessels, and penstocks for mechanical inspectors/reviewers to use during Power Reviews (RM D&S FAC 04-01), Associated Facilities Reviews (RM D&S FAC 01-04), and High and Significant Hazard Dam Reviews (RM D&S FAC 01-07).

When tests and alignments, as outlined in FIST 4-1A, *Maintenance Schedules for Mechanical Equipment,* or the database, are completed, facilities or regional personnel should submit the recorded data to the Mechanical Equipment Group (bordromechequipdb@usbr.gov). A service agreement is established with TSC to update the database and keep it accurate. The PRO&M review programs use this database to ensure tests and alignment are up to date and are being tracked.

The link to the Mechanical Equipment Database is: https://mechdb.usbr.gov/MechDB/.

2.0 Penstocks and Outlet Pipes

Penstocks and outlet pipes are constructed from steel, concrete, or, in some cases, wood staves. A penstock is a conduit that conveys water from a reservoir, forebay, or other source to a hydraulic turbine in a hydroelectric powerplant. An outlet pipe is a conduit that conveys water from a reservoir for irrigation, run of the river, municipal or industrial water supply, or other purposes. Both may be entirely embedded or partially in concrete, placed under ground, through a tunnel, or carried on suitable supports above ground. Both penstocks and outlet pipes may have expansion joints, manholes, drain and fill lines, and other accessories which require periodic maintenance.

Many of the penstocks and outlet pipes in Reclamation facilities were built in between the 1930 and 1960. In addition to periodic basic inspections, these aged structures should be evaluated for safety reasons. Due to corrosion and other factors, a penstock or outlet pipe may no longer be safe for water hammer conditions that may occur during a load rejection or closure of an outlet valve. This document provides useful information, maintenance, and engineering techniques for the assessment, of all types of pipes.

3.0 Inspection Planning

No two facilities have the same penstock design. Variations of slope, lining material, parent material thickness, and penstock exposure change the way a penstock should be inspected. A proper inspection requires thorough pre-inspection work in order to be successful. Previous inspection reports, the powerplant DOC, and relevant penstock drawings should be consulted in the planning phase. These will aid in selection of the inspection type and inspection method, and assist in the development of the inspection plan and safety plan.

3.1 Inspection Types

Two types of penstock inspections should be regularly scheduled: a basic and a detailed inspection. These inspections should include examination of the penstock's shell, supports, joints, appurtenances, penetrations, operating equipment, and geotechnical considerations. Refer to POM-186, Penstock Inspection Checklist.

3.1.1 Basic Inspection

A basic inspection is completed at shorter intervals and encompasses a smaller scope than a detailed inspection. A basic exterior inspection is suggested more frequently than the periodicity outlined in FIST 4-1A, *Maintenance Schedules for Mechanical Equipment,* to discern visible defects with the penstocks to the best extent practicable. If a full walkdown is not practical because of excessive length, rough terrain, operations, etc., then perform the walkdown per FIST 4-1A, *Maintenance Schedules for Mechanical Equipment*. If possible, an interior walkdown to the best extent practicable is suggested more frequently than the periodicity outlined in FIST 4-1A, *Maintenance Schedules for Mechanical Equipment,*, but interior inspections should occur per FIST 4-1A, *Maintenance Schedules for Mechanical Equipment.* Basic inspections can be used to track a penstock defect development over a short-term basis or find serious problems that should be addressed immediately. **[Complete a visual inspection of the penstock and its components. This inspection should note any damage to the penstock shell, supports, joints, appurtenances, penetrations, and operating equipment, as well as assess any concerns with penstock vibration and geotechnical aspects. As necessary, readjust or replace packing in joints, clean and relubricate sliding surfaces of supports, and repair general penstock damage.]** This document discusses the inspections that should be conducted on each of these items.

3.1.2 Detailed Inspection

A detailed penstock inspection, which should be conducted at a minimum per FIST 4-1A, *Maintenance Schedules for Mechanical Equipment,* encompasses more thorough and quantitative assessments in addition to the scope of a basic penstock inspection. A detailed inspection requires accessing the interior of the penstock to thoroughly inspect the lining system. To properly assess the condition of the penstock, take shell thickness readings and perform other quantitative analyses deemed necessary. **[Complete a detailed inspection of the penstock and its components. Document results and findings in a report. A detailed penstock inspection shall include, in addition to a basic inspection, ultrasonic thickness measurements and pertinent penstock stress analyses. Note any major defects found in the penstock shell, supports, and operating**

equipment. If a visual inspection has revealed significant levels of unaddressed coating failure, corrosion, or other defects that may affect the penstock wall thickness or structure, a detailed inspection shall occur more frequently.]

The results of this detailed inspection shall be recorded in a penstock inspection report written by one or more of the penstock inspectors. **[An inspection report shall document the results of ultrasonic thickness measurements, pertinent penstock stress analyses, and note any major defects found in the penstock shell, supports, and operating equipment.]**

3.2 Inspection Methods

To properly prepare for a penstock inspection, first determine how the inspection will be conducted. Consider penstock gradients, surrounding terrain, and penstock size. These variables dictate the appropriate inspection method required to complete a thorough and comprehensive inspection.

3.2.1 Standard Inspection

A standard inspection is one that requires no special equipment to complete. Inspectors may walk the interior and exposed exterior of the penstock if the penstock is large enough to accommodate the inspector, the gradient is shallow enough, and the traction does not warrant rope access.

Inspectors may want to use felt-bottomed boots, waders, or other traction–improving soles to aid in walking in the penstock shell and to protect them from getting wet if leakage past the headgate is significant. The inspector may request a fall protection line used in conjunction with a harness and rope grab to limit the risk of injury.

3.2.2 Rope Team Inspection

For penstocks on steep grades, trained rope access personnel are required to properly inspect the penstock. It is up to the inspector to judge whether a penstock will require rope access. Per Reclamation's "Guidelines for Rope Access Work," a job is rope access if ropes are used as the primary means of support.

From experience, penstocks up to angles of 21-degrees (38% grade) have been inspected without rope, given dry conditions and a high level of traction. When slippery conditions exist, slopes around 10-degrees (18% grade) may require rope access procedures. At minimum, for slopes where a serious fall hazard exists, a fall protection line should be deployed to ensure inspectors do not slide down the penstock. Rope team inspections require a minimum of two rope access technicians to complete the inspection. Three rope access technicians are commonly desired for penstock inspections due to the dangerous nature of the task.

3.2.3 Remote Inspection Vehicles

RIVs offer the opportunity to inspect a structure while decreasing risk to personnel. The feasibility of using RIVs for penstock inspections is currently in its infancy. Options for drone and magnetic crawler inspections are being actively researched and developed. Challenges with inspecting a penstock with an RIV include navigating confined spaces, proper lighting, identifying defects hidden under a silt-covered lining, taking UT measurements, and the time required to complete a remote inspection. At the time of this publication, no Reclamation penstock has been thoroughly inspected with an RIV.

3.2.3.1 Unmanned Aerial Vehicle

A UAV is an air-based RIV typically referred to as a "drone". Drones can be a useful tool in quickly examining exterior portions of an exposed penstock and anchor blocks. Within Reclamation, these drones are required to be operated by trained personnel. More information on the Reclamation Aviation Program can be found in the National Aviation Management Plan.

Recently, drone technology has advanced to a point where an interior visual inspection of a penstock is possible. Challenges still exist with drone equipment that can make a penstock inspection impractical, including improper lighting, short battery life, and equipment cost. For exposed penstocks, a drone inspection of the exterior is more viable because most of the challenges associated with interior inspections are eliminated.

3.2.3.2 Crawlers

A crawler is a land-based RIV designed to travel on a structure using wheels or tracks. Crawlers sometimes have integrated magnets that allow them to travel on vertical surfaces or while underwater on ferrous materials. Limitations of a crawler inspection include crawler speed and visibility when in large penstocks. In penstocks of diameters too small to fit a human inspector, crawlers can prove useful over borescopes that have limited ranges of motion.

3.2.3.3 Remotely Operated Underwater Vehicle

ROUV would be used if the penstock is unable to be dewatered. Limitations with this method are apparent in areas with strong current, water with high turbidity, or in penstocks with small diameters. ROUVs capable of taking shell thickness readings do exist; however, maneuvering the submersible to get a clear representation of penstock shell thickness can be difficult.

3.2.3.4 In-Line Inspection Tools

In-line inspection tools or "smart pigs" are commonly used in oil and gas pipeline inspections. A "pig" refers to a barrel shaped device that is sent through a pipe to clean or inspect a pipeline. These are often pushed through the pipe via the working fluid or self-propelled. "Smart" pigs are equipped with various cameras, sensors, and gauges to inspect and view a pipe for defects, measure pipe wall thickness, collect geometrical data, and can even detect leaks. These can provide an unparalleled inspection resolution, locating interior or exterior wall-thinning, along the length of the pipe to within a few inches. Traditional smart pigs are typically better suited for smaller diameter pipes of 4-56 inches in diameter and require pipes to be of continuous diameter. For these reasons, pigs typically used in the oil and gas industry are not ideally suited for penstock inspections; however, they could prove useful for other facility piping inspections.

More recently, in-line inspection tools more applicable for steel water conveyance pipes have been developed. These platforms can accommodate larger pipe diameters and variations in pipe shape. Limitations to these devices usually include special flow requirements, pipe geometry restrictions, coating thickness limitations, data resolution setbacks, and large mobilization costs. However, this equipment is constantly evolving in capability and should be researched to find the most recent advancements.

3.3 Inspection Plan

The inspection plan is a key element of a successful penstock assessment. The plan should include:

1) Scope and goal of the inspection.
2) List of personnel involved or required.
3) A checklist of the items to be inspected.
4) Dates and times of the inspection.
5) List of clearance points and equipment to be locked out/tagged out to ensure a safe penstock inspection.

Traditionally, detailed penstock inspections have been performed in the following sequence:

1) Visually inspect the following items: penstock shell condition (interior and exterior), welds, bolts and rivets, expansion joints and sleeve-type couplings, air valves and vents, control valves, manholes and other penetrations, anchor blocks and supports, appurtenances, linings and coatings, and instrumentation. Note any areas of concern to document in the inspection report.
2) Measure and record penstock shell thickness using NDE methods, usually UT, at selected locations along the penstock. This task can be combined with the visual inspection in Step 1.
3) Perform additional deficiency assessment using NDE techniques for specific items of concern that were observed during the Step 1 visual inspection.
4) Perform a stress analysis of the data obtained during Step 3. This stress analysis should be performed by a qualified individual with substantial experience in designing and analyzing penstocks or pressure conduits.

For efficiency, the following procedures are also often performed around a penstock inspection:

- Simulate the emergency control system operation to ensure the emergency gates or valves will close. Document that they will completely close with physical tests or calculations. Reference FIST 4-1A, *Maintenance Schedules for Mechanical Equipment,* under the gates and valve section.
- Perform load rejection tests for comparison against hydraulic transient analysis results and design criteria to ensure safe operating conditions. Reference FIST 2-7, *Mechanical Overhaul Procedures for Hydroelectric Units*. Reference POM-184, *Load Rejection Test Data Sheet*, for information that is required to be monitored and recorded.
- Readjust the governor to establish a safe wicket gate timing to prevent over-pressurization of the penstock and to ensure maximum response capability. Reference FIST 2-3, *Mechanical Maintenance of Mechanical and Digital Governors for Hydroelectric Units*.

3.4 Frequency and Scheduling

Refer to FIST 4-1A, *Maintenance Schedules for Mechanical Equipment,* for the required inspection frequency. Penstock inspections need to be planned and scheduled to minimize down time of the turbine units. The opportunity window for a penstock inspection may be narrow; thus, planning for an inspection well ahead of time is important. Factors to consider when recommending the next inspection date include:

1) Accessibility for inspection.

2) Overall condition of the penstock or pressure conduit.
3) Type of design and the age of the penstock or conduit.
4) Existence of significant public safety concerns.
5) Existence of significant environmental concerns.
6) The need to document the condition of the penstock or pressure conduit.
7) Criticality of the facility to power production and water operations.

3.5 Safety Plan

Reference FIST 1-1, *Hazardous Energy Control Program,* for any safety planning. A job hazard analysis shall be prepared for the penstock inspection. Review previous penstock inspection reports, if available, to ensure all potential safety concerns are planned for and mitigated. Make certain that all personnel involved in the inspection are aware of the hazards, understand the safety requirements for the tasks they are performing, and will implement the safety requirements during the field work.

FIST 1-1, *Hazardous Energy Control Program,* shall be referenced for any safety planning; however, listed below are some items that should be considered for a penstock inspection job hazard analysis:

1) List the contacts for reporting accidents.
2) List emergency telephone numbers.
3) List addresses and directions for local hospitals.
4) Reference the facility's safety manual that pertains to site investigation activities.
5) Field review the site working conditions and possible safety hazards. A safety checklist containing some, but not all, important safety items would include:
    a) Lock out/tag out procedures are followed to ensure a safe work area. Equipment that is out of service must be locked in the off position or open in the case of a hatchway. Gates or valves that control the entry of water into a dewatered space should be mechanically locked in the closed position.
    b) Ensure all operational clearances are obtained before entering penstocks, climbing ladders, or even walking through the plant.
    c) Review a checklist of safety items with the person holding the operations clearance and the plant safety officer or equivalent.
    d) Vertical ladders normally require platforms every 30 feet; ladder heights more than 20 feet require safety cages or safety climbs. Temporary staging or ladders should be properly assembled and secured before personnel use. Personnel should use a safety harness or safety line. Refer to RSHS Section 13 for proper ladder use or RSHS Section 16 for fall protection requirements.
    e) The air in vaults and penstocks should be tested for oxygen content and toxic gases before and during entry. Inspection of a confined space requires an air source and an air circulator. If in doubt concerning the air quality, wear a self-contained breathing pack. A person should always stand by on the outside at all times when personnel are working in an enclosed space. If an emergency occurs, the outside person should obtain help rather than go inside.
    f) Penstock inverts are usually inclined and slippery. Falls are common. Wear rubber boots with safety soles. Take a coworker with you and always proceed with caution. A fall

protection line used in conjunction with a rope grab can be installed in the penstock to prevent sliding in the event of a fall.

g) Use caution when walking on top of penstocks and pressurized conduits. Be careful near pressurized water escaping from leaks. Do a visual inspection first from a distance. Probe the leakage with a piece of wood. Never enter leakage spray or a leakage water jet. These situations can cause serious injury.
h) Be careful when running your hand over bare metal; edges are often sharp.
i) Adequate lighting should always be provided.
j) If the penstock requires rope access, the job hazard analysis should describe the procedure to rescue a casualty that is on rope.

3.6 Background Information

3.6.1 Design and Construction History

Before inspecting a penstock or pressure conduit, the design and construction history must be understood. This preparation includes a review of the design drawings, design criteria, geology and soils (foundation information), design calculations, supplier information, construction, maintenance, and operation and safety information.

3.6.2 Operational History

Each penstock will experience different loadings and changing conditions during its operation history. After years of operation, a penstock undergoes loading cycles from dewatering, watering, partial filling conditions, hydraulic transients (water hammer), equipment operations, and hydraulic turbine loading and unloading. Hydraulic equipment will change with turbine capacities. Internal pressure will increase as dams are raised in height. Pumping pressures could increase to meet irrigation and public water supply demands. Each change of condition is part of the operational history.

The operating characteristics of the penstock and the equipment that controls the penstock pressure must be fully understood. A careful inventory of the intake, venting, flow conduit restrictions, surge devices, turbine and governor characteristics, gates and operators, valves and operators, and draft tube and tailrace characteristics is necessary.

The steady state and transient flow conditions must also be defined. Perform a hydraulic analysis and review the following items to define the steady state and transient flow conditions:

1) Steady state conditions:
    a) Operating records
    b) Reservoir rule curves
    c) Headwater and tailwater rating curves
    d) Generating or pumping station use:
        i) Base
        ii) Peaking
2) Transient flow conditions:
    a) Load acceptance and rejection tests
    b) Valve opening/closing times

c) Water column separation

3.6.3 Previous Inspection and Maintenance Reports

Review monitoring and maintenance records completed by facility personnel for documentation of any leakage, settlement, movement, geometric changes, or equipment modifications or changes.

4.0 Penstock Inspections

A basic penstock inspection should be completed at regular intervals to discern visible defects in the penstock and its components. A detailed penstock inspection should be completed at longer intervals to quantitatively assess the penstock and its components. Both should note the condition of the penstock shell, supports, joints, appurtenances, and operating equipment. If areas of severe damage are found, take or plan mitigation action for future outages. POM-190, *Hydraulic Unit, Mechanical Inspection Report*, has a section to record the penstock inspection and POM-186, *Penstock Inspection Checklist*, provides details for a thorough inspection.

4.1 Penstock Shells

Due to their size and relatively thin wall thicknesses, penstock shells are vulnerable to multiple failure modes. For this reason, the penstock shells should be inspected as often as practicable. During these inspections, pay particular attention to the penstock shape, and both interior and exterior surfaces.

4.1.1 Dimensions and Shape

Measure the physical dimensions and shape of the penstock during an inspection to verify information shown on the design drawings.

4.1.1.1 Alignment

Check penstock alignment to verify substantial agreement with the original design drawings. Penstock misalignment could indicate slope movement and settlement that could cause a penstock rupture if the movements were of sufficient magnitude to allow joints to open.

The inspector should look for signs of misalignment including cracked thrust blocks, ovaling of the penstock, and cracks in the earth surrounding the penstock. Pipe movement may also cause misalignment of bolted sleeve-type couplings. Coupling misalignment can stress the gaskets, resulting in leakage.

4.1.1.2 Ovalization/Out-of-Roundness

Measure the penstock diameter to determine the penstock roundness. Take horizontal and vertical measurements. A certain amount of out-of-roundness may be acceptable. If the measurements differ, indicating ovaling of the penstock, investigate the cause of the ovaling.

Thin-walled penstocks are most susceptible to losing their shape and becoming out of round; however, penstocks with thicker walls can also lose their shape. Some of the most common causes of penstock ovalization are:

1) When normal internal pressures are low and wall thickness calculations have not included the effect of the fluid weight on the penstock shell, the penstock typically will not maintain its shape under normal operating conditions. For low-head sections, the stiffening effect associated with pressurizing the conduit may not be sufficient to offset the weight of the fluid which acts downward to flatten out the pipe.

2) Improper installation of buried or partially buried penstocks can cause the penstock to lose its shape. Typically, either improper compaction or the application of excessive surcharge loads can cause the penstock to lose its shape. Proper compaction from penstock invert to springline is essential for proper installation. Over-compaction at the springline can deflect the penstock sides inwardly, and under-compaction can cause the sides to splay outward. Exceeding the design surcharge or external pressure design loading (e.g., under road crossings) can also result in ovalization of the penstock.
3) Penstock sections that have not been designed for external loads and that are backfilled in soil or encased in concrete can become ovalized.

4.1.1.3 Wall Thickness Determination

During a detailed inspection, assess the structural condition of the penstock by determining the integrity and available wall thickness. A detailed wall thickness survey will allow an accurate structural assessment of the penstock. Take and record penstock shell thickness measurements at selected locations along the penstock. These readings can be taken on the outside of an exposed penstock, eliminating the need for dewatering. A history of these readings may indicate the expected yearly decrease in shell thickness. Shell thickness readings of a buried penstock can be taken from the inside during dewatered periods. Compare these thickness readings to the minimum acceptable plate thickness specified by design criteria to determine if corrective action is needed.

4.1.2 Coatings and Linings

When referring to penstock finishes, a "lining" is a material layer that protects the interior surface; a "coating" is a material layer that protects the exterior surface. Both are equally important in ensuring the longevity of a penstock as they provide a barrier between the penstock substrate and water, soils, or other corrosive materials to prevent corrosion and ensure water tightness. Linings and coatings for penstocks typically are polymer based; common examples include epoxies, polysiloxanes, vinyls, and polyurethanes. Penstock coatings and linings will hide defects or cracks in the steel. Inspectors should look for areas of distress such as cracking, spalling, or missing areas in the coating or lining which could indicate further problems, such as cracks in the base metal. Even small pinholes in a degraded coating or lining allow for concentrated areas of corrosion to occur, pitting the substrate. The presence of rust or stains indicates damaged lining or coating that may no longer be offering adequate protection. Both the coating and lining should be examined to verify that they are protecting the penstock structural material. Detail any significant damage to a coating or lining, noting approximate size, location, and type of defect. Defects and damaged areas can be tracked, and the information used to determine the remaining service life of the coating or lining and help plan for repairs. Common types of damage to penstock finishes can be found in FIST 4-5, *Corrosion Protection*.

4.1.2.1 Repair of Coatings and Linings

The typical method of repairing both coatings and linings include removing the existing coating surrounding the damaged area, preparing the substrate, and applying the new coating. Refer to FIST 4-5, *Corrosion Protection,* for more detail on the selection, preparation, and application practices of new coating systems.

4.1.3 Interior Surfaces

Interior surfaces of the penstock are the most susceptible to physical damage. Therefore, a visual inspection should be regularly conducted. **[Visually inspect interior surfaces for lining**

deterioration, corrosion, and cavitation damage to the best extent practicable. Pay particular attention to rivet heads, welded joints, and bolted connections. Check condition of tie rods and supports at bifurcations. Prepare corroded or deteriorated surfaces by sandblasting or other acceptable means and repaint with an appropriate paint.]

If a detailed inspection is conducted at the required frequency, the above visual inspection should encompass the entirety of the penstock even if rope access is required.

4.1.3.1 Dewatering

Dewatering is preferred for an interior penstock inspection. Caution should be taken when dewatering a penstock because several problems may occur. For instance, if the grout curtain at the upstream end of the penstock is not completely effective or if the penstock has excessive leakage, water pressure can build up behind a tunnel liner or buried penstock. Water pressure on the outside of a buried penstock or tunnel liner could become high enough to buckle the penstock after dewatering. If there is potential for this condition, the penstock can be dewatered slowly to allow the external water pressure to decrease before a problem develops. Another potential problem to be aware of is a clogged vent line (or a closed valve on the vent line) at the upstream end of the penstock. Excessive negative internal pressures could develop when attempting to dewater, which may result in collapsing or buckling the penstock.

If dewatering is not economically or technically feasible, i.e., if the penstock was not designed for this condition, an ROUV may be a feasible method of inspection.

4.1.3.2 Organic Growth

The interior surfaces of the penstock may have become fouled with organic growth over time, thus restricting water flow. Infestations of marine organisms such as freshwater clams, zebra mussels, and quagga mussels are rapidly increasing at Reclamation dams. Left unchecked, growth of these organisms can significantly reduce the hydraulic capacity of a penstock.

4.1.3.3 Corrosion, Erosion, and Cavitation

The degree of erosion, corrosion, and the condition of the lining are important. Turbulent water (typically occurring at discontinuities and bends), high velocity, or scouring caused by abrasive material carried in the water (typically occurring along the penstock invert) can cause erosion or cavitation inside the penstock. Check mismatched surfaces at inside joints to verify their integrity. Corrosion can also occur on the inside of a penstock. Pinhole leaks may occur at any location, although general corrosion and deep pitting is more likely to occur in relatively horizontal penstock regions and in crevices. Look for rust streaks or discoloration, which may indicate penstock deterioration. The extent of wall thinning caused by uniform corrosion and erosion may be difficult to measure visually, so further testing may be necessary to determine the average wall thickness.

Corrosion often found in Reclamation penstocks includes:

General Corrosion: A level of corrosion in which metal loss is relatively even throughout a pipe.

Pitting: A localized form of corrosion where the rate of corrosion has accelerated, thereby creating a pit or hole.

Crevice Corrosion: Form of localized corrosion that occurs at or adjacent to joining surfaces or overlapping surfaces, thereby creating a gap or crevice. Water typically gets trapped inside these crevices, which increases the rate of corrosion.

Galvanic Corrosion: Occurs when two dissimilar metals are electrically connected, causing the less noble metal to corrode. (Carbon/Mild Steel vs Stainless Steel or Carbon Steel vs Brass). This type of corrosion can be mitigated by coating or lining the dissimilar metals.

Erosion Corrosion: Liquid or gas that flows across a surface, removing the corroded material and exposing non-corroded substrate to be corroded. This is an accelerated form of corrosion.

Rust Nodules: Irregular dome shaped structures created from a buildup of corroded material. These appear as a bump in the surface but once removed, leave a crater-shaped pit in the material.

More information on causes of corrosion and corrosion types can be found in FIST 4-5, *Corrosion Protection.*

4.1.4 Exterior Surfaces

Exposed exterior sections of a penstock are generally easier to inspect than the interiors. Exterior coating damage is often caused by excessive exposure to UV light. In some cases, for those penstocks accessible to the public, damage may be caused by vandalism. Preferably, the exterior surface of the penstock is inspected while the penstock is under hydrostatic pressure and in operation to aid in observing leaks. Before starting the inspection, all debris or slides covering the penstock should be removed. Any leakage observed should be investigated and the source identified. Leakage must be evaluated immediately upon discovery by appropriate personnel. Leakage should be repaired at the first practicable opportunity. **[Visually inspect exposed exterior surfaces for deterioration of paint and for corrosion, paying particular attention to rivets, bolts, and welds. Prepare corroded or deteriorated surfaces by sandblasting or other acceptable means and repaint. Steel pipe, where it emerges from concrete, is subject to galvanic corrosion. These areas should be repaired by thoroughly cleaning, sandblasting, and painting with a zinc-rich primer. Look for leakage from gasketed joints such as mandoors or at drain or fill lines.]**

4.1.4.1 Corrosion

Corrosion can occur on the outside of a penstock. Pinhole leaks may occur at any location, although general corrosion and deep pitting is more likely to occur in relatively horizontal penstock regions and in crevices. Also look for rust streaks or discoloration, which may indicate penstock deterioration. The extent of wall thinning caused by uniform corrosion may be difficult to measure visually, so further testing using UT may be necessary to determine the average wall thickness.

4.1.4.2 Localized Buckling

Localized circumferential buckling can indicate longitudinal overstressing of the penstock. This phenomenon only occurs if provisions for penstock expansion and contraction are inadequate. This defect is most commonly caused by thermal changes that affect a section of penstock between two fixed points, such as anchor blocks. This phenomenon is most likely to occur when the penstock has been dewatered and the ambient temperatures exceed the penstock's normal operating temperatures.

Therefore, dewatering of the penstock for prolonged periods must be avoided during the warmest seasons of the year.

4.1.4.3 Voids in Backfill or Concrete-Encased Penstock Sections

For buried or concrete-encased penstock sections, voids may be present in the backfill or concrete. The external pressure from surrounding groundwater in the areas of these voids can cause the penstock shell to partially collapse in the form of an inward bulge.

Voids in backfill are typically caused by groundwater erosion of the backfill material near the invert of the penstock. Prolonged erosion of the backfill can undermine the penstock foundation, leading to differential settlement and potential failure. This type of defect can usually be detected by striking the penstock shell with a hammer at multiple locations and listening for a hollow sound.

Voids in concrete are caused by poor consolidation of the fresh concrete during concrete placement or by the trapping of excess water in the concrete "bleed water" near the penstock invert. Typically, these types of voids are localized and relatively small. However, voids large enough to cause damage to the penstock can occur. The detection of voids in concrete is similar to the detection of voids in backfill.

4.2 Penstock Supports

Penstock supports are a critical component for penstock integrity. Failure of these supports can lead to an overstressed penstock shell which may result in the eventual break of the pressure boundary. **[Inspect concrete supports for cracks, spalling, or signs of movement. Check lubrication of sliding supports and clean exposed bearing surfaces. Check rocker bearing for cracks and evidence of wear. Ensure sliding surfaces are not obstructed and bearing plates are fully seated.]**

4.2.1 Ring Girders

Ring girders, which are used to support long span-elevated penstocks, are constructed by welding steel plate rings to penstocks. All loads are transferred from the penstock to the ring girder and support legs. The support legs are welded to the ring girder, then attached to bearing plates. The bearing plates are attached to a concrete foundation.

Ring girders should be visually inspected for signs of deterioration, distortion, and cracking. Inspection of ring girders should also include the condition of the coatings. The potential for premature coating failure is greater at ring girders than at adjacent smooth penstock surfaces because ring girder surfaces are irregular.

Often, ring girder supports must allow penstock movement caused by changes in temperature. This movement is usually accommodated in bearings located under the support legs. Rocker, roller, and low friction slide bearings are commonly used for ring girder support, Figures 1-3. The bearings should be inspected to verify their integrity and to ensure they are fully seated. There have been instances where a penstock has contracted or expanded enough to force a rocker support beyond its designed range of operation. The rocker supports should be clean and well maintained to allow full penstock movement through the full range of design temperatures. Clean, well maintained bearings will help minimize forces in the penstock and anchorages.

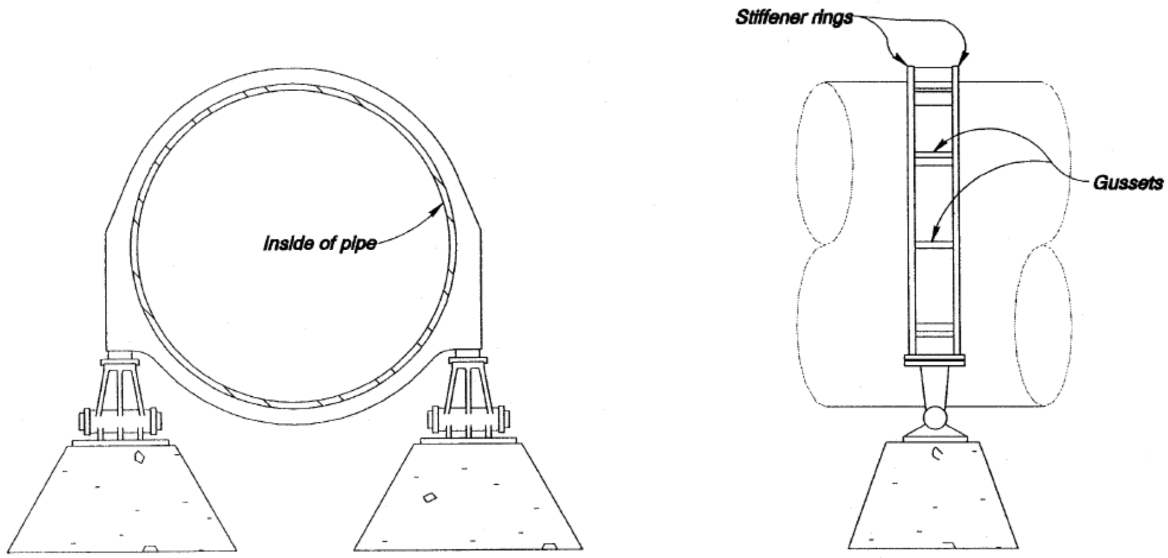

Figure 1. Steel pipe on ring support and rocker assembly.

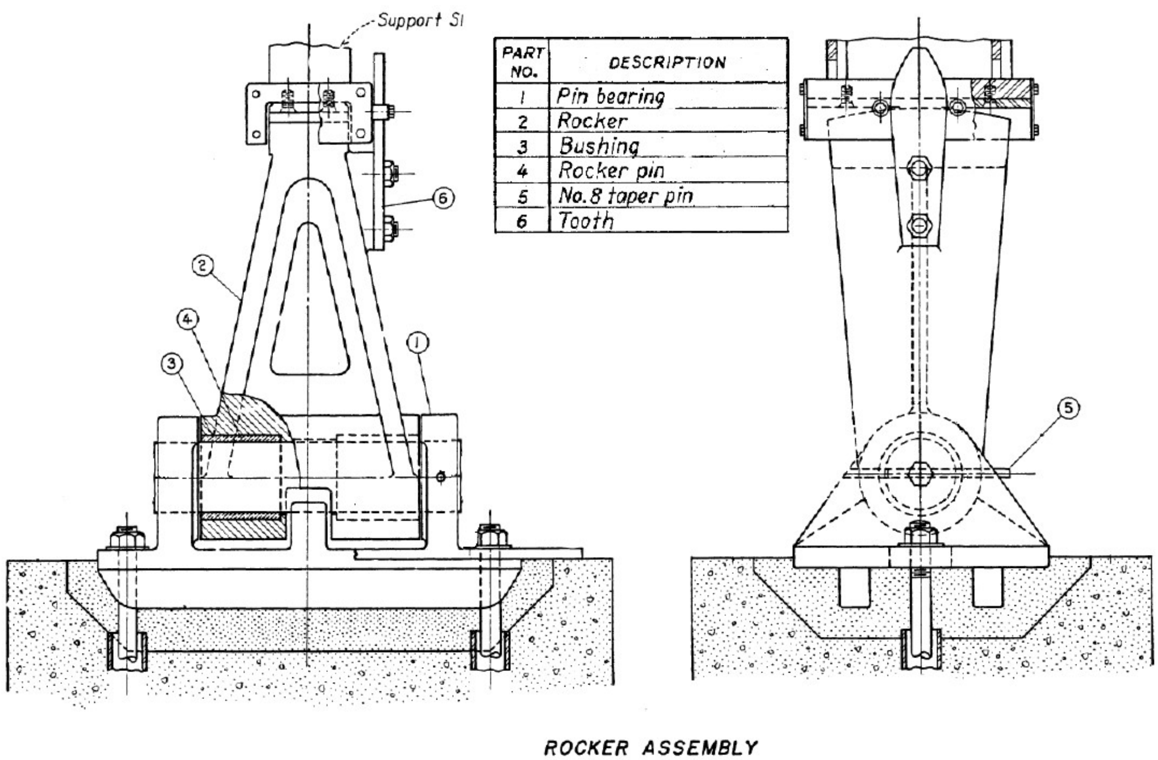

Figure 2. Rocker assembly detail.

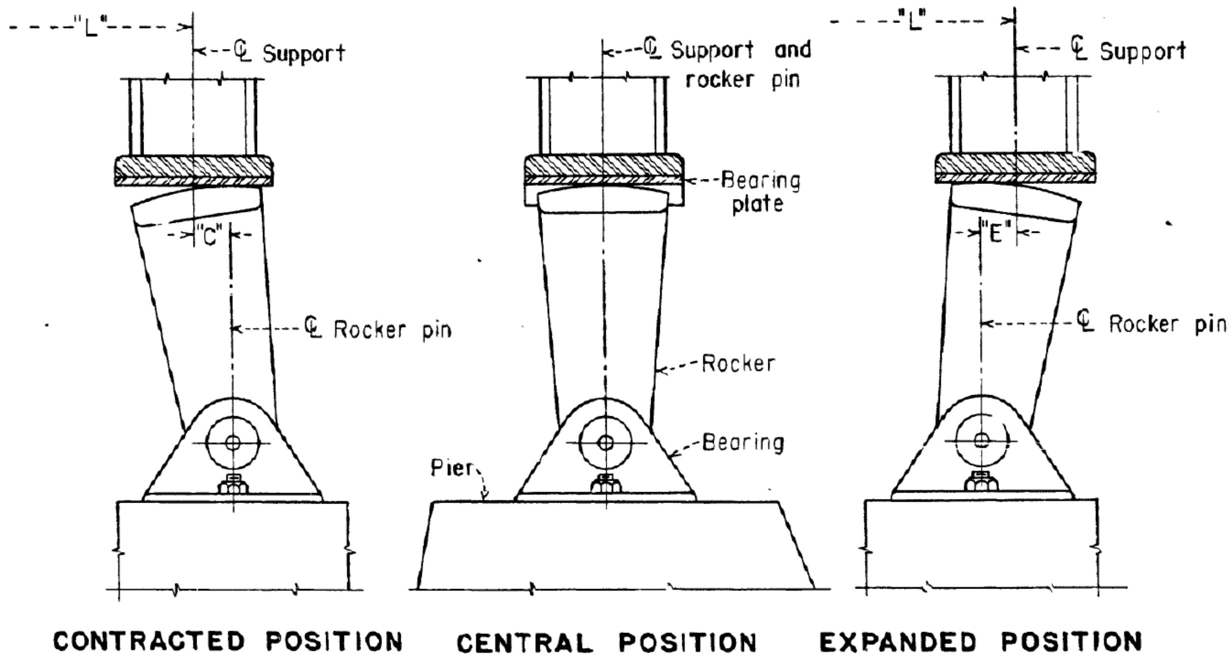

Figure 3. Rocker support motion.

4.2.2 Saddle Supports

Saddle supported penstocks typically span shorter distances between supports than ring girder supported penstocks discussed above. Stress concentrations occur at the tip of the saddle where "horn stresses" result in the penstock shell becoming unsupported. Saddles are usually constructed from reinforced concrete and support the lower 120-degree arc at the penstock invert. However, saddle supports may also be fabricated from rolled steel plate. Sheet packing that may be lubricated with graphite can be used as a cushion between the saddle support and the penstock. The sheet packing also permits limited movement of the penstock relative to the support as a result of temperature changes.

If required, the penstock shell at saddle supports is stiffened by welding steel rings to the shell at each side of the saddle support.

Saddle supports should be inspected for signs of deterioration and areas of high stress. Localized buckling or distortion can occur at the penstock's upper contact points with a saddle support. In addition, the condition of the concrete saddles should be noted and investigated for any signs of settlement or concrete deterioration. Inspection of the surfaces between the saddle and the shell is difficult but important because significant corrosion may be occurring in the contact area.

4.2.3 Anchor/Thrust Blocks

Anchor/thrust blocks are designed to provide restraint to exposed penstocks at changes in alignment. They should be assessed to verify their support function has not been compromised. Thrust blocks should be examined for signs of settlement, movement, and any cracking or spalling of concrete.

4.2.4 Stiffener Rings

Penstock stiffener rings are used along the circumference of penstocks to increase the strength of a penstock's shell from internal pressures. These are often steel plate, angle, T-bar or I-beam welded to the penstock shell exterior. Look for flawed welds (including undercutting), base metal flaws, and heavily corroded areas.

4.3 Joints

4.3.1 Unrestrained Joints

The two most common types of unrestrained joints at Reclamation facilities are expansion joints and bolted sleeve-type couplings. Typically, these joints require little maintenance; however, water leaking past the seals or the joint becoming seized are both symptoms of an ineffective joint and corrective action should be taken. **[Check for leakage past packing and tighten as necessary. Clean rust and scale from sliding surfaces as required.]** Check these joints for loose or missing bolts, cracked welds, base metal flaws, and areas of heavy corrosion.

4.3.1.1 Expansion Joints

The main problem found on expansion joints is leakage. Causes of this include packing material dryness or deterioration, loosened gland bolts, or joint misalignment, Figure 4. Leakage past the packing material can lead to erosion and corrosion of the gland sleeve. Promptly correct any leakage past an expansion joint. To eliminate leakage, first retighten gland bolts. If leakage persists, replacement of packing may be necessary. Following is a brief procedure of how to complete an expansion joint repacking:

1) Unwater pipe.
2) Remove outside gland nuts.
3) Turn pushoff nuts to move gland out.
4) Remove old packing and clean packing box.
5) Install new packing.
6) Fit around pipe and cut square to the exact size, then grease well.
7) Tamp in each ring individually.
8) Stagger packing seams at 90 degrees.
9) Push gland against packing, lubricate bolts and replace corroded bolts.
10) Finger-tighten nuts against gland (Measure at 90 degrees to make sure gland is not cocked).
11) Wrench-tighten bolts to 10 ft-lbs.
12) After refilling pipe, check for leaks.
13) If it leaks, tighten to 25 ft-lbs.
14) If leak continues, tighten in 5 ft-lbs. increments to a maximum of 60 ft-lbs.

Overtightening of the gland bolts in an effort to stop joint leakage is a common problem associated with expansion joint maintenance. Overtightening the gland bolts compresses joint packing to a point of ineffectiveness and may distort the gland ring. Avoid this when maintaining these joints. Consider total replacement of the expansion joint if an inspection reveals significant thinning of the gland sleeve or deterioration of the packing box bearing surfaces that is beyond repair.

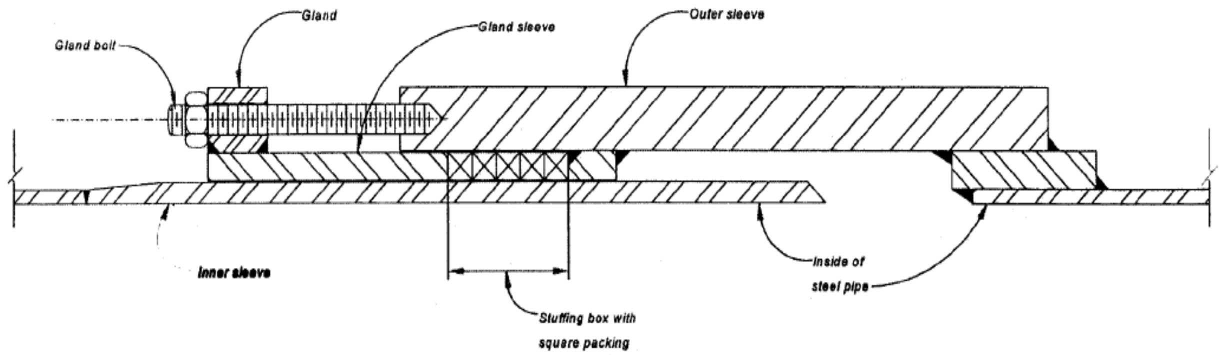

Figure 4. Cross section of expansion joint.

4.3.1.2 Bolted Sleeve-Type Couplings

Leakage in this type of joint can originate from a blemish in the middle ring, the gasket bearing surface of the middle ring, the shell, or a worn-out gasket, Figure 5. Most of the time, these leaks are caused by shell corrosion, which inhibits proper joint motion. Inspection of the bolted sleeve-type coupling sealing surfaces and gasket is possible by disassembling the joint.

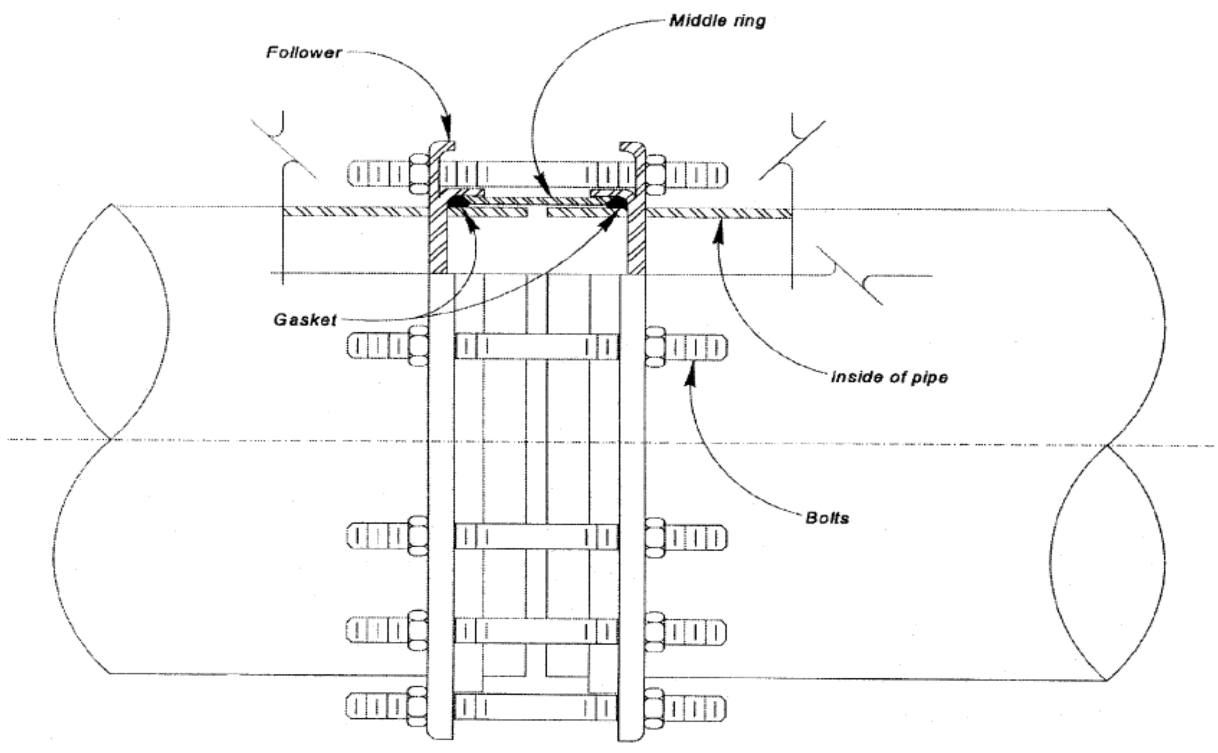

Figure 5. Sleeve-type coupling.

4.3.2 Restrained or Fixed Joints

Some basic types of restrained joints include lap welds, butt welds, flanges, butt straps, and various rubber-gasketed joints, Figure 6. Several methods used to attach these types of connections include rivets, forged welds, and arc-welds. Corrosion, erosion, and flaws in the original construction can affect the condition of structural welds, bolts, and rivets in the penstock.

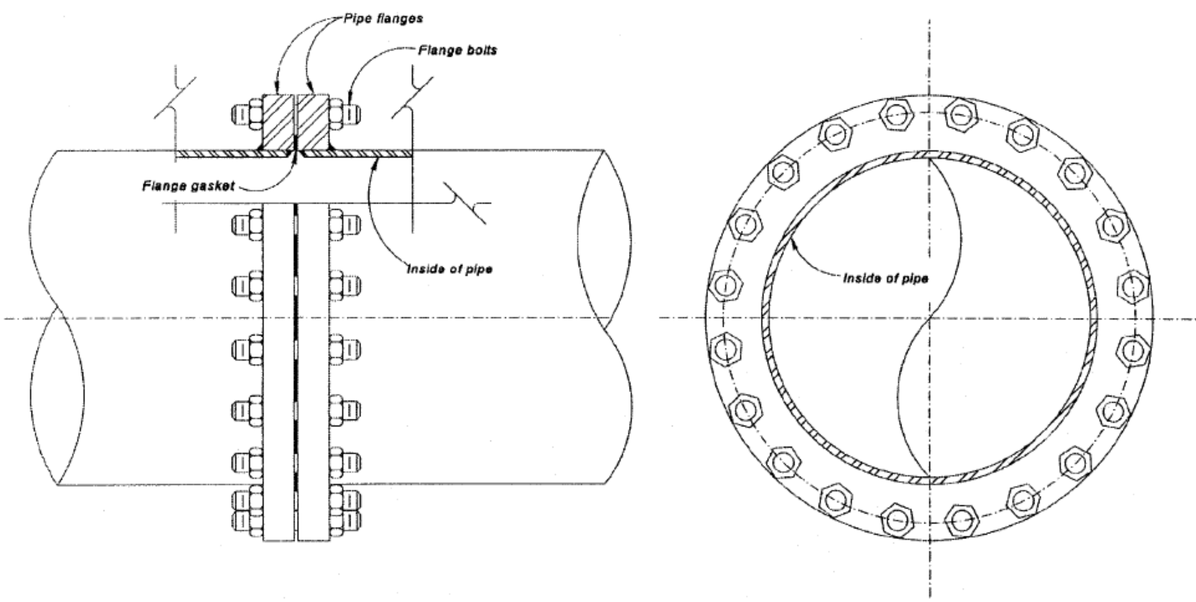

Figure 6. Flanged joint.

4.3.2.1 Riveted Joints

In riveted joints, examine the rivet head, butt strap, plate, and caulked edge conditions, Figure 7. Look for leakage past the rivets or the edges of the bands. Rivets may be missing, broken, or may have corroded or abraded heads. The base metal may also be corroded to the extent that rivets can pull through and be ineffective.

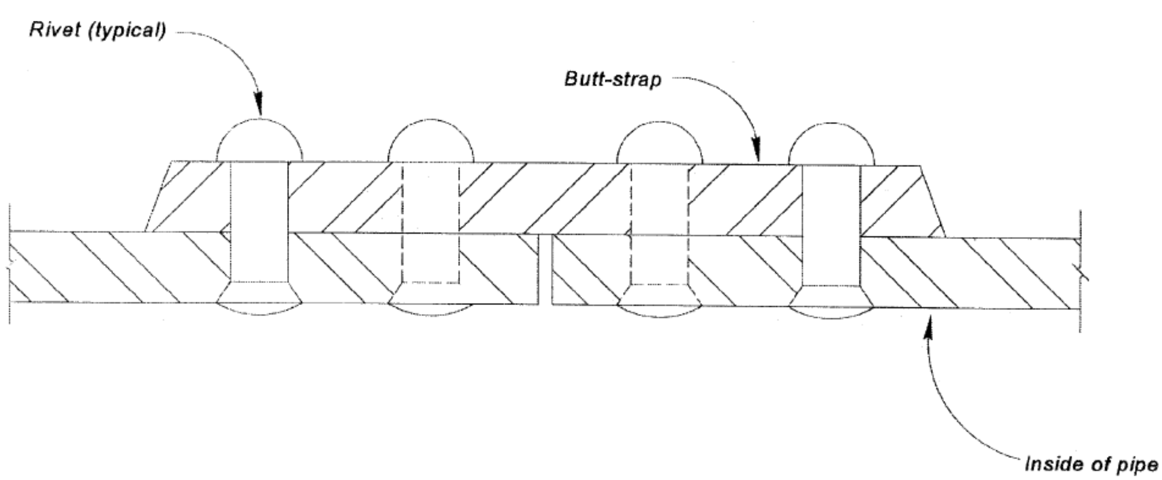

Figure 7. Riveted butt-strap.

4.3.2.2 Forge-Welded Joints
Forge-welded joints have historically been unreliable. Flaws and other fabrication defects, such as lack of fusion and slag, may be prevalent. The welding process used in forge-welded penstocks, in which the steel is heated to about 2000°F, reduces the carbon content, which makes the steel more susceptible to corrosion. As a result, if forge-welded joints are not well protected, corrosion may occur faster in the joints than in the base metal.

4.3.2.3 Welded Joints
A representative portion of all structural welding performed on the inside and outside of the penstock should be visually examined for signs of rusting, pitting, or other structural defects. For welded joints, look for cracked base metal or welds, surface flaws, etc., Figure 8. Flaws in welds during construction can occur from a high carbon content base material, embrittlement of the heat affected zone, improper preheat, and improper rate of cooling after welding. Typically, these problems are more likely to occur in thicker plating or when the joint is made under adverse construction conditions.

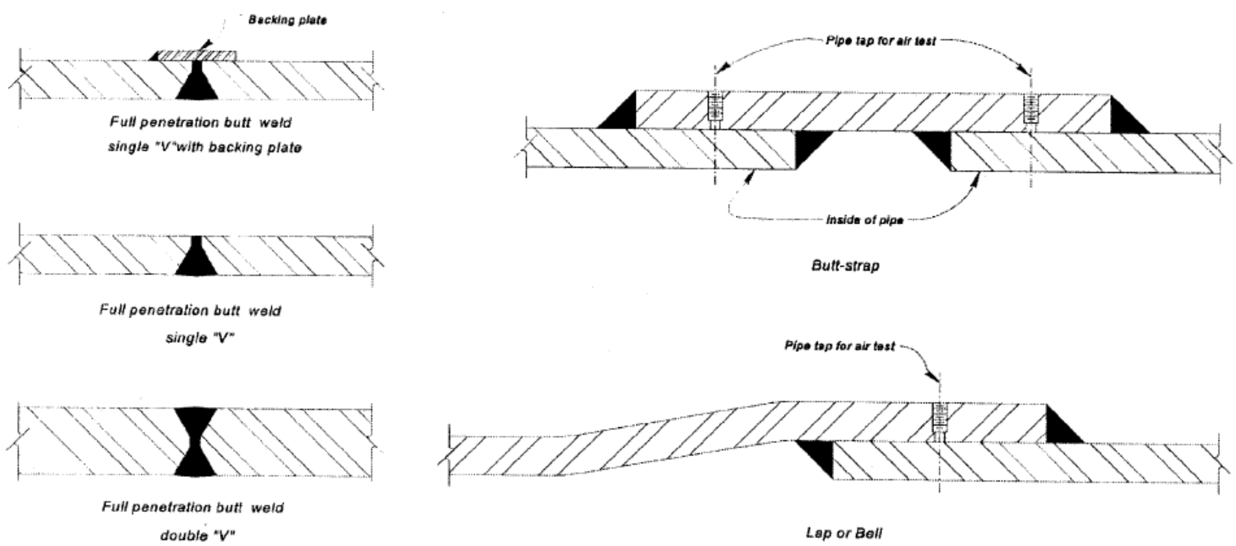

Figure 8. Welded joints.

4.4 Appurtenances

Appurtenances, which include bifurcations, Figure 9, transitions, bends, tees, elbows, and reducers, may be particularly susceptible to vibration, aging, and lining loss. Look for damage to the lining, cracked welds, loose or missing rivets, damage from cavitation, broken tie rods, and heavily corroded areas. Casting defects, which include porosity, cracks, slag, and sand, may also be present.

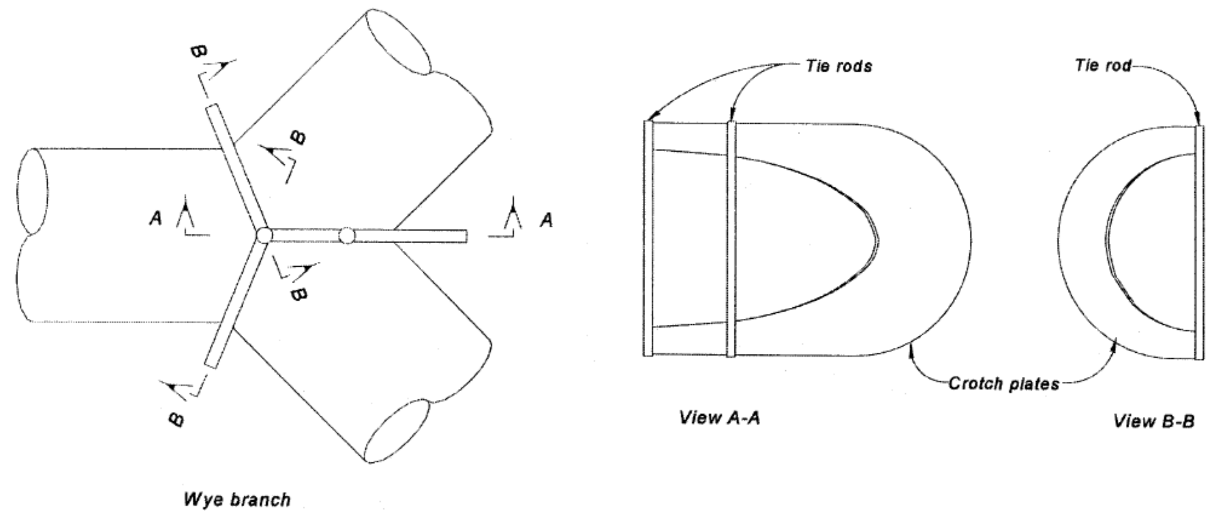

Figure 9. Wye branch with reinforcing crotch plates.

4.5 Penetrations

Penetrations include items directly attached to the penstocks and exposed to the internal pressure carried by the penstock. Some examples of penetrations are manholes, air vent connections, filling line connections, etc. Look for damaged or missing parts, cracked welds, cracked or broken castings on valve bodies, broken or missing bolts and rivets, heavy corrosion, and leakage from gasketed joints, packings, flanges, couplings, and manholes. Check the surface of all penetrations for distortions, cracks, and other defects, paying particular attention to the welds or riveting used for attaching such parts and their reinforcement.

4.5.1 Drains

Penstock dewatering drains, typically located at low points along the penstock profile, should be examined to verify that they are in working condition and are not leaking. Inspect the integrity of drain grates, which prevent large chunks of debris from clogging drain internals. Examine the valves that control these drains. Overtightened packing gland bolts could lead to bolt failure and packing gland rupture. The drains must safely discharge water away from the penstock to prevent undermining of the penstock foundation during dewatering.

If possible, check drainage systems for penstocks that are located in tunnels to verify proper operation. Drainage systems that are installed to relieve water pressure against the penstock, thus protecting the penstock from possible collapse, can become blocked over time. Blockage consisting of debris or waterborne minerals such as rock fines or calcium can render the drains ineffective. Maintain and clean the drains on a regular basis.

4.6 Operating Equipment

Penstock operating equipment includes standpipes and vent pipes, surge tanks, gates, and valves, including bypass valves, filling valves, shutoff valves, piezometer taps, and air valves.

4.6.1 Standpipes and Vent Pipes

Standpipes and vent pipes are usually located at high points along the penstock profile and immediately downstream from gates. They should provide an unrestricted air inlet or air release to the penstock. In cold climates, the pipes should be inspected for ice blockage. Standpipes and vent pipes should be inspected regularly to verify they have not become blocked.

4.6.2 Surge Tanks

Surge tanks are installed to limit pressure rise and fall in penstocks. Surge tanks are fabricated of steel plate, wood, or reinforced concrete.

Surge tank assessment must consider the type of surge tank, condition of tank coatings and linings, and tank mechanical appurtenances. Surge tanks often have roofs and vents that can become blocked similar to standpipes. Note the condition of the ladders, handrails, grating, and other surge tank access equipment.

4.6.3 Gates and Valves

Gates are normally provided to shut off water flow to the penstocks and are usually located at the upstream end of the penstock. Penstock installations incorporate many different types of gates to control flow into the penstock.

Because most gates are of steel construction, assessment techniques used for inspection of steel penstocks may be appropriate. Inspectors should pay attention to the condition of the coatings. Gate seals, which are often fabricated from rubber but can also be fabricated from alloy metals, will wear out over time. Note and document the condition of the seals and the amount of leakage past the emergency gates while in the closed position.

Bypass, filling, and shutoff valves are often installed in penstocks for the purpose of filling, dewatering, or redirecting flows. Butterfly, globe, and gate valves are typical for bypass and shutoff applications. In addition to coating condition, assessment should include the condition of the valve operators, packing glands, and moving and stationary parts that may experience wear.

4.6.4 Piezometer Taps

Piezometer taps are typically located in the penstock several pipe diameters upstream from the turbine and are used to measure flow. The taps, which are often forged steel pipe couplings less than 1-inch in diameter, are welded through the penstock shell; four taps located 90 degrees apart are common. The taps are often equipped with petcocks or gate valves and are connected by copper tubing to a flow measuring location in the powerhouse. Assessment should include verifying that the piezometers are not blocked and that the taps, tubing, and valves are not leaking. Often, piezometers have been removed and plugged. Check these to ensure excessive corrosion and leakage does not exist.

4.6.5 Air Valves

Air and vacuum release valve assemblies are installed along the penstock to vent air to and from the penstock under service conditions and during penstock filling and draining. To permit isolation and servicing, air and vacuum relief valves are normally equipped with a ball, gate, or butterfly shutoff valve. Malfunctioning of these air valves could result in penstock rupture if, for example, they are installed to mitigate transient pressures. Thus, assessment of air and vacuum release valve assemblies must verify they are not plugged, restricted, or leaking, and that they are operating properly and are in good working condition. In cold climates, the valve should be protected from freezing. Where employed, heaters should be operational.

4.7 Vibration

Penstocks should be assessed for both flow-induced and equipment-induced vibrations. Resonant vibrations can cause material fatigue and may cause penstock problems if not corrected. The penstock should be inspected while operational, and operators or maintenance personnel should document abnormal vibration. If excessive vibration appears to exist, instrumentation should be used to record vibration frequency and relative amplitude.

4.8 Geotechnical Considerations

Frequently, vegetation growth and changes to the area adjacent to the penstock alignment affect the penstock and its foundation. Drainage can become restricted. Adjacent soil and rock slopes that move or settle can cause foundation failure in the form of cracking or movement. Collect topographical and alignment information.

The inspector should note the types and locations of penstock joints and any noticeable misalignments. Span distances and ground elevations between penstock supports should be checked and compared with the as-built drawings. Frequently, joint leakage, distortion, or misalignment can indicate other problems that might require further field and analytical evaluation.

Assess penstock foundations and supports for deterioration and movement. Foundation movement may cause structural distress along the penstock itself. For example, foundation settlement can overstress steel penstocks with welded steel joints that are supported by steel ring girder foundations.

4.8.1 Ground Movements

The ground immediately surrounding the foundations should be evaluated for signs of distress or movement relative to the foundation. Evidence of ground movement or distress includes cracking, slumping, or vertical displacement of the ground. Concrete slabs or shotcrete applied on the ground provides excellent indications of tensile or shearing movements. Paint lines that do not match the edge they were originally applied against or ground that pulls away from foundations may indicate settlement, shrinkage, or heaving. Check foundations to ensure that surfaces have remained level or plumb. Buckling metal structural elements or spalling concrete can indicate excessive loads caused by movements of the penstock foundations.

In rocky areas, look for open joints, unstable blocks of rocks, shear zones, or rock that exhibits severe weathering. Freshly exposed rock will have a different color than the surrounding rock. Displaced rock or soil at the bottom of slopes indicates unstable or eroding formations on the slope above. Look for deformation or leaning of retaining walls.

The evaluator should look for changes in the ground surface near the penstock that have occurred since construction. A variety of factors could cause these changes. Ground excavation near the penstock foundation could cause permanent deformation, even if the excavation was properly backfilled. Erosion of soil from around footings may undermine them and cause failure.

New construction or surcharging nearby may cause increased loads to the penstock foundation. Appurtenant structures that have been hung from the existing foundations or parallel penstocks that have been constructed in close proximity to the penstock will add loads to the bearing material.

4.8.2 Water-Related Effects

The effects of water on the foundations or the surrounding ground should be noted. Signs of piping, subsurface erosion, or ground collapse include slumps and cracks or craters with eroded edges that appear to have had water flowing into them. Unchecked erosion could destabilize the foundation. Look for seeps, springs, and areas that are continuously wet or support water-loving plants. Leakage from the penstock may have caused these wet areas. On slopes, these wet areas indicate barriers to flow or the high groundwater levels that are often associated with landslides.

Often, drains may be installed to dewater slopes that have potential stability problems. Monitoring the flows from these drains will indicate their effectiveness at intercepting groundwater and controlling its level within the slope. A stopwatch and a measured volume container, such as a bucket, provide the simplest way to measure flow from a drainpipe. When flows from individual drains cannot be measured, the flows can be collected on the ground and monitored at a common weir. Weir flows are determined by measuring the height of the backwater behind the weir and calculating the corresponding flow for the type of weir. This measurement is done most simply with a staff gage placed in the backwater. Weirs can also be automated by placing a pressure transducer in the backwater.

Where slope stability problems exist, changes in the water level within the slide mass should be correlated to other measurements of the slide movement. Year-to-year comparisons of piezometer readings will indicate changes in overall groundwater levels and response times to precipitation events. An overall rise in groundwater level may indicate drain system failure or an increase in the amount of leakage into the slope. These changes may also indicate plugged piezometers.

4.8.3 Surrounding Slopes

A thorough geotechnical examination will also consider the slopes surrounding the penstock. Slopes above the facility should be inspected for possible rockfalls or landslides that could damage the penstock. Large slope movement features are often difficult to discern from the ground. Aerial flyovers with drones or inspection of aerial photographs may be useful. Recent advancements in photogrammetry allow users to survey slopes and quickly analyze them for changes from previous surveys. Unstable slopes are often barren of vegetation or have younger vegetation than the surrounding slopes. They may exhibit fresh scars or head scarps where materials have moved downslope. Slowly moving ground will often have rock strata that bend downslope or tree trunks with bottoms that curve upward. Evidence of small rockfalls includes dents on metal, spalls on concrete structures, and material piled on the uphill sides of structures.

4.8.4 Rock and Soil Tension Members

The exposed ends of rock and soil anchors should be inspected where possible. The anchor metal may corrode with time. Suspected corrosion calls for load testing or exposure of bolts for inspection. In soil and in certain weak rock formations, deadmen or anchors under constant load can creep, allowing the foundation to move. Tensioned anchors with free, unbonded portions may be tested to determine if the locked-in load has changed since construction and to verify the design capacity.

4.8.5 Tunnel Portals

Inspect the exposed section of the penstock where it enters or exits tunnel portals. This penstock section can show signs of corrosion and local stress concentration.

5.0 Deficiency Analysis Methods

Information obtained during the visual inspections are used to plan other analyses. Based upon this information, the base material and welds of certain components may require examination with appropriate NDE techniques. Destructive testing methods may be required in some instances but should be avoided if possible. The following section details the known methods available to analyze common deficiencies.

5.1 Penstock Shell

A reduction in wall thickness is usually attributed to uniform corrosion, localized corrosion or pits, cavitation at sharp boundary edges, or scour/abrasion via hydraulic transport of sediment. Corrosion and pitting can occur on exterior or interior surfaces and can be caused by chemical or microbiological-induced corrosion. Often, corrosion will form where a coating or lining system has failed. These areas should be inspected closely to determine the severity of material loss and depths of possible pitting. **[Conduct an ultrasonic thickness survey of the penstock shell and calculate maximum bound wall-loss. Use this data to complete pertinent stress analyses to ensure penstock integrity.]**

During a detailed inspection, in addition to a basic inspection, an inspector should perform an ultrasonic thickness survey and stress analysis of the penstock shell to ensure corrosion has not significantly impacted the penstock's integrity. From this data, a baseline wall thickness survey can be established, and the associated stress levels in the pipe shell can be determined and compared against the original design criteria and acceptable safety margins.

5.1.1 Ultrasonic Thickness Survey

An ultrasonic thickness survey is used to gain an understanding of the general condition of a penstock shell by calculating the average wall-thinning occurring on a penstock substrate. It is unlikely to reveal localized defects such as pinhole leaks. Localized defects are typically found during the visual inspection.

Depending on the length and diameter of the penstock, a set of 5 to 10 ultrasonic thickness readings are typically taken every 10 to 30 feet on the invert of the penstock. These readings can be taken from the interior or exterior of the penstock. Reference historical penstock reports for details and locations of previous shell thickness surveys. This data is compared to the nominal shell thickness readings on the as-built drawings. A maximum wall loss percentage is then calculated to be used for the stress analysis.

5.1.2 Coatings and Linings

If the integrity of a coating or lining system is undeterminable from a visual inspection, quantitative measures for testing the covering's thickness, adhesion to the steel substrate, and the barrier properties can be tested with the following techniques:

1) **Dry Film Thickness -** A dry film thickness test is a non-destructive test that can be used to determine the thickness of a coating or lining on a metallic substrate. This test is useful to

determine if the finish is thinner in certain areas of the penstock, implying erosion is affecting the coating or lining.

2) **Tensile Adhesion Test -** A tensile adhesion test is a destructive test that can be completed to determine the force at which the coating or lining will break off its substrate. Test many locations to get a good representation of the overall coating or lining adhesion.
3) **Electrochemical Impedance Spectroscopy -** EIS is non-destructive test that can be performed on coatings or linings to quantitatively evaluate the covering system's barrier properties. It measures a coating's or lining's impedance value to an electrical charge in order to estimate the permeability. This test provides data that can be used to determine how well a coating or lining is protecting the substrate and if corrosion is occurring underneath.

Coating and lining defects are commonly combated by applying a new coating/lining system. Depending on the extent of damage to the existing system, this could mean repairing areas as small as one square foot, partial relining, or full relining of the penstock. This process is completed by removing the old coating or lining system, cleaning the penstock substrate, ensuring all corrosion has been removed and the surface is clean, then applying the new coating/lining system to the affected area. Coal tar enamel, a common and effective lining used in many older penstocks, is no longer a viable option due to environmental concerns. The TSC has dedicated many years of research into finding the best lining product on the market. When selecting a product to repair a lining or coating, consult the TSC's Materials and Corrosion laboratory group for the most up-to-date information.

5.1.3 Cracks

Cracks develop at areas of high localized stress because of inherent material, weld defects, or excessive loading. Once formed, certain types of cracks tend to propagate because of in-service conditions. Factors such as chemical composition, material properties, fracture toughness, crack geometry, and applied loading (frequency) determine whether a crack will propagate. To determine if repairs are required or even possible, perform both a fracture mechanics and a metallurgical evaluation. The following NDE techniques may be used to evaluate cracks or discontinuities in the base material or welded joints of the penstock shell and its various components:

1) **Liquid Penetrant Examination (PT) -** Used to detect small flaws such as cracks and pores that are open to the surface of the material being inspected.
2) **Magnetic Particle Examination (MT) -** Can detect cracks, porosity, seams, inclusions, lack of fusion, and other discontinuities in carbon and low alloy steels.
3) **Radiographic Examination (RT) -** Used to detect porosity, inclusions, cracks, and voids in the interior of castings, welds, and other structures. An RT provides a permanent film record of defects that is easy to interpret but is limited by the direction of the discontinuity and its accessibility, and the film process is very slow and expensive.
4) **Ultrasonic Examination (UT) -** Used to detect surface and subsurface discontinuities. UT allows very accurate detection, location, and mapping of discontinuities within base material, welded joints, and heat affected zones, and can locate internal flaws not discoverable by other NDE methods.

5.1.4 Material Properties

Often, particularly for older penstocks, a penstock shell material with unknown composition may require evaluation or repair. This evaluation may require that a sample be taken from the penstock and taken to a laboratory for analysis. Tests can be performed to determine the chemical composition, weldability, tensile properties, and toughness of the material.

5.2 Penstock Supports

The components and welds associated with ring girder and saddle supports can be examined with various NDE techniques. If corrosion is occurring, UT can be used to help determine the amount of sound metal path remaining.

Radiographic examination can be used to evaluate interior pitting or plate/weld cracking and corrosion between the penstock shell and concrete saddles. The film must be placed between the steel and the concrete, and the radiographic source must be placed on the other side of the penstock. The penstock must be dewatered; otherwise, exposure time becomes excessive.

5.2.1 Concrete Anchor/Thrust Blocks

NDE techniques can be used to further evaluate the condition of concrete anchor and thrust blocks as well as concrete penstocks. The following techniques may be considered.

5.2.1.1 Direct Measuring Techniques

Direct measuring techniques can be used to determine the compressive strength of concrete or to locate steel reinforcement within the concrete.

Devices that measure compressive strengths of concrete record the impact or energy applied to the surface of the concrete and relate that value to the compressive strength of the concrete. Available methods include:

1) **Schmidt Hammer Technique -** A Schmidt hammer consists of a spring driven plunger that strikes the surface of the concrete and records the rebound of the plunger, which is related to the compressive strength of concrete on a built-in scale on the hammer side. This instrument is best used to quickly determine the uniformity of in-place concrete. The accuracy of the measurements improves with calibration against compression tests of drilled core samples. The test method is governed by ASTM C805 and the procedure is described in ASTM D5873.
2) **Windsor Probe Technique -** The Windsor probe uses a gun that drives a probe into the concrete and produces a specific energy. The protruding ends of three probes driven at a particular location are measured and related to the compressive strength of concrete. The test method is described in ASTM C803.
3) **Reinforcing Steel Locators -** Small, hand-held, electromagnetic indicators have been used to locate reinforcing steel within concrete. The meters can determine the amount of cover over reinforcing steel and the bar size within an accuracy of one bar.

5.2.1.2 Indirect Measuring Techniques

1) **Sonic/Seismic Technique -** The sonic/seismic technique applies an energy source (impact) to the surface of the concrete. Sensors record the values of the compression and shear wave velocities resulting from the impact at designated intervals. The resulting measured waves are used to determine the dynamic elastic properties, Young's modulus of

elasticity, bulk modulus, and Poisson's ratio. Competent concrete has high compression and shear wave velocities. Low velocity values indicate cracking, deterioration caused by weathering, and other defects.

2) **Ground Penetrating Radar Technique -** Ground penetrating radar uses an electromagnetic pulse and an antenna to receive echoes from the pulse. The technique is capable of detecting water concentrations in delaminations, cracks, and voids within a concrete lining, reinforcing steel, or other steel locations.
3) **Electrical Resistivity Technique -** Electrical resistivity measurements can be made in concrete by introducing a current through two electrodes and measuring the potential drop across two other electrodes. Vary the configuration of the electrodes and spacing to produce the best information. Profiling resistivity measurements is advantageous for evaluating the relative quality of the concrete. Unwatered concrete penstocks can be inspected by electrical resistivity techniques to define cracks that have higher water content caused by leakage.
4) **Destructive Examination -** If the quality of the concrete is questionable, destructive testing may be required to gather more data. Concrete cores can be cut from selected locations to obtain representative samples of the suspect material. Strength tests can be made on the cores, or the cores can be examined by a petrographer. From microscopic analysis and various chemical tests, a petrographer can determine the air content of hardened concrete, estimate the cement content, find evidence of carbonation or other reactions, and detect admixtures or contaminating substances that may have been present during construction. A petrographer may also make general observations about the water-cement ratio, degree of cement hydration, early frost damage, excessive bleeding, and similar phenomena.

5.3 Joints

5.3.1 Unrestrained Joints

The two most common types of unrestrained joints at Reclamation facilities are expansion joints and bolted sleeve-type couplings. NDE techniques such as an UT thickness measurement can be used to verify the integrity of unrestrained joints, such as expansion joints and bolted sleeve-type couplings.

5.3.1.1 Expansion Joints

UT can be used to take thickness measurements of the expansion joint inner sleeve, outer sleeve, and gland sleeve to determine if any wall thinning has occurred. A stress analysis can then be performed to determine if wall thinning has compromised the design strength of the expansion joint. **[Perform a thorough inspection of expansion joints and document results in a penstock inspection report. Thoroughly clean packing area and sliding surfaces and install new packing if required.]**

5.3.1.2 Bolted Sleeve-Type Couplings

UT can also be used to take thickness measurements of the sleeve-type coupling middle ring to determine if any wall thinning has occurred. A stress analysis can then be performed to determine if wall thinning has compromised the design strength of the sleeve-type coupling.

5.3.2 Restrained or Fixed Joints

Accurate determination of joint efficiency is critical to stress analysis. Causes of reductions in joint efficiencies can be characterized by the type of joint or connection. The most common connections and associated problems are described below.

5.3.2.1 Riveted Joints

Design joint efficiencies for riveted connections usually range from 46 to 95 percent. Reductions in design joint efficiency or, conversely, an increased stress distribution across the joint, can be caused by improper installation of the rivet or corrosion of the rivet shanks. Scour or abrasion of a rivet head indicates a loss of plate thickness. UT can be used to help determine plate thickness of bands and to evaluate rivet shanks. Destructive testing methods may be required to determine the true tensile properties and efficiencies of riveted connections.

5.3.2.2 Forge-Welded Joints

Problems with forge-welded joints include variable joint efficiency and accelerated joint corrosion. To verify the efficiency of a forge-welded joint, "coupons" may be removed and tested. From these data, an acceptable joint efficiency can be determined and used to ascertain the necessity of repair or replacement schemes. If tested joint efficiencies are low, a fracture mechanics evaluation can be performed to demonstrate that certain flaw sizes and orientations are acceptable for the service operating loads. In addition, if the design steel specification is unknown, a metallurgical evaluation must be performed to determine the material's chemical composition and ascertain if weld repairs may be appropriate.

5.3.2.3 Welded Joints

Typically, joint efficiency for welded connections is established during the original design phase. The joint efficiency will vary depending upon the NDE technique used to evaluate the welds. Any of the NDE techniques discussed at the beginning of Section 4 may be used to evaluate possible defects in the welded joint.

5.4 Casting Defects in Appurtenances

Old steel castings are typically associated with penstock elbow, tee, transition, and wye branch sections. Casting defects range from superficial lineation and blemishes to structural defects, such as cracks associated with shrinkage during cooling near discontinuities, inclusions of foreign material in the casting, and poor chemical or crystal grain structure. UT or RT techniques may be useful in evaluating discontinuities associated with casting defects.

5.5 Penetrations

UT may be used to determine the actual thickness of the reinforcement pads. Other NDE techniques may be used to examine the welds.

5.6 Vibration

If vibration is occurring, a vibrometer or accelerometer can be used to measure the vibration frequency of the penstock. The deformations associated with the vibration of the penstock can be monitored using strain gauges to determine the incremental dynamic stress changes created between peak amplitudes of circumferential deformation in the radial direction. In addition, the maximum peak radial deformations should be located and measured for evaluation purposes. Vibration is considered excessive when the associated incremental dynamic stress exceeds 20 percent of the design stress or when the amplitude of the measured radial deformation exceeds D/1000, where D is the penstock internal diameter in inches. Consider remedial measures when excessive vibration is present. As an alternative to remedial measures, a fatigue assessment, as described in ASME Code Section VIII, Division 2, is recommended.

5.7 Geotechnical Considerations

Evidence of foundation failure or slope movement requires a more detailed geotechnical investigation to determine the nature of the problem and a range of possible solutions. A detailed geotechnical investigation may require soil or rock borings, laboratory testing of the soil or rock, geophysical surveys, an instrumentation program, and detailed geologic mapping. Gradual downslope movement or settlement may require a long-term monitoring program to determine the extent and rate of deformation occurrence.

Positive identification of a slope stability problem under or near a penstock usually requires determining the volumetric extent of the sliding mass and the rate of movement. An inclinometer is most commonly used to make this assessment. The inclinometer measures the changes in inclination of a cased boring that extends through a slide mass. Inclinometer casings are normally read manually, but in-place accelerometers allow automatic monitoring. The three-dimensional nature of inclinometer data hinders interpretation of the results. Experienced personnel should evaluate the results of inclinometer readings.

Extensometers, tiltmeters, and surveying can also be used to monitor slope movement. Because groundwater often has a significant impact on slide movements, piezometers may be installed in a suspected slide mass to monitor the piezometric level.

Evaluators should monitor geotechnical instrumentation on a regular basis. The time interval between readings should be based upon the rapidity with which the measured physical phenomenon will change and its importance to penstock integrity.

Instruments used to make readings must undergo regular calibration against known standards. This calibration is particularly important for long-term monitoring because present readings may have to be compared to future readings made by different instruments.

The rates and timing of the movement of the slide mass, as determined from the instrumentation program, can often provide clues to the sliding mechanism. Sliding that occurs at a nearly constant rate throughout the year probably indicates a creeping movement controlled primarily by slope geometry and gravity. Periodic movements, especially if they coincide with periods of high precipitation or high groundwater, may indicate transitory groundwater level as a major contributor to the sliding.

Normally, for most soils, the structure settlement rate peaks immediately after construction and decreases with time. Cases where settlement rate remains constant or increases with time may require an assessment of the foundation conditions to determine the cause(s).

Slope movements that accelerate with time often indicate incipient, large scale failure. The potential impact of such movements on penstock integrity requires immediate evaluation.

6.0 Stress Analysis

Once the basic and detailed assessments have been completed and all the pertinent data obtained, a qualified individual with substantial experience in analyzing and designing penstocks or pressure conduits should perform a penstock evaluation that includes the following analyses:

1) Lower bound allowable stress determination.
2) Lower bound wall thickness determination.
3) Lower bound joint efficiency determination.
4) Maximum pressure at critical locations determination.
5) Stress analysis of related penstock components (shell, joints, supports, anchor blocks, etc.).
6) Safety factor determination.

The results of these analyses should be presented in a formal penstock inspection report for the facility records.

7.0 Penstock Inspection Report

Whether conducting a basic or detailed penstock inspection, an inspection report will enable a facility to track the degradation of a penstock and its components over time.

Establish a log at each plant to record the date, type of inspection performed, and results of all inspections performed on penstocks. Forward inspection results to the engineering staff or other appropriate personnel for review and evaluation. A documented chronology of inspections, results, evaluations, and repairs is essential for the proper maintenance of safe penstocks and will help identify the development of any adverse trends. Photographs taken of damaged and repaired areas will provide future inspectors references for comparisons.

One or more inspectors should prepare an inspection report. The report will document the following items:

1) Dates of inspection.
2) Inspectors.
3) Name(s) of facility(ies) inspected.
4) Description of inspection activities.
5) Photographs and descriptions of areas of concerns.
6) All technical investigations, data analyses, and design studies.
7) All recommendations made during or as a result of the inspection.

The inspectors will distribute inspection reports to the facility.

8.0 Simulation of Emergency Control System Operation

All of the information in this section is covered in detail by FIST 4-1A, *Maintenance Schedules for Mechanical Equipment*, including maintenance tasks.

Testing and simulation of the emergency control system is essential to ensure rapid and remote closure of the emergency gates in case of failure or damage to a penstock between the service gates and the wicket gates. The emergency closure system will:

1) Prevent rapid dewatering of the penstock.
2) Minimize the loss of water from the upper reservoir.
3) Minimize the resulting property damage or loss of life.
4) Provide a means for regaining control of the hydraulic system.

8.1 Emergency Gate Tests

A critical part of testing the emergency control system is testing the penstock emergency gates. Prior to any gate tests, perform an air vent analysis to ensure that adequate venting capacity is available in the event of an emergency closure to prevent collapse of the penstock shell.

Performance of a balanced head closure test of the penstock emergency gates is important to ensure confidence in equipment operation. The gates should open and close freely without binding. For fixed wheel gates, the wheels should bear against the rails and roll freely as the gate moves up and down. Record critical data related to the gate tests, such as opening/closing times and operating pressures. These data will allow comparison to future gate tests to assist in determining if a problem exists as evidenced by an increase in opening/closing times and operating pressures.

Performance of a full flow, unbalanced head closure test of the penstock emergency gates is also of high importance to ensure confidence of equipment operation. Record critical data related to the gate tests, such as opening/closing times and operating pressures. These data will allow comparison to future gate tests to assist in determining if a problem exists as evidenced by an increase in opening/closing times and operating pressures.

9.0 Load Rejection Tests and Readjustment of Governor

9.1 Hydraulic Transient Analysis

Prior to performing load rejection tests, perform a hydraulic transient analysis. The transient analysis consists of a computer simulation of the penstock to calculate pressures at all critical locations along the penstock. The magnitude of the hydraulic transients or water hammer that occurs during rapid load changes or load rejection depends largely on the full rate closing and opening wicket gate timing.

Reclamation uses a computer program to simulate water hammer and mass oscillation in the penstocks and water conduits. The programmer specifies the components, boundary conditions, schedule of the gate or valve position and turbomachinery operating conditions, and parameters which initiate and control the hydraulic transient. The output of the program, as used by Reclamation, consists of gate position, unit speed, and penstock or spiral case pressure versus time graphs for various initial conditions and rates of gate closure.

The program is used to predict optimum full rate wicket gate timing very accurately prior to testing. The results of the program can then be verified with tests at less than worst case conditions to minimize the risk of damage and equipment wear.

9.2 Load Rejection Tests

A load rejection test is not a requirement of the maintenance tasks outlined in FIST 4-1A, *Maintenance Scheduling for Mechanical Equipment,* for penstocks.

Load rejection analysis and testing is required to be performed when a runner replacement or rewind has occurred, initial unit commissioning, or for other testing requirements. A governor alignment shall be completed to verify the wicket gate timing prior to a load rejection test, reference FIST 2-3, *Mechanical Maintenance of Mechanical and Digital Governors for Hydroelectric Units*. A load rejection test is completed to verify permissives function correctly, wicket gate timing is correctly set to prevent over pressurization of the penstock, and excessive overspeed of the generator doesn't occur.

Perform a full series of load rejection tests and document the results. These tests should include all conditions that can occur during the full range of operation. Reference FIST 2-7, *Mechanical Overhaul Procedures for Hydroelectric Units*, for requirements of load rejection testing. Reference POM-184, *Load Rejection Test Data Sheet*, for information that is required to be monitored and recorded.

Based upon the information obtained from the load rejection tests or hydraulic transient study, adjust and calibrate the governor as required, reference FIST 2-3, *Mechanical Maintenance of Mechanical and Digital Governors for Hydroelectric Units*.

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RECLAMATION
Managing Water in the West

RECLAMATION MANUAL TRANSMITTAL SHEET

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Ensure all employees needing this information are provided a copy of this release.

Reclamation Manual Release Number and Subject

FIST 2-8, Inspection of Steel Penstock and Pressure Conduits

Summary of Changes

The following is a summary of changes in FIST 2-8:

- **Added black bold and bracketing for particular maintenance requirements**
- **Maintenance Tables: Consolidated requirements from different FIST manuals**
- **Removed maintenance tables for insertion to FIST 4-1A upon publishing**
- **Removed checksheet from appendix, it is now POM ### Form**
- **Revised formatting for consistency**
- **Section 3: expanded on types of inspections and methods for inspections**
- **Section 3.1.2: Added language if there is significant damage to coatings or signs of corrosion, detailed inspection frequency shall increase.**
- **Section 3.5: added more detail under safety checklist items**
- **Section 4.1.2: added information about coatings and linings**
- **Section 4.1.3.3: added definitions about types of corrosion**
- **Section 4.2: expanded information on rocker supports and added detail drawing**
- **Section 4.3: added details on repacking expansion joint**
- **Section 5.1.1: Added section describing ultrasonic thickness survey**
- **Section 5.1.2: Added descriptions on methods for quantitative coating assessments**
- **Section 9.2: Clarified requirements for load rejection testing**
- **Expanded and clarified information on equipment and how to perform maintenance tasks**
- **Incorporated comment revisions from formal review**

NOTE: This Reclamation Manual release applies to all Reclamation employees. When an exclusive bargaining unit exists, changes to this release may be subject to the provisions of collective bargaining agreements.

Filing instructions

Remove Sheets	Insert Sheets
NEW RELEASE	**FIST 2-8 pp 1-48**

All Reclamation Manual releases are available at http://www.usbr.gov/recman/

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